Received: 30 March 2021 | Revised: 29 July 2021 | Accepted: 20 August 2021
DOI: 10.1002/rra.3857

RESEARCH ARTICLE

WILEY

Developing a taxa-related physical habitat score based on the response of macroinvertebrate community structure to fine bed sediment composition in the Tsitsa River, Eastern Cape, South Africa

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Funding information
Department of Forestry, Fisheries and the Environment, South Africa, Grant/Award Number: Tsitsa Project; Water Research Commission, Grant/Award Numbers: Project Number K5/2423, Project Number K5/2433

Abstract

Biomonitoring techniques such as the South African Scoring System version 5 (SASSv5) is widely used in South Africa to rapidly assess river water quality, but there are currently no equivalent rapid monitoring tools for fine sediment assessments. This article presents a tool that monitors the effects of fine sediment on macroinvertebrates that can be used alongside the SASSv5 assessment. Sampling was carried out in the Tsitsa River in the Eastern Cape province of South Africa. Five sampling surveys were conducted over one hydrological year to capture a range of flow conditions resulting in a total of 90 sampling points across five sampling sites. Using an adaption of the SASSv5 methods, sampling was undertaken at a quadrat scale, rather than at a site scale, to identify macroinvertebrate families in different habitat types and degrees of sediment deposition. Fine sediment sampling using a disturbance technique was undertaken immediately upstream of 78 of the biological sampling points. A taxa-related sediment deposition score was created in which taxa were scored in terms of their sensitivity to fine sediment accumulation. The index was tested as a monitoring tool at 11 monitoring sites along the Tsitsa River in different seasons and flow conditions in 2019 and 2020.

KEYWORDS
aquatic habitat, fine sediment, macroinvertebrates, monitoring, South Africa

1 | INTRODUCTION

Natural concentrations of sediment comprise an essential part of the ecosystem, creating substrate-related habitat for a variety of organisms (Apitz, 2012). Habitat alteration can result from either an increase or decrease in sediment supply and deposition, especially of fine sediment. This in turn affects habitat quality and the associated macroinvertebrate taxa. While the negative impacts of fine sediment accumulation on channel beds are well recognized, the susceptibility of different macroinvertebrate families to changes in fine sediment loads within their respective habitats is little understood (Murphy et al., 2017).

Organic pollution is historically seen as the dominant threat to a river's water quality (Jones, Davy-Bowker, Murphy, & Pretty, 2010); however, this is not necessarily the case for rivers in rural catchments where additional physical stressors such as increased sedimentation have a more significant impact on the condition of the river system (Jones et al., 2010; McKenzie, England, Foster, & Wilkes, 2021; Murphy et al., 2015). It has been recognized by many authors that increased sedimentation and turbidity have a direct impact on ecological health in fluvial systems and are commonly seen as the most detrimental aquatic pollutant (Allan, 2004; Ellis, 1936; Henley, Patterson, Neves, & Lemly, 2000; Jones et al., 2012; Lemly, 1982; Murphy et al., 2015; Ritchie, 1972).

The assessment of benthic macroinvertebrates is an effective means of determining river condition as macroinvertebrate species composition responds to the alteration of stream habitat and water quality. Biomonitoring techniques such as the UK's River Invertebrate Prediction and Classification System (Wright, 2000), Australian River Assessment System (Parsons, Thoms, & Norris, 2002) and the South African Scoring System version 5 (SASSv5) (Dickens & Graham, 2002) have been used as rapid assessment tools for river water quality and other health aspects related to the state of aquatic ecosystems, the spatial and temporal trends in ecological state, and the prediction and monitoring of changes to ecosystems due to developments. However, biomonitoring using techniques such as SASSv5 do not directly assess the sediment-related physical habitat conditions in which macroinvertebrates are found.

A number of recent studies have contributed to our understanding of macroinvertebrate responses to changes in fine sediment concentrations in the water column (or the concentration of suspended sediment) (Conroy et al., 2018; Jones et al., 2012; Murphy et al., 2015, 2017; Zuellig & Schmidt, 2012) and current management targets are frequently defined in terms of the suspended sediment concentration at a particular time (Jones et al., 2012). However, Jones et al. (2012) report that the majority of impacts on macroinvertebrates due to fine sediments are related to the deposition of material that can be linked to local hydraulic, hydrological, and geomorphological conditions.

Studies such as those by Relyea, Minshall, and Danehy (2012) and Zweig and Rabeni (2001) in the United States and Extence et al. (2011) and Murphy et al. (2015, 2017) in the United Kingdom look at macroinvertebrates as indicators of fine sediment accumulation. These studies are for locally adapted fauna and commonly go down to species level. Conroy et al. (2018) also showed that macroinvertebrate responses can be species specific with different species within one family responding in varying degrees to changes to sedimentation. Unfortunately, species-specific studies are limited by the need for specialist knowledge and cannot be used widely as a rapid catchment scale biomonitoring tool. Zuellig and Schmidt (2012) warn that indices based on macroinvertebrate family composition might be limited to the region in which the index is developed. Jones et al. (2012) propose that studies are required that gather data covering community-level responses of macroinvertebrates to current river conditions including fine sediment deposition, hydrology, and geomorphic parameters, over a range of river types.

South African research on macroinvertebrate response to fine sediment accumulation is limited. Gordon, Griffin, and Palmer (2015) investigated the macroinvertebrate response to suspended sediment. They found that all three SASSv5 metrics (SASS score, Number of Taxa (NOT), and Average Score per Taxa (ASPT)) were negatively correlated to turbidity, but high scatter in the relationship pointed to the need to extend the research to deposited sediment. Likewise Ellis (2018), researching a groundwater fed stream in South Africa, recommended that the SASSv5 scoring system be adapted to include sensitivity to fine sediment. The research presented in this article was conducted in the Tsitsa River, a tributary of the Mzimvubu River (Figure 1). Madikizela and Dye (2003) established that, overall, macroinvertebrate families in the Mzimvubu River system were not found in high abundance but species sensitive to poor water quality were present, indicating good water quality but possible secondary effects of sedimentation and reduction in suitable habitat.

The response of macroinvertebrates due to site-specific changes in fine sediment deposition is clear, but there are few studies that replicate these responses over a range of river types for the purpose of catchment management or monitoring. There is currently a lack of

