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Pollution impacts on the aquatic ecosystems of the Kruger National Park, South Africa

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ABSTRACT

The Kruger National Park (KNP) is a savanna ecosystem situated in the middle reaches of five large, dynamic and biologically diverse transboundary river systems. The KNP has been at the forefront of applied river ecosystems research for over 30 years. Meanwhile each of its rivers has a unique set of challenges from both a river flow and water quality management perspective. These have often arisen from anthropogenic changes in the catchments of the park. The resultant challenges give rise to an array of effects that bear upon the parks' ability to maintain the viability of aquatic ecosystems in a large and bio-diverse landscape.

This paper sets the scene through a synopsis of the investments made by the KNP to improve river management practices and the present status-quo of these aquatic systems. Moreover, it details through particular case studies where emergent impacts of diffuse pollution sources have affected the aquatic biotic processes within the park and downstream.

Issues are framed within a conservation management context with respect to broad ecosystem health and species of conservation concern. Comparisons are also made to other aquatic ecosystems within the KNP where the impacts of diffuse pollution effects are as yet unapparent.

Introduction

Protected areas globally are invariably constrained by a multitude of challenges and in larger such areas situated within major river basins a number of these challenges arise from both upstream and sometimes also downstream catchment management activities. Moreover, the historical discourse has typically been for protected areas to be managed in isolation, as fortress islands of conservation in an anthropogenically altered landscape. This was especially relevant up until the 21st century whereupon the socio-ecological systems perspective became a strong paradigm for conservation managers globally to begin working systemically. The needs of river management in large protected areas have demonstrated that requirement

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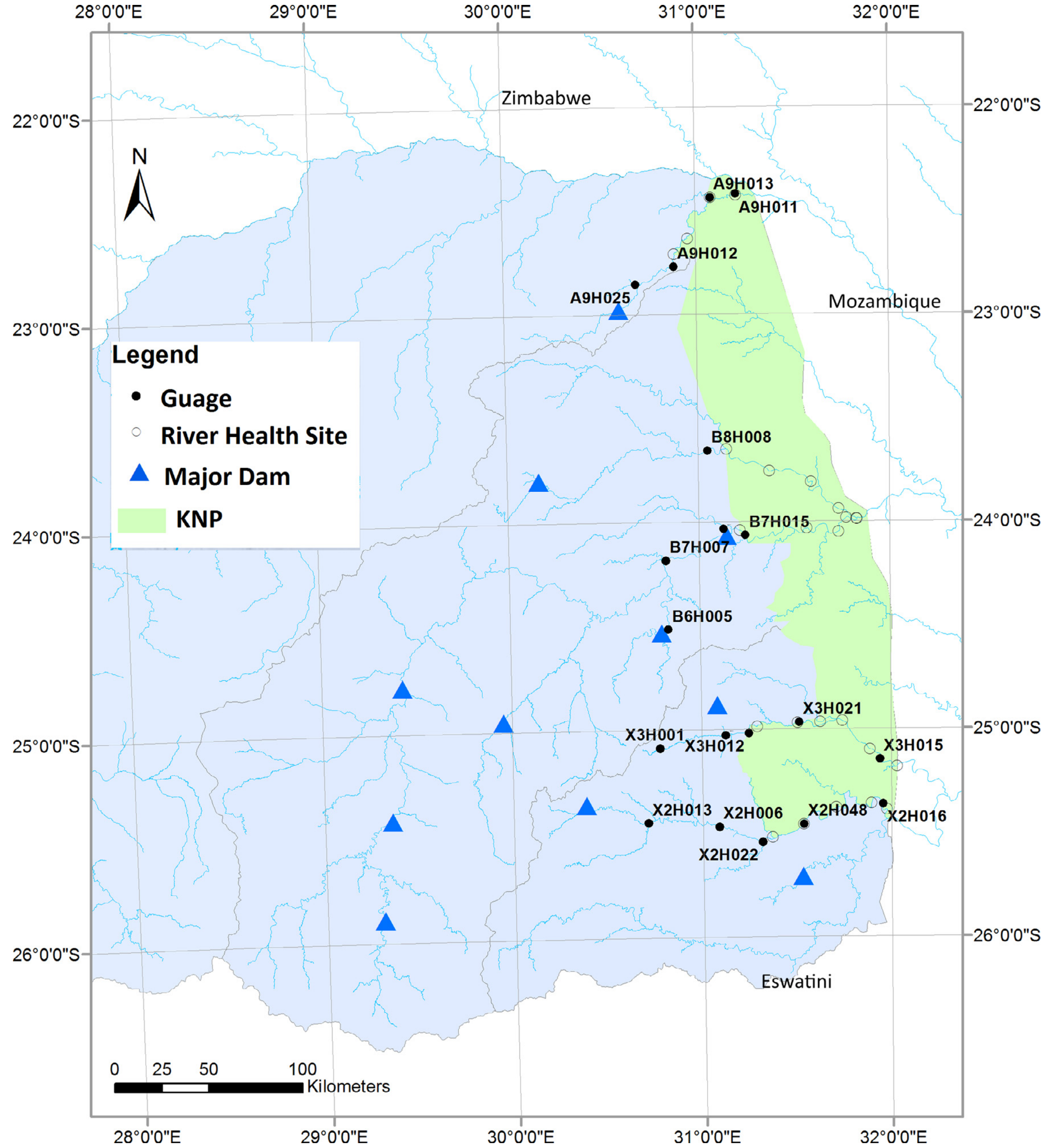

Fig. 1. Location of the KNP in relation to its perennial river catchments, location of key water quality driver sites and bio-monitoring sites.

and this is especially true of the Kruger National Park (KNP; [30]) where there has been a three decade history of proactive informed river management engaging with upstream sectors. This being strongly tied into the biophysical response of the lotic environment within the KNP itself.

