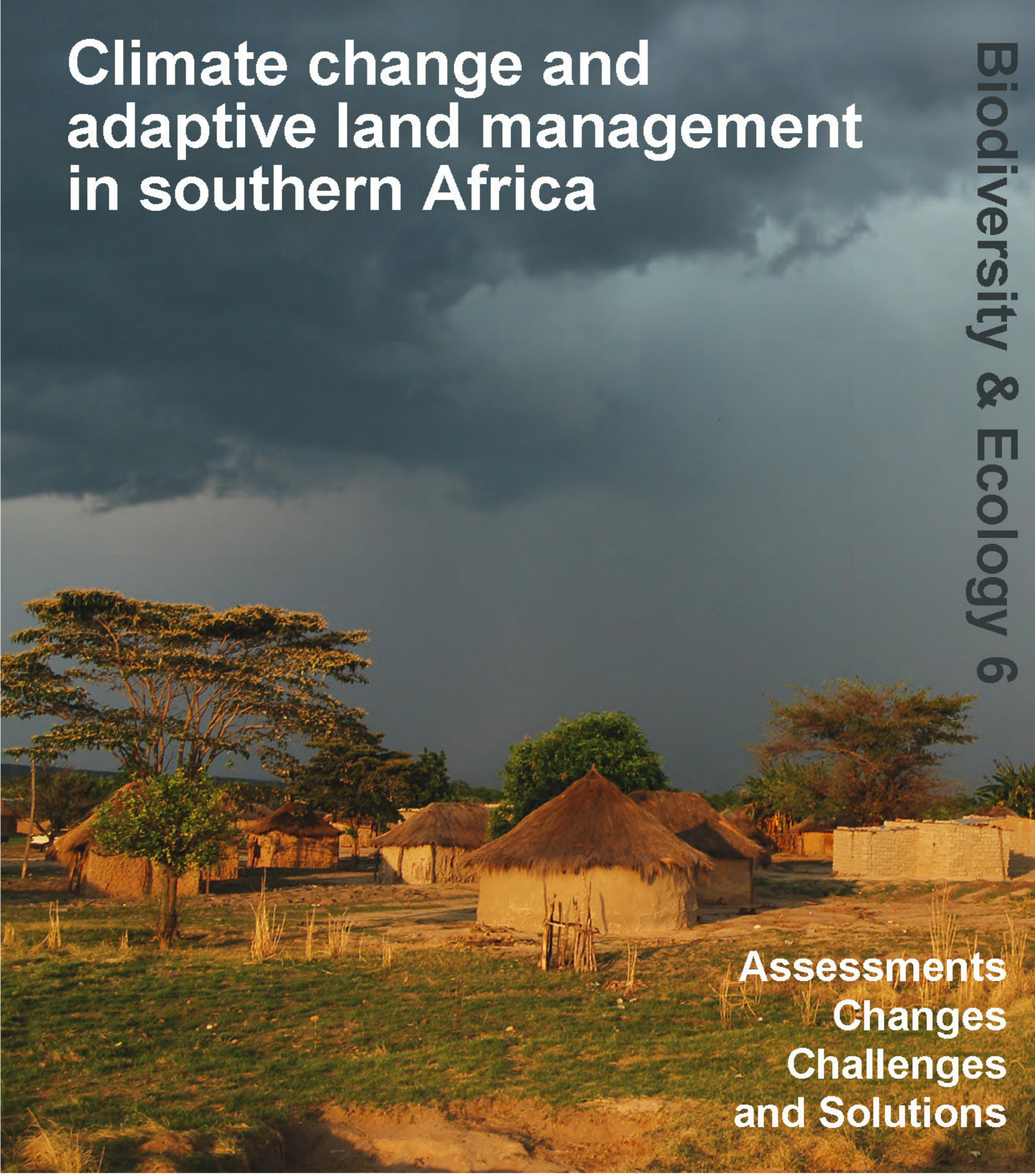
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



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Changes
Challenges
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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

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Monitoring water quality of the Upper Okavango Delta

