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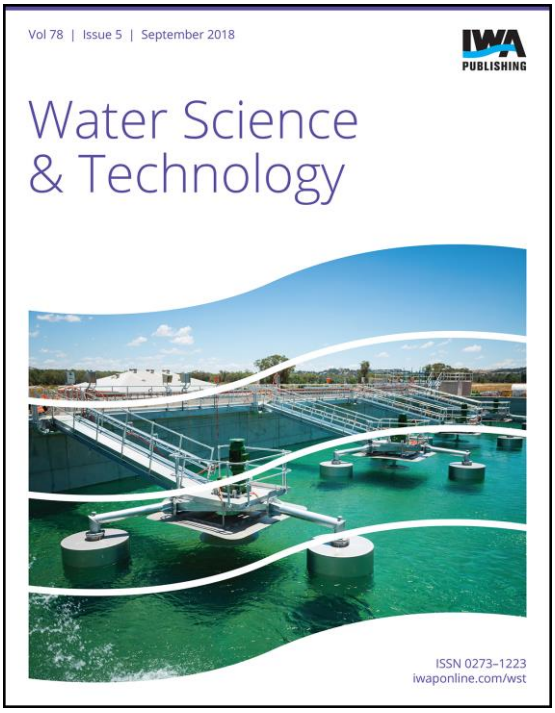

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Quantification of water purification in South African palmiet wetlands

Alanna J. Rebelo, Willem-Jan Emsens, Karen J. Esler and Patrick Meire

ABSTRACT

Despite the importance of water purification to society, it is one of the more difficult wetland ecosystem services to quantify. It remains an issue in ecosystem service assessments where rapid estimates are needed, and poor-quality indicators are overused. We attempted to quantify the water purification service of South African palmiet wetlands (valley-bottom peatlands highly threatened by agriculture). First, we used an instantaneous catchment-scale mass balance sampling approach, which compared the fate of various water quality parameters over degraded and pristine sections of palmiet wetlands. We found that pristine palmiet wetlands acted as a sink for water, major cations, anions, dissolved silicon and nutrients, though there was relatively high variation in these trends. There are important limitations to this catchment-scale approach, including the fact that at this large scale there are multiple mechanisms (internal wetland processes as well as external inputs) at work that are impossible to untangle with limited data. Therefore, secondly, we performed a small field-scale field survey of a wetland fragment to corroborate the catchment-scale results. There was a reasonable level of agreement between the results of the two techniques. We conclude that it appears possible to estimate the water purification function of these valley-bottom wetlands using this catchment-scale approach.

Key words | agricultural runoff, channel erosion, degradation, fen, self-purification capacity, valley-bottom wetland

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INTRODUCTION

Wetlands are considered to be one of the most important types of ecological infrastructure to society in terms of the ecosystem services they provide (Russi *et al.* 2013). The type of wetland, landscape configuration and hydrological connectivity have been cited to be important in determining the type and magnitude of ecosystem services that will be provided (Moor *et al.* 2017). Valley-bottom and floodplain wetlands in particular, due to a combination of their position in the landscape and their composition (alluvium, peat beds and vegetation), have been shown to attenuate flood events (Rebelo *et al.* 2015), mitigate water pollution (Fisher & Acreman 2004), sequester carbon (Mitsch *et al.* 2013), retain sediment (Venterink *et al.* 2006), provide clean water and food for local communities (Schuyt 2005) and provide a host of other cultural ecosystem services underpinned by their high biodiversity (Raymond *et al.* 2009). Despite their value, the complexity of wetland ecology has resulted in wetlands being the least studied system in terms of ecosystem services (de Bello *et al.* 2010). Water purification is noted to be one of three key ecosystem service complexes provided by wetlands (Moor *et al.* 2017). However, it is difficult to quantify wetland water purification in the field (as opposed to artificial wetlands) given the internal complexity of wetland ecosystems (Jordan *et al.* 2003).

