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Title: Spatial and seasonal variability in surface water chemistry in the Okavango Delta, Botswana: a multivariate approach

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**Abstract:** The annual flood pulse in the Okavango Delta (Botswana), has a major influence on water chemistry and habitat. We explore spatial and temporal patterns in a suite of chemical variables, analysed from 98 sample points, across four regions, taken at different stages of the flood cycle. The major pattern in water chemistry is characterised by an increasing gradient in ionic concentration from deep-water sites in the Panhandle to more shallow, distal regions to the south. Concentrations of cations, anions, dissolved organic carbon, and SiO<sub>2</sub> are significantly higher in the seasonally inundated floodplains than in permanently flooded regions. Several variables (including Na and total nitrogen) significantly increase from low flood to high flood, while others (including HCO<sub>3</sub>, SiO<sub>2</sub>, and Cl) increase in concentration, initially between low flood and flood expansion, before declining at maximum flood extent. Redundancy analysis (RDA) revealed that hydrological variables (water depth, flow velocity, flood frequency, and hydroperiod class) significantly explain 17% variation in surface water chemistry. Predictions of increasing flood volume in the near future may result in a decline in alkalinity and dilution of DOC. Our study provides an important baseline from which to monitor future change in the Delta.

Response to Reviewers: I have added a title page to the Supplementary material and saved all the excel worksheets into one PDF file.

I have also turned-off track changes on the revised manuscript and tables. Sorry about that!

Anson

1 **Spatial and seasonal variability in surface water chemistry in the Okavango Delta,**  
2 **Botswana: a multivariate approach**

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22

## 1 **Abstract**

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3 chemistry and habitat. We explore spatial and temporal patterns in a suite of chemical variables,  
4 analysed from 98 sample points, across four regions, taken at different stages of the flood cycle.  
5 The major pattern in water chemistry is characterised by an increasing gradient in ionic  
6 concentration from deep-water sites in the Panhandle to more shallow, distal regions to the south.  
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8 the seasonally inundated floodplains than in permanently flooded regions. Several variables  
9 (including Na and total nitrogen) significantly increase from low flood to high flood, while others  
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11 expansion, before declining at maximum flood extent. Redundancy analysis (RDA) revealed that  
12 hydrological variables (water depth, flow velocity, flood frequency, and hydroperiod class)  
13 significantly explain 17% variation in surface water chemistry. Predictions of increasing flood  
14 volume in the near future may result in a decline in alkalinity and dilution of DOC. Our study  
15 provides an important baseline from which to monitor future change in the Delta.

16 **Keywords: floodplains; multivariate techniques; water chemistry; wetlands**

## 18 **Introduction**

19 Wetlands provide vital ecosystem services for human populations worldwide through the  
20 provision of freshwater, food and biodiversity, and the mitigation of climate change (Millennium  
21 Ecosystem Assessment 2005). Yet these ecosystems are particularly vulnerable to threats from  
22 human impact through increasing economic development and population growth. For example,  
23 over the last 100 years, biodiversity of inland waters has been especially impacted by habitat  
24 change and excessive nutrient loading (Jenkins 2003). Over the next 100 years, climate change is

1 expected to exacerbate these problems, although in some regions, such as southwest Africa,  
2 climate change scenarios are still highly uncertain (Hughes et al. 2010).

3         The Okavango Delta (hereafter referred to as the Delta) in northern Botswana is one of the  
4 largest wetlands in Africa, and one of the few where human impact is minimal. The Delta is a low-  
5 gradient alluvial fan, and occupies the lowest region of the Kalahari Basin. The Delta is fed by  
6 rivers with their source in the highlands of Angola, and both the rivers and the Delta together form  
7 the Okavango River Basin (Fig. 1). The Delta is a flood-pulse ecosystem (Junk et al. 1989),  
8 controlled mainly by an annual pulse of water, turning dry floodplains into productive aquatic  
9 environments (Mendelsohn et al. 2010). Every year, precipitation falling in the highlands of  
10 Angola during October, flow down the Cubango and Cuito rivers, which join to form the  
11 Okavango River at the border between Angola and Namibia. This flood pulse reaches the northern  
12 part of the Delta (in Botswana) in February–May, before slowly expanding out, and reaching the  
13 distal regions by July–August. Maximum flood extent occurs towards the end of the dry season  
14 between July–September, and declines again during the summer, between October–March.

15         The flood pulse is ultimately forced by climate, although as it expands out in the Delta  
16 there is strong spatial variability, due to the Delta's flat topography and vegetation-controlled  
17 channel-floodplain interactions (Wolski and Murray-Hudson 2006a). Currently, technological  
18 modifications of the Delta are few, but threats are real. For example, dam building upstream for  
19 hydroelectricity and agriculture in Angola and Namibia have the potential to alter the volume of  
20 water flowing into the Delta (Mendelsohn et al. 2010). Increasing tourism, on the other hand, may  
21 increase habitat disturbance, while population growth in villages and towns brings with it the  
22 possibility of deteriorating water quality (Masamba and Mazvimavi 2008). There is substantial  
23 seasonal, inter-annual, and decadal variation in size of the flood and the extent of inundated area  
24 (Mazvimavi and Wolski 2006). This variation is mainly due to variation in flow of the Okavango  
25 River ( $9 \times 10^9 \text{m}^3/\text{yr}$ ), but also to local summer rainfall ( $6 \times 10^9 \text{m}^3/\text{yr}$ ) and to a lesser extent the

1 nature of the previous year's flood (McCarthy et al. 2003). Rainfall falls mainly during December,  
2 January, and February and is higher in the north (c. 550 mm/yr) than in the south (450 mm/yr).  
3 Approximately 2% of water leaves the Delta through rivers in the south; the remainder is lost  
4 through evaporation (74%) and transpiration processes (24%) (Mendelsohn et al. 2010).  
5 Hydrology and wetland chemistry are closely linked (Mitsch and Gosselink 2000). However,  
6 while the hydrology of the Delta has been comprehensively studied (see Milzow et al. 2009 for a  
7 review), there have been considerably fewer investigations into how the flood pulse in the Delta  
8 impacts nutrients (Mubyana et al. 2003; Lindholm et al. 2007) and inorganic chemistry (Sawula  
9 and Martins 1991). Previous studies focussed only on very short time periods (Ashton et al. 2003),  
10 or were restricted to the Jao / Boro river system (Sawula and Martins 1991; Cronberg et al.  
11 1996a,b). Here we report on a large, comprehensive, surface water chemistry dataset that covers  
12 four important regions in the Delta, sampled over a complete flood cycle. Given the importance of  
13 the Delta in terms of biodiversity (Ramberg et al. 2006) and ecosystem services (Mendelsohn et  
14 al. 2010) it is important to characterise baseline information on surface water chemistry across  
15 different regions, and at different stages, of the hydrological cycle. This information is  
16 fundamental for the detection and monitoring of future ecosystem change. The first aim of this  
17 study was to characterise variation in surface water chemistry in relation to (i) the different regions  
18 of the Delta, (ii) different stages of the flood cycle over a period of one year, and (iii) between  
19 habitats which were either seasonally or permanently flooded. The second aim was to explore the  
20 influence of four hydrological variables linked to the flood pulse (water depth, flow velocity, flood  
21 frequency and hydroperiod class) on surface water chemistry, using multiple regression  
22 techniques.

## 23 **Methods**

### 24 *Regional descriptions and site selection*

1 Study sites were selected across four regions in the Delta (Fig. 1). The upper Panhandle  
2 (UPH) in the north is a fault-bounded, flat-bottomed valley dominated by fluvial input from the  
3 Okavango River. Downstream from the UPH is the region known as the lower Panhandle (LPH),  
4 where the Okavango River meanders across the floodplain. South of the LPH, the Okavango River  
5 spreads out into channels, which get progressively smaller with distance. The main distributary  
6 (Maunachira / Khwai) is an eastern extension of the Okavango River, with many large, flow-  
7 through lagoons such as Xakanaxa (XAK). Several secondary distributaries branch off from the  
8 Okavango River, including the Jao / Boro (BOR) river system to the west of Chief's Island (Fig.  
9 1). Fifty sites were selected to capture a strong hydrological gradient, and built on previous  
10 aquatic research undertaken in the Delta (Ashton et al. 2003; Dallas and Mosepele 2007).

#### 11 Sample collection and analysis of chemical response variables

12 Ninety-eight sample points were analysed for water chemistry. These consisted of 23  
13 sample points visited only once in the study. The remaining 75 sample points were from 27 sites  
14 visited on more than one occasion, during different stages of the flood-pulse cycle: low flood (28  
15 Nov–10 Dec 2006; n=28); flood expansion (23 Apr–6 May 2007; n=23); high flood (24 Jul–7 Aug  
16 2007; n=26); and flood recession (2 Oct–12 Oct 2007; n=21). Across the regions, 15 sample  
17 points were analysed from UPH, 17 from LPH, 31 from XAK, and 35 from BOR. Sample points  
18 were further characterised by the dominant habitat, including marginal vegetation in channels  
19 (MV-IC), marginal vegetation in lagoons (MV-L), floating vegetation (FV), inundated floodplains  
20 (IF), and isolated, seasonally flooded pools (SP) (after Dallas and Mosepele 2007). The first three  
21 habitat types are permanently wet (WET), while IF and SP experience wet-dry cycles  
22 (WET/DRY). Sample point co-ordinates are given in Online Resource 1(i).

23 pH, conductivity ( $\mu\text{S}/\text{cm}$ ), and dissolved oxygen (DO) ( $\text{mg}/\text{L}$ ) were analysed in situ. pH  
24 and conductivity were measured using a portable *Fisher Scientific accumet AP85* portable  
25 waterproof pH/conductivity meter. A *YSI 550* dissolved oxygen instrument was used to measure

1 DO and water temperature (temp) ( $^{\circ}\text{C}$ ). Field equipment was calibrated before each trip. Total  
2 suspended solids (TSS) were determined by filtering Delta water (at least 1L) and measuring the  
3 residue weight on GF/C filter papers after being dried at  $105^{\circ}\text{C}$  for 24 h (mg/L). 250 ml of water  
4 was filtered through a GF/C filter into acid-washed bottles for non-metal ( $\text{HCO}_3$ , Cl,  $\text{NO}_3$ ,  $\text{SO}_4$ ,  
5 dissolved organic carbon (DOC)) analyses. A second 250 ml of water was also filtered using  
6 cellulose nitrate papers for cation analyses (Na, K, Mg, Ca) and immediately acidified with three  
7 drops of concentrated  $\text{HNO}_3$ . A final 250 ml of water was filtered using cellulose nitrate filter  
8 papers for silica analysis. All filtered samples were stored on ice in acid-washed plastic sample  
9 bottles, then transported to the Okavango Research Institute where they were either analysed  
10 immediately on their return, or frozen until analyses could be carried out.  $\text{HCO}_3$  was determined  
11 within 48 h of sample collection. DOC and anions were analysed within 7 days, while TN and TP  
12 were determined within three weeks of collection. Metals were analysed within 2 months after  
13 collection.

14 Mg (mg/L) and Ca (mg/L) levels were determined by flame atomic absorption  
15 spectrometry using a *Varion Spectra 220* instrument. Lanthanum was used as a releasing agent to  
16 reduce interferences during Ca analysis (Eaton et al. 1995). Na (mg/L) and K (mg/L) were  
17 determined by flame photometry using a *Sherwood Flame Photometer 410* instrument.  $\text{HCO}_3$   
18 (mg/L) was analysed using an auto-titrator (Mettler Toledo model DL 50). Cl (mg/L) and  $\text{SO}_4$   
19 (mg/L) were analysed by ion chromatography using a *DX-120* ion chromatograph (Eaton et al.  
20 1995). An approximation of DOC (mg/L) was obtained by measuring the absorbance of the water  
21 samples at 280 nm using a *Perkin Elmer Lamda 20 UV/Vis* spectrophotometer (Mladenov et al.  
22 2005). Total phosphorus (TP (mg/L)), total nitrogen (TN (mg/L)), and nitrates ( $\text{NO}_3$  (mg/L)) were  
23 analysed by an air segmented flow analyser (*Bran + Luebbe AA3*) after persulphate digestion.  
24  $\text{SiO}_2$  (mg/L) was measured using the heteropoly blue method at 815nm.

25 *Collation of hydrological explanatory variables*

1 Water depth (m) and velocity (m/s) variables were measured in situ at each sample point.

2 Water depth was usually measured using a *Plastimo Echotest II* handheld depth sounder. In

3 locations with dense, submerged vegetation, water depths were instead measured using a

4 graduated metal pole. Water flow velocities were estimated using an *OTT Nautilus C 2000*

5 *Electromagnetic Flow Sensor*, which was designed to measure water currents in the marginal

6 zones of river banks, shallow water, and waters with low flow velocities. Annual flood frequency

7 and hydroperiod class variables were derived from remotely sensed images, hydrometric data, and

8 general understanding of hydrological variability in the system. We used 16 data layers depicting

9 maximum annual inundation extent during years 1989–2006 (excluding 1991 and 2003). The

10 layers were obtained from Landsat (5 and ETM) images, using a classification procedure

11 involving spectral clustering and contextual classification (Wolski and Murray-Hudson 2006a). To

12 depict the Delta, four Landsat scenes had to be mosaicked for each coverage. Inundation layers

13 had spatial resolution of 30 by 30 m, and 97% accuracy of determination of inundation extent

14 (Wolski and Murray-Hudson 2006a). Dates of the imagery were selected to coincide with the

15 period of maximum, annual inundation. The flooding in the Delta takes the form of a single,

16 annual event with progressive transition between low inundation and high inundation taking place

17 throughout a year. Earlier work, with weekly NOAA AVHRR images, revealed that the crest of

18 the flood lasts approximately 1–2 months in distal parts, but 3–4 months in the proximal parts of

19 the Delta proper, and fast recession occurs only in October (Wolski and Murray-Hudson 2006b).

20 Based on these findings, Landsat scenes from end of August to mid-September were selected for

21 high-resolution inundation mapping. Number of years inundation occurred was calculated for the

22 entire Delta on a pixel-by-pixel basis, by stacking up all individual layers. Flood frequency was

23 then obtained by dividing number of years with inundation by the total number of flood maps.