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Abstract: The water quality of the Upper Okavango River has been described as pristine for many years since the water chemistry of the system was first studied. However, modern developmental activities and natural environmental processes are now threatening the quality and quantity of this river water. Continuous monitoring is important for providing scientific data that can be used to detect early warning signs of system changes and support effective management and protection of the resource. In this project, water quality of the Upper Okavango delta (Panhandle) was studied continuously from July 2014 to 2017 using physicochemical parameters. Field parameters were measured on-site using calibrated meters, and major ions were analysed in the laboratory using standard methods. Levels of electrical conductivity, pH, dissolved oxygen, and turbidity showed significant differences between sampling sites but still within international freshwater and drinking water guidelines. Statistical analysis showed no significant variations in water quality parameters over the years of the study. Parameters displayed seasonal cyclic variations controlled mainly by temperature (concentrated chemical species in summer) and flood levels (diluted most parameters during high floods). High floods also reduced dissolved oxygen concentration in river waters to a minimum of less than 1 mg/l, concentrations lethal to aquatic organisms, especially fish. This depletion occurred because high floodwaters bring in high levels of organic matter, which has a high oxygen demand for decomposition processes. The ionic composition of the Panhandle waters was found to be dominated by calcium (1.1–32.8 mg/l) and bicarbonate (0.9–77.2 mg/l), but still remained fresh. Although major land use changes are reported in the upper Namibian Kavango area, no apparent impact on water quality has been observed in this study.

Resumo: A qualidade da água na parte superior do Rio Okavango foi descrita como pristina durante muitos anos, desde que a química da água do sistema foi estudada pela primeira vez. Porém, actividades de desenvolvimento modernas e processos ambientais naturais estão agora a ameaçar a qualidade e quantidade desta água fluvial. A monitorização contínua é importante de modo a fornecer dados científicos que possam ser utilizados para detectar sinais de alerta precoces de alterações no sistema e apoiarem a gestão efectiva e protecção do recurso. Neste projecto, a qualidade da água do Delta de Okavango (panhandle) foi estudada continuamente de Julho de 2014 a 2017, com recurso ao uso de parâmetros físico-químicos. Os parâmetros de campo foram medidos no local com aparelhos calibrados, e os iões principais foram analisados no laboratório com recurso a métodos padrão. Os níveis de condutividade eléctica, pH, oxigénio dissolvido e turbidez mostraram diferenças significativas entre os locais amostrados, mas ainda dentro das normas internacionais de água doce e potável. A análise estatística não mostrou variações significativas dos parâmetros de qualidade da água entre os anos de estudo. Os parâmetros exibiram variações cíclicas sazonais, essencialmente controladas pela temperatura (espécies químicas concentradas no Verão) e níveis de inundação (diluição da maioria dos parâmetros nas altas inundações). As grandes inundações reduziram também a concentração de oxigénio dissolvido nas águas fluviais até a um mínimo inferior a 1mg/l, concentrações letais para organismos aquáticos, em especial os peixes. Este empobrecimento ocorreu pois as grandes inundações trazem altos níveis de matéria orgânica que possui uma elevada exigência de oxigêncio para os processos de decomposição. Descobriu-se que a composição iónica das águas do panhandle é dominada por cálcio (1,1 – 32,8 mg/l) e bicarbonato (0,9 – 77,2 mg/l), mas esta mantém-se doce. Apesar de serem relatadas importantes alterações no uso das terras na área superior do Kavango na Namíbia, este estudo não observou nenhum impacto aparente na qualidade da água.

