WATER BALANCE, NUTRIENT AND CARBON LOADING OF THE KAFUE FLOODPLAIN, A WETLAND IN SOUTH CENTRAL ZAMBIA

By

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A thesis submitted to the University of Zambia in partial fulfillment of the Degree of Master of Science in Integrated Water Resources Management.

University of Zambia

LUSAKA

DECLARATION

This thesis was written and submitted in accordance with the rules and regulations governing the award of Master of Science in Integrated Water Resources Management of the University of Zambia. I further declare that the thesis has neither in part nor in whole been presented as substance for award of any degree, either to this or any other University. Where other people's work has been drawn upon, acknowledgement has been made.

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APPROVAL

This thesis of Jason Wamulume is approved as fulfilling the requirements of the Degree of Master of Science in Integrated Water Resources Management of the University of Zambia.

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ACKNOWLEDGEMENTS

Special thanks go to my lovely wife and two children for their understanding, patience, love and support during the time I undertook this program. I say thank you also to Prof. Imasiku Nyambe, Prof. Bernhard Wehrli and Dr. David Senn my supervisors for their guidance and support without which this thesis would not be possible. Thanks also go out to Dr. Manuel Kunz and Mr. Roland Zurbrügg for the help with the science and the laboratory set up and analysis. Many thanks also go to the IWRM Centre, Ms. Ingrid Kawesa and Ms. Caroline Mweemba for providing space and help with many logistics. I also cherish the opportunity of having worked with great minds and hearts- Nanina Blank and Jan Landert. Special thanks go to Swiss Federal Institute of Aquatic Science and Technology (Eawag) for their financial support, help in providing the laboratory facilities and training in Switzerland. My gratitude goes to Department of Water Affairs in the Ministry of Energy and Water Development and Zambezi River Authority for the data and equipment - Mr. Sam Mwale in particular. Many thanks also to the friendly staff at Eawag, who made the cold winters warm, and University of Zambia (UNZA). Last but not least, many thanks go to my fellow postgraduate students with whom we endured this long journey.

ABSTRACT

Wetland processes are strongly influenced by hydrologic factors such as precipitation, surface runoff, and flooding dynamics. Anthropogenic disturbances to flooding regimes can thus substantially alter wetland habitat and biogeochemistry. The Kafue Flats, a large floodplain (~6,500 Km^2) along the Kafue River in South-Central Zambia, is a wetland impacted by upstream and downstream hydropower dams. The main purpose of this study was to develop a water budget for the Kafue Flats under current conditions, quantify nutrient and organic carbon concentrations in the river, and use the combined information to estimate biogeochemical budgets. A water balance was developed for the Kafue Flats at a subcatchment scale for the years 2002-2009 using daily hydrological data. In addition, bimonthly flow and chemical measurements were performed over one year (May 2008-May 2009) at multiple stations. Evapotranspiration was an important process in the Flats, accounting for up to 49% of total hydrologic outputs in some subcatchments. Direct precipitation contributes substantial to water inputs to the flats: runoff from the upstream catchment accounted for 45% of water inputs to the Kafue Flats, while the remaining 55% came from direct precipitation to the Kafue Flats from its subcatchment. Estimates from the wet season suggest that ~75% of the water flowing in the river's main channel as it exits the Flats spent some time within the highly productive floodplain. This exchange between the floodplain and the river appeared to play an important role in nutrient and carbon export to the river's main channel and out of the wetland. The floodplain was a net source of phosphate (220 t/yr), total nitrogen (1300 t N/yr, of which ~90% was organic nitrogen) and total organic carbon (50,000 t C/yr) to downstream systems. Thus, when considering dam impacts and altered flooding dynamics in this system, potential changes to carbon and nutrient cycling also need to be taken in to consideration, which may have implications for nutrient availability within the Kafue Flats and nutrient export to downstream systems.

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Chapter 1.0 Introduction

1.1 Introduction

The Kafue River Basin is one of the major sub-basins of the Zambezi River Basin in Zambia. The Kafue River is almost 1,500 km in length up to its confluence with the Zambezi River, with a catchment area of approximately 157,629 km^2. The Kafue River is one of the major tributaries of the Zambezi River. Its drainage basin can be subdivided into three sub basins: (a) the upper half of the catchment area in the wetter northern part of Zambia, roughly north of Itezhi Tezhi Dam, (b) the middle, area referred to as the "Kafue Flats" from Itezhi Tezhi to the Kafue Gorge, and (c) the lower part of the river, the Gorge where the river drops steeply from the plateau to the level of the Zambezi River (Pinay, 1988; Scott Wilson Piésold, 2003; Euro Consult Mott Mac Donald, 2007). The Kafue River Basin is the most economically active basin in Zambia. The various uses of water in the basin range from domestic, industrial, irrigation, hydropower, livestock, mining, recreation and environmental purposes. These activities have led to the degradation of the water quality and reduction of quantity in the Kafue River Basin (Kambole, 2002).

Two large dams, Itezhi Tezhi and Kafue Gorge, regulate the flow through the lower Kafue River Basin. In between the dams is a wetland known as Kafue Flats. The Kafue Flats have a population of about 1.3 million people, with relatively higher population densities of about 10 people per sq km in the southern part of the flats (Shamboko, 2006). The important socioeconomic activities in the flats are crop production, cattle rearing and fishing (Yachiko, 1995; Shamboko, 2006). There are about 250,000 herds of cattle in Namwala District alone. According to Shamboko (2006) the Kafue Flats fisheries are very productive with an average yield of 7,700 metric tons per annum.

The construction of these large dams has affected downstream water quality in the Kafue Flats due to changes in hydro-peaking and seasonal changes in the hydrological regime (Friedl and Wuest, 2002). Dams impact the hydrology, physical, chemical and biological characteristics by changing the characteristics of a water body from rivers to lakes. According to Friedl and Wuest (2002) construction of reservoirs further interrupts the flow of organic carbon, changes the nutrient balance and alters oxygen and thermal conditions. While the hydrology of the upper Kafue River Basin has been studied extensively, there is limited information on the hydrology of the Kafue Flats, floodplain- river interactions and how this influences the biogeochemistry of Kafue River (Chimatiro, 2004). The study was thus conducted to capture information on the hydrology, floodplain and river interactions and how these influence the biogeochemistry of the Kafue Flats. Further the study was conducted to provide insights and baseline data in a pristine floodplain in the Kafue River Basin.

The study aimed at conducting a water balance and quantifying nutrient and carbon loading in the Kafue Flats floodplain. During the study a chemical and discharge measuring network was set up in the Lower Kafue Basin to monitor water quality and quantity over duration of one year (May 2008 - May 2009). In addition, to presenting synoptic concentration data along the river, simultaneous flow measurements and chemical data at multiple stations and at bimonthly frequency were used to develop mass transfer estimates for the Kafue River in this area.

1.2 Study Area

The study area covers an area of 61,000 Km^2 from Kafue Hook Bridge, upstream Itezhi Tezhi Dam, up to the confluence with the Zambezi River. It is located between 15 to 16° S and 25 to 29° E. From Kafue Hook Bridge the river meanders through a distance of approximately 500 Km to the confluence with the Zambezi River (Figure 1.0). The Kafue Flats is located between 15 to16 ° S and 26 to 28° E.