24 Flood frequency for each of the sampling sites was obtained by averaging flood frequency from

25 the nine surrounding pixels, corresponding to the sampling point, using neighbourhood statistics



1 procedure. This was done to reduce possible influence of errors resulting from image  
2 misclassification and misregistration. In the seasonally inundated parts of the Delta, annual  
3 inundation frequency can be considered as a proxy for mean duration of inundation. This results  
4 from the nature of the flood event where parts of the system are likely to be inundated longer only  
5 in high flood years, for a short term only in moderate years, and not inundated at all in low flood  
6 years. However, the relationship between the amplitude of annual water level fluctuations and  
7 flood frequency varies for different parts of the system. Available hydrometric data were not  
8 enough to formalize these relationships in strict mathematical form. Instead, a set of seven  
9 hydroperiod/amplitude classes was defined, and a hydroperiod class was attached to each of the  
10 sample points. The classification was based on flood frequency maps and hydrometric data from  
11 hydrometric stations in the vicinity of sampling points.

## 12 *Statistical Analyses*

13 Prior to all analyses, chemical and hydrological variables were tested for normality on the  
14 basis of frequency histograms, quantile-quantile (Q-Q) plots, and Shapiro-Wilk tests using SPSS  
15 Statistics 17.0. Differences in chemistry and hydrology were determined among (i) sample points  
16 in different regions; (ii) sample points at different stages of the flood cycle; and (iii) permanently  
17 or seasonally inundated sample points. Initially, Levene's tests for equality of variances were  
18 undertaken to ensure that appropriate parametric and non-parametric tests were used. Variables  
19 with equal variance were analysed using either analysis of variance (ANOVA) or 2-tailed t-tests.  
20 Regional and flood cycle differences were further investigated using post-hoc tests with  
21 Bonferroni corrections. Variables with unequal variances were analysed using Kruskal-Wallis  
22 (KW) tests. KW has no equivalent post-hoc test, so where the KW test did reveal significant  
23 differences among regions, and within the flood cycle, pairwise Mann-Whitney U tests were  
24 undertaken to determine significant relationships between pairs of regions and between pairs of  
25 flood cycle stages. Pearson product moment correlations (PPMC; 2-tailed) using SPSS Statistics

1 17.0 revealed substantial inter-correlation among water chemistry variables (47% of variables  
2 were significantly correlated at the  $p=0.05$  level; Online Resource 1(ii)). Main gradients in the  
3 chemistry dataset were therefore explored using principal components analysis (PCA), with  
4 symmetric scaling of the ordination scores, to both summarise our multivariate data, and to  
5 determine any underlying structure. Variables were not log transformed, but were centred and  
6 standardised as they were measured in different units (Lepš and Šmilauer 2003). Like Cronberg et  
7 al. (1996b), we have chosen to include conductivity and alkalinity because not all ionic species  
8 were measured in our study. However, we have chosen to exclude DO and temp variables from  
9 multivariate analyses because they have such a strong diurnal component, which we did not  
10 systematically take account of during our sampling. As measurements for Ca,  $\text{NO}_3$ , and TSS were  
11 incomplete, these variables are also omitted (Table 1). A broken stick model was used to test the  
12 significance of PCA axes (Joliffier 1986) using BSTICK v1.0 (Line and Birks 1996). In order to  
13 assess the influence of the four hydrological, explanatory variables, we used the linear, direct  
14 gradient technique of redundancy analysis (RDA), which constrains ordination axes as linear  
15 combinations of explanatory variables. Initially, the explanatory power and significance of each  
16 hydrological variable was determined through a series of single constrained RDAs, together with  
17 Monte Carlo permutation tests ( $p = 0.002$ ;  $n = 499$ ). The unique contribution of each variable was  
18 then assessed through a series of partial RDAs with the remaining hydrological variables as  
19 covariables. A further, partial RDA determined the influence of flood cycle stage. To assess the  
20 influence of habitat, a similar set of analyses were undertaken, this time grouping permanently wet  
21 habitats (MV-IC+MV-L+FV;  $n=77$ ) and seasonally flooded habitats (IF+SP;  $n=21$ ). A major  
22 feature of spatial datasets such as ours is the influence of site proximity (e.g., Legendre 1993), and  
23 here we partial out sample point co-ordinates using RDA (ter Braak 1987). Ordination analyses  
24 were undertaken using Canoco v. 4.5 (Lepš and Šmilauer 2003).

## 25 **Results**

1           Summary statistical analyses for hydrochemistry data are given in Table 1. Output from all  
2 statistical tests is given in Online Resource 1(iii-v). Unfortunately, data are not available for NO<sub>3</sub>  
3 and TSS during low flood, nor for Ca during flood expansion. In Figure 2, boxplots are shown for  
4 variables that demonstrated significant regional variability. Only conductivity showed significant  
5 differences among all the regions, with values increasing along a north-south gradient. DOC also  
6 shows significant regional variability along a north-south gradient, except between LPH and  
7 XAK. Ca concentrations were only not significant among sites in the Panhandle, and between  
8 UPH and XAK. HCO<sub>3</sub> and SiO<sub>2</sub> show a significant increase between Panhandle and distal regions,  
9 although there is no significant difference between UPH and LPH, nor between XAK and BOR.  
10 The reverse pattern is true for water depth. The pH of surface water is significantly higher at XAK  
11 than at BOR or LPH (Fig. 2). DO was similar across most of the Delta, except in the BOR region,  
12 where values are significantly lower. Na was significantly lower in UPH than in the other three  
13 regions. Cl was significantly lower only between LPH and BOR, and between LPH and XAK.  
14 Velocity, SO<sub>4</sub>, TSS, and nutrients (TP, TN, and NO<sub>3</sub>) did not show any significant regional  
15 differences. In Figure 3, boxplots are shown only for variables that demonstrated significant  
16 variability among different stages of the flood cycle. Only two variables (Na and Mg) differed  
17 significantly among all stages; both had highest concentrations during flood recession, and lowest  
18 concentrations during low flood. Pair-wise comparisons for Ca are limited because of  
19 measurement problems during flood expansion for this variable. However, these data indicate that  
20 Ca concentrations are significantly higher during low flood than during either high flood or flood  
21 recession. All other variables shown, exhibited some form of pair-wise significant variation.  
22 Surface water temperatures were only not different between flood expansion and flood recession,  
23 while pH was significantly different during flood expansion. K and Cl were significantly lower,  
24 and TN significantly higher, during high flood. Peak concentrations of SiO<sub>2</sub> during flood  
25 expansion, were significantly higher than during high flood and flood recession. DO was

1 significantly higher during high flood than during either low flood or flood expansion.  $\text{HCO}_3$  was  
2 significantly higher was during flood recession than either low or high flood, while TP was  
3 significantly higher during flood recession than either low flood or flood expansion. Six variables  
4 exhibited no significant variability with stage of the flood cycle: conductivity, DOC,  $\text{NO}_3$ ,  $\text{SO}_4$ ,  
5 velocity, and water depth (Table 1; Online Resource 1(iv)). In Figure 4, boxplots are shown only  
6 for variables that demonstrated significant variability between either seasonally or permanently  
7 inundated habitats. Many variables exhibited no significant difference between the two habitat  
8 types, including pH, temp, DO, TP, TN, Cl, Ca, and  $\text{SO}_4$ . The remaining variables, however, were  
9 significantly higher in seasonally inundated habitats, including conductivity, DOC, K,  $\text{SiO}_2$ , Mg,  
10  $\text{HCO}_3$ , Na, and  $\text{NO}_3$  (Table 1; Online Resource 1(v)). In contrast, velocity and water depth were  
11 significantly lower in seasonally inundated habitats.

12         PCA axes 1 and 2 capture 30% and 16% of variation in the chemistry dataset, respectively.  
13 Broken stick reveals axis 1 to be significant, and although the eigenvalue of axis 2 is the same as  
14 its broken stick variance, here we exercise caution and treat axis 2 as being not significant (Table  
15 2). Main patterns in our dataset are shown in the form of a PCA biplot (Fig. 5). Axis 1 represents a  
16 significant gradient in surface water chemistry of increasing conductivity,  $\text{HCO}_3$ , K, Mg, DOC,  
17  $\text{SiO}_2$ , TN, and Cl, with highest values in sample points mainly in BOR and XAK. These variables  
18 have lowest concentrations in the Panhandle region of the Delta. PPMC analyses show that most  
19 of these correlations are significant (Online Resource 1(ii)). Axis 2 is associated mainly with TP  
20 and  $\text{SO}_4$  (Fig. 5). RDA reveals that the four hydrological variables (depth, velocity, flood  
21 frequency, and hydroperiod class) significantly account for 17.0% of variation in the chemistry  
22 data (Table 3i), with axis 1 being by far the most important gradient (Fig. 6). The RDA triplot  
23 shows that axis one is dominated by a strong gradient of positively correlated variables, including  
24 conductivity, alkalinity,  $\text{SiO}_2$ , DOC, nutrients, and cations, all of which are negatively correlated  
25 with hydroperiod class and water depth (Fig. 6). Measured chemical variables are generally lowest

1 in concentration in UPH and LPH sample points, associated with greatest water depths and  
2 hydroperiod class. Hydroperiod class and water depth are the most significant variables  
3 influencing water chemistry, even after other hydrological variables, flood extent, and site  
4 proximity are partialled out (Table 4).

## 5 **Discussion**

6         Interpreting the datasets collected is complicated by several factors. Not only are there  
7 regional and habitat influences on water chemistry, but the slow moving flood pulse adds an extra  
8 dimension to the complexity of the system. For example, as the flood expands in northern part of  
9 the Delta, the previous year's flood is still receding in the south. Cronberg et al. (1996b) correlated  
10 solute concentrations with discharge measurements to account for some of this hydrological  
11 variability. Here, we took a multivariate approach, and used four explanatory variables linked to  
12 the flood pulse to model impacts on hydrochemistry across different regions of the Delta.

13 *Do significant differences exist within the surface water chemistry dataset among the different*  
14 *regions of the Delta, among different stages of the flood cycle, and between seasonally or*  
15 *permanently flooded habitats?*

16         Water depth and duration of inundation were found to influence surface water chemistry in  
17 the seasonally inundated floodplains of the Jao/Boro river system (Cronberg et al. 1996a). For that  
18 reason, we have decompiled our datasets, so that average values for each of the chemical  
19 constituents can be determined for each of the four regions during each stage of the flood cycle  
20 (Online Resource 1(vi)). Much of the comparative work, therefore, can only be done with previous  
21 work on the BOR region, although significant differences among regions in this study are also  
22 highlighted.

23         Conductivity of the Okavango River is very low, dominated by silica and bicarbonates of  
24 Ca, Mg, Na, and K (McCarthy and Ellery 1994). These cations are generally very dilute, but show  
25 a significant increase between the Panhandle and distal regions of the Delta (Table 1; Fig. 2). The

1 increase in SiO<sub>2</sub> and cations is due to evapo-transpiration processes (Dinçer et al. 1978) and an  
2 increase in area of seasonally inundated floodplains (Sawula and Martins 1991; Krah et al. 2006).  
3 Yet total concentration of dissolved ions even in the distal regions of the Delta is still very low,  
4 despite evaporation being 2–3 times greater than precipitation (Ramberg and Wolski 2008). This  
5 is because of a unique combination of processes that allows the formation of geochemical islands,  
6 and density-driven sinking of saline waters beneath them, removing solutes permanently from the  
7 surface waters.

8         Concentrations of Mg are highest during flood expansion and recession phases, but decline  
9 during peak flood, which can be attributed to the removal and dissolution of precipitated  
10 magnesium salts (Cronberg et al. 1996a). Na however, is lowest during low flood and increases  
11 steadily throughout the year (Fig. 3). At these concentrations, it is unlikely that Na is co-  
12 precipitating out of solution, and further work needs to be done to understand these trends in  
13 relation to evaporation. Ca concentrations were significantly higher during low flood, similar to  
14 trends reported by Cronberg et al. (1996a). Ca is linked mainly to reactions of the carbonate  
15 system and dissolution of silicate materials (Sawula and Martins 1991), and it is the most  
16 abundant cation throughout the Delta: Ca >K >Na >Mg. When concentrations are converted to  
17 milliequivalents/litre (mequiv/L), the abundance order changes to Ca >Na >Mg >K, identical to the  
18 relative proportions determined by Cronberg et al. (1996b). Similar to both Sawula and Martins  
19 (1991) and Cronberg et al. (1996b), HCO<sub>3</sub> is by far the most dominant anion (over 90%)  
20 throughout the Delta because of circumneutral pH (Wetzel 2001).

