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If a fish comes out of the river and speaks, we should believe it: South African perspective on fish kills

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Abstract

In South Africa, fish kill events are increasing in frequency because of multiple stressors associated with managing natural resources. Despite the ecosystem services associated with fish, South Africa's progressive legislation towards environmental protection seems to negate the management of fish kills. In this study, we provide an overview of reports and regulations associated with acute pollution spills resulting in fish kill events in South Africa. In addition, we highlight the implication of these using a fish kill event from 2019 on the Msunduzi River, South Africa, as a case study. The fish kill on the Msunduzi River showed a decline in relative abundance by up to 41%, and its ecological condition was already impaired by poor management. The poor condition of the Msunduzi River has jeopardised the recovery of the fish populations, and intervention is needed to restore the fish population that includes species red-listed as vulnerable by the International Union for the Conservation of Nature. We found that despite the severity of fish kills and the detriment to the fish fauna, including near-threatened species, there is a general apathy, incapacity and lack of knowledge on managing fish kills in South Africa. In addition, although several legislated Acts have good intentions for protecting nature, they do not align and show that a fish kill is an afterthought rather than a need to prevent. Poor management practices have exacerbated this in an already stressed state from excessive use of environmental water. As a way forward, the alignment of the various Acts associated with various ministerial departments in South Africa is needed so that better protection of the environment may occur. Finally, we argue that the African proverb '*If the fish comes out of the river to tell you that the crocodile has one eye, you should believe it*' is not considered when managing water resources and that with the

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present ecological state and water resource use there may be no fish to 'come out of the water' warning us that our water is unsafe even for human consumption and use.

Keywords

anoxic; biodiversity; legislation; pollution; rehabilitation; river; spill; toxic; water resources; water use

1 Introduction

Globally, peri-urban and urban development and infrastructure, mining, agriculture and industry development have negatively affected water resources on large regional scales (Jewitt et al., 2015; Rodell et al., 2018; Sibanda et al., 2015; Tickner et al., 2020; Wade et al., 2021). In a global context, these impacts are considerable (Feio et al., 2022; Jaureguiberry et al., 2022; Rodell et al., 2018). In southern Africa, including South Africa, this is no exception since the latter's environmental performance has recently been listed as one of the world's worst-performing nations (Du Plessis, 2019; Feio et al., 2022; Hsu et al., 2013). Despite South Africa's progressive legislation, one important indicator of the poor environmental management of South Africa's water resources is the occurrence of anthropogenically driven fish kill events and the management of these events (Grant et al., 2014; O'Brien et al., 2019; Wepener et al., 2011).

Fish are ideal ecological indicators of ecosystem well-being as they are relatively long-lived, well-known, easily identifiable, habitat selective, vary in tolerance to water quality and move within the aquatic environment (Burnett et al., 2021; Chovanec et al., 2003; Harris, 1995; Lucas & Baras, 2000). These characteristics allow for the adequate assessment of fish as they respond to their environmental conditions (Burnett et al., 2020; Wepener, 2008). In southern Africa, fish community assessments are used to evaluate the aquatic ecosystem well-being (Bennett, 1995; Evans et al., 2022; O'Brien et al., 2009), with the first indices used in the 1990s (Kleynhans, 1999; Kleynhans & Louw, 2007). These indices and management tools use fish, along with other biota, dependencies on specific attributes to evaluate ecological well-being and can be used to monitor aquatic environments for anthropogenic impacts (Dickens et al., 2019; Kleynhans & Louw, 2007; Li et al., 2010). Unpacking the levels of organisation in freshwater fish communities to determine adverse outcomes is important when assessing stressor events in the aquatic environment (Wepener, 2008). Understanding the response sensitivity and ecological relevance of fish assists managers in determining an acceptable limit to environmental degradation to allow for sustainable use of a water resource and are used by the Department of Water and Sanitation (DWS) in South Africa (Dickens et al., 2019; O'Brien et al., 2018; Wepener, 2008). Despite fish indices presently used to detect river degradation (Evans et al., 2022), a fish kill event is a key indicator of an acute pollution event that can lead to degradation of river health but does not fall within the scope of routine sampling (Grant et al., 2014).

In southern Africa, fish have contributed to local culture and livelihoods throughout modern history (Plug et al., 2010; Skelton, 2000a, 2000b). Ancient human middens of fish bones around shelters and the depiction of fish in rock paintings can be dated over 2000 years back

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and demonstrate the historical value of fish to human communities in the region (Impson et al., 2008; Mitchell et al., 2012). Today, human communities still depend on fish for food (Dlamini et al., 2022; Impson et al., 2008; O'Brien et al., 2009), and recreational angling sectors have high economic values (Du Preez & Lee, 2010; Brand et al., 2013; Potts et al., 2022). In South Africa, there is a dedicated recreational angling activity targeting one group or genus of fish, the *Labeobarbus* spp., established to be worth over ZAR 133 million per annum (~USD 8.6 million) in 2013 (Brand et al., 2013). Potts et al. (2022) updated the value of the broader recreational fisheries in South Africa to be an estimated ZAR 32.6 billion (~USD 2.2 billion) per annum.

Fish kills represent acute pollution events that negatively impact both the social and economic value of fish worldwide (Grant et al., 2014; La & Cooke, 2011). A fish kill constitutes a mass mortality of fish or fishes in a short period that is notable and indicates that the environmental condition has changed to the point that the survival of fish has been severely jeopardised, rendering the causal activity unsustainable (Grant et al., 2014; La & Cooke, 2011). To quantify this, it is an amount of more than 25 dead fish per 1 km^2 of a lentic ecosystem (such as a lake) or 1-km length of a lotic ecosystem (river) in a 48-h period, whereby the mortality causation is not linked to part of the life cycle of the fish (e.g. the death of adult salmon after spawning) or a result of a fisheries harvest (Grant et al., 2014). The cause of mass fish mortalities may occur naturally, for instance, in the event of sudden temperature inversions from climatic events, such as an intense hailstorm (Allanson et al., 1962), the upswelling of deep water in lakes (Ochumba, 1990), or oxygen depletion arising from algae blooms (Bruton and Taylor, 1979). Unnatural or specifically anthropogenic fish kills have recently become prevalent because of toxic anthropogenic inputs into the aquatic ecosystem and are occurring at higher frequencies and are more intense than some naturally caused fish kills (Grant et al., 2014; Karssing, 2008; Kleynhans et al., 1992; Riddell et al., 2019; Sibanda et al., 2015). These inputs vary considerably and can relate to one or more causes that affect the fish's ability to survive, and examples include excessive reduction of flows and chemical contamination associated with anoxic conditions, nutrient enrichment, cyanobacterial blooms, ammonia and metal toxins (Grant et al., 2014; Sibanda et al., 2015). Although these causes can be natural events, in some cases, they are often directly associated with the excessive use of or pollution of water resources and are unnatural events (Riddell et al., 2019; Sibanda et al., 2015). Fish kills visually indicate when water use is polluted and potentially hazardous for people who physically contact the water resource and or use the fish as a food source (Dlamini et al., 2022; Grant et al., 2014; Wepener et al., 2011).

There is no specific 'fish kill' legislation in South Africa, but as a recognised consequence of the pollution of a water resource in South Africa, the National Water Act 36 of 1996 (NWA) and National Environmental Management Act (NEMA) provide guidelines on the management of fish kill events (NEMA, 1998). Chapter 3 of the NWA deals with preventing water pollution and stipulates that resource users responsible for water pollution are also responsible for remedying the situation (NWA, 1998). As a principle, NEMA requires that the loss of biological diversity, important habitats and ecosystem processes must be avoided, and the mitigation and remediation cost of any pollution events, which includes fish kill events, must be paid for by any and or all parties who caused the degradation to the environment (NEMA, 1998). In 2014, NEMA was amended to supersede legislation that protected directors of companies or members of close corporations from being liable for the harm caused by their respective entities polluting the environment. This amendment renders the directors or the members, as the case may be, individually or collectively liable for any negative environmental impact arising from advertent or inadvertent pollution these entities may have caused (NEMA, 2014).

1.1 Development of policy on fish kills

In the early 1990s, South Africa identified the lack of appropriate policy and legislation pertaining directly to anthropogenically driven fish kills and endeavoured to provide appropriate management decisions to prevent future incidents. In 1993, the regulators of water resources in South Africa, the Department of Water and Forestry (DWAF), now the DWS, released an internal report describing the identification of unnatural fish kills and their management (Badenhorst, 1993), followed by a field guide for fish kill assessments in 2001 (Hohls & Kühn, 2001) and sampling protocols in 2004 (DWAF, 2004). These informal policy documents were developed as guidelines for government regulators but have not been implemented or enforced. Alternatively, Wepener et al. (2011) used a risk assessment approach that included higher-tier assessment endpoints to clarify the adverse effects of multiple stressors resulting in fish kills in aquatic ecosystems to manage these events. In 2014, the Water Research Commission of South Africa developed a national protocol for fish kill investigations (Grant et al., 2014). This protocol has also not been implemented, and, as a result, a policy or governance lacuna regarding the prevention and, importantly, the poor management of fish kills persists in the country.

Against this backdrop, and predictably (Wepener et al., 2011), fish kills have become frequent events in South African rivers (O'Brien et al., 2014) that are poorly managed. Consequently, we argue that the age-old African proverb '*If the fish comes out of the river to tell you that the crocodile has one eye, you should believe it*' (African Proverb, 2020), should be amended to be appropriate for our context to, '*If the fish comes out of the river to tell you it can no longer live there, believe it*'. This study draws on the impacts of a severe fish kill event in the chronically stressed Msunduzi River, KwaZulu-Natal Province, South Africa, to an acute pollution event and highlights the detrimental impacts of this fish kill. In addition, we reviewed and evaluated existing published literature and reports from the DWS on how fish kill events in South Africa have historically been managed. Lastly, we evaluated anthropogenically driven fish kill events management and the appropriate resource management legislation to protect vulnerable river resources in South Africa.

2 Case Study Methods

2.1 Study area

The case study we rely on includes the fish kill event that occurred in the Msunduzi River, a significant tributary of the uMngeni River, KwaZulu-Natal. The Msunduzi River is one of the country's most socio-economically important rivers (Hughes et al., 2018a, 2018b). It originates in the Midlands of the Drakensberg Mountain Range and flows to the KwaZulu-Natal Provincial capital, Pietermaritzburg, before entering into the mid-reaches

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on the uMngeni main stem (Figure 1). The upper uMngeni and Msunduzi rivers flow through similar geographical and ecological zones and have similar habitats and fish species compositions (Evans et al., 2022; Jordaan et al., 2016). The entire uMngeni Catchment provides water to >4 million people in the eThekwini Municipality (Ethekwini, 2018; Roberts & O'Donoghue, 2016).

A total of 17 native fish species occur in the Msunduzi River (Skelton, 2001). Today, four of these fishes have conservation status as threatened on the International Union for the Conservation of Nature (IUCN) Redlist. These species include Mozambique tilapia *Oreochromis mossambicus* (Bills, 2019), the chubbyhead barb *Enteromius anoplus* (Chakona et al., 2022) and *Enteromius gurneyi* (O'Brien et al., 2017) listed as Vulnerable and one listed as Near Threatened, *Amphilius natalensis* (Chakona et al., 2022). *E. gurneyi* is listed as vulnerable because of increased anthropogenic use in its distribution range and near-endemic to the Msunduzi River (Evans et al., 2022; O'Brien et al., 2017). *A. natalensis* was recently listed as near threatened following a taxonomic review of the species as endemic to the upper uThukela and uMngeni catchments (Chakona et al., 2022; Mazungula & Chakona, 2021). The KwaZulu-Natal yellowfish *Labeo-barbus natalensis* are long-lived, slow-growing and relatively large fish that, when mature, are important ecological indicators of ecosystem well-being (Crass, 1964; Karssing, 2008; Skelton, 2000b). Other species of yellowfish *Labeobarbus* spp. are known only to mature when older than 5 years (Impson et al., 2008; Paxton et al., 2013), and this could be similar for *L. natalensis* (Karssing, 2008). *L. natalensis* has recently been highlighted to have high genetic variance, with the potential of the uMngeni River population being unique to this catchment, increasing the ecological value of this particular population (Stobie et al., 2018). In addition, *L. natalensis* is targeted by subsistence fishers along with other fish species, such as the sharp-tooth catfish *Clarius gariepinus* and other Cichlid spp. (*O. mossambicus*, red-breasted tilapia *Coptodon rendalii* and banded tilapia *Tilapia sparmanii*) on the Msunduzi River.

The Msunduzi-uMngeni River is also home to one of the world's most popular and toughest canoe races, the Duzi Canoe Marathon, which starts in the city of Pietermaritzburg and ends in the city of Durban (Kruger and Saayman, 2013). This event brings in ca. ZAR 3-6 million (~USD 0.2–0.4 million) per annum through direct spending and a total of ~ZAR 23 million (~USD 1.5 million) per annum combined with the known indirect spending for KwaZulu-Natal (Houdet et al., 2020; Kruger and Saayman, 2013). There is a growing concern for this event, given the continual decline in the condition of the Msunduzi and uMngeni Rivers to human health from increasing levels of pathogens that consistently exceed recommended guidelines set out by the World Health Organisation and the South African DWS (Kruger and Saayamn, 2013). Gemmell and Schmidt's (2013) microbiological analyses of the Msunduzi River assert the water is unsuitable for domestic, recreational or agricultural use, given the frequent occurrence and high titre of pathogens in the water body. Despite the poor water quality of the river, the Duzi Canoe Marathon continues to be held annually but has been marred with human health incidences (Carnie, 2022). There are other riverine recreational activities and livelihoods at risk in the area. There is a noticeable informal subsistence fishery along the Msunduzi River that supports a considerable number of fishers present in the city of Pietermaritzburg (Makhathini, 2024; Nkomo, 2023). Despite these rising water quality concerns, the river has been identified as a strategic water resource important for potable water, recreational activities and fish health (Figure 1; Houdet et al., 2020; Le Maitre et al., 2019; Van Deventer et al., 2020).

2.2 An acute fish kill event

A noticeable fish kill event in 2019 occurred in the Msunduzi River that catalysed our review of the approach taken to address fish kills in South Africa. On the 13th of August 2019, a media statement released by the South African Government first announced that a support structure of a cooking oil storage tank at a manufacturing plant situated in Pietermaritzburg city on the Msunduzi River had failed, collapsing the tank into a neighbouring caustic soda storage tank (Department of Water and Sanitation (DWS), 2019). On the 13th of August 2019, both tanks ruptured, releasing ~1600 tons (±30,000 L) of a soap derivative composed of crude cooking oil and caustic soda into the Baynespruit (Bayne's Stream), 3.7 km upstream of the confluence of the Msunduzi River (Figure 1; DWS, 2019; Kanyile, 2019a, 2019b; Willowton Group, 2019). The spill affected an 82 km reach of the Msunduzi River downstream of the Baynespruit and the uMngeni River as far as the inlet to Inanda Dam (Figure 1; DWS, 2019; Graham et al., 2021; Kanyile, 2019a; Mdletshe, 2019; SAPA+, 2019). The soapy mixture spill caused the pH to rise to 8.5, however, in the heavily polluted areas a pH of 10.78 was recorded (DWS, 2019; Graham et al., 2021). As the pollutants moved down the river, an anaerobic (<0 mg/L O_2) condition occurred in the water column, which potentially was the main driver of the fish kill. The following day, water was released from Henley Dam upstream of Pietermaritzburg to dilute the spill and aerate the affected reach of the river. Despite this intervention, dead fish from all size classes and species were evident and died *en masse*, clogging up the river while some drifted downstream as far as Inanda Dam (Burnett M. J. pers. obs.; Harper, 2019; Kanyile, 2019b; SAPA+, 2019).