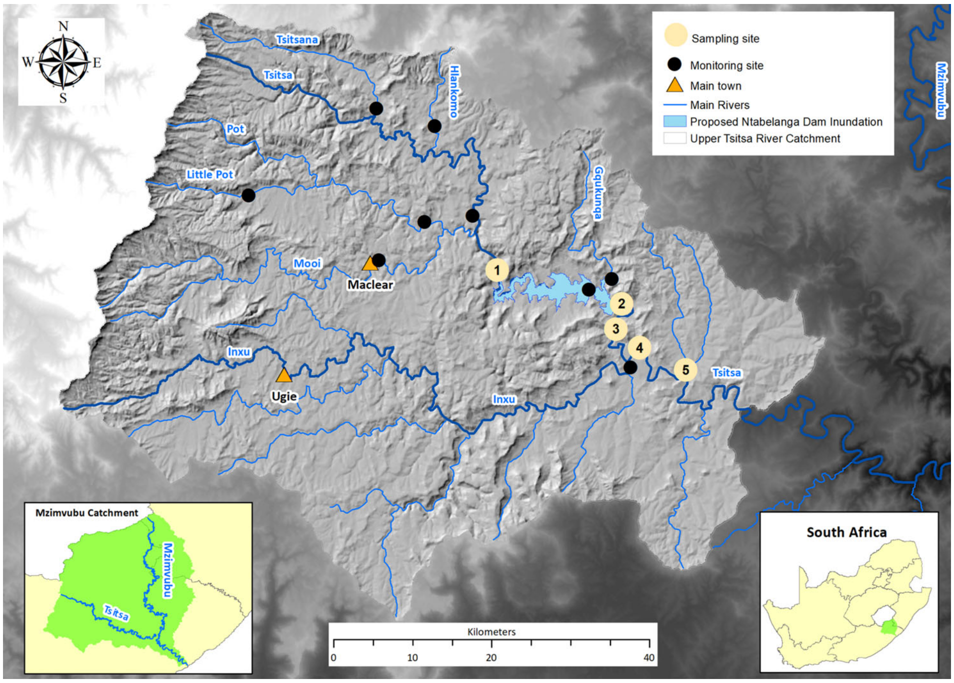


FIGURE 1 Study area in the Eastern Cape province of South Africa [Color figure can be viewed at wileyonlinelibrary.com]

data in South Africa on macroinvertebrate community response to deposited sediment that can be used to interpret SASSv5 results if habitats are impacted by fine sediment. This creates an opportunity to investigate the use of macroinvertebrates as a barometer of river habitat health in terms of fine sediment accumulation. The aim of this article is to propose a monitoring tool that includes the effects of fine sediment on aquatic habitats that are characterized by fine sediment issues. By using a sediment-related macroinvertebrate index, it is proposed that river sites can be monitored concurrently for both water quality and/or sedimentation issues using the same taxonomic data collected for regular SASSv5 monitoring.

2 | METHODS

2.1 | Study area and site selection

This study was conducted in the Tsitsa River (Figure 1), initially as part of a baseline survey of channel geomorphology prior to the construction of the proposed Ntabelanga Dam (Huchzermeyer, 2017), with particular reference to the effects of sediment characteristics on ecosystem health. The five sampling sites referred to in this article derive from this broader study and are located in relation to the proposed dam inundation area. These sites have since been incorporated into the Tsitsa Project biophysical monitoring program. This project undertakes integrated catchment restoration in the Tsitsa River catchment. It aims to improve the sediment retention capacity of ecological infrastructure through erosion control interventions and improved livestock management. An important aspect of the project is to monitor the impact of catchment wide rehabilitation on river health, which in turn guides catchment management decision-making.

The Tsitsa River originates in the Drakensberg Mountains in the north east of the Eastern Cape Province of South Africa, in the Great Escarpment geomorphic province, and flows through the southeastern Coastal Hinterland geomorphic province (Partridge, Dollar, Moolman, & Dollar, 2010) to its confluence with the Mzimvubu River. Elevations in the area range from ~2,700 m in the Drakensberg in the north-east, to ~600 m toward the confluence with the Mzimvubu. The topography is steep in the headwaters and middle catchment. The remainder of the landscape is hilly to rolling with steep gorges below prominent waterfalls where the river is deeply incised due to Miocene uplift (Partridge et al., 2010). The area experiences summer rainfall between October and March, often in the form of intense afternoon thundershowers. Winter months are characterized by long dry periods. Snowfalls can be expected during the winter months in the upper part of the catchment and may occur infrequently in the lower catchment.

The Tsitsa River transitions between a bedrock and mixed bedrock alluvial river. The channel gradient through the sampling sites is strongly influenced by rock type, where steeper sections form on more resistant bedrock (such as basalt and dolerite) and lower gradient sections with sand beds form on sandstones, mudstones, and mudrocks. Instream vegetation is generally absent or limited to grasses and sedges.

There are a number of factors that result in increased sediment in the Tsitsa River (Itzkin et al., 2021). These include highly erodible duplex soils, a high rural population density in the former Transkei homeland, unsustainable land use practices including lack of grazing controls and abandoned cultivated land, and increased landscape connectivity due to gully erosion. Altered sediment dynamics due to these combined factors increase turbidity, suspended sediment concentrations, and deposited sediment.

The location of the five sampling sites is shown on Figure 1. The three upstream sites are characteristic of the upper foothills category (Rowntree, Wadeson, & O'Keeffe, 2000), with gradients between 0.006 and 0.008. Bedrock and cobble riffles and rapids are common in this part of the river. The two downstream sites fall into the lower foothills category with lower gradients (0.002 and 0.003). Additional sediment input from a major tributary, the Inxu River, increases the amount of accumulated deposited sediment and reduces habitat diversity at sampling Sites 4 and 5 further downstream. Site 4 is dominated by a mobile sandbed, whereas Site 5 is more complex with pools, backwater, slack water, rapids, and riffles. All sites are impacted by increased sediment loads due to the ubiquitous catchment degradation, but the propensity for deposition depends on the reach gradient and the within-site gradient variability.

At all the sampling sites, physical habitat variables (substrate, water depth, and velocity) and chemical water quality were monitored by Huchzermeyer (2017). Huchzermeyer (2017) found that within the range of parameters monitored over the study period, water quality could be discounted for having any noticeable effects in altering the types of macroinvertebrates that would naturally occur in the river. Velocity was analyzed with respect to fine sediment deposition, which showed minimal sediment deposited at higher velocities. However, the flow–biota relationship was not investigated for this study.

2.2 | Sampling strategy

Five sampling surveys were conducted over one hydrological year (June 2015, October 2015, February 2016, April 2016, and August 2016) at the five sampling sites described above. Physical habitat and macroinvertebrate community composition were sampled at a total of 90 sampling points.

The sampling strategy across a site took into account the observation that deposited fine sediment is unlikely to be evenly distributed across a river bed (Duerdoth et al., 2015). Four to six cross-sectional surveys were conducted per site. The basic sampling unit across the transects was a 1 m by 1 m quadrat. In most cases, three to five quadrates were placed along the surveyed transects using a stratified random sampling strategy, covering all biotopes, but this varied between sampling surveys depending on the flow conditions and accessibility of points within the channel. The macroinvertebrate community was described for each surveyed quadrat, and fine-sediment sampling was undertaken directly upstream of the biological sampling quadrat wherever possible.

2.3 | Biological sampling

The macroinvertebrate community structure was established at a family level using an adaption of the SASSv5 (Dickens & Graham, 2002). In order to relate macroinvertebrate families to habitat type, sampling was undertaken at the quadrat scale, rather than at the site scale as is more normal in SASSv5 practice. Following SASSv5 protocols, sample collection was conducted using a net with fine mesh, held downstream of the sample point, catching macroinvertebrates dislodged from the substrate or marginal vegetation. In addition, fine sediments were sieved through the net. Observations of substrate and vegetation were recorded.

A total number of 540 individuals and 45 families of macroinvertebrates were found in the 90 sampled quadrats.