Water purification, sometimes referred to as 'water quality' in ecosystem service studies, has been estimated in many different ways (Boerema *et al.* 2017). Besides rapid assessments or scores, the simplest way to attempt to quantify water purification is to measure either the physical or chemical properties of a water body at one point in time, focusing on parameters of interest and their known thresholds (Kandziora *et al.* 2013; Boerema *et al.* 2017). Other studies

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use modelling techniques: investigating nutrient retention at a catchment scale, using the InVEST model or modelling nutrient retention, export or turnover rates in vegetation or in the ecosystem itself (Bai *et al.* 2011; Boerema *et al.* 2017). Some studies measure properties of the soil (nutrients or elements of interest), nutrient retention in vegetation or nutrient removal potential of particular land-covers (Boerema *et al.* 2017). Lastly, other studies quantify processes such as decomposition rates and net primary productivity, relating these to water purification (Kandziora *et al.* 2013; Boerema *et al.* 2017). Many of these methods can be problematic because they study water quality, or impacts on water quality, rather than the water purification function of a particular ecosystem; or they are modelled estimates, often not validated (Boerema *et al.* 2017). However, quantitative water and nutrient budgets of wetlands are difficult and costly because of the high variation amongst wetlands as well as within wetlands, due largely to interannual variation in rainfall (Jordan *et al.* 2003). Therefore, there is a need for a compromise between full water and nutrient budgets and the inadequate rapid assessments of water quality when estimating the ecosystem service of water purification.

In South Africa, the value of valley-bottom/floodplain wetlands in terms of water purification has often been overlooked in favour of their fertile soils for potential food provision. Therefore South African wetlands and associated river systems are in a critical state, with over 65% reported to be damaged, and 50% estimated to have been destroyed (Nel *et al.* 2007). Increasing concern over the loss of water-related ecosystem services following wetland degradation (mainly in terms of water provision, but also of water purification) has prompted conservation and restoration efforts in South Africa. South African Palmiet wetlands are a type of unchannelled valley-bottom wetland with peat layers ranging between 0.5 and 10 m deep (Sieben 2012; Job 2014). Palmiet wetlands are named after the plant species that dominates the system: *Prionium serratum*. Palmiet is a super-dominant ecosystem engineer (species that significantly modify their environment in their favour) and peat-forming species (Sieben 2012). However there has been little research done on these unique wetlands, and there is little understanding of their structure and functioning. Therefore, in the face of the threats to these wetlands, there is an urgency to better understand these systems and the ecosystem services they provide.

In this study, we attempt to quantify the ecosystem service of water purification in South African palmiet wetlands. We investigate how water quality changes spatially in three of these wetlands subjected to agricultural pollution at a catchment scale as well as in a small-scale field survey. We ask the following research question: do pristine palmiet wetlands act as a sink for pollutants (nutrients and metals) linked to agricultural fertilizer application?

METHODS

Study sites

Palmiet wetlands occur in valley bottoms throughout the Cape Floristic Region of South Africa. This region is characterised by oligotrophic and acidic soils due to the highly leached dystrophic lithosols associated with the sandstone mountains of the Cape Supergroup. Therefore, palmiet wetlands are naturally slightly acidic.

Three palmiet wetlands were selected as study sites in three different catchments throughout the Cape Floristic Region: the Theewaterskloof and Goukou wetlands (Western Cape) and the Kromme wetland (Eastern Cape) (Figure 1). The catchments are of varying sizes, with the Theewaterskloof being the smallest and the Kromme the largest. All wetlands have been transformed to some degree, all with some level of channel erosion and invasion of alien trees (especially in tributaries), and the Goukou and Kromme are situated in an agricultural context, receiving runoff from liming and fertilizers (Figure 1). This impact tends to intensify in a downstream direction, with the least impact upstream in the catchment, and the greatest impact (most transformed wetlands) downstream. The Theewaterskloof catchment had agriculture upstream prior to the building of the impoundment that supplies Cape Town. The land upstream of the impoundment is now part of a nature reserve.

Study design

We used two approaches to estimate the water purification ability of South African palmiet wetlands: firstly, a catchment-scale analysis of three wetlands and secondly, a small field survey. To quantify the service of water purification at a catchment scale, we compared the ability of relatively pristine (least disturbed in terms of gully erosion) wetland sections to attenuate pollution with that of wetland sections that had lost their ecological infrastructure through degradation by channel erosion. In the field survey we attempted to follow pollutants through one wetland fragment to see whether they were exported from the wetland or whether the wetland attenuated them at this smaller field scale.