21         The Okavango River itself is oligotrophic, and nutrients brought in by surface flow are  
22 quickly taken up by fringing vegetation along the channels in the Upper Panhandle. The seasonal  
23 floodplains link the aquatic habitats in the Delta to terrestrial habitats. Several chemical  
24 constituents were significant higher in seasonally inundated habitats, including conductivity,  
25 DOC, K, SiO<sub>2</sub>, Mg, HCO<sub>3</sub>, Na, and NO<sub>3</sub> (Table 1; Fig. 4). Floodplains contain greater

1 concentrations of chemical constituents because flooding acts to mobilise ions and nutrients from  
2 previously dry soil surfaces into solution (Cronberg et al. 1996b). Nutrients in the floodplains are  
3 derived from a number of sources, including river flow (Cronberg et al. 1996b), in situ from  
4 accumulated sedimentary stores over many thousands of years (Mendelesohn et al. 2010), from  
5 wind-blown dust (Garstang et al. 1998; Krah et al. 2006), and animal faeces (Lindholm et al.  
6 2007). Lindholm et al. (2007) measured highly elevated nutrient concentrations during a period of  
7 low flood extent in a BOR floodplain, which they attributed to low dilution of stored nutrients.  
8 Further work needs to be done, however, to determine if such observations are more widely  
9 applicable, or are particular to that floodplain. Nitrogen and phosphorus are two of the most  
10 important macronutrients in wetlands, dependent on a number of factors, including oxygen  
11 content, redox potential, temperature, pH, and microbiological processes (Mitsch and Gosselink  
12 2000). Our measurements of macronutrients are rather incomplete; nitrate was not measured  
13 during low flood, and there were technical problems with analyses of phosphate, nitrite, and  
14 ammonium, and so those are not presented here. However, TN and TP have been measured in  
15 every region during each stage of the flood cycle, and these still serve as useful macronutrient  
16 indicators. Inorganic  $\text{NO}_3$  concentrations did not vary significantly with seasonal changes in  
17 hydrology (Table 1), perhaps confirming observations by Krah et al. (2006) who also did not  
18 detect any nitrate “boost” as the flood arrived and expanded. Garstang et al. (1998) suggests that  
19 this may be because most of the nitrogen has been taken up by plant growth at the end of the  
20 previous flood period or has undergone denitrification. However, TN concentrations are  
21 significantly higher during the period of high flood, perhaps because the floodwaters contain  
22 slightly higher nitrogen concentrations than wetland soils (Cronberg et al. 1996a). Mean TP  
23 concentrations are low ( $<0.04$  mg/L), similar to levels determined by Krah et al. (2006) for a Boro  
24 floodplain, but lower than values obtained by Lindholm et al. (2007). Statistically, however, TP  
25 shows no significant regional variation (Table 1). TP concentrations do vary significantly with

1 stages of the flood cycle (Table 1, Fig. 3), especially during flood recession, when concentrations  
2 are highest. These findings are in contrast to previous studies, which reported the highest  
3 concentrations of TP occurred during the initial flood stage at the Boro floodplain (e.g., Krah et al.  
4 2006; Lindholm et al. 2007), and as the flood expanded, concentrations declined. Lindholm et al.  
5 (2007) undertook a comparison of two years of nutrient data with different flood sizes, and  
6 concluded that local differences are overwhelmed when flood sizes are large because connectivity  
7 between river channels and floodplains is increased. It may be that our TP data are a reflection of  
8 overall flood size; however, more work needs to be done on the regional and long-term changes of  
9 this important macronutrient. TN/TP ratios are useful in determining whether P and/or N is  
10 limiting growth in freshwater ecosystems, and how susceptible that ecosystem is to developing  
11 algal blooms. For example, high levels of TP might suggest impacted ecosystems through elevated  
12 phosphorus supplies (and will give a smaller ratio, e.g., less than 10), while ratios above 15  
13 suggest potential P-limitation (Abell et al. 2010). The TN/TP ratio for BOR was 20.4, a figure  
14 very similar to that determined by Cronberg et al. (1996b), which suggests potential P limitation in  
15 this region. Ratios for the other regions were lower: 13.6 (UPH), 11.8 (LPH), 15.7 (XAK), and it  
16 is likely that the availability of N and P in these regions is close to that needed for balanced  
17 growth of primary producers, i.e., these nutrients are co-limiting (Abell et al. 2010). Threats of  
18 nutrient enrichment from increasing economic activity (e.g., tourism and aquaculture) pose serious  
19 management issues for these delicately balanced ecosystems.

20         Dissolved organic matter (of which DOC is an important component) is formed mainly on  
21 the seasonal floodplains, with the arrival of the annual flood (Cronberg et al. 1996b), and from the  
22 decomposition of vascular plant material (Mladenov et al. 2007). Few studies have investigated  
23 DOC in the Delta, and again, these are restricted to the Jao/Boro river system and associated  
24 floodplains. Our data show that there is substantial variation in DOC concentrations throughout  
25 the Delta, which are significantly higher in BOR and significantly lower in UPH than elsewhere in



1 the Delta (Fig. 2). Mladenov et al. (2005) found that DOC concentrations declined just before  
2 peak flood, which may be due to a dilution effect from the increased volume of water, together  
3 with decomposition by bacterial degradation and UV light (Mladenov et al. 2007). Our study,  
4 however, shows no significant differences linked to different stages of the flood cycle, although  
5 this may be due to the differences in temporal resolution between our studies.

6 *How do hydrological variables, linked to the flood-pulse, influence variation in surface water*  
7 *chemistry?*

8 Cronberg et al. (1996a) concluded that spatial heterogeneity and seasonal flow was  
9 responsible for most of the variation of water chemistry in the Jao/Boro river system. Here we  
10 provide the first quantitative estimates that seasonal flow and spatial heterogeneity significantly  
11 account for 19% and 17% variation in Delta chemistry, respectively (Table 3). The influence of  
12 biogeochemical processes that take place in seasonally inundated floodplains on surface water  
13 chemistry is very important (e.g., Cronberg et al. 1996a,b; Mladenov et al. 2005; Krahl et al. 2006).  
14 By grouping the sites as seasonally or permanently flooded, we show that this habitat distinction  
15 accounts for 8% significant variation in the chemistry data (Table 3iii). This lower value may be a  
16 reflection of larger flood sizes experienced at the time of the study, diluting nutrients, and other  
17 chemical constituents in the floodplains (Lindholm et al. 2007), and the balance between the  
18 numbers of permanently and seasonally inundated sites visited in the study.

19 The four hydrological variables significantly account for 17% of variation in the chemistry  
20 data (Table 3i). Even after taking into account variation in the flood cycle, depth and hydroperiod  
21 class are still highly important variables (Table 4iii). Water depth is likely to act as a proxy for  
22 inundation (Cronberg et al. 1996a), and chemical constituents in shallow water sample points are  
23 present in higher concentrations than deep-water sample points (Fig. 6). However, even taking  
24 into account whether sites are permanently or seasonally flooded, still leaves depth and  
25 hydroperiod class as significant explanatory variables (Table 4iv). It is to be expected that our

1 dataset will be subject to spatial autocorrelation, especially given the proximity of many sample  
2 points to each other (Fig. 1; Legendre 1993). This can lead to over-estimation of the interactions  
3 between the chemical variables and hydrological predictors. Variation captured by each  
4 hydrological variable taking into account proximity, declines by approximately two-thirds (Table  
5 4v). It is notable, however, that depth and hydroperiod class variables are still highly significant.

6         The size of the flood pulse in the Delta has increased over the last five years, and is likely  
7 to continue to increase into the near future due to a quasi, 80-year, climatic oscillation (Gumbricht  
8 et al. 2004). A key question therefore remains as to how an increase in volume of water in the  
9 flood pulse will influence surface water chemistry. Here we use t-value biplots to further explore  
10 significant relationships between hydroperiod class and water depth with chemical variables.  
11 Variables that fall within the Van Dobben circles in the t-value biplot are significantly correlated  
12 either positively (solid circle) or negatively (dashed circle) with the variable under investigation  
13 (Fig. 7). Hydroperiod class has a significant, positive relationship with pH values in the Delta, but  
14 a significant, negative relationship with conductivity,  $\text{HCO}_3$ , Mg, and DOC. Therefore, an  
15 increasing area of sites with higher hydroperiod class may result in a decline in DOC,  
16 conductivity,  $\text{HCO}_3$ , and certain cations such as Mg, through dissolution of precipitated salts  
17 (Cronberg et al. 1996a). An increase in water depth would not have a positive effect on any of the  
18 variables that we measured, but would result in a significant decline in concentration of many  
19 variables (conductivity,  $\text{HCO}_3$ , DOC, Mg, K, and  $\text{SiO}_2$ ). Water depth likely represents a proxy for  
20 volume of water, and so in shallow water regions, concentrations of solutes are greater. Therefore,  
21 in sites that currently experience flooding, an increase in flood size is likely to result in an overall  
22 dilution of chemical constituents (Cronberg et al. 1996a). Other factors not measured here are also  
23 likely to have a strong influence on water chemistry in the Delta, especially history of the water  
24 prior to sampling, and vegetation composition at any one location. Moreover, an increase in flood  
25 size will also result in new, dryland regions becoming inundated for the first time in many

1 decades, resulting in new, productive floodplains. This is a large and important uncertainty and  
2 requires much more intensive spatial and temporal monitoring in key regions.

### 3 **Conclusions**

4 We provide, for the first time, a quantitative assessment of factors that influence surface water  
5 chemistry in the Okavango Delta. Significant variation in surface water chemistry exists,  
6 especially between the Panhandle and distal regions of the Delta. Seasonal variation linked to  
7 different stages in the flood pulse is also very important, although influence on different chemical  
8 variables appears to be quite individualistic. It is apparent that hydroperiod class and water depth  
9 are important variables in influencing surface water chemistry across the Delta, even when taking  
10 into account influences from other hydrological variables, stage of the flood cycle, habitat, and  
11 proximity of the sites to each other. Our analyses ignore the likely increase in extent of new  
12 floodplains being wetted by expanding floodwaters, a process which is likely to continue into the  
13 near future. However, the work presented here provides an important baseline study for spatial  
14 variability in water chemistry of this internationally important wetland, from which to monitor  
15 future change associated with both natural variability and human impact.

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### 23 **References**

1 Abell JM, Özkundakci D, Hamilton DP (2010) Nitrogen and phosphorus limitation of  
2 phytoplankton growth in New Zealand lakes: implications for eutrophication control. *Ecosystems*  
3 13:966–977

4 Ashton PJ, Masundire H, Hart R, Prince-Nengu J, Botshelo O, Lekhuru M, Mehlo Makulu M,  
5 Tylol I (2003) Water quality of the Okavango Delta, Botswana. In: Alonso LE, Nordin L (Eds) A  
6 rapid biological assessment of the aquatic ecosystems of the Okavango Delta, Botswana: High  
7 water survey. RAP Bulletin of Biological Assessment 27. Conservation International, Washington  
8 DC, pp 38–53

9 Cronberg G, Gieske A, Martins E, Prince Nengu J, Stenström I-M (1996a) Hydrobiological  
10 studies of the Okavango Delta and Kwando/Linyanti/Chobe River, Botswana 1. Surface water  
11 quality analysis. *Botswana Notes and Records* 27:151–226

12 Cronberg G, Gieske A, Martins E, Prince Nengu J, Stenström I-M (1996b) Major ion chemistry,  
13 plankton, and bacterial assemblages of the Jao/Boro River, Okavango Delta, Botswana: the  
14 swamps and floodplains. *Archiv für Hydrobiologie* 107:335–407

15 Dallas H, Mosepele B, (2007) A preliminary survey and analysis of the spatial distribution of  
16 aquatic invertebrates in the Okavango Delta, Botswana. *African Journal of Aquatic Science* 32:1–  
17 11

18 Dinçer T, Hutton LG, Khupe BBJ (1978) Study, using stable isotopes, of flow distribution,  
19 surface-groundwater relations and evapotranspiration in the Okavango Swamp, Botswana. *Isotope*  
20 *Hydrology Proc Symp Neuherberg IAEA*:3–36

21 Eaton AD, Clesceri SL, Greenberg EA (1995) Standard methods for the examination of water and  
22 wastewater. American Public Health Association, Washington DC

23 Garstang M, Ellery WN, McCarthy TS, Scholes MC, Scholes RJ, Swap, RJ, Tyson PD (1998) The  
24 contribution of aerosol- and water-borne nutrients to the functioning of the Okavango Delta  
25 ecosystem, Botswana. *South African Journal of Science* 94:223–229

1 Gumbricht T, Wolski P, Frost P, McCarthy TS (2004) Forecasting the spatial extent of the annual  
2 flood in the Okavango Delta, Botswana. *Journal of Hydrology* 290:178–191

3 Hughes DA, Kingston DG, Todd MC (2010) Uncertainty in water resources availability in the  
4 Okavango River Basin as a result of climate change. *Hydrology and Earth System Sciences*  
5 7:5737–5768

6 Jenkins M (2003) Prospects for biodiversity. *Science* 305:1175–1176

7 Jolliffe IT (1986) *Principal components analysis*. Springer-Verlag, New York, 271 pp

8 Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river–floodplain systems.  
9 *Canadian Journal of Fisheries and Aquatic Sciences* 106:110–127

10 Krah M, McCarthy TS, Huntsman–Mapila P, Wolski P, Annegarn H, Sethebe K (2006) Nutrient  
11 budget in the seasonal wetland of the Okavango Delta, Botswana. *Wetland Ecology and*  
12 *Management* 14:253–267

13 Legendre P (1993) Spatial autocorrelation: trouble or new paradigm? *Ecology* 74:1659–1673

14 Lepš J, Šmilauer P (2003) *Multivariate analysis of ecological data using CANOCO*. CUP,  
15 Cambridge

16 Lindholm M, Hessen DO, Mosepele K, Wolski P (2007) Food webs and energy fluxes on a  
17 seasonal floodplain: the influence of flood size. *Wetlands* 27:775–784

18 Line JM, Birks HJB (1996) *BSTICK* Version 1.0. Unpublished computer program. Botanical  
19 Institute, University of Bergen.

20 Masamba WRL, Mazvimavi D (2008) Impact on water quality of land uses along Thamalakane–  
21 Boteti River: an outlet of the Okavango Delta. *Physics and Chemistry of the Earth* 33:687–694

22 Mazvimavi D, Wolski P (2006) Long-term variations of annual flows of the Okavango and  
23 Zambezi Rivers. *Physics and Chemistry of the Earth* 31:944–951

24 McCarthy TS, Stanistreet IG, Cairncross B (1991) The sedimentary dynamics of the active fluvial  
25 channels on the Okavango fan, Botswana. *Sedimentology* 38:471–487

1 McCarthy TS, Ellery WN (1994) The effect of vegetation on soil and ground water chemistry and  
2 hydrology of islands in the seasonal swamps of the Okavango Fan, Botswana. *Journal of*  
3 *Hydrology* 154:169–193

4 McCarthy JM, Gumbrecht T, McCarthy T, Frost P, Wessels K, Seidel F (2003) Flooding patterns  
5 of the Okavango Wetland in Botswana between 1972 and 2000. *Ambio* 32:453–457

6 Mendelsohn JM, Vanderpost C, Lamberg L, Murray-Hudson M, Wolski P, Mosopele K (2010)  
7 *Okavango Delta: floods of life*. RAISON, Windhoek Namibia

8 Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: wetlands and*  
9 *water synthesis*. World Resources Institute, Washington, D.C.