The KNP (Fig. 1) is a 2 million hectare protected area situated in the savanna biome of north-eastern South Africa and straddles the border with Mozambique in the east and Zimbabwe in the north. The KNP is therefore positioned within two transboundary river basins. It is within this context that the 5 perennial rivers flow easterly across the KNP and into Mozambique, namely the Luvuvhu, Letaba, Olifants Rivers contributing to the Limpopo Basin, and the Sabie and Crocodile Rivers to the Incomati Basin. Furthermore, in the South African context, the KNP is the most downstream 'user' of these water resources and has worked diligently to ensure the progressive implementation of each rivers environmental water requirements (EWRs) as mandated under South Africa's National Water Act (of 1998). These EWRs provide for riverine ecosystem goods and services to the benefit of all society by allowing for the environments right to water. To date, this has had a specific focus on the quantity component of the EWR and in particular to dry winter low flows.

Notwithstanding, the KNP is well aware that many of the impacts on its aquatic biodiversity in recent history are not purely related to the poor delivery of low flows [5,31], but rather due to water quality issues manifested through both point discharges and diffuse sources in the catchments upstream.

Whilst the progress made to date on EWR implementation are reviewed elsewhere [5,15,32,33], this paper presents a historical overview of the KNPs river management focusing on the rather more pressing issues related to water quality management.

History

The history of water quality impacts in the catchments that drain into the KNP can be traced back to well over a 100 years ago, even to the time when the park was proclaimed. The Sabie River is now considered one of the most pristine and biodiverse rivers in the whole of South Africa, however up until the mid-1940s when livestock farmers successfully lobbied for the South African government to prevent upstream gold mine tailings along the Drakensberg Escarpment, the effects of cyanide leachate were noted all the way down to the KNP [41].

Similar effects are occasionally still observed in the Crocodile River when cyanide spills occur from active mining in the Kaap River tributary. Moreover, it was during the 1950s, following the discovery of copper and phosphate at Phalaborwa, that extensive mining developed along the banks of the Ga-Selati River, a tributary of the Olifants River at KNPs western boundary. Following this mining expansion the Olifants River suffered serious salt enrichment primarily from sulphate and phosphate through controlled effluent discharge. In 2002, however the KNP successfully lobbied for the implementation of a zero discharge policy from the Phalaborwa Mining Complex (F Venter *pers com*, [5]) which resulted in clear improvements in river water quality. The impacts of heavy metal bio-accumulation as a result of mining activities in the Olifants catchment have been well known for quite some time, with discernible effects apparent in studies from the early 1990s such as Avenant-Oldewage & Marx [4] and Heath et al. [16].

The Olifants River does still occasionally suffer the impacts of large point source effects such as the Industrial phosphate plant spill of 2013 [26,34]. On the whole however the governance of these problems has significantly improved, as exemplified by the successful litigation in 2015 of the aforementioned industrial phosphate plant by a state entity, SANParks [5]. Meanwhile, the Olifants River within the KNP still experiences intermittent fish kills arising from anoxic sediment sluicing at the Phalaborwa Barrage, which provides bulk water to the local Phalaborwa mines and regional economy.

Contemporary impacts on the KNPs aquatic ecosystems – stock pollutants

Despite some apparent improvements locally to the KNP it is still highly probable that a multitude of water quality related impacts persist. Both point and diffuse sources are likely responsible for creating a 'cascade of environmental pressures' bearing upon the well-publicised large scale mortalities of Nile crocodile (*Crocodilus niloticus*) in the Olifants River Gorge [11]. Whilst the die-off itself was attributed to the disease pansteatitis, it is believed this disease manifested as a result of upstream pollution impacts and eutrophication leading to a trophic level shift, with both crocodiles and sharptooth catfish (*Clarias gariepinus*) changing to a more piscivourous diet [39]. Furthermore, elevated heavy metals such as iron and aluminium in the sediments of the gorge sampled during the initial die-off suggested an increasingly lentic environment upstream of the Massingir Dam in Mozambique, in which heavy metals were deposited in the gorge as silts and clays [3]. The debate on the causes of crocodile mortalities has since moved on somewhat to include the role of an exotic pelagic filter feeder species in the lotic system upstream of the dam, [18] and the possible role of the indigenous omnivore the Mozambique Tilapia (*Oreochromis mossambicus*). Nonetheless, it was clearly demonstrated that the bio-accumulation of heavy metals, partially correlated to sedimentation is nevertheless having an impact on top predators such as the Tigerfish (*Hydrocynus vittatus*) in the aquatic food chains, not only of the Olifants River, but also the seemingly less polluted Letaba and Luvuvhu Rivers [12]. Meanwhile, diffuse accumulation of Copper, Mercury and build up in egg-shells of crocodiles in the Olifants River are known to have eco-toxicological effect, whilst accumulation of iron leads to the thickening of egg-shells and thus potential hatching success of infant crocodiles [10].

Whilst, there has been a focus on understanding pollutant impacts on seminal species such as crocodiles, recent studies suggest the serious human health risks associated with regular subsistence protein consumption of tissue from fish caught in impoundments upstream of the KNP, notably from bio-accumulation of other heavy metals including antimony, chromium and lead in *O. mossambicus* [1], silver butter catfish (*Schilbe intermedius)* [2], and *C. gariepinus* [25].

Whilst the aforementioned cases give the reader a sense of the formative impacts of water quality from various sources on aquatic ecosystem conservation in this large protected area, this paper sets-out to explore the contemporary impacts of potential diffuse pollution sources on the aquatic ecosystems of selected perennial rivers in the KNP. It does so by utilising readily available water quality time-series and recent bio-monitoring data collected over the past decade.

Methods

This paper presents case study comparisons of the major rivers which flow through the KNP, and draws upon various existing or transformed datasets to determine the impacts of diffuse pollution on the aquatic ecosystems of the park.

Bio-responders

SANParks contributes to the national aquatic monitoring system known as the River Ecostatus Monitoring Program (REMP) which consists of a suite of biological matrices that assess a rivers' ecological status. This ecostatus represents the integrated ecological status of the water resource combining drivers (hydrology, geomorphology and physico-chemical processes) and the responses (fish, macroinvertebrates and riparian vegetation) [21].