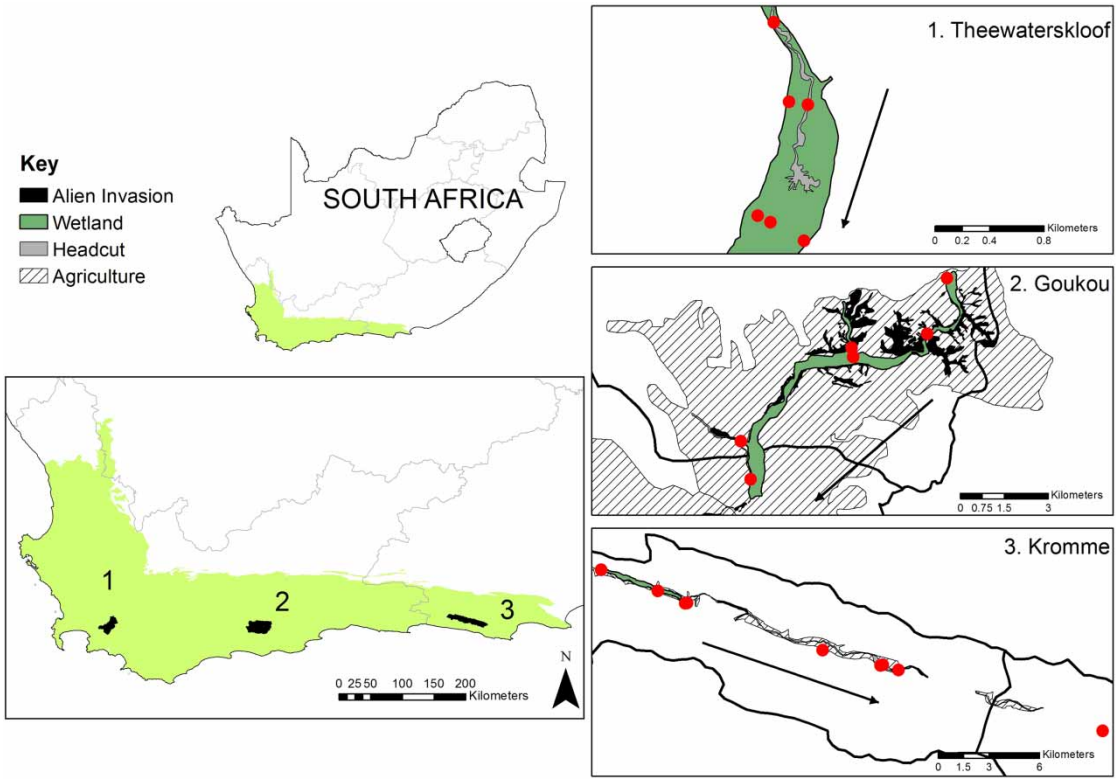

Figure 1 | The three study palmiet wetlands in their respective catchments (back areas labelled 1–3) in the Cape Floristic Region of South Africa (light green). Provinces are indicated with grey lines in the map of South Africa. Catchment boundaries are represented by solid black lines. The three insets may not show the catchment boundary due to the small size of the wetland relative to the catchment. Invasion by alien trees is represented in solid black in the insets, whereas 'headcut' refers to gully erosion. The direction of riverflow within each catchment is indicated by arrows. Water quality sampling points are indicated with red points in each catchment. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2018.389.

