DIEL CARBON CYCLING IN VEGETATIVE RIVER SYSTEMS IN ARID ENVIRONMENTS: THE OKAVANGO DELTA, NW BOTSWANA

By

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Bachelor of Science in Geology

Oklahoma State University

Stillwater, Oklahoma

2013

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2016

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ACKNOWLEDGEMENTS

This study was funded by the US National Science Foundation under the International Research Experience for Students (IRES) initiative (NSF grant # OISE-0927841). We thank the government of Botswana, particularly the Ministry of Education, for providing us with research permits to conduct the study and the University of Botswana for providing logistical support for field work. We thank the Department of Water Affairs, especially the workers at the Mohembo station and the proprietor and workers of Crocodile Camp in Maun for providing access to the Okavango River from their property.

This work could not have been completed without the financial support of the Boone Pickens School of Geology. I thank my committee members Dr. Anna Cruse and Dr. Tracy Quan. Dr. Cruse thank you for the guidance and mentorship in every aspect of my time here at Oklahoma State, it was truly invaluable to me. Dr. Quan thank you for all your advice and support throughout my time here, from the weekly geochemistry group meetings to the Association for Women Geoscientists programs and writing, you and Dr. Cruse were of the core group of influential women that guided me this field. Dr. Eliot Atekwana thank you for supporting me as my advisor and mentor who patiently provided your time in the lab, field and in the writing process. It has been greatly invaluable to me in my academic and future career, thank you. Dr. Loago Molwalefhe is acknowledge for his guidance and mentoring while conducing field work for this research.

The assistance and field support of Christopher Geyer, Eric Akoko, Oratile Kgaodi and Thobo Koontse is greatly appreciated. Thank you to Christopher and Eric for your help in the lab and all the laughs after long days of prepping equipment, I could not have done it without you guys. I thank Dr. Pride Abongwa for his advice, friendship and support in the lab and writing, as well as allowing me to bounce ideas around whenever I needed help. Thank you to the geochemistry group, for allowing me to bounce ideas off and figuring out a meaningful way to get them across.

To my friends, thank you, your friendship means the world to me. Thank you to my family, who provided me with constant support, encouragement and love. I would not be here today without you guys truly believing in me, seeing the potential in a little girl who just really loved digging for rocks and fossils.

Name: NICOLE CONSTANCE PAIZIS

Date of Degree: MAY, 2016

Title of Study: DIEL CARBON CYCLING IN VEGETATIVE RIVER SYSTEMS IN
ARID ENVIRONMENTS: THE OKAVANGO DELTA, NW
BOTSWANA

Major Field: GEOLOGY

Abstract: We investigate the effects of evapoconcentration, photosynthesis and respiration on diel carbon cycling in densely and non-densely vegetated portions of the Okavango River in semi-arid northwestern Botswana. Previous studies have shown that evapotranspiration has a profound effect on the river water chemistry over seasonal and spatial scales. However, the effect of vegetation induced evapotranspiration in controlling river chemistry and carbon cycling over short term daily cycles is not well understood and has not been previously investigated. We conducted diel investigations in the river channel in the Okavango Delta at two locations that are about 400 km apart. The channel at the proximal end of the delta in Mohembo is located in a permanently flooded wetland ecotone, with a deep channel and is sparsely vegetated, while Maun at the distal end of the delta is located in an occasional flooded wetland ecotone with a shallow channel that is densely vegetated. The physical, chemical and isotopic parameters of river water measured every hour for 24 h showed much higher solute concentrations and more enriched stable isotopic composition of water (δD and $\delta^{18}O$) and stable carbon isotopes of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) in the distal portion of the delta due to modification by evapoconcentration and atmospheric interaction during river transit over the 400 km distance. The total dissolved solids (TDS) and silica show diel variations with higher concentrations during the day and lower concentrations at night. The increased solute concentrations during the daytime is attributed to transpiration of aquatic vegetation coupled to evaporation. The pH, alkalinity and $\delta^{13}C_{DIC}$ show clear diel trends that were more prominent in the distal portion of the delta at Maun. The controls of carbon cycling during the diel cycle is not dominated by biotic processes, such as, water column photosynthesis, $CO_{2(g)}$ evasion or photo-oxidation during the day and respiration during the night. Our results suggest mostly an abiotic control on solute and carbon cycling, despite the occurrence of extensive vegetation in the river channel, floodplain and adjacent wetlands. We conclude that despite extensive vegetation in the Okavango River, the hydrology and abiotic processes mostly control diel solute and carbon cycling.

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CHAPTER I

INTRODUCTION

Inland surface waters release an estimated 1.2 Pg C per year to the atmosphere, making them an important component of the global carbon cycle (Tranvik et al., 2009; Raymond et al., 2013). River systems play a key role in carbon cycling by sequestering carbon as organic matter (OM) and carbonates and exchanging $CO_{2(g)}$ with the atmosphere (e.g., Cole et al., 2007). Carbon in the dissolved inorganic (DIC) form (DIC = $CO_{2(aq)} + H_2CO_3 + HCO_3^- + CO_3^{2-}$) in the water column is used to produce the OM, carbonates or exchanged with the atmosphere (e.g., Stumm and Morgan, 1981). DIC input into rivers occur from influx of groundwater, organic matter (OM) respiration, photo-oxidation of OM and atmospheric $CO_{2(g)}$ invasion. DIC output from the water column includes chemical precipitation (carbonates), uptake by aquatic photosynthesis and $CO_{2(g)}$ evasion to the atmosphere (Fig. 1) (Atekwana and Krishnamurthy, 1998; Telmer and Veizer, 1999; Parker et al., 2007; Doctor et al., 2008).

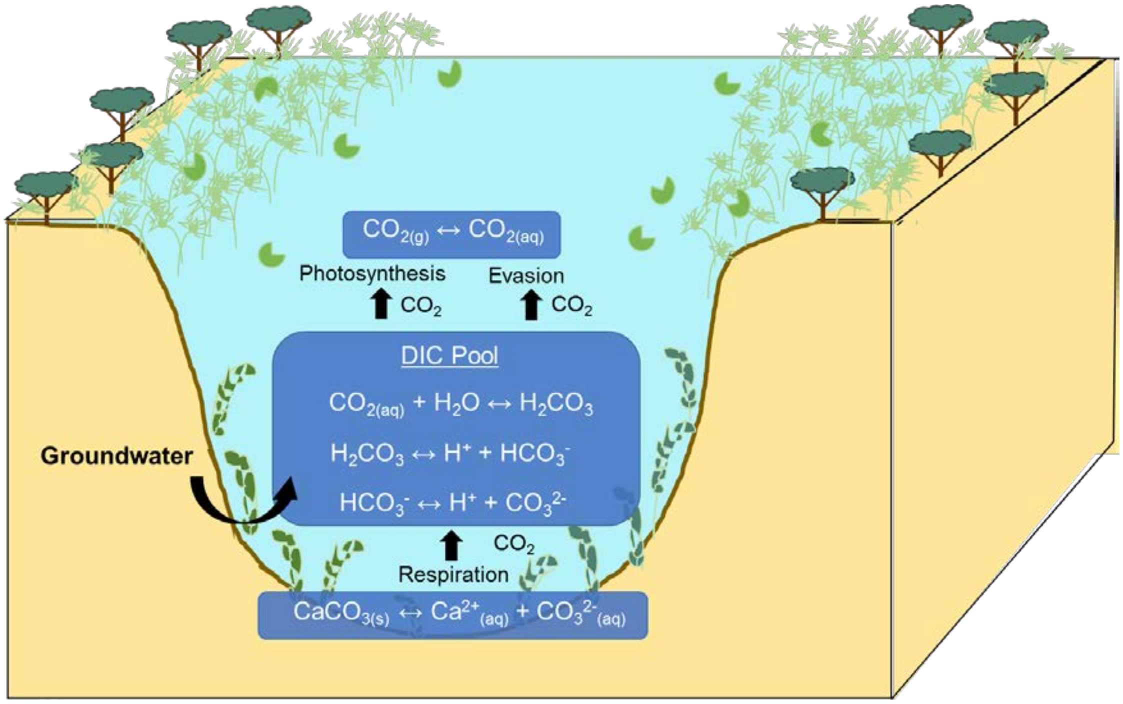

Figure 1: Conceptual model showing processes that add or remove dissolved organic carbon (DIC) in the carbon pool in the Okavango Delta (Modified from Atekwana and Krishnamurthy 1998 and Akoko et at., 2013)

DIC influx from groundwater depends on groundwater-surface water interaction. Rivers which receive groundwater (effluent rivers) have a significant amount of their DIC contributed from soil zone $CO_{2(g)}$ and aquifer carbonates which is absent from rivers that predominantly feed groundwater (influent rivers). Although the status of groundwater-surface water interaction for rivers is defined mainly by the relationship between the groundwater table and river level, rivers in humid climates are most likely to be dominated by groundwater DIC input while rivers in arid environments mostly lose water to aquifers. The amount of DIC input into the water column from OM respiration and photo-oxidation of OM depends on the concentration of dissolved organic matter (DOC) in the water column and the lability of the DOC (Miller and Zepp, 1995; Granéli et al., 1996; Cory et al., 2015).

In rivers that are hydrologically connected to extensive vegetated floodplains and wetlands, flood pulses releases OM from vegetative litter stored in the seasonal floodplains, which can dominate the DOC pool (e.g., Mladenov et al., 2005; Cawley et al., 2012). As this newly released OM travels downstream, it is affected by biogeochemical processes and thus has the potential to contribute significant amounts of DIC into the water column (Graneli et al., 1996). $CO_{2(g)}$ will dissolved in river water if the partial pressure of CO_2 (pCO_2) in river water is less than atmospheric (Stumm and Morgan, 1981; Drever, 1997; Abongwa and Atekwana, 2013). Chemical precipitation removes carbon from the DIC pool if river water is supersaturated with respect to carbonate minerals (Stumm and Morgan, 1981; Tobias and Böhlke, 2011). The extent to which photosynthesis removes carbon depends on the abundance and types of aquatic photosynthetic vegetation (Falkowski and Raven, 1997). Rivers will lose CO_2 to the atmosphere if the pCO_2 of river water is greater than atmospheric CO_2 (Stumm and Morgan, 1981; Cole et al., 2001).

When carbon is removed or added to the DIC pool, the DIC concentration changes. Each of the processes that adds or removes carbon from the DIC pool is characterized by distinct isotopic fractionation. For example, for natural and unpolluted rivers in humid regions with C-3 vegetation ($\delta^{13}C$ of -25‰), groundwater will add DIC to a river with an isotopic composition that will vary from -23‰ to -12‰ depending on (1) whether carbonate evolution in the groundwater is “open” or “closed” and (2) the extent to which carbonate evolution has occurred in the groundwater (Clark and Fritz, 1997). Where OM respiration or OM photo-oxidation contributes to DIC, the $\delta^{13}C_{DIC}$ depends on that of the DOC which is approximately -25‰ and -12‰ for C-3 and C-4 vegetation, respectively (e.g., Clark and Fritz, 1997; Falkowski and Raven, 1997). Although not common, atmospheric $CO_{2(g)}$ can dissolve into river water and increase the DIC concentration. If this reaction is in equilibrium with atmospheric $CO_{2(g)}$, then the final $\delta^{13}C_{DIC}$ will be dictated by the equilibrium isotopic fractionation at a specific temperature (Tamooh et al., 2013). For temperatures at the earth's surface and a $\delta^{13}C$ of atmospheric $CO_{2(g)}$ of ~8‰, the DIC formed by equilibration with surface waters have a $\delta^{13}C_{DIC}$ of 0 ± 1.0‰ (e.g., Clark and Fritz, 1997). Carbonate precipitation is an equilibrium process which will decrease the DIC concentrations and enrich the $\delta^{13}C_{DIC}$ of the remaining DIC pool (Tobias and Böhlke, 2011). Photosynthesis will decrease the DIC concentration by taking CO_2 out of the water column, and the extent to which $\delta^{13}C_{DIC}$ will be enriched depends on the intensity of photosynthesis (O'Leary, 1988; Tamooh et al., 2013). $CO_{2(g)}$ evasion will decrease the DIC concentration and the $\delta^{13}C_{DIC}$ will increase. At equilibrium, it will be controlled by equilibrium isotopic fractionation between DIC and atmospheric $CO_{2(g)}$ (e.g., Abongwa and Atekwana, 2013). Given that both the DIC concentrations and the $\delta^{13}C_{DIC}$ in river water change from processes that induce loss and gain of carbon in the riverine DIC pool, these processes can be characterized by evaluating changes in the DIC concentrations and the $\delta^{13}C_{DIC}$ (e.g., Atewana and Krishnamurthy, 1998; Telmer and Veizer, 1999; Abongwa and Atekwana, 2013).

Complex interplay between climate, hydrology, vegetation, microbes, aquatic respiration and photosynthesis control the chemical and isotopic properties of river water on both seasonal and daily cycles (Parker et al., 2005). The seasonal to annual cycling of carbon in rivers varies on a scale similar to rainfall and temperature that define the climate of a region. Therefore, we expect that carbon cycling in rivers in arid compared to humid regions will differ in magnitude and timing.

On an even shorter time scale of a day, differences in the night and day caused by the solar photo-cycle have an effect on the physical and chemical properties of river water (Parker et al., 2007; Nimick et al., 2011). The physical and chemical responses in the river water that occur on a daily basis, and differ between night and day are known as diel cycles. Under ideal conditions, most diel cycles exhibit a sinusoidal pattern, with higher magnitude in the measured parameter during the day and lower magnitude at night or vice versa. Knowing the processes affecting the biogeochemistry of surface waters on a diel cycle is critical for understanding the function of aquatic ecosystems, water quality and the response of chemical and biological processes to ever changing river conditions impacted by industrialization, drought or climate change (Nimick et al., 2011).

Studies of daily carbon cycling have been conducted mainly in humid and temperate regions (Parker et al., 2005; Nimick et al., 2011). These studies have greatly improved our understanding of diel carbon cycling in temperate regions. However, there are no published studies that have investigate diel cycling of carbon in rivers in arid environments, leaving a large gap in our understanding of diel carbon cycling in arid regions. Additionally, this is especially true in rivers that have dense vegetation in the river channels and floodplains which potentially can significantly affect river hydrology and ecology. We investigated diel carbon and solute cycling in the Okavango Delta in semi-arid northwestern Botswana. The Okavango River which developed distributaries on an alluvial fan to form an inland delta, flows for more than 400 km within an extensive freshwater wetland (McCarthy et al., 2003). We measured the hydrologic, physical and chemical responses over a diel cycle in sparsely vegetated and heavily vegetated regions of the Okavango River. We hypothesize that evaporation coupled with transpiration from aquatic vegetation will enhance diel cycling of solutes and carbon. Our objectives were to measure the diel response in densely and non- densely vegetated portions of a river to: (1) characterize the effect of evaporation using changes in river water levels and the stable hydrogen (δD) and the stable oxygen ($\delta^{18}O$) isotopes, (2) assess the effects of evapotranspiration on the diel cycling of solutes and (3) determine how vegetation affects the diel cycling of solutes and carbon cycling from concentrations of major ions, DIC species and the $\delta^{13}C_{DIC}$. Our results provide new insights into the role of hydrology and evapotranspiration in the short term cycling of solutes and carbon in heavily vegetated rivers in arid environments.

CHAPTER II

STUDY SITE

This study was conducted in the Okavango Delta in semi-arid northwest Botswana (Fig. 2). The physiographic outline of the Okavango Delta consists of a panhandle region and a delta region. The panhandle is developed within a NW-SE fault trough and a delta region is formed in a SW-NE fault trough, a nascent arm of the SW branch of the East African Rift Zone (Modisi, 2000; Gumbricht et al., 2001; Kinabo et al., 2007; Mosley-Bufford et al., 2012). The faulted troughs of the Panhandle and the Delta region are filled with 300 to 600 m thick Quaternary Kalahari alluvium and recent sediments of lacustrine, fluvial and deltaic origin (McCarthy et al., 1993; Modisi, 2000; Kinabo et al., 2007). Bedrock in the region is Precambrian crystalline igneous and metamorphic rocks of the Damara and Ghanzi-Chobe orogenic belt, exposed to the northwest and southeast of the Okavango Delta (Modie, 2000; Kinabo et al., 2007).

The width of the panhandle is about 10-30 km within which the Okavango River flows in a meandering pattern (Fig. 2). The average depth of the Okavango River in the Panhandle is 1.5 m (McCarthy et al., 1988; Tooth and McCarthy, 2004), the average velocity is 0.4-0.8 ms^{-1} (McCarthy et al., 1988) and the average channel width is approximately 50 m (Wilson and Dincer, 1976).

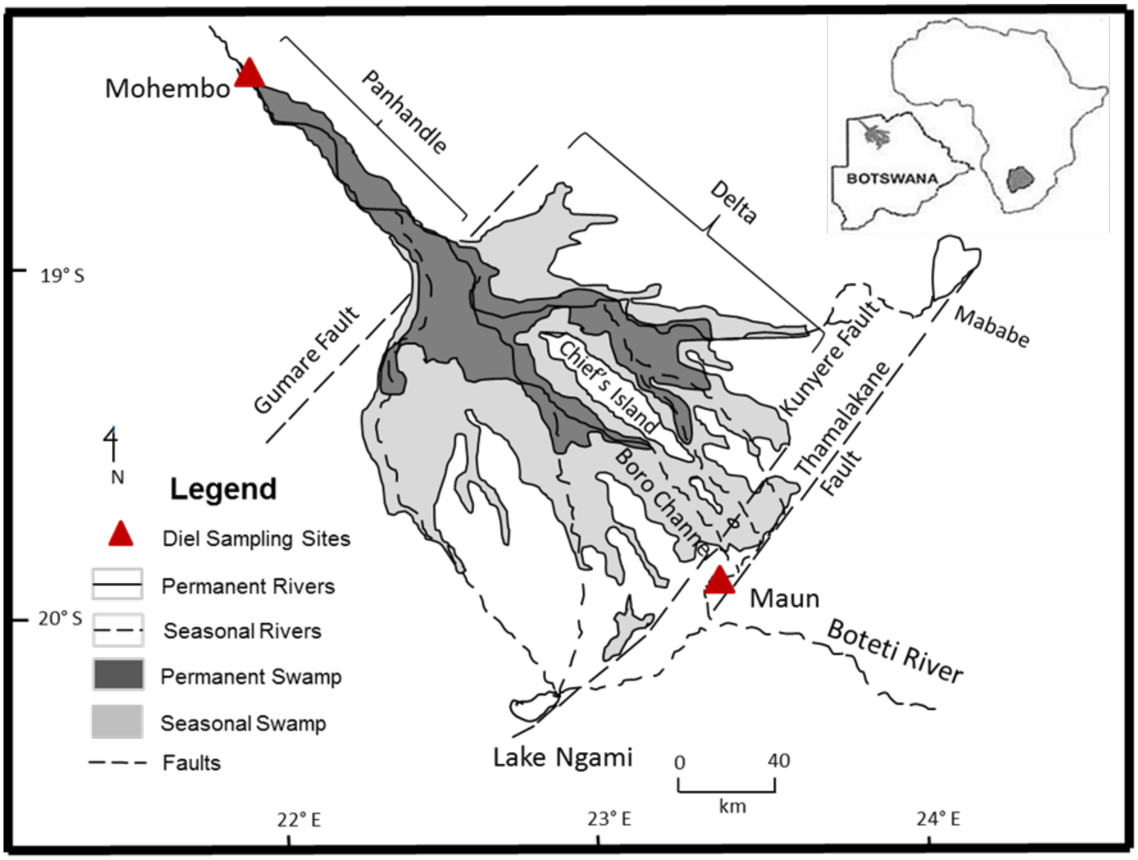

Figure 2: Map of the Okavango Delta showing the Okavango River and distributaries, faults, swamps and sampled locations. (Modified from Ellery et al., 2003)

In contrast, the Delta region is characterized by several distributaries formed on a low gradient alluvial fan approximately 22,000 km^3 (McCarthy et al., 1992; McCarthy et al., 1993; Stanistreet and McCarthy, 1993; Mackay et al., 2011). The Delta region has an average channel depth of 1 m and an average flow velocity of 0.1 ms^{-1} (McCarthy et al., 1988; Tooth and McCarthy, 2004) The average channel width in the lower delta region is 5 to 7 m (McCarthy et al., 1988).

The climate of the Okavango Delta region is arid, with a rainy season from November to March and a dry season from April to October (Wilson and Dincer, 1976; Sawula and Martins, 1991; McCarthy et al., 1993; McCarthy et al., 2012).

The mean annual temperature between 1996 and 2015 for the region is 24.2 °C (O.R.I., 2015). The mean annual temperature for 2010 is 23.7° C with a mean of 26.5°C in the rainy season and 21.8°C in the dry season (O.R.I., 2015). The mean annual rainfall between 1969 and 1994 for the region is 513 mm/y (McCarthy et al., 2012). The mean annual precipitation for 2010 was 627.9 mm (O.R.I., 2015). Potential evapotranspiration estimated at 1672 mm/y exceeds the annual precipitation by a factor of 3 (Wilson and Dincer, 1976; Dincer et al., 1987; Ellery, 1990; McCarthy et al., 2012).

The Okavango River is fed from its catchment in the subtropical highlands in Angola where the annual rainfall is approximately 983 mm/y. The average discharge of the headwater basins are 165 m^3/s in the Cubango River and 170 m^3/s in the Cuito River (Steudel, 2013). The Okavango River discharges 10 km^3/y of water into the Okavango Delta mostly as an annual flood pulse between April and August (McCarthy and Ellery, 1995; McCarthy, 2006). The extent of the inundation of the floodplains of the Okavango River and the distributaries is controlled by the magnitude of the annual discharge from the Angolan highlands (e.g., Gieske, 1997; McCarthy et al., 1998; McCarthy et al., 2003). The residence time of the flood pulse as it travels approximately 400 km through the Okavango Delta is four to six months (Wilson and Dincer, 1976; Gumbricht et al., 2004; Mackay et al., 2011). As water travels across the Okavango Delta, 2% or less infiltrates into the groundwater and approximately 2% of the water leaves through the Boteti River, while the rest is lost to evapotranspiration (Wilson and Dincer, 1976).

