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Suspended sediment load estimation in a severely eroded and data poor catchment

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Abstract

Soil erosion rates are high in many parts of Southern Africa, and are likely to rise because of climate change. Suspended sediment loads (SSL) and yields (SSY) are used to measure and benchmark soil erosion and/or sediment transport rates and determine trajectories of change. Some modelled SSY are available for Southern African catchments, but there is a dearth of contemporary observed data. Northern hemisphere approaches to suspended sediment measurement and the calculation of loads and yields are often unsuited to Southern Africa: locally appropriate methods are required. The manual, flood-focused suspended sediment sampling programme that we implemented in the eroded and data-scarce Tsitsa River catchment (Eastern Cape, South Africa) monitored four sub-catchments from December 2015 to June 2019 at a sub-daily timestep. We used a discharge-weighted interpolation SSL estimator, investigating the effects of catchment area, hydrological regime, and sampling strategy on SSL, SSY, and variability, comparing our estimates with modelled results. Discharge increased with catchment area whilst flashiness (expressed by the Richards-Baker Flashiness Index) mainly decreased, and was similar to that of North American catchments. The sampling frequency required to maintain precision was inversely related to catchment area. Mean annual SSL ranged from 18 121 t year^{-1} in the 204 km^2 Gqukunqa River catchment to 984 267 t year^{-1} in the 1452 km^2 Inxu River catchment. Mean annual SSY ranged from 61 t km^2 year^{-1} in the 432 km^2 Pot River catchment to 678 t km^2 year^{-1} in the Inxu River catchment. Data stratification to limit sampling to wet-season flows did not significantly impact SSL estimates, but year-round sampling is required to maintain the citizen-technician sampling network through regular income. Modelled SSY estimates were higher than our measured estimates. Our approach to suspended sediment sampling, load and yield estimation is robust, sustainable, precise, and can be adapted for similar, remote catchments.

KEYWORDS
citizen technicians, hydrological variability, load and yield estimation, manual sampling, suspended sediment

1 | INTRODUCTION

1.1 | The development of suspended sediment load estimation methods

Excessive erosion rates negatively affect land and livelihoods, aquatic ecosystems, and water storage, transfer, and power generation infrastructure (Vercruysse et al., 2017). Suspended sediment load (SSL) and specific sediment yield (SSY) are used to benchmark, monitor and manage soil erosion and reservoir siltation.

From the 1970s, Walling and co-authors (e.g., Phillips et al., 1999; Walling, 1977a; Walling, 1977b; Walling & Webb, 1981; Walling & Webb, 1985) investigated the comparative precision and accuracy of integration/averaging/interpolation estimators, ratio estimators, and regression/extrapolation estimators (sediment rating curves) for estimating SSL. These researchers concluded that sampling method, frequency, and representativeness were responsible for much of the uncertainty associated with SSL estimation, but that the choice of estimator also impacted the bias, precision and accuracy of the resulting SSL. Largely working in humid-temperate systems, researchers were usually able to access good quality, decades-long, continuous SS data. These data were derived from manual sampling programmes, or from instrumented water sampling equipment (Horowitz, 2010). Increasingly, turbidity data from installed probes were used as a surrogate for SSC (e.g., Wass & Leeks, 1999). Where decadal, continuous, SSC and discharge data were available throughout the study period, sediment rating curves were found by these researchers to be the most accurate and precise method (Walling & Webb, 1985). However, when SSC data were few, and/or were weakly correlated with discharge data, interpolation or ratio estimators could be used (Quilbé et al., 2006).

Rating curves, initially developed by Campbell and Bauder (1940) express the empirical relationship between discharge and SSC (Walling & Webb, 1981). Commonly, least squares regression was performed using log-transformed SSC and discharge data. The regression equation was used to calculate SSC values from the continuous discharge data (Walling & Webb, 1981) for those periods where no SSC data existed. The resulting input-time-step SSL (for example, daily), including those calculated from the "synthetic" SSC values given by the rating curve, was summed to give, for example, annual SSL. This estimation method is precise, but may require a correction factor to be applied to compensate for the negative bias that occurs due to the retransformation from log-space to arithmetic-space (Ferguson, 1987; Horowitz, 2003). Importantly, whilst sediment rating curves can accommodate relatively sparse SSC data, they require a strong correlation between discharge and SSC (Grenfell & Ellery, 2009; Quilbé et al., 2006). Where the relationship is weak, subdividing or "stratifying" the available data for example by stage and/or season may improve the correlation, where intra-seasonal SSC and discharge variability is less than inter-seasonal variability (Walling et al., 2007).

1.2 | The status of measured suspended sediment data in Southern Africa

Soil erosion rates in some parts of South Africa are estimated to be among the highest in the world, with SSY of up to 2500 t km^{-2} $year^{-1}$. (Le Roux et al., 2015; Msadala et al., 2010). This may increase in future, since regional climate change is expected to result in longer droughts that will increase sediment availability, and more intense storm events that will increase soil erosion and sediment transport (Theron et al., 2021).

In Southern Africa there is a dearth of reliable, contemporary, directly-measured SSL and SSY data (Gwapedza, 2020). Vanmaercke et al. (2014) found that in nine of eleven global studies, suspended sediment yield data from African rivers typically contributed less than 10% of the total data used. According to Vanmaercke et al. (2014), nearly 138 reliable estimates of sediment yield have been published for Southern Africa that were based either on reservoir sedimentation (e.g., Foster et al., 2008) or on river monitoring (e.g., Scott et al., 1998). However, few of these data extend into the current millennium, and many were limited either by short term monitoring periods, or unreported measurement time-steps (Foster & Boardman, 2018). Rooseboom (1978) provided arguably the most comprehensive overview of South African sediment yields from a combination of river monitoring, (notably in the Orange River catchment), and dam sedimentation studies between 1911 and 1973. However, compared with SSC record lengths for European rivers (average ~13 years), most African SSYs were on average based on only 6 years of SSC data and most were undertaken pre-2010 (Vanmaercke et al., 2014): They provide historical benchmarking or localized case studies, but do not meet suspended sediment data needs of contemporary land and water resources planners and managers. A Google Scholar search for papers referencing Vanmaercke et al. (2014) returned 72 publications, but none dealt with measured suspended sediment data in Southern Africa (except Nyamela (2018), discussed later).

National, regional and catchment-scale SSL and SSY estimations in South Africa have relied on modelling and GIS, using hydrology and/or earlier dam sedimentation data for calibration and validation. Msadala et al. (2010) used the Revised Universal Soil Loss Equation (RUSLE) and GIS to predict sediment yield across South Africa. The USLE cannot however account for gully erosion, storage or hillslope coupling (De Vente et al., 2013). Assessing the uncertainty of modelled SSY using hydrology in South Africa is challenging, due to limited and failing Government rainfall and discharge monitoring networks (Kapangaziwiri et al., 2012). The sediment trapped in a reservoir or dam is a time-integrated sample that represents the minimum SSY of the upstream catchment, uncorrected for trap efficiency, from the date of construction (Hicks & Gomez, 2016; Verstraeten & Poesen, 2000; Verstraeten & Poesen, 2002). The estimation of SSY from dam sedimentation is self-evidently limited to catchments where suitable impoundments occur.

In the Tsitsa River catchment, Le Roux et al. (2008), Le Roux et al. (2015), Pretorius et al. (2016) and Le Roux (2018) used the Soil and Water Assessment Tool (SWAT). Gwapedza et al. (2021) used the sediment component (WQSED) of the Water Quality Assessment tool (WQSAM). SWAT and WQSED are based on the Modified USLE (MUSLE). No measured suspended sediment data were available to calibrate or validate these modelled results, with the exception of Gwapedza et al. (2021) who compared their findings for the Inxu River (a tributary of the Tsitsa) with measured SSY estimated by Nyamela (2018).

Nyamela's (2018) study was a component of the citizen technician-based manual suspended sediment sampling programme (2015-current) undertaken in the Tsitsa River catchment (Bannatyne et al., 2017). Designed specifically to meet the need for directly measured suspended sediment data in this highly-eroded, data-scarce catchment, the Tsitsa River catchment suspended sediment sampling programme supports the only estimation of measured SSL and SSY in Southern Africa based on long-term (i.e., >5 year) SS sampling since the 1980s (Foster & Boardman, 2018). The outputs from this catchment-wide programme provided the basis of this paper.

1.3 | Challenges to suspended sediment load and yield estimation in South Africa

In the global North, studies were often implemented by government environmental agencies, and facilitated by a well-developed road network that enabled ready access to river monitoring sites and water resources infrastructure that provided suitable structures for the installation and protection of equipment, and electricity available to power instruments such as probes and data loggers. Scientific and technical expertise were readily available to design, implement and maintain sophisticated suspended sediment monitoring regimes, guided by research which had been carried out in similar biophysical and socio-economic circumstances.

The contribution of northern hemisphere suspended sediment studies to the global literature has burgeoned since the early work of Walling and colleagues, both in terms of further investigations of estimators (e.g., Asselman, 2000; Horowitz, 2003; Phillips et al., 1999; Raymond et al., 2009) and of case studies, often using rating curves as the preferred SSL estimation approach (e.g., Harrington & Harrington, 2013; Skarbøvik et al., 2012). With the data and technical resources available, researchers were able to establish benchmark or true SSL, using these to compare the effects of sampling and data stratification, differences in catchment areas, and the effects of using a range of curve types and correction factors on bias, accuracy, and precision. This growing body of knowledge has provided a broad and reliable base upon which to extend research to other, similar, catchments. In contrast to the global North, there is a scarcity of contemporary, region-specific literature and expertise to guide direct suspended sediment monitoring and SSL estimation in Southern Africa. A general dearth of financial, technical, and human resources further hampers the design and implementation of suspended sediment monitoring programmes and the analysis of samples and data (Gwapedza, 2020).