Introduction

Water is a natural resource essential for supporting all forms of life. Rivers, streams, lakes, and other freshwater bodies are used as sources for drinking, irrigation, industrial development, fish and wildlife habitats, and maintenance of ecosystem balance (Carr & Neary, 2008). The value of these water resources in providing for human needs and ecosystem health depends largely on their quantity and quality. The quality of a water body is defined by its physical, chemical, biological, microbiological, and aesthetic properties (Carr & Neary, 2008). There is a need for protection of water resources for sustainable use, and water quality research is critical for providing scientific data to inform policy decisions in water resources management. The Okavango delta in Botswana is an important water source for riparian communities, wildlife, and the national tourism industry (McCarthy & Ellery, 1998). The headwaters of the river are located in Angola, where most of the runoff is generated, and each year rainwater travels through the Cubango and Cuito River system into Namibia, where about 9,200 million m^3 enter the delta (McCarthy & Ellery, 1998). Given its international importance as a Ramsar site and a UNESCO World Heritage site, the Okavango delta has been the subject of several studies aimed at assessing changes in surface water quality for supporting effective management of the resource (Ashton et al., 2003; Mackay et al., 2011; Gondwe & Masamba, 2016; Tubatsi et al., 2014; West et al., 2015). Major ion chemistry of the Okavango was also studied (Masamba & Muzila, 2005; Sawula & Martins, 1991). The conclusion from these studies was that the water quality of the upper delta varied seasonally as a result of natural influences such as temperature changes and annual flooding but that the influence of human activities was not apparent. Because the studies were short-term undertakings, however, no conclusions could be drawn regarding whether the water quality of the Okavango system was changing over time, from year to year. Land use changes in the delta and upstream have the potential to affect the water quality of the Okavango River (Masamba & Mazvimavi, 2008). Large-scale industrialised agriculture and increasing human settlements have been reported in the Namibian Kavango area (Propper et al., 2015). These are likely to increase fertiliser, pesticides, and sediment loadings in the delta and lead to a deterioration of water quality and loss of biodiversity in the Okavango delta. The water quality changes may seem negligible (such as temperature rise resulting from climate change) and be masked by seasonal changes in short-term studies, so long-term studies are critical to reveal real trends. The main objective of this study was to assess spatial-temporal variations in water quality in the Okavango Panhandle over 3 years using physicochemical indicators. These data will provide information on water quality trends with respect to different locations in the Panhandle, seasons, and year-to-year changes.

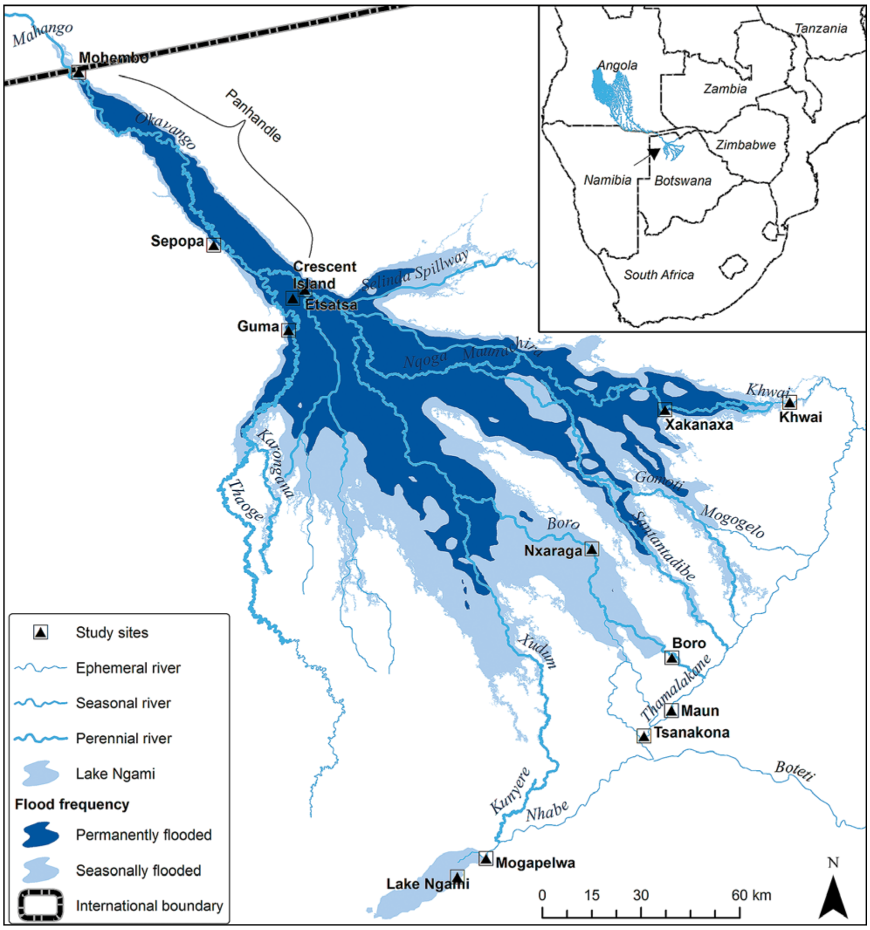

Figure 1: Map showing sampling sites in the Okavango Delta panhandle and lower delta.