2.4 | Fine-sediment sampling

An objective assessment of substrate condition was conducted by following methods taken from Lambert and Wailing (1988) and Duerdoth et al. (2015). This allows for the measurement of spatial variability in deposited fine sediment and samples both the surface drape (only sediment deposited on the surface) and the subsurface sediment (combined surface drape and subsurface deposits in the top 10 cm of the bed). A cylindrical bucket, 31 cm high, with the bottom removed, was placed over the substrate on the channel bed. The diameter of the bucket was 33 cm permitting for a known area of 0.086 m^2 to be sampled for each disturbance. The depth of the water level in the bucket was recorded so that the water volume could be calculated.

The disturbance sampling was undertaken in two steps. First, the fine sediments on the bed surface were disturbed by vigorously stirring the water with a sturdy graduated 1.5 m long staff with a diameter of 4 cm, without touching the river bed, for 60 s. A water sample was taken immediately after stirring ceased using an open 500 ml water bottle, subsequently sealed with a lid. A further 30 s of disturbance was conducted by stirring up and digging in the top 10 cm of the bed substrate to raise any subsurface fine sediment into suspension, and a second water sample was taken. Both the surface and subsurface deposited fine sediments were collected for each disturbance sampling to quantify separately the surface drape and subsurface fine sediment deposits.

Fine sediment sampling was undertaken immediately upstream of the biological sampling points wherever possible. In several cases, the disturbance technique was limited to fine gravels and sands as the bucket could not be firmly fixed into coarse gravels or cobble beds without flow of water into or out of the bucket. However, where the bucket could be firmly fixed to the substrate, including coarse gravels, cobbles, and bedrock, surface disturbance samples were taken. Subsurface sampling was often precluded where the bed material was coarse and or highly imbricated.

Coarse gravels and cobble beds found in fast flowing rapids were not suitable for disturbance sampling, and, furthermore, they were considered not to be conducive to the deposition of fine materials. During high flow, disturbance samples could only be taken where water depth did not exceed the depth of the bucket, commonly limited to areas of reduced flow near the edges of the bank.

Surface sediment drapes and subsurface sediment were sampled adjacent to 49 quadrats. An additional 22 samples were taken for fine sediment only and 7 samples for subsurface sediment only. No sediment samples were taken adjacent to 12 biological sampling quadrats due to water depth exceeding the bucket.

A laboratory analysis of the water samples was conducted after each field visit. The concentration of sediment was measured by using the filtration method described by Gordon, McMahon, Finlayson, Gippel, and Nathan (2004). The volume of water measured in the bucket was used to convert the laboratory weights to a mass of fine-grained sediment per square meter of river bed sampled (Collins & Walling, 2007; Duerdoth et al., 2015; Lambert & Wailing, 1988).

The Bovée embeddedness index (Gordon et al., 2004) was used as a qualitative descriptor of the channel bed sediment in each quadrat. This is a three-digit index in which the first digit indicates the size class of the largest clast, the second is the next largest class, and the third is the percentage fines visible on the surface (sand or finer), a measure of embeddedness. The index was used to subdivide the quadrats for further analysis, namely, (a) coarse sediment consisting of boulder, cobble, and gravel as the largest clast and gravel or larger as the second size largest class and (b) fine sediment consisting of sand and silt or quadrats where the second largest class was sand or silt. Bedrock was included as a separate class. Bedrock is immobile but often has a shallow silt drape and occasionally a deeper sediment deposit that includes a subsurface component.

The flow velocity over each quadrat was measured using a Marsh-McBirney electro-magnetic current meter. Readings were taken at a distance from the bed equivalent to 0.4 of the water column height.

2.5 | Bed sediment analysis

A correlation analysis was undertaken to investigate the relationship between surface and sub-surface sediment by quadrat to assess their potential as predictors for the overall fine sediment concentration on the bed of the river. The relationship to flow velocity was also investigated.

2.6 | Index development

Biological and corresponding surface sediment drape data from 71 sampling points from the five sampling sites were combined as one composite sample to develop an index of macroinvertebrate sensitivity to fine sediment. Sensitivity scores were assigned to the 45 macroinvertebrate families according to the maximum degree of fine sediment accumulation as measured across the 71 quadrats. In order to test whether or not the assigned sensitivity scores provided a measure of habitat quality that is independent of water quality as measured by the SASSv5 sensitivity score, the two measures were plotted against each other for the 45 families.

An ASPT was calculated from the macro-invertebrate assemblage in each quadrat following the procedure described for SASSv5, where the ASPT is the sum of sensitivity scores for all observed families, divided by their number. As explained below, the method was modified to put more weight on the most sensitive taxa. The new index, based on sediment sensitivity, is termed ASPT-sed. To demonstrate the efficacy of the ASPT-sed score as a measure of sediment deposition, scores were regressed against the mass of sediment accumulated in each quadrat. A separate analysis was carried out for quadrats with coarse and fine substrates. The results were used to classify levels of sediment accumulation according to ASPT-sed values.

2.7 | Monitoring

The index was tested as a monitoring tool by applying ASPT-sed to macroinvertebrate families collected according to conventional SASSv5 methods, that is, the families list was assembled by site. In addition to the quadrat sampling, monitoring surveys using the SASSv5 methodology were conducted at each sampling site during each field visit in 2016. Thereafter, sampling sites 1 and 4, together with a further 9 sites in the Tsitsa River and its tributaries, were monitored in May 2019 (high baseflow) and August 2020 (low baseflow) on behalf of the Tsitsa Project. Site locations are shown in Figure 1. The SASSv5 sampling protocol (Dickens & Graham, 2002) for site monitoring was followed as described above for biological sampling (Section 2.2). At each site, the range of biotopes present was sampled, and observed families were combined into a single ASPT-sed score.

River health, specifically water quality, was assessed following the methods of SASSv5 interpretation (Dickens & Graham, 2002) and an ASPT calculated for each site by sampling period. The ASPT scores were interpreted using Table 1, which differentiates between sites dominated by coarse and fine substrate.

Derived ASPT-sed scores were used to classify habitat quality for fine and coarse beds classified in a similar manner to Table 1, using the findings from the methods outlined in Section 2.6.

Because ASPT-sed scores are derived from the same taxa identified during a standard SASSv5 procedure, it is proposed that the modified version be termed SASS-sed.

3 | RESULTS

3.1 | Bed sediment analysis

The distribution of surface and subsurface sediment by bed material size class is shown in Figure 2. The amount of both surface and subsurface sediment is clearly related to the size of bed material. Fines (sand) have a variable and at times high sediment accumulation, whereas gravel and coarser bed material tend to have much less fine sediment. One significant outlier is evident for the subsurface sediment for gravel. This sample came from an alluvial fan that had developed where a small tributary entered the channel into a pool in Site 3. It is likely that a highly mixed sediment would be deposited at this site; the gravel surface would develop as deposited fines were winnowed out by the channel flow. This sample is therefore uncharacteristic of normal in-channel sites where the deposition and scouring of subsurface fines are the result of ambient flow conditions.