The channels of the Okavango River in the Panhandle occur in permanently flooded swamps and in the Delta region, the channels occur within permanently, seasonally and occasionally flooded swamps (Fig. 2) (McCarthy et al., 1992). The vegetation in the Panhandle include emergent strands of grass (*Miscanthus Junceus*), reeds (*Phragmites mauritianus*) and giant sedges (*Cyperus papyrus* and *Eliocharis*) (McCarthy and Ellery, 1998; Ellery et al., 2003). The submergent aquatic vegetation is dominated by water lilies (*Nymphaea, Brasenia schrebrei* and *Nympoides indica*) (McCarthy and Ellery, 1998; McCarthy et al., 2005). The permanently flooded swamps of the Delta region are inhabited by giant sedges (*Cyperus papyrus*) and reeds (*Phragmites mauritianus*) (Ellery et al., 2003; McCarthy et al., 2005). In the seasonal floodplains the main submergent plants are water lilies (*Nymphaea, Brasenia schrebrei* and *Nymphoides indica*) similar to the permanently flooded swamps (McCarthy and Ellery, 1998). The dominant emergent vegetation in the seasonal swamps are sedges (*Cyperus articulates, Cyperus papyrus* and *Schoenoplectus corymbosus*) (McCarthy and Ellery, 1998; Thito et al., 2015). In the occasional flooded areas, the emergent vegetation are mainly grasses (*Imoerata cylindrical*) as well as sedges with wild rice (*Oryza longistaminata* and *Leersia hexandra*) (McCarthy and Ellery, 1998). The permanently dry plains support trees (*Ficus verruculosa, F. sycamorus* and *Acacia nigrescens*) (Ellery et al., 1993; Ringrose et al., 2003; Thito et al., 2015).

CHAPTER III

METHODOLOGY

We conducted the 24 h experiments in the Okavango River at the proximal end of the Okavango Delta in Mohembo (18°16.647’S, 21°47.211’E) between 21 July 2010 19:00 to 22 July 2010 19:00 and in the Thamalakane River at the distal end of the Okavango Delta in Maun (19°94.1875’S, 23°49.638’E) between 14 July 2010 19:30 to 15 July 2010 19:30. At Mohembo, the discharge hydrograph was at the receding stage (Fig. 3a) and the discharge was ~998 m^3/s on 21 July 2010 and ~989 m^3/s on 22 July 2010 (O.R.I., 2015). In contrast at Maun, the hydrograph was in the rising stage (Fig. 3b) and nearly at peak discharge of ~26.2 m^3/s on 14 July 2010 and ~26.7 on 15 July 2010 (O.R.I., 2015). We sampled the Okavango River during the dry season, with clear skies and no precipitation. The wind speeds for Mohembo during the sampling period averaged of ~8.9 km/h to ENE and in Maun it was recorded at ~7.9 km/h to NE (WWO, 2010).

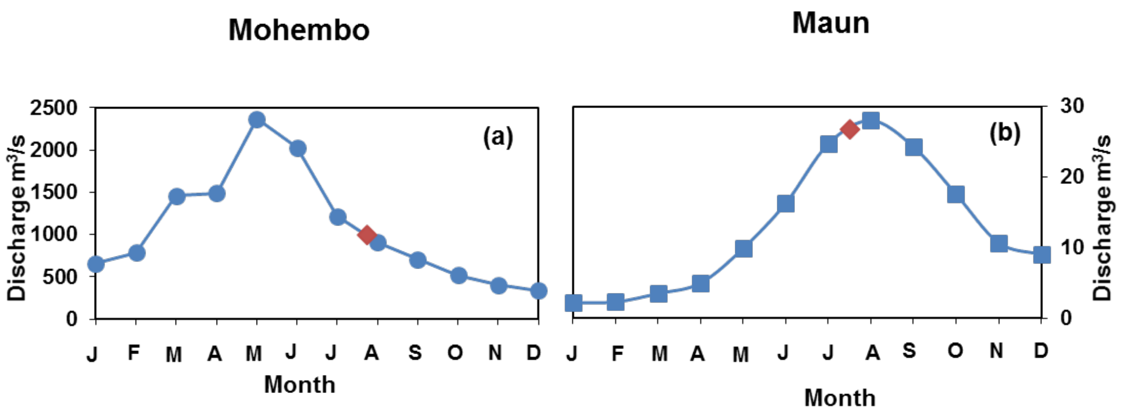

Figure 3: Plot of discharge hydrograph for 2010 at (a) Mohembo in the proximal portion of the Okavango Delta and (b) Maun in the distal portion of the Okavango Delta. The filled diamonds are the times during the flood stage samples were collected at the Mohembo and Maun stations for the 24 hr experiments.

Section 1. Air Temperature, River Level and Photosynthetic Available Radiation (PAR)

At each sampling site, we deployed a Solinist Levelogger Junior and Solinist Barologger Gold (Solonist, Ontario, Canada). The data loggers were hung with Kevlar rope in 50 mm poly vinyl chloride (PVC) tubes. Air temperature was measured using the Solonist Barologger with a precision of ±0.05°C. The Solonist barologger was deployed 1.5 m above the river level about 20 cm from the top of the PVC tube, which was perforated to allow for free flow of air. River level was measured with the Solonist Levelogger Junior and photosynthetically available radiation (PAR) was measured with a Li-192 underwater quantum sensor coupled to a Li-Cor 1400 data logger (LI-COR Environmental, Lincoln, NE). The Solonist Levelogger Junior had an overall precision of ±0.1% and ±0.1 cm and the Li-192 sensor had an overall precision of <1 µA/mol*sm^2.

The Solonist Levelogger and Li-192 sensor were mounted on a steel pole which was pounded into the stream bed. The Li-192 sensor and the Solonist Levelogger were mounted at 25 cm and 50 cm, respectively below the water surface. We calibrated the data loggers according to the manufacturer's recommendations before deployment. We programmed the Li-Cor 144 data logger, Solonist Levelogger and Barologger to collect readings every 15 minutes, comparing the hourly equivalent with our chemical data.

Section 2. Water Sampling and Analyses

We measured the water temperature, specific conductance (SPC), total dissolved solids (TDS), dissolved oxygen (DO) and pH at each sampling location using a Yellow Spring Instrument (YSI) multi-parameter probe calibrated according to the manufacturer's recommendations. The YSI probe has an accuracy reported with respect to: DO mg/L of ±0.2 mg/L, temperature of ±0.15°C, SPC of ±0.001 µS/cm and pH of ±0.2 units. Every hour, the YSI probe was lowered to about 25 cm below the water surface and the readings were allowed to stabilize before the readings were recorded.

Water samples were taken hourly at approximately 25 cm below the water surface using the grab technique. We attached a 2 L high density polyethylene (HDPE) bottle to a telescopic pole to reach into the river to collect the water. The water samples were filtered using a 0.45 µM nylon filter attached to a syringe, after collection and aliquots were dispensed into un-acidified 30 mL HDPE bottles for anions and into 60 mL HDPE bottles that were acidified with high purity nitric acid to a pH <2 for cations. Samples for DIC quantification and $\delta^{13}C_{DIC}$ determination were collected in 15 mL pre-evacuated vacutainer tubes that were preloaded with 1 mL of 85% H_3PO_4 and magnetic stir bars (Atekwana and Krishnamurthy, 1998). Samples for measurement of the δD and $\delta^{18}O$ were collected in 20 mL scintillation vials with inverted cone closure. All samples were kept cool in the field and during transportation to the USA, where they were stored in a refrigerator at 4°C until analyses.

Alkalinity was determined by sulfuric acid titration immediately after filtration in the field (HACH Company, 1992). The concentrations of K^+ Na^+ Ca^{2+} Mg^{2+} and Cl^-, SO_4^{2-} and NO_3^- were measured by ion chromatography using a Dionex ICS-3000 (Thermo Fisher Scientific, Sunnyvale, CA). Silica was measured by heteropoly blue colorimetry using a V-2000 multi-analyte photometer (CHEMetrics, Midland, VA). For DIC quantification, $CO_{2(g)}$ was extracted from the vacutainer tubes under vacuum and the $CO_{2(g)}$ yield determined manometrically (Atekwana and Krishnamurthy, 1998). The $\delta^{13}C_{DIC}$ of the extracted $CO_{2(g)}$ was measured on a Thermo Finnigan Delta Plus XL isotope ratio mass spectrometer (IRMS). The δD and $\delta^{18}O$ was measured by a high temperature conversion elemental analyzer (TCEA) coupled to a Thermo Finnigan Delta Plus XL IRMS. The stable isotope ratios are reported in the delta notation (δ) in per mill (‰):

$$\delta\ (‰) = ((R_{sample} - R_{standard}) / R_{standard}) \times 1000$$

Where R is D/H, $^{18}O/^{16}O$ or $^{13}C/^{12}C$. The δ values are reported relative to Vienna Standard Mean Ocean Water (VSMOW) for $\delta^{18}O$ and δD, and the $\delta^{13}C$ are reported relative to Vienna Pee Dee Belemnite (VDPB). Routine measurements of in-house standards and replicate samples have an overall precision of better than 0.2‰ for $\delta^{18}O$, 0.1‰ for δD and 0.1‰ for $\delta^{13}C$.

Section 3. Partial Pressure of CO_2 (pCO_2), Carbonate Speciation and Saturation Index with Respect to Calcite and Quartz

We used PHREEQC version 2 (Parkhurst and Appelo, 1999) to calculate the pCO_2 in the samples, using the DIC concentrations and the corresponding pH and temperature, as well as to model carbonate speciation (H_2CO_3, HCO_3^- and CO_3^{2-}). The saturation index with respect to calcite ($SI_{calcite}$) was calculated with PHREEQC version 2 (Parkhurst and Appelo, 1999) using DIC and Ca^{2+} concentrations and corresponding pH and temperature. The saturation index with respect to quartz (SI_{quartz}) was calculated with PHREEQC version 2 (Parkhurst and Appelo, 1999) using silica and corresponding pH and temperature.

CHAPTER IV

RESULTS

The physical, chemical and isotopic results for the Okavango River at Mohembo and Maun over a diel cycle are presented in Table 1. Also presented in Table 1 are the calculated values for pCO_2 and the saturated index of calcite ($SI_{calcite}$). Data not used in the main discussion is presented in the appendices tables (S1, S2, S3, S4 and S5).

Section 1. Physical Parameters

The air temperature in Mohembo ranges from 15.4°C to 29.5°C and in Maun it ranges from 5.5°C to 26.8°C (Table 1). The air temperature in Mohembo (Fig. 4a) and Maun (Fig. 4b) show cyclical variations over the 24 hrs. The air temperature was lowest at 8:00 at 15.4°C and was highest at 15:00 at 29.5°C in Mohembo and was lowest at 5.5°C at 7:30 and was highest at 26.8°C at 16:30 in Maun. Water temperature ranged from 16.5°C to 17.0°C in Mohembo and 15.5°C to 18.7°C in Maun (Table 1). The water temperature in Mohembo (Fig. 4c) and Maun (Fig. 4d) show cyclical variations over the 24 hrs.

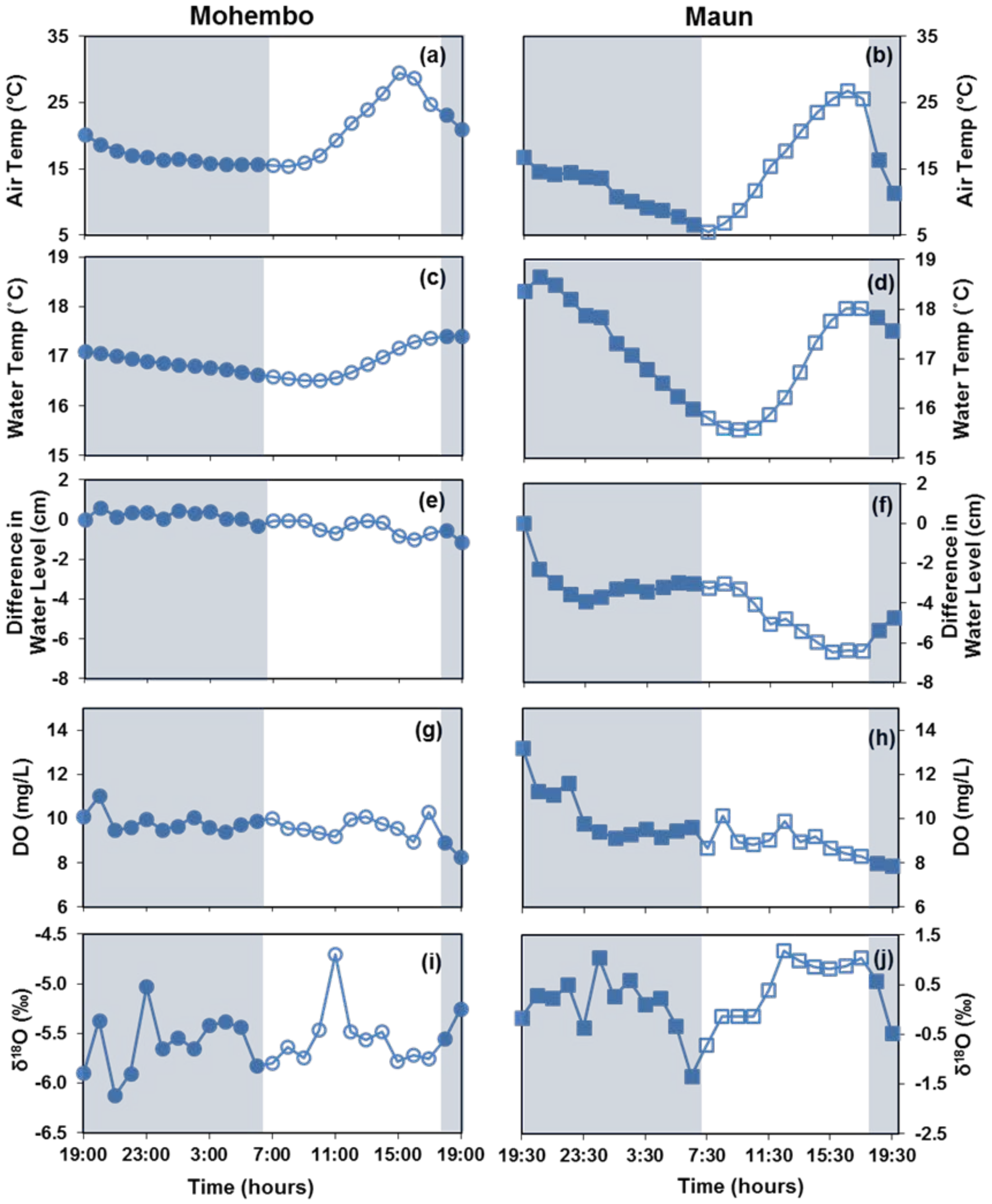

Figure 4: Plot of daily (24 h) variations of air temperature (a and b), water temperature (c and d), relative water level (e and f), dissolved oxygen (DO) (g and h) and the stable oxygen isotope ($\delta^{18}O$) of water (i and j) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The shaded areas and filled circles and squares represent night time and the unshaded portions and the open circles and squares represent daytime.

The minimum water temperature in Mohembo of 16.5°C was measured at 10:00 and the maximum of 17.0°C was measured at 17:00, while the minimum water temperature in Maun of 15.5°C was measured at 9:30 and the highest temperature of 18.7°C was measured at 18:30. There appears to be a 2 h lag time between the lowest and the highest air temperature and the lowest and highest water temperatures measured at Mohembo and Maun.

The water level from the start to the end of the 24 h in Mohembo decreases by -0.5 cm and by about -6.0 cm in Maun (Table 1). The water level in Mohembo decreases slowly throughout (Fig. 4e). There appears to be minor perturbations showing lower levels at Maun where the rate of decrease levels off at 23:30, then begins a steeper decrease at 7:30 before starting to rise at 16:30. The DO concentrations (Table 1) at Mohembo ranges from 8.3 mg/L to 11.0 mg/L and varies around 10 mg/L over the 24 h (Fig. 4g). The DO concentrations in Maun range from 7.9 mg/L to 13.2 mg/L and decrease steeply at night and continue over the 24 h (Fig. 4h). At Maun, the rate of decrease in the DO concentrations is steeper during the night compared to a slight DO decrease during the day. The δ^{18}O for Mohembo varied about 2.0 ‰ with no clear diel trend (Fig. 4i), in contrast, the δ^{18}O in Maun varied by 2.0 ‰ and shows slight enrichment over the 24 h period. The δ^{18}O increases from 19:30 to 24:00 followed by a decrease to a minimum of -1.3 ‰ at 6:30 and increases to a maximum of 1.2 ‰ at 12:30 which then stays nearly constant at 0.98 ‰ to 17:30 before decreasing to -0.5 ‰ by 19:30 (Fig. 4j).

Section 2. Solute Chemistry

The total dissolved solids at Mohembo ranges from 7 mg/L to 7.8 mg/L and in Maun from 39.5 mg/L to 44.9 mg/L (Table 1). The TDS in Mohembo (Fig. 5a) show slight decreasing concentrations at night and increasing concentrations during the day. In contrast, the TDS concentrations in Maun (Fig. 5b) steadily decrease during the night and increase sharply during the day. Throughout the 24 h, the TDS concentrations in Mohembo are lowest at 23:00 and then gradually increase to its highest value of 7.8 mg/L at 18:00. In Maun, the TDS concentration are lowest at 9:30 at 39.5 mg/L and highest at 44.9 mg/L at 19:30. The silica concentration in Mohembo ranges from 5.1 mg/L to 14.4 mg/L and in Maun, it ranges from 25.2 mg/L to 49.5 mg/L (Table 1). The silica concentration in Mohembo (Fig. 5c) decreases from the maximum of 14.4 mg/L at 19:00 to 8:00 followed by an increase until 19:00. In contrast, the silica concentration in Maun (Fig. 5d) is lowest at 5:30 at 25.2 mg/L and highest at 21:30 at 49.5 mg/L, showing a distinct diel behavior, with decreasing concentration from 21:30 to 5:30 and steadily increasing to the day time maximum of 46.2 mg/L at 15:30 followed by a decrease to 19:30. The Ca^{2+} concentrations at Mohembo ranges from 3.6 mg/L to 4.2 mg/L and in Maun it ranges from 8.8 mg/L to 9.6 mg/L (Table 1). The Ca^{2+} concentrations in Mohembo spikes at 19:00 with the night high of 4.1 mg/L then decreases sharply to a low of 3.6 mg/L, staying relatively constant until 2:00 followed by a steady increase until three spikes at 11:00, 7:00, and 11:00 at 4.1 mg/L and then decreasing to the low of 3.7 mg/L, staying steady until 19:00 (Fig. 5e).

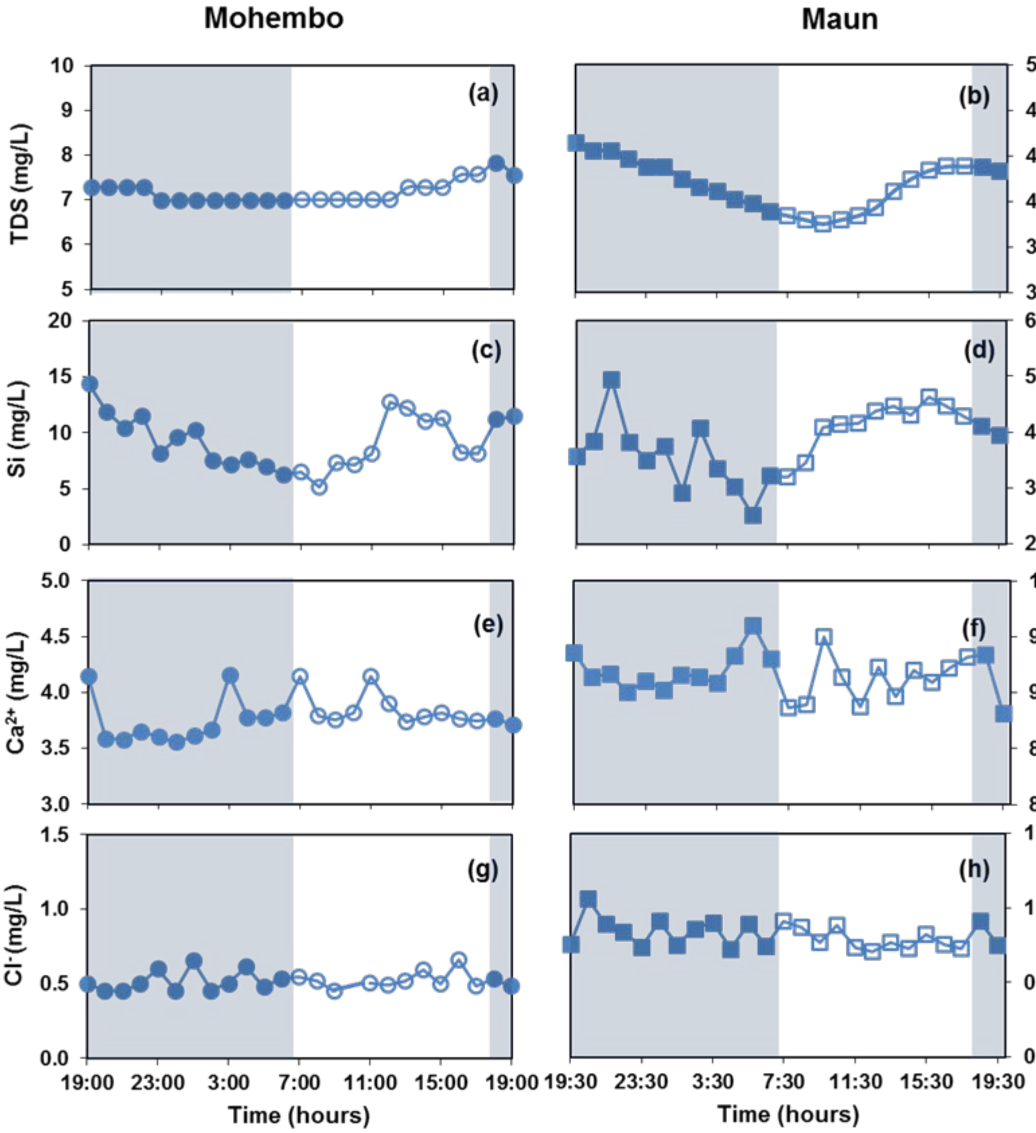

Figure 5 : Plot of daily (24 h) variations of total dissolved solids (TDS) (a and b), Si (c and d), Ca^{2+} (e and f) and Cl^- (g and h) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The shaded areas and filled circles and squares represent night time and the unshaded portions and the open circles and squares represent daytime.

The Ca^{2+} concentrations in Maun 19:30 start at 9.4 mg/L, and then decrease continuously to 9.1 mg/L then a sharp increase to 9.6 mg/L at 5:30 continued to a sharp decrease to the low at 7:30 of 8.9 mg/L then increase steadily until 18:30 with 9.3 mg/L, followed by a decrease to the low at 19:30 with 8.8 mg/L (Fig. 5f). The Cl^- concentrations at Mohembo ranges from 0.5 mg/L to 0.7 mg/L and in Maun they range from 0.7 mg/L to 1.1 mg/L (Table 1). The Cl^- concentrations varied slightly and showed no clear diel trend in Mohembo (Fig. 5g) and in Maun (Fig. 5h), the Cl^- concentrations vary around 0.8 mg/L, showing a very gentle decreasing trend throughout the diel cycle.