An estimated 15 tons of dead fish carcasses were removed from the river (DUCT, 2019a, 2019b), and a considerable amount of additional dead fish was removed by wildlife and by people from vulnerable communities for food. Local regulators identified people harvesting dead fish to eat and so warned all those along the affected river, including residents around Inanda Dam, not to drink or come into contact with the river or dead fish until the river clean-up efforts had taken effect (DWS, 2019; Graham et al., 2021; SABC, 2019). The 20 tons of dead fish observed were estimated to have been comprised of >51,000 fish (750 fish or 294 kg of dead fish per linear kilometre) as calculated using a size class sample and the species observed in the clean-up (DUCT, 2019a, 2019b). The unfortunate death of a person was linked to the event when a young cattle herder drowned in suddenly rising water levels during the 'dilution release' from Henley Dam upstream of the incident. The deceased was collecting dead fish from the polluted river, presumably for food (Mdletshe, 2019).

2.3 River health sampling

The severity of the fish kill warranted an evaluation of how it impacted the fish community structures and abundances. Data from various fish community assessment projects on the uMngeni and Msunduzi Rivers, such as the River Eco-status Monitoring Programme (REMP) (Dlamini, 2019; Evans et al., 2022; Thirion & Jafta, 2020), were used to evaluate the fish community composition before the spill at sites shown in Figure 1. Unfortunately,

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no data could be obtained after the fish kill in 2019 because of limited resources and commitment to address this fish kill event. A river health survey was conducted in 2020 to coincide with previous seasonal surveys on the Msunduzi River and evaluate the post-spill fish community status. These sites selected for the assessment included a relatively unimpacted reference site on the uMngeni River to compare with the Msunduzi River upstream of the spill, impacted sites (FK1-4) and downstream (DSTR) sites, see Figure 1 and Table 1. These sites were surveyed per the REMP approach, previously used in the Msunduzi River and KwaZulu-Natal region, and described by Evans et al. (2022). Quantitative fish community data based on species, abundances and size classes were log-transformed for comparability.

2.4 Fish community data analyses

Descriptive analyses were plotted in MS-Excel, and the statistical data analyses used CANOCO for Windows (version 4.53) and assessed using redundancy analysis test from principal component analysis (PCA) testing to evaluate the fish communities' abundances, size class structures and habitats pre- and post-impact of the spill (Evans et al., 2022). The PCA uses the linear response between the fish assemblages and environmental variables and plots the ordination results as a two-dimensional plot, reflecting the dissimilarities or similarities between samples (Nasir et al., 2011; O'Brien et al., 2009; van den Brink et al., 2003). The redundancy analysis tests determine which species, guilds or environmental variables were probably responsible for these groupings and then presented as biplots onto the original PCA plot (Shaw, 2003; Ter Braak and Smilauer, 2004).

3 Case Study Results and Discussion

3.1 Environmental response

The analyses from the fish kill event showed that habitat did not affect the fish community structures between all sites (Figures S1–S3). The multivariate assessment did, however, result in a significant ($p < 0.05$) change in the fish communities between sites, which was correlated with other stressors (Figure 2). When evaluating the pre- and post-spill fish community structures, the spill was identified as having a significant ($p < 0.05$) effect on the fish community (abundance and diversity) for the Msunduzi River in impacted areas (Figure 3). The significant effect of the spill on the fish communities extended downstream to Inanda Dam, where the extent of the fish kill was observed (Figure 1). There was a significant ($p < 0.05$) decline in the abundance of the southern mouthbrooders *Pseudocranulabrus philander, L. natalensis* and *C. gariepinus* within the impacted areas of the spill (Table 2, Figures 3 and 4). The size classes of these species were also significantly disrupted with reduced abundances of adult fish (Figures 5 and 6). This is particularly concerning for *L. natalensis*, which are long-lived and mature at 3–4 years (Karssing, 2008). Based on the upstream sampling site (ASCO, Figure 1), the population structures post-spill showed a reduction in adult individuals that may have dispersed post the fish kill into the depauperate affected area. *L. natalensis* are highly mobile species within the system, seeking refugia in deeper pools in winter (Burnett et al., 2021). These pool habitats occur predominantly downstream of the spill site and would have been highly impacted by the spill, as fish would be in refugia habitat at the time of the spill. Considering that the 2020 survey was conducted 9 months later post a summer high flow when *L. natalensis* migrate and spawn, it indicated that relatively little recruitment into the upstream area occurred (no adult *L. natalensis* were caught in the highly impacted sites (FK1-3), suggesting that no movement into the impacted area downstream occurred). Three *L. natalensis* fry (<15 mm in size) were caught in the uppermost impacted site (BSTW, Figure 1). The low numbers of *L. natalensis* fry and their locations suggest that these may have been recruited from fish spawning upstream of the impacted area. *C. gariepinus* showed better recovery than *L. natalensis*, although adult fish abundance decline was still significant ($p < 0.05$). *C. gariepinus* can withstand anaerobic conditions better than *L. natalensis* and is frequently found in poor water quality areas (Evans et al., 2022). This suggests that *C. gariepinus* was more resistant to the spill, although still heavily impacted, and may recover quicker than other species, such as *L. natalensis*. The negative effect of the spill on poor water quality tolerant fish species, such as *C. gariepinus, L. natalensis* and *P. philander*, suggests the severity of this event and consequentially slow recoveries are expected. O'Brien et al. (2014) described how some populations of *Labeobarbus* spp. and other fish species can take decades to recover, especially in areas affected by multiple stressors. In the Msunduzi River, the more cryptic species that may be undetected during clean-up operations, for example, *P. philander, E. anoplus* and *E. gurneyi*, are expected to recover relatively slowly, if at all. The absence of *P. philander* during the 2020 survey showed how little is known about these species and warrants further investigation as they are traditionally considered a tolerant species when relating to water quality conditions (Evans et al., 2022; Kleynhans, 2007).

In addition to the impact of the 2019 spill, the recent monitoring of the Msunduzi River identified important anthropogenic stressors that affected the river ecosystem (Dlamini, 2019; Ngcobo, 2024; Ngozi, 2024). This was evident by the presence of species intolerant to poor water quality, such as *A. natalensis* and *E. gurneyi*, at the reference sites and not in the Msunduzi River (Table 2; Figure 2). This was not unexpected considering the plethora of anthropogenic stressors within the upper catchment of the Msunduzi River before the spill with periodic minor fish kill events (<100 fish/km) (pers. obs.; DUCT, 2018). *E. gurneyi*, for example, has a museum record collection from 1996 from the MOTO site (Figure 1), where this species was not collected in the present study in the Msunduzi River even when surveying the same site. Before the fish kill, *E. gurneyi* was extirpated from the Msunduzi River from pre-spill stressors (Evans et al., 2022; O'Brien et al., 2017). There is now greater uncertainty for this species in the study area, and as an indicator for the sustainable use of water resources and the region's biodiversity is in question (Du Plessis, 2019).

3.2 Social-ecological impacts

The 2019 spill was a catalyst to the demise of the fish communities in the already stressed Msunduzi River, which was jeopardised by the plethora of anthropogenic stressors that go unchecked (Evans et al., 2022; Fouchy et al., 2019; Hughes et al., 2018a, 2018b). This is especially true for an urban river that provides direct access to recreational activities (Houdet et al., 2020; Potts et al., 2022). Recreational value already exists with the Duzi Canoe Marathon and has potential for other activities if conditions improve, including recreational angling for *L. natalensis* if parallelled to the targeted yellowfish fly-fishing industry in the Vaal River (Brand et al., 2013). The Duzi Canoe Marathon has decreased participants as the *E. coli* counts have risen yearly (Gemmell & Schmidt, 2013; Kruger and Saayman, 2013; Wyllie & Kohler, 2017). Despite the protests from the canoeing community, little has been done to mitigate this trend, potentially causing a decrease in attendance of 42% from 2010 to 2017 (Wyllie & Kohler, 2017) and a further 7% decrease between 2018 and 2019 (Fischer, 2019; Ngcobe & Tiller, 2019). The condition of the Msunduzi River should not be overlooked as a factor in deterring participation in the Dusi Canoe Marathon (Houdet et al., 2020). The river condition pre-spill had unacceptable pathogen levels (Gemmell & Schmidt, 2013). This could be seen in the fish community assessment in the present study, as shown by the lack of diversity and abundance when compared with the reference sites.

3.3 Potential economic impact

Fish provide for the livelihoods of those with direct access to rivers as a source of protein (Impson et al., 2008; Skelton, 2000a, 2000b). The >51,000 fish or >20 tons of fish killed in the Msunduzi River 2019 spill could not be allocated for human consumption because of health concerns related to the cause of death of the fish, but many of the local communities along the impacted area of the spill attempted to harvest dying fish, contributing further to the negative impact of the spill. A quick summary of the monetary value of the 20 fish tonnage lost in the spill had it been sold on the market at a value of ~ZAR 60.00 (~USD 3.28) per kilogram (Kourie & Somyo, 2022) amounts to ~ZAR 1.2 million (~USD 65,633.50). The benefits of this provided at a daily rate over a year can provide ~ZAR 3287.67 (~USD 179.82) worth of fish per day, well above the minimum wage for South Africa at ZAR 1203.36 per day. Sustainable harvesting suggests that this can be higher and would contribute to livelihoods indefinitely (McCafferty et al., 2012; O’Brien et al., 2009; Potts et al., 2022; Weyl et al., 2007). It is estimated that the fish abundance collapse from the spill amounted to ~31% and 41% when comparing the catch per unit effort for 2020 against the catch per unit effort for 2017 and 2018, respectively. The collapse of abundances has reduced interest and catch by the informal subsistence and recreational fisheries in the impacted area (pers. comm. fishers on the Msunduzi River), with successional recruitment of fish expected to be low, especially for long-lived species like *L. natalensis*. The exact contribution this fishery underpins livelihoods along the Msunduzi River remains unknown, but other studies suggest that it is higher than expected, especially around recreational (Brand et al., 2013; Britz et al., 2015; Potts et al., 2022) and small-scale fisheries (Ellender et al., 2009; Tapela et al., 2015).

4 Overview Of Documented Fish Kills In South Africa

While documented recordings of naturally occurring and anthropogenically driven fish kills in South Africa are available, most relatively smaller fish kills are undocumented (Cyrus & McLean, 1996; Grant et al., 2014; Whitfield & Paterson, 1995). Examples of reported anthropologically driven fish kills are available from the DWS in the fish kill incident reports from 1999 to 2004. These reports detail fish kills resulting from high levels of organic material depleting oxygen (DWAF, 1999), dissolved pesticides and herbicides (Hohls & Van Niekerk, 2000) and contaminants possibly from wastewater treatment works (Hohls & van Ginkel, 2004). Fish kills in the Vaal River barrage area have also been attributed to decreasing water quality within the Vaal River (Wepener et al., 2011). Still, determining the exact reason for fish kill events (Grant et al., 2014) and whether a specific land-owner or organisation is responsible is often difficult. More recently, however, reoccurring fish kills from the Phalaborwa barrage on the Olifants River, Limpopo Province, have resulted from anoxic sediment sluicing to maintain the water supply that supports the wider economy around Phalaborwa (Riddell et al., 2019). The largest documented fish kill event recorded in South Africa from anthropogenic causes occurred in 1989 (Kleynhans et al., 1992; O'Brien et al., 2014). This accidental effluent spill from a paper mill on the Elands River severely impacted the fish communities and decimated the sub-population of Incomati suckermouth *Chiloglanis bifurcus* (Kleynhans et al., 1992; O'Brien et al., 2014). This species was already threatened then and is now critically endangered (O'Brien et al., 2014). This fish kill event was assessed for recovery, and it was found that it would take decades, and reintroduction would be necessary to assist in the recovery (Kleynhans et al., 1992). The reintroduction was implemented, yet populations of affected fish species (including *Labeobarbus* spp.) have not returned to previously known abundances (O'Brien et al., 2014). This event has demonstrated aquatic ecosystems' sensitivity and vulnerability to significant fish kill events. Although re-introduction has aided recovery, questions have been raised on the dilution in sub-population genetics (O'Brien et al., 2014), which are being considered for species-level, especially for the *Labeobarbus* family (Stobie et al., 2018).

Despite the cases reviewed in the present study, fish kills are seldom documented or addressed in South Africa. Other than reported by media houses, action is rarely taken against the polluter (Foord and Fouché, 2016; Karssing, 2008; O'Brien et al., 2014). In addition, in some instances, fish kills are considered by regulators to include 'acceptable losses' where routine maintenance is carried out on water security infrastructures (Riddell et al., 2019; Wepener et al., 2011) or when industry processes are in a state of flux after planned maintenance shutdowns, and effluent does not initially meet required environmental or licence standards (Wade et al., 2021). The example from the Phalaborwa barrage on the Olifants River aligns operational procedures to the first summer rains, and high increased river flows to ensure adequate flushing of the barrage (Riddell et al., 2019). Flushing the barrage mobilises sediment, creating significant changes in the physical and chemical characteristics of the river, resulting in low oxygen levels and local and often regional fish kills (Riddell et al., 2019), potentially impacting 42 known fish species in the conservation-focused Kruger National Park which occurs downstream of the barrage (Scott et al., 2000). Riddell et al. (2019) also identified other major industries in the region, including mining activities that have frequently affected the quality of the Olifants River in the Kruger National Park, resulting in extensive fish kills. These events have, historically (pre-2010), not resulted in noteworthy litigation against the polluter. From 2010 onwards, however, polluters were increasingly held responsible and liable for pollution events. Other fish kill examples include the operation of a barrage on the Vaal River, Gauteng Province (Wepener et al., 2011), and pulp and paper mill activities where water quality regulatory requirements are not met over short to medium terms (hourly to many days) after the process re-starts (Wade et al., 2021).

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5 Fish Kill Management: Relevant South African Environmental Legislation

5.1 The Constitution of South Africa

The legislation regulating the use and protection of South Africa's water resources, as well as other components that constitute the 'environment,' is rooted in what is commonly referred to as the 'Environmental Right' (section 24) in the Bill of Rights in the Constitution of the Republic of South Africa, 1996, which includes the right of South Africans to; '(a) an environment that is not harmful to their health or well-being and, (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and (c) other measures that prevent pollution and ecological degradation, promote conservation and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development' (Blackmore, 2018; Constitution of the Republic of South Africa, 1996; Van der Schyff, 2010).