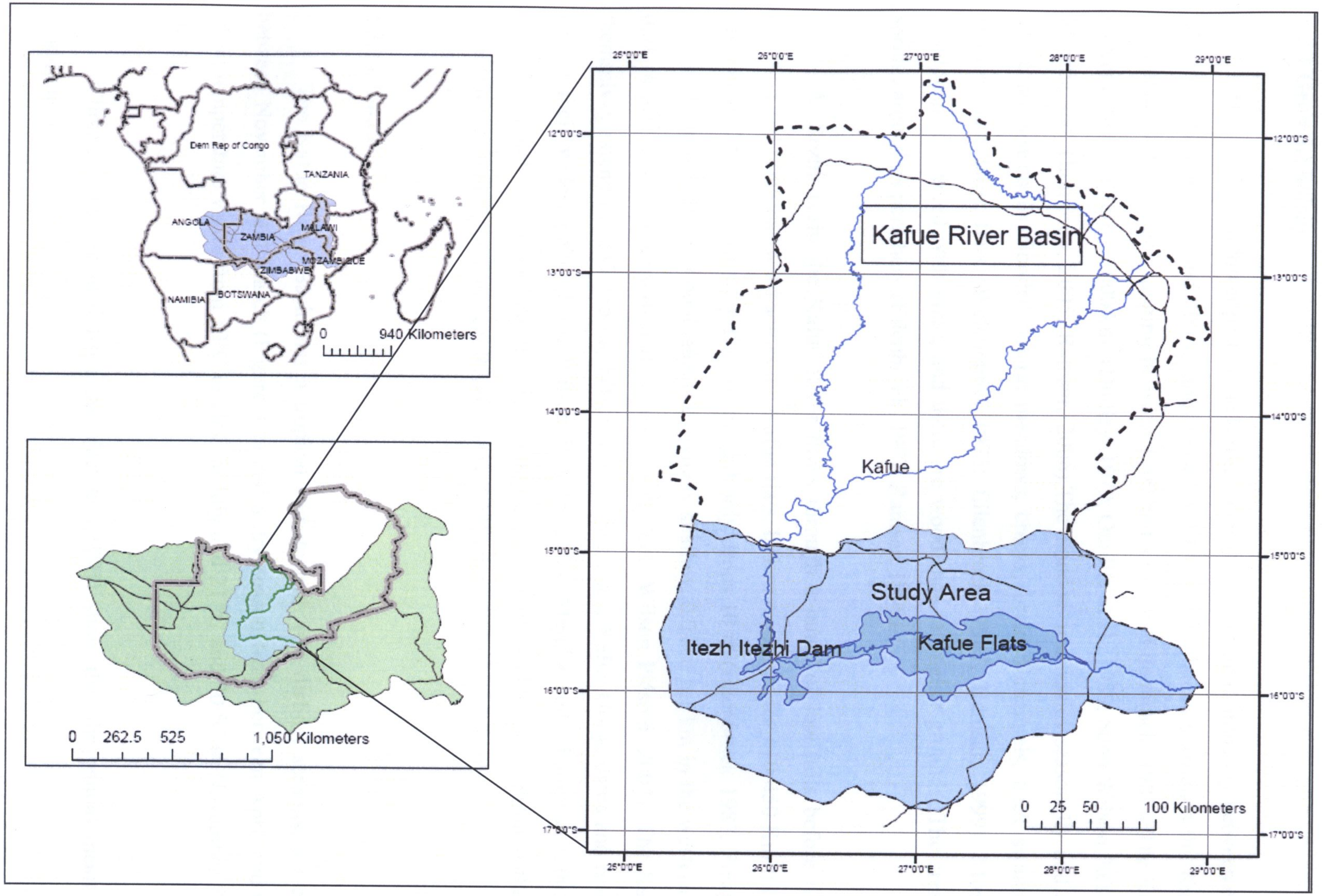


Figure 1.0: Location of study area - Kafue Flats, Lower Kafue Basin, in relation to Southern Africa (top left), Zambia (bottom left).

1.2.1 Geomorphology

The middle and lower part of the Kafue River Basin, lies predominately between elevations of approximately 1100 and 300 m above sea level (ASL). A plateau surrounds the Kafue Flats floodplain with elevation ranging between 1100 and 1350 m (Ellenbroek, 1987). The Kafue flats covers between 4,380 – 7,000 km^2 (Dudley, 1979; Obrdlik et al., 1989; Scott Wilson Piésold, 2003; Mumba and Thompson, 2005; Ramsar, 2006).The flooded area varies seasonally and annually. There are seasonally flooded natural meadows, creeks, braided channels, back swamp levees, lagoons, and large flats (Welcomme, 1975; Ellenbroek, 1987; Ramsar, 1999). Most of the floodplain is covered with grass, and there are woodlands on higher grounds. The area has hot springs around its periphery (Ellenbroek, 1987; Ramsar, 1999).

At Itezhi Tezhi the Kafue River flows through a range of low hills before it changes direction and flows eastward across the Kafue flats. It then meanders for 410-450 Km traversing a distance of 250 Km across the floodplain, and only drops 10 m (Ellenbroek 1987; Pinay, 1988). The gradient through the floodplains is extremely shallow, 0.04 m per km in the western half and 0.01 m per km in the eastern half (Pinay, 1988; Scott Wilson Piésold, 2003). The Kafue flats themselves extend for 235-255 km between Itezhi-Tezhi and Kafue Gorge dams and reach 40-56 Km at their widest point (Scott Wilson Piésold, 2003; Mumba and Thompson, 2005). After flowing through the floodplain, the river plunges down 670 m as it flows through the 30 Km Kafue Gorge Dam to the Zambezi River (Pinay, 1988).

1.2.2 Climate

The Kafue River Basin has a tropical climate with two distinct seasons, a wet season between November and March (Figure 1.1) and a dry season from between April and October. Mean temperature varies from 13°C to 20°C in July and 21 °C and 30 °C in November (Yachiko, 1995).

Climatic data obtained from the Yachiko (1995) show that the annual mean climatic conditions are:

- Annual mean temperature - 21.3 ºC;
- Annual mean Rainfall - 850 mm; and
- Annual mean Evaporation - 2100 mm.

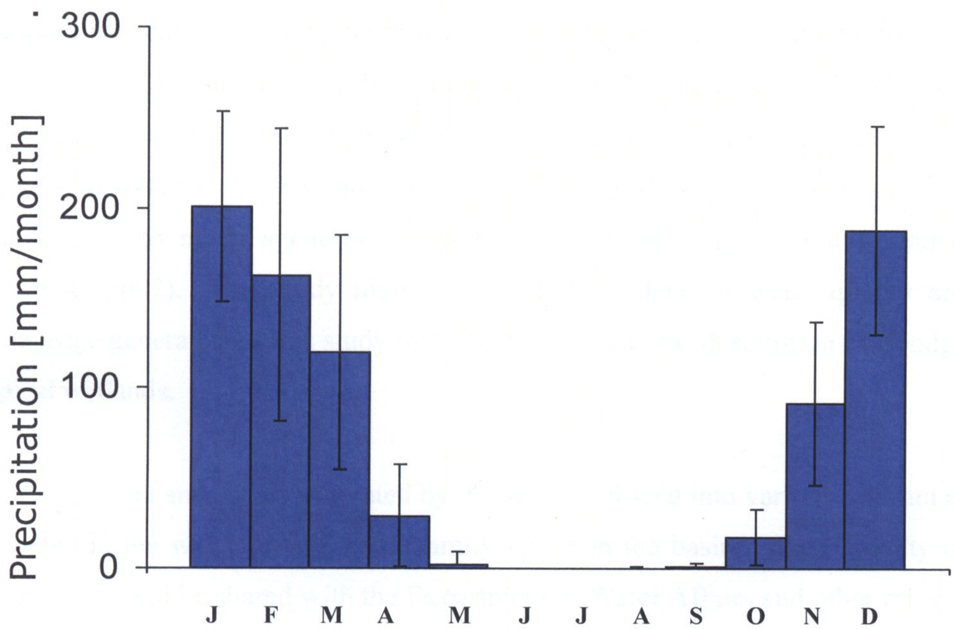


Figure 1.1: Average precipitations in the Kafue flats (1998-2007), Southern Province, Zambia.