TABLE 1 Water quality classes according to SASSv5 scores (Dickens & Graham, 2002)

Sensitivity score (ASPT-SASSv5) (Dickens & Graham, 2002)		
Site dominated by coarse substrate	**Site dominated by fine substrate**	**Habitat and water quality (WQ) description**
>7.9	>6.9	Very high habitat diversity and natural WQ
6.9–7.9	5.9–6.9	High habitat diversity and largely natural WQ
6.2–6.8	5.0–5.8	Moderate habitat diversity and WQ
5.1–6.1	4.4–4.9	Low habitat diversity and poor WQ
<5.1	<4.4	Very low habitat diversity and very poor WQ

Abbreviations: ASPT, Average Score per Taxa; SASSv5, South African Scoring System version 5; WQ, water quality.

The reduced fines in gravel and cobble quadrats is likely to be related to associated current velocities as fine sediment will settle out where velocities are lower. Figure 3 shows the relationship between quadrat velocity and the mass of sediment accumulated. Both surface and subsurface sediment show a similar relationship with an envelope describing the maximum sediment for a given velocity. There is much variability at low velocities, but as velocity increases above 0.5 m/s, insignificant amounts of surface or subsurface sediment were observed. A similar relationship was found between velocity and proportion of fines, but there are more outliers.

Figure 4 shows the relationships between the sediment drape and subsurface sediment, and these two variables and embeddedness expressed as % surface fines visible on the bed. There is a significant positive relationship ($R^2 = .59$, $n = 49$) between surface and subsurface sediment combined for all quadrats sampled over the five sampling visits (Figure 4a,b). High correlations exist for the coarser bed material classes, but the significance is lower because of smaller sample sizes. The relationships with % surface fines are weaker (Figure 4c,d). All relationships were significant at the 5% level despite low sample numbers in some cases.

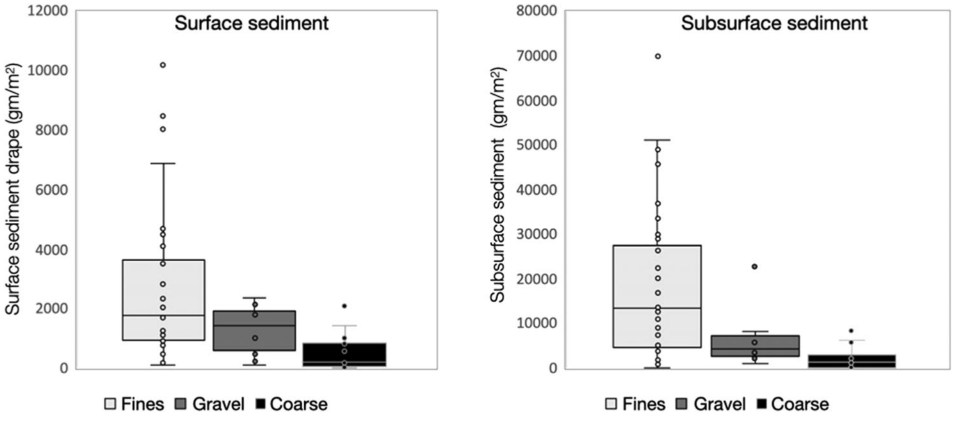


FIGURE 2 Distribution of bed sediment accumulation by bed material class for surface sediment drape and subsurface sediment

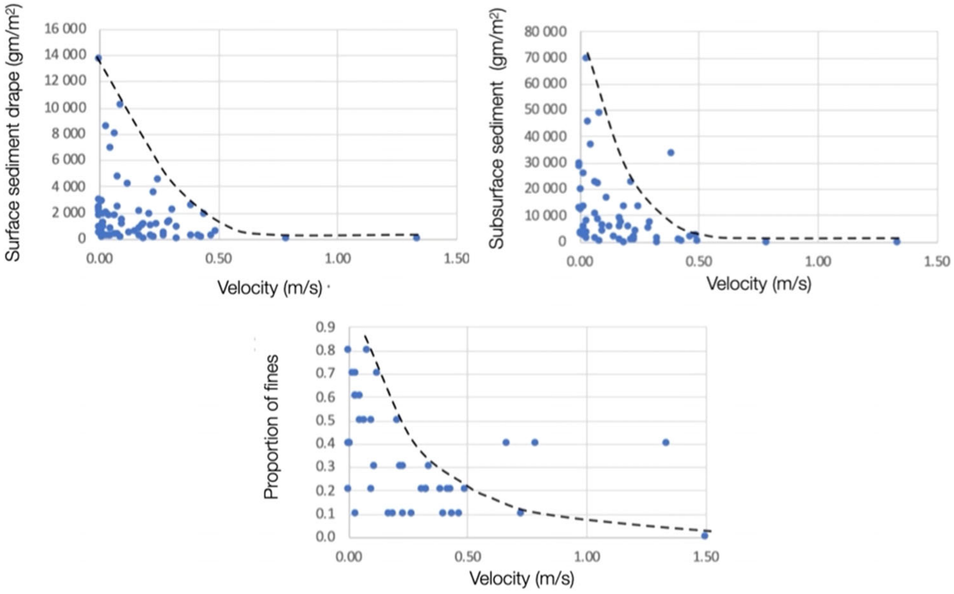


FIGURE 3 Fine sediment deposition as a function of quadrat velocity [Color figure can be viewed at wileyonlinelibrary.com]

Macroinvertebrates were sampled for all 90 quadrats, but the surface sediment drapes and subsurface sediment were only sampled adjacent to 49 quadrats, with an additional 22 samples taken for fine sediment only and 7 samples for subsurface sediment only. The strong and significant correlations between surface and subsurface sediment and the greater number of surface sediment samples justify the use of the surface sediment drape as the measure of bed sediment for assigning sediment sensitivity scores to macroinvertebrate taxa.

3.2 | Index development

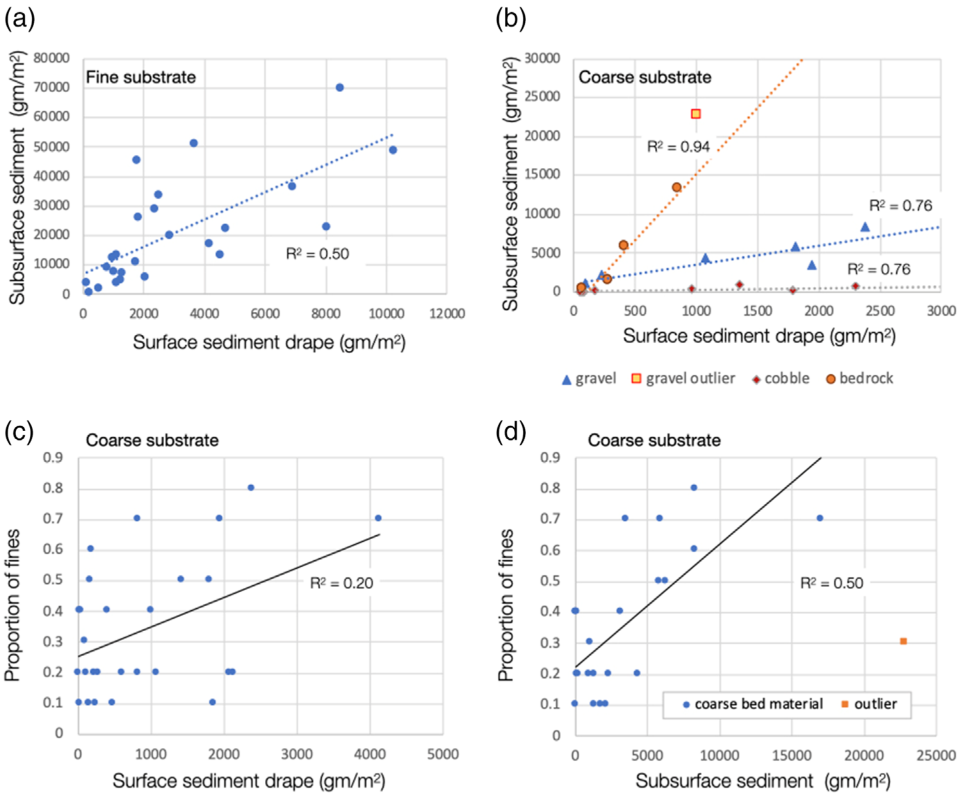
Surface sediment drape concentration was found to be a good predictor of subsurface fine bed sediment (see Figure 4), and therefore, fine sediment accumulation in terms of sediment drape was seen as representative of the current habitat condition.