Materials and methods

Study site

The Okavango delta occupies an area of about 40,000 km^2 in northern Botswana. It is one of the largest inland delta fans in the world (Gumbricht, 2004) and one of Africa's most pristine wetlands (McCarthy & Ellery, 1998). Annually, the delta receives 6,140 million m3 of water from local rainfall, and an additional 9,200 million m^3 is supplied by Angolan tributaries (Nash et al., 2006). The delta consists of two distinct sections, the Panhandle and the alluvial fan. The Panhandle (Fig. 1), approximately 90 km long and 15 km wide, is the entry corridor to the Okavango delta (McCarthy et al., 2007). It consists mostly of permanent swamps with well-defined deep water channels and seasonal marshes on the fringes of the channels. The water quality monitoring sites for the SASSCAL Task 344 project were spread out to cover most of the delta (Fig. 1) to document the water quality status of the entire area. For the Panhandle, five sampling sites were selected representing the entry point of the river water from Namibia (Mohembo), middle point (Sepopa), side tributary (Etsatsa and Crescent Island), and lower point of the Panhandle (Guma). In the Lower Okavango delta, known as the alluvial/distal fan, eight sampling sites were selected for monitoring (Fig. 1), but only selected results of the Panhandle will be reported in this chapter.

Sampling

Water sampling began in July 2014 and continued to July 2017. Samples were collected monthly in triplicate from each sampling location. The monthly sampling cycles were meant to cover all essential events occurring within the river systems that were likely to influence water quality in the delta, such as seasons and flooding cycles. The international grab sampling protocol for surface waters was followed during sampling. Samples for laboratory analysis were preserved accordingly and transported to the laboratory of the Okavango Research Institute for processing. Discharge values reported here are for Mohembo only and were obtained from the Department of Water Affairs, Botswana, which measures discharge daily at Mohembo and other sites in the delta.

Analysis

Field water quality parameters (electrical conductivity, pH, dissolved oxygen, turbidity, and temperature) were all measured on-site using calibrated field meters. Major ions (calcium, magnesium, potassium, sodium, bicarbonates, chlorides, sulphates) and other parameters were analysed at the laboratory of the Okavango Research Institute in Maun, following protocols provided in the American Public Health Association's *Standard Methods for the Examination of Water and Wastewater, 22nd edition* (Rice et al., 2012).

Data analysis

We used descriptive statistics and one-way analysis of variance (ANOVA) to evaluate similarities and dissimilarities among sampling periods and sampling sites with a significance level at $p \leq 0.05$. Time series plots were used to illustrate the variations of some water quality parameters over the study period.

Results

Field parameters

Although discharge is not a water quality parameter, it is presented here because it was used in this study to determine low and high flood periods (Fig. 1). High floods were considered to occur from January to June, and low floods occurred from July to December. Results of water quality parameters (temperature, pH, electrical conductivity, dissolved oxygen, and turbidity) measured in the Panhandle are given (Tab. 1). The statistical analysis (ANOVA) revealed that all field parameters tested, except temperature, varied significantly among sites ($p < 0.05$). However, the temporal variations were not significant for all field parameters tested.

The highest recorded discharge at Mohembo in the year 2014 was 665 m^3s^{-1}; in 2015, 573 m^3s^{-1}; in 2016, 777 m^3s^{-1}; and in 2017, 445 m^3s^{-1}.

Temperatures in the Panhandle varied across sampling sites and seasons, with a range of 15.7–36.6 °C (Tab. 1). Crescent Island recorded the lowest temperature of 15.7°C at low floods, and the highest of 37.7°C was recorded at Etsatsa, also during a period of low floods. ANOVA revealed that the differences observed among sampling sites and between the flood stages were not significant ($p > 0.05$). Figure 2a illustrates the general cyclic pattern during the study period, the overlaps between the solid line and dotted line revealing close similarity in water temperature between the upper Panhandle (Mohembo) and the lower Panhandle (Guma).