Findings from northern hemisphere studies show that the multiscale spatial and temporal variability of suspended sediment transport is largely driven by climate, and thus by hydrology (Horowitz et al., 1990; Vercruysse et al., 2017; Williams, 2011). Flood events carry most of the SSL during a given period (Regüés, 2013; Sun et al., 2001): SSL and SSY are underestimated if flood events are not monitored (Gwapedza et al., 2021; Harrington & Harrington, 2013; Horowitz, 2008). Vanmaercke et al. (2012) found in a study of mainly northern hemisphere catchments that the frequency and rapidity of rising discharge, or “flashiness”, impacted the variability of estimated SSL.

In Southern Africa, it is more challenging to relate suspended sediment to discharge. Hydrological analyses intended to represent and predict hydrological responses (for example, flow duration curves and flood frequency analyses) typically require at least 20 years of continuous streamflow data (Olden & Poff, 2003). The required long-term hydrological data are often lacking for Southern African catchments, hampering the reliable determination and comparison of hydrological variability and flashiness, and making flood prediction difficult (Poff et al., 2006). Hydrological variability in the southern hemisphere is said to exceed that of the northern hemisphere, with the greatest variability occurring in Southern Africa and Australia (Peel et al., 2004). These factors present challenges for flood-focused sampling programme design, whilst heightening the risks involved with manual suspended sediment sampling (Bannatyne et al., 2017).

In both urban and rural areas in South Africa, adverse social conditions lead to extremely high rates of theft and vandalism (Bannatyne et al., 2017). Sparse and poorly maintained rural road infrastructure makes access to remote rural sites difficult and time-consuming, limiting the ability of researchers to undertake sampling programmes that aim to focus on flood events (Bannatyne et al., 2017). The absence of suitable structures and power supply precludes the use of all but the simplest and robust installed equipment, such as pressure loggers fixed securely and unobtrusively to the riverbed.

Credible, affordable, locally-appropriate approaches to suspended sediment measurement and SSL estimation are required in developing regions. This paper describes our approach to manual suspended sediment sampling and SSL estimation in the highly eroded and data scarce Tsitsa River catchment in South Africa. We present the measured SSL and SSY for four sub-catchments, describe the suspended sediment concentration (SSC) and discharge data distributions and relationships, and investigate the effects of catchment size, hydrological regime, sampling strategy, and data stratification on SSL and SSY variability. Lastly, we compare our results with those from other studies.

2 | STUDY AREA DESCRIPTION

The Tsitsa River catchment is a 4900 km^2 tributary of the Mzimvubu River in the Eastern Cape Province of South Africa (Figure 1). It flows south-eastwards from the Drakensberg escarpment (~2700 m a.s.l.) to its confluence with the Mzimvubu River (~200 m a.s.l.). The upper part of the catchment is mainly privately owned, whilst the lower catchment comprises a communally owned former "homeland" area, that is, an area reserved for black South Africans who were restricted from residing in "white" areas under the Apartheid regime (Rowntree et al., 2018). The communal area of the Tsitsa River catchment is one of the poorest and least developed regions in the country (Calmeyer & Muruven, 2015). Reliance on subsistence land-based livelihoods contributes to continued degradation (Hoffman & Todd, 2000; Rowntree et al., 2018).

The climate is sub-humid with mean annual rainfall ranging from ~1300 mm in the headwaters to ~620 mm in the lower catchment (ARC, 2012). Rainfall is seasonal, with 75% of MAP (824 mm) occurring between November and March (Moore, 2016). Monthly mean minimum/maximum temperatures range from −4.5/10.7°C (winter), and 17.1/29.8°C (summer). Sub-humid environments typically have distinct dry periods when sediment is generated and stored, to be mobilized particularly at the start of the wet season (Rowntree et al., 2017).

The topography is hilly to rolling with steep escarpments in the headwaters and middle catchment. Drakensberg basalt dominates the headwaters, whilst Clarens sandstone in the upper catchment and Elliot sand- and mudstones in the middle catchment give way to the Molteno and Tarkastad geology in the lower catchment, where mudstone (with some sandstone) predominates (Council for Geoscience, 2007). Dispersive, duplex soils occur frequently on the Tarkastad mudstones, where the lower Tsitsa, Gqukunqa, and Inxu Rivers are located and are highly vulnerable to soil piping and gullying (Le Roux & Sumner, 2012).

Although soil types vary considerably throughout the catchment, land ownership and geology/soils are spatially related: the upper part of the catchment is typified by relatively stable soils supporting commercial farmland and plantation forestry, whilst the lower catchment is characterized by dispersive duplex soils and extensively gullied areas throughout the degraded communal rangelands (Le Roux et al., 2015; Le Roux & Sumner, 2012). Figure 1 shows the location, geological formations, and mapped gullied areas of the Tsitsa River catchment, and the sub-catchment boundaries, four monitoring sites, and the Department of Water and Sanitation (DWS) gauging station used in this study.

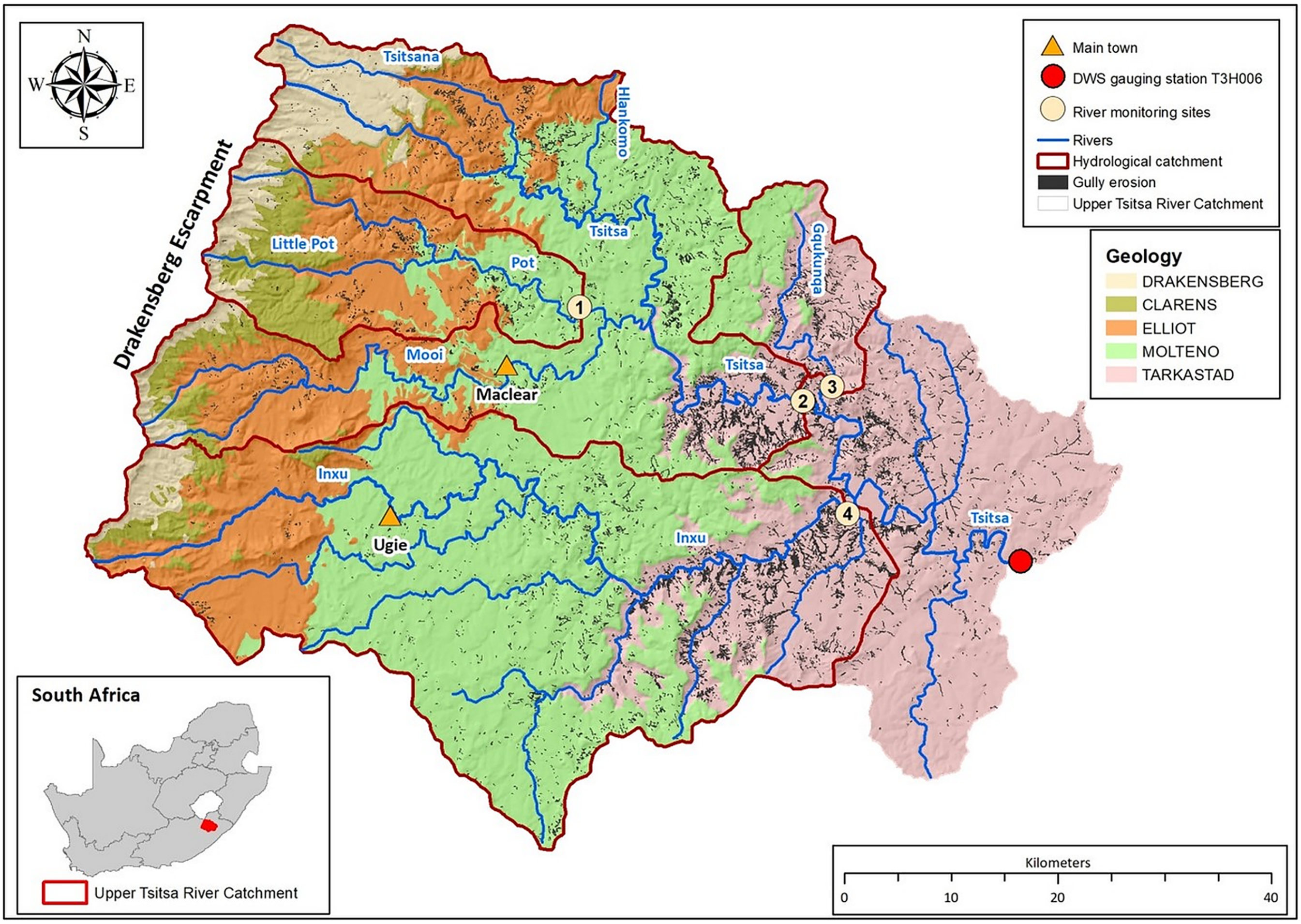

FIGURE 1 The Tsitsa River catchment. Geological formations, mapped gullied areas, sub-catchment boundaries, monitoring sites, and the DWS gauging station used in this study are shown. Monitoring site 1 = Pot; 2 = Tsitsa; 3 = Gqukunqa; 4 = Inxu. Map by N.H. Huchzermeyer

TABLE 1 River names, monitoring site coordinates and catchment characteristics (in order of increasing catchment area)

Site number (Figure 1)	River	Site coordinates	Catchment area (km^2)	Average catchment thalweg gradient (%)	Dominant catchment vegetation	Dominant catchment geology
3	Gqukunqa	−31.09027 28.66896	204	1.71	Grassland	Mudstone and sandstone
1	Pot	−31.0262 28.43181	432	2.00	Crops, pasture	Sandstones and mudstones
4	Inxu	−31.18838 28.69073	1452	0.85	Grassland	Mudstone and sandstone
2	Tsitsa	−31.10318 28.63863	1881	1.11	Grassland	Mudstone and sandstone

Table 1 summarizes the specific characteristics of the four monitoring sites. Data monitored at the Pot River site (Site 1 on Figure 1) are representative of the upper part of the Tsitsa River catchment. The data from the sites on the Tsitsa (Site 2), Gqukunqa (Site 3) and Inxu (Site 4) rivers represent the lower part of the Tsitsa River catchment.