The maximum mass of sediment drape (g/m^2) in which macroinvertebrate families were observed were plotted along a logarithmic axis and divided into 15 equally spaced logarithmic sections that took into account the observed grouping of samples (Figure 5). These class breaks were used to assign sediment sensitivity scores to different values of fine sediment. Each of the 45 macroinvertebrate families was then assigned a score depending on the maximum mass of sediment drape in which they were observed. The resulting scores are given in Table A1.

The most sensitive families, indicating low sediment accumulation, were Gerridae, Planaria, Oligoneuridae, Hydropsychidae, Hirudinea, Nepidae, Belostomatidae, Psychodidae, Dixidae, Sphaeriidae, and Potamonautidae. Given the low sediment values, it is likely that these families are found in gravel or cobble habitats.

Eight families had a sensitivity of 1 and can be found in highly sedimented habitats. These include Baetidae, Caenidae, Chironomidae, Simuliidae, Culicidae, Dytiscidae, Ceratopogonidae, and Oligochaeta. If two Baetidae species were present, they were assigned sensitivities of 3, and if more than 2 were present, they were assigned a score of 6. Many of these families with low sensitivity ratings are cosmopolitan in their habitat preference and can be found across a wide range of surface sediment conditions. Their presence, therefore, does not necessarily imply sedimented conditions. For example, Chironomidae make up 7% of taxa found where sediment is

FIGURE 4 Relationship between surface and subsurface sediment in fine substrates (A) and coarse substrates (B) and surface (C) and subsurface (D) sediment mass and the proportion of fines by quadrat. The subsurface outlier from the alluvial fan is not included in the regression [Color figure can be viewed at wileyonlinelibrary.com]



below 100 g/m^2 yet are scored 1 because they are also found in highly sedimented substrates.

Several anomalies emerged between the expected habitats of families, as described in South African field guides such as Gerber and Gabriel (2002), and the assigned sensitivity scores. This may have been, in part, to do with the abundance at which different families were found. Families found in low abundance, such as Athericidae, Dixidae, Gerridae, Hirudinea, Psychodidae, Tabanidae, Nepidae, and Sphaeriidae, are poorly represented and may occur across a wider range of habitats than reported. Families found in high abundance such as Baetidae, Chironomidae, Caenidae, and Simuliidae are well represented and were found in a high variety of habitats including course substrates and in fine sediment drape on organic matter. These sensitivity scores, therefore, should be considered as preliminary and need to be tested using an expanded sample extending across a range of river types in order to reduce the observed anomalies.

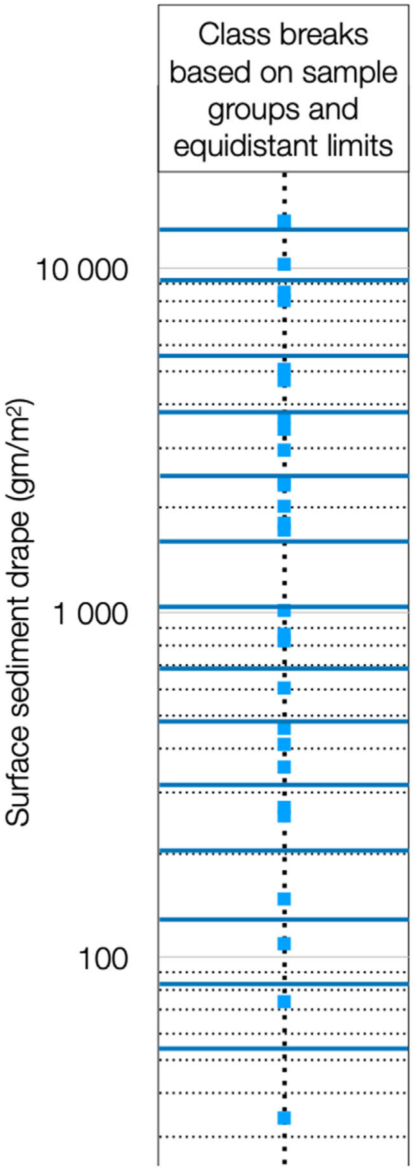
If the sediment sensitivity scores are to be used to augment the SASSv5 water quality scores by identifying sediment related rather than water quality–related impacts, it is important that the two scores are independent of each other. Figure 6 shows that the two scores assigned to a given taxa are not correlated. Only ten taxa had the same or very similar sensitivity score, and there was no pattern to the remaining 35 taxa. Although independent, it should be noted that the number of sediment sensitive taxa were reduced as water quality becomes poorer, as did the water quality sensitive species as sediment levels increased. The ASPT-sed index, therefore, is likely to be most useful in less polluted rivers where chemical water quality has not reduced the number of taxa, including sediment sensitive families.

3.3 | Interpreting the sensitivity score

ASPT-sediment (ASPT-sed) for a quadrat is the sum of sensitivity scores for all observed families, divided by their number. If the scoring system is an effective representation of sediment sensitivity, there should be a good relationship between ASPT-sed and the surface sediment drape. Because the low scoring cosmopolitan species can bring down the score of low-sediment habitats, it was decided to test the ASPT-sed using the four most sensitive species. Using only the top four taxa increased the R^2 value from .62 to .71 for coarse substrate and from .10 to .12 for fine substrates. It was therefore decided to derive the ASPT-sed score using the top four taxa. Figure 7 was used to define classes of sediment accumulation for coarse and fine substrates as given in Table 2. For coarse substrates, low sediment is associated with an ASPT-sed score greater than 8 and highly sedimented substrates with an ASPT-sed score less than 4. For fine substrates, ASPT-sed scores greater than 4.2 identified low sediment conditions and less than 2 high sediment, but low sediment was also associated with a wide range of scores due to the presence of cosmopolitan taxa.