The pH in the Panhandle ranged from 5.2, recorded at Etsatsa, to 7.5, recorded at Crescent Island, indicating acidic waters

Table 1: Mean, minimum, maximum and standard deviation of water quality parameters in the Okavango Panhandle from 2014 to 2017

	Mohembo				Sepopa				Etsatsa				Crescent				Guma			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Low Floods																				
T (°C)	22.4	3.9	16.5	27.6	22.9	4.6	16.2	29.1	22.9	5.2	16.3	36.6	22.4	4.5	15.7	28.6	22.5	4.3	16	28.5
pH	6.7	0.3	6.3	7.2	6.5	0.2	6.0	7.0	6.6	0.4	5.2	7.3	6.5	0.3	5.7	7.5	6.6	0.3	5.8	7.4
EC (µS/cm)	31.5	3.1	27.3	41.8	35.3	4.3	26.6	46.1	37.6	5.7	30.5	53.9	38.6	4.7	28.5	45.9	42.4	8.7	28.7	56.9
DO (mg/L)	6.7	1.4	2.5	8.4	5.3	1.0	2.2	6.7	5.3	1.4	2.4	10	4.2	1.3	1.5	7.1	5.0	1.0	2.3	6.4
Turbidity (NTU)	14.1	3.4	7.3	21.7	9.1	4.8	0.7	16.5	6.7	4.9	0.8	17.6	5.2	3.8	0.4	13.5	1.7	0.7	0.3	3.6
High floods																				
T (°C)	24.7	4.1	17.6	28.7	24.5	4.1	17.1	29.3	24.5	3.7	17.3	29.2	24.4	3.7	17.3	29.3	24.3	3.8	17.5	29.9
pH	6.4	0.3	5.6	6.8	6.3	0.2	5.9	6.8	6.3	0.3	5.7	7.0	6.2	0.3	5.8	6.7	6.3	0.3	6.0	6.9
EC (µS/cm)	37.2	3.8	31.1	43.6	40.7	10.3	30.9	67.7	43.1	14.7	30.4	73	46.9	22.5	30.3	99.8	42.4	11.2	31.5	64.8
DO (mg/L)	5.2	1.9	0.7	8.9	2.6	1.8	0.6	6.8	3.5	2.3	0.6	7.3	2.9	2.3	0.2	6.8	3.8	1.9	0.9	6.6
Turbidity (NTU)	4.8	1.9	3.1	8.8	2.5	1.7	0.3	7.5	3.2	2.7	0.8	8.8	3.7	3.9	0.6	13.5	2.3	0.9	0.7	3.8
Major ions (mg/l)																				
Na	1.7	0.5	ND	3.2	1.9	0.5	0.9	4.1	1.8	0.6	0.1	3.6	2.1	0.9	1.1	5.3	2.0	0.4	1.4	3.1
Ca	3.8	0.7	2.8	7.5	3.9	0.8	3.1	9.1	4.1	1.4	1.1	13.6	4.7	3.7	1.5	32.8	4.9	1.6	2.7	10.5
Mg	1.0	0.2	0.3	1.6	1.1	0.2	0.5	2.0	1.1	0.8	0.8	8.8	1.2	0.4	0.9	3.0	1.3	0.4	0.8	2.4
K	1.4	0.5	ND	3.4	1.4	0.6	ND	4.0	1.3	0.8	ND	4.4	1.8	1.5	ND	7.7	1.2	0.6	ND	2.9
HCO_3	23.2	6.8	4.6	39.8	23.8	14.9	ND	130.6	25.3	10	ND	51.7	24.2	12.4	0.9	50.1	28.3	11.3	3.3	77.2
SO_4	0.5	0.9	ND	8.4	5.2	20.8	ND	120.4	0.3	0.4	ND	1.6	0.4	0.4	ND	2.6	0.6	0.7	ND	5.6
CL	0.4	0.8	ND	7.3	0.9	3.3	ND	19.5	0.6	0.9	ND	3.1	0.4	0.6	ND	2.8	0.1	0.1	ND	1.1