3 | DATA AND METHODS

3.1 | Suspended sediment monitoring

Full descriptions of the sampling and laboratory analysis methods are given in Bannatyne et al. (2017). The aspects which were most relevant to the reliability of measured SSL and SSY are described here.

Data collection for the study period spanned four wet seasons from 1 December 2015 to 31 May 2019. Suspended sediment monitoring or sampling using installed equipment was precluded by the described biophysical, socio-economic and infrastructural conditions. Samples were manually collected by people who lived close to the river and were trained and paid as Citizen Technicians (CTs). The funding for the CTs was provided by a job-creation scheme, the main aim of which was to meet set targets across all government departments for person-days achieved by part-time, labourer-level employment (Cockburn et al., 2018).

Suspended sediment samples were collected according to a flood-focused, stratified regime, that is, sampling was done at least once per day and increased to catchment-specific shorter intervals (flood sampling) when a rise in water level was observed by the CT. CTs were paid per sample. To maximize their opportunities for sampling floods, CTs sampled (and therefore checked the river for a rise in water level) before 11:00 AM and again after 2:00 PM in the wet, summer months. For the relatively small Pot and Gqukunqa river catchments, flood samples were taken at 15-min intervals to record the changes in SSC occurring throughout the hydrograph. In the larger Tsitsa and Inxu river catchments where floods were expected to be more attenuated, a flood sampling interval of 45 minutes was adopted. In the winter dry season, one sample per day was collected, mainly to retain the CT until the wet season by providing a basic income, but also because of the possibility of their observing and sampling any infrequent high flows resulting from rainfall or snowmelt.

FIGURE 2 A citizen technician who has used a pole-and-jar isokinetic sampler to take a depth-integrated suspended sediment sample through the water column at the river bank. The inset shows the 450 ml plastic jar being screwed into the head assembly of the wooden pole

Sampling was suspended when bank conditions were unsafe, (for example during extreme flooding or lightning) and was never undertaken at night. The rising limbs of floods were therefore often missed, and the overnight floods that frequently occurred due to late afternoon summer thunderstorms were never sampled, thereby reducing the representativeness of the resulting suspended sediment data.

The CTs collected depth-integrated samples using a 2 m pole-and-jar isokinetic sampler. The head assembly of the sampling pole had a protruding 5 mm diameter plastic inlet pipe, and a breather pipe extending up the handle of the pole (Figure 2).

FIGURE 3 A researcher attaching a Solinst 3001 pressure logger (in a tamper-proof steel housing) to a rock outcrop in a riverbed, during winter low flow conditions

To take a sample, the CT labelled a 450 ml plastic jar with a site code and sample number, screwed it into the head assembly, and then lowered it down to the riverbed and back up to the surface, being careful not to disturb any bed sediments. Unlike an open-jar sample, the resulting sample was representative of the water column at the river bank (Rooseboom & Annandale, 1981).

Once taken, each sample was dosed with a commercially available water purification tablet as an algaecide (17 mg sodium dichloroisocyanurate) and firmly capped. Replicate samples intended as an indication of data precision were taken at each site once each week, by collecting three samples as quickly as possible. Sample jars were stored in the CTs homes before being picked up at ~8-weekly intervals by a laboratory and field technician and taken to Rhodes University. Smartphones loaded with electronic forms guided the CTs through their sampling protocol. Manual entries, GPS, and photographs were used to recorded sample numbers, positional data, river and weather conditions, and the date and time of sampling. The forms were sent to a database platform using the local cellular network. Sampling information was therefore usually available to researchers at Rhodes University in near real-time, ensuring compliance with sampling protocols as the first step in data quality control.

3.2 | Discharge monitoring and calculation

Solinst model 3001 pressure loggers were installed on hard rock outcrops in riverbeds (Figure 3) and synchronized with nearby Solinst Gold barologgers to collect continuous water level data at 20-min intervals. Figure 3 shows the installation of a pressure logger (in a tamper-proof steel mounting) during winter when the clear, low baseflow allowed safe access to the river bed. Data from the loggers were downloaded annually, again during winter baseflow conditions. Discharge ($m^3\ s^{-1}$) was calculated using rating curves based on measured flows at a range of stages.

3.3 | Spatial and temporal suspended sediment data representativeness

The selection of study sites, and therefore the overall spatial design of the sampling programme, was constrained by the availability of a CT who was resident within 500 m of a river sampling site that was safe to access under all but extreme flow conditions, and suitable for pressure logger installation. No reliable CT was available to sample the site at the DWS gauging station located on the Tsitsa River at the outlet of the study catchment (Figure 2). A continuous recording acoustic backscatter SSC probe that we installed and connected to existing DWS infrastructure at the gauging station was destroyed twice by lightning, each time during the first storm of the wet season.

The depth-integrated samples taken by the CTs were representative of the water column close to the bank, but it was unsafe for researchers to collect the necessary width and depth-integrated samples to determine the representativity of CT bank-side sampling except during low-flow conditions.

Over 70% of the available days were sampled at least once at the Pot, Inxu, and Tsitsa monitoring sites, and 61% of days at the Gqukunqa site. This was good temporal SSC data coverage according to Richards (1998) who considered 29 samples per year (8%) to be adequate temporal coverage.

3.4 | Hydrological representativity of suspended sediment sampling

Sampling frequency does not equate directly to data representativeness unless high, sediment-transporting flows are sampled (Walling et al., 1992). The hydrological representativity of the sampling period was determined by comparing the annual maximum peak flows of the study period with the long-term hydrological record, using data from DWS gauging station T3H006 (see Figure 2).

The degree of high flow sampling achieved at each site was assessed by comparing the quartile distribution of sampled mean daily discharges (i.e., 0%–25%; 26%–50%; 51%–75%; 76%–100% of maximum mean daily discharge) with the quartile distribution of all mean daily discharges at that site over the study period.

3.5 | Hydrological variability

The Richards-Baker Flashiness Index (R-B Index) allows comparison of the annual hydrologic variability between catchments, independent of their area and climatic zone (Baker et al., 2004). The R-B Index can be reliably determined with annual, rather than multi-decadal, discharge data. The R-B Index was determined per site per year (Equation (1)).

$$\mathrm{R-BIndex} = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}, \tag{1}$$

where: R-B Index = Richards-Baker Flashiness Index; q_i = mean daily discharge ($\mathrm{m^3\ s^{-1}}$).

The Gqukunqa and Pot catchments were relatively small (<400 $\mathrm{km^2}$) whilst the Inxu and Tsitsa were relatively large catchments (~1400 $\mathrm{km^2}$ ~ 1900 $\mathrm{km^2}$). The effect of catchment area was investigated using the range of inter-annual R-B Index, together with the results of stratification and decimation.

3.6 | Laboratory analysis of suspended sediment concentration

Evaporation was the main method used to determine suspended sediment concentration (SSC, $\mathrm{g\ m^{-3}}$). Sample jars were allowed to settle for at least one month, the supernatant was siphoned off using a J-tube, and the remaining 50 ml (i.e., 11%) was evaporated. Turbidity was also used as a measure of suspended sediment, with no further analysis taking place for samples that measured less than 200 nephelometric turbidity units (ntu). At each site, ~500 samples measuring 0–999 ntu (the instrument maximum) were analysed using both methods, in order to determine the site-specific turbidity/SSC relationships using linear regression.

During the first six months of the sampling programme, electrical conductivity (EC) was measured and converted to total dissolved solids (TDS, $\mathrm{mg\ L^{-1}}$) for 100 whole-water samples at each site, that were representative of the range of flows. The maximum mass of TDS in the 11% of the sample remaining after siphoning was calculated, to determine if TDS levels (including the 17 mg sodium dichloroisocyanurate algicide) were high enough to influence SSL estimation.

3.7 | Suspended sediment load estimation

SSL is the mass of suspended sediment transported through a river gauging site (Equation (2)).

$$\mathrm{SSL} = \mathrm{SSC} \cdot Q, \tag{2}$$

where: SSL = suspended sediment load (e.g., $\mathrm{g\ s^{-1}}$); SSC = suspended sediment concentration (e.g., $\mathrm{g\ m^3}$); Q = discharge (e.g., $\mathrm{m^3\ s^{-1}}$).

Mean daily SSC and mean daily discharge were used as the input timestep or "unit load" for the estimation of annual SSL. Instantaneous SSL was not computed, due to the workload required to align the sporadic, asynchronous SSC data with the 20-min discharge data for 16 data-years.

A site-specific turbidity/SSC relationship was developed from paired turbidity/SSC values for samples with low suspended sediment (i.e., turbidity = <200 ntu) using linear regression. Calculated SSC values were derived by applying the resulting equation to the samples in the laboratory analysis dataset for which only turbidity had been measured.