Section 3. Carbon Response

The PAR in Mohembo ranges from 0 µA/mol*sm^2 to 1077 µA/mol*sm^2 and from 0 µA/mol*sm^2 to 423 µA/mol*sm^2 in Maun (Table 1). The PAR in Mohembo (Fig. 6a) and in Maun (Fig. 6b) show clear increases and decreases over 24 h. PAR increases slowly from 6:00 to the highest value of 1077 µA/mol*sm^2 measured at 13:00, creating a sharp peak at this time and decreasing to 0 µA/mol*sm^2 at 18:00. In Maun the minimum PAR of 0 µA/mol*sm^2 is measured at 8:30, then increasing slowly to 10:30 and steeply to the highest PAR value of 423 µA/mol*sm^2 at 13:30 and decreases steeply to 0 µA/mol*sm^2 at 18:30. The pH in Mohembo ranges from 5.6 to 6.3 (Table 1) increasing from 6.2 at 19:00 to 6.4 at 9:00, then decreases steeply to 11:00 followed by a gradual increase to 5.7 and a sharp increase to 6.1 at 19:00 (Fig. 6c). The pH in Maun (Fig. 6d) ranges from 6.6 to 7.1, gently decreasing from 19:00 to its minimum of 6.6 at 6:30, followed a steep increase from 6:30 to its maximum of 7.1 at 17: 30 then staying stable until 19:30. The alkalinity concentrations at Mohembo ranges from 5 mg/L to 20 mg/L and at Maun from 45.7 mg/L to 49.5 mg/L (Table 1). The alkalinity concentrations in Mohembo shows a gentle cyclical variation over the 24 h (Fig. 6e) decreasing from its highest concentration of 20 mg/L at 22:00 to the lowest concentration of 5 mg/L at 15:00 followed by an increase to 10 mg/L to 19:00. The alkalinity concentrations in Maun (Fig. 6f) decreases gently from 49.5 mg/L at 23:30 to the minimum of 45.7 mg/L at 9:30 followed by variations around a general increasing trend from 9:30 to its daytime maximum of 49.1 mg/L at 15:30 before decreasing to 46.9 mg/L at 19:30. The variations in alkalinity in Maun could be affected by human error, because multiple people titrated the samples and could have different color end points. The DIC concentrations in Mohembo ranges from 5 mg C/L to 7.5 mg C/L and from 9 mg C/L to 7 mg C/L in Maun (Table 1). The DIC concentrations in Mohembo vary between the highest concentration of 7.4 mg C/L at 20:00 and the lowest concentration of 4.9 mg C/L at 16:00 with mostly decreasing concentrations over the 24 h (Fig. 6g). In Maun (Fig. 6h), the DIC concentrations varied between the highest measurement of 8.8 mg C/L at 21:30 and the lowest of 7.4 mg C/L at 16:30 with decreasing concentration throughout 24 h. The $\delta^{13}C_{DIC}$ ranges from -11‰ to -7.5‰ at Mohembo and -7‰ to -5‰ at Maun (Table 1). The $\delta^{13}C_{DIC}$ in Mohembo decreases from -7.9 ‰ at 22:00 to 12:00 then increases sharply to -8.4 ‰ at 13:00 staying relatively steady the rest of the sampling period (Fig. 6i). In contrast, the $\delta^{13}C_{DIC}$ in Maun varied by 2‰ and shows clear enrichment with a general decrease from 19:30 to the minimum of -6.7 ‰ at 7:30 followed by an increasing trend to the maximum value of -4.8 ‰ at 15:30 before decreasing to -5.6 at 19:30 (Fig. 6j).

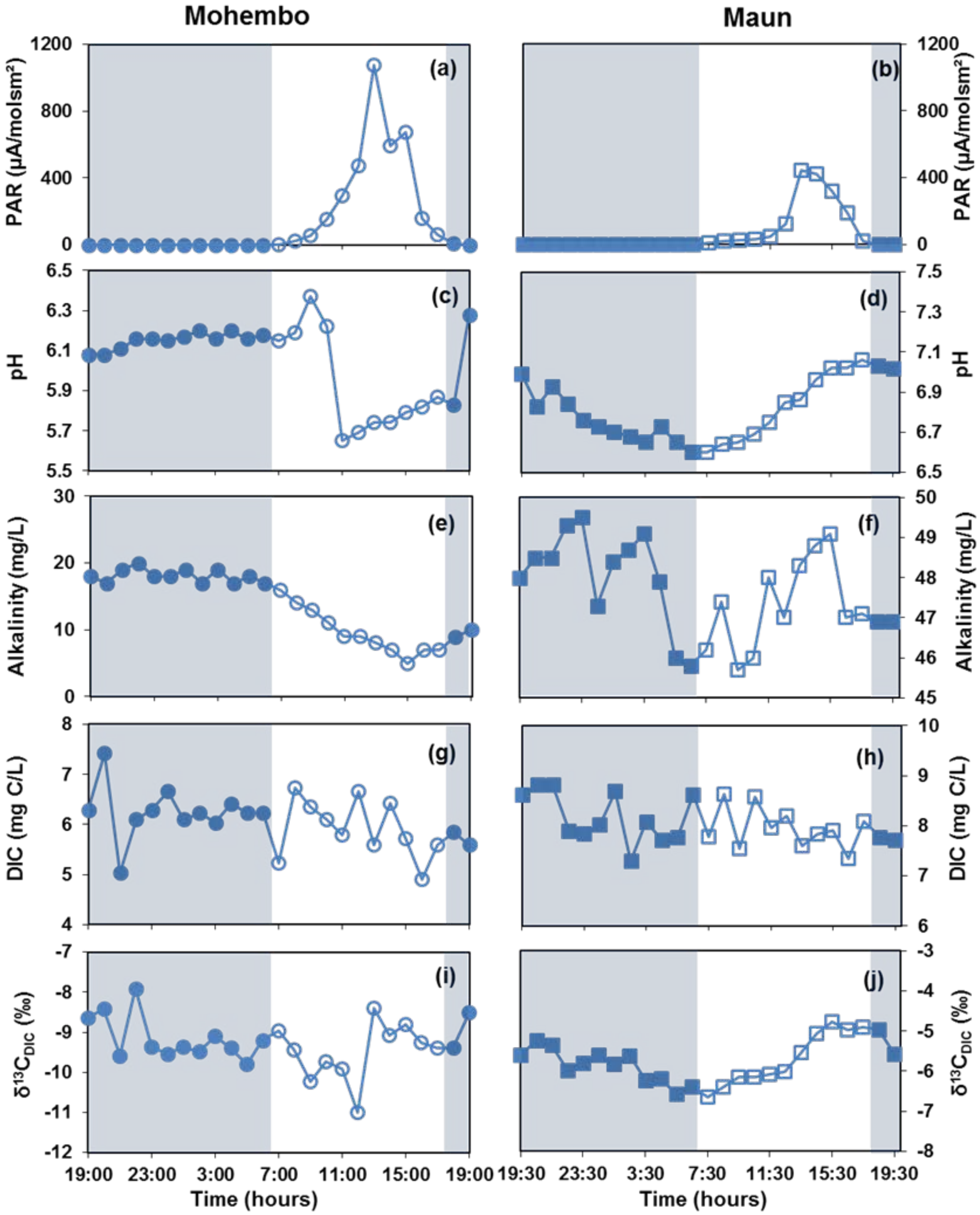

Figure 6: Plot of daily (24 h) variations of photosynthetically available radiation (PAR) (a and b), pH (c and d), alkalinity (e and f), dissolved inorganic carbon (DIC) (g and h) and the stable carbon isotope composition of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) (i and j) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The shaded areas and filled circles and squares represent night time and the unshaded portions and the open circles and squares represent daytime.

Table 1: Physical, chemical and isotopic results of river water from the proximal portions of the Okavango Delta at Mohembo and at the distal portion of the Okavango Delta at Maun over 24 h

Sample Station	Time (hr)	Air Temp (°C)	Water temp (°C)	Water level (cm)	DO (mg/L)	$\delta^{18}O$ (‰)	Cond (µs/cm)	Cl^- (mg/L)	Ca^{2+} (mg/L)	Si (mg/L)	PAR (µA/ $molSm^2$)	pH	Alk (mg/L)	DIC (mgC/L)	$\delta^{13}C_{DIC}$	Log pCO2 (atm)	SI_{cal}
Mohembo	**19:00**	20.1	17.1	177.67	10.1	-5.9	11.2	0.5	4.1	14.4	0	6.1	18	6.3	-8.6	-2.8	-4.4
	20:00	18.8	17.1	178.28	11.0	-5.4	11.2	0.5	3.6	11.9	0	6.1	17	7.4	-8.4	-2.7	-4.4
	21:00	17.8	17.0	177.82	9.5	-6.1	11.2	0.5	3.6	10.5	0	6.1	19	5.0	-9.6	-2.9	-4.5
	22:00	17.1	16.9	178.05	9.6	-5.9	11.2	0.5	3.7	11.6	0	6.2	20	6.1	-7.9	-2.8	-4.3
	23:00	16.8	16.9	178.04	9.9	-5.0	10.8	0.6	3.6	8.2	0	6.2	18	6.3	-9.4	-2.8	-4.3
	0:00	16.4	16.9	177.73	9.5	-5.7	10.8	0.5	3.6	9.6	0	6.2	18	6.7	-9.5	-2.8	-4.3
	1:00	16.6	16.8	178.14	9.7	-5.5	10.8	0.7	3.6	10.2	0	6.2	19	6.1	-9.3	-2.8	-4.3
	2:00	16.2	16.8	178.01	10.1	-5.7	10.8	0.5	3.7	7.5	0	6.2	17	6.2	-9.5	-2.8	-4.2
	3:00	15.9	16.8	178.10	9.6	-5.4	10.8	0.5	4.2	7.2	0	6.2	19	6.0	-9.1	-2.8	-4.3
	4:00	15.7	16.7	177.72	9.4	-5.4	10.8	0.6	3.8	7.7	0	6.2	17	6.4	-9.4	-2.8	-4.2
	5:00	15.7	16.7	177.70	9.7	-5.4	10.8	0.5	3.8	6.9	0	6.2	18	6.2	-9.8	-2.8	-4.3
	6:00	15.8	16.6	177.36	9.9	-5.8	10.8	0.5	3.8	6.2	0	6.2	17	6.2	-9.2	-2.8	-4.3
	7:00	15.5	16.6	177.63	10.0	-5.8	10.8	0.5	4.1	6.5	0	6.2	16	5.2	-8.9	-2.9	-4.4
	8:00	15.4	16.6	177.63	9.5	-5.6	10.8	0.5	3.8	5.1	20	6.2	14	6.7	-9.5	-2.8	-4.2
	9:00	15.9	16.5	177.59	9.5	-5.8	10.8	0.5	3.8	7.4	54	6.4	13	6.4	-10.2	-2.9	-4.0
	10:00	17.0	16.5	177.16	9.4	-5.5	10.8	2.2	3.8	7.1	150	6.2	11	6.1	-9.7	-2.9	-4.2
	11:00	19.3	16.6	176.97	9.2	-4.7	10.8	0.5	4.1	8.2	295	5.7	9	5.8	-9.9	-2.7	-5.2
	12:00	21.9	16.7	177.48	9.9	-5.5	10.8	0.5	3.9	12.8	474	5.7	9	6.7	-11.0	-2.7	-5.0
	13:00	23.9	16.8	177.60	10.1	-5.6	11.2	0.5	3.7	12.2	1077	5.7	8	5.6	-8.4	-2.8	-5.0
	14:00	26.4	16.9	177.54	9.8	-5.5	11.2	0.6	3.8	11.0	590	5.7	7	6.4	-9.1	-2.7	-5.0
	15:00	29.5	17.2	176.82	9.6	-5.8	11.2	0.5	3.8	11.3	672	5.8	5	5.7	-8.8	-2.8	-4.9
	16:00	28.7	17.3	176.66	8.9	-5.7	11.6	0.7	3.8	8.2	159	5.8	7	4.9	-9.3	-2.8	-4.9
	17:00	24.7	17.4	176.96	10.3	-5.8	11.6	0.5	3.7	8.2	59	5.9	7	5.6	-9.4	-2.8	-4.8
	18:00	23.1	17.4	177.15	8.9	-5.6	12.1	0.5	3.8	11.3	6	5.8	9	5.9	-9.4	-2.8	-4.9
	19:00	20.9	17.4	176.53	8.3	-5.3	11.6	0.5	3.7	11.5	0	6.3	10	5.6	-8.5	-2.9	-4.2
Maun	**19:30**	16.8	18.4	161.21	13.2	-0.2	69.1	0.8	9.4	35.7	0	6.9	48.0	8.6	-5.6	-3.2	-2.6
	20:30	14.6	18.7	158.92	11.2	0.3	68.3	1.1	9.1	38.5	0	6.8	48.5	8.8	-5.2	-3.0	-2.8
	21:30	14.2	18.5	158.25	11.1	0.2	68.3	0.9	9.2	49.5	0	6.9	48.5	8.8	-5.4	-3.1	-2.6
	22:30	14.4	18.2	157.66	11.6	0.5	67.4	0.8	9.0	38.3	0	6.8	49.3	7.9	-5.9	-3.1	-2.8
	23:30	13.8	17.9	157.30	9.8	-0.4	66.6	0.7	9.1	35.0	0	6.8	19.5	7.8	-5.8	-3.0	-2.9
	0:30	13.7	17.8	157.54	9.4	1.1	66.6	0.9	9.0	37.6	0	6.7	47.3	8.0	-5.6	-3.0	-3.0
	1:30	10.9	17.3	157.91	9.2	0.3	65.4	0.8	9.2	29.2	0	6.7	48.4	8.7	-5.8	-2.9	-3.0
	2:30	10.1	17.1	158.05	9.3	0.6	64.5	0.9	9.1	40.8	0	6.7	48.7	7.3	-5.6	-3.0	-3.1
	3:30	9.2	16.8	157.81	9.5	0.1	64.1	0.9	9.1	33.6	0	6.7	49.1	8.1	-6.2	-2.9	-3.1
	4:30	8.8	16.5	157.01	9.2	0.2	63.3	0.7	9.3	30.3	0	6.7	47.9	7.7	-6.2	-3.0	-3.0
	5:30	7.8	16.2	158.23	9.5	-0.3	62.9	0.9	9.6	25.2	0	6.7	46.0	7.8	-6.6	-2.9	-3.1
	6:30	6.7	15.9	158.21	9.6	-1.3	62.0	0.7	9.3	32.2	0	6.6	45.8	8.6	-6.4	-2.9	-3.1
	7:30	5.5	15.8	157.96	8.7	-0.7	61.6	0.9	8.9	31.9	7	6.6	46.2	7.8	-6.7	-2.9	-3.2
	8:30	6.8	15.6	158.20	10.1	-0.1	61.2	0.9	8.9	34.5	22	6.6	47.4	8.6	-6.4	-2.9	-3.1
	9:30	8.8	15.6	157.90	8.9	-0.1	60.8	0.8	9.5	40.9	27	6.7	45.7	7.5	-6.2	-2.9	-3.1
	10:30	11.7	15.6	157.13	8.8	-0.1	61.2	0.9	9.1	41.3	33	6.7	46.0	8.6	-6.2	-2.9	-3.0
	11:30	15.3	15.9	156.13	9.0	0.4	61.6	0.7	8.9	41.6	47	6.8	48.0	8.0	-6.1	-3.0	-3.0
	12:30	17.6	16.2	156.41	9.9	1.2	62.5	0.7	9.2	43.7	121	6.9	47.0	8.2	-6.0	-3.1	-2.8
	13:30	20.7	16.7	155.79	8.9	1.0	64.1	0.8	9.0	44.6	443	6.9	48.3	7.6	-5.5	-3.1	-2.8
	14:30	23.5	17.3	155.22	9.2	0.9	65.4	0.7	9.2	43.0	423	6.9	48.8	7.8	-5.1	-3.2	-2.7
	15:30	25.5	17.8	154.75	8.7	0.8	66.2	0.8	9.1	46.2	314	7.0	49.1	7.9	-4.8	-3.2	-2.6
	16:30	26.8	18.0	154.83	8.4	0.9	66.6	0.8	9.2	44.7	188	7.0	47.0	7.4	-4.9	-3.3	-2.6
	17:30	25.5	18.0	154.77	8.3	1.0	66.6	0.7	9.3	42.8	21	7.1	47.1	8.1	-4.9	-3.3	-2.5
	18:30	16.4	17.8	155.84	7.9	0.6	66.6	0.9	9.3	41.2	0	7.0	46.9	7.8	-4.9	-3.2	-2.6
	19:30	11.3	17.6	156.49	7.9	-0.5	66.2	0.8	8.8	39.5	0	7.0	46.9	7.7	-5.6	-3.2	-2.6

CHAPTER V

DISCUSSION

Section 1. Evapoconcentration During River Transit

Some of the physical, chemical and isotopic parameters measured in this study show distinct diel variations in the Okavango River at Mohembo and Maun. For example, the water temperature is increasing during the day and decreaseing at night (Fig. 4c and d), river level which is a proxy for discharge shows a greater decrease during the day than at night, with a larger fluctuation observed in Maun (Fig. 4e and f). The solute concentrations represented by TDS decreases at night and increase during the day, due to evapotranpirative effects changing the ratio of water to solutes in the water column (Fig. 5a and b). Our results show that the concentrations of the measured parameters are generally much higher in Maun than in Mohembo and that the magnitude of variations in the physical and chemical parameters measured over 24 h is greater in Maun compared to Mohembo.

Water in the Okavango River in Mohembo flows for more than 400 km over a 4 to 6 month period to arrive Maun (Wilson and Dincer, 1976; Gumbricht et al., 2004; Mackay et al., 2011). River water flowing from Mohembo to Maun undergoes chemical changes from the hot climate regime which enhances evapotranspiration of the river water.

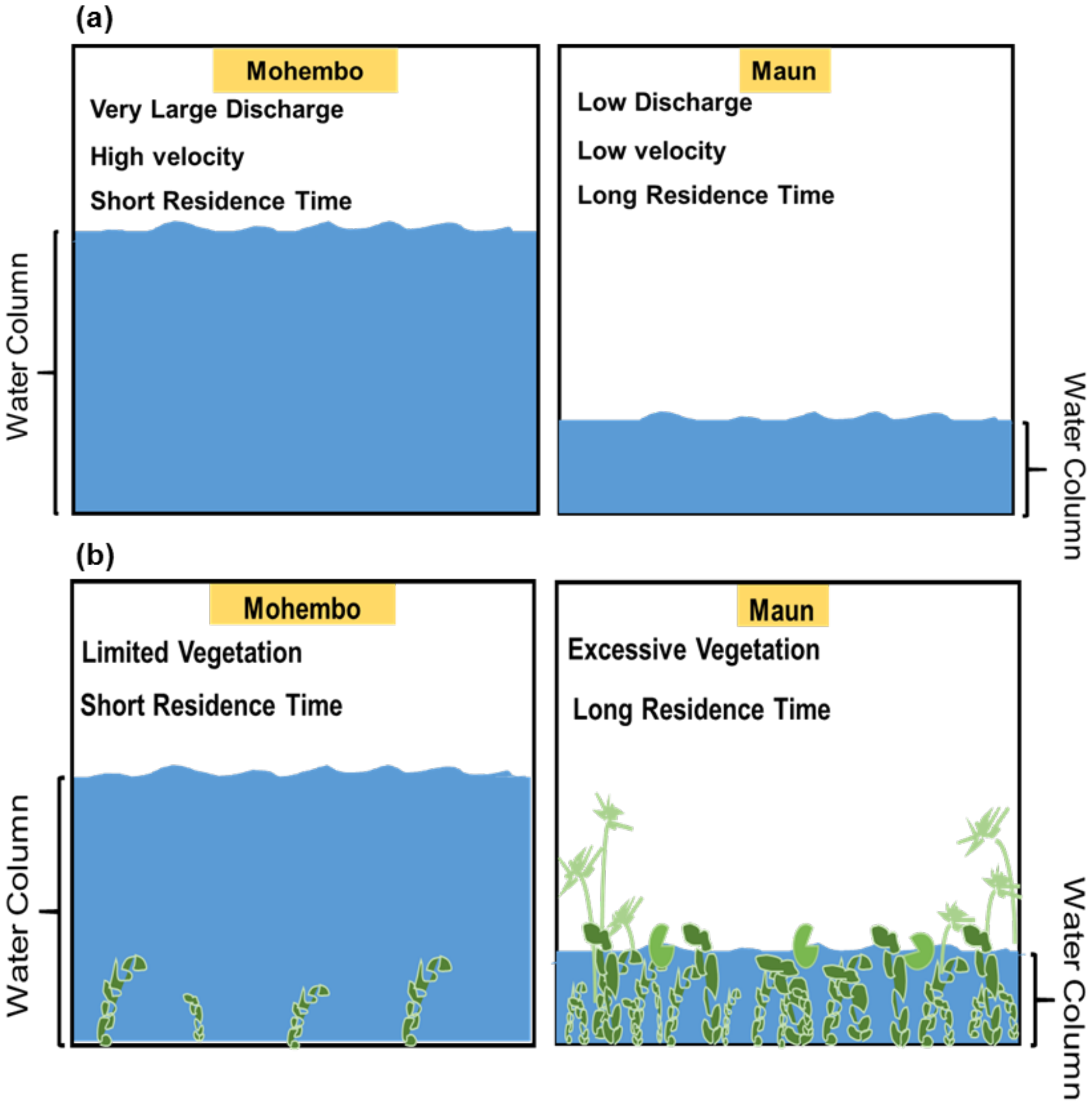

Figure 7: Schematic showing the hydrologic differences (a) and vegetative differences (b) between Mohembo in the proximal portion of the Okavango Delta and Maun in the distal portion of the Okavango Delta.

Modification of river water properties reported in other studies include much higher concentrations of solutes (Sawula and Martins, 1991; Krah et al., 2006; Bauer-Gottwein et al., 2007; Mackay et al., 2011; Akoko et al., 2013), DIC (Akoko et al., 2013) and DOC (Bauer-Gottwein et al., 2007; Mackay et al., 2011; Cawley et al., 2012; Akoko et al., 2013) in the Okavango River sampled in Maun compared to Mohembo. We use a conceptual model (Fig. 7a) to explain how the hydrologic conditions at both locations can cause variations in the physical and chemical parameters. Thus, the higher concentrations in the measured parameters (e.g., TDS, silica, alkalinity and DIC) in Maun relative to Mohembo (Table 1) is explained by the difference in discharge residence times and evapoconcentration during river transit between the two locations. Discharge in Mohembo is ~998 m^3/s which is 38 times greater than discharge of ~26 m^3/s at Maun. The River flows faster in Mohembo compared to Maun. This allows for greater volume and shorter contact time for water in Mohembo decreasing the magnitude of change imposed to river water from physical (solar energy) and biogeochemical alteration.