ND = Not detected with the analytical technique used

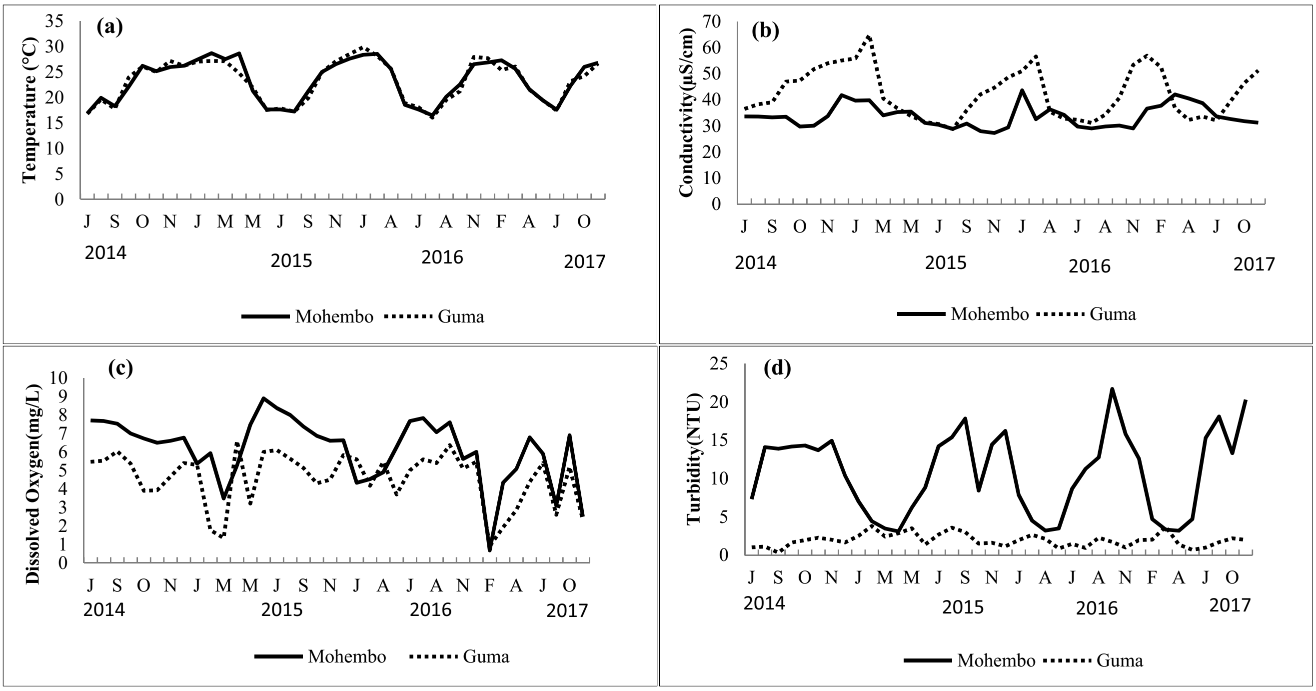

Figure 2: Time series plots for averages (a) temperature (b) conductivity (c) dissolved oxygen (d) turbidity in the Upper (Mohembo) and Lower (Guma) Panhandle

to neutral and even near-alkaline conditions. An ANOVA test revealed that pH varied significantly among the five study sites, with the highest mean at Mohembo and the lowest at Crescent Island. Flood stage influences were observed, as pH was also significantly higher ($p = 0.000$) during low floods than at high floods.

Electrical conductivity is a measure of dissolved salts in a water body. Mohembo recorded the lowest EC of 27.3 µS/cm, and Crescent Island recorded the highest of 99.8 µS/cm (Tab. 1). Although average concentrations at all sampling sites remained relatively low (all below 100 µS/cm), EC increased significantly ($p = 0.01$) downstream from the Panhandle, exhibiting a trend of Mohembo < Sepopa < Etsatsa < Crescent < Guma. Figure 2b shows cyclical trends and differences in salt concentration between the upper and lower Panhandle. Significant variations between low and high floods were observed, with higher conductivities at low floods.

The concentration of dissolved oxygen in the Panhandle ranged from 0.2 to 8.9 mg/l. Dissolved oxygen was significantly higher at Mohembo compared to the other four sites, with the lowest concentrations at Crescent Island. Figure 2c shows consistently lower DO levels at Guma compared to Mohembo during the study period. An ANOVA test showed significant differences among sampling locations and at flood stages, with high DO levels at low floods and low concentration levels at high floods.