Mean daily SSC was derived from the resulting measured and calculated SSC data that were available for each day ($n = 1$ to ~40, depending on river conditions) using time-weighted mean concentration (TWMC, Equation (3)), whilst daily discharge was averaged from the 72 × 20-min discharge values recorded from 12:00 AM to 11:40 PM.

$$\mathrm{TWMC} = \frac{\sum_{i}^{n} (c_i * t_i)}{\sum_{i}^{n} (t_i)}, \tag{3}$$

where: TWMC = time weighted mean concentration ($\mathrm{mg\ L^{-1}}$); c_i = SSC ($\mathrm{g\ m^3}$) for the ith sample; t_i = time for the ith sample; n = number of samples.

Mean daily SSL was estimated by adding a constant to Equation (2) to account for the time-period and convert the measurement units, for example $\mathrm{g\ s^{-1}}$ to $\mathrm{t\ d^{-1}}$. (Equation (4)) (Gray & O'Halloran, 2015; Gray & Simoes, 2008; Nolan et al., 2005).

$$\mathrm{SSL} = kQC, \tag{4}$$

where: SSL = Suspended sediment load ($\mathrm{t\ d^{-1}}$); $k = 0.08604$, a factor to convert $\mathrm{g\ m^3\ s^{-1}}$ to $\mathrm{t\ d^{-1}}$; Q = Mean daily discharge ($\mathrm{m^3\ s^{-1}}$); C = Mean daily SSC ($\mathrm{g\ m^3}$).

SSY ($\mathrm{t\ km^2\ year^{-1}}$) for a particular catchment was determined by dividing the SSL measured at the monitoring site by the area of the effective catchment.

A decision tree was used to assist with estimator selection (Figure 4, after Quilbé et al., 2006), using their measure of success

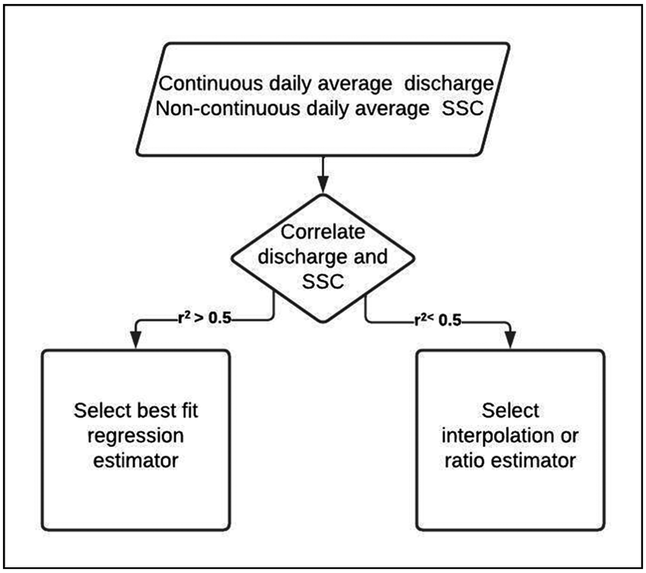

FIGURE 4 Flow diagram for SSL estimator selection, based on R^2 of SSC/discharge regression (after Quilbé et al., 2006)

criterion (R^2 of SSC/Q < > 0.5) to choose between regression, and interpolation (also called integration or averaging estimators) or ratio estimators.

A common form of discharge-weighted mean interpolation estimator is given in Equation (5) (Walling et al., 1992). When continuous discharge data are available, this estimator is less biased than, and therefore preferable to, estimators that use only the discharge data associated with suspended sediment sampling (Walling et al., 1992).

$$\text{Total SSL} = \frac{K\sum_{i}^{n}(C_i * Q_i)}{\sum_{i}^{n} Q_i} Q_r, \tag{5}$$

where: $k = 0.08604$ a factor to convert g m^3 s^{-1} to t d^{-1}; C_i = Mean daily SSC (g m^3); Q_i = mean daily discharge (m^3 s^{-1}); Q_r = mean discharge for the study period (m^3 s^{-1}); N = number of samples.

Equation (6) (Quilbé et al., 2006) is an interpolation estimator that weights mean daily SSL by the mean of measured discharge. It has the advantage of providing insight into the representativeness of sampled discharge through the term $\frac{\mu_q}{\overline{Q}}$.

$$\text{Total SSL} = \overline{CQ}\frac{\mu_q}{\overline{Q}} n, \tag{6}$$

where: $\overline{CQ}$ = mean daily load (g m^3); $\overline{Q}$ = mean discharge of sampled days (m^3 s^{-1}); μ_q = mean annual discharge (m^3 s^{-1}); n = number of samples.

Ratio estimators such as Beale's ratio estimator (Littlewood, 1995) are appropriate when continuous discharge data, but few suspended sediment data, are available. As noted (see Section 3.3), suspended sediment data were available for 61% to 73% of the sampling period, therefore ratio methods were not considered for use in this study.

3.8 | Data stratification and decimation

The SSL calculated from all the available data was taken to be the true (i.e., best estimate of) annual SSL. At each site, data were stratified by mean daily discharge and by season. Stratified SSLs were expressed as a percentage of the true annual SSL estimated from the full dataset. One stratification subset was limited to suspended sediment data collected during the highest 20% of mean daily discharge, to determine the effect on annual SSL of sampling only during high water conditions. A second stratification subset comprised all suspended sediment data collected between 1 October and 31 May, to determine the effect on annual SSL of sampling only during the wet season.

Sampling interval has a recognized impact on SSL precision (Horowitz et al., 2015; Walling et al., 2007). Mean daily SSLs were decimated to determine the effect on precision of restricting sampling to a given number of days per week. The SSLs resulting from the decimated data sets were analysed using percent coefficient of variation (%CV), and also expressed as a percentage of true annual SSL. The mean daily SSLs were sorted using the days of the week, and SSLs were calculated for all the subsets resulting from the permutations of 1 to 6 days per week. For example, the seven subsets for one day per week comprised Mondays; Tuesdays; and so on. The 21 subsets for two days per week comprised Mondays + Tuesdays; Mondays + Wednesdays; Mondays + Thursdays; and so on.

4 | RESULTS

4.1 | Representativity of bankside sampling

As noted, sampling did not take place during unsafe conditions which led to some days on which no samples were taken, or at night. Researchers could not determine the site-specific relationships between bank-side and mean channel SSC due to safety concerns. The samples collected by the CTs were likely to have lower SSC than channel mean SSC, especially during turbulent flood flows (Horowitz et al., 1990; Walling & Webb, 1981). Unsampled high flows (described later) and the unknown relationship between bank-side and mean channel SSC during the target flood flows contributed to the uncertainty of the resulting measured SSL and SSY.

4.2 | Total dissolved solids

The mean and maximum TDS of ~100 whole water samples, and the TDS calculated for the 50 ml of sample that remained after siphoning were compared with mean and maximum SSC at each site (Table 2).

The mass of TDS calculated from 11% of the maximum TDS at each site was insignificant in terms of the high-sediment samples which were the focus of this study. TDS was not considered in SSL estimation.

TABLE 2 Mean and maximum whole water TDS and SSC, and TDS after siphoning, at the four study sites from 1 December 2015 to 31 May 2016

Site	Whole water samples (450 ml)				Siphoned samples (50 ml)
	Mean TDS (mg L^{-1})	Mean SSC (mg L^{-1})	Maximum TDS (mg L^{-1})	Maximum SSC (mg L^{-1})	11% of maximum TDS (mg L^{-1})
Gqukunqa	146.20	795.92	243.43	15628.87	26.78
Pot	106.90	195.70	133.58	2751.12	14.69
Inxu	127.73	5011.42	188.18	69157.41	20.70
Tsitsa	93.68	488.05	147.23	9297.74	16.20

TABLE 3 Summary of samples analysed for SSC; for turbidity <200 ntu; for both; and the resulting SSC/turbidity relationships at the four study sites

Site	# Samples analysed for SSC	# Samples <200 ntu analysed for turbidity	# Samples analysed for both	Equation	R^2
Gqukunqa	1846	866	498	$y = 1.2137x + 36.547$	0.76
Pot	462	1386	634	$y = 0.8607x + 85.063$	0.68
Tsitsa	1787	986	504	$y = 1.2548x + 46.197$	0.82
Inxu	855	1073	564	$y = 1.2919x + 50.169$	0.77

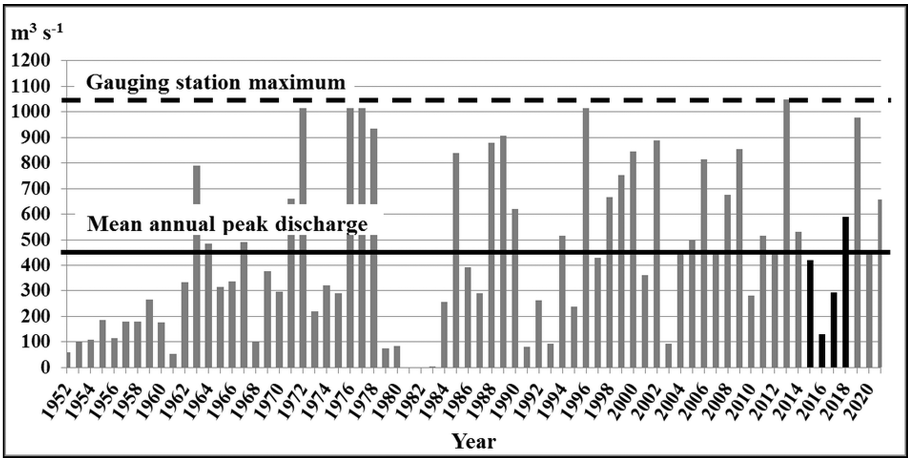

FIGURE 5 Annual peak discharges for the Tsitsa River at DWS gauging station T3H006 1952–2020 (DWS, 2002). The four darker bars represent the study period 2015–2019

4.3 | SSC and turbidity analyses and relationships

Table 3 summarizes the number of SSC and turbidity analyses at each site, and the SSC/turbidity relationships that were derived by linear regression of SSC and turbidity.