The environmental rights form the foundation for the establishment of the South African NEMA 107 of 1998 (NEMA, 1998), which forms the framework for specific legalisation directed at the protection and sustainable use of the natural environment, and in particular water (Couzens & Dent, 2006). In addition, this environmental right brings into South African law and jurisprudence the Roman common law public trust doctrine, which is articulated in the country's NEMA as 'The environment is held in public trust for the people, the beneficial use of environmental resources must serve the public interest and the environment must be protected as the people's common heritage' (Blackmore, 2015; NEMA, 1998).

Fish kills are indicative of degraded environments that are harmful to people, and where affected ecosystems are unsustainable for present and future generations, and/or when fish kills are indicative of serious pollution events resulting in ecological degradation, the constitutional rights of South Africans are applicable, but it seems not implemented. In addition, environmental legislation that holds valuable ecosystems in public trust that are not protected should also be triggered after fish kills occur.

5.2 National Environmental Management Act

The South African NEMA was drafted as a 'framework statute' that encompasses the core legal disciplines that constitute the natural environment, including inland water resources. The NEMA framework encompasses, amongst others, principles to be adhered to when making decisions that may affect the environment, the need for integrated environmental management, including the environmental impact assessment process, offences and penalties. All these components of the framework, where relevant, must be applied when exercising the provisions of the specific environmental legislation.

Environmental law and the South African NWA 36 of 1998 (administered by the ministry of the DWS) and Water Services Act 108 of 1997 (WSA—administered water services institutions and water services intermediaries such as water boards and water services

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committees) regulate the use and protection of water resources and in many respects overlap in jurisdiction.

The NWA is administered by the ministry of the DWS, whereas the WSA is administered by water services institutions and water services intermediaries such as water boards and water services committees, which are subject to the oversight of and direction by the ministry of DWS. These institutions and intermediaries may be, depending on the type and scale of the water resource being used, established at regional (sub-national) to local (e.g. municipal or sub-municipal) scale. Nevertheless, in terms of fish kills and in simple terms, the NWA is overarching in that it caters for the use and safe-guarding of the country’s water resources (i.e. catchment management and the regulation of demand) and the WSA is primarily focused on the provision of water to people (i.e., the provision of water and the regulation of supply) (A’Bear & Davis, 2001; Qumbu, 2021). The magnitude of the overlap is determined by the context in which the legislation is applied. From a fish kill perspective, the two key domains of overlap are the abstraction of water and its release into the environment following its use. Thus, to simplify the analysis below, the relevance of the WSA is included in the scrutiny of the NWA.

The complexity of overlapping legislation is heightened beyond the NWA and the WSA, in that the remainder of the specific and other environmental laws are generally applied and administered by the ministry of the Department of Environmental Affairs (presently the Department of Forestry Fisheries and the Environment) and various provincial conservation authorities. There are two additional considerations that must be made by the ministry of the Department of Mineral Resources, which applies to the NEMA Environmental Impact Assessment (EIA) process with mining applications and DWS in administering the NWA and WSA must consider the EIA processes in water resource development applications. Thus, in the context of fish kills, several governmental ministries (i.e. the water and environmental ministries) and at least one conservation agency in which the event occurs would need to co-operate to apply the law to its fullest extent. There is evidence that this is not occurring in South Africa (Grant et al., 2014; O’Brien et al., 2014; Riddell et al., 2019; Wepener et al., 2011).

5.3 NWA and WSA

The South African NWA is an internationally recognised and progressive water resources protection legislation (Cullet, 2011; Schreiner, 2013). This accolade is founded on the post-constitutional democratic incorporation of the public trust doctrine into this Act, section 3 of the Act and complementary environmental law (Adom et al., 2022; Blackmore, 2018; Feris, 2012). In so doing, the DWS, the custodian of water resources in South Africa and the ministry responsible for the implementation of the NWA has a fiducial mandate to achieve from a water management perspective. To achieve this, there needs to be implementation of Chapter 3 of the NWA, which specifically describes how water resources can be sustainably developed through careful use, development, conservation, management and control to ensure sustainable use and protection of the ecological integrity of aquatic ecosystems (NWA, 1998). The Resource-Directed Measures of Chapter 3 aim to safeguard South Africa’s water resources, namely by (a) a water resources classification system, (b) determining the ecological and useable water reserve and (c) setting the Resource Quality Objectives (RQOs) for each class of resource (Pienaar et al., 2020). The Resource-Directed Measures provisions of the NWA have been established to reach a sustainable balance between the use and protection of water resources (Pienaar et al., 2020; Xu et al., 2003). Here, the NWA provides for the mandatory determination of a vision for the sustainable use and protection of the resource through the Water Resources Classification process and the 'Reserve', which defines the quantity and quality required to (a) 'satisfy basic human needs' and (b) 'protect the aquatic ecosystems of the water resource' or the 'Ecological Reserve' (NWA, 1998). The flow or quantity of water resources to meet the class or vision of the resource and quality, habitat and biota characteristics that represent the use and protection balance are formalised through the RQOs, which are gazetted and binding on all authorities (Dickens et al., 2019; NWA, 1998). This process, culminating in legislated RQOs, should afford suitable protection measures, comparable with Sustainable Development Goal targets (Dickens et al., 2019), to South Africa's vulnerable water resources and the biodiversity that lives in them. Importantly, Resource-Directed Measures outcomes are used to allocate water resource use and thus would need to comply with complementary legislation that includes the WSA (WSA, 1997) and the NEMA (NEMA, 1998). When fish kills occur, often representing the excessive use of water resources, the relevance of Resource-Directed Measures, including water use allocations aligned to the vision of the resources and associated sustainability requirements, are not evaluated and amended to ensure the balance between the use and protection of water resources is achieved.

In the WSA, the sustainability of habitat and biodiversity conservation requirements are established for the water resources through the application of the environmental impact assessment, resulting in Environmental Authorisation, which is considered when issuing a Water Use Licence (WSA, 1997) by the custodians of water resources, the DWS (NWA, 1998).

5.4 National Environmental Management: Biodiversity Act

Limited protection of riverine habitats and associated species in South Africa can be provided in terms of Chapter 4 of the National Environmental Management: Biodiversity Act (NEM:BA) 10 of 2004, which states that they are either threatened or require protection. For an ecosystem to be listed, it must be either degraded and in need of protection or be of high conservation value or high national or provincial importance, such as identified, for example, as a National Fresh-water Ecosystem Protected Area (NFEPA). Likewise, this Act identifies a threatening process (i.e. an anthropogenic activity). Regulation of the use of a listed ecosystem or exercising a threatening process is via the environmental impact assessment process stipulated in NEMA and through the environmental implementation or environmental management plans that must be adopted by the municipality (NEMA, 1998; NEMBA, 2004). Similar provisions apply to listed species, but section 56 NEM:BA provides the mechanism to identify, regulate and prohibit certain activities that impact the survival of a listed threatened or protected species (TOPS). Similarly, fish kill events that may indicate extreme damage to ecosystems and or selected species do not automatically trigger the NEMA:BA legislation to review and or consider changes in habitat or species sustainability.

While probably appropriate, regulators have not implemented NEMA:BA legislation and/ or mechanisms after fish kill events.

5.5 National Environmental Management: Protected Areas Act

Similar circumstances apply to the South African National Environmental Management: Protected Areas Act (NEM:PAA) 57 of 2003. While it is possible to declare a river or a portion thereof as a protected area, at the time of this study, this provision of NEM:PAA had not been exercised. To do so, would require a protected area management authority to be appointed (NEMPAA, 2003). Hence, it is uncertain whether the powers of the management authority would conflict with the powers of the various management instruments provided in the NWA and, therefore, remain unchartered territory. Therefore, the current application of the NEM:BA and NEM:PAA does not enhance the legal protection afforded by the NWA to South African rivers and associated fish habitats and populations.

6 Monitoring And Reporting

The monitoring of anthropogenic, and in particular industrial, use of water in South Africa is ultimately the responsibility of the DWS viz. the NWA, and WSA, and the relevant national Department of Environmental Affairs and provincial conservation organisations who assign sustainable water resource use responsibility, and therein liability, to the holder of the relevant licence or environmental authorisation. The Water Use Licences includes monitoring requirements that enforce its compliance and stipulations for each user, which the DWS should align to evaluate and ensure the sustainable use of water resources (NWA, 1998; Wade et al., 2021; WSA, 1997). Unfortunately, the ability of the DWS to reconcile the environmental performance of water resource users, integrate user performances and monitor water resource well-being on a national scale is limited, and this is hindering the ability of the DWS to hold users accountable for unsustainable environmental degradation (Dickens et al., 2019; O’Brien et al., 2019; Schreiner, 2013; Thirion & Jafta, 2020; Van Rooyen et al., 2017). Similarly, the holder of environmental impact assessment authorisations issued in terms of NEMA would be accountable for any non-compliance with the Act as well as any conditions the authorisation may have. Both the NWA and NEMA (see, for instance, s29(1) and 24(10)(a)(iii) respectively) empower the issuing authority to specify monitoring and reporting requirements the holder of the licence or authorisation would need to adhere to. These requirements would potentially alert the respective departments of at least a pollution event.

Notwithstanding the challenges in and around self-incrimination, potential pollution may arise from sources other than water licence or environmental authorisation holders. In these instances, section 28 NEMA provides for a ‘duty of care and remediation of environmental damage’, which requires any person who directly or indirectly causes or may cause, amongst others, a significant pollution event to ‘take reasonable measures to prevent such pollution or degradation from occurring, continuing or recurring, or, in so far as such harm to the environment is authorised by law or cannot reasonably be avoided or stopped, to minimise and rectify such pollution or degradation of the environment’ and in so doing, notify the relevant department that the event has or is about to occur.

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Furthermore, and as part of the duty of care provisions, section 31 of NEMA provides whistle-blowers the right to protection for having disclosed any aspect of a potential or pollution event that has occurred. Such protection is granted where the disclosure was in good faith and in the public interest, and the whistleblower has followed a particular process. This process includes the circumstance where the whistle-blower is of the opinion that approaching the press and popular media is necessary to avert an imminent significant threat or to ensure that the threat is timeously and appropriately investigated by the relevant authority (Du Plessis & de la Harpe, 2007). For fish kills, this authority would be the DWS.

7 Liability and Offences

In the case study of the Msunduzi River fish kill, sections 19, ‘Prevention and remedying effects of pollution’ and 20, ‘Control of emergency incidents’, and other legislation described would apply. In keeping with the prevention of pollution of the environment provisions within NWA, any person (including juristic persons) who is in control, occupies or uses the land on which a water-polluting event may occur or has occurred is obligated to ‘take all reasonable measures to prevent any such pollution from occurring, continuing or recurring’. Furthermore, NWA provides for pollution liability to be jointly and severally applied. Thus, in simple terms, any person (the polluter) reasonably linked to the requirement to prevent a pollution event taking place or allowing pollution to take place may be wholly or partly liable for, at least, the costs for the necessary prevention interventions and importantly the costs associated with, amongst others, the recovery of the pollution and any mitigation required to remedy ‘effects of the pollution’ and ‘any disturbance to the bed and banks of a watercourse’ (NWA, 1998). Given that the purpose of NWA includes the obligation to protect aquatic and associated ecosystems and their biological diversity, it is a common cause that the polluter would be responsible for and, in turn, liable for the fish kills discussed above (NWA, 1998). Where the polluter fails to fulfil the remediation obligation, the regulator, in terms of the NWA, may undertake the necessary interventions to remedy the pollution event and recover the costs thereof, apportioning liability from the polluter (NWA, 1998).

The NWA prescribes an array of offences, two of which directly apply to a pollution event. The first occurs when the polluter ‘unlawfully and intentionally or negligently commits any act […] which pollutes […] a water resource. The second is a failure of the polluter to comply with a directive (or a “notice”) issued by a ‘water management institution’, which includes the DWS (NWA, 1998).

In the instance of the present study’s spill, the public was advised that there was sufficient bunding on the manufacturer’s premises to contain the contents of one of the storage tanks deemed sufficient by DWS (2019). Thus, given this circumstance, it is unlikely that the polluter would have been found to have acted unlawfully or negligently or intentionally caused the pollution event. A directive was likely issued to the polluter to ensure that the pollution removal and remediation undertaken meets a reasonable standard set by the DWS or the catchment management agency. This standard should naturally, in accordance with the DWS-mandated trusteeship of South Africa’s water resources, be equivalent to or improve the state and integrity of the river systems that occurred immediately before the pollution event (NWA, 1998). Finally, penalties for listed offences range from a fine and/or imprisonment up to 5 years for a first offence and double this for a second or subsequent conviction (NWA, 1998).

The obligation to protect the biological diversity in South African water courses is broad and consequently provides equal weight to common or abundant, endemic, rare and threatened species. Likewise, the NEMA act does not discriminate between an unspoiled and a significantly anthropogenically spoilt water course. Should a distinction between important and lesser important biodiversity be required, such distinction could be exercised at the discretion of the official in the directive issued to the polluter. Reliance on discretion to cause a particular outcome is risky on one or more of at least four fronts. These being, the official is (a) unwilling to apply discretion, (b) cannot appreciate the significance of the state of the water course before the pollution event, or (c) there is insufficient defendable information for discretion to be applied with confidence or (d) the directive, and the discretion therein, may be appealed or taken on review by the courts. Consequently, it may be argued that the application of NWA is fallible, particularly in those instances where fish kills are to be prevented or adequately remedied when significant pollution events occur. Finally, other than the provision for expropriation of land and that embodied in the Resource-Directed Measures, the Act does not provide any mechanism to protect watercourse habitats or water-dependent species in that the *modus operandi* of the Act is to manage water quality, quantity and habitat through the regulation of anthropogenic use of the country's water resources (NWA, 1998).

In terms of the NEM:BA, a person convicted of an offence involving a listed species or ecosystem would be liable for a fine not exceeding ZAR 10 million (~USD 595,880.50) and/or imprisonment for a period not exceeding 10 years. In the case of a subsequent offence, double these penalties would apply. Eight freshwater fishes are listed in the TOPS regulations associated with the NEM:BA (DEA, 2015), with more listed as threatened (from Vulnerable to Critically Endangered) by the IUCN (Chakona et al., 2022). The regulated activities associated with the listed species are limited to direct consumptive uses, for example, fishing, capturing and trading. Furthermore, at the time of drafting this manuscript, publishing the 2009 draft set of listed ecosystems had not progressed further than the public consultation phase (DEA, 2015). Although rivers are recognised in the preamble of this notice to contain endangered or threatened ecosystems, none were included in the list appended to the notice (DEA, 2015). Consequently, in its present form, the NEM:BA provides little protection to freshwater fish or in-stream habitats.