Measurements of turbidity showed a range of 0.3–21.7 NTU across sampling sites. Turbidity showed significant differences between sites, with more turbid waters at Mohembo compared to Guma. Significant variation was also observed between low and high floods, with the highest turbidity at low floods. Figure 2d highlights the turbidity variations over time at Mohembo and a different environment at Guma, where turbidity is relatively uniform throughout the study period.

Major cations analysed in the river water were calcium, magnesium, sodium, and potassium, while the anions analysed were bicarbonates, chlorides, and sulphates. Concentrations of cations ranged from undetectable levels to 32.8 mg/l of calcium recorded at Crescent Island, whereas anions ranged from undetectable levels to 130 mg/l of bicarbonate at Sepopa. Of particular interest at Sepopa is another high value of sulphate, at a concentration of 120 mg/l. The Okavango Panhandle waters were found to be of a calcium bicarbonate type, dominated by calcium and bicarbonate ions. A general concentration increase downstream was observed for these major ions (Tab. 1).

Discussion

Water quality in rivers and streams is generally linked with land cover and land use patterns in the catchment (Ngoye & Machiwa, 2004). The most sustainable freshwater sources in the world originate in forest ecosystems (Neary et al., 2009). Forest surfaces act as water filters because they have high organic matter content, which also increases the stability of soil aggregates, reducing soil erosion and moderating sediment and nutrient fluxes (Neary et al., 2009). The water quality of the Okavango delta has been reported to fluctuate spatially and seasonally (Gondwe & Masamba, 2016; West et al., 2015). These variations were said to be influenced by climate and geology as well as the pulsing of the river (Mackay et al., 2011). Nevertheless, clearing of land for human settlements, large-scale agriculture, and increased tourist facilities may all contribute to the deterioration of water quality in the delta.

Discharge

Though not a basic water quality parameter, discharge is reported in this paper because it has been reported to influence the water chemistry of the Okavango delta (Mackay et al., 2011). The highest measured discharge in 2017 was lower than for the other years. The data are not reliable, however, as equipment broke down and there were no measurements of discharge during very high floods that year.

Temperature

The time series plots (Fig. 2a) for water temperature show a fairly stable, seasonal cyclical variation with no apparent trend. These repetitive patterns may form because the riparian vegetation with thick forest canopies shields and protects the waters from heating up too much in summer despite high air temperatures. The stable temperatures may also be a result of the continuous inflow of water from upriver and the effective environmental management practises in protecting the area by minimising land and industrial development around the delta. Temperature influences biochemical reactions and the solubility of gases, especially oxygen in this case. In addition, aquatic organisms have certain a tolerance range for temperature; if it changes quickly by 3°C, it may be lethal to some fish species (Caissie, 2006). The stable temperature among sites and years indicates favourable environmental conditions for aquatic life and sustenance of biodiversity in the Panhandle. A water quality study conducted between 2006 and 2009 (West et al., 2015) reported summer maximum temperatures of 35° C in the Panhandle, similar to maximums obtained for Mohembo and Sepopa in this study (Tab. 1).

pH

The recommended pH range for freshwater ecosystems by US and New Zealand standards (ANZECC, 1992; USEPA, 1992) is 6.5–9.0, and the World Health Organization (WHO, 2006) recommends a range of 6.5–8.5 for drinking water. About 57% of the samples of the Panhandle were within these international water quality standards, and 1.7% of samples were in the range of 5.1 to 5.5, a range where fish and other aquatic organisms will experience very restricted populations and fish eggs and larvae may die (Robertson-Bryan, 2004). The pH of the study sites decreased from Mohembo to Guma, probably as a result of increased concentrations of humic acids from the decomposition of aquatic plants brought in from upstream. During low floods, the higher pH may be attributed to the increased evaporation rate, which results in a concentration of salts in the river water. Wetlands have good buffering capacity, however, and this may explain why the year-to-year variations in pH were not significant. A study carried out in 2000 (Ashton et al., 2003) reported a mean pH of 6.74 in Mohembo (Gondwe & Masamba, 2016), a study conducted between 2008 and 2010 reported a mean of 6.92, and the present study reported a mean pH of 6.6.