3.4 | Application of macroinvertebrate taxa to monitor changes to fine bed sediment in the Tsitsa River

Water quality and fine sediment deposition classes were derived for the 11 monitoring sites over two monitoring periods using a



Sensitivity score	Surface sediment drape (g/m2)
1	>13 000
2	8 500.1 – 13 000.0
3	5600.1 – 8 500.0
4	3 700.1 – 5 600.0
5	2 450.1 – 3 700.0
6	1 600.1 – 2 450.0
7	1 050.1 – 1 600.0
8	700.1 – 1 050.0
9	470.1 – 700.0
10	205.1 – 470.0
11	
12	90.1 – 205.0
13	
14	
15	<90.0

FIGURE 5 Sensitivity scores based on surface sediment drape [Color figure can be viewed at wileyonlinelibrary.com]

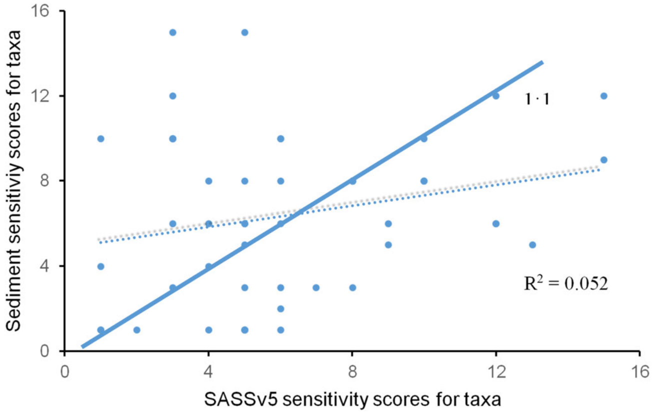


FIGURE 6 Relationship between sediment sensitivity scores assigned to macroinvertebrate taxa versus South African Scoring System version 5 (SASSv5) scores [Color figure can be viewed at wileyonlinelibrary.com]

combination of SAASSv5 and SASS-sed. The variation in water quality and fine bed sediment in the Tsitsa River can be seen from Figure 8. Results by site and monitoring period are given in Table A2.

Monitoring sites are seen to be affected by multiple stressors. Some sites are negatively impacted by either or both poor water quality and high concentrations of fine sediment concentration during high- and low-flow baseflow conditions. A poor condition in high-flow months is commonly caused by input from nonpoint sources of pollution (Table A2). Nutrients, derived from pit latrines, waste water treatment effluent, and commercial agriculture, reduce the water quality. High baseflows will flush the river system of excess nutrients and generally increase water quality. High baseflows that are free of sediment will also flush fines from the bed. In the low flows of winter months, water and habitat quality is reduced as flushing of pollutants and fine sediment drapes is less effective. Cold water temperatures also affect biota.

FIGURE 7 Relationship between Average Score per Taxa (ASPT)-sed scores derived using the top 4 most sensitive taxa [Color figure can be viewed at wileyonlinelibrary.com]

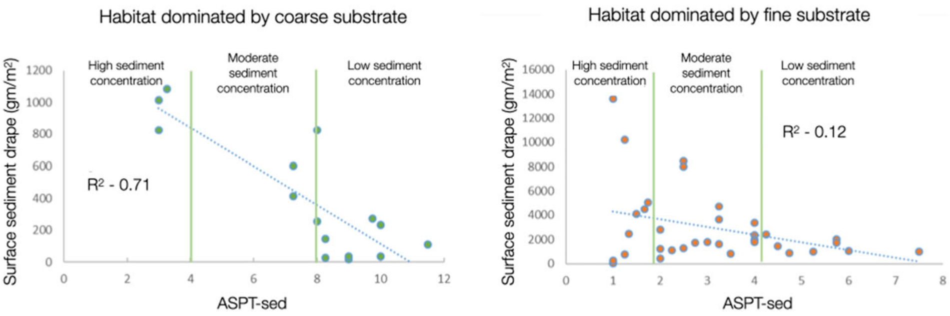


TABLE 2 Fine sediment classes according to Average Score per Taxa (ASPT)-sed scores

Sensitivity score (ASPT-sed)		
Site dominated by coarse substrate	**Site dominated by fine substrate**	**Fine sediment concentration**
>8.0	>4.2	Low
4.0–8.0	2.0–4.2	Moderate
<4.0	<2.0	High

Fine sediment concentration on the bed of the river is controlled by the amount of sediment entering the river system from the catchment as well as the propensity for sediment deposition afforded by the channel morphology in different reaches of the river. Both low and high flows indicate moderate levels of sediment concentration on the bed of the river at 91% (high baseflow) to 82% (low baseflow) of the monitoring sites. High sediment accumulation impacts the remaining monitoring sites. Land management and soil erodibility are key factors controlling sediment inputs along the river. In the north-eastern, eastern, and lower catchment (monitoring sites 1, 2, 6–11), uncontrolled grazing by livestock in the former homeland areas gives rise to high rates of soil loss. Intensive cultivation of row crops in the commercial farms also contributes sediment in the middle catchment (monitoring sites 5 and 6). Soils become increasingly erodible as one moves down the Tsitsa catchment, resulting in a cumulative effect of fine sediment on the bed.

Steeper sections of the river bed have limited fine sediment deposits due to the high energy in these areas. Low gradient river beds, as found further down the catchment where soils are also more erodible, result in reduced flow velocities and an increase in fine sediment on the bed of the river.

3.5 | Sediment response to flow variability

Variability in the flow prior to site assessments and monitoring surveys resulted in different bed sediment concentrations at sites (Figure 9). Fine sediment accumulation did not necessarily follow current discharge trends alone. Fine sediment accumulation increased the more turbid the flows were. Summer baseflows entrained sediment (sampling survey 3 and 4, monitoring survey 1) whereas medium, turbid flows deposited sediment on the bed (sampling survey 5), increasing surface disturbance concentrations. During periods of low flow (sampling survey 1 and 2 and monitoring survey 2), the energy slope was insufficient to entrain fine sediments, resulting in higher disturbance concentrations. Small local rainfall events increased the turbidity of the river but not the flow, which in turn increased the amount of sediment deposited on the bed (sampling survey 2).

4 | DISCUSSION

Macroinvertebrates are the preferred group of aquatic organisms used in the biomonitoring of streams due to a range of family-related sensitivities (Dickens & Graham, 2002; Türkmen & Kazanci, 2010). A number of authors have used macroinvertebrates to monitor fine sediment accumulation (Conroy et al., 2018; Cummins, 2016; Extence et al., 2011; Juvigny-Khenafou et al., 2021; Murphy et al., 2015, 2017; Relyea et al., 2012; Zuellig & Schmidt, 2012; Zweig & Rabeni, 2001), but there have been few such applications in South Africa. The SASS-sed scoring system developed in this study provides one of the first to do this. The research in the Tsitsa River sought to extend catchment condition monitoring to include assessing fine sediment–related impacts on habitat quality. Characteristics of the Tsitsa River catchment, including highly erodible duplex soils, a high rural population density, and unsustainable land use practices, made conditions conducive to researching the effect that fine bed sediment has on aquatic habitats and associated macroinvertebrates.