8 General Discussion

8.1 Environmental effects

The 2019 Msunduzi River fish kill is likely to be the worst fish kill recorded in South Africa since the 1989 Elands River fish kill, and/ or as severe. Quantifying and comparing fish kill severity between different cases is difficult to quantify, especially when monitoring responses are slow and not formally required. For example, a fish kill in the Murray-Darling Basin, Australia, in 2018–2019 described >5 millions of fish being killed between 40 and 600 km stretch of river (Koehn, 2021; Stocks et al., 2021). This places the Msunduzi

River fish kill on the same level of severity, yet little to no attention has been drawn to the negative socio-ecological and economic implications. The Murray-Darling Basin and the present study of fish kill events indicate that pre-existing stressors in the system that were linked to the management of the river were also indicative of a chronically stressed river impacted by an acute trigger causing a fish kill and have complexities associated with the river's management (Jackson and Head, 2020; Stocks et al., 2021; the present study). It is understood that fish kill incidents are predominantly associated with chronic anthropogenically inflicted disturbances that stress the affected fish community and are exacerbated by a subsequent pollution event (Ashton, 2010; Desai et al., 2021; Riddell et al., 2019; Roux et al., 1995). This observation is not unique to the Msunduzi River as many fish populations in South Africa are at risk of regional decline and go unnoticed as they are not aligned with acute fish kill events (Chokona et al., 2022). We advocate that these regional declines negatively impact the overall well-being of freshwater fish communities in South Africa, and acute fish kill events can seriously threaten the viability of important populations and have received little attention (O'Brien et al., 2014). Generally, large growing yellowfish (*Labeobarbus* spp.) are the most notable species affected during fish kills (Impson et al., 2008; Skelton, 2000b). Despite yellowfish's tolerance to poor water quality (Kleynhans, 2007), cryptic and often more sensitive species that are affected and potentially lost through fish kills generally go unnoticed (O'Brien et al., 2014). In a multiple-species fish kill, it is important to consider the rate at which a population may return. This can shift the conservation status of a species from vulnerable to critically endangered, as with *C. bifurcus* in the Elands River fish kill from 1989, with similar cause for concern regarding *E. gurneyi*. The age at which *Labeo-barbus* spp. mature may present slow recovery rates of species. River connectivity issues in South Africa can further jeopardise the recruitment and recovery of populations from water protection areas to impacted areas (O'Brien et al., 2019). There are few published examples of the long-term effects of a pollution event on fish locally. However, the Msunduzi River fish kill in the present study shows parallels to the Eland River fish kill in 1989, and the system had not fully recovered 20 years later (Kleynhans et al., 1992; O'Brien et al., 2014). Macroinvertebrates recover at a higher rate (approximately a year, Smith et al., 2010) than to fish that can take over 4.3 years until abundances and species compositions stabilise (Kubach et al., 2011). Remediation should be required post any fish kill event, either through translocating suitable stock into the impacted area or ensuring connectivity to a potential source of a fish population upstream of the fish kill event. Allowing the system to self-heal may be counterintuitive, especially if the system is consistently in a poor ecological state and has poor river connectivity. This is particularly true for the Msunduzi River. The continued stressors impacted South African rivers, including periodic acute fish kills, have resulted in the red-listing of several fish species' as vulnerable or critically endangered by the IUCN, for example, the red-tailed barb *E. gurneyi* (O'Brien et al., 2017) and *C. bifurcus* respectively (Chakona et al., 2022; Roux & Hoffman, 2017). The Msunduzi River fish kill may only be lessened to that of the Elands River fish kill from 1989, because species such as *E. gurneyi* and *A. natalensis* have already been extirpated from the river from previous chronic and acute pollution events and the high level of alien species present for example, common carp *Cyprinus carpio*, at least from a conservation perspective.

Not knowing or having little understanding of the reference state before a fish kill event should not excuse polluters from lessening the impact a fish kill may have had or reason for mitigation. In the event of rivers that are continually in a poor ecological state, as the case with the Msunduzi River (Dlamini, 2019; the present study), remedial action or rehabilitation is required to return to the previously known ecological state rather than the managed ecological state set out by regulators (DWS, 2019). The DWS, through the REMP, has shown that unacceptable ecological status classes of ‘E’ and ‘F’ can be a result of poor water resource management (Evans et al., 2022). However, management action is needed to meet the required ecological state or even improve on it (Evans et al., 2022). The DWS sets out the ecological state necessary for a given site and these are broadscale guidelines to indicate the overall health of rivers and are not designed to address fish kills specifically (Avenant, 2010; Kleynhans & Louw, 2007). Areas at risk of fish kills, for example, directly downstream of industry, should be assessed separately.

8.2 Social impacts

Fish kills indicate a severely altered state of the ecological health of a river (Grant et al., 2014; La & Cooke, 2011). In South Africa, the increased frequency and severity of fish kills and how they are managed are of concern to the future health of its aquatic ecosystems. South Africa is exploring economic diversification opportunities, including wild-caught fisheries as they see the value in having healthy fish stocks to support the green economy (Adeleke et al., 2021; DFFE, 2020), yet fish kills, and the management response to them does not reflect this. These social benefits related to other recreational activities that are associated with the river, such as canoeing, fishing and swimming would have a higher contribution to the economy given a healthy river to facilitate these. The present study of a fish kill could potentially be a catalyst to highlight the negative impacts on the river and improve the management of the Msunduzi River after seeing the severity of the fish kill. However, this has not been the case. The advocation by polluters and regulators to rehabilitate the Msunduzi River back to its pre-spill ecological state suggests that multiple stressors are affecting the Msunduzi River. The chronic levels before the present study’s fish kill event indicate that water resource use has exceeded the Resource-Directed Measure targets for sustainability (NWA, 2017) and is seen as ‘acceptable’ with little to no intervention to improve the ecological state to acceptable water quality to recreation levels. This challenge would require a collective effort from all stakeholders involved and increased capacity to monitor environmental conditions and enforce the rule of law to improve the water quality of the Msunduzi River intentionally. Unfortunately, this currently seems unlikely as, based on further media reports, little has been done since with several other pollution events in the same system and fewer, if any, consequences for polluters (media article: Regchand, 2020). This concern highlights some of the challenges faced in the Msunduzi River that seemingly undermine the livelihoods of vulnerable human communities dependent on this aquatic ecosystem’s well-being for, not only for recreational activities, but also subsistence living that use the Msunduzi River for irrigation, cleaning and watering livestock.

First and foremost, fish kills should be prevented by determining and managing the potential risk of fish kill events occurring and should be incorporated into management practice where needed. It is important that the DWS put in place fish kill preventative measures and criteria developed for various Water Use Licences to reduce the risk of potential polluters. Furthermore, licence providers and regulators must hold users accountable to their licence requirements and enforce the polluter pays principle when spill events occur (Wade et al., 2021). Fish kill prevention can be considered through implementing Water Use Licence restrictions as mitigation practices developed into the Water Use Licence. Often, there is little previous knowledge of fish communities and populations before a fish kill event, making assessing the full impact of fish kill events problematic.

The ecological risk assessment on the Vaal River in 2011 indicated that its ecological state would degrade by 2020 if its wastewater management status quo was maintained (Wepener et al., 2011). As reported through media outlets, several fish kill events in the Vaal River have shown its continual degradation despite recommendations to mitigate against operation at the status quo (Smillie, 2022). These highlight management authorities' apathy towards the ecological state of rivers (Wade et al., 2021). A similar case has been in the uThukela River, where a proposal to create a wetland to rehabilitate and treat wastewater on the eMadini Stream (heavily augmented by industrial release) before entering the uThukela River was declined by the DWS (Wade et al., 2021). In the consideration of scientifically viable solutions not being supported by local regulators in South Africa. There is a concern that regulators are not supporting sustainable alternative water resource use options because of the aversion to risk by the regulator out of fear that they may be held personally liable for adverse impacts from developments they approve. This is suggested to have been the case for a proposed wetland treatment development on the eMandeni Stream adjacent to the uThukela River (Wade et al., 2021). Improving water quality and setting measures in place to prevent fish kills is important when managing for sustainability and should take precedence (Dickens et al., 2019).

8.3 Need for management reform

The increase in anthropogenic associated stressors with water resource use reduces refuge areas for fish (Nel et al., 2011; O'Brien et al., 2019, 2021). South Africa recognises areas of importance for freshwater fish biodiversity conservation through the NFEPA determined by identifying where fish are listed by TOPS as critically endangered or endangered are present (Driver et al., 2011; Nel et al., 2011), but to date, no conservation of these areas by government or private stakeholders has occurred. In the context of fish kill events, the NFEPA database provides information on the seriousness of fish kill events when the event occurs in an NFEPA area, but there is no additional opportunity for action (Driver et al., 2011). Furthermore, NFEPA and TOPS will need to be updated given the increase in species moving onto the IUCN threatened list since their latest publication (Chakona et al., 2022).

The disconnect between aquatic scientists, licencing, regulators and ministerial departments is worrying (Sarakinsky, 2016). Healthy ecosystems can support human livelihoods, and the authorities' intention to enhance or protect and the need to be maintained for this purpose (Jennings et al., 2016; Parkes & Horwitz, 2009). The drive to meet the green economies should prioritise mitigating practices that do not jeopardise their intended outcome (D'Amato & Korhonen, 2021) and be driven by all stakeholders to balance the use of water resources and protecting freshwater ecosystems (King & Brown, 2006). The value of inland fisheries around rivers is still largely neglected (Tapela et al., 2015). In South Africa, an inland policy released in 2022 details the need to address the neglect with an intention to improve the way inland fisheries are managed (DFFE, 2020). Water resources are not managed to meet fisheries, biodiversity or conservation endpoints or targets but rather to ensure that the mechanisms to achieve these targets, such as environmental flow requirements, are met (King & Brown, 2006) along with other RQO limits, for example (Evans et al., 2022; Kleynhans & Louw, 2007). This lessens the value of fish in the freshwater ecosystem, and it is no surprise when a large fish kill happens, little is done to mitigate it. Polluters are educated to ensure that every effort following a fish kill event is made to meet the RQOs without considering the object of the RQOs, including the fish species that have been decimated as a consequence of the pollution. Because of this, sufficient remedial actions must be taken post a pollution event that causes a fish kill. As seen with the Msunduzi River fish kill in 2019, the fish population structures and abundances were severely impacted negatively.

In the event of a fish kill it is important to act swiftly and collect data associated with the pollution event that caused a fish kill to acquire sufficient evidence for prosecution. Actions to mitigate the pollution event should be required as soon as possible to reduce further exposure of the toxicant to the environment. Investigations and associated data should be collected as soon as possible to adequately determine the drivers of a fish kill event and link these to the polluter. The training of scientific investigators and or technicians is needed to collect the evidence base securely while understanding the chain of custody process. Water quality can determine causal relationships more accurately than symptoms shown by fish carcasses (Grant et al., 2014). Understanding the pollutant associated with the fish kill can go a long way to identifying the perpetrator. Therefore, in the event of a fish kill, a standard protocol should be developed as a ‘fish kill analyses kit’ that can be operated by technicians, the public and or concerned citizen, supported by or reported to the authorities, and form part of a database as a primary means for evidence-based data collection. The public is often the first to report fish kills and can assess to see if the authorities need to take the investigation further. Equipping the public with the skills and equipment needed may go a long way to bridging capacity issues. These ‘fish kill analysis kits’ should be simple to use and include a protocol for collecting and storing water samples, handling carcasses for investigation and assessing the source of pollution resulting in where a fish kill has occurred. Such a tool was developed during the 2011 Vaal River study but is yet to be published (Wepener et al., 2011; Table S1). This way, acute fish kill events that do not always get attention from authorities would also have associated data that can be logged and recorded for prosecution or future understanding of anthropogenic impacts. This can extend to streams where fish kills are not evident as fish abundances are naturally low, but a pollution event has occurred, causing a notable deterioration in the ecological state. Interestingly, as an incentive, section 34B of NEMA enables the Court to grant an order of no more than a quarter of the fine to be paid to the person or informant (excluding government officials) whose evidence led to the conviction or who assisted in bringing the [polluter] to justice. In the instance where evidence is provided by an informant that a significant pollution event took place and where this evidence is deemed sub-stantial, the legal counsel for the state or the applicants in a civil prosecution may request the Court to grant this award. This award may be substantial with the understanding that fines associated with pollution and other environmental crimes are punitive. The quantum granted by the Court would need to be argued by the prosecuting legal council. For this provision to act as an incentive, the granted quantum would need to significantly exceed the information's costs. When completing this study, it appears that this provision of NEMA remains to be used in a fish kill case.

8.4 Challenges

When a pollution event occurs, and a resultant fish kill ensues, there is relatively poor capacity in the DWS to respond as often there is only one aquatic scientist assigned to a region and therefore under-represented to fill their mandate (King & Pienaar, 2011; Thirion & Jafta, 2020). As seen in the present study, the lack of capacity carries over into the prosecution of polluters after a fish kill event, with action often slow or inadequate and held up in legal constraints. The prosecution should be swift, and measures should be put in place to know what polluters would be held accountable for. An accepted protocol as a response to a fish kill should be developed and accepted to ensure adequate documentation of the event to support the legal battle. For environmental laws, and in this instance, those laws regulating the quality of South Africa's water resources to act as a deterrent, prosecution and criminal sanction must follow the pollution event as quickly as possible. The corollary is that the longer delay between the cause (the pollution event) and the effect (prosecution and criminal sanction), the less likely potential polluters will appreciate the serious consequences resulting from non-compliance with the law (Ariffin, 2019; Qumbu, 2021).

In the event of translocation or restocking of native fish into a river impacted by a severe fish kill, little infrastructure currently exists to support this. Seemingly lessons from the 1989 Elands River fish kill (O'Brien et al., 2014) are taken lightly, and although some progress is being made to characterise fish species across the region (Stobie et al., 2018) more work is needed to guide introduction programmes or breeding of stock to prevent the hybridisation of species or sub-species as in the case of the 1989 Elands River fish kill.

9 Conclusions

Fish kills highlight the degradation of freshwater ecosystems. They have become the norm in South Africa with little to no alarm to them by authorities. The fish have come out of the river and are not just '*speaking*' but '*screaming*' about the excessive use of our water resources, and unfortunately, this is generally disregarded. If a fish comes out of the river and speaks, we should believe it and appropriately manage the stressors driving our natural resources' impacted state. This study shows that fish kills in South Africa are key indicators of something seriously wrong with the water resources that needs an appropriate response. The fish frequently attempt to escape, '*come out*', the waterbody because of the poor water quality of the country's rivers and the degraded state of associated ecosystems. Responding to fish kills timeously and collecting enough evidence to understand the impacts of the fish kill is important. The continued follow-up of the remedial actions and consequences needs to be timely, and parties need to be actively held accountable. Documenting the timing, severity and species impacted by fish kill events is one step closer to ensuring that polluters can be held accountable and pollution impacts reduced to improve river health and can be done using citizen science monitoring tools and trained technicians (Martel & Sutherland, 2019; Vogel et al., 2016).

Increased frequency of fish kills reduces fish abundances and ecological conditions in highly stressed rivers, such as the Msunduzi River, lessening the notable number of fish killed off in an equally severe pollution event, creating a dead river. Pollution events may become less notable as the fish population continues to decline because of increased pollution events and chronic stress, resulting in no fish '*to talk to us*'. The plethora of stressors present in a river system such as the Msunduzi River highlights the importance of accountability between all stakeholders and for the national government to increase capacity to monitor such events adequately, timeously, and with consequence to polluters. Presently, the fishers and concerned stake-holders who often lobby on behalf of the fish have little influence on pressuring private and public sector water users to reduce the frequency of pollution events. This is seen by the lack of priority given towards inland fisheries in South Africa (Weyl et al., 2020). Leadership is risk-averse, with little investment in ecological infrastructure to improve aquatic environments locally (Wade et al., 2021). This has been seen in the present case study spill.