Macro-invertebrates

The index used to monitor aquatic macroinvertebrate responses is the South African Scoring System version 5, SASS5 [9], an internationally recognised rapid bio-assessment technique using three indices (viz. SASS Score, number of macroinvertebrate families and the Average Score Per Taxa, ASPT). These indices allow for temporal and spatial comparisons on a specific river with a focus on micro-habitat.

Although Dickens & Graham [9] stated the advantages of SASS5 (including its rapid assessment, affordability, and that it can be used by less specialised practitioners), macroinvertebrates are not as precise as the traditional chemical methods in detecting the exact type of chemical pollutant in the system. The species can however create assemblages that aid in identifying the overall types of chemical pollutants in their environment [37].

Macroinvertebrates can also indicate the temporal condition of a concerning river or site. For example the richness of orders such as Ephemeroptera and Trichoptera can positively indicate the improvement of a once degraded system [17]. Some orders are specific to certain chemicals for example Ephemeroptera, Plecoptera and Trichoptera were found to be negatively affected by DDT with few of their members found on sites with DDTR [38]. In some cases even species can indicate the specific chronic pollution at relatively low concentration e.g. the larval stages of the midges *Chironomus decorus* to copper [22] and *Chironomus riparius* to cadmium [28]. Some species such as the caddisfly *Hydropsyche californica* can show the concentration levels of various mining metals they are exposed to [6], and therefore can indicate the levels and types of pollutions within different locations of their river system or other river systems.

Diatoms

De la Rey et al. [8] demonstrated that diatoms show meaningfully greater correlation with broad water quality parameters, than would be revealed through SASS data. The KNP has recently begun using diatoms to complement the REMP to give greater temporal resolution to the sampling in the large perennial rivers since they are largely inaccessible for safe ecostatus monitoring (due to presence of dangerous wildlife) except under dry winter low flow conditions.

Diatom sampling in the KNP follows the methodology of Taylor et al. [36]. This uses the Specific Pollution sensitivity Index (SPI) (Coste in [7]) determined alongside the Biological Diatom Index (BDI) [24]. These indices are established using the Omnidia v.3.1 software [23].

Fish

Being relatively long-lived and mobile, fish are good indicators of long-term influences on the general habitat conditions within the river. The number of fish species that occur in a specific reach, as well as factors such as different size classes and the health of fish can be used as indicators of river ecosystem integrity. In this instance, each geomorphic habitat unit (GHU) is sampled separately, using an electro-shocking device (SAMUS^{TM} 4254). The electro-shocker works favourably to collect fish in fast-flowing waters (Rapids-runs) and shallow back-waters and pools amongst vegetation. Stunned fish are identified to species level using taxonomic keys by Pienaar [29] and Skelton [35].

Load duration curves

In order to understand the range of hydrological conditions and associated water quality variability in the KNPs large perennial rivers, load duration curves (LDC) were plotted at different points in the catchment, associated with stream flow gauges to allow for a catchment wide assessment. The method provides a visual display of the relationship between stream flow and loading capacity. These data were accessed through the South African Department of Water & Sanitations (DWS) Resource Quality Services portal, available at http://www.dwa.gov.za/iwqs/wms/data/000key.asp. The flow gauge in closest proximity to the water quality sampling point was used to derive the historical hydrological range using the flow duration curve framework, the dataset can be accessed through DWS verified flow data portal at https://www.dwa.gov.za/hydrology/Verified/hymain.aspx. Furthermore, the load data for each hydrological year (October to September) were determined as input to the statistical analysis. Table 1 summarises the meta-data for flow and quality sampling points.

Statistical tests

Fish, diatom and invertebrate data were analysed separately due to the different sampling methods and frequencies, as described. However, the same load duration data (Table 2) were used across all 3 taxa. All analyses were performed using the software package PAST3 [14]. As both taxonomic and environmental data were available Canonical Correspondence Analyses (CCA) were performed to identify patterns and important load duration variables in the data. The CCA is used to infer causality rather than absolute responses in the biotic data to abiotic drivers including potential diffuse pollution effects. Correlation coefficients were used in cases where environmental variables needed to be omitted.

Table 1
Table of flow gauge locations used to calculate load durations, and proximate water quality sampling points.*

River system	Drainage region	WQ station	Description	Lat	Long	Flow guage	Time period
Crocodile	X2	102,958	Montrose	−25.45	30.71	X2H013	1977–2017
		102,953	Karino	−25.47	31.10	X2H006	1969–2017
		102,965	Kaap River at Dalton	−25.54	31.32	X2H022	1969–2017
		102,987	Malelane-Riverside	−25.46	31.54	X2H048	1983–2017
		102,963	Tenbosch	−25.36	31.96	X2H016	1970–2017
Sabie	X3	103,007	Sabie Town	−25.09	30.78	X3H001	1966–2017
		103,012	Hazyview Perry's Bridge	−25.03	31.13	X3H006	1969–2017
		103,016	Phabeni KNP	25.02	31.25	X3H012	1983–2017
		103,019	Lower Sabie KNP	−25.15	31.94	X3H015	1983–2017
		103,014	Sand River at Exeter	−24.77	31.39	X3H008	1977–2016
Olifants	B7	90,492	Driehook	−24.51	30.83	B6H005	1969–2017
		90,503	Oxford/Mica	24.18	30.82	B7H007	1969–2017
		90,518	Selati River at Loole	−24.03	31.12	B7H019	1989–2017
		90,512	Mamba	−24.06	31.24	B7H015	1983–2017
Luvuvhu	A9	90,404	Tshidzini	−22.85	30.69	A9H025	1997–2017
		90,399	Mhinga	−22.77	30.89	A9H012	1988–2017
		85,326	Mutale River at Mutale Bend	−22.44	31.08	A9H013	2003–2017
		90,398	Pafuri	−22.42	31.21	A9H011*	1983–2017

* approximate loads determined by combining flow data from both A9H012 + A9H013.

Results and discussion

The CCA analysis were run for data on the Crocodile, Sabie, Olifants and Luvuvhu rivers. The macro-invertebrate data represents the most robust dataset due to length of record (8 samplings seasons, 2010–2017) and the quantitative method of sampling. Resultantly, these data allow the most potential to use historical load time series to infer causality to diffuse source impacts on the aquatic ecology.