If the greater magnitude in the concentrations of solutes in Maun compared to Mohembo is from evapotranspiration, it is not clear why the short term daily response in the water properties such as temperature (Figs. 4c and d), river level (Fig. 4e and f), TDS (Fig. 5a and b) and silica (Fig. 5c and d) show greater change at Maun than at Mohembo. Diel variations in the physical, biological and chemical processes in the water columns of rivers are controlled by their response to light and energy difference during daytime and night time as depicted in Figure 8 (e.g., Nimick et al., 2005; Parker et al., 2007; Westhorpe et al., 2012). For example, during the day, solar energy causes the air and water temperatures to increase which causes increased evapotranspiration, while at night, lack of solar radiation causes air and water temperatures to decrease, stopping transpiration and causing evaporation decreases. Also, during the day, photosynthesis causes a decrease in the concentration of aquatic $CO_{2(aq)}$ and at night, $CO_{2(g)}$ produced by respiration causes increase in aquatic $CO_{2(aq)}$ concentration with the shutdown of photosynthesis (Falkowski and Raven, 1997).

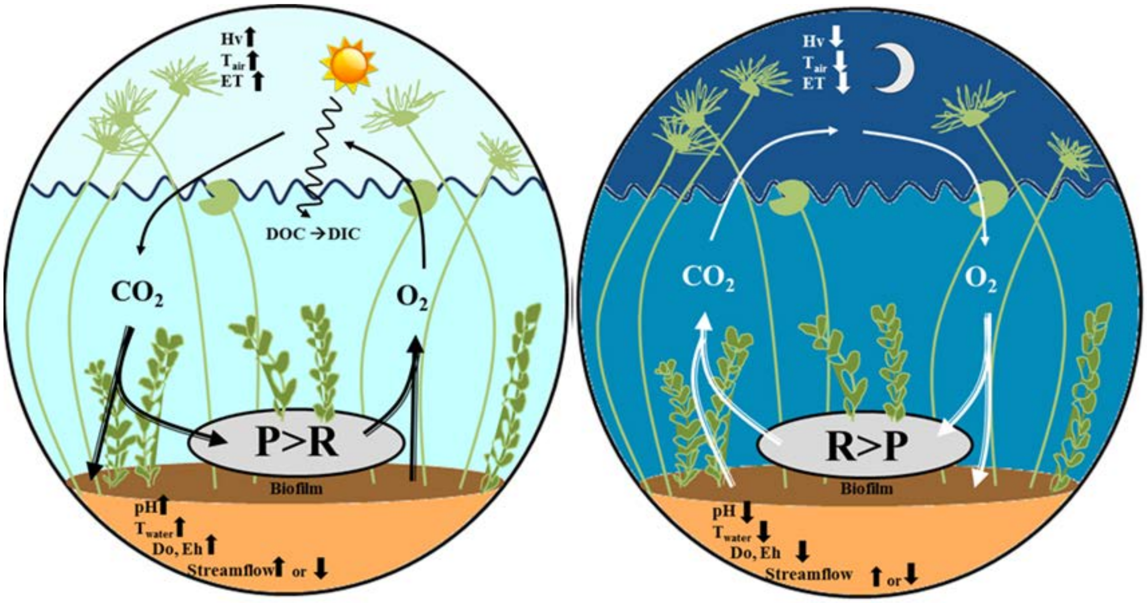

Figure 8 : Schematic showing diel biogeochemical processes affecting chemistry of the Okavango River. Bold arrows indicate increase (↑) or decrease (↓), Hv = photons, T = temperature, ET = evapotranspiration, DO = dissolved oxygen, P = photosynthesis, R = respiration, DOC = dissolved organic carbon, DIC = dissolved inorganic carbon (modified from Nimick et al., 2011).

The length of daylight hours (11 hours) is similar while the range in daylight air temperature (Mohembo 15.3°C - 29.5°C, Maun 5.5°C – 29.5°C) is dissimilar between Mohembo and Maun and can be used to argue that the differences in the magnitude of the variations in the physical and chemical properties of river water over 24 h is controlled by solar energy. The Okavango River is not shaded and if we assume that the physical, biological and chemical processes driven by the presence or absence of solar radiation occur equally at both locations, then river conditions that affect the physical, biological and chemical processes must be important over 24 h. These processes must describe input of mass or removal of mass from the water column which will affect water column chemical and isotopic properties. The addition of mass into the water column from groundwater influx (hydrological considerations) and from biological and chemical conversion and the removal of mass by biological and chemical conversion can explain the variations observed over 24 h. We note that in this scenario, removal of water from the water column into the groundwater system does not partition dissolved solutes. As our sampling locations were stationary, we did not follow a particular parcel of water as it evolved through the delta. The processes controlling the water we sampled mainly occurred further up river of our sampling locations and we can estimate the upriver distance using the averaged river flow velocity at each location. By the end of the 24 h sampling at Mohembo, the river water we sampled came from a distance of ~35 km/day. The river reach is a wetland and has an open channel bordered by a floodplain ecotone that is seasonally flooded and consist of sedges (*Cyperus articulates*, *Cyperus papyrus* and *Schoenoplectus corymbosus*) (Shaw and K., 1947; McCarthy and Ellery, 1998; Thito et al., 2015). In Maun, our samples came from a distance of ~9 km/day upriver. Here, the river channel is vegetated and bordered by a wetland and floodplain ecotone that is occasionally flooded and consists of grasses (*Imoerata cylindrical*) as well as sedges with wild rice (*oryza longistaminata* and *Leersia hexandra*) (McCarthy et al., 1998; McCarthy and Ellery, 1998).

Section 2. Cause of Diel Cycling of River Level

Over the 24 h of the experiment, the river level which decreases continuously, shows steeper decreases during the day compared to apparent increases in the early evening followed by slow declines later at night time (Fig. 4e and f). Over 24 h, the river level decreased in Mohembo by 0.5 cm, while it decreased in Maun by 6 cm (Table 1). There was no precipitation during this study, eliminating influx of rainwater as the cause of river level increases. In arid climates with effluent streams, phreatophytes cause diel cycles in stream discharge, whereby stream levels decrease during the day from groundwater interception and increase at night as transpiration is shutoff (e.g., Loheide et al., 2005; Chen et al., 2011). The nature of the tree distribution and the types of trees found to lower groundwater is dissimilar to shrubs and grasses that line the channel edges of the Okavango River. Transpiration from trees lower groundwater levels on islands in the Okavango delta (McCarthy and Ellery, 1994; McCarthy et al., 2005; Bauer-Gottwein et al., 2007). The shallow rooted emergent vegetation and shrubs and grasses mostly responsible for transpiration do not intercept groundwater influx into the river because the river is influent. Groundwater flow in the Okavango Delta at the edge of the Okavango wetlands is characterized by potentiometric surfaces with steep hydraulic gradients away from the wetlands (McCarthy and Ellery, 1998; McCarthy, 2006). With the flow of river water away from the Okavango wetlands into deeper aquifers, groundwater is unlikely to discharge into the Okavango River. River infiltration into the groundwater, evaporation and transpiration are the mechanisms that cycle water in the Okavango Delta (e.g., Wilson and Dincer, 1976) although the groundwater recharge is considered small or negligible (Dincer et al., 1987). If infiltration is occurring, it will likely be a continuous process along the river channel, and as the water temperature is above 15°C (Table 1), the infiltration will not be slowed due to increased water viscosity at night.

We argue that the diel cycle observed in river levels is associated with evaporation and transpiration induced by solar energy. The $\delta^{18}O$ and the δD co-vary, and are positively correlated (Fig. 9a and b). The $\delta^{18}O$ vs. δD relationships are defined by the least squares regression equations: $\delta D = 3.5\delta^{18}O - 14.8$ for samples from Mohembo and $\delta D = 3.0\delta^{18}O - 9.2$ for samples from Maun. The nearly similar slopes (3.5 for Mohembo vs. 3.0 for Maun) can be used to suggest that the effect of evaporation is similar at both sampling locations. In Figure 9a the correlation of the daytime trend line, closely follows the Global Meteoric Water Line (GMWL), suggesting that the source waters have not undergone extensive evaporation from the headwater of the catchment to Mohembo. The correlation of the daytime correlation in Maun is similar Okavango Delta Evaporation Line (ODEL), as the water has undergone extensive evaporation by the time it reaches the distal end of the delta (Fig. 9b). Thus, the hydrologic condition and the greater magnitude in decrease in the river level at Maun compared to Mohembo could be due to transpiration as transpiration does not discriminate against ^{16}O vs. ^{18}O or H vs. D during the uptake of water (Walker and Richardson, 1991). This is supported by the greater relative abundance of vegetation in the river channel and the abundance of emergent aquatic vegetation in the wetland ecotones upstream from the Maun sampling location (Fig. 7). In Mohembo, emergent vegetation was absent from the main channel while in Maun, the channel was heavily populated with emergent vegetation. We use a conceptual model (Fig. 7b) to depict the vegetative differences between our sampling locations. The excessive emergent and submergent vegetation in the distal end of the delta in Maun will affect solute cycling, by transpiration and affect aqueous CO_2 through the processes of photosynthesis and respiration.

Although we compare hydrologic conditions at Mohembo and Maun, sampling in Mohembo was conducted during the receding state of the flood pulse (Fig. 3a), whereas in Maun, sampling was conducted during the rising flood discharge (Fig. 3b). The discharge at Mohembo was 38 times greater than at Maun and the greater discharge and the relatively faster flow velocity may dampen the river level change from evapotranspiration. In this scenario, the river at Maun flows slowly in a shallow channel which allows for greater effect of solar radiation induced evaporation and transpiration causing the greater lowering of the water level (e.g., Fig 7).

Although evaporation is only one of the two mechanisms responsible for removal of water from the river water column, its effect relative to transpiration, which dominates in the daylight period can be qualitatively tested. The relationship between the $\delta^{18}O$ and river temperature and river level can be used to independently support the importance of evaporation. There is no relationship between the $\delta^{18}O$ and daytime water temperature (Fig. 9c) and water level (Fig. 9e) in Mohembo, while in Maun, the $\delta^{18}O$ is positively correlated ($R^2=0.53$) with daytime river temperature (Fig. 9d) and negatively correlated ($R^2=0.71$) with river level (Fig. 9f). In general, the nighttime relationship between the $\delta^{18}O$ and river temperature and river level mirrors that for the daytime, even though the correlations (Fig. 9c and f) are not robust. Transpiration is active during daylight hours and shuts down at night. However, evaporation is promoted by the higher ambient air temperature and low relative humidity, in addition to wind speed which promotes greater moisture transfer to the air. This may explain why nighttime river temperature and river level are somewhat positively related and similar to that of the daytime.

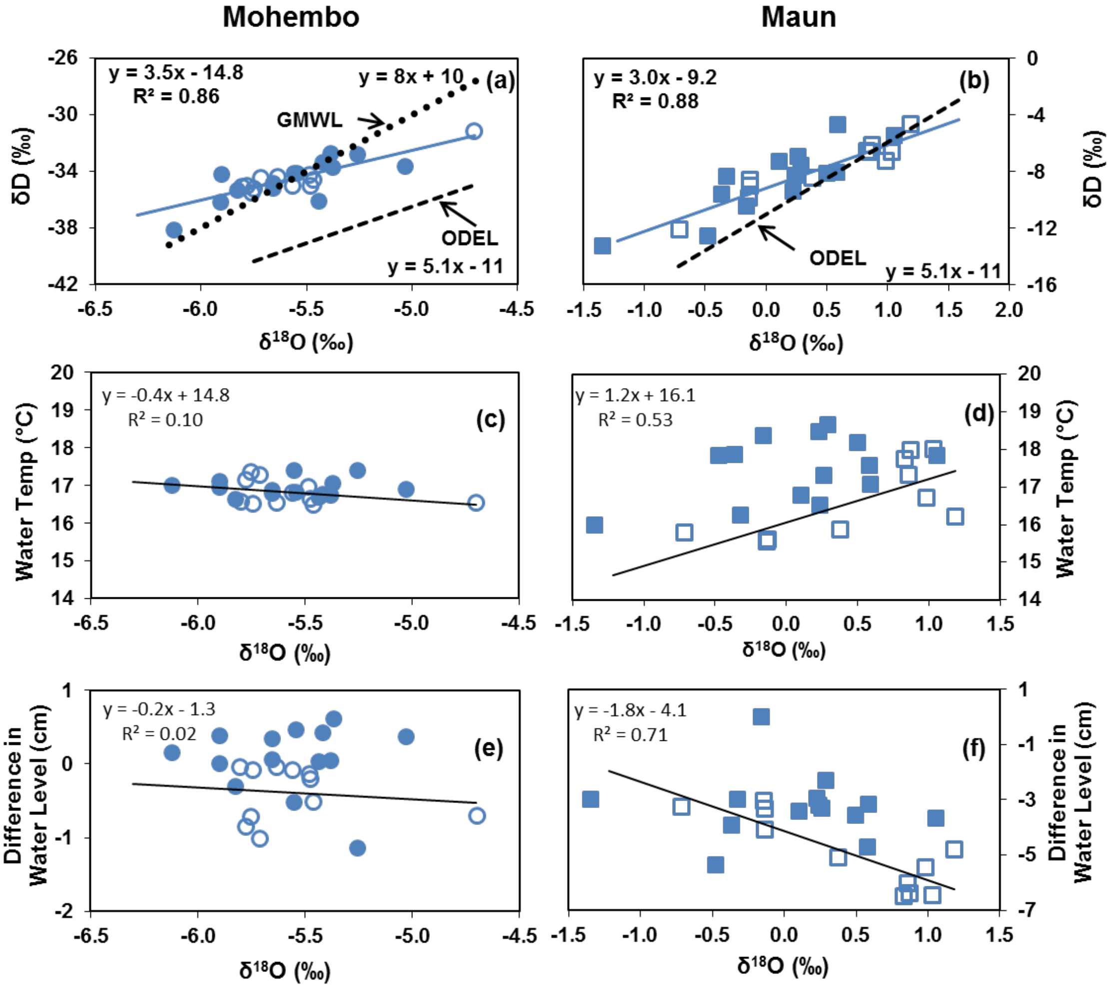

Figure 9: Plots of the stable oxygen isotope ($\delta^{18}O$) of water vs. the stable isotope of hydrogen (δD) (a and b), $\delta^{18}O$ vs. water temperature (c and d) and $\delta^{18}O$ vs. relative water level (e and f) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The filled square and circle symbols denotes night time and the open square and circle symbols represents day time. GMWL is Global Meteoric Water Line and ODEL is Okavango Delta Evaporation Line.

Transfer of thermal energy is a function of contact time or time of exposure of a specific parcel of water. The effect of transpiration depends upon light duration, while evaporation depends on ambient heat. The ambient heat lingers after dusk, as seen in the two hour lag time between maximum and minimum air and water temperatures (Fig. 4 a through d).

Section 3. Effect of Hydrologic Variations on Diel Cycling of Solutes

In the absence of physical, chemical and biological processes that remove solutes from the water column, water removed by evaporation and transpiration will cause the concentrations of the solutes to increase. We tested this concept against the $\delta^{18}O$ which we use as a proxy for evaporation and thus water removal from the river. In Mohembo, the relationships for daytime $\delta^{18}O$ and TDS, a proxy for the total solutes (Fig. 10a), Si (Fig 10c) and Cl^- (Fig. 10e) are poor, similar to river temperature (Fig. 9c) and river level (Fig. 9e); this relationship is most likely dampened by the high discharge rates of the river. In contrast, the daytime relationship between $\delta^{18}O$ vs. TDS (Fig. 10b) is positive (R^2=0.73) and between $\delta^{18}O$ vs. Si (Fig 10d) is positive (R^2=0.71) and are similar to the $\delta^{18}O$ vs river temperature (Fig. 9d) $\delta^{18}O$ vs. river level (Fig. 9f).

To determine if evapotranspiration is mainly responsible for the changes in the concentrations of the major solutes indicated by TDS (Fig. 5a and b) we plot the ionic proportions in a Piper diagram (Fig. 11). If evapoconcentration is the only factor affecting the ionic concentrations, then concentration variations observed in the diel cycle will have similar ionic proportions. This is because although evapotranspiration increases the concentrations of solutes in river water, removal of solutes will only occur from oversaturation with respect to mineral phases (e.g., Drever, 1997). The data in Figure 11a shows that the ionic proportion of the cations in river in Mohembo do not change much. However, the proportion of the anions changes mainly from variation in the HCO_3^- concentrations.

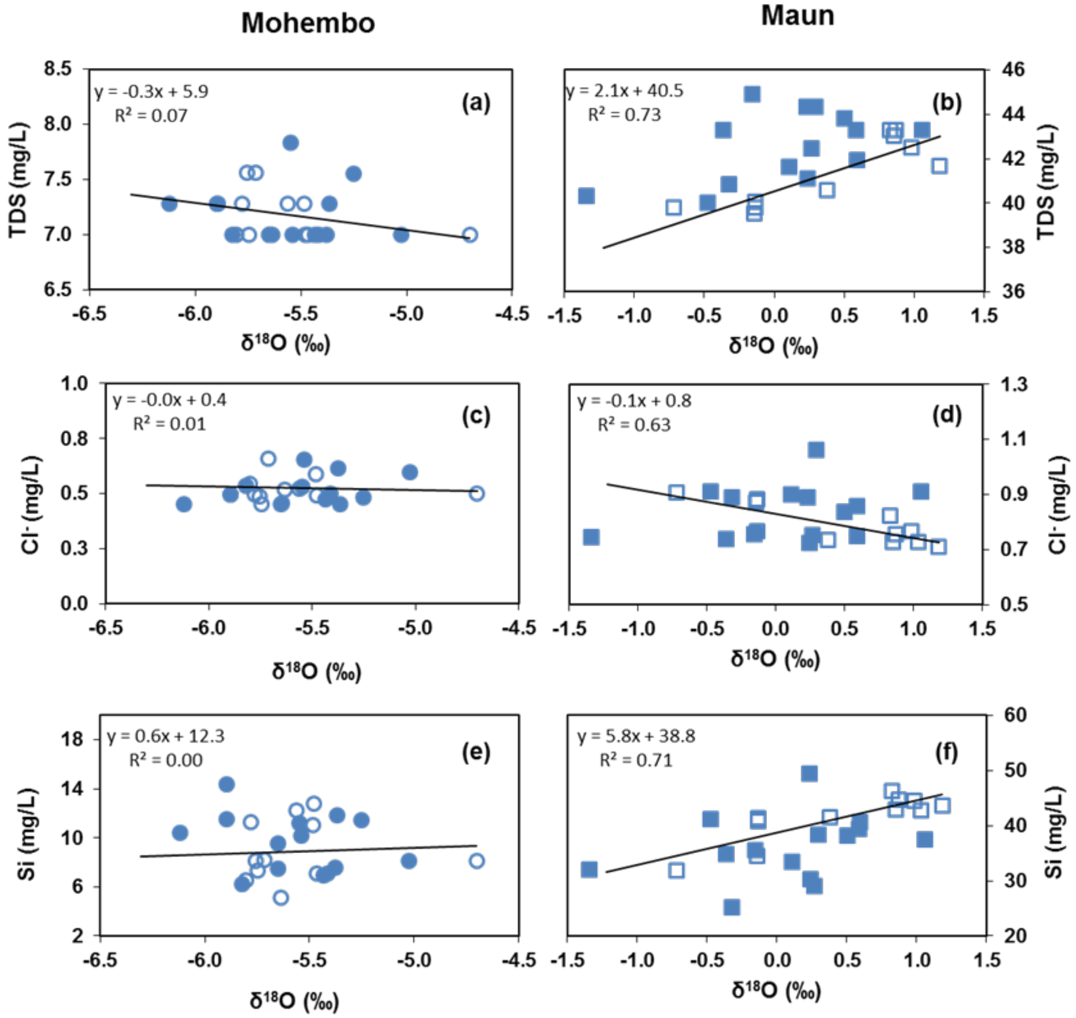

Figure 10: Plots of the stable oxygen isotope ($\delta^{18}O$) of water vs. total dissolved solids (TDS) (a and b), $\delta^{18}O$ vs. Cl^- (c and d) and $\delta^{18}O$ vs. Si (e and f) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The filled square and circle symbols denotes night time and the open circle and square symbols represents day time.

In contrast, despite the greater magnitude of change in the solute concentrations in Maun, the diel variations show constant proportions of cations and anions (Fig. 11b).

The constant proportion of ionic species indicates the dominance of evapoconcentration even at daily time periods. Although $\delta^{18}O$ vs. Cl^- show no relationship for samples from Mohembo (Fig. 10c) it is interesting to note that despite the constant proportion of anions, the correlation of $\delta^{18}O$ vs. Cl^- in Maun (Fig. 10d) is negative (R^2=0.63) and is similar to $\delta^{18}O$ vs. river level (Fig. 9f). The negative relationship between $\delta^{18}O$ vs. Cl^- requires that greater amounts of Cl^- be removed from the water column with greater evaporation, which is inconsistent with the concept of evapoconcentration. We are unable to explain this relationship, as we know of no vegetation-solute relationship that should preferentially remove Cl^- from the water column and the saturation indices with respect to chloride minerals (e.g., thermonatrite) were not reached during the 24 h period.