Finally, it is important that when '*the fish speaks, we believe it*'. This would lead to action taken by the relevant authorities and at the appropriate time, leading to future mitigation against these events. With the case study on the Msunduzi River, the known degraded state of the river before the fish kill and return to the 'status quo' post the fish kill has not been the desired result from concerned stakeholders that recreationally or subsistently use the river. Here, if the management of the associated stressors causing fish kills are not addressed and fish kills are not adequately placed within the context of the law, continued degradation of the freshwater ecosystems will occur, as seen in Wepener et al. (2011). The ecological state of the Msunduzi River remains a concern and seemingly is a sacrificed river for the advancement of unsustainable practices. Alternatively, and ideally, the reverse would be desired, whereby stakeholders from all disciplines could rally together to restore the Msunduzi River ecosystem or other river ecosystems in South Africa and implement sustainable practices.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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The data belong to the University of KwaZulu-Natal and are available from the lead author on reasonable request.

References

A'Bear, D; Davis, R. Institutional responses to water-sector responsibilities; People and systems for water, sanitation and health 27th Water Engineering and Development Centre Conference, Lusaka, Zambia; Loughborough, UK. 2001. https://hdl.handle.net/2134/29983

Adeleke B, Robertson-Andersson D, Moodley G, Taylor S. Aquaculture in Africa: A comparative review of Egypt, Nigeria, and Uganda Vis-À-Vis South Africa. Reviews in Fisheries Science and Aquaculture. 2021; 29: 167–197. DOI: 10.1080/23308249.2020.1795615

Adom RK, Simatele MD, Reid M. Addressing the challenges of water-energy-food nexus programme in the context of sustainable development and climate change in South Africa. Journal of Water and Climate Change. 2022; 13: 2761–2779. DOI: 10.2166/wcc.2022.099

African Proverb. World Proverbs/African Proverb. 2020. https://www.listofproverbs.com/source/a/african_proverb/182373.htm

Allanson, BR; Ernst, MH; Noble, RG. In: Tarzwell, CM, editor. An experimental analysis of the factors responsible for periodic fish mortalities during winter in bushveld dams in the Transvaal, South Africa; Biological problems in water pollution third seminar 1962; 1962. 293–298.

Ariffin M. Enforcement of environmental pollution control laws: A Malaysian case study. International Journal of Public Law and Policy. 2019; 6: 155. doi: 10.1504/IJPLAP.2019.097559

Ashton PJ. Demise of the Nile crocodile (*Crocodylus niloticus*) as a keystone species for aquatic ecosystem conservation in South Africa: The case of the Olifants River. Aquatic Conservation: Marine and Fresh-water Ecosystems. 2010; 20: 489–493. DOI: 10.1002/aqc.1132

Avenant MF. Challenges in using fish communities for assessing the ecological integrity of non-perennial rivers. Water SA. 2010; 36: 4. doi: 10.4314/wsa.v36i4.58407

Badenhorst, JE. Fish kills: What to do? Internal report. Hydrological Research Institute, Department of Water Affairs and Forestry; 1993.

Bennett BA. The fish community of the Berg River estuary and an assessment of the likely effects of reduced freshwater inflows. Oceanographic Literature Review. 1995; 5: 391.

Bills R. Oreochromis mossambicus (errata version published in 2020). The IUCN Red List of Threatened Species 2019. 2019; e.T63338A174782954 doi: 10.2305/IUCN.UK.2019-3.RLTS.T63338A174782954.en

Blackmore A. The relationship between the NEMA and the public trust doctrine: The importance of the NEMA principles in safeguarding South Africa's biodiversity. South African Journal of Environmental Law and Policy. 2015; 20: 89–118.

Blackmore AC. Getting to grips with the public trust doctrine in biodiversity conservation: A brief overview. Bothalia. 2018; 48: 1–8. DOI: 10.4102/abc.v48i1.2308

Brand, M, Maina, J, Mander, M, O'Brien, G. Characterisation of the social and economic value of the use and associated conservation of the yellowfishes in the Vaal River. Water Research Commission; 2013.

Britz, PJ, Hara, MM, Weyl, OLF, Tapela, BN, Rouhani, QA. Scoping study on the development and sustainable utilisation of inland fisheries in South Africa. Report, No TT/615. Water Research Commission; 2015.

Bruton MN, Taylor RH. Cichlid fish mortality in a freshwater lake in Natal. Lammergeyer. 1979; 27: 1–4.

Burnett MJ, O'Brien GC, Jacobs FJ, Botha F, Jewitt G, Downs CT. Southern African inland fish tracking programme (FISHTRAC): An evaluation of the approach for monitoring ecological consequences of multiple water resource stressors, remotely and in real time. Ecological Indicators. 2020; 111 106001 doi: 10.1016/j.ecolind.2019.106001

Burnett MJ, O'Brien GC, Jacobs FJ, Jewitt G, Downs CT. Fish telemetry in African inland waters and its use in management: A review. Reviews in Fish Biology and Fisheries. 2021; 31: 337–357.

Carnie, T. Our Burning Planet Gross Negligence. Published by the Dailey Maverick Newspaper; 2022. https://www.dailymaverick.co.za/article/2022-02-16-ethekwini-warned-of-criminal-charges-over-poo-lagoon-pollution-as-dusi-canoe-marathon-kicks-off/

Chakona, A, Jordaan, MS, Raimondo, DC, Bills, RI, Skelton, PH, van der Colff, D. Journal of Fish Biology. Vol. 100: Portico; 2022. Diversity, distribution and extinction risk of native freshwater fishes of South Africa; 1044–1061.

Chovanec, A, Hofer, R, Schiemer, F. Trace metals and other contaminants in the environment. Markett, BA, Breure, AM, Zechmeister, HG, editors. Elsevier; 2003. 639–676.

Constitution of the Republic of South Africa. Pretoria: 1996.

Couzens E, Dent M. Finding NEMA: The National Environmental Management act, the De hoop dam, conflict resolution and alternative dispute resolution in environmental disputes. Potchefstroom Electronic Law Journal/Potchefstroomse Elektroniese Regsblad. 2006; 9: 1–51.

Crass, RS. Freshwater fishes of Natal. Shuter and Shooter; 1964.

Cullet P. Water law in a globalised world: The need for a new conceptual framework. Journal of Environmental Law. 2011; 23: 233–254. DOI: 10.1093/jel/eqr003

Cyrus DP, McLean S. Water temperature and the 1987 fish kill at Lake St Lucia on the south eastern coast of Africa. Southern African Journal of Aquatic Science. 1996; 22: 105–110. DOI: 10.1080/10183469.1996.9631377

D'Amato D, Korhonen J. Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. Ecological Economics. 2021; 188 107143

Department of Environmental Affairs (DEA). National Environmental Management: Biodiversity Act 10 of 2004: Threatened or Protected Species Regulations in Government Gazette 38600 Notice 255 of 31 March 2015. 2015.

Department of Forestry, Fisheries, and Environment (DFFE). National freshwater (Inland) wild capture fisheries policy for South Africa (4th Draft). Department of Forestry, Fisheries, and Environment; 2020.

Department of Water Affairs and Forestry (DWAF). A fish kill in the Hartbeespoort dam, South Africa, October 1999. Report No N/-A210/02/DEQ/4299. Institute for Water Quality Studies, Department of Water Affairs and Forestry; 1999.

Department of Water Affairs and Forestry (DWAF). Water resource quality monitoring volume 5: Fish kill investigations. Department of Water Affairs and Forestry; 2004.

Department of Water and Sanitation (DWS). Water and Sanitation investigates Duzi River water pollution. 2019. https://www.gov.za/speeches/duzi-river-water-pollution-18-aug-2019-0000

Desai M, Hanzen C, Downs CT, O'Brien GC. Environmental drivers of ichthyofauna community composition of the river ecosystems draining the Lake St. Lucia basin, South Africa. Hydrobiologia. 2021; 848: 3539–3554. DOI: 10.1007/s10750-021-04609-7

Dickens C, Smakhtin V, McCartney M, O'Brien G, Dahir L. Defining and quantifying national-level targets, indicators and benchmarks for management of natural resources to achieve the sustainable development goals. Sustainability. 2019; 11: 462. doi: 10.3390/su11020462

Dlamini, PV. Assessment of the current ecological integrity of the uMngeni river, KwaZulu-Natal, South Africa, using fish community structures and attributes of the Labeobarbus natalensis (Castelnau, 1861) populations. MSc thesis. University of KwaZulu-Natal; 2019.

Dlamini V, Samson M, Curtis C, O'Brien G. Co-opting small-scale fishers' knowledge with scientific data to improve understanding of fish community structures in the lower Komati River, South Africa. Marine and Freshwater Research. 2022; 74: 111–124. DOI: 10.1071/MF22169

Driver, A, Nel, JL, Snaddon, K, Murray, K, Roux, DJ, Hill, L, Swartz, ER, Manuel, J, Funke, N. Implementation manual for freshwater ecosystem priority areas. Draft Report for the Water Research Commission. Water Research Commission; 2011.

Du Plessis, A. Water as an inescapable risk. Du Plessis, A, editor. Springer; 2019. 147–172.

Du Plessis W, de la Harpe S. The duty to disclose and the right to refuse: Undefined dilemma of environmental practitioners: South Africa and other jurisdictions. South African Journal of Environmental Law and Policy. 2007; 14: 83–103.

Du Preez M, Lee DE. The contribution of trout fly-fishing to the economy of Rhodes, North Eastern Cape, South Africa. Development Southern Africa. 2010; 27: 241–253.

Duzi Umgeni Conservation Trust (DUCT). Mystery over dead fish. 2018. https://www.duct.org.za/duct-news/18-news/97-mystery-over-dead-fish.html

Duzi Umgeni Conservation Trust (DUCT). Durban-Pietermaritzburg river pollution is a microcosm of nationwide water pollution control failures. 2019a. https://www.duct.org.za/duct-news/18-news/105-the-dead-dusi-what-s-being-done-to-resurrect-it-and-other-rivers.html

Duzi Umgeni Conservation Trust (DUCT). Toxic sludge chokes Duzi. 2019b. https://www.duct.org.za/duct-news/18-news/107-toxic-sludge-chokes-duzi.html

Ellender BR, Weyl OL, Winker H. Who uses the fishery resources in South Africa's largest impoundment? Characterising subsistence and recreational fishing sectors on Lake Gariep. Water SA. 2009; 35: 679–684.

Ethekwini. Municipal spatial development framework 2018–2019. eThekwini Municipality; 2018.

Evans W, Downs CT, Burnett MJ, O'Brien GC. Assessing fish community response to water quality and habitat stressors in KwaZulu-Natal, South Africa. African Journal of Aquatic Science. 2022; 47: 47–65. DOI: 10.2989/16085914.2021.1952158

Feio MJ, Hughes RM, Serra SR, Nichols SJ, Kefford BJ, Lintermans M, Robinson W, Odume ON, Callisto M, Macedo DR, Harding JS. Fish and macroinvertebrate assemblages reveal extensive degradation of the world's rivers. Global Change Biology. 2022; 29: 355–374. DOI: 10.1111/gcb.16439 [PubMed: 36131677]

Feris L. The public trust doctrine and liability for historic water pollution in South Africa. Law Environment Development Journal. 2012; 8: 1.

Fischer. BSc thesis. Water quality modelling and quantitative microbial risk assessment of Msunduzi River. BSc thesis. Chalmers University of Technology; 2019.

Foord S, Fouché P. Response of instream animal communities to a short-term extreme event and to longer-term cumulative impacts in a strategic water resource area, South Africa. African Journal of Aquatic Science. 2016; 41: 29–40. DOI: 10.2989/16085914.2015.1125336

Fouchy, K, McClain, M, Conallin, J, O'Brien, GC. Multiple stressors in river ecosystems: Status, impacts and prospects for the future. Sabater, S, Elosegi, A, Ludwig, R, editors. Elsevier; 2019. 179–191.

Gemmell ME, Schmidt S. Is the microbiological quality of the Msunduzi River (KwaZulu-Natal, South Africa) suitable for domestic, recreational, and agricultural purposes?. Environmental Science and Pollution Research. 2013; 20: 6551–6562. [PubMed: 23608984]

Graham, M, Meyer, C, Tedder, J. Willowton Spill: 12-month follow-up aquatic impact monitoring report (No GT1030-31-03–2021). Willowton Group; 2021. 46.

Grant, B, Huchzermeyer, D, Hohls, B. Manual for fish kill investigations in South Africa. Report No: TT 589/14. Water Research Commission; 2014.

Harper P. Rivers die after oil, chemical spill. 2019. https://mg.co.za/article/2019-08-23-00-rivers-die-after-oil-chemical-spill/

Harris JH. The use of fish in ecological assessments. Austral Ecology. 1995; 20: 65–80.

Hohls, BC, Kühn, AL. Institute for water quality studies. Department of Water Affairs and Forestry; 2001.

Hohls, BC, Van Niekerk, H. Fish kill in the Apies River: 6th October 2000. Report No N/A230/00/REQ/1100. Institute for Water Quality Studies, Department of Water Affairs and Forestry; 2000.

Hohls, BC, van Ginkel, C. Fish Kill in the Roodeplaat Dam from 11th October 2004. Report No N/0000/00/DEQ/0804. Resource Quality Services, Department of Water Affairs and Forestry; 2004.

Houdet, J, Browneb, M, Lewisb, F. Impact of degraded freshwater ecosystems on tourism towards 2030. Report No: K5/2620. Water Research Commission; 2020.

Hsu A, Lloyd A, Emerson JW. What progress have we made since Rio? Results from the 2012 environmental performance index (EPI) and pilot trend EPI. Environmental Science & Policy. 2013; 33: 171–185.

Hughes CJ, de Winnaar G, Schulze RE, Mander M, Jewitt GPW. Mapping of water-related ecosystem services in the uMngeni catchment using a daily time-step hydrological model for prioritisation of ecological infrastructure investment–part 1: Context and modelling approach. Water SA. 2018a; 44: 577–589.

Hughes CJ, de Winnaar G, Schulze RE, Mander M, Jewitt GPW. Mapping of water-related ecosystem services in the uMngeni catchment using a daily time-step hydrological model for prioritisation of ecological infrastructure investment–part 2: Outputs. Water SA. 2018b; 44: 590–600.

Impson, ND, Bills, IR, Wolhuter, L. Technical report on the state of yellowfishes in South Africa. Water Research Commission; 2008.

Jackson S, Head L. Australia's mass fish kills as a crisis of modern water: Understanding hydrosocial change in the Murray-Darling Basin. Geoforum. 2020; 109: 44–56. DOI: 10.1016/j.geoforum.2019.12.020

Jaureguiberry P, Titeux N, Wiemers M, Bowler DE, Coscieme L, Golden AS, Guerra CA, Jacob U, Takahashi Y, Settele J, Díaz S. The direct drivers of recent global anthropogenic biodiversity loss. Science Advances. 2022; 8: 9982. doi: 10.1126/sciadv.abm9982 [PubMed: 36351024]

Jennings V, Larson L, Yun J. Advancing sustainability through urban green space: Cultural ecosystem services, equity, and social determinants of health. International Journal of Environmental Research and Public Health. 2016; 13: 196. doi: 10.3390/ijerph13020196 [PubMed: 26861365]

Jewitt D, Goodman PS, Erasmus BF, O'Connor TG, Witkowski ET. Systematic land-cover change in KwaZulu-Natal, South Africa: Implications for biodiversity. South African Journal of Science. 2015; 111: 1–9.