The correlations for macro-invertebrate responders are shown in Fig. 2. It is clear from the four correlation matrices that each of the rivers appears to have different macro-invertebrate associations to water quality. In the Crocodile River, there is a weak negative correlation between the SASS/ASPT scores with Cl, K, Mg but particularly so for Na where this is a moderate negative correlation. To some extent there is also a negative correlation also with Si and SO_4 in the Crocodile River.

The Sabie River does not show any negative correlation with the SASS/ASPT scores. It is only moderately negative-correlated with dissolved major salts (DMS), whilst the SASS score appears to be only weakly negative-correlated with Na. Similarly, the Luvuvhu has SASS scores that are also weakly negative-correlated by these parameters. By contrast, the Olifants River shows strong negative correlations of the SASS score with all the water quality parameters included in the analysis, in particular N, Cl, F, Mg and P and moderately by DMS, EC and SO_4.

When examining the ordination data which summarises these relationships by biotic order as shown in Fig. 3 one notes that Na seems to have the most effect in this system, being a positive influence against axis-1, which explains the majority of variation in the data set (~55%). However, P has the most influence overall with a −0.41 correlation against axis-1 and −0.6 against axis-2. In this way it is appears that particularly the diptera (true flies), hemiptera (true bugs) and trichoptera (caddisflies) are negatively associated with the strong influence of Na in the system. Meanwhile the over-riding effect of P appears in particular to influence the annelida (ringed worms), gastropoda (snails) and to some extent the hydracarina (water mites).

The ordination plot for the Sabie system however reveals no strong influences against axis-1 (~59% of the variation) and whilst DMS is strongly associated with this axis, so too are the nitrogen oxides (−0.53 correlation against axis-1). Speculatively then, since the coleoptera (beetles) and to some extent the hemiptera plot away from these two variables, it could explain a minor impact of these two parameters in the Sabie system. It should however be noted that salinity appears to have a role in the Sabie system, with EC −0.56 negatively correlated along axis-1.

The Olifants River in Fig. 3 meanwhile is striking since axis-1 accounts for the most significant variation in the dataset (~66%), and all the water quality parameters are strongly associated with it. Notably, this appears to have a strong negative bearing on the occurrence of turbelaria (flat worms) in particular, but also the gastropoda and lepidoptera (butterflies and moths). Given the ordination plots, it could be that K, Mg, nitrogen oxides and Si explain most of the impact on the presence or absence of these taxa.

In the Luvuvhu system meanwhile (Fig. 3), axis-1 accounts for ~66% of the variation in the dataset and it is K (−0.54) followed by Na (−0.41) that appears most strongly associated with it. Interestingly, it is the ephemenoptera (mayflies), hemiptera and diptera that are most negatively associated with the axis-1, and in this case K could be the explanatory variable of concern in that system. This result could be expected, since recent literature has pointed to the potentially diffuse mobilisation of nitrates from small-scale agriculture in the Luvuvhu catchment [13], and whilst nitrogen oxides do not have a strong negative correlation along axis 1 (−0.23) in this analysis, K is obviously associated with agricultural fertilisers. One may therefore have expected to see this impact on the macro-invertebrate responses downstream.

Table 2
Mean loadings per hydrological year (kg/day).*

	Hydro-Year	Ca	Cl	DMS	EC	F	K	N	Mg	Na	NH_4_N	NO3_NO2	P	PO_4_P	Si	SO_4
Crocodile Riverside (X2H046)	2009/10	3885	4154	*	54,694	*	751	*	2800	3025	900	1800	*	699	1670	1028
	2010/11	19,438	18,586	325,809	150,144	267	2621	*	23,118	21,937	3241	10,538	*	5143	9837	38,831
	2011/12	17,171	32,933	258,048	29,386	147	1460	*	19,660	21,091	49	362	*	27	6976	38,299
	2012/13	*	45,641	*	77,106	*	*	*	*	*	312	2064	*	334	*	64,341
	2013/14	26,928	41,428	*	72,069	*	*	1730	26,660	*	458	1584	39	234	11,125	70,069
	2014/15	*	23,668	*	30,863	*	*	*	*	22,130	1814	759	*	560	*	29,238
	2015/16	5526	8062	76,917	12,215	88	575	223	4942	10,530	20	261	10	16	2172	9580
	2016/17	*	6658	*	11,560	*	*	*	*	9474	*	*	*	13	*	*
Sabie Lower Sabie (X3H015)	2010/11	14,698	23,330	195,511	28,285	531	4991	731	9885	24,705	182	189	75	14	15,802	8449
	2011/12	9610	17,127	130,994	23,943	244	3770	*	7508	16,675	32	32	*	6	2489	7057
	2012/13	36,798	37,065	450,620	71,253	691	5577	*	24,689	43,550	127	153	*	22	23,170	20,343
	2013/14	6934	9683	*	13,767	*	*	*	5156	*	45	186	*	9	5968	3539
	2014/15	5776	10,277	66,381	12,946	95	1385	*	4777	8372	213	104	*	19	6205	1544
	2015/16	2942	3812	34,267	4751	127	654	*	1878	3017	16	26	*	13	1524	1039
	2016/17	6261	10,786	80,385	12,337	203	1350	*	4034	8556	44	239	*	59	6048	3032
Olifants Mamba (B7H015)	2009/10	205,278	156,393	1,074,626	382,157	1286	28,405	1719	128,336	165,548	182	1196	70	83	44,230	530,059
	2010/11	201,669	183,005	2,545,384	312,392	3200	26,821	10,440	129,407	198,666	266	1610	980	199	52,232	571,309
	2011/12	22,731	28,948	289,568	38,854	268	2598	*	22,423	25,180	19	320	*	13	5848	31,651
	2012/13	68,956	89,733	846,632	124,224	1674	11,782	*	56,901	84,591	114	1156	*	1647	21,084	107,879
	2013/14	86,043	117,113	509,467	148,602	1515	5123	*	62,558	47,522	104	892	*	146	22,072	189,995
	2014/15	32,421	38,947	269,467	54,979	507	2395	*	29,959	23,725	58	279	*	13	8702	56,188
	2015/16	19,244	21,205	233,026	29,320	252	2207	303	15,147	20,624	31	241	19	21	5316	23,189
	2016/17	43,914	30,158	430,176	55,423	381	5158	*	27,701	29,503	121	1109	*	56	11,066	43,566
Luvuvhu Mhinga (A9H012)	2009/10	3527	4275	20,284	6148	20	977	*	2818	3275	11	30	0	2	2726	720
	2010/11	2700	2966	31,969	4487	67	656	*	2101	2664	9	109	0	2	2499	567
	2011/12	1530	1890	11,124	2758	59	467	*	990	1889	15	31	0	1	1245	310
	2012/13	3883	4720	40,721	6547	60	1085	*	2247	3706	28	181	0	6	3283	818
	2013/14	14,058	17,857	*	24,241	47	*	*	7331	*	104	338	0	41	13,955	3209
	2014/15	5923	8138	18,753	10,392	332	359	*	3948	1426	38	108	0	32	4906	510
	2015/16	1139	1528	13,584	1861	30	191	*	813	1127	7	13	0	4	931	193
	2016/17	6941	9049	76,135	12,242	233	970	*	4220	5690	42	134	0	117	6405	904