Catchment analysis

We collected water samples in September 2014 at 21 points throughout the three study catchments containing valley-bottom palmiet wetlands (Figure 1). These points were opportunistically selected as locations where all the surface water moving through the wetland could be sampled. Therefore, these points were either places where the wetland had become channelized and all the surface water was directed through one main channel or places where multiple small channels were evident and accessible along a cross section of the wetland. Finally, we selected 19 of the 21 points for further analysis. At each water quality sampling point we estimated discharge by measuring channel area (averaging cross-sectional depth and width measurements) and flow velocity of the surface using the float method, as the water level was often too shallow for the use of a flow velocity meter. A correction factor of 0.9 was used to correct surface flow velocity to average flow velocity. Water quality parameters were selected according to their potential link to fertilizer or pesticide application by adjacent agriculture. *In situ*, we measured pH (water), electrical conductivity and temperature using a MultiLine F/Set-3 meter (WTW, Germany). Also in the field, we filtered (0.45 μm) and preserved samples for the analysis of multiple parameters later in the laboratory. The concentration of phosphate (PO_4^{3-}-P), sulphate (SO_4^{2-}-S), nitrate (NO_3^--N), ammonium (NH_4^+-N), total phosphorus (P-tot), total Kjeldahl nitrogen (Kj-N) and chloride (Cl^-) were measured on a continuous-flow analyzer (CFA) (SKALAR: SAN + +). Total dissolved K, Na, Mg, Ca, Fe, Cu, Mn, Zn and Al were acidified with HNO_3 and concentrations thereof (as well as total dissolved Si) were measured on an inductively coupled plasma spectrometer using optical emission spectroscopy (ICP-OES) (Thermo Scientific, type: iCAP6300 Duo). Chemical oxygen demand was measured according ISO15705 using the LCI500 kit and the DR2800 spectrophotometer (ISO 2002).

Field survey

In April 2015 we conducted a more detailed field experiment in the Kromme catchment to examine the effects we

had seen at a catchment scale at a smaller field scale. The study site included a small patch of relatively pristine wetland (approximately 300 m by 70 m of uneroded palmiet wetland vegetation) surrounded by intensive irrigated agriculture applying fertilizers at high rates (Figure 2). A channel entered the wetland patch from a degraded section of the wetland (all alluvium washed away) and then dispersed through the wetland (i.e. there was no more noticeable channel within the wetland as the alluvium and peatbeds were intact). The pristine palmiet wetland fragment ended at a concrete weir which was constructed to protect this remaining wetland from headcut erosion approaching from downstream. Nine water quality samples were taken in the channel entering the wetland (degraded section), another nine samples were taken 30 m apart along a transect through the relatively pristine part of the wetland and eight samples were taken at various points at the outflow (above and below the weir) (Figure 2). In this field survey, the same parameters were used as for the catchment-scale analysis, but in addition dissolved organic carbon was also measured by UV/persulfate oxidation on a CFA (Gershey *et al.* 1979).

Analysis

For the catchment-scale analysis, we used an instantaneous mass balance type sampling approach to estimate changes in water quality over wetland sections (sections of wetland between sampling points) (see Supplement, Figure A1, Figure A2, available with the online version of this paper). Therefore at each sampling point the quantity (mg/s) of each water quality parameter entering the wetland was calculated by multiplying its concentration (mg/l) by the discharge (l/s). This was not done for conductivity and pH. Where there were multiple channels or tributaries, these were taken into consideration in calculations by adding these quantities to that of the water entering the wetland section via the main channel (see Supplement, Figure A2). Each wetland section was classified as either 'degraded' or 'pristine' according to one criterion: the physical condition of the wetland (whether