At the Gqukunqa and Tsitsa sites, the CTs took approximately twice as many high-sediment samples (>200 ntu) that were analysed for SSC, than low sediment samples (<200 ntu) that were analysed only for turbidity. At the Pot site, the reverse was the case, whilst the samples taken by the CT at the Inxu site were more evenly split. This distribution was due to a combination of CT diligence in observing and sampling flood flows, and the discharge characteristics of the river they were sampling: Not all CTs had the opportunity and/or were equally motivated to sample floods, and not all flood flows were high in suspended sediment. SSC was calculated from turbidity for low-sediment samples by applying the site-specific equations listed in Table 2. Time-weighted mean daily SSC was calculated from the resulting dataset using Equation (3).

4.4 | Representativity of sampled discharge

4.4.1 | Long term flow record

The high inter-annual variation of maximum peak flows in the Tsitsa River catchment is evident from Figure 5, from which it can also be seen that the study period was representative of dry conditions. Analysis of peak annual discharges recorded at the outlet of the study catchment (DWS gauging station T3H006, see Figure 2) show that although the 2018–2019 wet season was ~20% above mean peak annual discharge, other years were below, with 2016–2017 among the 12 lowest peak annual discharges since records began in 1952.

4.4.2 | Study period

The distribution of flows within the study period is summarized in Table 4 which lists the percentage distribution of mean daily discharge volumes (i.e., 25%; 50%; 75%; 100% of maximum mean daily discharge) at each site.

Flows during most of the study period, that is, 1200 of 1278 days, occurred in the lowest discharge range (0%–25%, Figure 6). These were sampled at least 69% of the time but were the least important flows for suspended sediment transport. Higher discharges (26% to 50% of maximum mean daily discharge) occurred on 18 to 57 days during the study period and were sampled at least 74% of the time.

The highest 49% of discharges, that is, the focus of the suspended sediment sampling programme, occurred only for six to twenty of the 1278 days. Figure 6 shows that flows on all 14 of these days were sampled at the Tsitsa River site, 5 of 6 days at the Inxu, 5 of 7 days at the Gqukunqa, and 16 of 20 days at the Pot, indicating that the “flood-focused” aim of the sampling programme was largely achieved.

4.5 | SSC and discharge relationships and the choice of SSL estimator

Figure 7 confirms that most suspended sediment samples were taken during the low flow/low sediment conditions that prevailed during the study period. Mean daily SSC values varied widely for the same mean daily discharge value, particularly for low to medium discharges.

The coefficient of determination (R^2) suggested that only ∼10% to ∼30% of the SSC variability was “explained” by discharge. Log

TABLE 4 Mean daily discharges ($m^3\ s^{-1}$) at each site expressed as percentage of maximum mean daily discharge for the study period

Site	25%	50%	75%	Maximum mean daily discharge (100%)
Gqukunqa	6.23	12.45	18.68	24.90
Pot	13.45	26.89	40.34	53.79
Inxu	44.81	89.62	134.43	179.24
Tsitsa	60.27	120.55	180.82	241.10

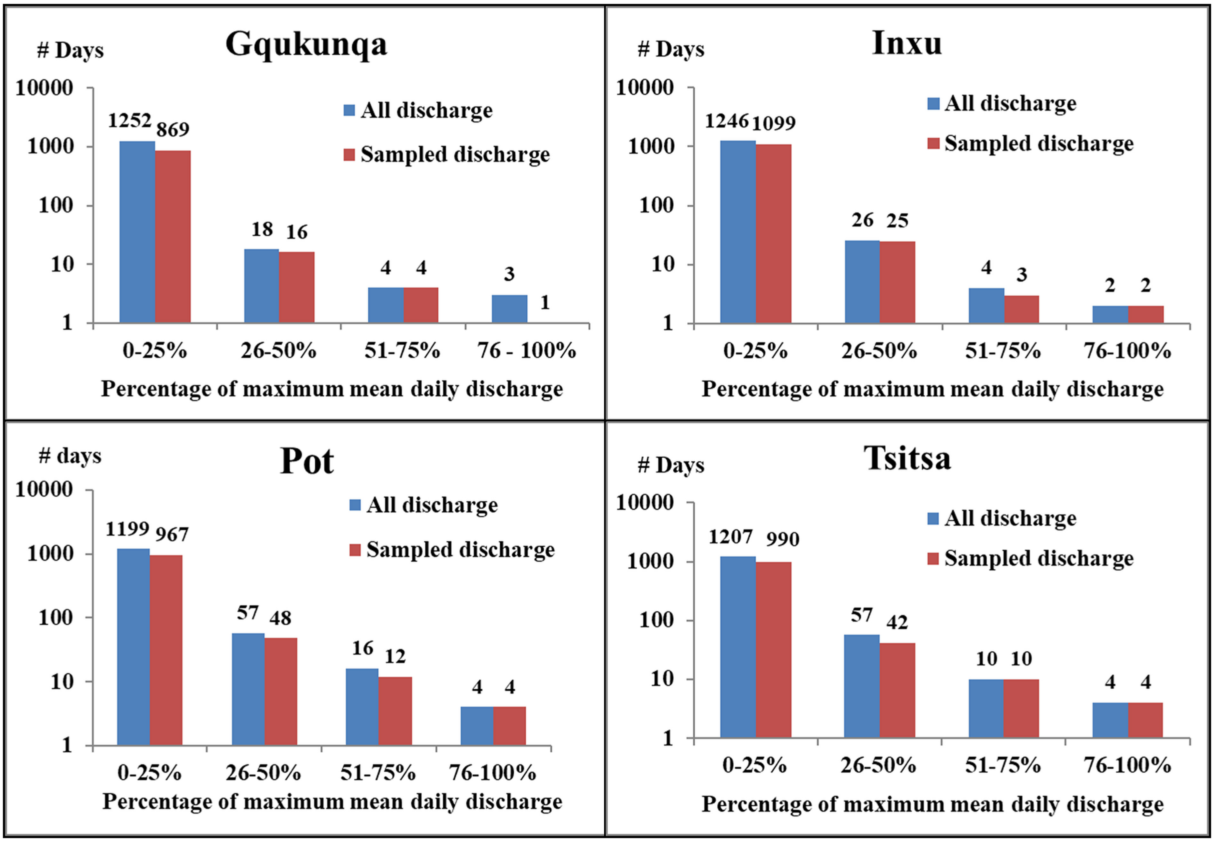

FIGURE 6 The frequency distributions (in days) of mean daily discharge (blue) at each site with the frequency distributions of mean daily discharges for days when suspended sediment was sampled (red)

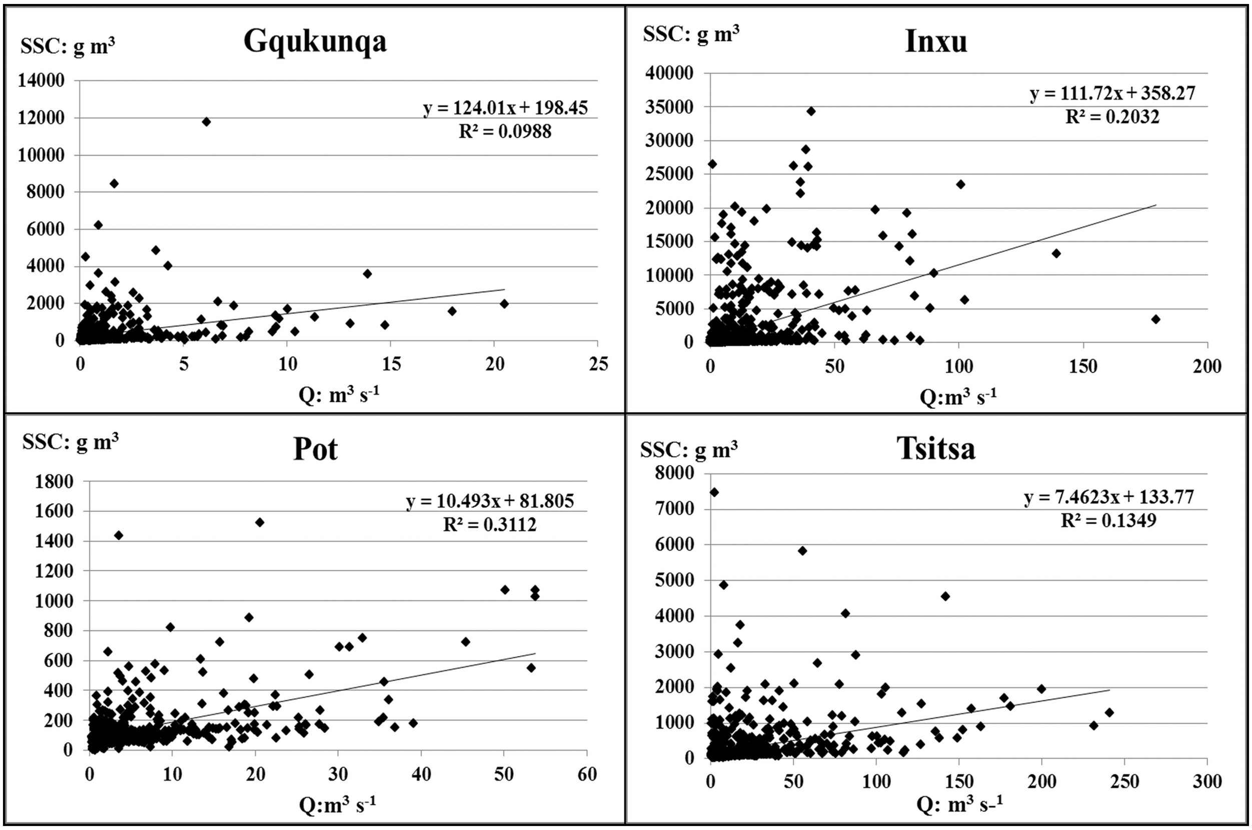

FIGURE 7 Mean daily discharge: Mean daily SSC relationships at the four study sites, 2015–2019. Outliers have already been removed as part of earlier data quality control