* denotes data missing from the record.

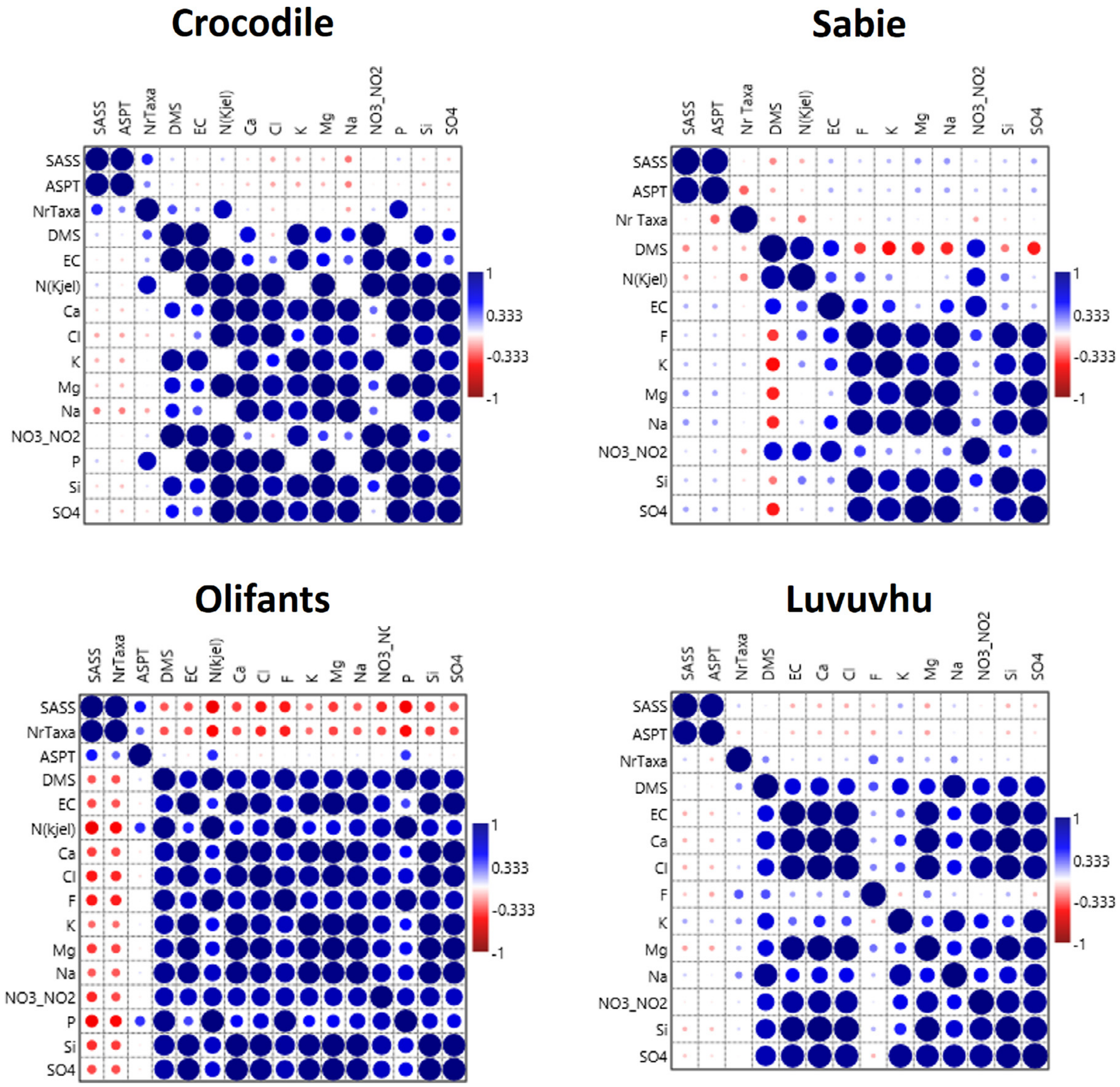

Fig. 2. Correlation matrices demonstrating the strength of association between water quality time-series parameters and macro-invertebrate indices in the rivers of KNP (2010–2017).

Since the diatom data collection in the KNP began recently (c. 2015) only two years of data are available (although a historical survey was done in 1983). This limited the ability to perform the CCA and disaggregate the data per river, the data is therefore lumped at the scale of the KNP for the purposes of ordination. Fig. 4 shows the resulting data and whilst the species level data is extremely cluttered due to the high diversity of diatoms in the river systems, it is the sample site data which reveals some interesting insights of load duration on diatom absence/presence. Axis-1 explains ~29% of the variation in the data, and whilst the low variation reduces the interpretation certainty it is apparent that nitrogen oxides, ammonia and ortho-phosphates are most strongly associated with diatom presence at park scale. Note in particular that it is the Sabie River sites (those labelled SLS – Lower Sabie, ST - Tinga, SP – Phabeni) that are most negatively associated with these parameters. Whilst we know ammonia is in the South African context mostly associated with point source discharges from waste water treatment works, nitrogen oxides and ortho-phosphates are commonly associated with agricultural runoff. Since this diatom dataset is still relatively small, it does suggest the need to continue to utilise this form of aquatic biomonitoring to ascertain the impact of these potentially diffuse sources on river water quality especially in the Sabie system through prolonged time-series data.