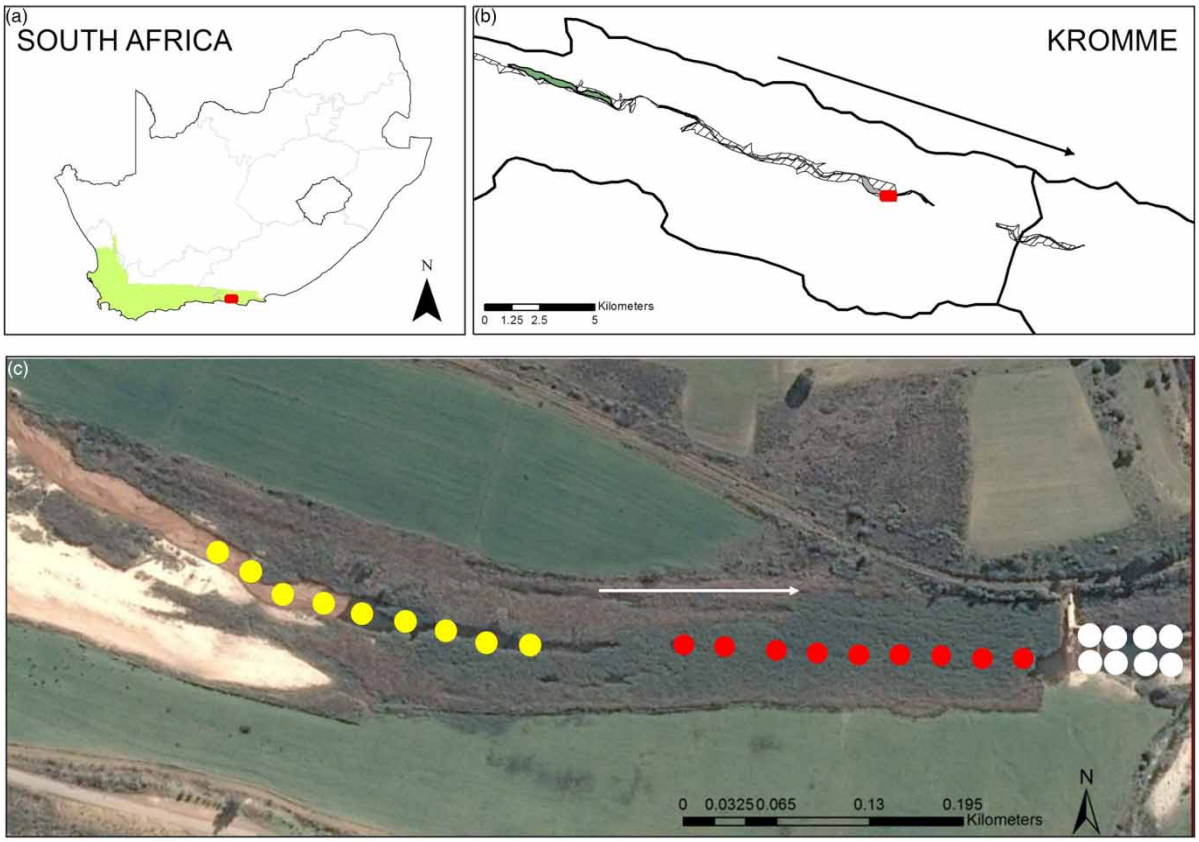

Figure 2 | (a) The map of South Africa indicates the location of the Kromme catchment (red box) within the Cape Floristic Region (green shaded area) – also see Figure 1. (b) The Kromme River inset shows the location of the study transect (red box). (c) The transect used for the field survey in the Kromme catchment. Points indicate water sampling points; yellow indicates degraded and red pristine parts of the wetland; white indicates points at the outflow of the weir. The river flows approximately west to east, as indicated by the arrows. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2018.389.

gully or channel erosion was evident at a large scale, and whether the alluvium had been washed away). The nine wetland sections were therefore classified into six pristine sections and three degraded ones (furthest downstream): one in the Goukou and two in the Kromme (see Supplement, Figure A1). For each of these nine wetland sections, the change in water quality was calculated for each parameter by subtracting the quantity (concentration*discharge) of each parameter leaving the wetland section from the quantity entering it. If that value was positive, it indicated that the parameter was decreasing, or that the wetland section was a net sink for that parameter (either the parameter was being used by internal wetland processes, or it was being deposited). If negative, the parameter was increasing, or the wetland section was a net source for that parameter (exporting that parameter).

To test whether the water purification ability of wetlands differed between degraded and pristine wetland sections, we fitted linear mixed models taking wetland (site) into account. We used the lme4 package in R (Bates *et al.* 2015). Wetland was entered as a random effect to account for the dependence between observations from within the same wetland/catchment. Degradation and the interaction between wetland and degradation were entered as fixed effects. First, the significance of the interaction was tested by comparing the fit of this model to a reduced model with only the main effect. This could not be done for the Theewaterskloof wetland, since we had no degraded sections there. Where the interaction term was significant, we could not test for the effect of degradation. In the case of a non-significant interaction, we excluded it from the model and tested the significance of the main effect: degradation. Significance was tested using an F-test with Kenward-Roger correction for degrees of freedom, as implemented in the 'pbKRtest' package of R.