10 Milzow C, Kgotlhang L, Bauer-Gottwein P, Meier P, Kinzelbach W (2009) Regional review: the  
11 hydrology of the Okavango Delta, Botswana – processes, data and modelling. *Hydrogeology*  
12 *Journal* 17:1297–1328

13 Mitsch WJ, Gosselink JG (2000) *Wetlands*, 3<sup>rd</sup> Edition. John Wiley and Sons, New York

14 Mladenov N, McKnight DM, Wolski P, Ramberg L (2005) Effects of the annual flood on  
15 dissolved organic carbon dynamics in the Okavango Delta Botswana. *Wetlands* 25:622–638

16 Mladenov N, McKnight DM, Macko SA, Norris M, Cory RM, Ramberg L (2007) Chemical  
17 characterization of DOM in channels of a seasonal wetland. *Aquatic Sciences* 69:456–471

18 Mubyana T, Krah M, Totolo O, Bonyongo M (2003) Influence of seasonal flooding on soil total  
19 nitrogen, organic phosphorus and microbial populations in the Okavango Delta, Botswana. *Journal*  
20 *of Arid Environments* 54:359–369

21 Ramberg L, Wolski P (2008) Growing islands and sinking solutes: processes maintaining the  
22 endorheic Okavango Delta as a freshwater system. *Plant Ecology* 196:215–231

23 Ramberg L, Hancock P, Lindholm M, Meyer T, Ringrose S, Sliva J, Van As J, Vanderpost C  
24 (2006) Species diversity in the Okavango Delta, Botswana. *Aquatic Sciences* 68:310–337

1 Sawula G, Martins E (1991) Major ion chemistry of the lower Boro River, Okavango Delta,  
2 Botswana. *Freshwater Biology*, 26:481–493

3 Ter Braak CJF (1987) The analysis of vegetation-environment relationships by canonical  
4 correspondence analysis. *Vegetatio* 69, 69–77

5 Wetzel RG (2001) *Limnology*, 3<sup>rd</sup> edition. Academic Press, San Diego

6 Wolski P, Murray-Hudson M (2006a) Flooding dynamics in a large low–gradient alluvial fan, the  
7 Okavango Delta, from analysis and interpretation of 30-year hydrometric record. *Hydrology and*  
8 *Earth System Sciences* 10:127–137

9 Wolski P, Murray-Hudson M (2006b) Reconstruction of 1989-2005 inundation history in the  
10 Okavango Delta, Botswana from archival Landsat imagery, *Globwetland Symposium*. ESA–  
11 ESRIN, Frascati, Italy, 19–20 October 2006.

12

### 13 **Figure Legends**

14 Figure 1: Map of the Okavango Delta with site locations indicated on aerial photographs from  
15 each of the four study regions

16 Figure 2: Boxplots for hydrochemical variables that show significant regional variation (see text  
17 for details). The central line is the median value, while the bottom and top of the box indicate 25<sup>th</sup>  
18 and 75<sup>th</sup> percentiles. T-bars extend to 1.5 times the height of the box. Outliers are given as points,  
19 whereas extreme outliers (i.e. values that are more than 3x the height of the box) are given as  
20 asterisks.

21 Figure 3: Boxplots for hydrochemical variables, that show significant variation among different  
22 stages of the flood cycle.

23 Figure 4: Boxplots for hydrochemical variables that show significant variation between sites that  
24 are either permanently or seasonally flooded.

1 Figure 5: PCA biplot of surface water chemistry in the Okavango Delta. Sample points have been  
2 coded according to their location in each of one of the four principal regions. Broken stick reveals  
3 that that first axis significantly explained 30% variation.

4 Figure 6: RDA triplot showing sample points (coded according to their location), surface water  
5 chemistry variables, and 4 hydrological explanatory variables (depth, velocity, flood frequency,  
6 and hydroperiod class).

7 Online Resource 1: PDF consisting of a number of worksheets: (i) sample point co-ordinates; (ii)  
8 PPMC analyses of chemistry data; (iii–v) statistical analyses of data showing main results from  
9 Levene's tests for equality, ANOVA, 2-tailed t-tests, Kruskal-Wallis tests, pairwise Mann-Whitney  
10 tests for (iii) regions; (iv) different stages of the flood cycle; (v) between permanently and  
11 seasonally inundated sites; and (vi) decompiled mean data for regions at different stages of the  
12 flood cycle.

13



table

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Table 1: Summary statistical analyses for hydrochemical data measured from 98 sample points. Mean values are also given for (i) each of the 4 regions, (ii) each stage of the flood cycle, and (iii) whether sample points were permanently inundated or not. \* = no significant difference; ND = not determined.

		Min	Max	Mean	SD	UPH	LPH	XAK	BOR	low	expand	high	recede	WET-DRY	WET
Depth	m	0.00	5.00	1.43	0.96	2.09	2.24	0.93	1.17	1.27*	1.35*	1.88*	1.15*	0.77	1.61
Velocity	m/S	0.00	1.56	0.15	0.26	0.25*	0.11*	0.16*	0.10*	0.11*	0.20*	0.14*	0.14*	0.05	0.17
pH	pH units	4.97	7.89	6.64	0.45	6.60	6.52	6.98	6.49	6.82	6.61	6.48	6.66	6.70*	6.62*
Temp	°C	13.60	35.00	23.47	4.65	22.46*	21.83*	23.92*	24.76*	28.12	23.92	17.24	24.87	22.83*	23.65*
DO	mg/L	0.39	10.37	3.49	2.13	4.19	3.70	4.59	2.15	3.10	2.74	4.63	3.37	3.63*	3.45*
Conductivity	µS/cm	19.30	119.10	61.72	23.59	36.27	43.64	70.77	80.14	67.90*	62.12*	52.16*	65.50*	84.91	55.39
TSS	mg/L	0.00	10.00	2.34	2.11	3.26*	2.17*	2.11*	1.06*	ND*	3.37*	3.51*	1.99*	2.38*	2.34*
DOC	mg/L	2.73	23.62	8.03	4.28	4.14	7.56	8.36	10.31	8.06*	9.08*	6.45*	8.92*	9.93	7.51
HCO <sub>3</sub>	mg/L	3.50	168.30	57.30	22.57	38.70	43.92	62.74	67.46	50.36	63.71	50.84	68.37	72.28	53.21
K	mg/L	0.33	6.90	2.28	1.34	0.94	1.37	3.29	2.81	2.64	2.93	1.26	2.42	3.08	2.07
Na	mg/L	0.10	7.19	2.01	1.43	1.03	1.57	2.19	2.41	0.97	1.28	2.36	3.86	2.87	1.78
SiO <sub>2</sub>	mg/L	3.00	32.34	11.35	6.48	8.18	8.93	11.09	14.00	11.42	15.74	9.44	8.76	13.90	10.65
Cl	mg/L	0.11	4.24	0.66	0.61	0.51	0.42	1.38	0.86	0.64	1.12	0.40	0.53	0.71*	0.65*
TP	mg/L	0.00	0.25	0.04	0.03	0.04*	0.05*	0.04*	0.03*	0.03	0.03	0.04	0.06	0.04*	0.04*
TN	mg/L	0.08	1.94	0.62	0.34	0.53*	0.63*	0.56*	0.71*	0.52	0.61	0.77	0.56	0.74*	0.58*
NO <sub>3</sub>	mg/L	0.00	0.71	0.20	0.15	0.16*	0.19*	0.13*	0.27*	ND*	0.21*	0.20*	0.19*	0.17	0.32
SO <sub>4</sub>	mg/L	0.01	2.58	0.35	0.60	0.28*	0.21*	1.01*	0.25*	0.58*	0.38*	0.19*	0.23*	0.55*	0.30*
Mg	mg/L	0.14	2.00	0.92	0.47	0.56	0.70	1.02	1.14	0.44	1.13	0.85	1.43	1.24	0.83
Ca	mg/L	3.20	15.46	7.68	3.37	5.27	5.24	7.23	10.24	10.42	ND	5.67	6.44	8.53*	7.36*

Table 2: Principal components analysis (PCA) of surface water chemistry.

	<b>Axes</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total variance</b>
<b>Eigenvalues (EVs)</b>		0.304	0.155	0.105	0.094	1
<b>Cum. % var.</b>		30.4	46.0	56.5	65.9	
<b>Broken stick variances</b>		0.221	0.155	0.121	0.099	

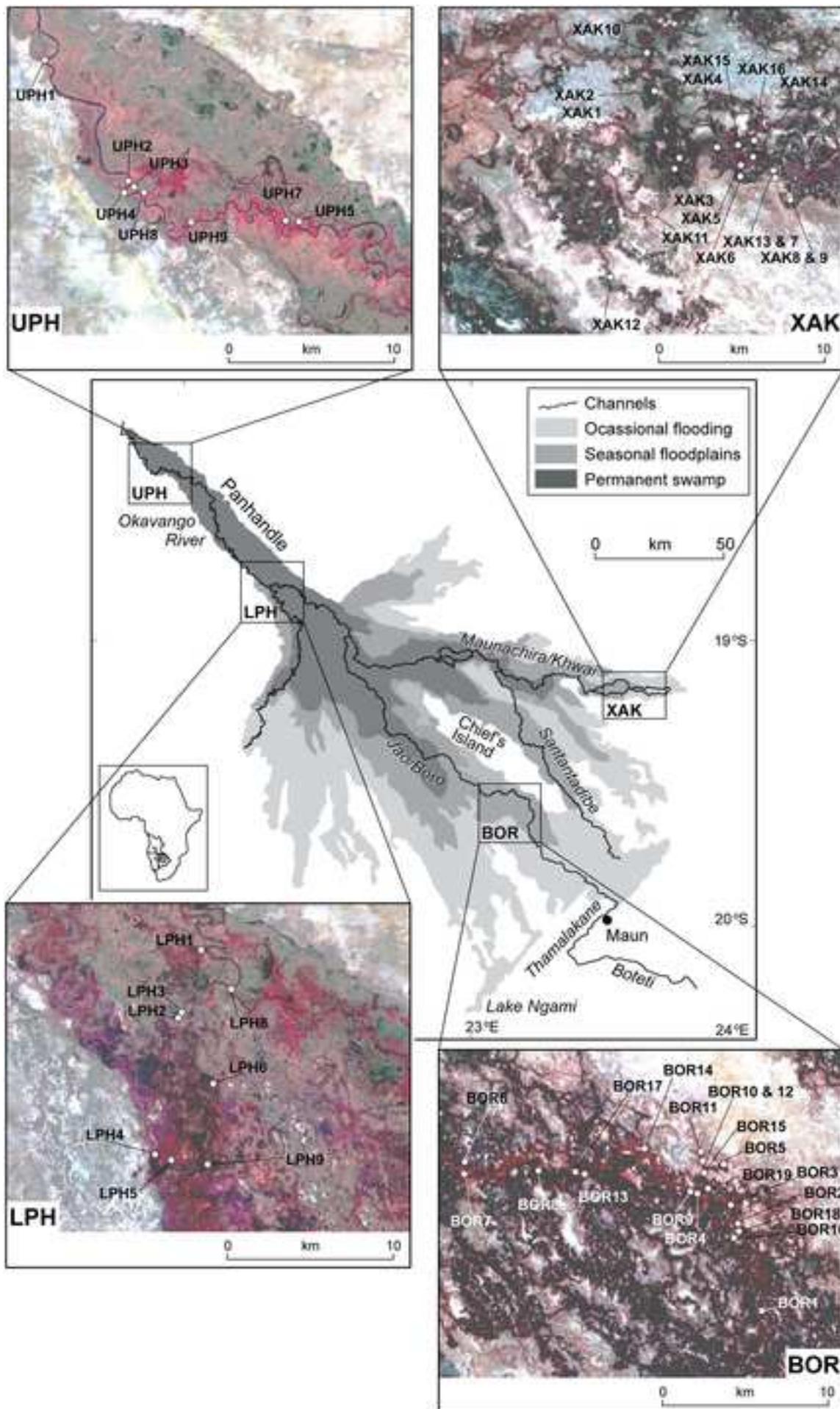
Table 3: Redundancy analysis (RDA) of surface water chemistry with (i) four hydrological variables; (ii) flood extent; (iii) habitat type; (iv) site locations as explanatory variables.

<b>Table 3i: 4 hydrological variables</b>	<b>Axes</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total variance</b>
Eigenvalues:		0.134	0.027	0.007	0.002	1
Cum. % variance of species data:		13.4	16.1	16.8	17.0	
$\Sigma$ <b>canonical EVs; p = 0.002</b>						<b>0.17</b>
<hr/>						
<b>Table 3ii: flood extent</b>	<b>Axes</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total variance</b>
Eigenvalues:		0.110	0.058	0.024	0.265	1
Cum. % var. spp data:		11.0	16.8	19.1	45.9	
$\Sigma$ <b>canonical EVs; p = 0.002</b>						<b>0.19</b>
<hr/>						
<b>Table 3iii: habitat</b>	<b>Axes</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total variance</b>
Eigenvalues:		0.085	0.239	0.155	0.103	1
Cum. % variance of species data:		8.5	32.4	48.0	58.2	
$\Sigma$ <b>canonical EVs; p = 0.002</b>						<b>0.085</b>
<hr/>						
<b>Table 3iv: location co-ordinates</b>	<b>Axes</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Total variance</b>
Eigenvalues:		0.147	0.026	0.180	0.155	1
Cum. % variance of species data:		14.7	17.3	35.3	50.8	
$\Sigma$ <b>canonical EVs; p = 0.002</b>						<b>0.173</b>