1.3 Significance of the Study

This research is a component in the African Large Dams Project (ADAPT), which is focused on the Zambezi River Basin. The overall goal of the ADAPT is to strengthen the interdisciplinary science of Integrated Water Resources Management by creating new models for real time control and multi-objective optimization of large hydraulic structures, and also the conceptual framework and data resources to drive those models.

The countries in the Zambezi Basin have data available on the water quantity but have very little data on water quality. While water levels and flows are monitored on a daily time step at numerous sites throughout the basin, most of the riparian countries do not maintain a systematic water quality monitoring system and database in the same way as discharge and water levels (Euro

Consult Mott Mac Donald, 2007). While the hydrology of the Upper Kafue River Basin has been studied extensively in the Kafue flats, there is limited information on the hydrology, floodplain and river interaction and how this influences the biogeochemistry of Kafue flats. Despite the importance of tropical wetlands, there are a few detailed biogeochemical studies of these systems. Whereas there is some chemical data for the Kafue flats (e.g. Salter, 1985), few studies have measured nutrients along with other water quality parameters, and none have worked at the scale of the Kafue River between Itezhi Tezhi and Kafue Gorge dams and during multiple seasons. In order to achieve sustainable environmental management as envisioned under the SADC protocol, research on water quality and quantity monitoring and documentation are crucial. The KRB is of great interest to many agencies in Zambia both for its socio-economic and ecological value (Kambole, 2002). This study aims to provide new data on water quality and quantity. The Knowledge generated by this study will also be useful in the description of floodplain dynamics in tropical wetlands.

The data and report generated by the study will feed into various relevant agencies who are interested in the water quality and quantity issues in the basin. Water quality data and updated rating curves will be shared with the Department of Water Affairs and other relevant agencies.

1.5 Research Objectives and Questions

The following were the specific objectives of the study:

- To develop a water balance for the Lower Kafue River Basin;
- To quantify the river - floodplain exchange; and
- To characterize the temporal and spatial variability of Nitrogen (N), Carbon (C), Phosphates (P) concentration, speciation and loads over an annual cycle, along with other water quality parameters (Temperature (T), pH, specific conductance, dissolved oxygen).

The main research questions for this study were:

- How important is river-floodplain exchange in the Kafue flats, and how does this vary over time?;
- How does this exchange influence river chemistry and nutrient/carbon cycling?; and

- How have the dams influenced these processes?

To explore these issues a network was designed during the study coupling a water sampling network with existing flow station that had a stage discharge relation. The rational was to conduct discharge measurements to check the reliability of these curves for use in the water balance and chemical model. Then water samples were collected on a bi-monthly time scale with simultaneous discharges at the selected stations in the Lower Kafue Basin.

Chapter 2.0 Literature Review

Hydrology is an important driver of biogeochemical processes in floodplain ecosystems (Junk et al., 1989; Tockner et al., 2000). Floodplain processes such as particle deposition (Olde Venterink et al., 2006), organic matter mineralization, mobilization, and nutrient turnover (Baldwin and Mitchell, 2000) are governed by the exchange between river and floodplain. In tropical areas with distinct rainy and dry seasons, floodplains are often seasonal wetlands (Figure 2.1) with high productivity (Neue et al., 1997) and high biodiversity. Whereas the effect of hydrological exchange between river and floodplain on biogeochemistry has received substantial attention in temperate systems (e.g. Tockner et al., 1999; Wiegner and Seitzinger, 2004; Hunsinger et al., 2010), studies in tropical systems are sparse (e.g. Bouillon et al., 2007; Nwankwor and Anyaogu, 2000) and the degree of hydrological exchange is often not quantified. Studies in the Okavango Delta have shown that organic matter mobilization and transport is a direct effect of hydrological river-floodplain exchange (Mladenov et al., 2005; 2007).

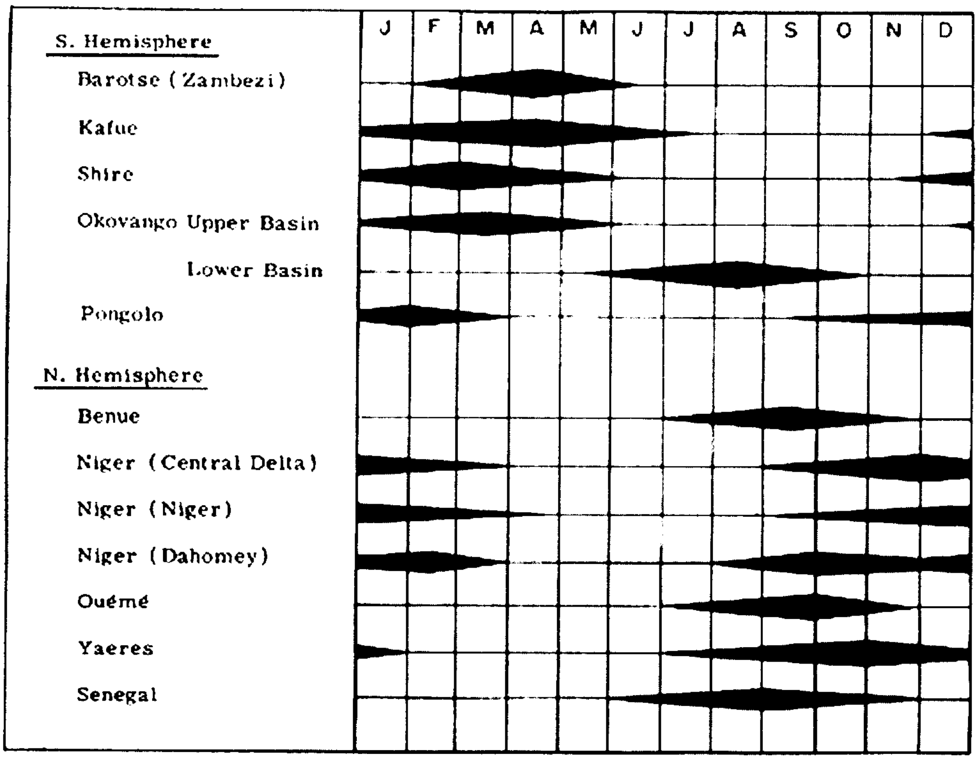


Figure 2.1 Flood regimes of some major African floodplains (Welcomme, 1975).

The hydrological year in Zambia begins in October but significant amounts of rain begin only after mid-November and continue until about the middle of March (Handlos, 1982). The initial flooding and water logging of the Kafue Flats floodplain between December and February is from the runoff from the local tributaries and rainfall (Handlos, 1982). According to Pinay (1988 after Carey, 1971) local rainfall and drainage can inundate depressions in the plain independently of any rise in river level. Rainfall from the northern catchment runoff to Itezhi Tezhi Dam has a peak in March, and then flows slowly southwards, finally reaching a peak at Kafue Gorge in May, often well after the local rains in the flats have ended (Obrdlik et al., 1989; Welcomme, 1975). Welcomme (1975) notes that the tendency for floods to arrive at different times from diverse tributaries leads to a complex flooding pattern or small fluctuation of the water stage. According to Dudley and Scully (1979) about 5,650 Km^2 may be inundated and the water recedes slowly until November. The rains in the northern part of the catchment continue until mid-April, thus continuing to feed water into the Kafue River for almost a month after the local rains in the Kafue Flats floodplain have ended (Hutchinson, 1974). Thus according to Pinay (1988) much of the flooding between March and June is due to runoff from the northern part of the Kafue River Basin. According to Obrdlik et al. (1989) at the peak of the flood the whole of the flats is inundated with 1-2 m of water. Pinay (1988) also shows that high water levels are maintained on the Kafue Flats floodplain for 6 to 7 months (December to June). The natural hydrological cycle of the Kafue Flats floodplain varies tremendously. Three-quarters of the floodplain can change from an aquatic to a terrestrial environment within one season (Pinay, 1988). At the eastern end of the Kafue flats, a shallow area of about 1,215 Km^2 is flooded more or less permanently (Pinay, 1988 after Burgis and Symoens, 1977).