For the field survey, we correlated each parameter against distance through the wetland fragment to see whether these parameters changed significantly passing through the pristine wetland. All nine samples entering the wetland were averaged, as well as all eight samples downstream of the wetland, yielding a sample size of 11. We used Spearman correlations in R. If the correlation was strongly and significantly negative, the wetland fragment is acting as a sink for the parameter. If the correlation was strongly and significantly positive, the wetland fragment is acting as a source for the parameter.

RESULTS

Catchment analysis

On average, pristine palmiet wetlands tended to act as a sink for water, base cations (total dissolved Ca, K, Mg, Na), anions (total dissolved Cl^- and SO_4^{2-}), dissolved Si, and nutrients (total phosphorus and Kjeldahl nitrogen), though there was

Table 1 | Summary results for change in quantity (concentration g/l * discharge l/s) of water quality parameters (mean ± standard deviation) across degraded and pristine sections of valley-bottom palmiet wetlands

	Degraded	Pristine	Statistics
Discharge (l/s)	−240.0 ± 377.45	401.2 ± 865.92	NS
pH	−1.0 ± 0.89	0.2 ± 0.92	NS
Conductivity (μS/cm)	−410.9 ± 587.24	−65.1 ± 131.28	NT
Ca (g/s)	**−2.5 ± 2.53**	**0.1 ± 0.33**	**F = 5.72, ndf = 1, ddf = 6.36, $p = 0.05$**
K (g/s)	−0.9 ± 0.94	4.3 ± 10.46	F = 5.69, ndf = 1, ddf = 5.00, $p = 0.06$
Mg (g/s)	−3.7 ± 4.00	0.2 ± 0.46	F = 5.52, ndf = 1, ddf = 6.20, $p = 0.06$
Na (g/s)	−28.8 ± 32.07	1.4 ± 3.79	F = 5.55, ndf = 1, ddf = 6.14, $p = 0.06$
Cl (g/s)	−47.7 ± 51.54	5.6 ± 13.45	F = 5.56, ndf = 1, ddf = 6.20, $p = 0.06$
SO_4 (g/s)	−6.1 ± 7.74	2.2 ± 5.37	NT
Si (g/s)	−0.4 ± 1.19	0.7 ± 1.40	NS
Chemical oxygen demand (g/s)	−4.7 ± 6.31	2.7 ± 7.31	NS
Total P (g/s)	0.0 ± 0.08	0.1 ± 0.15	NS
Kjeldahl N (g/s)	−0.2 ± 0.31	0.2 ± 0.50	NS

Values used to calculate means and standard deviations are presented in the Supplement, Table A1 (degraded $n = 3$, pristine $n = 6$). Negative values indicate that wetlands are a net source of a parameter and positive values indicate a net sink. For discharge, pH, conductivity and chemical oxygen demand, negative values indicate an increase and positive values a decrease. Statistics are results from linear mixed models and F tests. Significant parameters are highlighted in bold. NS: not significant; NT: not tested (interaction effects significant); ndf: numerator degrees of freedom; ddf: denominator degrees of freedom. Water quality parameters not presented here can be found in the Supplement, Table A4. (Tables A1 and A4 are available with the online version of this paper.)

relatively high variation in these trends (Table 1, and Supplement, Table A1, available with the online version of this paper). The pH of the water of pristine wetlands ranged from 4.3 to 7.7. Where water from agricultural runoff entered a wetland patch (typically with a higher than natural pH), pH was observed to decrease through the wetland patch in most cases. Similarly, chemical oxygen demand decreased over these pristine wetland sections. Conductivity was the only parameter that increased over the pristine sections of palmiet wetland. Degraded wetland patches behaved differently from pristine ones, though not significantly so. These sections of eroded wetland tended to export water, cations, anions, dissolved silicon, and Kjeldahl nitrogen. Additionally, pH, conductivity and chemical oxygen demand tended to increase over these wetland sections, though there was also large variation in these trends.

Field survey

Results show that at this point in time, the Kromme wetland fragment acted as a sink for dissolved K, dissolved organic carbon and Al (Table 2). pH also decreased significantly (6.96 to 6.12) along the length of the wetland, becoming slightly more acidic (Rho = −0.72, $p < 0.05$). However, it is noteworthy that the gradients of each of these parameters are relatively flat, except for K (m = −0.45). At first glance, this wetland fragment seemed to be a source of the following parameters: Ca, Mg, Na and dissolved Si, as all of them have quite strong correlations (Rho = ±0.69–0.77). However, the gradients are quite flat (m < 0.04), except for Na, which has a gradient of 0.18. Low gradients would suggest little change over the wetland fragment. Conductivity, Cl^-, Fe, SO_4^{2-}, chemical oxygen demand, and nutrients (total phosphorus and Kjeldahl nitrogen) did not change significantly over the 300 m stretch.