TABLE 5 SSC/Q R^2 for untransformed, log-transformed and stratified data 2015–2019

Site	Data set	R^2 (Q/SSC)
Gqukunqa	All	0.10
	All, log transformed	0.18
	Upper 20% of discharge	0.04
	Wet season	0.10
Pot	All	0.31
	All, log transformed	0.22
	Upper 20% of discharge	0.27
	Wet season	0.35
Inxu	All	0.20
	All, log transformed	0.31
	Upper 20% of discharge	0.10
	Wet season	0.16
Tsitsa	All	0.13
	All, log transformed	0.28
	Upper 20% of discharge	0.13
	Wet season	0.10

TABLE 6 The ratio of mean sample discharge to mean annual discharge at all sites

Year	Gqukunqa	Pot	Inxu	Tsitsa
2015–2016	0.84	0.95	0.93	1.11
2016–2017	0.81	0.97	0.99	0.87
2017–2018	0.78	1.08	1.02	1.02
2018–2019	1.05	1.02	0.89	1.06

transformation, and stratification using data only from the highest 20% of discharge, and data only from the wet season (1 October to 31 May) were performed. This did not improve linear R^2 above the 0.5 suggested by Quilbé et al. (2006) as a minimum criterion for selecting rating curves as SSL estimators (Figure 4, Table 5).

Rating curves were therefore rejected in favour of using Equation (6) as an SSL estimator which also provided an indication of the representativity of sampled discharge. The ratio derived from $\frac{\mu_q}{Q}$ (Equation (6)) typically ranged from 0.80 to 1.20, (Table 6) indicating that mean sampled discharge was generally within 20% of mean annual discharge.

4.6 | Suspended sediment load estimation

Table 7 provides the values for the annual and mean SSL, SSY and discharge at the study sites for the four years of the study period, as well as the area, %CV SSL/Y, %CV discharge, and flashiness for each catchment.

TABLE 7 Annual and mean SSL, SSY; annual and mean discharge; variability expressed as %CV: And Richards-Baker Flashiness Index at the four study sites, arranged by catchment area

Year		Gqukunqa	Pot	Inxu	Tsitsa
Catchment area (km^2)		204	432	1452	1881
2015–2016	SSL (t year^{-1})	15 774	23 334	342 849	174 734
	SSY (t km^{-2} year^{-1})	77	54	236	93
	Mean discharge (m^3 s^{-1})	0.39	3.85	6.11	13.67
2016–2017	SSL (t year^{-1})	11 737	34 082	395 724	199 668
	SSY (t km^{-2} year^{-1})	58	79	273	106
	Mean discharge (m^3 s^{-1})	0.69	3.73	7.04	11.93
2017–2018	SSL (t year^{-1})	29 709	28 286	2 094 703	417 387
	SSY (t km^{-2} year^{-1})	146	65	1443	222
	Mean discharge (m^3 s^{-1})	1.12	4.44	10.32	19.24
2018–2019	SSL (t year^{-1})	15 264	20 104	1 103 793	238 599
	SSY (t km^{-2} year^{-1})	75	47	760	127
	Mean discharge (m^3 s^{-1})	0.67	2.82	7.31	14.16
Mean SSL (t year^{-1})		18 121	26 451	984 267	257 597
Mean SSY (t km^{-2} year^{-1})		89	61	678	137
Mean discharge (m^3 s^{-1})		0.72	3.71	7.69	14.75
% CV SSL/Y		37.9	20.0	71.9	36.9
% CV discharge		36.4	15.6	20.5	18.5
Flashiness (R-B Index)		0.44	0.35	0.28	0.28

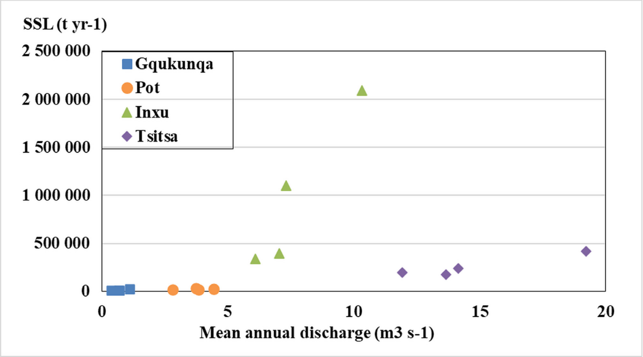

FIGURE 8 Annual SSL plotted against mean annual discharge for the four study sites

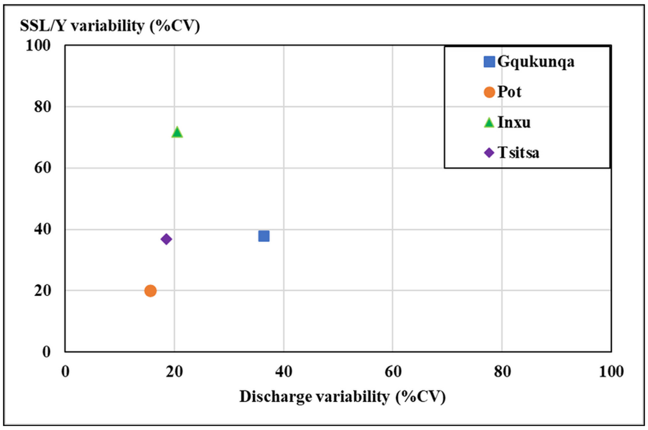

FIGURE 9 SSL variability plotted against discharge variability (expressed as %CV) at the four study sites

Mean discharge increased with catchment area (Table 7, Figure 8), with SSL echoing this trend as expected in the Gqukunqa, Pot, and Tsitsa catchments. The Inxu River catchment was a prominent outlier to the area-related SSL trend shown by the other three catchments. Figure 8 illustrates that annual SSLs were two to five times higher for the Inxu than for the Tsitsa, although the Inxu catchment is smaller than the Tsitsa by ~430 km^2. The Gqukunqa River catchment is ~50% smaller than the Pot River catchment, yet SSY was ~30% higher. SSY for the Inxu River catchment was five times that of the Tsitsa River catchment although catchment characteristics were broadly similar. Flashiness broadly showed the expected inverse relationship to catchment area (Table 7): the Gqukunqa River was flashier than the Pot River, whilst the R-B Index was the same for the Inxu and Tsitsa Rivers (Table 1). The R-B Index of the four catchments was similar to rivers in the United States of similar catchment size (Baker et al., 2004).

Inter-annual variability of SSL/Y (expressed as %CV in Table 7 and Figure 9) and of discharge were not strongly related to catchment area. Discharge variability was not a predictor of SSL/Y variability: Generally, higher variability was linked to higher SSL/Y.

These findings echo those of Vanmaercke et al. (2012) for catchments in Europe, the Middle East, and the USA.

4.7 | Data stratification

SSL estimated from the wet season data only (1 October—31 May, Figure 10) did not differ significantly from SSL estimated from the full dataset (−11% to +8%). 2015–2016 is identical in all cases because the study began in December 2015.

SSL estimated from the highest 20% of discharge was ~25% higher than true SSL estimated from the full dataset (Figure 10).