According to the water balance by Pinay (1988 after Burgis and Symoens, 1977) of the entire runoff (12.6 Km^3) from the upper basin, only 73 % of the runoff reaches the Kafue Rail Bridge (downstream of the Kafue flats). Pinay (1988) after Burgis and Symoens (1977) estimate that Kafue Flats floodplain accounts for 15.4 per cent (or 1.84 Km^3) of the runoff lost through evapotranspiration. Pinay (1988 after Burgis and Symoens, 1977) also estimates that the Kafue Flats Floodplain catchment only provides an average runoff of 1.1 Km^3 which they attribute to the lower amounts of precipitation and high evapotransipiration in the floodplain. Thus according to Pinay (1988) the balance between precipitation and evapotranspiration is negative within the Kafue Flats floodplain. Water bodies on the floodplain lose water by evaporation and to a lesser degree by infiltration throughout the dry season (Welcomme, 1985). Yachiko (1995) has a water balance for the dams in the study area. It estimates mean annual open surface evaporation from Itezhi Tezhi and Kafue Gorge dams to be 0.17 Km^3 and 0.03 Km^3 respectively.

Chapter 3.0 Study Methods

3.1 General Remarks

This study was part of the ADAPT project, a large scale study in the Zambezi River Basin. The project had various components. The water quality component under the Kafue River basin consisted of four components; floodplain ecology, reservoirs biogeochemistry, floodplain biogeochemistry and a basin-scale biogeochemistry. This study focused on basin-scale biogeochemistry. The study methods are described below.

3.2 Water Balance

During the study the Kafue flats were first delineated into three subcatchments. Next water balances for the years 2002-2009 were developed for each individual sub-catchment and used to quantify the relative importance of various water inputs and outputs at the sub-catchment scale.

3.2.1 Data collection

The water balance is based largely on existing daily hydrologic data from various local sources (water elevation, discharge, precipitation and evaporation). To complement these local resources the potential utility of remote-sensed precipitation was explored. In addition, discharge measurements were performed at multiple stations to verify existing stage-discharge relationships and develop updated stage-discharge relationships where necessary.

Field measured data was obtained from the Zambia Electricity Supply Company (ZESCO) and Department of Water Affairs, Zambia (DWA). These agencies also have flow measuring stations with rating curves (stage and flow data) in the study area. Due to a lack of weather data measuring stations, remote sensed precipitation was explored to determine if it could capture the temporal and spatial variation in precipitation over the large study area.

3.2.2 Catchment Delineation

The sub-catchments were delineated to coincide with existing flow gauging stations in the study area for which long term flow data was available from ZESCO and DWA (Figure 3.1). The stations are located at Itezhi Tezhi Dam, Namwala, Nyimba, Kasaka and Kafue Gorge Dam. Raster data on the study area was obtained from US Geological Survey (USGS) Earth Resources Observation and Science (EROS). Raster data sets of flow accumulation, flow direction, streams

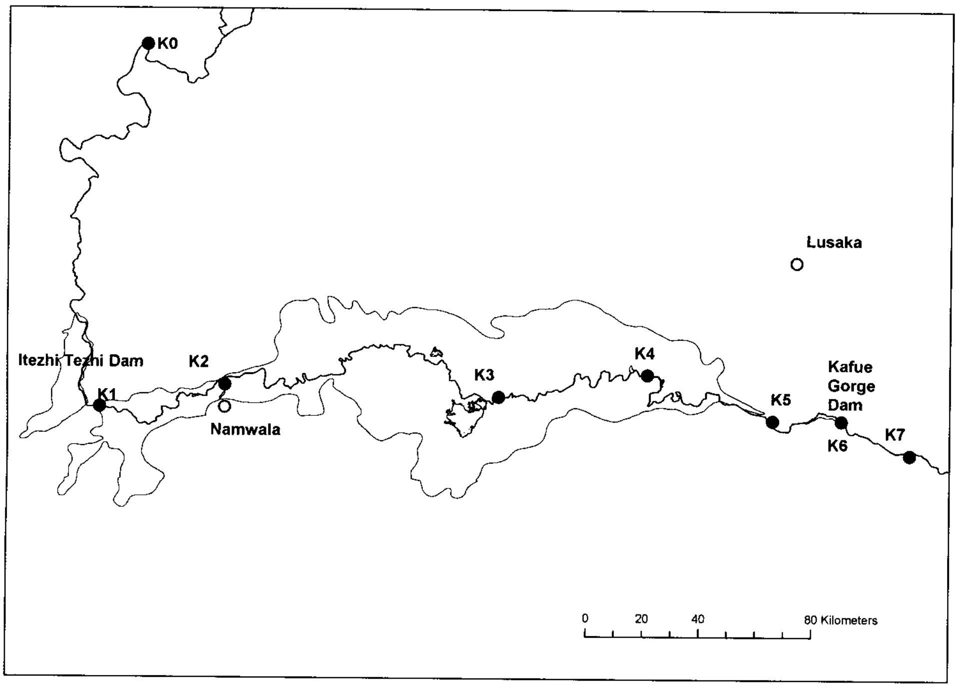


Figure 3.1: Control points used to generate sub-catchments from Lower Kafue River Basin (Zambia) for the model. K1 = Itezhi Tezhi Dam, K2 = Namwala, K3 = Nyimba, K5= Kasaka and K6 = Kafue Gorge Dam.

and elevation geographic data layers were obtained from HYDRO 1k and USGS 30 arc-second digital elevation model of the world (GTop30). The digital elevation model is corrected for flow and has a resolution of 1 km. The data layers were then imported into ArcGis 9.2 and spatial analysis tools were used to delineate the sub-catchments. Due to the flatness of the land at Nyimba two scenarios (Figure 3.2 A and B) were used to develop the sub-catchments. The full procedure of catchment delineation is attached in Appendix A. To ascertain the accuracy of the generated sub-catchments, a comparison was done with shape files obtained from a project by DWA, Ground Water Resources for Southern Province Project (GReSP). Scenario two (Figure 3.2B) compared closely with GReSP, thus it was adopted for this study.