The strong positive relationship between surface and subsurface sediment indicated that surface sediment is a good predictor of subsurface sediment and can be used with confidence in assessing macroinvertebrate sensitivity to sediment. The Bovée embeddedness index (Gordon et al., 2004), which estimates the percentage of fines on the bed of a river, is a poor predictor of the surface bed sediment but better for subsurface sediment and can be used as a supplementary tool to monitor sediment-related habitat quality.

A taxa-related physical habitat score (ASPT-sed) for the Tsitsa River was developed by scoring taxa in terms of their sensitivity to bed conditions, with an emphasis on fine sediment accumulation. This provides a rapid assessment tool that can be used by practitioners to monitor the amount of fine sediment drape affecting habitats, while simultaneously monitoring water quality using SASSv5 methodology. The South African Scoring System (SASSv5) was developed by Chutter (1998) and has undergone several refinements and is now incorporated as an integral

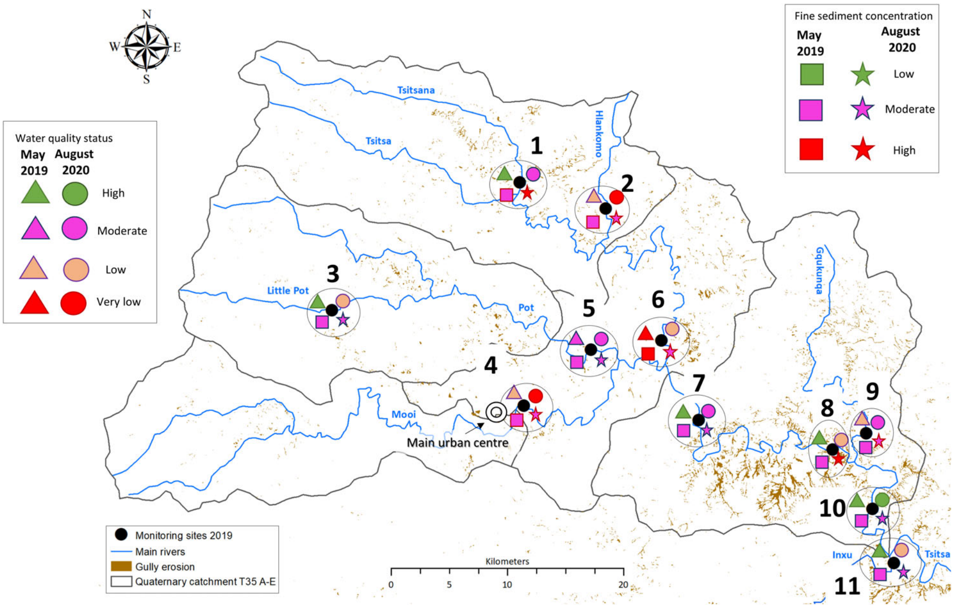


FIGURE 8 Integrated monitoring results using South African Scoring System version 5 (SASSv5) and SASS-sed at monitoring sites on the Tsitsa River system at high baseflow (2019) and low baseflow (2020) [Color figure can be viewed at wileyonlinelibrary.com]

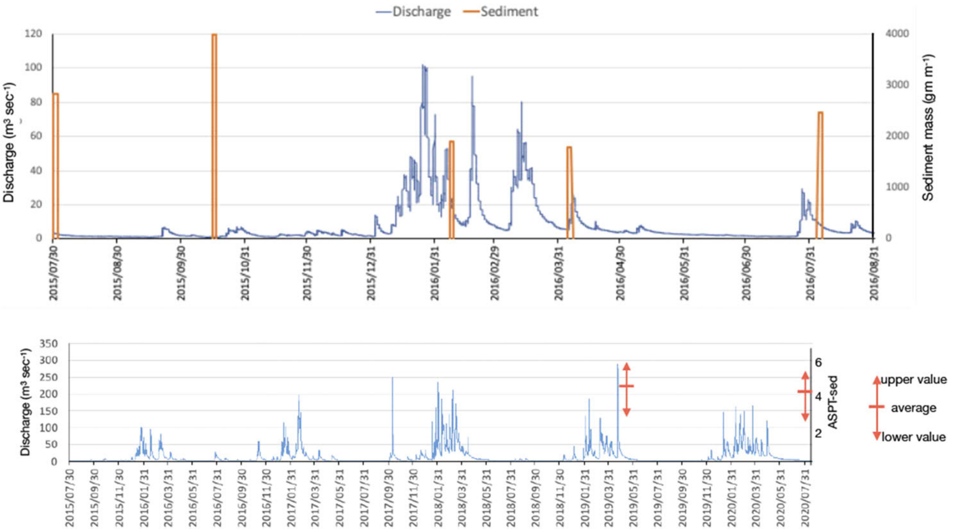


FIGURE 9 Temporal variation in discharge and average surface sediment concentration during the sampling and monitoring surveys [Color figure can be viewed at wileyonlinelibrary.com]

part of the South African National River Health Programme (Dickens & Graham, 2002). Practitioners are accredited in the SASSv5 methods ensuring data quality and consistency.

The macroinvertebrates found following the SASSv5 protocol at a site can also be scored using the scoring system set out in this research to assess not only the water quality at a site but also the effects of fine sediment on river habitat quality. This is particularly relevant in less polluted rural rivers where sedimentation rather than chemical water quality is the dominant factor in the reduction of ecosystem health. Therefore, low SASSv5 scores can be used to pick up a significant change in a river's water quality due to the influx of a pollutant, whereas the low SASS-sed scores indicate habitats that are negatively impacted by fine sediment accumulation. This is a rapid technique that needs to be applied over the long term to pick up significant changes in sediment accumulation and corresponding macroinvertebrate community structure.

Globally, freshwater systems are experiencing anthropogenic pressures with rivers being affected directly by point source pollutants and indirectly by the reduction of functional ecosystems within the catchment (Allan, 2004; Juvigny-Khenafou et al., 2021). Multiple stressors include fine sediment concentration in addition to excessive nutrient input and flow velocity (Juvigny-Khenafou et al., 2021). Juvigny-Khenafou et al. (2021) concluded that multiple stressor impacts on the aquatic environment vary between sampling sites and sampling events depending on the input from different stressors. Application of the ASPT-sed index to 11 monitoring sites in the Tsitsa River demonstrated its effectiveness as a monitoring tool when combined with SASSv5. Figure 8 incorporates the results of multiple stressors on the Tsitsa Catchment and can be used by natural resources or catchment managers to inform decisions regarding processes or restoration efforts occurring in different parts of the catchment.

Antecedent conditions such as flow are linked to sediment supply, transport, and retention in rivers (McKenzie et al., 2021). Antecedent flow conditions prior to sampling and monitoring surveys in the Tsitsa had a clear effect on the bed sediment concentration, with the lowest bed sediment concentrations found during prolonged high velocity flows in summer months. Increased sedimentation was observed following localized floods during low flow periods. To more meaningfully understand the relationships between abiotic factors, such as flow, a more targeted study would be required.

The SASS-sed scoring system is based on a limited data set from one river and only five sampling sites with a restricted geographic range. There is wide scope to test and refine the method in a range of South African river types. The relationship between macroinvertebrates and the amount of fine sediment accumulation that constitutes optimal habitat conditions needs to be further developed. Work conducted in the contrasting landscapes, such as by Ellis (2018) in the semi-arid Karoo, can be linked to this study, improving the understanding of the current conditions of rivers and their catchments as well as the impact of deposited fine sediment on macroinvertebrates in South Africa.