This emphasized the importance of sampling high discharges, particularly within the context of the relatively dry study period

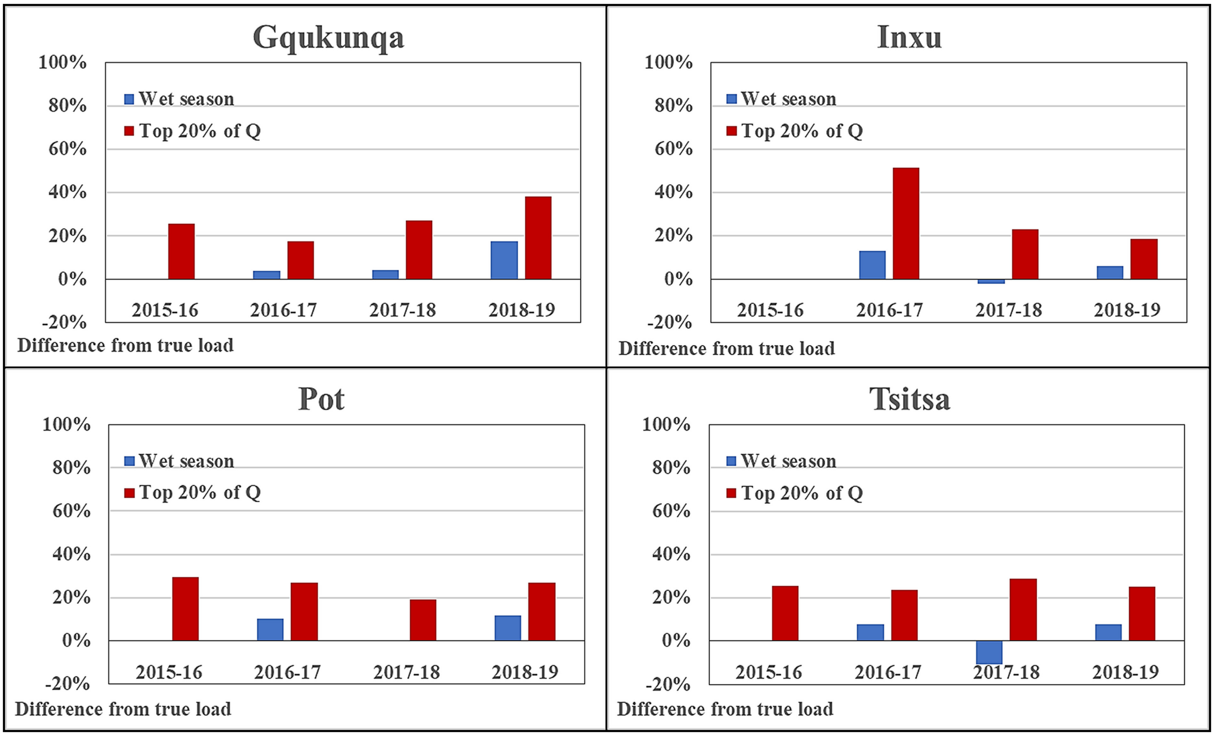

FIGURE 10 The percentage difference from true annual SSL: SSL estimated from the highest 20% of discharge only, and from wet season data only at the four study sites. True load was estimated from all the available data)

(Figure 5) given that SSL estimations were heavily biased by data from low flow/low suspended sediment samples (Figure 6) and that some high flows were not sampled (Figure 7).

4.8 | The effect of sampling frequency and catchment area on SSL variability

SSL precision was expected to improve with more frequent sampling (Walling & Webb, 1981, 1985). Datasets were decimated to simulate sampling regimes of between 1 and 6 days per week. Figure 11 shows the variation in SSLs derived from these datasets expressed as %CV, indicating the precision resulting from different sampling frequencies.

SSL variability decreases markedly with increasing sample frequency, and less obviously with catchment area. The sampling frequency required to limit variability and optimize precision is inversely related to catchment area: In the Gqukunqa, sampling to achieve <20 %CV for SSL needed to be undertaken for six days per week, for the Pot five days per week, for the Inxu four, and for the Tsitsa three days per week.

5 | DISCUSSION AND CONCLUSIONS

5.1 | The sampling approach

SSL and SSY data are needed for land and water resource management in Southern Africa, but conditions are challenging, and resources are scarce in the region, constraining the use of established approaches to sampling, analysis and SSL estimation. Therefore, we developed and implemented a locally appropriate manual suspended sediment sampling programme to meet suspended sediment data needs in the remote, highly eroded and resource poor Tsitsa River catchment.

Our sampling programme is still ongoing since 2019, indicating that employing and training residents to undertake manual suspended sediment sampling is a feasible and effective approach. Basic sampling equipment has proved adequate, and sampling protocols and data quality control have been maintained using smartphone technology and a cloud-based data collection platform. Providing work experience and paying wages to the CTs was a positive input to individuals and local communities, whereas the purchase of a probe had no local benefit (Bannatyne et al., 2017). Despite the challenges presented by distance, climate, terrain, and lack of resources, the longest, sub-daily timestep, measured suspended sediment record in southern Africa since the 1980s has been achieved. This approach can be applied in other similar catchments.

5.2 | Sampling program design

5.2.1 | Seasonal and discharge stratified sampling

In the dry season collecting one sample a day incurred extra expense for little to no effect on SSL (Figure 10). It was, however, essential to

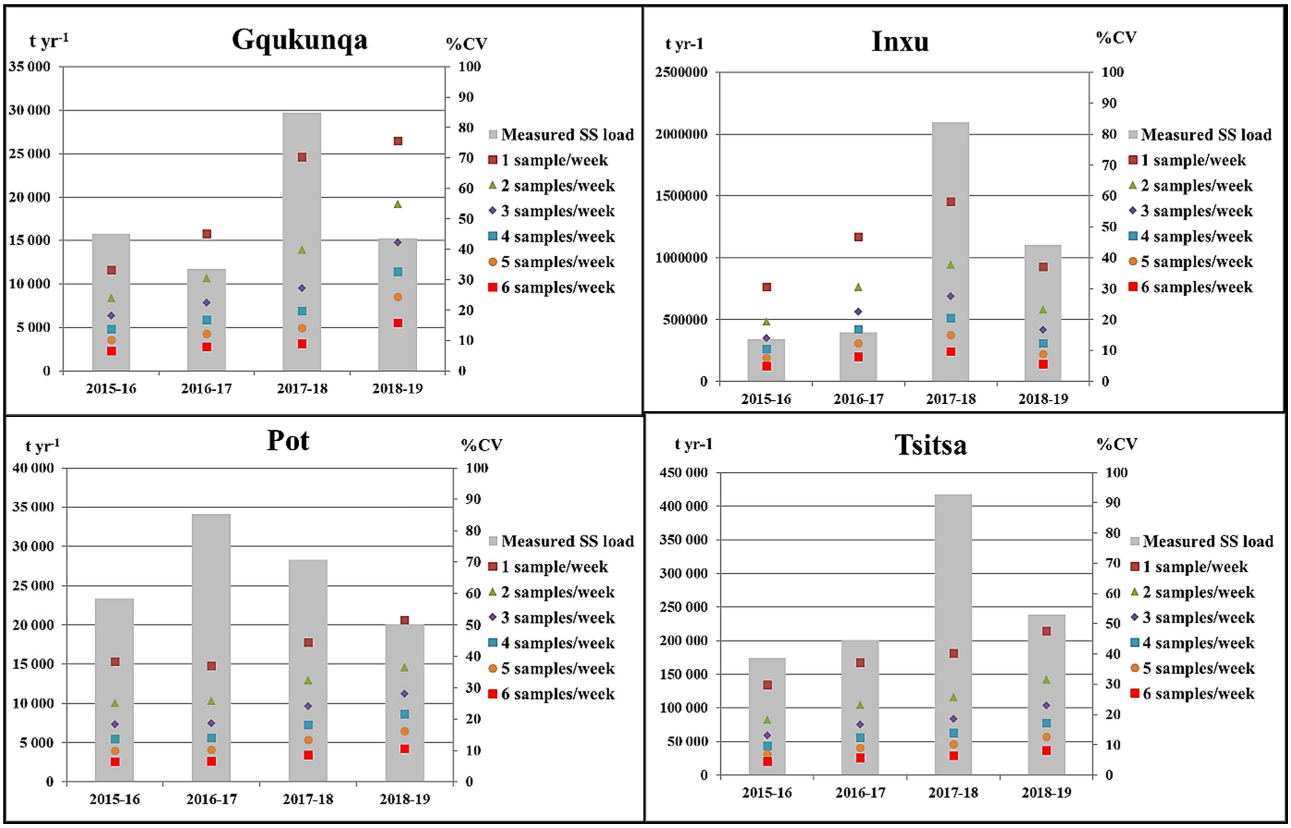

FIGURE 11 Graph showing the effect of sampling frequency on the variability (expressed as %CV) of calculated SSL at the four study sites. Columns represent the measured SS load for each year

maintain the continuity of the sampling programme. The reduced but regular income allowed the CTs to stay in the area rather than leaving to seek other employment. It also allowed CTs to observe and sample any high flows for example from snowmelt.

Initial protocols directed all samples to one of the two laboratory processes, that is, turbidity analysis or evaporation for SSC analysis. The seasonal stratification results indicate that adding a "dry season rule" would allow laboratory technicians to (discretely) discard most dry season samples except when the sample was >200 ntu. This would save time and cost, since far fewer jars would then be transported from the study area to the laboratory.

The results from discharge stratified sampling highlighted the importance of flood sampling, indicating that sampling high flows only would save time and costs. Again, the reduction/disruption of income would negatively affect the CTs willingness to remain with the programme, and floods would be more frequently missed rather than more frequently sampled without twice daily observation motivated by payment.

5.2.2 | Precision

We found that it would be possible to sample for fewer days per week in larger catchments while achieving the same precision as sampling at sub-daily timestep in smaller catchments (Figure 11). Again, the disadvantages of potentially missing flood flows and of not retaining the CTs due to intermittent periods without sampling likely outweigh the cost saving in most cases.

5.3 | The accuracy problem

The precision of our results was relatively straightforward to determine (Figure 11), but it was not possible to determine their accuracy. We planned to compare our results with those from an acoustic backscatter suspended sediment probe that we installed at an existing government discharge gauging weir in the Tsitsa (Station T3H006, Figure 1). Our assumption was that the probe would continually and consistently monitor SSC, providing the true SSL at that site sensu Walling and Webb (1981). SSL estimated using manually sampled data from a site upstream of the weir (collected only during daylight hours and in a potentially less consistent manner) could be compared with true SSL, giving insight to the accuracy of our sampling programme.