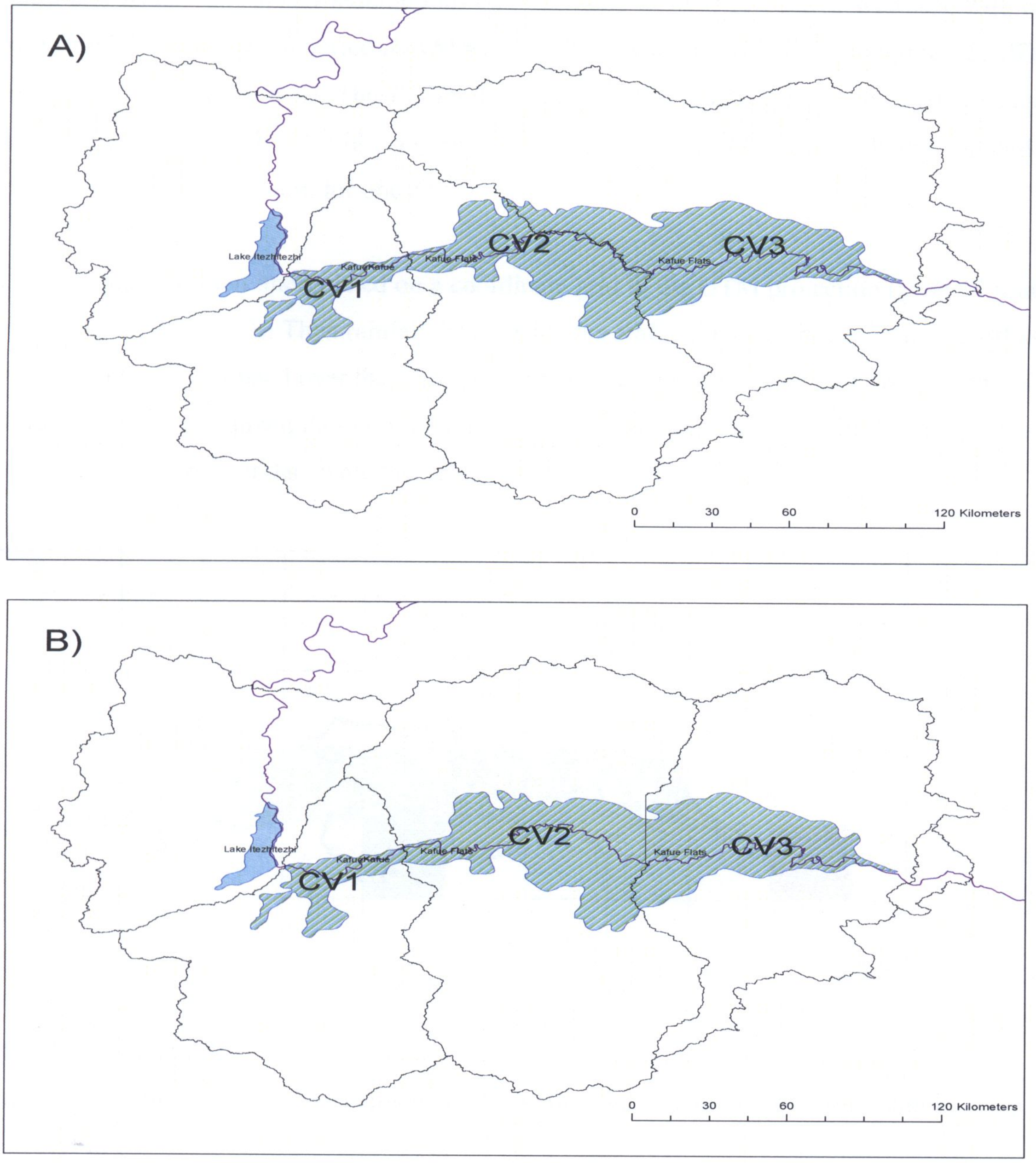


Figure 3.2: Delineated sub-catchments (A) under scenario 1 and (B) under scenario 2 in the lower Kafue River Basin.

3.2.3 Precipitation

Remote sensed daily precipitation data was obtained from two sources: the Tropical Rainfall Measuring Mission (TRMM; http://www.trmm.gsfc.nasa.gov/) and Famine Early Warning System (FEWS; http://earlywarning.usgs.gov/adds/). Detailed information on the rainfall products and underlying model assumptions can be found at their respective websites. The raw TRMM or FEWS data was imported into MATLAB. The raw TRMM data is a compressed HDF-file (Hierarchical Data Format). The FEWS data is a BIL-file (band-interleaved data) with only one band, thus it is read directly like any other binary file. For TRMM data, 3-hourly rainfall is summed up so as to get the sum for one day.

The data was then interpolated on a coordinate grid in the UTM projection (zone 35 south, WGS84 geoids, Figure 3.3). Then rainfall data outside the Kafue flats watershed is clipped off and an average value is calculated over the whole watershed. Detailed procedure is shown in Appendix B. Physically measured precipitation was obtained from a weather station at ZESCO Itezhi Tezhi offices. The two sources of data were then compared.

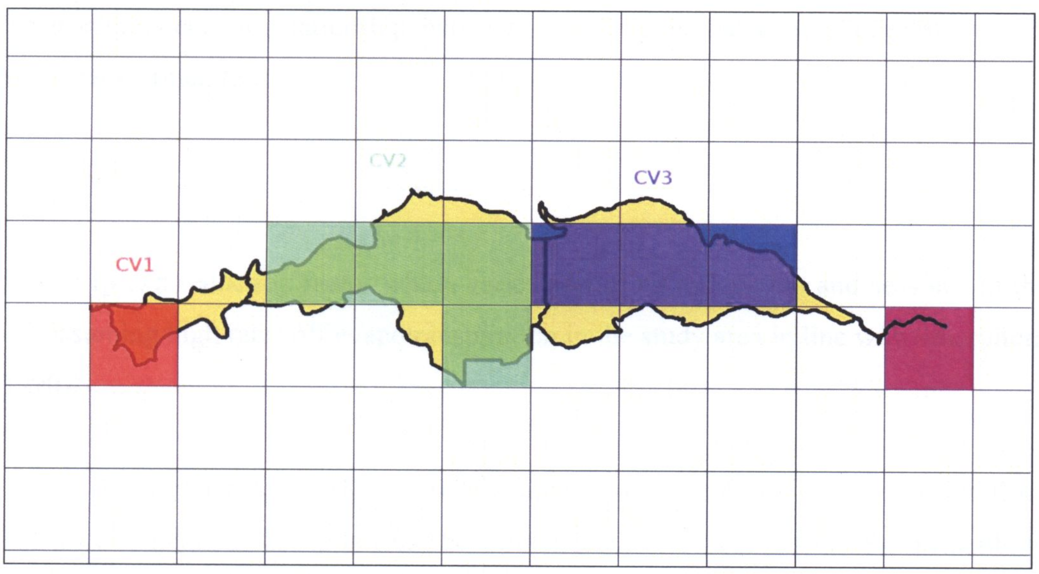


Figure 3.3: Geoids from TRMM as applied to the Kafue flats, Southern Province, Zambia.

The data from various sources was compared to check for correlation between the different sources of precipitation data. Cumulative and correlation plots of the data were made over the various sub-catchments. Comparisons were then done on the various sources of rainfall data. On a daily time scale the correlation between physically measured and remote sensed data was very low. But when cumulative daily rainfall data was compared the differences in the data become relatively smaller. An analysis of different rainfall sources of data was done at different resolutions. The ground measured rainfall was used because there were only small variations in the spatial and temporal variability of the rainfall over the Kafue flats, as observed from data from different sources.

3.2.4 Evapotranspiration (ET)

Daily open surface evaporation (Eo) figures were obtained from ground measurements at Itezhi Tezhi Dam performed by ZESCO. The Eo measurements are done using a class A evaporation pan. The assumption was made that the open surface evaporation measures at Itezhi Tezhi Dam were representative of the rates of evaporation taking places over the whole study area. The assumption was made due to non availability of daily surface evaporation in the study area. Then using Penman relationship between Eo and potential evapotranspiration (PE), Eo values were transformed to PE.

$$PE = fp * Eo \qquad (1)$$

Where fp is a reduction factor which varies according to location and season. In this study fp = 0.8 assuming high rates off evapotranspiration in the study area in line with other literature (Ettrick, 1990).