DISCUSSION

Overall palmiet wetland systems are oligotrophic, therefore it is noteworthy that the absolute concentrations of each parameter are quite low during low flow periods (see Supplement, Table A2, available with the online version of this paper), and are not of concern in terms of exceeding national water quality regulations for toxicity (DWAF 1996). Across all three catchments, results are similar in that pristine wetlands tended to act as sinks for most parameters during low flow, including water, mostly accompanied by a decrease in pH across the length of the wetland and an increase in conductivity. We can only

Table 2 | Change in water quality parameters over distance downstream in a field survey of the Kromme wetland, South Africa

	Rho	Spearman statistics	Gradient (m)
pH	**−0.72**	S = 491.36, *p*-value = 0.01	**−0.07**
Conductivity (μS/cm)	−0.09	NS	−0.34
Ca (mg/l)	**0.76**	S = 68.09, *p*-value = 0.004	**0.04**
K (mg/l)	**−0.79**	S = 512.19, *p*-value = 0.002	**−0.45**
Mg (mg/l)	**0.76**	S = 69.72, *p*-value = 0.004	**0.00**
Na (mg/l)	**0.69**	S = 89.31, *p*-value = 0.01	**0.18**
Cl (mg/l)	−0.07	NS	−0.13
Fe (mg/l)	0.26	NS	0.01
Zn (mg Zn/l)	**0.67**	S = 95.60, *p*-value = 0.02	**0.00**
Al (mg Al/l)	**−0.75**	S = 500.07, *p*-value = 0.005	**0.00**
Si (mg/l)	**0.77**	S = 64.72, *p*-value = 0.003	**0.03**
SO_4 (mg/l)	0.21	NS	0.05
Chemical oxygen demand (g/s)	−0.36	NS	−0.39
Total P (mg/l)	0.24	NS	0.00
Kjeldahl N (mg/l)	−0.51	NS	−0.01
Dissolved organic carbon (mg/l)	**−0.65**	S = 470.65, *p*-value = 0.02	**−0.08**

Spearman's Rho and statistics indicate significance of the gradient (gradient of the relationship between each parameter and distance), indicating the relevance of the relationship (steeper gradient indicates more change, a gentler gradient indicates less). In this case, negative values indicate that this wetland is acting as a net sink for a parameter (decreasing); positive values indicate a net source (increasing). See the Supplement, Table A3 for absolute values (available with the online version of this paper). Significant parameters are highlighted with bold text. NS: not significant.

speculate as to the mechanisms behind the attenuation of these parameters as these may be a complex combination of internal wetland processes and external inputs from agriculture. In terms of water (discharge) being taken up by the wetland, it may be that the wetland is facilitating percolation into aquifers (Job 2014; de Haan 2016). It may also be a simple effect of transpiration by wetland vegetation, which is known to use relatively large amounts of water (Rebelo 2012). Most likely it is a combination of these factors. Ultimately the partitioning of water between the various stages of the hydrological cycle in these wetlands will have a large impact on that of the various water quality parameters measured in this study.

The results of the instantaneous catchment mass balance analysis show that wetlands in good condition tend to act as a sink for base cations (Ca, Mg, K). The field survey confirms this for K, but in this case the other two cations do not seem to change over the length of the wetland. It appears that these wetlands are acting as a sink for base cations, resulting in an overall decrease in pH along the wetland section. This may possibly be linked to two conflicting mechanisms: first, liming practices from agriculture causing a spike in base cations and carbonates and a concomitant increase in pH in degraded wetland stretches (Beukes *et al.* 2012), and second, an increase in CO_2 in the wetland due to respiration of wetland vegetation and microbes in the soil (Trumbore 2000), or the release of humic acids upon decomposition, causing a decrease in pH further down the wetland (Keller *et al.* 2009). The disappearance of nutrients (total phosphorus, potassium and Kjeldahl nitrogen), other ions, and dissolved silicon may be explained to some extent by plant uptake (Fisher & Acreman 2004), microbial immobilization within the wetlands or adsorption to and retention by the soil (Fisher & Acreman 2004).