In the case of fish, again the data was lumped at the scale of the KNP rather than by river, due to the short time series nature of the dataset (2015–17, it is only within these last 3 years that the sampling approach has been modified to collect quantitative data based on frequency of occurrence, whereas historical data was simply based on presence/absence).

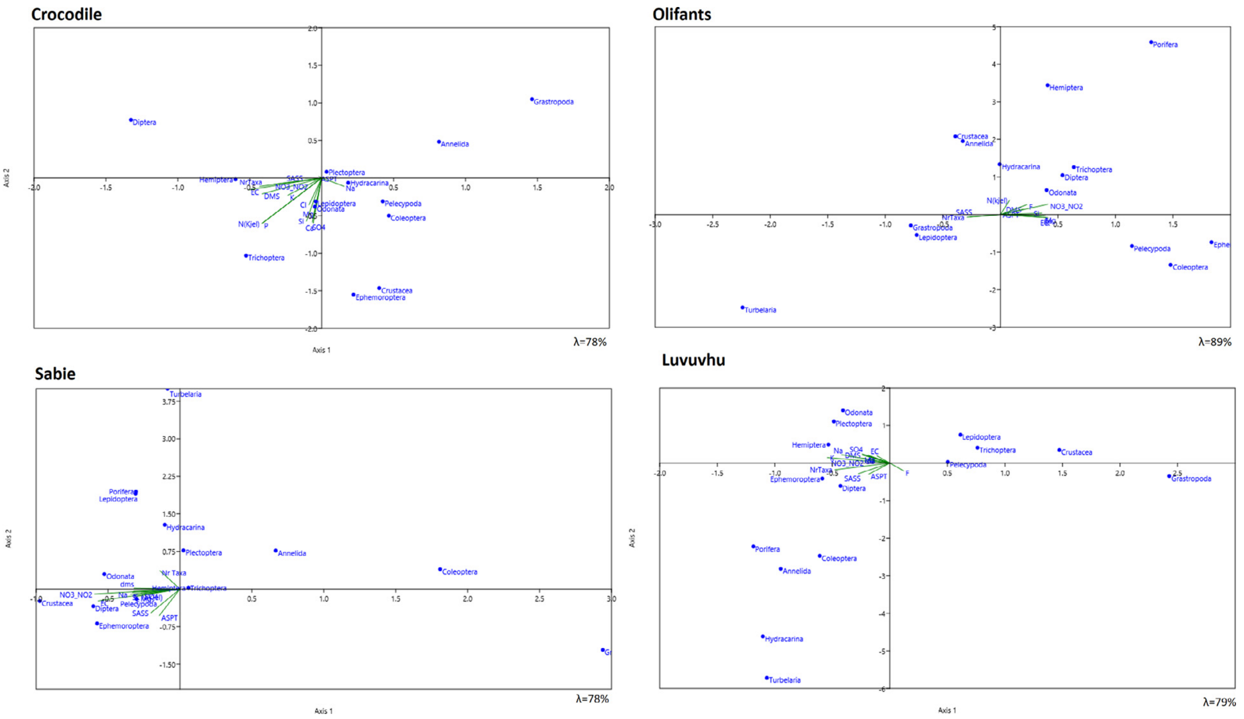

Fig. 3. CCA ordination of water quality parameters and the presence of macro-invertebrate orders in the rivers of KNP (2010–2017). Note λ attributes the total variation of axis 1 & axis 2 to the dataset.