A correction factor (Kp) of 0.70 adapted from Ellenbroek (1987) for non floodplain areas. For the floodplain areas Kp is 1.0. The correction factors were derived from Ellenbroek's work on evapotranspitration in the Kafue flats. Thus potential evapotranspiration was calculated using this correction factor as:

$$PE = fp * Kp * Eo \qquad (2)$$

The data obtained and used in the model was checked against other estimates of potential evapotranspiration in the study area. This was done by comparing the annual average potential evapotranspiration with other studies by Ellenbroeck (1987) and YACHIKO (1995) done in the Kafue flats. The evaporation data had some negative evaporation figures, especially during the rainy season. The negative figures were assumed to be gross evaporation figures after verification with ZESCO. Then to obtain the net evaporation figures on a particular day, precipitation figures were added to these negative evaporation figures. Where the sum was still negative, linear interpolation was then used to fill in evaporation figures for days where net evaporation was negative.

3.2.5 Discharge Data

Between May 2008 to May 2009, discharge measurement were performed using an Acoustic Doppler Current Profiler (ADCP, River Surveyor, SonTek) to measure flows at water sampling stations and at stations with existing rating curves (Figure 3.1). Flow measurements were conducted approximately bimonthly at each of the flow monitoring stations to check the accuracy of the existing rating curves. Daily stage and flow data was obtained from DWA and ZESCO. Rating curves that existed for the stations had been developed either by DWA or ZESCO. Newly measured flow were compared against calculated discharge (rating curves), and where necessary new rating curves were calculated.

It is assumed that the sub-catchments are watertight and that no subsurface movement of water across the defined watershed is occurring. Infiltration is assumed negligible by assuming that ground water recharge is equal to ground water base flow. The evapotranspiration estimates have a high uncertainty due to the variations in the size of the flooded area, which in this study has been assumed to be constant and also due to difficult associated with quantifying this parameter.

As noted above, flow measurements were performed on multiple dates at stations where daily elevation data is available in the Kafue flats. These measured flows were compared with calculated flows based on the rating curves. Where large differences were observed between measured and calculated relationships, new stage-discharge curves were developed.

Additional plots of flow data were made for exploratory data analysis. Flow data which were calculated using the stage-discharge relationships on a daily basis, from concurrent flow stations were plotted to check for consistency in recorded flow. Coefficient of correlation (R^2) values were then computed to check for correlation between stations. Quantile (Q-Q) plots were also used to compare data distributions between concurrent hydrographic stations. The plotting positions are calculated using the Weibull formula:

$$P = i/(n+1) \qquad (3)$$

Where P is the plotting position, i is the rank of each value in the sample (smallest data value is assigned a rank i = 1, while the largest receives a rank i = n) and n is the sample size.

3.2.6 Water Balance Equation

A water balance was developed for each sub-catchment for the period October 2002 - May 2009 using daily precipitation, evapotranspiration and flow data (Figure 3.4). For each sub-catchment the drainage basin water balance equation was used as shown below (Savenije and De Laat, 1996; Shaw, 1988; William and Gosselink, 2007):

$$P^* A_{flooded} + Q_{gwi} + Q_{in} + Q_{lat} - E_t {}^* A_{flooded} - Q_{out} - Q_{gwo} = \Delta S/\Delta t \qquad (4)$$

where $\Delta S/\Delta t$ is the change of storage per time (m^3/d), P is the floodplain precipitation (m/d), E_t is floodplain evapotranspiration (m/d), Q_{in} and Q_{out} (m^3/d) are the flow into and out of the sub-catchment respectively, along the Kafue River main channel; $A_{flooded}$ (m^2) is the maximum flooded area of the Kafue flats within each sub-catchment, and Q_{lat} (m^3/d) is the lateral flows from the non-flooded area of the control volume. Q_{gwi} *and* Q_{gwo} (m^3/d) represent infiltration and exfiltration, respectively, and were assumed to be minor components and were not quantified. Daily measured estimates are available of P, E_t, Q_{in} *and* Q_{out}.

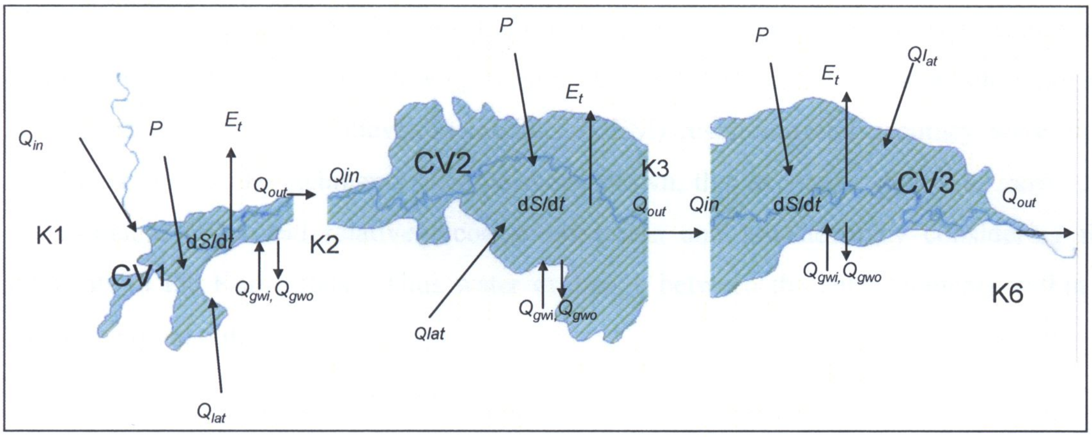


Figure 3.4: Schematic of the water balance for the Kafue flats, Southern Province, Zambia, divided into sub-catchments CV1, CV2 and CV3.

Initially an attempt was made to quantify E_t over each sub-catchment (flooded plus typically dry areas). However, large negative cumulative changes in storage during these initial modeling efforts indicated that evapotranspiration was being overestimated when the E_t rate (even after applying land-cover correction factors) was applied over the entire sub-catchment. The areas that experiences substantial flooding in the central KRB represent only 10-15% of each sub-catchment (Figure 3.4). To address this problem, each sub-catchment was divided into the maximum flooded area and the "dry" area. P and E_t rates measured at ITT were applied directly to this maximum flooded area. Runoff (R) contributions draining from the dry areas to flooded areas were incorporated into the water balance as lateral flows, Q_{lat}, calculated as:

$$Q_{lat} = P \times (A_{subcatch} - A_{flooded}) \times R \quad (5)$$

Where P is the precipitation rate measured at ITT, $A_{subcatch}$ is the area of the entire sub-catchment, and R is a runoff coefficient. R was assigned a value of 0.1, based on other studies in the area (e.g., Yachiko, 1995).

The water balance was explored on monthly and annual time steps. Particular attention was directed toward evaluating the relative importance of the different input and output terms within each sub-catchment because of the relevance of this information for understanding river-floodplain exchange and its effects on river chemistry. Water flowing along the main river channel is considered to be the only hydrologic pathway connecting the sub-catchments in the Kafue flats (CVs), e.g., water flowing from CV2 to CV3 through the floodplain is not explicitly considered. If the digital elevation model's (DEM) resolution and accuracy were sufficiently accurate and the sub-catchments were correctly drawn, this exchange should be zero. However, the available DEM had relatively coarse resolution and low accuracy considering the slight gradients in the Kafue flats. Thus water exchange between the subcatchments within the flats cannot be ruled out.