Jordaan LJ, Wepener V, Huizenga JM. The major and trace element chemistry of fish and lake water within major south African catchments. Water SA. 2016; 42: 112–128.

Kanyile N. Toxic sludge chokes Duzi. 2019a. https://www.pressreader.com/south-africa/the-witness/20190815/281505047857767

Kanyile N. Long job to clean Duzi. 2019b. https://www.pressreader.com/south-africa/the-witness/20190819/281578062309198

Karssing, RJ. Status of the KwaZulu-Natal yellowfish Labeobarbus natalensis (Castelnau, 1861). Technical report on the state of yellowfishes in South Africa. Impson, ND, Bills, IR, Wolhuter, L, editors. Water Research Commission; 2008.

King J, Brown C. Environmental flows: Striking the balance between development and resource protection. Ecology and Society. 2006; 11: 26.

King, J, Pienaar, H. Sustainable use of South Africa's inland waters: A situation assessment of resource directed measures 12 years after the 1998 National Water Act. WRC Report number TT. Vol. 491. Water Research Commission; 2011.

Kleynhans C. The development of a fish index to assess the biological integrity of south African rivers. Water SA. 1999; 25: 265–278.

Kleynhans, C; Louw, M. Module A: EcoClassification and EcoStatus determination. River EcoClassification: Manual for EcoStatus Determination (Version 2). Joint Water Research Commission and Department of Water Affairs and Forestry Report. 2007.

Kleynhans, CJ. Module D: Fish response assessment index in river ecoclassification: Manual for ecostatus determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report. 2007.

Kleynhans CJ, Schulz GW, Engelbrecht JS, Roussaeu FJ. The impact of a paper mill effluent spill on the fish populations of the elands and crocodile Rivers (Inkomati system, Transvaal). Water SA. 1992; 18: 73–80.

Koehn JD. Key steps to improve the assessment, evaluation and management of fish kills: Lessons from the Murray–Darling River system, Australia. Marine and Freshwater Research. 2021; 73 (2) 269–281. DOI: 10.1071/mf20375

Kourie R, Somyo V. Mozambique tilapia: big plans for a small fish. 2022. https://www.farmersweekly.co.za/animals/aquaculture/47ozambique-tilapia-big-plans-for-a-small-fish/

Europe PMC Funders Author Manuscripts

Kruger M, Saayman M. Why keep on paddling? Evidence from a South African canoe marathon. African Journal for Physical, Health Education, Recreation and Dance. 2013; 19: 1158–1173.

Kubach KM, Scott MC, Bulak JS. Recovery of a temperate riverine fish assemblage from a major diesel oil spill. Freshwater Biology. 2011; 56: 503–518.

La VT, Cooke SJ. Advancing the science and practice of fish kill investigations. Reviews in Fisheries Science. 2011; 19: 21–33.

Le Maitre, D, Seyler, H, Holland, M, Smith-Adao, L, Maherry, A, Nel, J, Witthuser, K. Strategic water source areas: Vital for South Africa's water, food and energy security. Water Research Commission; 2019.

Li L, Zheng B, Liu L. Biomonitoring and bioindicators used for river ecosystems: Definitions, approaches and trends. Procedia Environmental Sciences. 2010; 2: 1510–1524. DOI: 10.1016/j.proenv.2010.10.164

Lucas MC, Baras E. Methods for studying spatial behaviour of freshwater fishes in the natural environment. Fish and Fisheries. 2000; 1: 283–316. DOI: 10.1046/j.1467-2979.2000.00028.x

Makhathini, N. An evaluation of present and potential inland fisheries in dams and rivers in the uThukela and uMngeni catchments, KwaZulu-Natal, South Africa. MSc thesis. University of KwaZulu-Natal; 2024.

Martel, P, Sutherland, C. The geography of climate change adaptation in urban Africa. Cobbinah, PB, Addaney, M, editors. Springer; 2019. 355–387.

Mazungula DN, Chakona A. An integrative taxonomic review of the Natal mountain catfish, Amphilius natalensis Boulenger 1917 (Siluriformes, Amphiliidae), with description of four new species. Journal of Fish Biology. 2021; 99: 219–239. [PubMed: 33635552]

McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. The use of water resources for inland fisheries in South Africa. Water SA. 2012; 38: 327–344.

Mdletshe M. Msunduzi River spill: Small farmers worried they will not be compensated for "losses". 2019. https://www.groundup.org.za/article/msunduzi-river-spill-small-farmers-worried-they-will-not-be-compensated-losses/

Mitchell P, Plug I, Bailey G, Charles R, Esterhuysen A, Thorp JL, Parker A, Woodborne S. Beyond the drip-line: A high-resolution open-air Holocene hunter-gatherer sequence from highland Lesotho. Antiquity. 2012; 85: 1225–1242. DOI: 10.1017/S0003598X00062025

Nasir MFM, Samsudin MS, Mohamad I, Awaluddin MRA, Mansor MA, Juahir H, Ramli N. River water quality modeling using combined principle component analysis (PCA) and multiple linear regressions (MLR): A case study at Klang River, Malaysia. World Applied Sciences Journal. 2011; 14: 73–82.

National Environmental Management Act (NEMA). National environmental management laws Amendment act of South Africa (Act 25 of 2014). Republic of South Africa: 2014.

National Environmental Management Act (NEMA). National Environmental Management act of South Africa (act 107 of 1998). Republic of South Africa: 1998.

National Environmental Management: Biodiversity Act (NEMBA). National Environmental Management: Biodiversity Act 10 of 2004. Republic of South Africa: 2004.

National Environmental Management: Protected Areas Act NEMPAA. National Environmental Management: Protected Areas Act 57 of 2003. Republic of South Africa; 2003.

National Water Act (NWA). National Water act of South Africa (act 36 of 1998). Republic of South Africa: 1998.

National Water Act (NWA). National Water Act, no 1386 of 2017 Published in the Government Gazette No 41306 on 08 December 2017. Rebuplic of South Africa: 2017.

Nel, JL, Murray, KM, Maherry, AM, Petersen, CP, Roux, DJ, Driver, A, Hill, L, Van Deventer, H, Funke, N, Swartz, ER, Smith-Adao, LB. Technical report for the national freshwater ecosystem priority areas project. Water Research Commission Report. Water Research Commission; 2011.

Ngcobe, N, Tiller, W. The FNB Dusi 2019 economic impact assessment: Topline summary Report. Tourisim KwaZulu Natal; 2019. https://www.zulu.org.za/archive/impact-assessments-of-events-in-kwazulu-natal-F57990

Ngcobo, NB. Evaluating multiple stressors on aquatic ecosystems in an urban environment. MSc thesis. University of KwaZulu-Natal; 2024.

Ngozi, L. Assemblage-based monitoring of the uMsunduzi River, using biotic and abiotic lines of evidence. MSc thesis. University of KwaZulu-Natal; 2024.

Nkomo, MN. Importance of freshwater systems and eels in the uMngeni and uThukela catchments, KwaZulu-Natal, South Africa: Community perspectives. MSc thesis. University of KwaZulu-Natal; 2023.

O'Brien G, Kubheka S, Evans SW. Enteromius gurneyi. The IUCN Red List of Threatened Species 2017. 2017; e.T63262A100141523 doi: 10.2305/IUCN.UK.2017-3.RLTS.T63262A100141523.en

O'Brien GC, Dickens C, Hines E, Wepener V, Stassen R, Landis WG. A regional scale ecological risk framework for environmental flow evaluations. Hydrology and Earth System Sciences. 2018; 22: 957–975. DOI: 10.5194/hess-2017-37

O'Brien GC, Ross M, Hanzen C, Dlamini V, Petersen R, Diedericks GJ, Burnett MJ. River connectivity and fish migration considerations in the management of multiple stressors in South Africa. Marine and Freshwater Research. 2019; 70: 1254–1264. DOI: 10.1071/MF19183

O'Brien GC, Smit NJ, Wepener V. Conservation of fishes in the Elands River, Mpumalanga, South Africa: Past, present, and future. Koedoe. 2014; 56: 1–8. DOI: 10.4102/koedoe.v56i1.1118

O'Brien GC, Swemmer R, Wepener V. Ecological integrity assessment of the fish assemblages of the Matigulu/Nyoni and Umvoti estuaries, KwaZulu-Natal, South Africa. African Journal of Aquatic Science. 2009; 34: 293–302.

O'Brien GC, Wepener W, Smit NJ. Regional scale risk to the ecological sustainability and ecosystem services of an African flood-plain system. Risk Analysis. 2021; 41: 1925–1952. [PubMed: 33709548]

Ochumba PB. Massive fish kills within the Nyanza gulf of Lake Victoria, Kenya. Hydrobiologia. 1990; 208: 93–99.

Parkes MW, Horwitz P. Water, ecology and health: Ecosystems as settings for promoting health and sustainability. Health Promotion International. 2009; 24: 94–102. [PubMed: 19171669]

Paxton B, O'Brien G, Slingsby J, Copin R. Validation of the periodicity of growth increment deposition in otoliths from the larval and early juvenile stages of two cyprinids from the Orange–Vaal river system, South Africa. African Journal of Aquatic Science. 2013; 38: 49–54. DOI: 10.2989/16085914.2013.775107

Pienaar H, Xu Y, Braune E, Cao J, Dzikiti S, Jovanovic NZ. Implementation of groundwater protection measures, particularly resource-directed measures in South Africa: A review paper. Water Policy. 2020; 23: 819–837. DOI: 10.2166/wp.2021.016

Plug I, Mitchell P, Bailey G. Late Holocene fishing strategies in southern Africa as seen from Likoaeng, highland Lesotho. Journal of Archaeological Science. 2010; 37: 3111–3123.

Potts, WM, Saayman, M, Saayman, A, Mann, BQ, Van der Merwe, P, Britz, P, Bova, CS. Fisheries Management and Ecology. Vol. 29: Portico; 2022. Understanding the economic activity generated by recreational fishing in South Africa provides insights on the role of recreational fisheries for social development; 29–43.

Qumbu B. The role of the courts in advancing water security in South Africa. Potchefstroom Electronic Law Journal. 2021; 24: 1–35. DOI: 10.17159/1727-3781/2021/v24i0a9004

Regchand S. Toxic spills in Duzi River a challenge for Pietermaritzburg. 2020. https://www.news24.com/witness/news/toxic-spills-in-duzi-river-a-challenge-for-pietermaritzburg-20201114

Riddell ES, Govender D, Botha J, Sithol H, Petersen RM, Shikwambana P. Pollution impacts on the aquatic ecosystems of the Kruger National Park, South Africa. Scientific African. 2019; 6 e00195 doi: 10.1016/j.sciaf.2019.e00195

Roberts, D, O'Donoghue, S. State of the world. Island Press; 2016. 337–342.

Rodell M, Famiglietti JS, Wiese DN, Reager JT, Beaudoing HK, Landerer FW, Lo MH. Emerging trends in global freshwater availability. Nature. 2018; 557: 651. doi: 10.1038/s41586-018-0123-1 [PubMed: 29769728]

Roux DJ, Badenhorst JE, Du Preez HH, Steyn GJ. Note on the occurrence of selected trace metals and organic compounds in water, sediment, and biota of the Crocodile River, Eastern Transvaal, South Africa. Water SA. 1995; 20: 333–340.

Europe PMC Funders Author Manuscripts

Roux F, Hoffman A. Chiloglanis bifurcus. The IUCN Red List of Threatened Species 2017. 2017; e.T4632A100193958 doi: 10.2305/IUCN.UK.2017-3.RLTS.T4632A100193958.en

SAPA+. Oil spill kills thousands of fish in KZN's KZN's Msunduzi river. 2019. https://www.youtube.com/watch?v=gf33gAdLkJE

Sarakinsky, I. Sustainability, climate change and the green economy. Godwell, N, Vuyo, M, editors. Africa Institute of South Africa; 2016. 19.

Schreiner B. Viewpoint—Why has the south African National Water act been so difficult to implement. Water Alternatives. 2013; 6: 239–245.

Scott LEP, Skelton PH, Booth AJ, Verheust L. The development of a GIS atlas of southern African freshwater fish. African Journal of Aquatic Sciences. 2000; 25: 43–48.

Shaw, PJA. Multivariate statistics for the environmental sciences. Arnold publishers; London, United Kingdom: 2003.

Sibanda T, Selvarajan R, Tekere M. Urban effluent discharges as causes of public and environmental health concerns in South Africa's aquatic milieu. Environmental Science and Pollution Research. 2015; 22: 18301–18317. [PubMed: 26408112]

Skelton, PH. A complete guide to the freshwater fishes of southern Africa. Struik; 2001.

Skelton PH. Flagships and fragments—Perspectives on the conservation of freshwater fishes in southern Africa. African Journal of Aquatic Sciences. 2000a; 25: 37–42.

Skelton PH. Heritage for all-the art and culture of fishes in Africa. South African Museums Association Bulletin. 2000b; 24: 1.

Smillie S. South Africa's once abundant Yellowfish are being wiped out by acid water, sewage and invasive species. 2022. https://www.dailymaverick.co.za/article/2022-03-23-south-africas-once-abundant-yellowfish-are-being-wiped-out-by-acid-water-sewage-and-invasive-species/

Smith P, Snook D, Muscutt A, Smith A. Effects of a diesel spill on freshwater macroinvertebrates in two urban watercourses, Wiltshire, UK. Water and Environment Journal. 2010; 24: 249–260.

South African Broadcasting Commission (SABC). KZN Environmental Affairs awaiting report regarding oil spill. 2019. https://www.sabcnews.com/sabcnews/kzn-environmental-affairs-awaiting-report-regarding-oil-spill/

Stobie, CS, Oosthuizen, CJ, Cunningham, MJ, Bloomer, P. Ecology and Evolution. Vol. 8: Portico; 2018. Exploring the phylogeography of a hexaploid freshwater fish by RAD sequencing; 2326–2342.

Stocks JR, Ellis IM, Van der Meulen DE, Doyle JI, Cheshire KJM. Kills in the Darling: Assessing the impact of the 2018–20 mass fish kills on the fish communities of the Lower Darling–Baaka River, a large lowland river of South-Eastern Australia. Marine and Freshwater Research. 2021; 73: 159–177. DOI: 10.1071/mf20340

Tapela, BN, Britz, PJ, Rouhani, QA. Scoping study on the development and sustainable utilisation of inland fisheries in South Africa: Volume 2. Case studies of small-scale inland fisheries. Water Research Commission; 2015.

Ter Braak, CJ, Smilauer, F. Canoco for windows version 453© 1997–2004. Biometrics–Plant Research International; Wageningen: 2004.

Thirion, C, Jafta, N. State of rivers report: River ecostatus monitoring programme, 2017–2018. Department of Water and Sanitation Report No: N/0000/00/REMP/2019. Department of Water and Sanitation; 2020. 97.

Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, Cooke SJ, Dalton J, Darwall W, Edwards G, Harrison I. Bending the curve of global freshwater biodiversity loss: An emergency recovery plan. Bioscience. 2020; 70: 330–342. DOI: 10.1093/biosci/biaa002 [PubMed: 32284631]

Van den Brink PJ, Van den Brink NW, Ter Braak CJ. Multi-variate analysis of ecotoxicological data using ordination: Demonstrations of utility on the basis of various examples. Australasian journal of ecotoxicology. 2003; 9: 141–156.

Van der Schyff E. Unpacking the public trust doctrine: A journey into foreign territory. Potchefstroom Electronic Law Journal/Potchef-stroomse Elektroniese Regsblad. 2010; 13: 5.

Van Deventer H, Van Niekerk L, Adams J, Dinala MK, Gangat R, Lamberth SJ, Lötter M, Mbona N, MacKay F, Nel JL, Ramjukadh CL. National Wetland map 5: An improved spatial extent and representation of inland aquatic and estuarine ecosystems in South Africa. Water SA. 2020; 46: 66–79.

Van Rooyen AF, Ramshaw P, Moyo M, Stirzaker R, Bjornlund H. Theory and application of agricultural innovation platforms for improved irrigation scheme management in southern Africa. International Journal of Water Resources Development. 2017; 33: 804–823.

Vogel C, Scott D, Culwick CE, Sutherland C. Environmental problem-solving in South Africa: Harnessing creative imaginaries to address 'wicked' challenges and opportunities. South African Geographical Journal. 2016; 93: 515–530.

Wade M, O'Brien GC, Wepener V, Jewitt G. Risk assessment of water quantity and quality stressors to balance the use and protection of vulnerable water resources. Integrated Environmental Assessment and Management. 2021; 17: 110–130. [PubMed: 33058386]

Water Service Act (WSA). Water service act of South Africa (act 108 of 1997). Water Service Act (WSA); 1997.

Wepener V. Application of active biomonitoring within an integrated water resources management framework in South Africa. South African Journal of Science. 2008; 104: 367–373.

Wepener VV, Van Dyk C, Bervoets L, O'Brien G, Covaci A, Cloete Y. An assessment of the influence of multiple stressors on the Vaal River, South Africa. Physics and Chemistry of the Earth, Parts A/B/C. 2011; 36: 949–962.

Weyl OL, Potts W, Rouhani Q, Britz P. The need for an inland fisheries policy in South Africa: A case study of the North West Province. Water SA. 2007; 33: 497–504.

Weyl O, Barkhuizen L, Christison K, Dalu T, Hlungwani H, Impson D, Sankar K, Mandrak N, Marr S, Sara J, Smit N, et al. Ten research questions to support South Africa's Inland Fisheries Policy. African Journal of Aquatic Science. 2020; 46: 1–10. DOI: 10.2989/16085914.2020.1822774

Whitfield AK, Paterson AW. Flood-associated mass mortality of fishes in the Sundays Estuary. Water SA. 1995; 21: 385–389.

Willowton Group. Willowton Group's statement on incident occurring 13th August 2019. 2019. https://www.willowtongroup.com/media_centre/willowton_incident/

Wyllie, R; Kohler, K. The FNB Dusi 2017 Economic Impact Assessment Topline Summary Report. Tourisim KwaZulu Natal Report. Tourisim KwaZulu Natal. 2017. https://www.zulu.org.za/archive/impact-assessments-of-events-in-kwazulu-natal-F57990

Xu, Y, Colvin, C, Van Tonder, GJ, Hughes, S, Le Maitre, D, Zhang, J, Mafanya, BE. Towards the resource directed measures: Ground-water component. WRC Report No 1090–2/1/03. Water Research Commission; 2003.

Europe PMC Funders Author Manuscripts

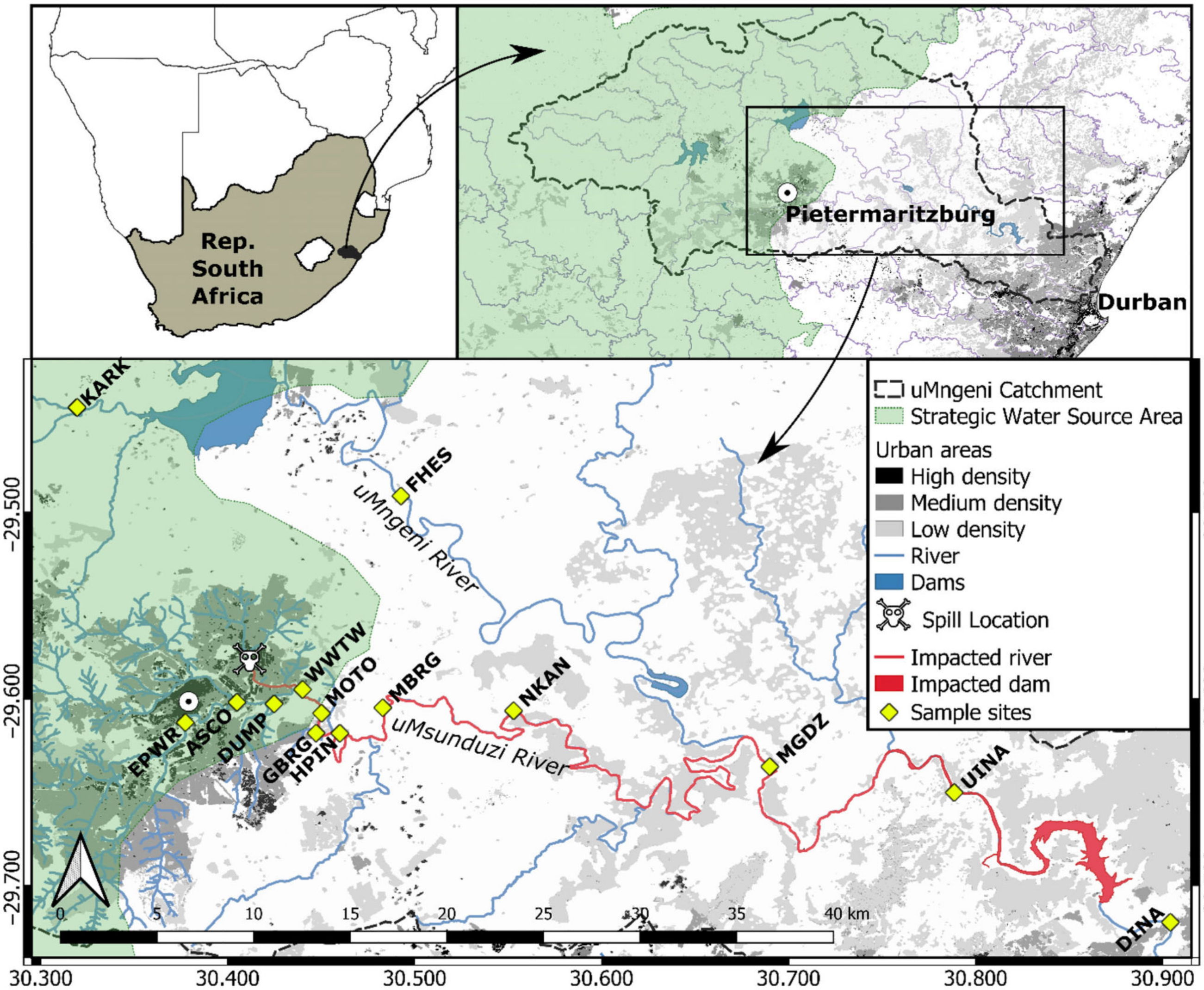

Figure 1.

Depicts the location of the case study and shows the sampled sites and the extent of the fish kill along the Msunduzi and uMngeni Rivers. Sampled sites are labelled according to their abbreviation used in the statistical component of the study. Sites were grouped by location to evaluate the pre and post-effects of the spill as follows: Upstream sites (UPST) included the upstream of the urban centre (EPWR), downstream of the urban centre (ASCOT) and the cities landfill site (DUMP); Fish kill one (FK 1) included the river at Darvill wastewater treatment works (WWTW); Fish kill two (FK 2) included the motorcross racetrack weir (MOTO), Grimthorpe bridge (GBRG), Mpushini conservancy (MBRG); Fish kill three (FK 3) included Nkanyenzini community (NKAN); Fish kill four (FK 4) included downstream of the uMngeni and Msunduzi river confluence (MGDZ) and upstream of Inanda Dam (UINA) and the Downstream site included a site downstream of Inanda (DINA). See Table 1 for site names, descriptions and abbreviations. [Color figure can be viewed at wileyonlinelibrary.com]

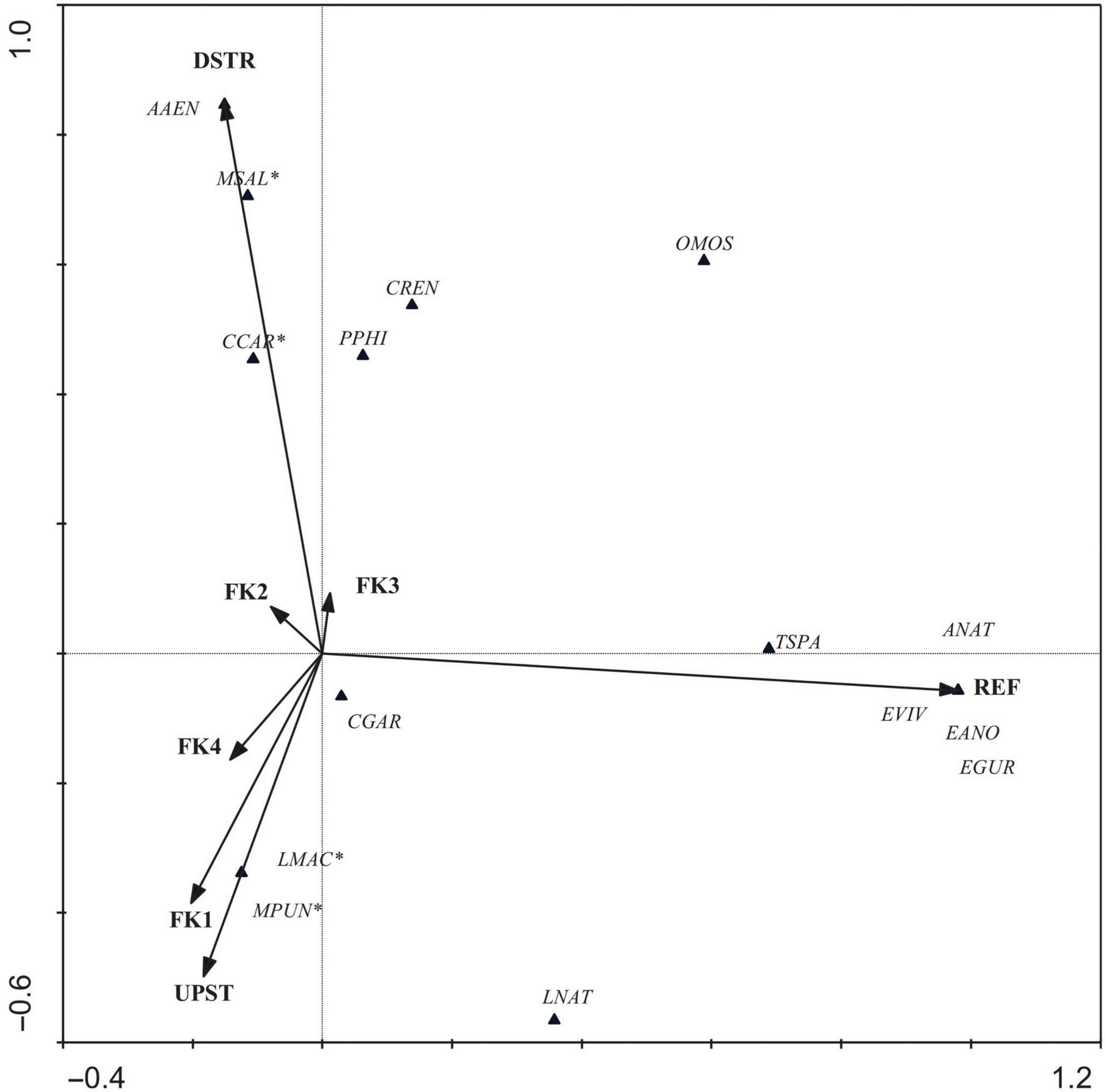

Figure 2.
The principal component analysis with redundancy analysis bi-plotted for sites surveyed for the Msunduzi River pre- and post- the 2019 fish kill. The distribution of fish species abundance is highlighted in the impacted sites and unimpacted sites. DSTR, downstream.

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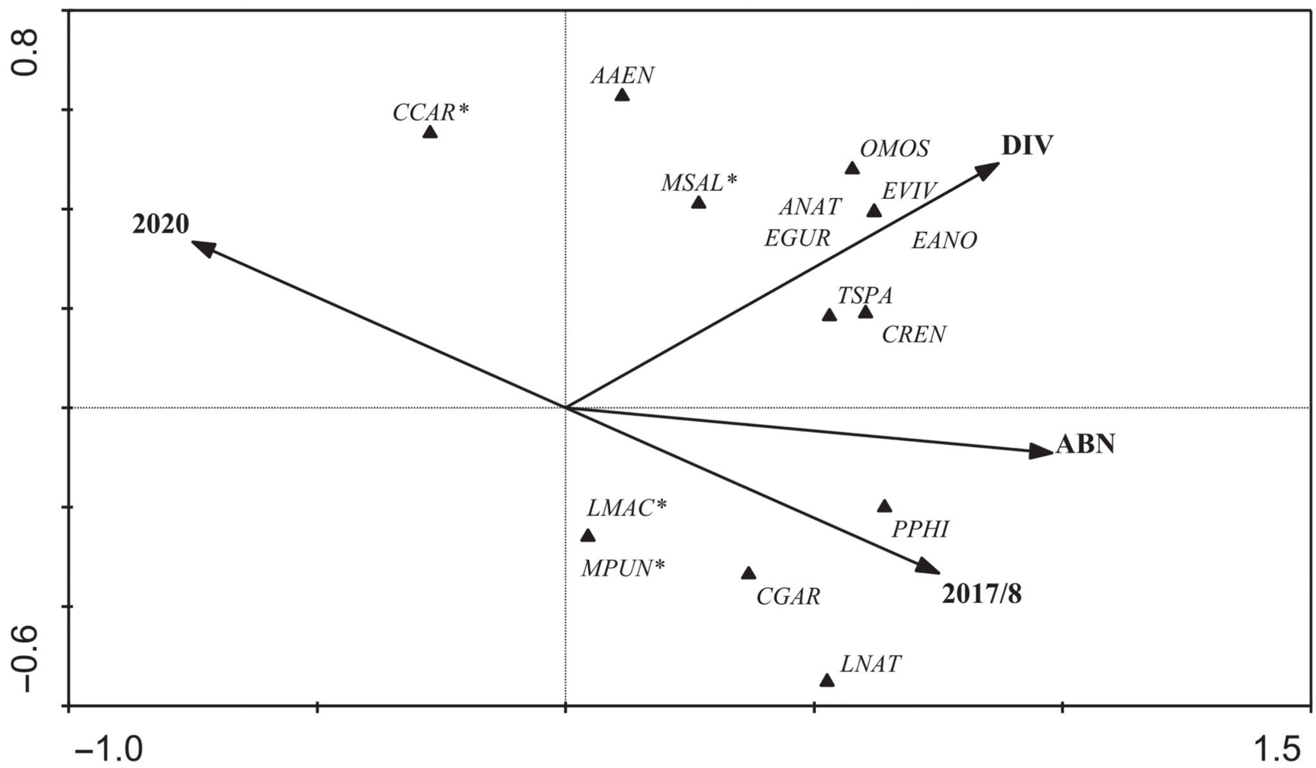

Figure 3.