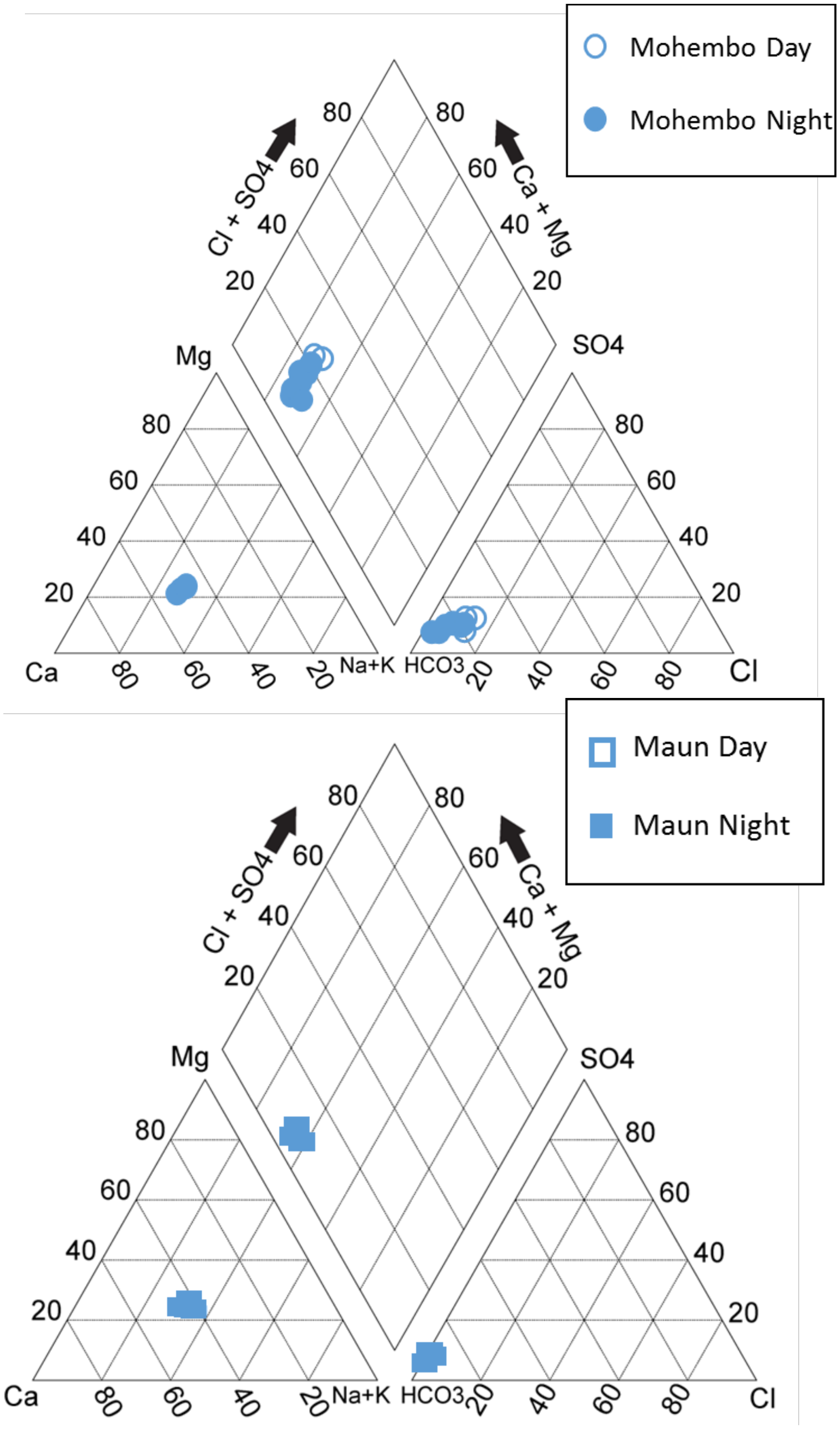

Figure 11: Piper plot of the ionic proportions for river water from (a) Mohembo in the proximal portion of the Okavango Delta and (b) at Maun in the distal portion of the Okavango Delta. The filled circles and squares represent night time and the open circles and squares represent daytime.

Silica concentration is not estimated as part of the TDS, yet the Si concentration shows a diel response (Fig. 5c and d) and a positive correlation with daytime $\delta^{18}O$ in Maun (Fig. 10d). The emergent vegetation in the Okavango Delta accumulate silica which is used to increase rigidity of the plants to withstand the force of environmental stressors (Struyf et al., 2014). In addition to vegetation, a variety of diatoms species adapted to different ecotones in delta uptake of silica from water in the river and wetlands (Davidson et al., 2012; Mackay et al., 2012). Previous studies have suggested rapid rates of silica recycling with silica stored in the first few centimeters of the floodplains sediments from the grass litter degradation (McCarthy et al., 1989; Struyf et al., 2007; Frings et al., 2014). Thus, the main controls on dissolved silica in river water is the uptake and production of biogenic silica and recycling of silica by vegetation, as well as removal of silicon by clay formation; although the stable isotope of silica ($\delta^{30}Si$) alone was unable to distinguish between the different processes (Frings et al., 2014; Struyf et al., 2014). Although the timeframe for the cycling of silica by diatoms can occur on a diel cycle, cycling between the water column and sediments is likely longer then the diel cycle. On a diel cycle, we expect the vegetation and diatoms to uptake dissolved silica, thereby decreasing the dissolved silica during the day during photosynthesis. The interaction between river and island groundwater provides a sink for the removal of silica from the water column (McCarthy et al., 2012; Struyf et al., 2014). The removal of silica by island groundwater is unlikely to affect short term diel cycling of silica. Finally, diatom utilization of silica will cause decrease in silica during daylight hours of photosynthesis which is not the case from the 24 h data (Fig. 5c and d). This discrepancy suggests that other processes that increase the silica are more effective than diatoms photosynthesis or vegetative removal. Our results show the opposite occurring (Fig. 5 c and d) indicating that abiotic processes (e.g., pH changes) dominate the silica cycling. The silica is oversaturated in the water column with respect to quartz (data not shown). Diel variations indicate that the increasing pH during daylight hours correspond to increasing Si concentration which is consistent with greater silica dissolution with increasing pH. Conversely, the decrease at night is related to removal from solution due to decreasing pH induced by CO_2 addition from respiration.

Section 4. Carbon Cycling

Carbon cycling on daily time scale in rivers is controlled by hydrology, light energy and uptake and release of chemical species. Photosynthesis, $CO_{2(g)}$ evasion and carbonate precipitation remove carbon from the DIC pool and respiration and photo-oxidation add carbon to the DIC pool (Fig. 1; Fig. 8) (Nimick and Gammons, 2011). For the pH range measured in the river samples from Mohembo and Maun (Table 1), the chemical transformation of DIC in the riverine pool is characterized by the carbonate equilibrium (e.g., Stumm and Morgan, 1981):

$$CO_{2(g)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \qquad (1)$$

$$CaCO_{3(s)} + H_2O + CO_{2(g)} \leftrightarrow 2HCO_3^- + Ca^{2+} \qquad (2)$$

Both the DIC concentrations and the $\delta^{13}C_{DIC}$ can be used to trace the processes that add and remove carbon from the riverine DIC pool (e.g., Atekwana and Krishnamurthy, 1998; Aucour et al., 1999; Doctor et al., 2008). Besides the chemical and biological processes that change the concentrations of DIC in river water, daily variations in the concentrations may also be due to evapotranspiration. Twenty four hour variations in the concentrations of solutes (e.g., TDS and Si) show that diel cycles in evapotranspiration cause increases during the day and decreases during the night (Fig. 5a, b, c and d). The results of the major ionic proportions in river water in Mohembo (Fig. 11a) and Maun (Fig. 11b) show constant proportions except for variations in HCO_3^- in Maun (Fig. 11b). The variations HCO_3^- concentration in Maun arise from processes that are unrelated to evapoconcentration. Furthermore, we can test the effect of evapotranspiration on carbonate evolution by assessing the relationships between evaporation and Ca^{2+}, alkalinity and DIC. A plot of the $\delta^{18}O$ (a proxy for evaporation) vs. Ca^{2+} (Fig. 12a), alkalinity (Fig. 12c) and DIC (Fig. 12e) show no correlation for river water at Mohembo. In Maun, the relationship for the $\delta^{18}O$ vs. Ca^{2+} (Fig. 12b), alkalinity (Fig. 12d) and DIC (Fig. 12f) are poor ($R^2 <0.4$). This is an indication that in the Okavango River, evapoconcentration does not dominate DIC evolution (Akoko et al., 2013) even on a daily basis.

The $\delta^{13}C_{DIC}$ shows overall increases during the day and decreases during the night for river water at Mohembo (Fig. 6i) and Maun (Fig. 6j). For the $\delta^{13}C_{DIC}$ to increase, carbon with a higher $\delta^{13}C$ composition compared to river water can be added to the DIC pool, or carbon can be evaded from river water to the atmosphere where the lighter ^{12}C is preferentially removed as $^{12}CO_{2(g)}$. For the $\delta^{13}C_{DIC}$ of the DIC pool to decrease, carbon with a lighter ^{13}C can be added to the DIC pool. In these cases, addition or removal of carbon from the riverine DIC pool is accompanied by changes in the DIC concentrations.

The same increases or decreases in the $\delta^{13}C_{DIC}$ can be observed if the riverine DIC pool exchanges carbon with a $CO_{2(g)}$ reservoir with heavier $\delta^{13}C$ or a $CO_{2(g)}$ reservoir with lighter $\delta^{13}C$ (e.g., Clark and Fritz, 1997).

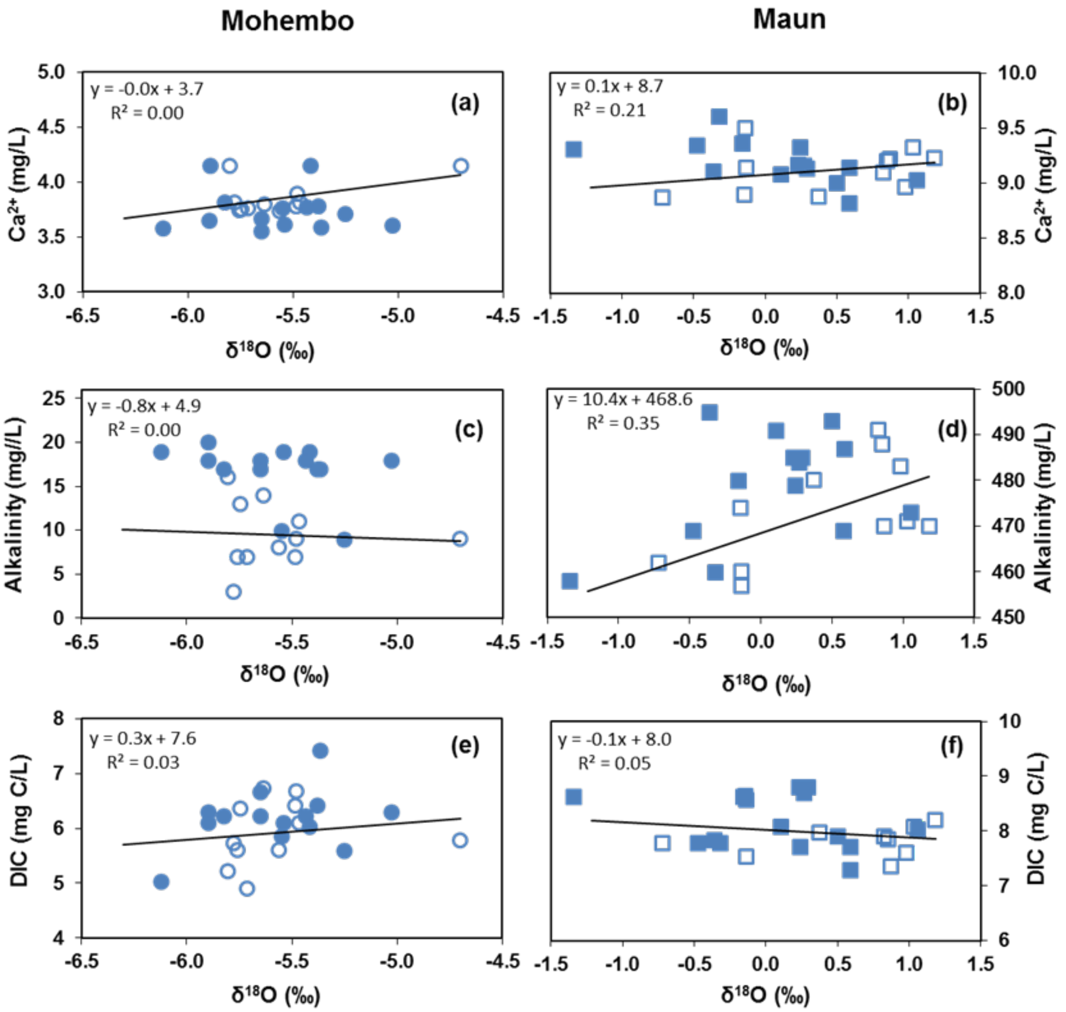

Figure 12: Plots of the stable oxygen isotope ($\delta^{18}O$) of water vs. Ca^{2+} (a and b), $\delta^{18}O$ vs. alkalinity (c and d) and $\delta^{18}O$ vs. dissolved inorganic carbon (DIC) (e and f) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The filled square and circle symbols denotes night time and the open square and circle symbols represents day time.

The exchange reactions that increase or decrease the $\delta^{13}C_{DIC}$ in river water will not change the DIC concentrations. The temporal changes in the pCO_2 in the river water and the saturation index with respect to carbonate minerals can be used to characterize if and when carbon is evaded to the atmosphere or precipitated as carbonates. Furthermore, insights into DIC evolution can be gained by characterizing the temporal concentration of the DIC species (H_2CO_3, HCO_3^-, and CO_3^{2-}). We use the temporal variations in the pCO_2, $SI_{calcite}$ and the concentrations of H_2CO_3, HCO_3^-, and CO_3^{2-} (Fig. 13) to assess DIC evolution during a 24 h cycle. The pCO_2 is higher than atmospheric ($10^{-3.4}$ atm.) and it is higher for Mohembo (Fig. 13a) compared to Maun (Fig. 13b). The higher pCO_2 in river water compared to atmospheric indicates that DIC in river water can potentially be evaded to the atmosphere. The pCO_2 in river water in Mohembo is nearly constant during the night and increases slightly during the day. This is in contrast to the pCO_2 of Maun which is higher at night and decreases during the day. The diel variations of the pCO_2 in Mohembo suggest that although it is higher than atmospheric, there is very little loss in the DIC from evasion, due to the higher discharge conditions of the river. In contrast, the diel variations of the pCO_2 in Maun indicate possible increases in the DIC concentrations at night and DIC drawdown during the day. The $SI_{calcite}$ in Mohembo is nearly constant at night and decreases markedly during the day (Fig. 13c), while in Maun, the $SI_{calcite}$ continuously decreases at night and increases during the day (Fig. 13d). Despite the variations in the $SI_{calcite}$ at night and during the day, the $SI_{calcite}$ of river water in both Mohembo and Maun are below saturation ($SI_{calcite} = 0$), indicating that no carbon is removed from river water by precipitation of a carbonate mineral phase.

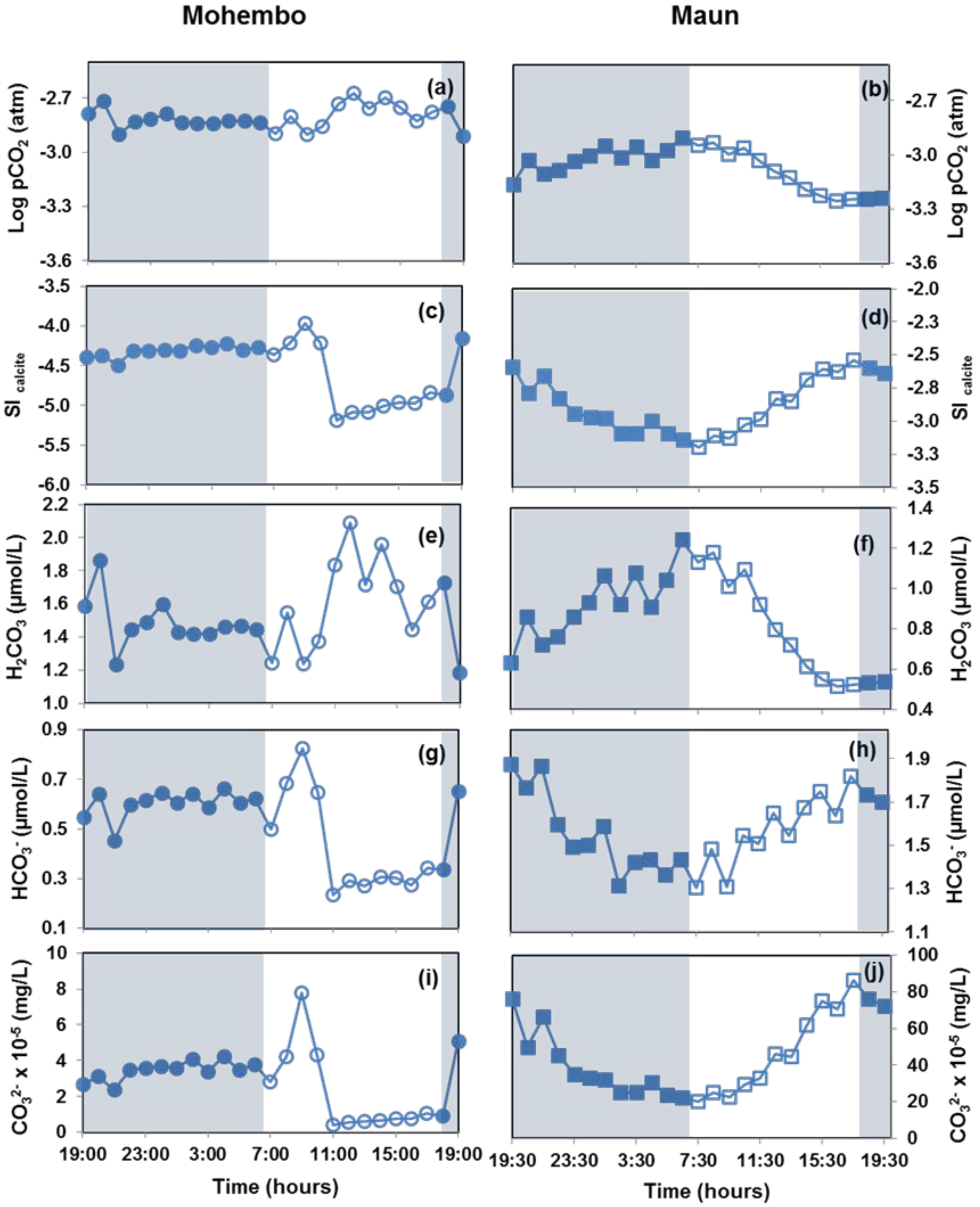

Figure 13: Plot of daily (24 h) variations in the partial pressure of CO_2 (log pCO_2) (a and b), the saturation index with respect to calcite ($SI_{calcite}$) (c and d), modelled concentrations of H_2CO_3 (e and f), HCO_3^- (g and h) and CO_3^{2-} (i and j) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The log of atmospheric pCO_2 is reported as -3.4 atm. The shaded areas and filled circles and squares represent night time and the unshaded portions and the open circles and squares represent daytime.

Akoko et al. (2013) suggested that the processes which controlled the $\delta^{13}C_{DIC}$ in the Okavango River include respiration, photo-oxidation, photosynthesis and $CO_{2(g)}$ evasion. The 24 h concentrations in the DIC fluctuate around 1 mg C/L and show no clear day vs. night variations (Fig. 6g and h), although there is significant speciation in the DIC (Fig. 13e-j). The $\delta^{13}C$ change in the DIC pool caused by respiration and photo-oxidation depends on the $\delta^{13}C$ of DOC. The $\delta\ ^{13}C$ of DOC in the Okavango River and its distributaries range from -23 to -25‰ (Akoko et al., 2013; Meier et al., 2015). When respiration dominates carbonate evolution in the water column, the contribution of carbon to the DIC pool from DOC respiration will cause the $\delta^{13}C_{DIC}$ to decrease as observed during night time, especially in Maun (Fig. 6j). During the nighttime at Mohembo, the pH in river water increases slightly (Fig. 6c) which is inconsistent with the addition of more $^{12}CO_2$ from DOC respiration to the DIC pool. We observe that the $\delta^{13}C_{DIC}$ does not reflect a decrease during nighttime either (Fig. 6i). We suggest that although respiration is occurring in the water column, the contribution of $^{12}CO_2$ to the DIC pool is minor, due to the short residence time of the water upstream from Mohembo. In Mohembo, a marked decrease in the $\delta^{13}C_{DIC}$ from 7:00 to 12:00 (Fig. 6i) is accompanied by decreases in pH (Fig. 6c) and alkalinity (Fig. 6e). This response is characteristic of addition of more $^{12}CO_2$ to the DIC pool. If respiration as we have argued is not occurring at a rate sufficient to decrease the pH and $\delta^{13}C_{DIC}$ at night, then it is unlikely to cause such a dramatic response in the morning hours. Photo-oxidation of DOC will contribute more $^{12}CO_2$ to the DIC pool and can cause the DIC to respond as observed in Mohembo in the morning hours. However, there is no reason for the DOC photo-oxidation to stop after

12:00 since photo-oxidation of DOC is stimulated by photons and thus should occur throughout daylight hours (Fig. 8a).

Akoko et al. (2013), have previously suggested that drainage of water from the permanent swamps into the river channel in the panhandle region of the Okavango Delta can account for the seasonal decrease in pH, decreases in alkalinity concentrations and decreases in the $\delta^{13}C_{DIC}$. It appears that such a process can occur on a short term daily basis and thus account for the abrupt decrease in the pH (Fig. 6c) and the $\delta^{13}C_{DIC}$ (Fig. 6i) observed early during the day in the Okavango River at the Mohembo. Photosynthesis which removes $CO_{2(aq)}$ from the water column should decrease DIC concentrations and shift the equilibrium distribution of the DIC species such that CO_3^{2-} (Fig. 13i) and HCO_3^- (Fig. 13g) are transformed to H_2CO_3 (Fig. 13e) (e.g., Abongwa and Atekwana, 2015). Although the pH (Fig. 6c) and DIC speciation (Fig. 13e, g and i) may be due to photosynthesis, the effect on the DIC concentration (Fig. 6g) and the $\delta^{13}C_{DIC}$ (Fig. 6i) is subdued. The evasion of $CO_{2(g)}$ from the DIC pool will decrease the DIC concentrations and increase the $\delta^{13}C_{DIC}$. The evasion of $CO_{2(g)}$ is controlled by the pCO_2 in river water relative to atmospheric. During the night, $CO_{2(g)}$ evasion has a counteracting effect to respiration, while during the day, it has a complementary effect to photosynthesis. There is no clear decrease in the DIC concentrations at night accompanied by increase in the $\delta^{13}C_{DIC}$ or any clear decrease in the DIC concentration accompanied by increases in the $\delta^{13}C_{DIC}$ during the day that can be linked to $CO_{2(g)}$ evasion; this makes $CO_{2(g)}$ evasion a minor process on a short term daily cycle. Overall, minor variations in the pCO_2 (Fig. 13a) is explained by a near balance in carbon removed from the DIC pool from photosynthesis and $CO_{2(g)}$ evasion and that produced from respiration and photo-oxidation during the day and between $CO_{2(g)}$ evasion and respiration at night (Akoko et al., 2013).

The DIC concentrations and the $\delta^{13}C_{DIC}$ variations over a daily cycle in the Okavango River in Maun are much different from that in Mohembo. The concentrations of H_2CO_3 (Fig. 13f) increase at night and decrease during the day and that of HCO_3^- (Fig. 13h) and CO_3^{2-} (Fig. 13j) decrease at night and increase during daylight hours. In Maun, the pCO_2 (Fig. 13b) in river water increases at night and decreases during the day consistent with the dominance of DOC respiration during the night and active photosynthesis which maybe augment by $CO_{2(g)}$ evasion during the day. The $SI_{calcite}$ (Fig. 13d) decreases during the night from increasing $CO_{2(aq)}$ from DOC respiration and increases during the day as $CO_{2(aq)}$ is removed from the DIC pool. Although the DIC concentration does not decrease in a cyclic manner, the decreases in the H_2CO_3 (Fig. 13f) appears to be balanced by increases in the concentrations of HCO_3^- (Fig. 13h) and CO_3^{2-} (Fig. 13j) during the day from photosynthesis and vice versa at night from respiration. This is consistent with the transformation of $CO_{2(aq)}$ into HCO_3^- and CO_3^{2-} due to pH increase (Fig. 6d) induced by photosynthesis during the day or to pH decrease (Fig. 6d) due to the transformation of HCO_3^- and CO_3^{2-} into $CO_{2(aq)}$ from respiration during the night. The lack of a decrease in the $\delta^{13}C_{DIC}$ during daylight hours is an indication that photo-oxidation is not an important source of DIC in the river water at Maun despite the much higher concentration of DOC than at Mohembo (e.g., Akoko et al., 2013). Like river water at Mohembo, the change in the pCO_2 (Fig. 13a) in Maun is cyclic and shows minor variations. Nevertheless, the minor variations in the pCO_2 is also explained by a near balance in carbon removed from the DIC pool from photosynthesis and $CO_{2(g)}$

evasion and that produced from respiration and photo-oxidation during the daylight hours and between respiration and $CO_{2(g)}$ evasion during the nighttime hours (Akoko et al., 2013). Since multiple processes occurring simultaneously and/or sequentially may be controlling the DIC and the $\delta^{13}C_{DIC}$ evolution, it is difficult to determine this from the raw DIC concentrations and $\delta^{13}C_{DIC}$ results.