3.3 Water Quality, Nutrient and Carbon Loading

3.3.1 Sampling network design

A sampling network was designed to cover the whole lower and middle KRB. The following criteria were used for selecting station: the location and co-occurrence with an existing of discharge/stage measuring station, well mixed river and accessibility. Based on the review of existing data and field visits seven site were chosen (Figure 3.1): Kafue River at Hook Bridge (K0), at Itezhi Tezhi (K1), at Namwala Pontoon (K2), Nyimba (K3), Upstream Sable Farm (K4), Kasaka (K5) and Chiawa Pontoon (K7).

3.3.2 Sampling collection and processing

Surface water samples were collected approximately bimonthly over a period of one year (May 2008- June 2009) by surface water dip/grab method. All the samples were collected at a depth of approximately 15 cm to avoid large floating debris in the river. At each of the sampling points, samples were collected for chemical and physical parameters. The samples were collected from the middle of the river using a boat or, in the case of Kafue Hook Bridge Station, from a bridge using a bucket. The sampling bucket was rinsed three times with river water before samples were collected, in the case of samples collected from the bridge. Large (250 ml) pre-cleaned polyethylene sampling bottles were rinsed three times with river water prior to collecting a final sample. The water in these 250 ml bottles was then sub-sampled and processed or preserved using various methods (e.g. acidifying with 2 M HCL, filtration, poisoning with CuCl) as depicted in Figure 3.5 and stored in individual pre-cleaned polythene and glass bottles. The samples were placed on ice for 8 to 24 hours and then frozen and brought to the freezer at lab. A field multiprobe (WTW 3400i, Germany made) was used for in-situ measurements of temperature (T), pH, dissolved oxygen and conductivity. Sampling was conducted following a protocol (Figure 3.5; Zurbrügg et al., in preparation) and a field sampling sheet (Appendix C) was completed every time samples were collected. Duplicate or triplicate samples were also collected at several stations as a quality assurance measure. In general, frozen water samples were transported to Switzerland for analysis. With the exception of some samples collected in May 2008 and April 2009, some of the samples for ammonium, nitrite and orthophosphate were analyzed at the Integrated Water Resources Management (IWRM) Centre, University of Zambia (UNZA).

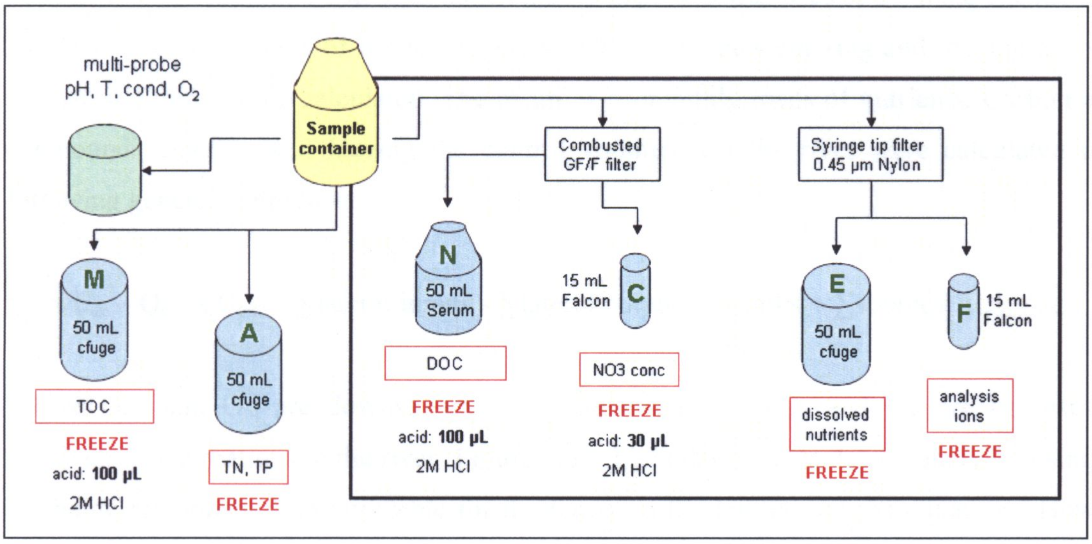


Figure 3.5: Sampling protocol used during the study.

3.3.3 Sample measurements

Nitrite, ammonium and ortho-phosphate were measured with a spectrophotometer. Nitrate was measured using an Antek 745 Vanadium reduction unit, coupled to an Antek 9000 chemoluminescense detector. Total Nitrogen (TN) and Total Phosphorus (TP) were determined by peroxidisulphate digestion and subsequent spectrophotometric nitrate/phosphate detection. A

Shimadzu 5000 TOC analyzer was used to determine total and dissolved organic carbon. When possible discharge measurements were performed using an Acoustic Doppler Current Profiler (ADCP; SonTek River Surveyor) simultaneously with water sample collection. For every station, 3-6 single transects were measured with a precision of 2-10%. ADCP data were processed using RiverSurveyor v4.60. All transects were corrected for a vertical bank slope. On some dates, an ADCP was not available and in those cases a stage-discharge relationship was used to estimate the flow.

3.3.4 Nutrients (N, P) and Carbon Loading

Loads (i.e., mass per time) of nutrients and other compounds are a function of both concentration and river discharge, with stream discharge often being the dominant factor (Li et al., 2003). For this reason, a chemical mass balance approach was used to estimate chemical loads to and from sub-catchments of the Kafue River. Mass of solutes entering and leaving a system and thus mass flows can be calculated. The mean of bi-monthly loads of nutrients, Carbon and other compounds entering and leaving the control volumes via the river were calculated using the following general expression:

$$Q_{in} \times C_{in} - Q_{out} \times C_{out} = \sum \text{lateral inputs} - \sum \text{lateral outputs} - \sum \text{sinks} + \sum \text{sources} \qquad (6)$$

Where Q_{out} and Q_{in} are downstream and upstream flows, C_{out} and C_{in} are downstream and upstream concentrations in the river (Figure 3.6). Field data or calculated data (e.g., using a stage-discharge relationship) are available for the terms on the left side of the equation. However, no measured data are available to distinguish between the terms on the right side of the equation. Thus, when there is an imbalance between river inputs and outputs (i.e., the left side of the equation), possible explanations based on various sources, sinks or lateral inputs/outputs are discussed qualitatively.

To explore whether the Kafue flats is a net source or sink of TP, TN and TOC to the river and to downstream systems, and how loadings vary in space and time, a basic box model approach was used that combined discharge data with chemical concentrations. Input loads, output loads (kg/d) and net exports via the main river channel were calculated for TP, TN and TOC.

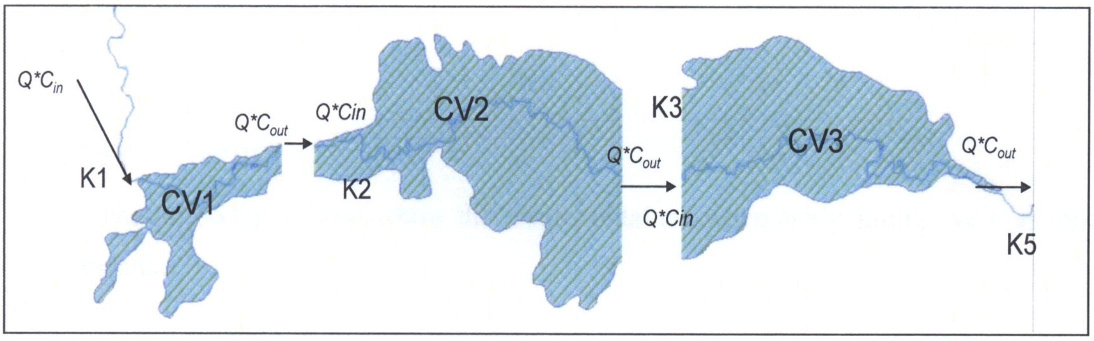


Figure 3.6: Schematic of the chemical mass balance, using the same control volumes as for the water balance, Kafue flats, Southern Province, Zambia.