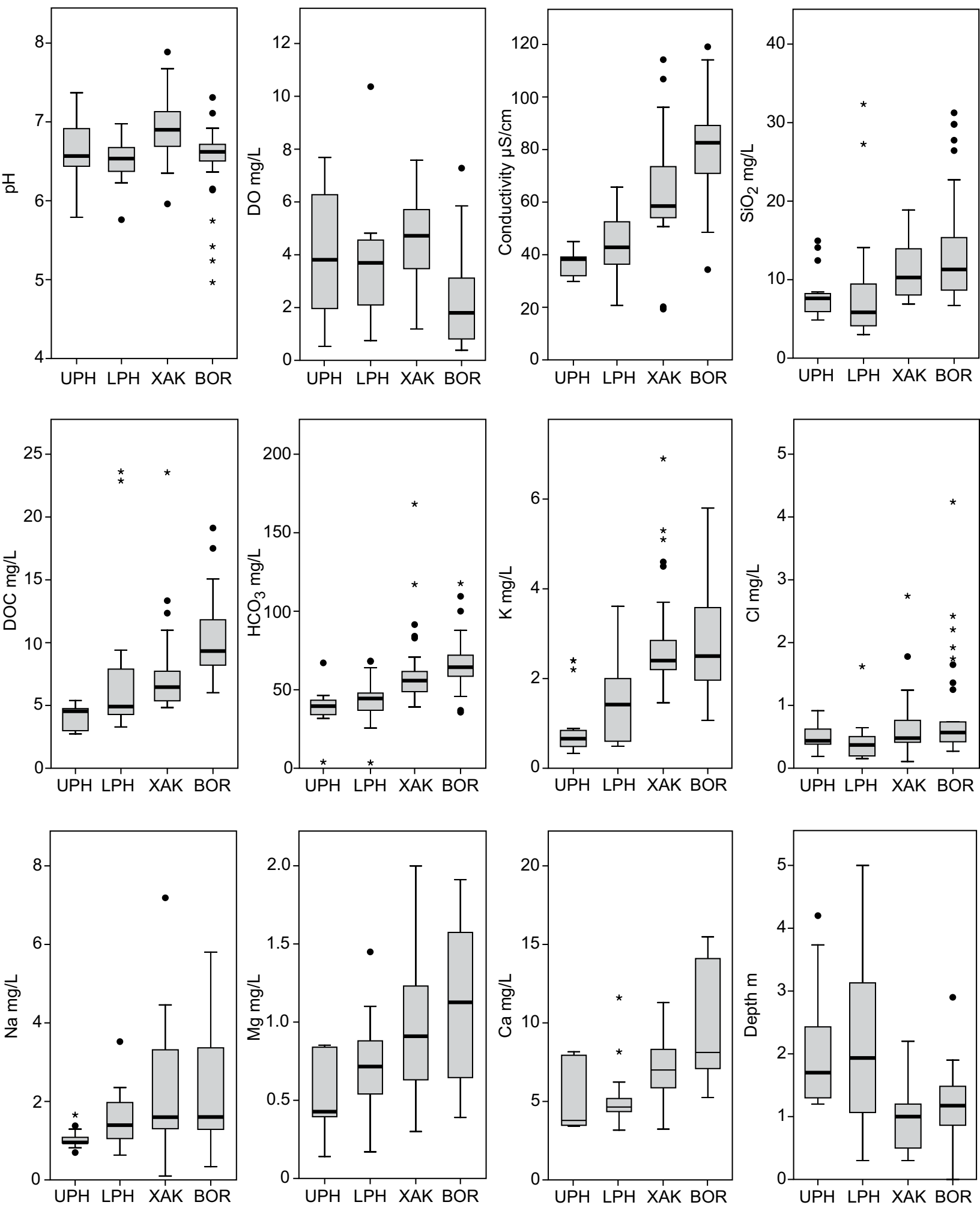
Table 4: (i) % variation explained by each of the four hydrological variables; (ii) unique variation explained by each variable with the remaining three variables as co-variables; (iii) variation explained by hydrological variables with flood extent as co-variables; (iv) variation explained by hydrological variables with habitat as co-variables; (v) variation explained by hydrological variables with locational co-ordinates as co-variables.  $p \leq 0.05$ ;  $n=499$  permutations).

<b>Hydrological Variables</b>	<b>(i)</b>		<b>(ii)</b>		<b>(iii)</b>		<b>(iv)</b>		<b>(v)</b>	
	% var	p	% var	p	% var	p	% var	p	% var	p
Depth	9.6	0.002	5.5	0.002	8.2	0.002	4.6	0.002	3.0	0.006
Velocity	1.7	0.088	1.7	0.056	1.9	0.030	1.1	0.310	1.5	0.072
Flood Frequency	3.6	0.010	2.6	0.012	4.3	0.002	1.1	0.332	2.0	0.036
Hydroperiod Class	7.9	0.002	5.5	0.002	8.8	0.002	3.3	0.002	3.6	0.002

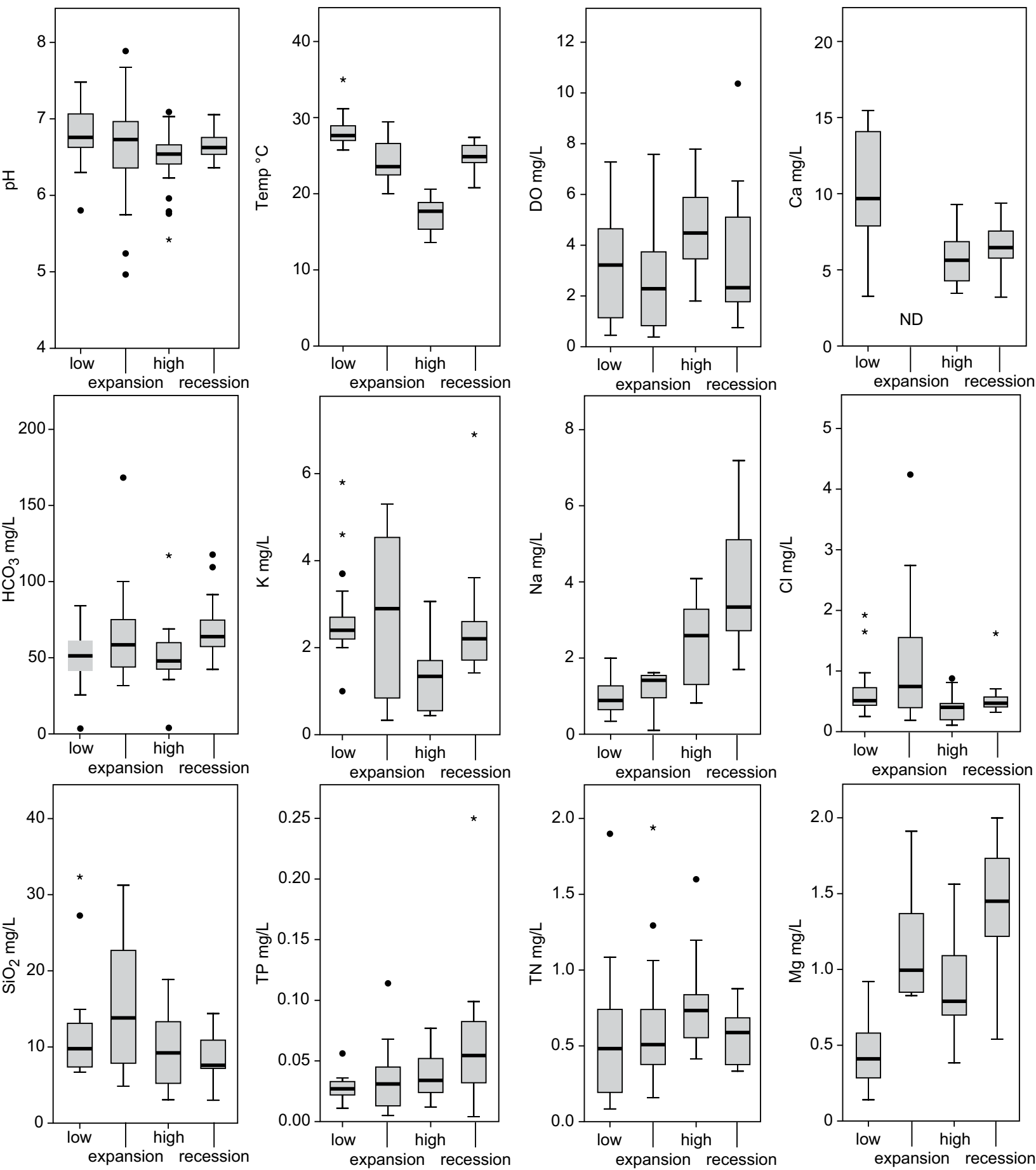
Fig 1  
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**Fig 2**  
[Click here to download line figure: Fig 2 Regions combin cs2.eps](#)



**Fig 3**  
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**Fig 4**  
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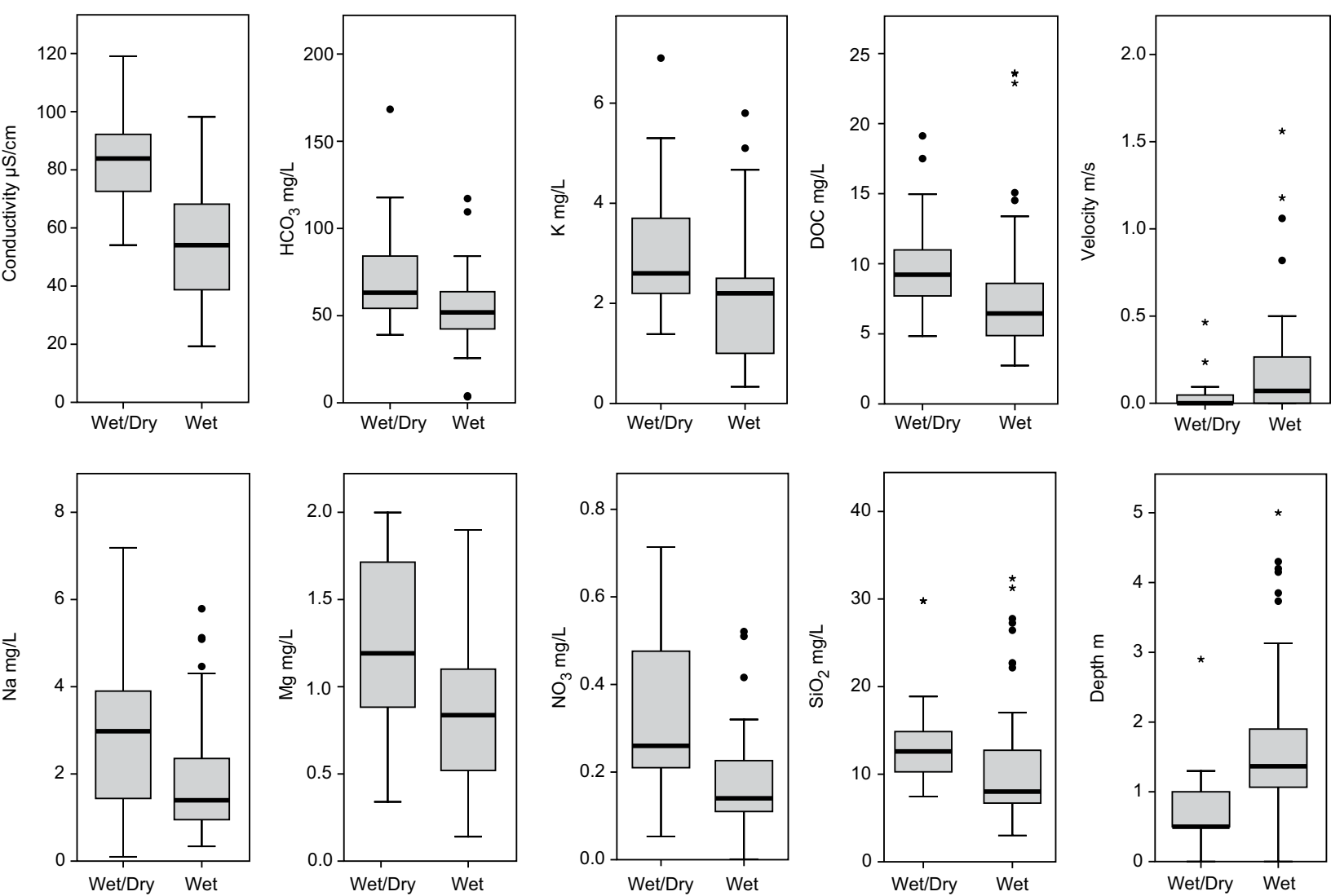