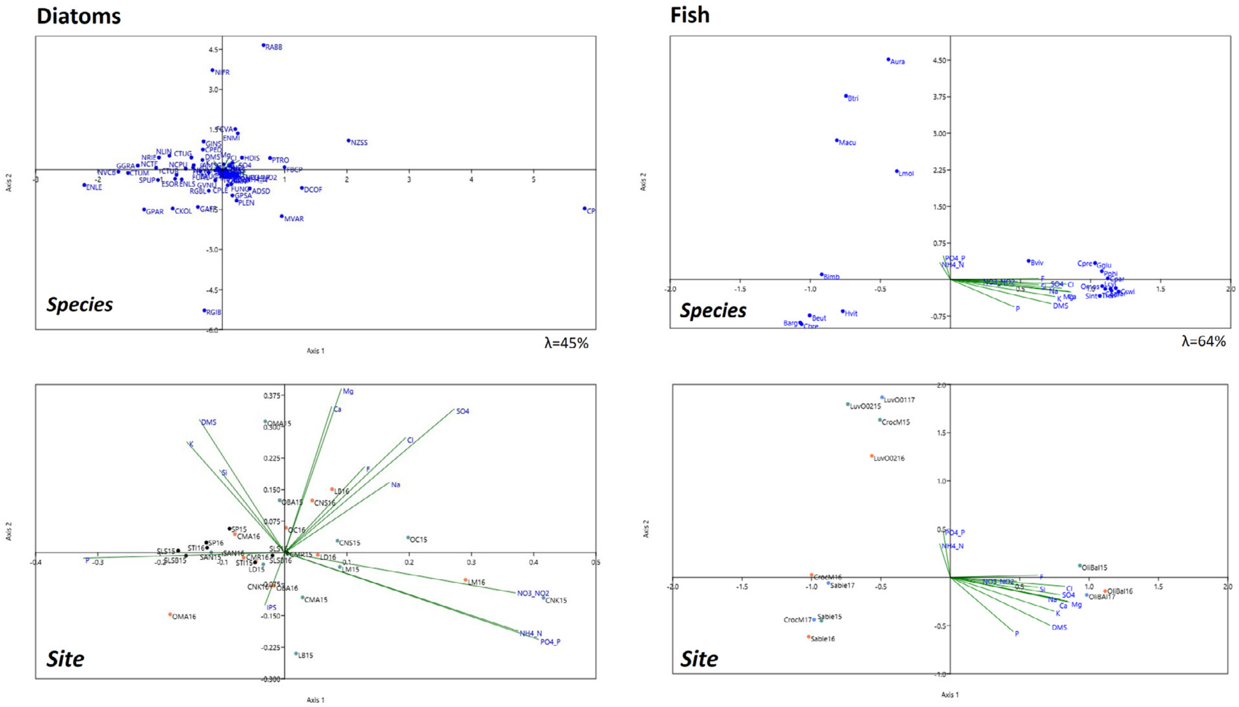

Fig. 4. CCA ordination of water quality parameters and the presence of fish species (2015–2017) and of diatom species (2015–2016) in the rivers of KNP. Note λ attributes the total variation of axis 1 & axis 2 to the dataset.

Interestingly axis-1 explains ∼44% of the variation in this dataset and clearly F, Na, Si, SO_4, are most strongly associated with it. Whilst there appears to be a positive association with a number of fish species and a negative association with *Brycinus imberi* (Spot tailed robber - Bimb), *Hydrocynus vittatus* (Tiger fish - Hvit), *Barbus eutaenia* (Orange fin barb - Beut), *Barbus argenteus* (Rosefin barn - Barg), *Chiloglanis pretoriae* (Shortspine suckermouth - Cpae), it would be too speculative to directly attribute these water quality parameters to their presence or absence. This being due to the overriding habitat influences on these species and their mobility, and lack of a longer term quantitative dataset. Nevertheless, the site level data where the fish were sampled reveals striking aspects especially for the Olifants River sites, which concurs with the macro-invertebrate data and shows that the fish sampling sites in this river are strongly influenced by the majority of the water quality parameters.

The supplementary files contain the historical load duration curves for selected water quality parameters in each of the rivers discuss. The Crocodile River is shown in A.1 and the parameters that appear to explain the negative correlations on macro-invertebrate diversity in that river system within KNP. One will note that Na appears to have low loads in the headwater regions of the catchment at Montrose, and this is true throughout the hydrological regime. Only being moderately mobilised at high flows (low% exceedance). This is to be expected in headwater regions with smaller catchment areas. Furthermore, upstream of Montrose the majority of the catchment is overlain by natural grassland and agro-forestry, commercial irrigated agriculture increases downstream of this point. Meanwhile at Karino in the central part of the catchment Na appears to be present throughout the hydrological regime in both high flows and low flows (high% exceedance). Considerable loads are experienced during flood events at Karino. It is worth noting that Karino is downstream of the City of Mbombela and the large densely populated peri–urban settlements of the former homeland areas (Kangwane Bantustan), it is also downstream of extensive commercial irrigated agriculture, primarily citrus and other fruits as well as some sugar. Dalton meanwhile is on the Kaap River a major tributary and here it is observed that the Kaap does contribute high loads of Na during flood events, the Kaap River is itself heavily converted to irrigated agriculture, and has extensive mining (gold and other heavy metals). Riverside and Tenbosch are both situated between the KNPs southern boundary and extensive irrigated sugar in the Nkomazi region and the shape of the load duration curves here suggest similar loadings of Na between these two points. Whilst salts are a cause for concern, the catchment wide ecostatus surveys [19] have attributed the lower ecostatus of the Crocodile River along KNPs border more broadly to over abstraction, river regulation and habitat degradation. However, given these water quantity changes elevated salts will also have a deleterious effect on the aquatic biota in that stretch of river.

Since the analytical approach suggested a strong influence of P on the macro-invertebrate ecology in the Crocodile River, it is interesting to note the load durations of P systemically in the catchment. Unfortunately poor data exists for this parameter in the headwaters but at Karino there appears to more P associated with low flow conditions, suggesting a point source origin within this region. Whilst there is certainly some mobilisation of P at higher flows (<20% exceedance), this does indicate diffuse origins, most likely from the extensive commercial fruit orchards upstream of the Karino site. However, since the P load seems minimal in the Kaap at Dalton, it does suggest some assimilation and dilution effect downstream of the Kaap Rivers confluence, and this may well be due to extensive reed-beds in that section of river assimilating the P under low flow conditions. This of course does not explain the apparently strong influence of P within the KNP itself. In a separate analysis PO_4-P appeared to have −0.32 negative correlation along axis 1 compared to P being −0.42. So there may well be an impact of ortho-phosphate immediately adjacent to the KNP from the agricultural lands on its southern boundary. This warrants further assessment.

The DMS loads for the Sabie River also shown in A.1 reveal a moderate major salt load at the headwaters of the system at Sabie Town, and this is noted throughout the hydrological regime of the river from low flows to high flows. Once the Sabie River emerges out of the foothills of the Drakensberg escarpment area at Perry's Bridge one observes that the river carries greater loads of major salts throughout the hydrological regime (even 2000 kg/day at low flow), but the effect is that peak flows bring high major salt loads downstream, which may be expected with the delivery of sediment from upstream, a region characterised by steep catchments under agro-forestry. By the time the Sabie River flows past Phabeni Gate the major salt load is already quite high even at low flow, and would appear to have greater loads than would otherwise be expected from the main tributary, the Sand River. The convex load duration curve of the Sand River actually suggests that this system only contributes elevated major salts during significant peak flows, and this is expected since the Sand Rivers hydrology is dominated by low flow conditions during most of the year. At Lower Sabie however, one observes a very high major salt load throughout the hydrological regime, and especially during median to high flows (0–50% exceedance) this can vary from 50–100 tons of major salt per day. Elevated sediment delivery to the Sabie system has recently been noted as a deleterious effect of upstream forestry activities and appears to already be impacting on the aquatic biodiversity upstream of the KNP [20]. Interestingly, there is a large bulk domestic water abstraction upstream of KNP on the Sabie River at the Hoxane Water Treatment Works, and in recent times the water board operating that treatment plant has noted with concern the increasing cost of maintaining it due to continual sedimentation of their abstraction impellors (Rand Water staff, *pers com*, 2017)

It is interesting to observe that nitrogen oxides appear to be mobilised only at high flow conditions at Phabeni Gate and also observed at Lower Sabie, whilst not entering the KNP stretch of the Sabie River via the Sand River. This is most likely attributable to the small-scale agriculture that exists (summer and winter irrigated vegetables) along the Sabie River between Hazyview and Kruger Gate. This represents an important opportunity for the KNP to encourage compatible land-uses on its shared riparian periphery, in order to promote conservative agricultural practices, in order to minimise the impacts on the aquatic resource.