Electrical conductivity

Despite an estimated annual input of about 381,000 t of solutes from upstream (McCarthy & Ellery, 1998), electrical conductivity of the upper delta recorded in this study was relatively low (27.3–99.8 µS/cm; Tab. 1) compared to other natural systems on the globe, which may vary between 1 and 1,500 µS/cm (WHO/UNEP, 1989). Research has shown that the bulk of the incoming solutes in the Okavango River are removed from surface waters by density-driven sinking of saline waters, and then stored beneath the delta's islands (McCarthy & Ellery, 1998). EC in the Panhandle increased downstream, with Mohembo having the lowest and Guma the highest (Fig. 2b). This observed salt concentration gradient was also documented in past studies (Ashton et al., 2003; Ellery et al., 2003; Gondwe & Masamba, 2016) and attributed to evapotranspiration leading to reduced water mass and thus an increase in the concentration of salts. Significantly higher EC was observed at low floods as a result of increased evaporation rates and salt enrichment in river waters, whereas at high floods, dilution effects resulted in low EC values.

Dissolved oxygen

Except for the seasonal differences, no changes in DO for the 3-year period of study were noticed. The Environmental Protection Agency (EPA, 1986) recommends a DO range of 5.0–9.5 mg/l for warm-water aquatic species at various life stages. A minimum of 2.4 mg/l DO is required for the survival of aquatic life (Mmualefe & Torto, 2011). In the Panhandle, concentration ranges from 0.2 mg/l to 8.9 mg/l were recorded. During high floods, minimum concentrations recorded at each sampling site were below 1 mg/l, but the annual mean values were above 2.6 mg/l (Tab. 1). Strong seasonal fluctuations take place, however, and of major concern is the depletion of dissolved oxygen occurring during high floods. This can be attributed to high biological oxygen demand associated with fine organic material that is mobilised by the flood waters. Fish kills have been reported by communities of the Okavango Panhandle during high floods, and the low concentration of oxygen may well be the reason for the fish kills. The lowest concentration of DO was recorded at Crescent Island, which may be due to point pollution sources from a nearby safari camp, demonstrating potential negative effects of some tourism activities on river water quality.

Turbidity

Turbidity in the Panhandle decreases downstream (Tab. 1). This decrease may be due to the filtration processes and the sedimentation of the suspended matter, with increasing distance as the river meanders downstream. Figure 2d shows the variation of turbidity at Mohembo and Guma, where Guma is much lower compared to Mohembo. Seasonally, turbidity was higher during low floods across all the study sites except Guma lagoon.

Major ions

The Okavango Panhandle is a freshwater system with low dissolved salts, as shown by the low conductivity values (< 100 µS/cm) obtained in this study and in previous studies (Mackay et al., 2011; Mmualefe & Torto, 2011). Chemical weathering and the resulting physical erosion of the parent material soils contribute significantly to the chemical composition of river water (Huang et al., 2009). These processes are accentuated by increased temperature and land cover clearing. The higher concentrations of calcium and bicarbonate in the Panhandle may be attributed to weathering of carbonate rocks in the headwaters. Concentrations of all major ions were very similar (within the same order of magnitude) to values obtained by Ashton et al. (2003) and Mackay et al. (2011). This similarity suggests that the river water has not been affected by upstream activities.

Conclusion

The study demonstrates that the general water quality of the Okavango Panhandle with respect to the parameters measured (temperature, pH, conductivity, dissolved oxygen, turbidity) was relatively good; most samples were within international guidelines for freshwater ecosystems. Cyclical seasonal variations of water quality parameters occurred, influenced by changes in temperature and flood levels, but no significant year-to-year variations were observed. Spatially, there were no significant differences in temperature, but other parameters showed significant variability that may be attributed to geology, soils, and land cover. There were no significant temporal (year-to-year) variations of water quality parameters, and this may reflect the effectiveness of the Okavango water resources management. However, human-related pressures are being experienced in the Namibian Kavango area, where population growth has led to land clearing and economic development has led to large-scale irrigation schemes and intensification of cattle production. These activities are likely to deposit residual fertilisers, pesticides, and nutrients in the Okavango River, deteriorating the water quality. Continuous water quality monitoring of the entire Okavango River system is critical for sustainability of the resource.

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