Fig 5  
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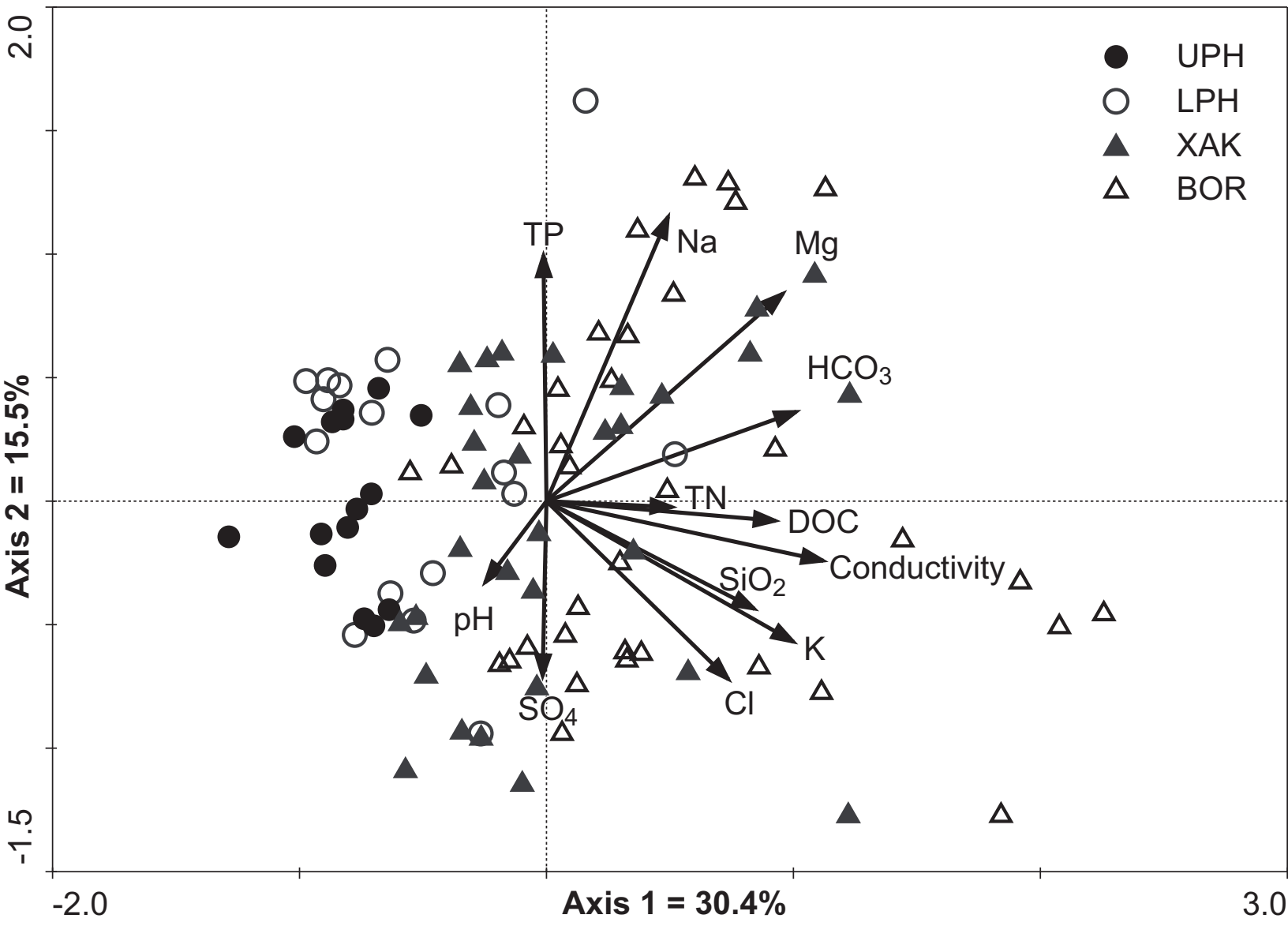
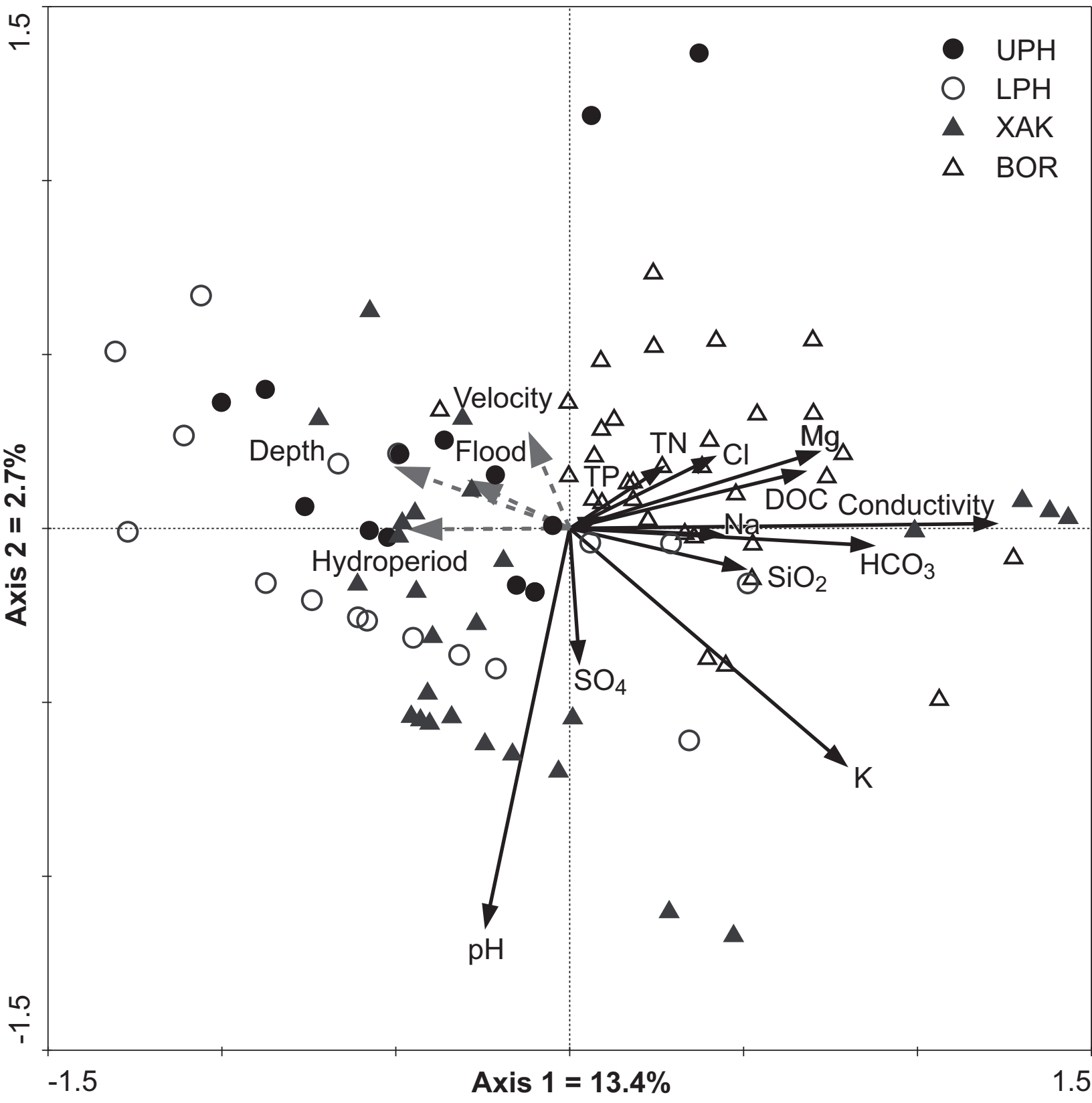
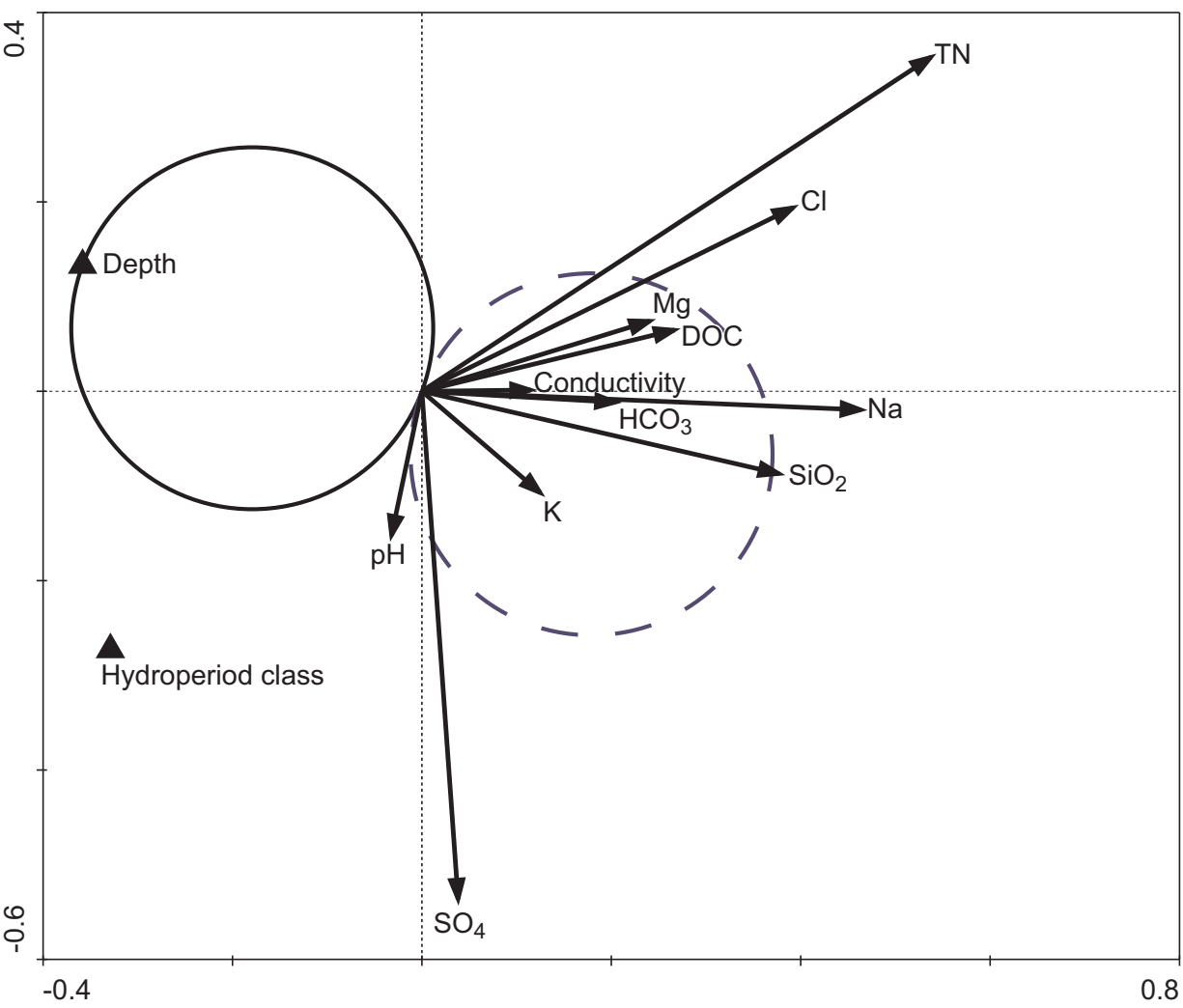
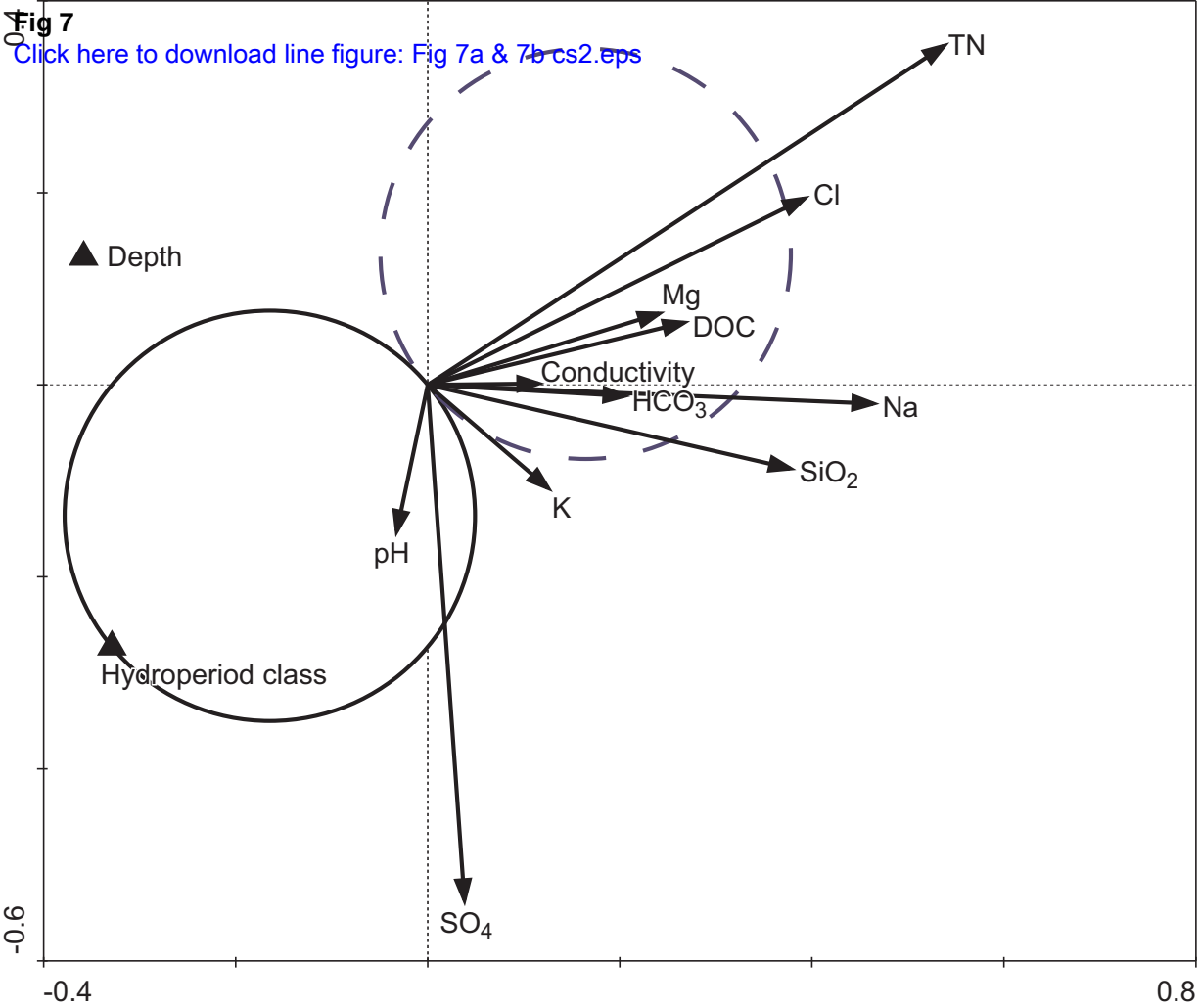


Fig 6  
[Click here to download line figure: Fig 6 cs2.eps](#)





## **Spatial and seasonal variability in surface water chemistry in the Okavango Delta, Botswana: a multivariate approach**

**Journal:** *Wetlands*

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Online Resource 1(i)

ESM-1(i): locational co-ordinates; 2=low flood; 3=flood expansion; 4=high flood; 5=flood recession