Supplementary A.2 takes some of the key water quality monitoring points in the Olifants catchment, where one can clearly identify the contribution of the tributaries in the lower Olifants region (below the Drakensberg escarpment). The Oxford gauge is upstream of KNP, on the Olifants mainstem, and here high loads of DMS, K, nitrogen oxides and Mg (also true for a multitude of other parameter not reported on in this manuscript) are observed at >300 tons per day at flows that occur <50% of the time (higher flows). This is similar within the KNP itself as observed at Mamba Weir. The Selati however, is a severely compromised river system, due to excessive upstream withdrawals and the impacts of mining and poor water treatment servicing. Here we see that the Selati delivers a greater major salt load, and under exceptional flows also K and Mg at high loadings, as compared to the Blyde system. This is a challenge for the KNP, since the Blyde system is protected to provide some relief for conditions in the mainstem of the Olifants. Driehoek is on the Blyde River, a relatively un-impacted river system that is protected with stringent Resource Quality Oobjectives, in order to provide assimilative capacity to the mainstem Olifants, especially during low flow conditions [40]. So, this data clearly demonstrates that positive water quality contributions in the Blyde system are often cancelled out by overly negative inputs from the Selati River.

In the case of the Luvuvhu River, shown in A.3 one observes that the K load is actually fairly low, especially if one compares it to the Olifants. However, it is clearly mobilised by flows in the mainstem river, and only at high flows (<10% exceedance), with very little observed upstream in the headwaters at Tshidzini (although there is little data available for this site). The Mutale tributary which enters the Luvuvhu River downstream of Mhinga can also be considered pristine from the perspective of K contributions. One suspects then that the main delivery of K to the mainstem of the Luvuvhu arises from agricultural areas east of the city of Thohoyandou.

Other emerging diffuse impacts & management responses

Whilst it hasn't been the focus of this manuscript it is worth noting that recent work has pointed to an emergent diffuse pollution source in the form of microplastics [27]. This work which accompanied the routine REMP monitoring, revealed the extent of microplastics (particles <5 mm diameter) and significantly both the Olifants and Crocodile Rivers had micro-plastics in their sediments, whilst they were absent from the Sabie River. Although this scoping study could not identify the source, it did reveal some disturbing evidence that micro-plastics could potentially impact the aquatic biota in the KNP most notably benthic feeders.

Furthermore, some heavy metals appear to be mobilised from sand and granite mining immediately upstream of the KNP, particularly with respect to elevating the levels of aluminium in the Sabie system [20].

The analysis presented in this paper has demonstrated to the KNP science-management contingent the advantages of modifying the national REMP approach to conditions in the KNP. In particular the requisite need to continue the SASS monitoring having moved from a few points per river, rotating by river each year (the historical approach) to 4 or 5 sites per river per year (recent changes since 2010). Moreover, whilst it is beyond the scope of this paper, it would have been advantageous to cover the intra-site and inter-site differences per river, in order to determine nuanced impacts of diffuse pollution sources on micro-habitats rather than at the scale of a river reach (the fish and diatom data has indicated the importance of this inter-site variation also). This therefore also accounts for the distinct habitats for macroinvertebrates at upper and lower reaches, even within the KNP. Crucially, accounting for these different habitats and therefore biota will allow the KNP in future to more adequately account for diffuse pollution effects, and to use the macro-invertebrate data as an early warning system to potential deleterious diffuse source impacts. Whilst this paper has explored some of the impacts of these pressures within the KNP, downstream of its large contributing catchments, the reality of course is that diffuse pollution effects on aquatic biota can only really be determined through a systemic catchment-based approach. In this respect it is encouraging to note that there is a revival in catchment ecostatus monitoring along some of the KNP Rivers with the Inkomati-Usuthu Catchment Management Agency (IUCMA) now systematically monitoring both the Crocodile and Sabie systems [19,20]. However, no systemic ecostatus monitoring has taken place in the KNPs northern rivers for at least 20 years and this is a cause for concern.

Conclusion

This manuscript set out to give an overview of the challenges that large protected areas such as the Kruger National Park face in terms upstream pollutants on in the viability of its aquatic ecosystems. Since it is the responsibility of the KNP to conserve these important ecosystems, the focus on the effect of diffuse pollutant impacts to the freshwater aquatic biota, and in particular the key responders such as macro-invertebrates and diatoms have begun to reveal the true diversity of these impacts. This is especially important in the context of managing these large perennial rivers that flow across the KNP from South Africa and into Mozambique, with each river appearing to have starkly different challenges from upstream diffuse sources, dependent on the diversity of anthropogenic activities upstream. It must also be acknowledged that there is a large and growing dependency on these water resources downstream of the KNP, in order to ensure future sustainable economic growth in Mozambique. Whilst there are unique circumstances in each river, there do also appear to be diffuse impacts common to all the river systems, notably the effect of major salts, likely arising from upstream agriculture and the large sediment delivery particularly during large peak flow events which are key characteristic of these large river systems. The nuances of these various diffuse pollution impacts and this inter-catchment comparison is key to ensure that the KNP can continue to engage upstream sectors and influence catchment management policy to effect sustainable catchment management into the future. A practical next step will be to determine the ecosystem service role that the KNP's protection has in terms of assimilation of these diffuse pollutants, to determine any improvement the river condition to the benefit of aquatic ecosystems and water users downstream.

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Supplementary materials

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