The physical, chemical and isotopic parameters measured in the Okavango River at Mohembo in the proximal and in Maun in the distal portion of the Okavango Delta represent different hydrologic conditions and ecotones. The Okavango River flowing through Mohembo does so at high velocities in a deep channel in a permanently flooded wetland and floodplain with little vegetation in the river channel. In Maun, the Okavango River flows at low velocities in a shallow channel in an occasional floodplain with dense vegetation in the river channel. The properties of the water we sampled at each location is altered upstream of the sampling location. The 24 h experiments were not conducted on the same day for both the Mohembo and Maun stations. Nevertheless, the amount of radiant energy available for evaporation and that drives transpiration may have been similar at both locations. We use the similar 24 h range in the water isotopes (e.g., 2‰ for $\delta^{18}O$) as evidence for this similarity. The major differences between the two locations were the discharge velocities and the vegetative characteristics of the channel. It is not clear if light stimulated activity has a strong relationship with chemical and biological changes from the aquatic vegetation. To explore this relationship, we plot the $\delta^{18}O$ vs. PAR, $\delta^{13}C_{DIC}$ vs. PAR and the $\delta^{18}O$ vs. $\delta^{13}C_{DIC}$ to assess the effect of evapotranspiration on solute and the $\delta^{13}C_{DIC}$ evolution. The relationship between $\delta^{18}O$ vs. PAR is poor in both Mohembo and Maun (Fig. 14a and b) indicating that PAR intensity does not correspond to the same period as ambient heat that drives evapotranspiration. During the period of active photosynthesis, the PAR should relate positively to the $\delta^{13}C_{DIC}$ as the cumulative effect of photosynthesis is greater with increasing daylight length. Since photosynthesis will cause DIC drawdown and an increase in the $\delta^{13}C_{DIC}$ the relationship between PAR vs. $\delta^{13}C_{DIC}$ (Fig. 14c and d) is positive, albeit poor. This poor correspondence indicates that the PAR intensity is not diagnostic of vegetative effect on solute and photosynthetic process. The $\delta^{18}O$ vs. $\delta^{13}C_{DIC}$ relationship in Mohembo is poor (Fig. 14e) but positive and significant (R^2= 0.60) in Maun (Fig. 14f) for daylight hours. The relationship is also positive for nighttime hours as the data follows a trend similar to the daytime data. Although the good relationship between $\delta^{18}O$ vs. $\delta^{13}C_{DIC}$ in Maun may be coincidental, it is likely that the period of hottest water temperature is also the time period of the most active photosynthesis. If this is true, then the relationship at night is explained by increasing effect of respiration $CO_{2(g)}$ which increase with time concomitant with decreasing water temperature and lower rates of evaporation.

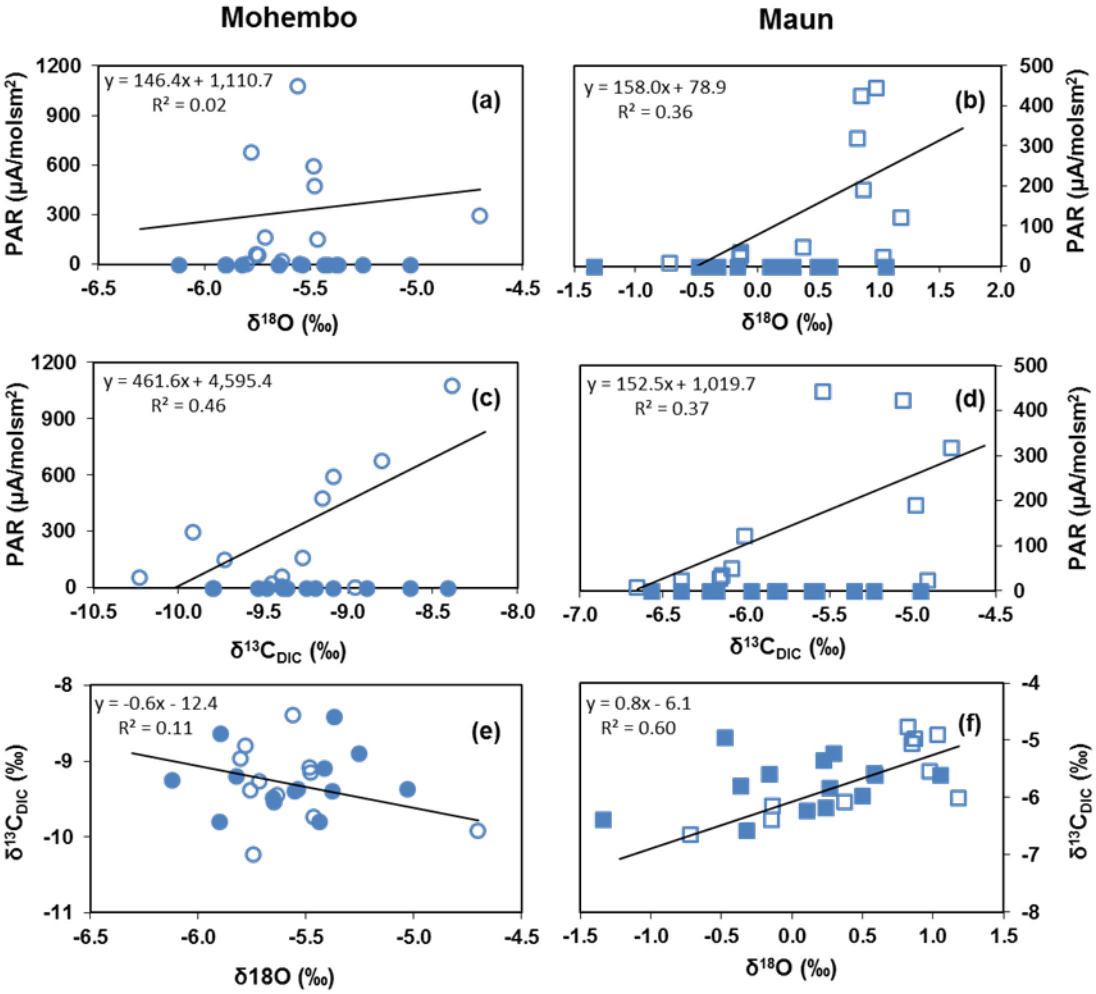

Figure 14: Plots of the stable oxygen isotope ($\delta^{18}O$) of water vs. photosynthetically available radiation (PAR) (a and b), the stable carbon isotope of dissolved inorganic carbon ($\delta^{13}C_{DIC}$) vs. PAR (c and d) and $\delta^{18}O$ vs. $\delta^{13}C_{DIC}$ (e and f) at Mohembo in the proximal portion of the Okavango Delta and at Maun in the distal portion of the Okavango Delta. The filled square and circle symbols denotes night time and the open circle and square symbols represents day time.

CHAPTER VI

CONCLUSIONS

We measured 24 h variations in the river temperature, river level, major ions, DIC, the δD and $\delta^{18}O$ of water and $\delta^{13}C_{DIC}$ in the Okavango River in semiarid northwest Botswana. The 24 h observations were made at the proximal end of the Okavango Delta as the Okavango River entered Botswana and at the distal portion about 400 km down river. Although the Okavango Delta is characterized as a wetland, these two locations are set in two contrasting ecotones where aquatic submergent and emergent vegetation was sparse, the channel 5 times wider and discharge was 20 times higher in the proximal as compared to the distal portion of the delta.

In general, the concentrations of chemical species were much higher and the isotopic composition were much more enriched in the distal portion of the delta. This concentration increase and the enrichment in the δD and $\delta^{18}O$ is caused by evapoconcentration during water transit between the two stations even though flood waters that were rising in distal portion of the delta should have cause greater dilution. The enrichment in the $\delta^{13}C_{DIC}$ was from exchange with atmospheric CO_2. River level and river temperature showed diel variations with lower levels during the daytime from evaporative and transpirative drawdown, although the magnitude was greater in the distal station compared to the proximal station. The TDS concentrations may reflect the additive effects of the solutes which are not clearly discernable in each of the chemical species. Clear diel variations were observed in the concentrations of the total dissolved solids and Si, while variations in the major ions were subtle with no distinct day and night trends. Clear diel variations in the Si is due to abiotic processes such as pH which dominates the silica cycling. The effect of evaporation is evident in the $\delta^{18}O$ which show evaporative relationship with the δD and is positively correlate with chemical species that show diel response such as Si and TDS.

The cycling of carbon was clearly indicted by diel variations in the pH, alkalinity and the $\delta^{13}C_{DIC}$, especially in the distal portion of the delta. Like the solute species, the response in the proximal station in the delta was subtle because of minor vegetational effects. The alkalinity increased during the day due to photosynthetic drawdown of DIC, which in turn increased the pH and cause greater DIC speciation to the bicarbonate form. The systematic and continuous increase in the $\delta^{13}C_{DIC}$ during the day is best attributed to water column photosynthesis, evasion of $CO_{2(g)}$ or both, while the decreases at night are due to respirative action of microbes in the water column.

That the greater magnitude of response in the physical, chemical and isotopic properties of river in the distal portion of the delta compared to the proximal portion is controlled by discharge and flow velocity; discharge as low as 1/10, flowing at velocity1/4 of that at the proximal location causes the water at the distal end to experience a greater magnitude of thermal and vegetational perturbation during the daylight hours. We suggest that although the vegetation was instrumental in controlling the diel cycling of nutrients and carbon, the greater length of exposure of the water mass to the physical, biological and chemical changes caused greater magnitude of change in the distal compared to the proximal portion of the Okavango Delta.

CHAPTER VII

FUTURE WORK

The conclusions from this study are from two locations across the Okavango Delta. In order to assess greater detail the interactions biogeochemical cycles across the delta, adding additional 24 h monitoring stations is necessary, to evaluate other ecotones, as we only sampled the permanently and occasional floodplains across the Delta. We conducted our study during the winter; it would be beneficial to conduct 24 h experiments during other seasons, to evaluate the variations of the seasons. The results from spatial and seasonal variation in short term experiments will be valuable in understanding how solutes and carbon evolve within the delta on a daily basis. To address other limitations of this study, the processes of macroinvertebrates and the degradation of organic material in the water column should be investigated. This could focus on the concentrations of DOC, SO_4^{2-} and NO_3^- in the bottom of the channel and floodplains.

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APPENDICES

Table S1: Physical, chemical and isotopic results of river water from Mohembo and Maun collected over 24 h

Sample Station	Time (hr)	DO (%)	ORP	SO_4^{2-} (mg/l)	NH_4^+ (mg/L)	K^+ (mg/L)	Mg (mg/L)	H_2CO_3 (µmol/L)	HCO_3^- (µmol/L)	CO_3^{2-} x10^{-5} (µmol/L)	SI Quartz	δD (‰)	TDS (mg/L)
Mohembo	**19:00**	104.6	-122	0.4	0.1	1.4	0.9	1.6	0.6	2.6	0.5	-34.2	7.3
	20:00	114.7	-124.4	0.3	0.2	1.7	1.0	1.9	0.6	3.1	0.4	-33.7	7.3
	21:00	97.6	-124.6	0.3	0.1	1.5	1.0	1.2	0.5	2.4	0.3	-38.1	7.3
	22:00	99.7	-124.8	0.3	0.0	1.3	1.0	1.4	0.6	3.5	0.4	-36.2	7.3
	23:00	103	-126.3	0.4	0.0	1.3	0.9	1.5	0.6	3.6	0.2	-33.7	7.0
	0:00	98.1	-126.6	0.3	0.1	1.3	1.0	1.6	0.7	3.7	0.3	-34.8	7.0
	1:00	99.8	-124.8	0.4	0.1	1.4	1.0	1.4	0.6	3.6	0.3	-34.2	7.0
	2:00	104.4	-124.8	0.3	0.0	1.3	1.0	1.4	0.6	4.1	0.2	-35.2	7.0
	3:00	98.4	-124.9	0.3	0.2	1.3	1.0	1.4	0.6	3.4	0.2	-33.4	7.0
	4:00	96.5	-124.1	0.5	0.2	1.4	1.0	1.5	0.7	4.2	0.2	-32.7	7.0
	5:00	100.3	-124.9	0.3	0.1	1.3	1.0	1.5	0.6	3.5	0.2	-36.1	7.0
	6:00	102.1	-124.6	0.3	0.1	1.4	1.1	1.5	0.6	3.8	0.1	-35.4	7.0
	7:00	102.6	-124.7	0.3	0.0	1.3	1.0	1.2	0.5	2.8	0.1	-35.1	7.0
	8:00	97.7	-124.9	0.4	0.1	1.3	1.0	1.6	0.7	4.2	0.0	-34.3	7.0
	9:00	97.3	-125.2	0.4	0.0	1.3	1.0	1.2	0.8	7.8	0.2	-35.2	7.0
	10:00	95.8	-124.3	0.4	0.1	1.4	1.0	1.4	0.7	4.3	0.2	-34.6	7.0
	11:00	94.2	-120.1	0.4	0.1	1.4	1.0	1.8	0.2	4.1	0.2	-31.1	7.0
	12:00	102.7	-121.4	0.4	0.1	1.4	1.0	2.1	0.3	5.7	0.4	-34.9	7.0
	13:00	106.9	-122.5	0.3	0.2	1.4	1.0	1.7	0.3	5.9	0.4	-34.9	7.3
	14:00	100.7	-121.3	0.3	0.1	1.4	1.0	1.9	0.3	6.8	0.4	-34.1	7.3
	15:00	99.2	-117.4	0.3	0.2	1.7	1.0	1.7	0.3	7.5	0.4	-34.9	7.3
	16:00	93.2	-123.3	0.4	0.2	1.6	1.1	1.4	0.3	7.4	0.2	-34.4	7.6
	17:00	107.9	-127.3	0.3	0.1	1.4	1.1	1.6	0.3	1.0	0.2	-35.4	7.6
	18:00	92.5	-123.4	0.4	0.1	1.4	1.1	1.7	0.3	9.3	0.4	-34.2	7.8
	19:00	85.1	-125.5	0.4	0.1	1.3	1.1	1.2	0.7	5.1	0.4	-32.9	7.6
Maun	**19:30**	139	-172.6	0.2	0.0	4.1	2.9	0.6	1.9	7.6	2.7	-10.48	46.3
	20:30	119	-167.7	0.3	0.1	4.3	3.1	0.9	1.7	5.0	2.7	-7.54	45.7
	21:30	117	-169.3	0.2	0.1	4.1	3.1	0.7	1.8	6.6	2.8	-9.41	45.7
	22:30	122	-168.6	0.2	0.3	4.2	3.1	0.8	1.6	4.6	2.7	-8.12	45.2
	23:30	102	-166.4	0.2	0.1	4.1	3.1	0.9	1.5	3.5	2.7	-9.60	44.6
	0:30	97.5	-165.9	0.2	0.1	4.1	3.1	0.9	1.5	3.3	2.7	-5.45	44.6
	1:30	93.7	-164.3	0.2	0.4	4.1	3.1	1.1	1.6	3.2	2.6	-6.93	43.8
	2:30	95.7	-163.7	0.2	0.2	4.0	3.1	0.9	1.3	2.5	2.8	-4.69	43.2
	3:30	97.5	-163	0.2	0.1	3.8	3.0	1.1	1.4	2.5	2.7	-7.31	43.0
	4:30	93.6	-164.2	0.2	0.0	4.0	3.1	0.9	1.4	3.0	2.6	-8.23	42.4
	5:30	95.3	-160.9	0.2	0.1	3.9	3.1	1.1	1.3	2.4	2.6	-8.34	42.1
	6:30	96.8	-160.3	0.2	0.2	4.0	3.2	1.3	1.4	2.2	2.7	-13.29	41.6
	7:30	87.4	-161.7	0.2	0.0	3.9	3.1	1.1	1.3	2.0	2.7	-12.09	41.3
	8:30	98.5	-160.5	0.2	0.0	3.9	3.2	1.2	1.5	2.5	2.7	-9.79	41.0
	9:30	90.1	-160.5	0.2	0.1	3.9	3.1	1.0	1.3	2.2	2.8	-8.96	40.7
	10:30	89.1	-161	0.2	0.1	3.8	3.0	1.1	1.5	2.9	2.8	-8.58	41.0
	11:30	92.1	-161.5	0.2	0.1	4.0	3.2	0.9	1.5	3.3	2.8	-8.43	41.3
	12:30	102	-165.1	0.2	0.1	4.0	3.2	0.8	1.6	4.6	2.8	-4.64	41.8
	13:30	93.6	-164.8	0.2	0.1	3.9	3.2	0.7	1.5	4.5	2.8	-7.24	43.0
	14:30	97.6	-166.7	0.2	0.1	4.1	3.3	0.6	1.6	6.2	2.8	-6.61	43.8
	15:30	92.7	-169.2	0.2	0.2	4.1	3.3	0.6	1.7	7.5	2.8	-6.48	44.3
	16:30	90.2	-169.7	0.2	0.1	3.9	3.2	0.5	1.6	7.1	2.8	-6.11	44.6
	17:30	89.3	-169.8	0.2	0.0	4.0	3.3	0.5	1.8	8.6	2.8	-6.56	44.6
	18:30	85.7	-169.9	0.2	0.1	4.0	3.3	0.5	1.7	7.6	2.7	-8.03	44.6
	19:30	84.4	-168.9	0.2	0.0	4.0	3.3	0.6	1.7	7.3	2.7	-12.53	44.3

Table S2: Compilation of Levelogger and barologger data of river water from Maun over 24 h recorded in five minute increments

Maun				
Date &Time (hrs)	**Water Level (m)**	**Water Temp. (°C)**	**Air Temp. (°C)**	**Cond. (μS/cm)**
7/15/10 19:30	1.612	18.4	16.8	69.1
7/15/10 19:35	1.613	18.8	16.5	68.3
7/15/10 19:40	1.596	18.8	16.3	68.3
7/15/10 19:45	1.595	18.8	16.0	68.3
7/15/10 19:50	1.591	18.7	15.8	68.3
7/15/10 19:55	1.590	18.7	15.6	68.3
7/15/10 20:00	1.589	18.7	15.4	68.3
7/15/10 20:05	1.593	18.7	15.2	68.7
7/15/10 20:10	1.586	18.7	15.0	68.3
7/15/10 20:15	1.589	18.7	14.9	68.3
7/15/10 20:20	1.587	18.7	14.7	68.3
7/15/10 20:25	1.586	18.7	14.6	68.3
7/15/10 20:30	1.589	18.7	14.6	68.3
7/15/10 20:35	1.589	18.6	14.5	68.3
7/15/10 20:40	1.588	18.6	14.5	68.3
7/15/10 20:45	1.588	18.6	14.4	68.3
7/15/10 20:50	1.585	18.6	14.3	68.3
7/15/10 20:55	1.584	18.6	14.2	68.3
7/15/10 21:00	1.583	18.6	14.2	68.3
7/15/10 21:05	1.584	18.6	14.2	67.9
7/15/10 21:10	1.584	18.5	14.1	68.3
7/15/10 21:15	1.585	18.5	14.1	68.3
7/15/10 21:20	1.579	18.5	14.1	68.3
7/15/10 21:25	1.583	18.5	14.1	68.3
7/15/10 21:30	1.583	18.5	14.2	68.3
7/15/10 21:35	1.580	18.5	14.3	67.9
7/15/10 21:40	1.579	18.4	14.4	67.9
7/15/10 21:45	1.581	18.4	14.5	67.9
7/15/10 21:50	1.580	18.4	14.5	67.9
7/15/10 21:55	1.581	18.4	14.6	67.9
7/15/10 22:00	1.578	18.4	14.6	67.9
7/15/10 22:05	1.578	18.3	14.6	67.4
7/15/10 22:10	1.578	18.3	14.6	67.9
7/15/10 22:15	1.580	18.3	14.6	67.4
7/15/10 22:20	1.578	18.3	14.5	67.4
7/15/10 22:25	1.577	18.2	14.5	67.4
7/15/10 22:30	1.577	18.2	14.4	67.4
7/15/10 22:35	1.573	18.2	14.4	67.4
7/15/10 22:40	1.574	18.1	14.3	67.0
7/15/10 22:45	1.573	18.1	14.2	67.0
7/15/10 22:50	1.571	18.1	14.2	67.0
7/15/10 22:55	1.578	18.1	14.1	67.0
7/15/10 23:00	1.573	18.0	14.1	67.0
7/15/10 23:05	1.572	18.0	14.1	67.0
7/15/10 23:10	1.573	18.0	14.0	67.0
7/15/10 23:15	1.572	18.0	14.0	67.0
7/15/10 23:20	1.575	17.9	13.9	66.6
7/15/10 23:25	1.574	17.9	13.9	66.6
7/15/10 23:30	1.573	17.9	13.8	66.6
7/15/10 23:35	1.573	17.9	13.7	66.6
7/15/10 23:40	1.575	17.8	13.7	66.6
7/15/10 23:45	1.575	17.8	13.6	66.6
7/15/10 23:50	1.576	17.8	13.5	66.6