Code	lat	long	Code	lat	long	Code	lat	long	Code	lat	long
UPH1-2	18.3391	21.8371	LPH1-2	18.8425	22.4043	XAK1-2	19.1830	23.3974	BOR1-2	19.6116	23.2188
UPH1-3	18.3391	21.8371	LPH2-2	18.8791	22.3912	XAK1-3	19.1831	23.3977	BOR10-2	19.5333	23.1829
UPH1-4	18.3391	21.8371	LPH2-4	18.8791	22.3912	XAK1-5	19.1827	23.3983	BOR10-3	19.5333	23.1829
UPH3-3	18.4097	21.8870	LPH2-5	18.8791	22.3912	XAK10-2	19.1253	23.3791	BOR10-4	19.5334	23.1831
UPH4-4	18.4109	21.8811	LPH3-2	18.8790	22.3911	XAK12-2	19.2401	23.3569	BOR10-5	19.5334	23.1831
UPH4-2	18.4109	21.8811	LPH3-5	18.8790	22.3911	XAK12-3	19.2401	23.3569	BOR11-2	19.5289	23.1825
UPH4-3	18.4109	21.8811	LPH3-4	18.8788	22.3913	XAK12-4	19.2401	23.3569	BOR13-3	19.5385	23.1181
UPH5-2	18.4275	21.9812	LPH4-2	18.9555	22.3763	XAK12-5	19.2401	23.3569	BOR13-5	19.5385	23.1181
UPH5-3	18.4275	21.9812	LPH4-4	18.9555	22.3763	XAK13-3	19.1915	23.4520	BOR14-3	19.5269	23.1506
UPH5-4	18.4275	21.9812	LPH4-5	18.9555	22.3763	XAK13-4	19.1915	23.4520	BOR14-4	19.5271	23.1507
UPH7-3	18.4270	21.9714	LPH5-2	18.9606	22.3826	XAK13-5	19.1915	23.4520	BOR14-5	19.5271	23.1507
UPH7-4	18.4270	21.9714	LPH5-4	18.9606	22.3826	XAK14-3	19.1830	23.4409	BOR15-3	19.5380	23.1841
UPH8-3	18.4118	21.8891	LPH5-5	18.9606	22.3826	XAK15-3	19.1773	23.4380	BOR16-3	19.5759	23.2016
UPH8-4	18.4118	21.8891	LPH6-4	18.9176	22.4095	XAK16-3	19.1726	23.4408	BOR17-4	19.5390	23.1133
UPH9-3	18.4284	21.9194	LPH6-5	18.9176	22.4095	XAK18-4	19.1957	23.4413	BOR17-5	19.5390	23.1133
			LPH8-4	18.8653	22.4198	XAK19-4	19.1870	23.4313	BOR18-4	19.5700	23.2045
			LPH9-4	18.9611	22.4069	XAK19-5	19.1870	23.4313	BOR19-4	19.5465	23.1867
						XAK2-2	19.1460	23.3836	BOR19-5	19.5465	23.1867
						XAK2-5	19.1454	23.3835	BOR2-2	19.5660	23.2032
						XAK3-2	19.1866	23.3966	BOR2-3	19.5660	23.2032
						XAK4-3	19.1753	23.4199	BOR2-4	19.5660	23.2032
						XAK4-5	19.1753	23.4199	BOR2-5	19.5660	23.2032
						XAK5-2	19.1878	23.4337	BOR20-5	19.5454	23.1847
						XAK5-4	19.1878	23.4337	BOR3-2	19.5558	23.2002
						XAK5-5	19.1878	23.4337	BOR4-2	19.5500	23.1794
						XAK6-2	19.1919	23.4321	BOR5-2	19.5344	23.1948
						XAK7-2	19.1889	23.4524	BOR6-2	19.5394	23.0474
						XAK7-3	19.1889	23.4524	BOR7-2	19.5437	23.0478
						XAK7-4	19.1889	23.4524	BOR8-2	19.5397	23.0896
						XAK9-2	19.2019	23.4607	BOR8-3	19.5397	23.0896
						XAK9-4	19.2019	23.4607	BOR8-4	19.5397	23.0896
									BOR9-2	19.5494	23.1775
									BOR9-3	19.5494	23.1775
									BOR9-4	19.5494	23.1775
									BOR9-5	19.5494	23.1775

**Online Resource 1(ii)**

Significant Pearson Product Moment Correlations between measured hydrochemical variables and location co-ordinates.

\* correlation is significant at the 0.05 level (2-tailed); \*\* correlation is significant at the 0.01 level (2-tailed).

	pH	Temp	DO	Conduct	DOC	HCO3	K	Na	SiO2	Cl	Mg	Ca	Depth	Veloc
Temp	0.225*													
DO	0.369**													
Conductivity		0.313**	-0.395**											
DOC		0.209*	-0.361**	0.546**										
HCO3			-0.247*	0.607**	0.445**									
K		0.454**	-0.297**	0.589**	0.411**	0.390**								
Na						0.311**								
SiO2		0.207*	-0.233*	0.378**	0.391**		0.511**							
Cl		0.216*	-0.286**	0.389**	0.294**	0.238*	0.498**		0.372**					
TP								0.222*		-0.229*				
TN	-0.292**			0.229*	0.221*	0.286**			0.241*					
SO4	0.234*	0.206*						-0.200*						
Mg	-0.207*		-0.251*	0.456**	0.290**	0.553**	0.349**	0.687**	0.268**	0.201*				
Ca		0.504**	-0.395**	0.651**			0.549**			0.397**	-0.257*			
Depth		-0.295**		-0.522**	-0.316**	-0.379**	-0.527**	-0.230*	-0.226*		-0.274**			
Veloc														

Online Resource 1(iii)

Test of Homogeneity of Variances for Regions

	Levene Statistic	df1	df2	Sig.
pH	.804	3	94	.495
Temp	4.907	3	94	.000
DO	1.620	3	94	.196
Conductivity	4.511	3	94	.005
DOC	2.658	3	94	.015
NO3	1.167	3	94	.326
K	1.503	3	94	.219
Na	14.136	3	94	.000
SiO2	5.926	3	94	.001
Cl	4.238	3	94	.007
TP	1.267	3	94	.290
TN	2.096	3	94	.106
NO3	4.894	3	57	.004
TSS	6.329	3	83	.001
NO4	21.348	3	94	.000
Mg	2.234	3	94	.089
Ca	18.685	3	71	.000
Depth	13.611	3	94	.000
Velocity	5.749	3	94	.001

ANOVA of variables with equal variances

	Sum of Squares	df	Mean Square	F	Sig.
<b>pH</b>	3.172	3	1.057	5.942	.001
<b>DO</b>	185.939	3	61.979	9.299	.000
<b>HC O3</b>	12577.621	3	4192.540	18.699	.000
<b>K</b>	68.424	3	22.811	16.712	.000
<b>TP</b>	0.005	3	.002	1.611	.192
<b>TN</b>	0.522	3	.174	1.499	.220
<b>Mg</b>	4.477	3	1.492	8.171	.000

Post Hoc Tests

Multiple Comparisons with

Dependent Variable	() REGION	() REGION	Mean Diff (i-j)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
pH	BOR	LPH	-0.029	0.123	1.000	-0.363	0.307
		UPH	-0.109	0.130	1.000	-0.460	0.242
		XAK	-0.411	0.108	0.001	-0.691	-0.131
	LPH	BOR	0.029	0.123	1.000	-0.307	0.363
		UPH	-0.079	0.149	1.000	-0.482	0.323
		XAK	-0.382	0.127	0.021	-0.725	-0.038
	UPH	BOR	0.109	0.130	1.000	-0.242	0.460
		LPH	0.079	0.149	1.000	-0.323	0.482
		XAK	-0.382	0.123	0.150	-0.660	0.055
	XAK	BOR	0.411	0.104	0.001	0.131	0.691
		LPH	0.382	0.127	0.021	0.039	0.725
		UPH	0.382	0.123	0.150	-0.055	0.660
DO	BOR	LPH	-1.553	0.556	0.038	-3.053	-0.054
		UPH	-2.043	0.581	0.004	-3.608	-0.477
		XAK	-2.401	0.660	0.000	-3.652	-1.158
	LPH	BOR	1.553	0.556	0.038	0.054	3.053
		UPH	-0.489	0.667	1.000	-2.286	1.308
		XAK	-0.848	0.568	0.833	-2.379	0.683
	UPH	BOR	2.043	0.581	0.004	0.477	3.608
		LPH	0.489	0.667	1.000	-1.308	2.286
		XAK	-0.359	0.592	1.000	-1.954	1.237
	XAK	BOR	2.401	0.660	0.000	1.150	3.652
		LPH	0.848	0.568	0.833	-0.683	2.379
		UPH	0.359	0.592	1.000	-1.237	1.954
HC O3	BOR	LPH	23.537	4.852	0.001	7.765	39.309
		UPH	28.761	6.109	0.000	12.296	45.226
		XAK	3.300	4.882	1.000	-7.858	18.459
	LPH	BOR	-23.537	4.852	0.001	-39.309	-7.765
		UPH	5.224	7.012	1.000	-13.675	24.124
		XAK	-18.226	5.974	0.018	-34.338	-2.135
	UPH	BOR	28.761	6.109	0.000	12.296	45.226
		LPH	-5.224	7.012	1.000	-24.124	13.675
		XAK	-23.461	6.226	0.002	-30.241	-6.880
	XAK	BOR	-3.300	4.882	1.000	-18.459	7.858
		LPH	18.226	5.974	0.018	2.135	34.338
		UPH	23.461	6.226	0.002	6.680	40.241
Mg	BOR	LPH	0.459	0.126	0.065	-0.099	0.780
		UPH	0.579	0.132	0.000	0.224	0.935
		XAK	-0.189	0.105	0.456	-0.095	0.473
	LPH	BOR	-0.459	0.126	0.065	-0.780	-0.099
		UPH	0.140	0.151	1.000	-0.268	0.548
		XAK	-0.250	0.129	0.332	-0.598	0.097
	UPH	BOR	-0.579	0.132	0.000	-0.935	-0.224
		LPH	-0.140	0.151	1.000	-0.548	0.268
		XAK	-0.390	0.133	0.028	-0.753	-0.028
	XAK	BOR	-0.189	0.105	0.456	-0.473	0.095
		LPH	0.250	0.129	0.332	-0.097	0.598
		UPH	0.390	0.134	0.028	0.028	0.753

Kruskal Wallis Test

Chi-Square	Temp	Conduct	DOC	Na	SiO2	Cl	NO3	TSS	SiO4	Ca	Depth	Veloc
3	5.497	53.604	49.075	13.917	19.346	10.026	7.694	.604	5.012	29.798	25.834	967
df	3	3	3	3	3	3	3	3	3	3	3	3
Asymp. Sig.	.139	.000	.000	.002	.000	.018	.055	.895	.171	.000	.000	.809

BOR / XAK	Conduct	DOC	Na	SiO2	Cl	Ca	Depth
Mann-Whitney U	268	203	527	496	486	166	412
Sig. (2-tailed)	.000	.000	.842	.550	.064	.005	.092

BOR / LPH	Conduct	DOC	Na	SiO2	Cl	Ca	Depth
Mann-Whitney U	27	112	231	130	141	32	167
Sig. (2-tailed)	.000	.000	.195	.001	.002	.000	.011

BOR / UPH	Conduct	DOC	Na	SiO2	Cl	Ca	Depth
Mann-Whitney U	9	0	131	122	192	58	94
Sig. (2-tailed)	.000	.000	.000	.002	.136	.000	.000

LPH / XAK	Conduct	DOC	Na	SiO2	Cl	Ca	Depth
Mann-Whitney U	99	184	193	121	161	61	118
Sig. (2-tailed)	.000	.087	.129	.002	.027	.000	.002

LPH / UPH	Conduct	DOC	Na	SiO2	Cl	Ca	Depth
Mann-Whitney U	72	71	39	89	90	53	27
Sig. (2-tailed)	.036	.031	.010	.141	.157	.336	.985

UPH / XAK	Conduct	DOC	Na	SiO2	Cl	Ca	Depth
Mann-Whitney U	45	14	80	110	190	53	44
Sig. (2-tailed)	.000	.000	.000	.004	.316	.076	.000

Online Resource 16(v)

	Levene Statistic	df	Sig.
pH	6.153	94	.001
Temp	2.216	94	.091
DO	1.284	94	.284
Conduct	6.403	94	.001
DOC	1.688	94	.175
HCO3	1.699	94	.173
K	9.524	94	.000
Na	25.342	94	.000
SO2	9.980	94	.000
Cl	15.966	94	.000
TP	7.116	94	.000
TN	2.745	94	.047
NO3	0.103	58	.902
TSS	2.733	59	.073
SO4	9.277	94	.000
Me	2.643	94	.054
Ca	26.486	71	.000
Depth	5.174	94	.002
Veloc	1.012	94	.391
Flood	0.701	94	.553
Hydroperiod	0.473	94	.702

	Sum of Squares	df	Mean Square	F	Sig.
Temp	1697.474	3	565.825	133.778	.000
DO	59.926	3	17.666	4.288	.003
DOC	108.391	3	36.130	7.041	.011
Conductivity	3824.507	3	1274.836	2300	.024
HCO3	5870.123	3	1956.707	4224	.000
TSS	18.113	2	8.058	1.904	0.153
NO3	.002	2	.001	.050	.951
Me	12.829	3	4.280	85.687	.000
Veloc	.112	3	.038	.573	.634