The principal component analysis with redundancy analysis bi-plotted for the Msunduzi River pre- and post-spill on 13th of August 2019. Included is the bi-plot for the abundance and diversity of fish. DSTR, downstream.

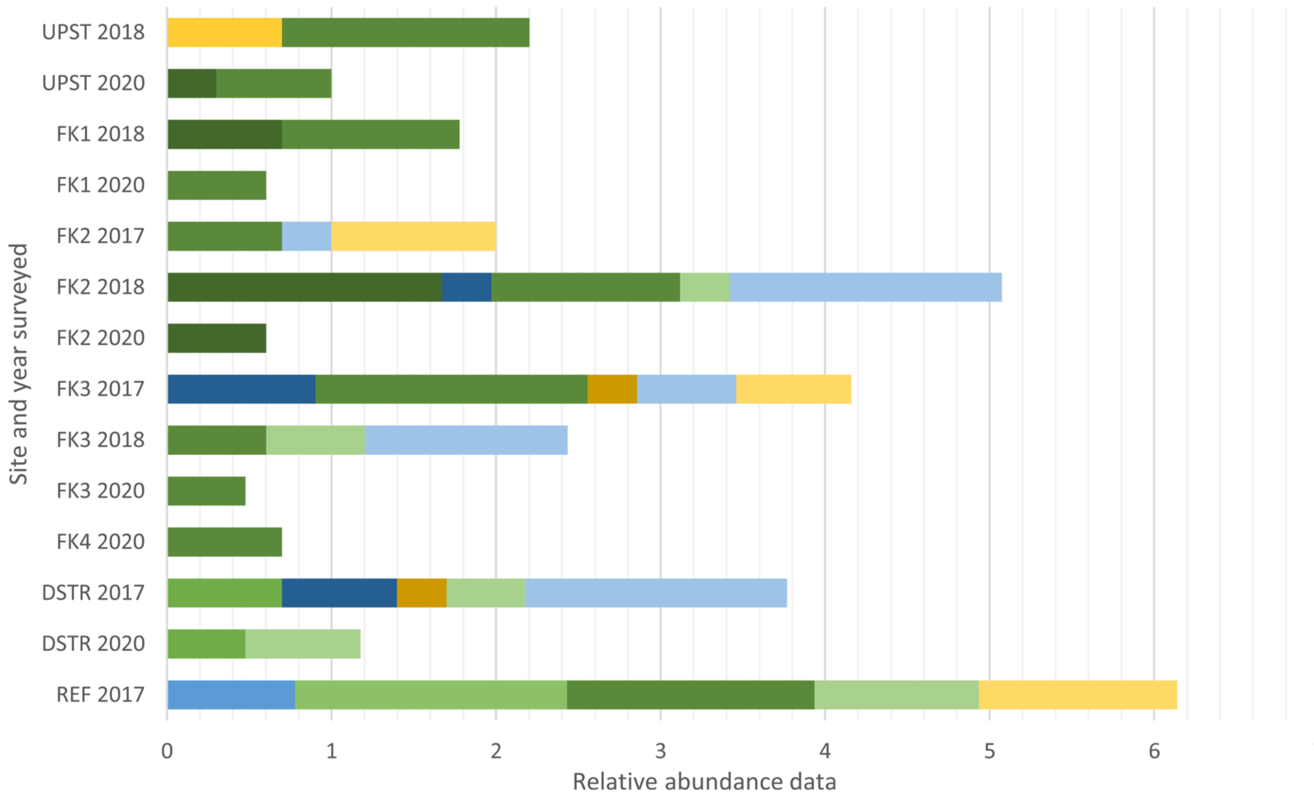

Figure 4.

The relative abundance data of fish and species composition study for sites sampled upstream of the fish kill (UPST), at different intervals in the fish kill (FK 1–4) and downstream of Inanda Dam (DSTR), included are the two reference sites (REF) pre-(2017 and 2018) and post-(2020) the Msunduzi River spill. The fish kill sites in 2020 showed a decline in species abundance and a shift in fish species composition. [Color figure can be viewed at wileyonlinelibrary.com]

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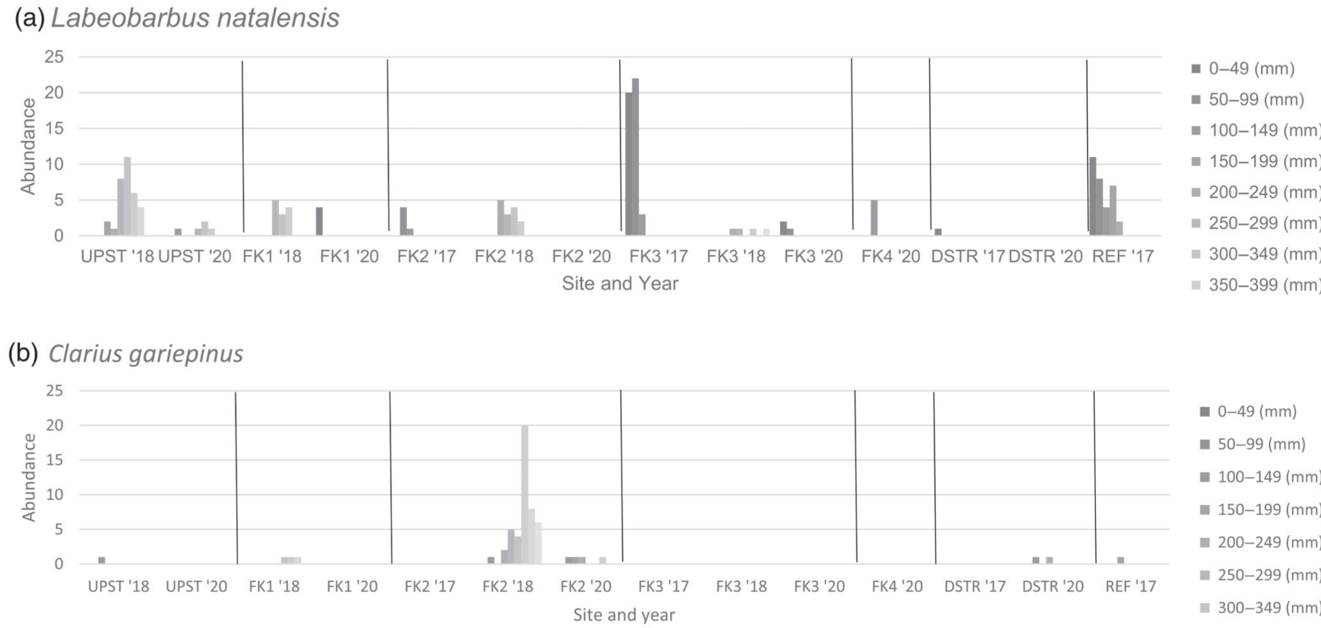

Figure 5.

Bar graphs depicting the size class representation for (a) *Labeobarbus natalensis* and (b) *Clarias gariepinus* caught during the surveys for sites sampled upstream of the fish kill (UPST), at different intervals in the fish kill (FK 1–4) and downstream of Inanda Dam (DSTR), included are the two reference sites (REF) for periods pre-, 2017 ('17) and 2018 ('18), and post-, 2020 ('20), the spill, while vertical lines depict separation between sites.

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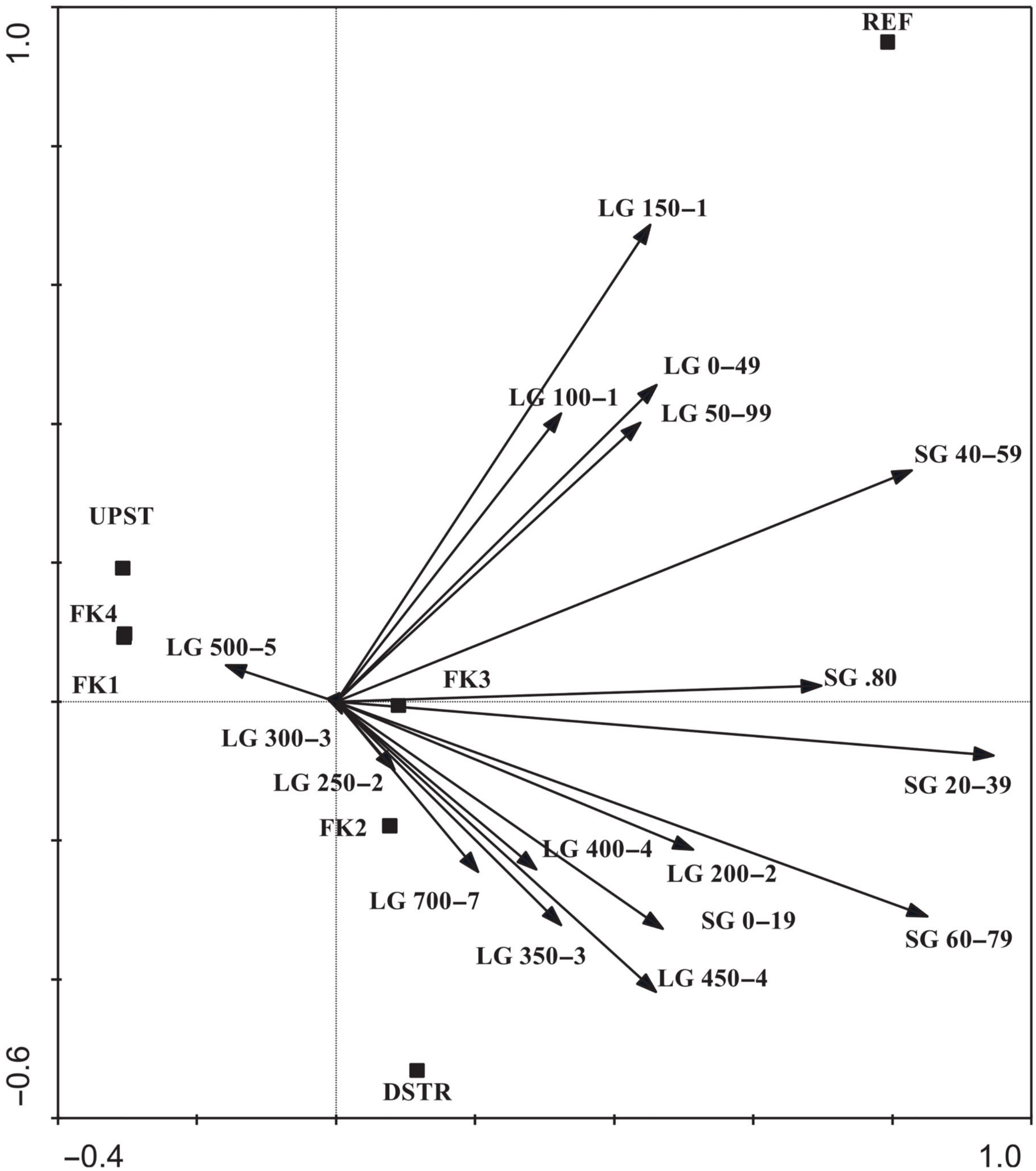

Figure 6.

A principal component analysis with redundancy analysis bi-plotted between the sites sampled, the size classes where LG, large growing; SG, small growing fish size classes.

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Table 1 Site description and codes used in the Msunduzi River case study.

Site code	Site description	Location		Component	Abbreviation
		X	Y		
EPWR	Msunduzi River upstream of Pietermaritzburg urban centre	−29.612663	30.377301	Upstream of pollution	UPST
ASCOT	Msunduzi River downtream of Pietermaritzburg urban centre	−29.601840	34.404874	Upstream of pollution	UPST
DUMP	Msunduzi River downstream of the landfill site	−29.602631	30.424797	Upstream of pollution	UPST
WWTW	Msunduzi River downstream of the wastewater treatment discharge site	−29.594987	30.439988	Immediate impact without influence of the wastewater treatment plant	FK1
MOTO	Msunduzi River at the motorcross racetrack gauging weir	−29.607707	30.450231	Immediate impact with influence of the wastewater treatment plant	FK 2
GBRG	Msunduzi River at the Grimthorpe low water bridge	−29.618312	30.447272	Immediate impact with influence of the wastewater treatment plant	FK2
MBRG	Msunduzi River in the Mpushini conservancy area	−29.604725	30.482953	Immediate impact with influence of the wastewater treatment plant	FK 2
NKAN	Msunduzi River in the rural community of Nkanyenzini	−29.60638	30.552901	Greater than 10 km downstream of the pollution spill	FK3
MGDZ	uMngeni River downstream of the confluence of the Msunduzi River	−29.63627	30.68988	Influence of the uMngeni River main stem	FK 4
UINA	uMngeni River upstream of Inanda Dam	−29.65016	30.78855	Influence of the uMngeni River main stem	FK4
DINA	uMngeni River downstream of Inanda Dam	−29.719687	30.904102	Downstream of Inanda Dam	DSTR
FHES	uMngeni River in a biosphere	−29.491252	30.492632	Reference site	REF
KARK	The Karkloof tributary on the uMngeni River	−29.443797	30.319403	Reference site	REF

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Table 2

The total abundance of fish species during the study for sites sampled upstream of the fish kill (UPST), at different intervals in the fish kill (FK 1–4) and downstream of Inanda Dam (DSTR), included are the two reference sites (REF) pre- (2017 and 2018) and post- (2020) the spill.

Site		UPST		FK1		FK2			FK3			FK4	DSTR		REF
Species	**Multivariate spp. code**	**2018**	**2020**	**2018**	**2020**	**2017**	**2018**	**2020**	**2017**	**2018**	**2020**	**2020**	**2017**	**2020**	**2017**
Awaous aeneofuscus	AAEN												5	3	
Amphilius natalensis	ANAT														6
Cyprinus carpio	CCAR							1						1	
Clarias gariepinus	CGAR		2	5			47	4					1		1
Coptodon rendalli	CREN						2		8			1	5	1	1
Enteromlus anoplus	EANO														1
Enteromlus gurneyi	EGUR														45
Enteromlus viviparus	EVIV														1
Lepomis macrochirus	LAMC	5													
Labeobarbus natalensis	LNAT	32	5[b]	12	4[a]	5	14		45	4	3	5	1		32
Micropterus punctulatus	MPUN	1													
Micropterus salmoides	MSAL								2				2	1	
Oreochromis mossambicus	OMOS						2			4	1		3	5	10
Pseudocrenilabrus philander	PPHI					2	45		4	17			39		1
Tilapia sparmanii	TSAP					10		0	5						16
TOTAL		38	7	17	4	17	110	4	64	25	4	6	56	11	114

[a] Adult *Labeobarbus natalensis* collected post fish kill event.

[b] Larval *Labeobarbus natalensis*.