Two of the three degraded wetlands are sources of most parameters, which should be indicative of the loss of water purification function of these wetlands (see Supplement, Table A1). This may either be through excessive pollution from agricultural runoff that has saturated the water purification ability of the wetlands, or may be indicative of peat degradation, which results in the release of large quantities of dissolved substances (Laine *et al.* 2013). That degraded wetlands appear to export water (are a net source of water) may possibly be explained by the gully erosion drawing down the water table, resulting in groundwater discharge. However this may also be a function of the hydrogeomorphology of different zones of the system and would need further research to confirm. In the case of the third degraded wetland (Kromme C), which appears to be largely acting as a sink for many parameters, it is known that there is high water abstraction in this region of the catchment (Rebelo 2012). Due to the fact that this is illegal and there are therefore no data, this is not accounted for in the instantaneous mass balance and could explain why these results seem contradictory. This wetland section was also a much larger area, suggesting that this technique works better for smaller areas or scales.

Although there are clear differences between degraded and pristine wetland sections, there are important limitations to this approach that need to be considered. Firstly, we have only one snapshot in time, and therefore have no information on temporal variation in water purification within these wetlands (Jordan *et al.* 2003). Secondly, channel structure is simplified and assumptions are made for discharge calculations, therefore affecting the instantaneous mass balance results. Thirdly, results are highly sensitive to discharge and discharge has relatively high uncertainty. Additionally, a large amount of discharge is in the form of subsurface water flow, which was not measured in this study (de Haan 2016). Fourthly, little is known about abstraction for irrigation, and frequency and amount of fertilizer and lime application at catchment scales. Lastly, the full extent of the water purification ability of a wetland cannot be calculated unless its capacity is exceeded by pollution, at which point its capacity would decline (Mitsch & Gosselink 2000; Fisher & Acreman 2004). Therefore, the attempts to measure water purification of pristine wetlands are likely to be underestimates.

Due to the uncertainty present in a catchment-scale approach, we conducted a field survey to investigate the water purification function of these valley-bottom wetlands in more detail at a smaller field scale. There is a good level of agreement between the findings of the catchment-scale study and the field survey. Similar results show that at the time of sampling, this wetland fragment also seemed to act as a sink for K, Kjeldahl nitrogen and Al. Most significantly, pH also decreased along this stretch of wetland by almost 1 unit over only 300 m. Dissolved organic carbon was not measured in the catchment-scale study, but in this field survey it was found to decrease over the stretch of pristine wetland. Since high concentrations of dissolved organic carbon may be indicative of decomposition (Freeman *et al.* 2004), the fact that this wetland acts as a sink for this parameter would suggest that this wetland is not suffering drainage (Evans *et al.* 2016; although see Kalbitz & Geyer 2002). Contrary to the catchment-scale study, some parameters seemed to be exported from the wetland, most notably Na. It is interesting that this wetland seems to be a

source of Na as this could be occurring as a result of the change in pH. Excess H ions may replace certain base cations on the soil adsorption complex, thereby releasing them.

CONCLUSION

There was a good level of agreement between the results of the catchment-scale study conducted in 2014, and a smaller, field-scale survey done in 2015. From these results, it appears possible to estimate the water purification function of these valley-bottom wetlands, though with some level of uncertainty. This method could be interesting for ecosystem service studies as it quantifies the ecosystem service itself rather than water quality, or impacts on water quality (a dis-service). From this research, these palmiet wetlands appear able to store water or aid percolation into groundwater, as well as act as a sink for pollutants (nutrients and metals) linked to agricultural fertilizer application. However much is still unknown, including detailed information on the water balance, and the role of sediments and their response to various parameters. This is a key area for future research. The temporal variation of palmiet wetlands as sinks for pollutants, as well as the full potential of these wetlands as sinks, was not measured. This would be an interesting area for further research in light of the urgency to protect these wetlands from further degradation.

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