This was unsuccessful for three reasons that highlight the difficulties of monitoring suspended sediment in such regions: Firstly, we were unable to engage and retain a CT to sample at a site near to the gauging weir. Secondly, although we installed the probe using existing built and electrical infrastructure, it was twice destroyed by lightning during the first storms of the two consecutive wet seasons. Thirdly, on each occasion, the probe could only be retrieved months later during the following dry season and had to be sent to the USA for repair, proving too lengthy and costly a process to repeat a third time.

5.4 | Representativity

The necessary restriction to sampling from the bankside during safe conditions and daylight hours was a significant constraint to suspended sediment data representativeness. This was compounded by the inability of researchers (again due to safety concerns) to establish the necessary site-specific relationships between bankside and channel cross-section SSC. This introduced an unknown degree of uncertainty into our SSLs.

Sampling was achieved on 61% to 73% of the project days, but the four years (2015–2019) spanned by our study were relatively dry (Figure 6) and included one of the lowest annual peak flood discharges on record. The most frequently occurring and hence most frequently observed and sampled flows were less than 25% of maximum discharge for the study period, although the high flows that did occur were sampled at all sites (Table 6).

Taking these constraints together, it is reasonable to assume that our SSLs and SSYs were lower than if they had been corrected by a site-specific factor obtained from width and depth integrated sampling (Horowitz et al., 1990; Walling & Webb, 1981), and if the study had covered a more typical period of conditions in the Tsitsa River catchment.

5.5 | Choice of load estimator

The choice of SSL estimator can limit further uncertainty, but not compensate for data inadequacies (Walling & Webb, 1981). We rejected rating curves in favour of an interpolation estimator due to the weak SSC/discharge relationships that were found at all sites; the relatively high sampling coverage; and the continuous discharge record. This precluded the prediction of SSC from discharge in the Tsitsa River catchment, either from historic records from the DWS gauging weir T3H006, or in the likely event of SSC sampling ceasing in the future.

In less variable systems than the Tsitsa River catchment, log transformation and data stratification have been found to improve R^2 values and allow the use of sediment rating curves to estimate SSL. Neither manipulation produced R^2 above 0.3 in the study catchments. Weak SSC/discharge relationships were also reported by Grenfell and Ellery (2009) for the Mfolozi River in Kwa-Zulu Natal, and by Gwapedza et al. (2021) for the Inxu River. Rainfall frequency, erosivity, and spatial patterns (including antecedent conditions and sediment availability) have not yet been investigated in the study catchments: these factors may account for a significant proportion of the remaining 70%–90% of the SSC/discharge relationship, particularly if factors such as episodic connectivity of roads, paths and gullies are included.

5.6 | Hydrology, SSL and SSY in the Tsitsa River catchment

Our findings broadly echoed those of northern hemisphere researchers in terms of hydrological variability (Baker et al., 2004), the effects of sampling frequency on precision (Walling & Webb, 1981, 1985), and the relationships between catchment size, discharge, SSY, and SSY variability (Vanmaercke et al., 2012). This was perhaps due to the relatively dry period over which the study took place, during which the potential extremes of rainfall volume, erosivity and discharge were absent.

Our results allowed comparisons of soil loss and sediment transport in the four study catchments, and insight into their variability. The Gqukunqa River catchment was the smallest in area, had the lowest but most variable and flashy discharge, and the second most variable SSL/Y (Table 7, Figure 9). SSY was higher than for the Pot River catchment (Table 7), probably due to the erodible, gullied Tarkastad geology and communal land ownership present throughout the Gqukunqa River catchment (Figure 1). The mean SSC for the catchment was the second highest recorded, yet owing to very low discharge, SSL was the lowest estimated (Table 7), making the suspended sediment contribution of the Gqukunqa River catchment the least significant of the four catchments studied.

The Pot River catchment had the lowest mean SSC and mean SSY (Tables 2 and 7), and the least variable SSL/Y and discharge (Figure 9) as may be expected from the less erodible soils and private land ownership in the catchment (Figure 2, Table 1).

The mean discharge of the Inxu River was 50% of the Tsitsa River, but the Inxu River catchment was by far the most significant and variable source of suspended sediment (Table 7), despite its apparent similarity to the slightly larger Tsitsa River catchment (Table 1, Figure 1). Data from the Tsitsa and Inxu River sites were representative of private ownership in the upper thirds of the catchments and communal ownership in the remaining lower parts, and of the range of geology and soils from headwater Drakensberg basalts to the Tarkastad formation with its associated dispersive soils and extensive gully systems proximal to the sampling sites. Proportionally more of the Inxu River catchment than of the Tsitsa River catchment was underlain by the Tarkastad formation (Figure 1). The age, stage and stabilization of gullies in the Tsitsa and Inxu River catchments have not been quantified: The rate of sidewall undercutting and soil piping, whilst recognized as significant, was unknown as were the pattern, frequency and degree of gully connectivity (Le Roux et al., 2015; Pretorius et al., 2016). These factors, together with those already mentioned in connection with the weak SSC/discharge relationship, may be significant in explaining the very high and variable SSY estimated for the Inxu catchment.

5.7 | The implications for catchment management decision making

Our findings for each of the study catchments indicated that the spatially related factors of land ownership (encompassing land use and management) and geology strongly influenced SSL, SSY, and SSL/Y variability. Land ownership can be used as a basis to consider the implications for land and water resource management decision-making.

Although still governed by relevant legislation, land and water resource management are the responsibility of individuals and companies in the privately-owned areas of the four study catchments. The data from the Pot River catchment were representative of these areas. The extent and nature of landscape restoration or rehabilitation, for example of wetland and riparian zones, may be closely linked to the productivity of commercial agriculture, and be more spatially fragmented than in the communally owned areas. Farming and development activities should aim to avoid further land degradation in order to maintain the existing relatively low soil loss rates from these areas.

In highly erodible, hydrologically variable and communally owned areas such as the Gqukunqa and the lower parts of the Inxu and Tsitsa River catchments, landscape restoration and rehabilitation requires not only a better understanding of the relevant biophysical processes, but also collaborative approaches to land management involving communities, researchers, and practitioners (Blake et al., 2021; Itzkin et al., 2021). Poverty has a recognized impact on land use and management: communally developed and implemented strategies such as grazing and fire management that improve and sustain rural livelihoods would also improve landscape conditions, reducing erosion and suspended sediment transport (Rowntree et al., 2018).

TABLE 8 Comparison of modelled SSY for the Tsitsa River catchment above T3H006

Approach	SSY t km^{-2} year^{-1}	Reference
Revised universal soil loss equation (RUSLE) and GIS	1200–15 000	Le Roux et al. (2008)
SWAT with GIS	500 average	Le Roux et al. (2015)
SWAT and remote sensing/ object-based image analysis (OBIA)	1050	Pretorius et al. (2016)
WQSED	153	Gwapedza, 2020
SWAT (average 2015–2035)	1 to 30	Theron et al. (2021)

5.8 | The effect of load estimator on SSY

The influence of different modelling approaches on SSY estimation is evident from the information summarized in Table 8, which compares five SSY estimates for the Tsitsa River catchment above the DWS gauging weir T3H006 (Figure 2).

Le Roux et al. (2015) used a combination of the SWAT model (representing rill-interill erosion) and a gully expansion and sediment contribution estimation/model (in a GIS).

However, the “potential sediment yield” of Le Roux (2018) is probably overestimated since latter-mentioned gully model did not model or account for discharge (sediment transport) and the simulated gully-derived sediment could not be calibrated and validated with measured data. The SWAT model/results of Theron et al. (2021) does not account for gully erosion processes and therefore underestimate the sediment yield in gullied catchments such as the Tsitsa.

SSYs modelled for the Pot, Lower Tsitsa and Inxu River catchments were all higher than those from our measured data (In brackets, Table 9).

Nyamela (2018) used the same measured SSC and discharge data as our study but a different approach to estimating annual SSL, that is, calculating instantaneous SSC and discharge to give instantaneous SSL; calculating average daily SSL; and summing daily SSL to give annual SSL. This may account for much of the difference between the measured SSY for the Inxu.

Gwapedza et al. (2021) calibrated their model using the measured SSY estimate published by Nyamela (2018). Gwapedza et al. (2021) noted that their estimates were double those of Le Roux and 10 times those of Nyamela (2018), acknowledging that the models may have over-estimated, but also pointing out that a year of observed suspended sediment data was insufficient for verification: Decadal data is recommended to represent of a wider range of catchment conditions and decrease uncertainty (Horowitz et al., 2015).

Although extreme river conditions play an important role, the major constraints to suspended sediment monitoring in Southern Africa are the lack of technical, infrastructural, human, financial, data, and knowledge resources. In terms of time, cost, and data availability, modelling may remain the most likely approach to predicting SSL and SSY, but the major constraint is not the resolution of remotely sensed data, but the dearth of precise, unbiased observed suspended sediment data for validation. Our results demonstrate that the manual suspended sediment sampling and analysis approach designed for the

TABLE 9 A comparison of estimated SSY in the Pot, lower Tsitsa and Inxu River catchments (Measured SSYs from this study are given in brackets)

Catchment	Approach	SSY t km^{-2} year^{-1} (this study)	Reference
Pot	SWAT with GIS	200–599 **(47–79)**	Le Roux et al. (2015)
Lower Tsitsa		100–2500 **(93–222)**	
Inxu		100–2500 **(236–1443)**	
Inxu (2016–2017)	Direct suspended sediment measurement	550 **(273)**	Nyamela (2018)
Inxu (2016–2017)	Modified USLE	5000 **(273)**	Gwapedza et al. (2021)

Tsitsa River catchment has the potential to be applied in other, similar catchments to provide these much-needed data in the region.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author after PhD submission.

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