7/15/10 23:55	1.572	17.8	13.4	66.6
7/16/10 0:00	1.574	17.8	13.3	66.2
7/16/10 0:05	1.573	17.7	13.1	66.2
7/16/10 0:10	1.574	17.7	13.0	66.2
7/16/10 0:15	1.573	17.7	12.8	66.2
7/16/10 0:20	1.572	17.7	12.7	66.2
7/16/10 0:25	1.576	17.6	12.6	66.2
7/16/10 0:30	1.571	17.6	12.5	66.2
7/16/10 0:35	1.574	17.6	12.3	66.2
7/16/10 0:40	1.574	17.6	12.2	65.8
7/16/10 0:45	1.576	17.5	12.0	65.8
7/16/10 0:50	1.573	17.5	11.8	65.8
7/16/10 0:55	1.571	17.5	11.6	65.8
7/16/10 1:00	1.578	17.5	11.5	65.8
7/16/10 1:05	1.576	17.4	11.3	65.8
7/16/10 1:10	1.576	17.4	11.2	65.4
7/16/10 1:15	1.575	17.4	11.1	65.4
7/16/10 1:20	1.573	17.3	11.0	65.4
7/16/10 1:25	1.574	17.3	10.9	65.4
7/16/10 1:30	1.579	17.3	10.9	65.4
7/16/10 1:35	1.575	17.3	10.9	65.4
7/16/10 1:40	1.576	17.3	10.8	65.4
7/16/10 1:45	1.576	17.3	10.8	65.4
7/16/10 1:50	1.577	17.2	10.8	65.4
7/16/10 1:55	1.581	17.2	10.8	65.4
7/16/10 2:00	1.577	17.2	10.7	65.0
7/16/10 2:05	1.574	17.2	10.7	65.0
7/16/10 2:10	1.577	17.1	10.6	65.0
7/16/10 2:15	1.576	17.1	10.5	65.4
7/16/10 2:20	1.576	17.1	10.4	65.4
7/16/10 2:25	1.578	17.1	10.2	65.0
7/16/10 2:30	1.581	17.1	10.1	64.5
7/16/10 2:35	1.573	17.0	10.0	65.0
7/16/10 2:40	1.579	17.0	9.9	64.5
7/16/10 2:45	1.580	17.0	9.8	64.5
7/16/10 2:50	1.578	17.0	9.7	64.5
7/16/10 2:55	1.577	17.0	9.6	64.1
7/16/10 3:00	1.578	16.9	9.5	64.1
7/16/10 3:05	1.577	16.9	9.4	64.5
7/16/10 3:10	1.576	16.9	9.4	64.1
7/16/10 3:15	1.574	16.9	9.3	64.1
7/16/10 3:20	1.578	16.8	9.2	64.1
7/16/10 3:25	1.578	16.8	9.2	64.1
7/16/10 3:30	1.578	16.8	9.1	64.1
7/16/10 3:35	1.575	16.8	9.1	63.7
7/16/10 3:40	1.578	16.7	9.1	64.1
7/16/10 3:45	1.578	16.7	9.1	63.7
7/16/10 3:50	1.576	16.7	9.1	63.7
7/16/10 3:55	1.576	16.7	9.1	63.7
7/16/10 4:00	1.581	16.7	9.0	63.7
7/16/10 4:05	1.583	16.6	9.0	63.7
7/16/10 4:10	1.578	16.6	9.0	63.7
7/16/10 4:15	1.577	16.6	8.9	63.7
7/16/10 4:20	1.578	16.6	8.9	63.7
7/16/10 4:25	1.577	16.5	8.8	63.3
7/16/10 4:30	1.580	16.5	8.8	63.3
7/16/10 4:35	1.581	16.5	8.7	63.3
7/16/10 4:40	1.576	16.5	8.7	63.3
7/16/10 4:45	1.579	16.4	8.6	63.3
7/16/10 4:50	1.577	16.4	8.5	63.3
7/16/10 4:55	1.579	16.4	8.4	63.3
7/16/10 5:00	1.582	16.4	8.4	63.3

7/16/10 5:05	1.576	16.3	8.3	62.9
7/16/10 5:10	1.583	16.3	8.2	62.9
7/16/10 5:15	1.583	16.3	8.1	62.9
7/16/10 5:20	1.583	16.3	8.0	62.9
7/16/10 5:25	1.576	16.3	7.9	62.9
7/16/10 5:30	1.582	16.2	7.8	62.9
7/16/10 5:35	1.579	16.2	7.7	62.5
7/16/10 5:40	1.580	16.2	7.6	62.5
7/16/10 5:45	1.579	16.2	7.5	62.5
7/16/10 5:50	1.580	16.2	7.4	62.5
7/16/10 5:55	1.577	16.1	7.3	62.5
7/16/10 6:00	1.579	16.1	7.2	62.5
7/16/10 6:05	1.583	16.1	7.1	62.5
7/16/10 6:10	1.579	16.1	7.0	62.0
7/16/10 6:15	1.582	16.1	6.9	62.0
7/16/10 6:20	1.583	16.0	6.8	62.0
7/16/10 6:25	1.580	16.0	6.8	62.0
7/16/10 6:30	1.582	16.0	6.7	62.0
7/16/10 6:35	1.585	16.0	6.6	62.0
7/16/10 6:40	1.582	16.0	6.4	62.0
7/16/10 6:45	1.585	15.9	6.3	62.0
7/16/10 6:50	1.581	15.9	6.2	62.0
7/16/10 6:55	1.581	15.9	6.1	62.0
7/16/10 7:00	1.581	15.9	5.9	61.6
7/16/10 7:05	1.581	15.9	5.8	61.6
7/16/10 7:10	1.585	15.8	5.7	61.6
7/16/10 7:15	1.584	15.8	5.6	61.6
7/16/10 7:20	1.581	15.8	5.6	61.6
7/16/10 7:25	1.583	15.8	5.5	61.6
7/16/10 7:30	1.580	15.8	5.5	61.6
7/16/10 7:35	1.581	15.8	5.4	61.6
7/16/10 7:40	1.582	15.8	5.4	61.6
7/16/10 7:45	1.585	15.7	5.5	61.6
7/16/10 7:50	1.582	15.7	5.5	61.6
7/16/10 7:55	1.584	15.7	5.7	61.2
7/16/10 8:00	1.583	15.7	5.8	61.2
7/16/10 8:05	1.584	15.7	6.0	61.2
7/16/10 8:10	1.585	15.7	6.1	61.2
7/16/10 8:15	1.582	15.7	6.3	61.2
7/16/10 8:20	1.585	15.6	6.5	61.2
7/16/10 8:25	1.579	15.6	6.6	61.2
7/16/10 8:30	1.582	15.6	6.8	61.2
7/16/10 8:35	1.577	15.6	7.0	61.2
7/16/10 8:40	1.581	15.6	7.2	61.2
7/16/10 8:45	1.579	15.6	7.3	61.2
7/16/10 8:50	1.578	15.6	7.5	61.2
7/16/10 8:55	1.577	15.5	7.7	61.2
7/16/10 9:00	1.577	15.6	7.8	61.2
7/16/10 9:05	1.579	15.6	8.0	61.2
7/16/10 9:10	1.583	15.6	8.1	61.2
7/16/10 9:15	1.581	15.6	8.3	60.8
7/16/10 9:20	1.578	15.6	8.5	61.2
7/16/10 9:25	1.576	15.6	8.6	60.8
7/16/10 9:30	1.579	15.6	8.8	60.8
7/16/10 9:35	1.577	15.6	8.9	60.8
7/16/10 9:40	1.576	15.6	9.1	60.8
7/16/10 9:45	1.574	15.6	9.4	60.8
7/16/10 9:50	1.576	15.6	9.6	60.8
7/16/10 9:55	1.575	15.6	10.0	60.8
7/16/10 10:00	1.571	15.6	10.3	61.2
7/16/10 10:05	1.573	15.6	10.5	60.8
7/16/10 10:10	1.573	15.6	10.8	60.8

7/16/10 10:15	1.572	15.6	11.0	61.2
7/16/10 10:20	1.576	15.6	11.3	61.2
7/16/10 10:25	1.571	15.6	11.6	61.2
7/16/10 10:30	1.571	15.6	11.7	61.2
7/16/10 10:35	1.572	15.6	11.9	61.2
7/16/10 10:40	1.572	15.6	12.2	61.2
7/16/10 10:45	1.570	15.6	12.4	61.2
7/16/10 10:50	1.574	15.7	12.6	61.2
7/16/10 10:55	1.566	15.7	12.8	61.2
7/16/10 11:00	1.574	15.7	13.2	61.2
7/16/10 11:05	1.567	15.7	13.6	61.2
7/16/10 11:10	1.570	15.8	14.0	61.6
7/16/10 11:15	1.570	15.8	14.4	61.6
7/16/10 11:20	1.563	15.8	14.6	61.6
7/16/10 11:25	1.567	15.8	14.9	61.6
7/16/10 11:30	1.561	15.9	15.3	61.6
7/16/10 11:35	1.569	15.9	15.7	61.6
7/16/10 11:40	1.564	15.9	15.9	62.0
7/16/10 11:45	1.566	16.0	16.2	62.0
7/16/10 11:50	1.558	16.0	16.4	62.0
7/16/10 11:55	1.565	16.0	16.5	62.0
7/16/10 12:00	1.562	16.0	16.7	62.0
7/16/10 12:05	1.562	16.1	16.9	62.5
7/16/10 12:10	1.563	16.1	17.0	62.5
7/16/10 12:15	1.566	16.1	17.2	62.0
7/16/10 12:20	1.566	16.2	17.2	62.5
7/16/10 12:25	1.566	16.2	17.3	62.5
7/16/10 12:30	1.564	16.2	17.6	62.5
7/16/10 12:35	1.562	16.3	17.8	62.5
7/16/10 12:40	1.562	16.3	18.0	62.9
7/16/10 12:45	1.563	16.3	18.3	62.9
7/16/10 12:50	1.557	16.4	18.6	62.9
7/16/10 12:55	1.564	16.4	18.9	62.9
7/16/10 13:00	1.560	16.5	19.0	63.3
7/16/10 13:05	1.562	16.5	19.3	62.9
7/16/10 13:10	1.562	16.6	19.5	63.3
7/16/10 13:15	1.558	16.6	19.7	63.3
7/16/10 13:20	1.560	16.6	19.9	63.7
7/16/10 13:25	1.562	16.7	20.3	64.1
7/16/10 13:30	1.558	16.7	20.7	64.1
7/16/10 13:35	1.555	16.8	20.9	64.1
7/16/10 13:40	1.553	16.8	21.1	64.1
7/16/10 13:45	1.555	16.9	21.3	64.1
7/16/10 13:50	1.556	16.9	21.6	64.1
7/16/10 13:55	1.556	17.0	21.7	64.5
7/16/10 14:00	1.552	17.0	21.9	64.5
7/16/10 14:05	1.555	17.1	22.1	65.0
7/16/10 14:10	1.550	17.1	22.3	65.0
7/16/10 14:15	1.555	17.2	22.7	65.0
7/16/10 14:20	1.554	17.2	23.0	65.0
7/16/10 14:25	1.555	17.3	23.2	65.4
7/16/10 14:30	1.552	17.3	23.5	65.4
7/16/10 14:35	1.550	17.4	23.8	65.4
7/16/10 14:40	1.551	17.4	23.9	65.4
7/16/10 14:45	1.554	17.4	24.0	65.4
7/16/10 14:50	1.553	17.5	24.1	65.8
7/16/10 14:55	1.553	17.5	24.4	65.8
7/16/10 15:00	1.549	17.5	24.5	65.8
7/16/10 15:05	1.552	17.6	24.6	65.8
7/16/10 15:10	1.548	17.6	24.8	65.8
7/16/10 15:15	1.551	17.6	25.0	66.2
7/16/10 15:20	1.551	17.7	25.2	66.2

7/16/10 15:25	1.552	17.7	25.3	66.2
7/16/10 15:30	1.548	17.8	25.5	66.2
7/16/10 15:35	1.550	17.8	25.6	66.2
7/16/10 15:40	1.545	17.8	25.7	66.2
7/16/10 15:45	1.552	17.8	25.9	66.6
7/16/10 15:50	1.547	17.9	26.0	66.6
7/16/10 15:55	1.548	17.9	26.1	66.6
7/16/10 16:00	1.548	17.9	26.2	66.6
7/16/10 16:05	1.549	17.9	26.4	66.2
7/16/10 16:10	1.546	17.9	26.5	66.6
7/16/10 16:15	1.552	18.0	26.5	66.6
7/16/10 16:20	1.549	18.0	26.7	66.6
7/16/10 16:25	1.553	18.0	26.7	66.6
7/16/10 16:30	1.548	18.0	26.8	66.6
7/16/10 16:35	1.549	18.0	27.0	66.6
7/16/10 16:40	1.549	18.1	27.2	66.6
7/16/10 16:45	1.548	18.1	27.2	67.0
7/16/10 16:50	1.548	18.1	27.2	67.0
7/16/10 16:55	1.549	18.1	27.4	67.0
7/16/10 17:00	1.547	18.1	27.5	67.0
7/16/10 17:05	1.542	18.0	27.6	67.0
7/16/10 17:10	1.546	18.0	27.6	67.0
7/16/10 17:15	1.548	18.0	27.5	66.6
7/16/10 17:20	1.545	18.0	27.1	66.6
7/16/10 17:25	1.546	18.0	26.4	66.6
7/16/10 17:30	1.548	18.0	25.5	66.6
7/16/10 17:35	1.549	18.0	24.6	66.6
7/16/10 17:40	1.550	18.0	23.8	66.6
7/16/10 17:45	1.548	18.0	23.0	66.6
7/16/10 17:50	1.550	18.0	22.3	66.6
7/16/10 17:55	1.554	17.9	21.5	66.6
7/16/10 18:00	1.552	17.9	20.7	66.6
7/16/10 18:05	1.550	17.9	19.9	66.6
7/16/10 18:10	1.555	17.9	19.1	66.6
7/16/10 18:15	1.556	17.9	18.4	66.6
7/16/10 18:20	1.556	17.9	17.7	66.6
7/16/10 18:25	1.554	17.9	17.0	66.6
7/16/10 18:30	1.558	17.8	16.4	66.6
7/16/10 18:35	1.556	17.8	15.8	66.6
7/16/10 18:40	1.559	17.8	15.2	66.6
7/16/10 18:45	1.562	17.8	14.7	66.6
7/16/10 18:50	1.559	17.8	14.2	66.6
7/16/10 18:55	1.559	17.7	13.7	66.6
7/16/10 19:00	1.562	17.7	13.3	66.2
7/16/10 19:05	1.564	17.7	12.9	66.2
7/16/10 19:10	1.562	17.7	12.5	66.2
7/16/10 19:15	1.564	17.6	12.2	66.2
7/16/10 19:20	1.563	17.6	11.9	66.2
7/16/10 19:25	1.563	17.6	11.6	66.2
7/16/10 19:30	1.565	17.6	11.3	66.2

Table S3: Compilation of Levelogger, Barologger and Photosynthetically Available Radiation meter data of river water from Mohembo over 24 h recorded in five minute increments

Mohembo					
Date &Time (hrs)	**Water Level (m)**	**Water Temp. (°C)**	**Air Temp. (°C)**	**Cond. (μS/cm)**	**PAR (μA/mol*Sm^2)**
7/21/2010 19:00	1.777	17.1	20.1	11.2	0.0
7/21/2010 19:05	1.786	17.1	20.0	11.2	0.0
7/21/2010 19:10	1.783	17.1	19.8	11.2	0.0
7/21/2010 19:15	1.783	17.1	19.7	11.2	0.0
7/21/2010 19:20	1.777	17.1	19.5	10.8	0.0
7/21/2010 19:25	1.782	17.1	19.4	11.2	0.0
7/21/2010 19:30	1.783	17.1	19.3	10.8	0.0
7/21/2010 19:35	1.784	17.1	19.2	11.2	0.0
7/21/2010 19:40	1.779	17.1	19.1	10.8	0.0
7/21/2010 19:45	1.781	17.1	19.0	10.8	0.0
7/21/2010 19:50	1.783	17.1	18.9	10.8	0.0
7/21/2010 19:55	1.783	17.1	18.8	11.2	0.0
7/21/2010 20:00	1.783	17.1	18.7	11.2	0.0
7/21/2010 20:05	1.775	17.1	18.7	11.2	0.0
7/21/2010 20:10	1.776	17.1	18.6	10.8	0.0
7/21/2010 20:15	1.780	17.0	18.5	11.2	0.0
7/21/2010 20:20	1.781	17.0	18.4	10.8	0.0
7/21/2010 20:25	1.780	17.0	18.3	10.8	0.0
7/21/2010 20:30	1.779	17.0	18.3	11.2	0.0
7/21/2010 20:35	1.777	17.0	18.2	11.2	0.0
7/21/2010 20:40	1.778	17.0	18.1	11.2	0.0
7/21/2010 20:45	1.778	17.0	18.0	11.2	0.0
7/21/2010 20:50	1.776	17.0	18.0	11.2	0.0
7/21/2010 20:55	1.777	17.0	17.9	11.2	0.0
7/21/2010 21:00	1.778	17.0	17.8	11.2	0.0
7/21/2010 21:05	1.785	17.0	17.7	10.8	0.0
7/21/2010 21:10	1.778	17.0	17.7	11.2	0.0
7/21/2010 21:15	1.778	17.0	17.6	10.8	0.0
7/21/2010 21:20	1.779	17.0	17.6	10.8	0.0
7/21/2010 21:25	1.778	17.0	17.5	11.2	0.0
7/21/2010 21:30	1.776	17.0	17.4	10.8	0.0
7/21/2010 21:35	1.782	17.0	17.4	11.2	0.0
7/21/2010 21:40	1.783	17.0	17.3	10.8	0.0
7/21/2010 21:45	1.780	17.0	17.2	10.8	0.0
7/21/2010 21:50	1.779	17.0	17.2	10.8	0.0
7/21/2010 21:55	1.779	17.0	17.1	10.8	0.0
7/21/2010 22:00	1.781	16.9	17.1	11.2	0.0
7/21/2010 22:05	1.781	16.9	17.0	10.8	0.0
7/21/2010 22:10	1.778	16.9	17.0	10.8	0.0
7/21/2010 22:15	1.772	16.9	17.0	10.8	0.0
7/21/2010 22:20	1.776	16.9	17.0	10.8	0.0
7/21/2010 22:25	1.778	16.9	17.0	10.8	0.0
7/21/2010 22:30	1.777	16.9	17.0	10.8	0.0
7/21/2010 22:35	1.779	16.9	16.9	10.8	0.0
7/21/2010 22:40	1.776	16.9	16.9	10.8	0.0
7/21/2010 22:45	1.780	16.9	16.9	10.8	0.0
7/21/2010 22:50	1.781	16.9	16.9	10.8	0.0
7/21/2010 22:55	1.780	16.9	16.8	10.8	0.0
7/21/2010 23:00	1.780	16.9	16.8	10.8	0.0
7/21/2010 23:05	1.784	16.9	16.7	10.8	0.0
7/21/2010 23:10	1.778	16.9	16.7	10.8	0.0

7/21/2010 23:15	1.778	16.9	16.6	10.8	0.0
7/21/2010 23:20	1.779	16.9	16.6	10.8	0.0
7/21/2010 23:25	1.779	16.9	16.5	10.8	0.0
7/21/2010 23:30	1.779	16.9	16.5	10.8	0.0
7/21/2010 23:35	1.779	16.9	16.5	10.8	0.0
7/21/2010 23:40	1.778	16.9	16.5	10.8	0.0
7/21/2010 23:45	1.784	16.9	16.5	10.8	0.0
7/21/2010 23:50	1.779	16.9	16.4	10.8	0.0
7/21/2010 23:55	1.779	16.9	16.4	10.8	0.0
7/22/2010 0:00	1.777	16.9	16.4	10.8	0.0
7/22/2010 0:05	1.779	16.9	16.4	10.8	0.0
7/22/2010 0:10	1.777	16.9	16.3	10.8	0.0
7/22/2010 0:15	1.783	16.8	16.3	10.8	0.0
7/22/2010 0:20	1.777	16.9	16.3	10.8	0.0
7/22/2010 0:25	1.778	16.9	16.4	10.8	0.0
7/22/2010 0:30	1.775	16.9	16.4	10.8	0.0
7/22/2010 0:35	1.774	16.9	16.5	10.8	0.0
7/22/2010 0:40	1.780	16.8	16.5	10.8	0.0
7/22/2010 0:45	1.779	16.8	16.5	10.8	0.0
7/22/2010 0:50	1.774	16.8	16.5	10.8	0.0
7/22/2010 0:55	1.781	16.8	16.6	10.8	0.0
7/22/2010 1:00	1.781	16.8	16.6	10.8	0.0
7/22/2010 1:05	1.777	16.8	16.6	10.8	0.0
7/22/2010 1:10	1.776	16.8	16.6	10.8	0.0
7/22/2010 1:15	1.780	16.8	16.5	10.8	0.0
7/22/2010 1:20	1.772	16.8	16.5	10.8	0.0
7/22/2010 1:25	1.775	16.8	16.4	10.8	0.0
7/22/2010 1:30	1.777	16.8	16.4	10.8	0.0
7/22/2010 1:35	1.777	16.8	16.3	10.8	0.0
7/22/2010 1:40	1.778	16.8	16.3	10.8	0.0
7/22/2010 1:45	1.777	16.8	16.3	10.8	0.0
7/22/2010 1:50	1.785	16.8	16.3	10.8	0.0
7/22/2010 1:55	1.780	16.8	16.2	10.8	0.0
7/22/2010 2:00	1.780	16.8	16.2	10.8	0.0
7/22/2010 2:05	1.782	16.8	16.2	10.8	0.0
7/22/2010 2:10	1.779	16.8	16.2	10.8	0.0
7/22/2010 2:15	1.780	16.8	16.2	10.8	0.0
7/22/2010 2:20	1.777	16.8	16.2	10.8	0.0
7/22/2010 2:25	1.779	16.8	16.2	10.8	0.0
7/22/2010 2:30	1.780	16.8	16.1	10.8	0.0
7/22/2010 2:35	1.778	16.8	16.1	10.8	0.0
7/22/2010 2:40	1.781	16.8	16.1	10.8	0.0
7/22/2010 2:45	1.778	16.8	16.0	10.8	0.0
7/22/2010 2:50	1.777	16.8	16.0	10.8	0.0
7/22/2010 2:55	1.779	16.8	15.9	10.8	0.0
7/22/2010 3:00	1.781	16.8	15.9	10.8	0.0
7/22/2010 3:05	1.776	16.8	15.8	10.8	0.0
7/22/2010 3:10	1.778	16.8	15.8	10.8	0.0
7/22/2010 3:15	1.776	16.8	15.8	10.8	0.0
7/22/2010 3:20	1.772	16.8	15.7	10.8	0.0
7/22/2010 3:25	1.777	16.8	15.7	10.8	0.0
7/22/2010 3:30	1.779	16.8	15.7	10.8	0.0
7/22/2010 3:35	1.775	16.8	15.7	10.8	0.0
7/22/2010 3:40	1.774	16.7	15.7	10.8	0.0
7/22/2010 3:45	1.778	16.8	15.7	10.8	0.0
7/22/2010 3:50	1.775	16.7	15.7	10.8	0.0
7/22/2010 3:55	1.779	16.7	15.7	10.8	0.0
7/22/2010 4:00	1.777	16.7	15.7	10.8	0.0
7/22/2010 4:05	1.774	16.7	15.7	10.8	0.0
7/22/2010 4:10	1.774	16.7	15.7	10.8	0.0
7/22/2010 4:15	1.776	16.7	15.6	10.8	0.0
7/22/2010 4:20	1.778	16.7	15.6	10.8	0.0