In conclusion, the scoring system presented in this article can be developed further for use by practitioners to carry out a rapid assessment of fine sediment accumulation based on sampling the macroinvertebrate community. Macroinvertebrate families with higher sensitivity scores are less tolerant to fine sediment on the channel bed as indicated by a fine sediment drape. An increase in occurrences and abundance of these sensitive macroinvertebrates therefore imply less fine sediment and better habitat conditions. This can be used in conjunction with well-known biomonitoring tools and protocols such as the SASSv5 with minimal addition of time constraints or costs to the practitioner.

ACKNOWLEDGMENTS

This research contributed to Water Research Commission (WRC) Project Number K5/2433: Constructing a baseline of environmental, agricultural, and socio-economic intersections for the Mzimvubu Water Project and to WRC Project Number K5/2423: The Green Village Project: Improving socio-economic conditions of Ntabelanga and Okhombo communities through integrated green innovations. The WRC, University of Fort Hare, and Rhodes University provided funding for both the field component and the university component of this research. The Tsitsa Project, funded by the Department of Forestry, Fisheries and the Environment (DFFE), funded the monitoring surveys.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, [Nicholaus H. Huchzermeyer], upon request.

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How to cite this article: Huchzermeyer, N. H., & Rowntree, K. (2021). Developing a taxa-related physical habitat score based on the response of macroinvertebrate community structure to fine bed sediment composition in the Tsitsa River, Eastern Cape, South Africa. *River Research and Applications*, 1–14. https://doi.org/10.1002/rra.3857

TABLE A1 Sediment sensitivity score sheet for common macroinvertebrate families

Macroinvertebrate class	Macroinvertebrate family & max g/m^2 fine sediment in habitat	Sensitivity score	Macroinvertebrate class	Macroinvertebrate family	Sensitivity score	Macroinvertebrate class	Macroinvertebrate family	Sensitivity score
Annelidae (leeches)	Hirudinea (109)	12	Ephemeroptera (mayflies excluding minnow mayflies)	Caenidae (13,630)	1	Hemiptera and coleoptera (bugs and beetles including larvae)	Belostomatidae (355)	10
Turbellaria (flat worms)	Planaria (34)	15		Heptageniidae (3,394)	5		Corixidae (8,019)	3
Crustacea (crabs or shrimps)	Potamonautidae (413)	10		Leptophlebiidae (2,951)	5		Dytiscidae (13,360)	1
Mollusca (snails or limpets)	Ancylidae (825)	8		Oligoneuridae (147)	12		Elmidae (862)	8
	Sphaeriidae (256)	10		Prosopistomatidae (602)	9		Gerridae (74)	15
Odonata-Zygoptera (damselflies)	Coenagrionidae (4,702)	4		Tricorythidae (2,029)	6		Gyrinidae (1,730)	6
Plecoptera (stoneflies)	Perlidae (2,029)	6	Diptera (flies)	Athericidae (1,012)	8		Hydraenidae	8
Trichoptera (cased and uncased caddisfly)	Hydropsychidae 1 sp (825)	8		Ceratopogonidae (13,630)	1		Hydrophilidae (8,481)	3
	Hydropsychidae 2 sp (460)	10		Chironomidae (13,630)	1		Naucoridae (8,019)	3
	Hydropsychidae >2sp (109)	12		Culicidae (13,630)	1		Nepidae (355)	10
	Ecnomidae (1,011)	8		Dixidae (271)	10		Notonectidae (2385)	6
	Leptoceridae (2,385)	6		Muscidae (5,066)	4		Psephenidae (825)	8
Annelidae (worms)	Oligochaeta (13,360)	1		Psychodidae (271)	10		Veliidae (3,667)	5
Ephemeroptera (minnow mayflies)	Baetidae 1 sp (13,630)	1		Simuliidae (13,630)	1	Odonata-anisoptera (dragonflies)	Aeshnidae (1,012)	8
	Baetidae 2 sp (8,481)	3		Tabanidae (825)	8		Corduliidae (8,480)	3
	Baetidae >2 sp (2,028)	6		Tipulidae (1,812)	6		Gomphidae (10,218)	2
							Libellulidae (2,334)	6
	Sub-total			Sub-total			Sub-total	

TABLE A2 Example of monitoring results giving an indication of sediment concentration, habitat quality, and water quality at different river monitoring sites in the Tsitsa Catchment in May 2019 (autumn, high flows) and August 2020 (winter, low flows)

Site number	River	Dominant substrate	Month/year	ASPT-sed	ASPT SASSv5	Sediment concentration	Water quality	Flow condition sampled	Potential source of pollutant close to site
1	Tsitsana	Coarse	May 2019	4.5	6.7	Moderate	High	High baseflow	Cultivation, pit latrines, sand mining
			August 2020	3.9	6.3	High	Moderate	Low baseflow	
2	Hlankomo	Coarse	May 2019	4.1	5.1	Moderate	Low	High baseflow	Cultivation, pit latrines, sand mining, brick making
			August 2020	4.1	4.6	Moderate	Very low	Low baseflow	
3	Little Pot	Coarse	May 2019	5.9	7.1	Moderate	High	High baseflow	Commercial cultivation
			August 2020	5.3	5.6	Moderate	Low	Low baseflow	
4	Mooi	Coarse	May 2019	4.6	6	Moderate	Low	High baseflow	Downstream of urban center
			August 2020	4.6	4.5	Moderate	Very low	Low baseflow	
5	Pot	Coarse	May 2019	5.3	6.7	Moderate	Moderate	Receding flood	Commercial cultivation
			August 2020	4.8	6.6	Moderate	Moderate	Low baseflow	
6	Tsitsa 1 (upstream)	Coarse	May 2019	3.9	4.9	High	Very low	Receding flood	Intensive commercial cultivation
			August 2020	4.3	5.9	Moderate	Low	Low baseflow	
7	Tsitsa 2 (Gorge)	Coarse	May 2019	5.5	7.1	Moderate	High	Rising flood	No immediate input of pollutants
			August 2020	4.3	6.5	Moderate	Moderate	Low baseflow	
8	Tsitsa 3	Coarse	May 2019	4.8	7.5	Moderate	High	Rising flood	Cultivation, pit latrines
			August 2020	3.2	5.1	High	Low	Low baseflow	
9	Gqukunqa	Coarse	May 2019	4.2	5.8	Moderate	Low	Rising flood	Cultivation, pit latrines
			August 2020	4.6	6.5	Moderate	Moderate	Low baseflow	
10	Tsitsa 4 (downstream)	Coarse	May 2019	5.1	7.2	Moderate	High	Receding flood	Road runoff
			August 2020	5.2	7.2	Moderate	High	Low baseflow	
11	Inxu	Fine	May 2019	2.9	6.0	Moderate	High	Receding flood	Sand mining; pit latrines
			August 2020	2.5	4.8	Moderate	Low	Low baseflow	

Abbreviations: ASPT, average score per taxa; SASSv5, South African Scoring System version 5.