Dependent Variable	(I) flood extent	(J) flood extent	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	Upper Bound	
Temp	low	expand	4.196	0.579	0.000	2.636	5.756	
		high	10.881	0.555	0.000	9.386	12.376	
	expand	low	-4.196	0.579	0.000	-5.756	-2.636	
		high	6.685	0.584	0.000	5.112	8.258	
	high	low	-10.881	0.555	0.000	-12.376	-9.386	
		expand	-6.685	0.584	0.000	-8.258	-5.112	
	recede	low	-3.250	0.602	0.000	-4.873	-1.627	
		expand	0.945	0.629	0.816	-0.749	2.640	
	DO	low	expand	7.630	0.607	0.000	5.995	9.266
			high	0.360	0.570	1.000	-1.177	1.897
		expand	low	-1.536	0.547	0.036	-3.009	-0.063
			high	-0.270	0.593	1.000	-1.869	1.329
high		low	-0.360	0.570	1.000	-1.897	1.177	
		expand	-1.896	0.575	0.008	-3.446	-0.346	
recede		low	-0.631	0.620	1.000	-2.301	1.038	
		expand	1.536	0.547	0.036	0.063	3.009	
recede		low	1.896	0.575	0.008	0.346	3.446	
		expand	1.246	0.598	0.222	-0.346	2.877	
HCO3		low	expand	0.270	0.593	1.000	-1.329	1.869
			high	0.631	0.620	1.000	-1.039	2.301
	expand	low	-1.246	0.598	0.222	-2.877	0.346	
		high	-13.345	6.056	0.180	-29.668	2.976	
	high	expand	-0.475	5.805	1.000	-16.121	15.170	
		recede	-18.007	6.301	0.032	-34.990	-1.025	
	recede	low	13.345	6.056	0.180	-2.979	29.668	
		high	12.869	6.107	0.226	-3.590	29.329	
	expand	low	-4.663	6.580	1.000	-22.398	13.072	
		high	0.475	5.805	1.000	-15.170	16.231	
	recede	low	-12.869	6.107	0.226	-29.329	3.590	
		expand	-17.532	6.349	0.042	-34.645	-0.419	
Me	low	expand	18.007	6.301	0.032	34.990	1.025	
		high	4.663	6.580	1.000	-13.072	23.398	
	expand	low	-17.532	6.349	0.042	-34.645	-0.419	
		high	-0.688	0.094	0.000	-0.921	-0.456	
	recede	low	-0.409	0.083	0.000	-0.631	-0.186	
		expand	-0.993	0.090	0.000	-1.234	-0.751	
	expand	low	0.688	0.084	0.000	0.456	0.921	
		high	0.279	0.087	0.011	0.045	0.514	
	recede	low	0.304	0.094	0.010	-0.556	-0.052	
		expand	0.409	0.083	0.000	0.186	0.631	
	high	expand	-0.279	0.087	0.011	-0.514	-0.045	
		recede	-0.584	0.090	0.000	-0.827	-0.340	
recede	low	0.993	0.090	0.000	0.751	1.234		
	expand	0.304	0.094	0.010	0.052	0.556		
high	expand	0.584	0.090	0.000	0.340	0.827		

	pH	K	Na	SO2	Cl	TP	TN	TSS	SO4	Ca
Chi-Square	11.402	28.196	54.992	10.261	15.219	10.719	12.476	59.633	4.387	26.092
df	3	3	3	3	3	3	3	3	3	2
Sig. (2-tailed)	.010	.000	.000	.016	.002	.013	.006	.000	.223	.000

	pH	K	Na	SO2	Cl	TP	TN	TSS	SO4	Ca
<b>low/expand</b>										
Mann-Whitney U	258	269	160	230	258	313	277	0		
Sig. (2-tailed)	.208	.284	.003	.104	.226	.864	.394	.000		
<b>low/high</b>										
Mann-Whitney U	254	103	303	191	266	202	0	103		
Sig. (2-tailed)	.208	.000	.000	.002	.058	.003	.000	.000		
<b>low/recede</b>										
Mann-Whitney U	177	211	3	308	224	137	227	0	103	
Sig. (2-tailed)	.031	.148	.000	.132	.003	.263	.000	.000	.000	
<b>expand/high</b>										
Mann-Whitney U	260	143	162	175	150	239	182	245		
Sig. (2-tailed)	.326	.001	.004	.008	.002	.161	.012	.199		
<b>expand/recede</b>										
Mann-Whitney U	229	176	0	119	160	144	224	117		
Sig. (2-tailed)	.971	.184	.000	.007	.088	.035	.884	.465		
<b>high/recede</b>										
Mann-Whitney U	200	87	122	259	173	188	145	86	199	
Sig. (2-tailed)	.129	.000	.001	.813	.037	.078	.007	.021	.127	



Online Resource 1(iv)

	Levene Statistic	df	Sig.
pH	6.155	94	.001
Temp	2.219	94	.091
DO	1.284	94	.264
Conduct	6.403	94	.001
DOC	1.688	94	.175
HCO3	1.699	94	.173
K	9.524	94	.000
Na	25.342	94	.000
SiO2	9.980	94	.000
Cl	15.966	94	.000
TP	7.116	94	.000
TN	2.745	94	.047
NO3	0.103	58	.902
TSS	2.733	59	.073
SO4	9.277	94	.000
Me	2.643	94	.054
Ca	26.486	71	.000
Depth	5.174	94	.002
Veloc	1.012	94	.391
Flood	0.703	94	.551
Hydroperiod	0.473	94	.703

	Sum of Squares	df	Mean Square	F	Sig.
Temp	1697.574	3	565.858	133.778	.000
DO	52.919	3	17.640	4.298	.007
DOC	108.931	3	36.310	9.041	.113
Conductivity	3824.507	3	1274.836	3390	.074
HCO3	8870.121	3	2956.707	4224	.000
TSS	16.117	2	8.058	1.990	0.155
NO3	.002	2	.001	.050	.951
Me	12.839	3	4.280	45.687	.000
Veloc	.142	3	.038	.921	.834

Dependent Variable	Hydroperiod	Temp	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Bound		
Temp	low	expand	-4.196	0.579	0.000	-5.350	-2.621	
		high	10.881	0.555	0.000	9.386	12.376	
	expand	recede	-3.750	0.602	0.000	-4.927	-2.573	
		high	-4.196	0.579	0.000	-5.756	-2.636	
	high	recede	-6.685	0.584	0.000	-7.849	-5.521	
		low	-10.943	0.629	0.000	-12.176	-9.386	
	DO	low	expand	-6.685	0.584	0.000	-7.849	-5.521
			recede	-7.630	0.607	0.000	-8.827	-6.433
		expand	high	-3.250	0.602	0.000	-4.453	-2.047
			low	0.945	0.629	0.814	-0.749	2.640
		high	expand	7.630	0.607	0.000	5.995	9.266
			recede	0.360	0.570	1.000	-1.177	1.897
DO	low	expand	-1.536	0.547	0.036	-3.009	-0.063	
		recede	-0.270	0.591	1.000	-1.869	1.329	
	expand	high	-0.360	0.570	1.000	-1.897	1.177	
		low	1.396	0.575	0.008	0.346	2.446	
	high	expand	-0.631	0.620	1.000	-2.301	1.039	
		recede	1.536	0.547	0.036	0.063	3.009	
	HCO3	low	expand	1.396	0.575	0.008	0.346	2.446
			recede	1.265	0.598	0.222	-0.346	2.877
		expand	high	0.270	0.593	1.000	-1.329	1.869
			low	0.631	0.620	1.000	-1.039	2.301
		high	expand	-1.265	0.598	0.222	-2.877	0.346
			recede	-13.345	6.056	0.180	-29.668	2.979
Me	low	expand	-0.475	5.805	1.000	-16.121	15.170	
		recede	-18.007	6.301	0.032	-34.990	-1.023	
	expand	high	13.345	6.056	0.180	-2.979	29.668	
		low	12.869	6.107	0.226	-3.590	29.329	
	high	expand	-4.663	6.580	1.000	-22.398	13.072	
		recede	0.475	5.805	1.000	-15.170	16.121	
	Ca	low	expand	-12.869	6.107	0.226	-29.329	3.590
			recede	-17.532	6.309	0.042	-34.665	-0.419
		expand	high	18.007	6.301	0.032	1.023	34.990
			low	4.663	6.580	1.000	-13.072	22.398
		high	expand	17.532	6.309	0.042	0.419	34.665
			recede	-0.688	0.086	0.000	-0.921	-0.455
Mg	low	expand	-0.409	0.083	0.000	-0.631	-0.186	
		recede	-0.993	0.090	0.000	-1.234	-0.751	
	expand	high	0.688	0.086	0.000	0.456	0.921	
		low	0.279	0.087	0.011	0.045	0.514	
	high	expand	-0.301	0.094	0.010	-0.556	-0.052	
		recede	0.409	0.083	0.000	0.186	0.631	
	TN	low	expand	-0.279	0.087	0.011	-0.514	-0.045
			recede	-0.584	0.090	0.000	-0.827	-0.340
		expand	high	0.993	0.090	0.000	0.751	1.234
			low	0.304	0.094	0.010	0.052	0.556
		high	expand	0.584	0.090	0.000	0.340	0.827
			recede					

	pH	K	Na	SiO2	Cl	TP	TN	TSS	SO4	Ca
Chi-Square	11.403	28.196	34.992	10.261	15.219	10.719	12.479	59.638	4.387	28.092
df	3	3	3	3	3	3	3	3	3	3
Sig. (2-tailed)	.010	.000	.000	.016	.002	.013	.006	.000	.221	.000

low/expand	pH	K	Na	SiO2	Cl	TP	TN	TSS	Ca
Mann-Whitney U	256	266	166	256	258	313	277	0	0
Sig. (2-tailed)	.208	.264	.003	.104	.226	.864	.394	.000	.000
low/high	pH	K	Na	SiO2	Cl	TP	TN	TSS	Ca
Mann-Whitney U	256	77	101	303	191	266	202	0	102
Sig. (2-tailed)	.208	.000	.000	.207	.007	.058	.013	.000	.000
low/recede	pH	K	Na	SiO2	Cl	TP	TN	TSS	Ca
Mann-Whitney U	177	211	5	208	224	157	227	0	102
Sig. (2-tailed)	.031	.148	.000	.132	.242	.003	.263	.000	.000
expand/high	pH	K	Na	SiO2	Cl	TP	TN	TSS	Ca
Mann-Whitney U	256	143	162	172	150	239	183	243	243
Sig. (2-tailed)	.326	.001	.004	.008	.002	.161	.012	.199	.199
expand/recede	pH	K	Na	SiO2	Cl	TP	TN	TSS	Ca
Mann-Whitney U	229	176	0	110	160	44	231	117	117
Sig. (2-tailed)	.971	.184	.000	.007	.088	.035	.864	.463	.463
high/recede	pH	K	Na	SiO2	Cl	TP	TN	TSS	Ca
Mann-Whitney U	200	87	122	259	173	188	143	86	199
Sig. (2-tailed)	.129	.000	.001	.811	.037	.078	.007	.021	.127

Online Resource 1(v)

Independent Samples Test

	Levene's Test for Equality of Variances		t-test for Equality of Means		
	F	Sig.	t	df	Sig. (2-tailed)
pH	2.203	.141	.696	96	.488
Temp	2.496	.117	-.716	96	.476
DO	1.661	.201	.331	96	.741
Conduct	.881	.350	5.903	96	.000
DOC	.047	.830	2.353	96	.021
HCO3	4.888	.029	3.642	96	.000
K	.841	.361	3.221	96	.002
Na	9.613	.003	3.233	96	.002
SiO2	.415	.521	2.069	96	.041
TP	.143	.706	.113	96	.910
TN	.924	.339	1.951	96	.054
NO3	8.771	.004			
TSS	.106	.746	.006	85	.936
Cl	.003	.955	.398	96	.692
SO4	11.355	.001	1.702	96	.092
Mg	2.913	.091	3.747	96	.000
Ca	1.432	.235	1.219	73	.227
Depth	3.454	.066	-3.802	96	.000
Veloc	5.877	.017	-2.007	96	.048

Mann-Whitney Test

Test Statistics

	HCO3	Na	SO4	Veloc
Mann-Whitney U	459	492	783	509
Sig. (2-tailed)	.002	.006	.825	.006

FOR NO3, TSS

	Levene Statistic	df1	df2	Sig.
NO3	8.771	1	59	.004
TSS	.106	1	85	.746

	HABITAT	N	Mean Rank
NO3	WetDry	13	43.46
	Wet	48	27.63
	Total	61	

	NO3
Chi-Square	8.144
df	1
Sig. (2-tailed)	.004

Online Resource I(vi)

Mean hydrochemical data for each of the 4 regions decomposed by field visit. ND = not determined

	Depth	Veloc	pH	Temp	DO	Conduct	DOC	HCO3	K	Na	SiO2	Cl	TP	TN	SO4	TSS	Mg	Ca
<b>UPH-low</b>	1.47	0.06	6.35	27.45	3.82	40.43	4.9	42.62	2.33	1.04	13.83	0.47	0.03	0.11	0.38	ND	0.16	8.02
<b>UPH-expand</b>	2.25	0.44	6.33	23.84	2.58	38.26	4.71	37.12	0.64	0.95	7.4	0.52	0.05	0.34	0.17	3.17	0.84	ND
<b>UPH-high</b>	2.25	0.09	6.49	17.53	6.67	30.98	2.9	38.55	0.53	1.15	5.88	0.51	0.03	1.06	0.36	5.34	0.41	3.62
<b>UPH-recede</b>	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
<b>LPH-low</b>	1.96	0.04	6.71	26.82	3.19	49.35	5.82	27.88	1.88	1.12	19.28	0.49	0.03	0.49	0.25	ND	0.3	6.95
<b>LPH-expand</b>	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
<b>LPH-high</b>	3.09	0.16	6.38	16.11	3.99	33.25	4.26	42.96	0.6	1.55	3.89	0.21	0.05	0.73	0.1	3.93	0.77	4.44
<b>LPH-recede</b>	1.32	0.13	6.54	24.85	3.81	52.47	13.94	61.31	1.94	2.03	5.63	0.65	0.08	0.62	0.32	2.34	1.01	4.67
<b>XAK-low</b>	1.21	0.22	7.15	29.74	4.36	63.14	8.41	50.77	2.69	1.15	10.76	0.58	0.03	0.61	1.21	ND	0.41	8.14
<b>XAK-expand</b>	0.96	0.1	7.05	21.45	4.43	53.9	7.51	73.95	3.49	1.28	12.22	1.01	0.03	0.44	0.67	3.76	1.11	ND
<b>XAK-high</b>	0.77	0.14	6.52	15.66	5.36	72.76	7.81	67.23	2.11	3.21	13.38	0.46	0.04	0.74	0.16	3.06	0.97	6.8
<b>XAK-recede</b>	0.89	0.23	6.8	25.29	4.11	64.1	6.38	58.26	3	4	8.45	0.49	0.04	0.4	0.12	2.11	1.45	6.47
<b>BOR-low</b>	0.95	0.07	6.73	27.57	1.82	87.72	9.64	62.35	3.02	0.73	7.72	0.79	0.03	0.56	0.27	ND	0.61	14.52
<b>BOR-expand</b>	0.97	0.11	6.02	26.47	1.18	91.23	14.46	76.72	4.38	1.56	26.57	1.76	0.02	1.03	0.28	2.15	1.39	ND
<b>BOR-high</b>	1.57	0.15	6.53	19.43	3.28	63.92	9.4	51.05	1.56	3.1	13.07	0.44	0.03	0.63	0.19	2.39	1.08	7.05
<b>BOR-recede</b>	1.26	0.07	6.61	24.51	2.43	74.85	8	81.63	2.22	4.88	10.99	0.49	0.07	0.65	0.26	1.65	1.68	7.53