7/22/2010 4:25	1.769	16.7	15.6	10.8	0.0
7/22/2010 4:30	1.777	16.7	15.6	10.8	0.0
7/22/2010 4:35	1.779	16.7	15.6	10.8	0.0
7/22/2010 4:40	1.775	16.7	15.7	10.8	0.0
7/22/2010 4:45	1.771	16.7	15.7	10.8	0.0
7/22/2010 4:50	1.778	16.7	15.7	10.8	0.0
7/22/2010 4:55	1.771	16.7	15.7	10.8	0.0
7/22/2010 5:00	1.777	16.7	15.7	10.8	0.0
7/22/2010 5:05	1.774	16.7	15.8	10.8	0.0
7/22/2010 5:10	1.777	16.7	15.8	10.8	0.0
7/22/2010 5:15	1.773	16.7	15.8	10.8	0.0
7/22/2010 5:20	1.776	16.7	15.8	10.8	0.0
7/22/2010 5:25	1.766	16.7	15.8	10.8	0.0
7/22/2010 5:30	1.775	16.7	15.8	10.8	0.0
7/22/2010 5:35	1.779	16.7	15.8	10.8	0.0
7/22/2010 5:40	1.779	16.6	15.8	10.8	0.0
7/22/2010 5:45	1.778	16.6	15.8	10.8	0.0
7/22/2010 5:50	1.777	16.6	15.8	10.8	0.0
7/22/2010 5:55	1.776	16.6	15.8	10.8	0.0
7/22/2010 6:00	1.774	16.6	15.8	10.8	0.0
7/22/2010 6:05	1.772	16.6	15.8	10.8	0.0
7/22/2010 6:10	1.779	16.6	15.7	10.8	0.0
7/22/2010 6:15	1.773	16.6	15.7	10.8	0.0
7/22/2010 6:20	1.776	16.6	15.7	10.8	0.0
7/22/2010 6:25	1.775	16.6	15.7	10.8	0.0
7/22/2010 6:30	1.775	16.6	15.6	10.8	0.0
7/22/2010 6:35	1.769	16.6	15.6	10.8	0.0
7/22/2010 6:40	1.774	16.6	15.6	10.8	0.0
7/22/2010 6:45	1.776	16.6	15.5	10.8	0.0
7/22/2010 6:50	1.769	16.6	15.5	10.8	-0.1
7/22/2010 6:55	1.778	16.6	15.5	10.8	-0.2
7/22/2010 7:00	1.776	16.6	15.5	10.8	-0.5
7/22/2010 7:05	1.775	16.6	15.5	10.8	-0.9
7/22/2010 7:10	1.775	16.6	15.5	10.8	-1.6
7/22/2010 7:15	1.775	16.6	15.5	10.8	-2.5
7/22/2010 7:20	1.780	16.6	15.5	10.8	-3.6
7/22/2010 7:25	1.780	16.6	15.4	10.8	-4.9
7/22/2010 7:30	1.777	16.6	15.4	10.8	-6.7
7/22/2010 7:35	1.777	16.5	15.4	10.8	-8.6
7/22/2010 7:40	1.775	16.6	15.4	10.8	-10.8
7/22/2010 7:45	1.775	16.6	15.4	10.8	-13.5
7/22/2010 7:50	1.773	16.5	15.4	10.8	-15.8
7/22/2010 7:55	1.779	16.5	15.4	10.8	-18.1
7/22/2010 8:00	1.776	16.5	15.4	10.8	-20.6
7/22/2010 8:05	1.775	16.5	15.4	10.8	-21.8
7/22/2010 8:10	1.774	16.5	15.4	10.8	-24.7
7/22/2010 8:15	1.781	16.5	15.4	10.8	-25.4
7/22/2010 8:20	1.776	16.5	15.4	10.8	-27.6
7/22/2010 8:25	1.773	16.5	15.5	10.8	-31.4
7/22/2010 8:30	1.771	16.5	15.5	10.8	-35.4
7/22/2010 8:35	1.775	16.5	15.5	10.8	-38.6
7/22/2010 8:40	1.773	16.5	15.6	10.8	-43.1
7/22/2010 8:45	1.776	16.5	15.7	10.8	-45.2
7/22/2010 8:50	1.776	16.5	15.7	10.8	-46.8
7/22/2010 8:55	1.777	16.5	15.8	10.8	-49.5
7/22/2010 9:00	1.776	16.5	15.8	10.8	-54.7
7/22/2010 9:05	1.774	16.5	15.9	10.8	-60.9
7/22/2010 9:10	1.774	16.5	16.0	10.8	-66.0
7/22/2010 9:15	1.775	16.5	16.1	10.8	-72.1
7/22/2010 9:20	1.774	16.5	16.2	10.8	-80.1
7/22/2010 9:25	1.775	16.5	16.2	10.8	-90.9
7/22/2010 9:30	1.775	16.5	16.3	10.8	-96.7

7/22/2010 9:35	1.771	16.5	16.4	10.8	-105.9
7/22/2010 9:40	1.771	16.5	16.5	10.8	-116.0
7/22/2010 9:45	1.770	16.5	16.6	10.8	-129.6
7/22/2010 9:50	1.773	16.5	16.8	10.8	-142.0
7/22/2010 9:55	1.772	16.5	16.9	10.8	-152.8
7/22/2010 10:00	1.772	16.5	17.0	10.8	-150.4
7/22/2010 10:05	1.770	16.5	17.2	10.8	-156.4
7/22/2010 10:10	1.775	16.5	17.3	10.8	-180.2
7/22/2010 10:15	1.773	16.5	17.5	10.8	-194.2
7/22/2010 10:20	1.770	16.5	17.7	10.8	-206.5
7/22/2010 10:25	1.775	16.5	17.8	10.8	-217.8
7/22/2010 10:30	1.774	16.5	18.0	10.8	-221.2
7/22/2010 10:35	1.775	16.5	18.2	10.8	-229.4
7/22/2010 10:40	1.771	16.5	18.4	10.8	-239.3
7/22/2010 10:45	1.779	16.5	18.6	10.8	-263.3
7/22/2010 10:50	1.775	16.5	18.9	10.8	-271.1
7/22/2010 10:55	1.773	16.5	19.1	10.8	-290.2
7/22/2010 11:00	1.770	16.6	19.3	10.8	-295.7
7/22/2010 11:05	1.769	16.6	19.6	10.8	-302.0
7/22/2010 11:10	1.777	16.6	19.8	10.8	-320.3
7/22/2010 11:15	1.776	16.6	20.1	10.8	-335.4
7/22/2010 11:20	1.769	16.6	20.4	10.8	-358.8
7/22/2010 11:25	1.774	16.6	20.6	11.2	-353.7
7/22/2010 11:30	1.774	16.6	20.8	10.8	-356.0
7/22/2010 11:35	1.769	16.6	21.1	11.2	-410.4
7/22/2010 11:40	1.771	16.6	21.3	10.8	-365.1
7/22/2010 11:45	1.772	16.6	21.5	10.8	-391.7
7/22/2010 11:50	1.770	16.6	21.6	10.8	-439.8
7/22/2010 11:55	1.772	16.7	21.8	10.8	-863.6
7/22/2010 12:00	1.775	16.7	21.9	10.8	-474.5
7/22/2010 12:05	1.776	16.7	22.1	10.8	-807.7
7/22/2010 12:10	1.773	16.7	22.2	10.8	-544.4
7/22/2010 12:15	1.770	16.7	22.3	10.8	-469.9
7/22/2010 12:20	1.772	16.7	22.4	10.8	-587.7
7/22/2010 12:25	1.770	16.7	22.6	11.2	-587.5
7/22/2010 12:30	1.772	16.7	22.8	11.2	-688.3
7/22/2010 12:35	1.779	16.7	22.9	11.2	-705.4
7/22/2010 12:40	1.773	16.8	23.1	11.2	-1089.4
7/22/2010 12:45	1.771	16.8	23.2	10.8	-841.7
7/22/2010 12:50	1.776	16.8	23.5	11.2	-824.0
7/22/2010 12:55	1.773	16.8	23.7	11.2	-864.4
7/22/2010 13:00	1.776	16.8	24.0	11.2	-1077.2
7/22/2010 13:05	1.775	16.8	24.3	11.2	-894.3
7/22/2010 13:10	1.765	16.9	24.5	11.2	-901.3
7/22/2010 13:15	1.778	16.9	24.8	11.2	-1815.6
7/22/2010 13:20	1.770	16.9	25.2	11.2	-632.4
7/22/2010 13:25	1.771	16.9	25.5	11.2	-668.7
7/22/2010 13:30	1.773	16.9	25.7	11.2	-707.1
7/22/2010 13:35	1.770	16.9	25.9	11.2	-776.6
7/22/2010 13:40	1.768	16.9	26.0	11.2	-722.1
7/22/2010 13:45	1.771	17.0	26.1	11.2	-547.8
7/22/2010 13:50	1.776	17.0	26.2	11.2	-538.9
7/22/2010 13:55	1.771	17.0	26.3	11.2	-590.4
7/22/2010 14:00	1.775	17.0	26.4	11.2	-590.1
7/22/2010 14:05	1.776	17.0	26.6	11.2	-541.3
7/22/2010 14:10	1.775	17.0	26.7	11.2	-600.0
7/22/2010 14:15	1.772	17.0	27.0	11.2	-1134.3
7/22/2010 14:20	1.770	17.0	27.3	11.2	-1232.5
7/22/2010 14:25	1.774	17.1	27.6	11.2	-649.1
7/22/2010 14:30	1.770	17.1	27.9	11.2	-1211.8
7/22/2010 14:35	1.774	17.1	28.3	11.2	-761.7
7/22/2010 14:40	1.772	17.1	28.6	11.2	-502.3

7/22/2010 14:45	1.772	17.1	28.7	11.2	-621.1
7/22/2010 14:50	1.772	17.1	29.0	11.2	-1047.9
7/22/2010 14:55	1.774	17.1	29.3	11.2	-555.3
7/22/2010 15:00	1.768	17.2	29.5	11.2	-674.7
7/22/2010 15:05	1.775	17.2	29.7	11.2	-524.4
7/22/2010 15:10	1.771	17.2	29.8	11.2	-427.9
7/22/2010 15:15	1.773	17.2	29.9	11.2	-501.2
7/22/2010 15:20	1.768	17.2	30.1	11.2	-487.0
7/22/2010 15:25	1.771	17.2	30.4	11.2	-732.4
7/22/2010 15:30	1.772	17.2	30.7	11.6	-622.5
7/22/2010 15:35	1.768	17.2	30.7	11.6	-415.9
7/22/2010 15:40	1.768	17.3	30.5	11.6	-371.4
7/22/2010 15:45	1.769	17.3	30.2	11.6	-231.9
7/22/2010 15:50	1.770	17.3	29.7	11.6	-213.9
7/22/2010 15:55	1.770	17.3	29.2	11.2	-182.1
7/22/2010 16:00	1.767	17.3	28.7	11.6	-159.8
7/22/2010 16:05	1.767	17.3	28.2	11.6	-128.3
7/22/2010 16:10	1.771	17.3	27.7	11.6	-107.5
7/22/2010 16:15	1.767	17.3	27.3	11.6	-94.5
7/22/2010 16:20	1.769	17.3	26.9	11.6	-88.9
7/22/2010 16:25	1.773	17.3	26.6	11.6	-83.7
7/22/2010 16:30	1.771	17.3	26.2	11.6	-85.8
7/22/2010 16:35	1.765	17.3	25.9	11.6	-87.0
7/22/2010 16:40	1.768	17.3	25.6	11.6	-83.4
7/22/2010 16:45	1.770	17.3	25.4	11.6	-77.3
7/22/2010 16:50	1.766	17.4	25.1	11.6	-70.7
7/22/2010 16:55	1.770	17.4	24.9	11.6	-62.0
7/22/2010 17:00	1.770	17.4	24.7	11.6	-59.2
7/22/2010 17:05	1.772	17.4	24.5	11.6	-53.9
7/22/2010 17:10	1.773	17.4	24.3	11.6	-48.5
7/22/2010 17:15	1.769	17.4	24.2	11.6	-43.3
7/22/2010 17:20	1.766	17.4	24.0	11.6	-37.4
7/22/2010 17:25	1.766	17.4	23.8	11.6	-32.3
7/22/2010 17:30	1.771	17.4	23.7	11.6	-27.5
7/22/2010 17:35	1.770	17.4	23.6	11.6	-29.9
7/22/2010 17:40	1.767	17.4	23.6	11.6	-23.2
7/22/2010 17:45	1.771	17.4	23.5	11.6	-15.8
7/22/2010 17:50	1.771	17.4	23.5	11.6	-12.1
7/22/2010 17:55	1.765	17.4	23.3	11.6	-8.9
7/22/2010 18:00	1.772	17.4	23.1	12.1	-6.5
7/22/2010 18:05	1.769	17.4	22.9	11.6	-4.5
7/22/2010 18:10	1.768	17.4	22.7	11.6	-2.8
7/22/2010 18:15	1.769	17.4	22.5	11.6	-1.8
7/22/2010 18:20	1.772	17.4	22.3	11.6	-1.0
7/22/2010 18:25	1.763	17.4	22.1	11.6	-0.5
7/22/2010 18:30	1.771	17.4	22.0	11.6	-0.2
7/22/2010 18:35	1.765	17.4	21.8	11.6	0.0
7/22/2010 18:40	1.771	17.4	21.6	11.6	0.0
7/22/2010 18:45	1.769	17.4	21.4	11.6	0.0
7/22/2010 18:50	1.770	17.4	21.3	11.6	0.0
7/22/2010 18:55	1.764	17.4	21.1	11.6	0.0
7/22/2010 19:00	1.765	17.4	21.0	11.6	0.0

Table S4: Compilation of Photosynthetically Available Radiation meter data of river water from Maun over 24 h recorded in fifteen minutes increments

Maun	
Date & Time (hrs)	**PAR (μA/mol*Sm^2)**
7/14/2010 19:30	0.0
7/14/2010 19:45	0.0
7/14/2010 20:00	0.0
7/14/2010 20:15	0.0
7/14/2010 20:30	0.0
7/14/2010 20:45	0.0
7/14/2010 21:00	0.0
7/14/2010 21:15	0.0
7/14/2010 21:30	0.0
7/14/2010 21:45	0.0
7/14/2010 22:00	0.0
7/14/2010 22:15	0.0
7/14/2010 22:30	0.0
7/14/2010 22:45	0.0
7/14/2010 23:00	0.0
7/14/2010 23:15	0.0
7/14/2010 23:30	0.0
7/14/2010 23:45	0.0
7/15/2010 0:00	0.0
7/15/2010 0:15	0.0
7/15/2010 0:30	0.0
7/15/2010 0:45	0.0
7/15/2010 1:00	0.0
7/15/2010 1:15	0.0
7/15/2010 1:30	0.0
7/15/2010 1:45	0.0
7/15/2010 2:00	0.0
7/15/2010 2:15	0.0
7/15/2010 2:30	0.0
7/15/2010 2:45	0.0
7/15/2010 3:00	0.0
7/15/2010 3:15	0.0
7/15/2010 3:30	0.0
7/15/2010 3:45	0.0
7/15/2010 4:00	0.0
7/15/2010 4:15	0.0
7/15/2010 4:30	0.0
7/15/2010 4:45	0.0
7/15/2010 5:00	0.0
7/15/2010 5:15	0.0
7/15/2010 5:30	0.0
7/15/2010 5:45	0.0
7/15/2010 6:00	0.0
7/15/2010 6:15	0.0
7/15/2010 6:30	0.0
7/15/2010 6:45	0.0
7/15/2010 7:00	-0.6
7/15/2010 7:15	-3.2
7/15/2010 7:30	-7.4
7/15/2010 7:45	-11.9
7/15/2010 8:00	-16.3
7/15/2010 8:15	-19.8

7/15/2010 8:30	-22.6
7/15/2010 8:45	-24.6
7/15/2010 9:00	-22.9
7/15/2010 9:15	-24.5
7/15/2010 9:30	-27.2
7/15/2010 9:45	-28.2
7/15/2010 10:00	-30.2
7/15/2010 10:15	-31.5
7/15/2010 10:30	-33.6
7/15/2010 10:45	-41.1
7/15/2010 11:00	-40.6
7/15/2010 11:15	-37.1
7/15/2010 11:30	-47.8
7/15/2010 11:45	-77.2
7/15/2010 12:00	-76.6
7/15/2010 12:15	-82.5
7/15/2010 12:30	-121.3
7/15/2010 12:45	-187.4
7/15/2010 13:00	-268.2
7/15/2010 13:15	-369.0
7/15/2010 13:30	-443.1
7/15/2010 13:45	-481.3
7/15/2010 14:00	-476.5
7/15/2010 14:15	-485.2
7/15/2010 14:30	-423.4
7/15/2010 14:45	-413.2
7/15/2010 15:00	-420.7
7/15/2010 15:15	-333.7
7/15/2010 15:30	-317.8
7/15/2010 15:45	-302.6
7/15/2010 16:00	-287.5
7/15/2010 16:15	-233.2
7/15/2010 16:30	-188.9
7/15/2010 16:45	-134.6
7/15/2010 17:00	-85.6
7/15/2010 17:15	-55.9
7/15/2010 17:30	-21.8
7/15/2010 17:45	-12.8
7/15/2010 18:00	-5.1
7/15/2010 18:15	-1.1
7/15/2010 18:30	-0.1
7/15/2010 18:45	0.0
7/15/2010 19:00	0.0
7/15/2010 19:15	0.0
7/15/2010 19:30	-0.1

Table S5: Compilation of raw Yellow Springs Instrument multi-parameter probe data of river water from Maun, recorded over 24 h at different locations in the water column.

Time (hrs)	**Water Column Location**	**Water Temp. (°C)**	**Cond (µS/cm)**	**DO (mg/L)**	**DO (%)**	**pH**	**ORP**	**Alk (mg/L)**	**Silica (mg/L)**	**Fe^{2+} (mg/L)**	**TDS (mg/L)**
19:30	**Top**	18.0	100.0	13.2	139.0	7.0	-172.6	48.0	35.7	0.0	0.1
	Bottom	17.9	100.0	11.8	124.6	6.9	-169.7	47.8	4.44	0.0	0.1
20:30	**Top**	17.9	100.0	11.2	118.5	6.8	-167.7	48.5	38.5	0.0	0.1
	Bottom	17.8	100.0	10.2	107.5	6.9	-168.7	48.2	38.5	0.0	0.1
21:30	**Top**	17.7	100.0	11.1	116.5	6.9	-169.3	48.5	49.5	0.0	0.1
	Bottom	17.6	100.0	10.1	105.2	6.9	-168.7	48.5	44.9	0.0	0.1
22:30	**Top**	17.5	100.0	11.6	122.2	6.8	-168.6	49.3	38.3	0.0	0.1
	Bottom	17.4	100.0	9.4	98.6	6.8	-168.3	48.5	37.4	0.0	0.1
23:30	**Top**	17.3	100.0	9.8	101.5	6.8	-166.4	49.5	35.0	0.0	0.1
	Bottom	17.2	100.0	9.1	94.6	6.8	-166.9	48.4	35.6	0.0	0.1
0:30	**Top**	17.1	100.0	9.4	97.5	6.7	-165.9	47.3	37.6	0.1	0.1
	Bottom	16.9	100.0	8.7	90.2	6.7	-165.2	48.3	29.2	0.0	0.1
1:30	**Top**	16.8	100.0	9.2	93.7	6.7	-164.3	48.4	29.2	0.0	0.1
	Bottom	16.7	100.0	8.7	89.5	6.7	-164.2	47.4	30.5	0.0	0.1
2:30	**Top**	16.6	99.0	9.3	95.7	6.7	-163.7	48.7	40.8	0.1	0.1
	Bottom	16.5	99.0	8.7	89.5	6.7	-103.5	48.0	37.2	0.0	0.1
3:30	**Top**	16.3	99.0	9.5	97.6	6.7	-163.0	49.1	33.6	0.0	0.7
	Bottom	16.3	99.0	8.7	88.3	6.7	-162.2	-	-	-	0.1
4:30	**Top**	16.2	99.0	9.2	93.6	6.7	-164.2	47.9	30.3	0.1	0.6
	Bottom	16.2	99.0	8.3	84.8	6.7	-162.0	48.5	28.4	0.0	0.6
5:30	**Top**	15.9	99.0	9.6	96.8	6.6	-160.3	45.8	32.2	0.0	0.1
	Bottom	15.9	99.0	8.5	86.3	6.6	-160.3	45.5	31.9	0.0	0.1
6:30	**Top**	16.0	99.0	9.5	95.3	6.7	-160.9	46.0	25.2	0.0	0.1
	Bottom	15.9	99.0	8.2	83.6	6.6	-161.3	-	-	-	0.1
7:30	**Top**	15.7	99.0	8.7	87.4	6.8	-161.7	46.2	31.9	0.0	0.1
	Bottom	15.8	99.0	8.5	85.5	6.7	-160.1	-	-	-	0.1
8:30	**Top**	15.7	99.0	10.1	98.5	6.6	-160.5	47.4	34.5	0.1	0.1
	Bottom	15.8	98.0	8.1	80.9	6.7	-161.2	47.5	40.3	0.0	0.1
9:30	**Top**	15.7	99.0	8.9	90.1	6.7	-160.5	45.7	40.9	0.0	0.1
	Bottom	15.9	98.0	7.9	79.4	6.7	-161.3	45.7	-	-	0.1
10:30	**Top**	16.1	99.0	8.8	89.1	6.7	-161.0	46.0	41.3	0.0	0.1
	Bottom	16.1	99.0	8.2	83.3	6.7	-161.5	45.6	40.9	0.0	0.1
11:30	**Top**	16.3	100.0	9.0	92.1	6.8	-161.5	48.0	41.6	0.1	0.1
	Bottom	16.4	99.0	8.2	83.6	6.8	-162.5	-	-	-	0.1
12:30	**Top**	16.9	99.0	9.9	102.3	6.9	-165.1	47.0	43.7	0.1	0.1
	Bottom	16.9	99.0	8.2	84.9	6.8	-165.9	48.2	43.1	0.1	0.1
13:30	**Top**	17.5	100.0	8.9	93.6	6.9	-164.8	48.3	44.6	0.1	0.1
	Bottom	17.6	100.0	7.9	83.2	6.9	-165.3	-	-	-	0.1
14:30	**Middle**	18.2	100.0	9.2	97.6	6.9	-166.7	48.8	43.0	0.1	0.1
15:30	**Middle**	18.6	100.0	8.7	92.7	7.0	-169.2	49.1	46.2	0.1	0.1
16:30	**Middle**	18.7	100.0	8.4	90.1	7.0	-169.7	47.0	44.7	0.1	0.1
17:30	**Middle**	18.9	100.0	8.3	89.3	7.1	-169.8	47.1	42.6	0.0	0.1
18:30	**Middle**	18.8	100.0	7.9	85.7	7.0	-169.9	46.9	41.2	0.0	0.1
19:30	**Middle**	18.7	100.0	7.9	84.4	7.0	-168.9	46.9	39.5	0.0	0.1

VITA

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