Chapter 4.0 Water Balance, Nutrient (N, P) and Carbon Loading

4.1 Water Balance

The following sections show the results obtained when analyzing the various inputs to the water balance.

4.1.1 Evaluation of Stage-Discharge relationships

Measured discharge and gauge plate readings for measurements conducted in 2008 and 2009 are presented in Table 4.1. From Table 4.1 the highest discharge measured was 849 m^3/s at Kasaka (K5) on 29th May 2010 compared to 720 m^3/s on 28th May 2008 at the same station. The lowest discharge measured was 30 m^3/s at Hook Bridge on 19th October 2008. From Table 4.1 it is observed that the measured flows at Hook Bridge (K0) are significantly higher than those at Itezhi Tezhi Dam outflow (K1) in the rainy season (December and February 2009) and substantially low in the dry season this can be attributed to the damming of the river. The flow from Itezhi Tezhi (K1) to Namwala Pontoon (K2) increases as the river flows downstream. But at Nyimba (K3) the measured flow reduces significantly. A detailed discussion is available under section 4.1.3 as to what causes this change in flow.

Comparison of measured discharge with the discharge calculated using the rating curves (where curves were available) shows that the rating curves are still accurate at some stations such as Kafue at Hook Bridge (K0), Itezhi Tezhi (K1 - Just downstream of Itezhi Tezhi Dam) and Namwala Pontoon (K2) (Figure 4.1). However, conditions at Nyimba (K3) and Kasaka (K5) have changed considerably (Figure 4.1). These changes are most likely due to backwater effects from the installation of Kafue Gorge Dam, which other studies have suggested can be observed as far upstream as Nyimba (K3) (Mumba and Thompson, 2005).

Table 4.1: Discharge measurements conducted during the study in the Kafue River Basin, Zambia.

Station	**Date**	**Gauge Plate (GP) reading (m)**	**Measured m^3/s**
Kafue River at Hook Bridge (K0)	18.08.08	1.8	77
	19.10.08	1.5	30
	10.12.08	1.9	96
	23.02.09	3.2	650
Kafue River at ITT ZESCO (K1)	18.08.08	3.4	78
	20.10.08	4.8	207
	10.12.08	5.2	238
	24.02.09	7.7	489
	06.05.10	8.0	531
Kafue River at Namwala Pontoon (K2)	19.08.08	3.3	58
	20.10.08		217
	11.12.08	4.9	251
	24.02.09	8.1	752
	07.05.10	8.1	728
Kafue River at Nyimba (K3)	21.08.08	4.3	54
	28.10.08	4.9	166
	19.12.08	5.6	165
	11.05.10	7.0	217
Kafue River Upstream Sable Sugar (K4) Pumping point	25.06.08	no GP	328
	20.08.08	no GP	153
	18.12.08	no GP	169
Between Sable Sugar and Mazabuka Sugar	25.06.08	no GP	306
Kafue River at Kasaka (K5)	27.06.08	8.4	440
	28.05.08	8.0	720
	20.12.08	7.4	257
	2/26/09	7.4	260
	5/30/09	8.1	505
	29.05.10	8.6	849
Kafue River at Chiawa Pontoon (K7)	30.05.08	6.0	574
	27.06.08	5.7	444
	20.12.08	5.4	267

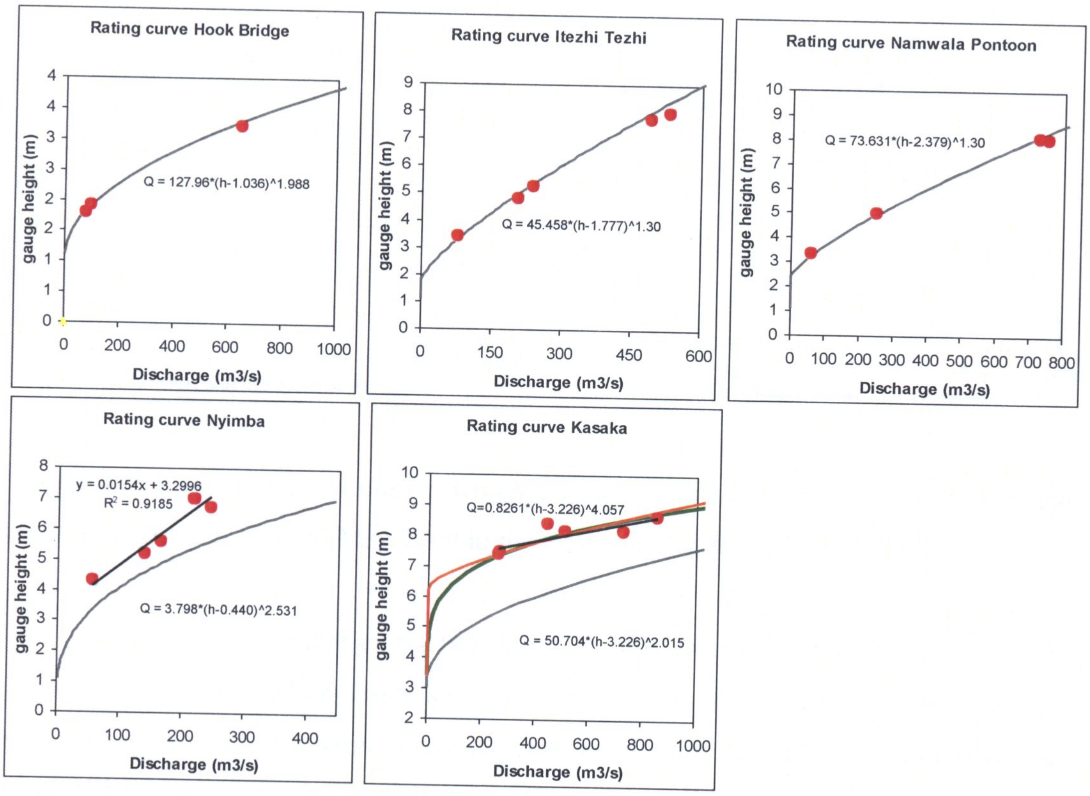


Figure 4. 1: Discharge measurements performed at Kafue Hook Bridge (K0), Itezhi Tezhi (K1), Namwala Pontoon (K2), Nyimba (K3) and Kasaka (K5) during the study in the Lower Kafue River Basin, Zambia. Original rating equations were obtained from DWA and ZESCO.

The poor agreement between measured flows and existing stage-discharge curves at Nyimba (K3) and Kasaka (K5) indicates that new stage-discharge relationships needed to be determined before existing daily water elevation data could be used to calculate discharge at these stations. At Nyimba (K3), a reasonably good linear fit was obtained for measured discharge vs. elevation (Figure 4.1, $r^2 = 0.91$). During these flow measurements, water elevations ranged from 4.3 to 7.0m. A comparison was made with the water elevation range over the modeling period (2002-2008) and it was observed that approximately over 85 % of the water elevations during this time period fell within this range (Figure 4.2). While under ideal circumstances additional flow measurements would be used to develop a more accurate stage-discharge relationship, given the altered flow conditions, the reasonably good fit for the new stage-discharge relationship, and the representativeness of the water elevation range, the new stage discharge relationship was used for quantifying flow at Nyimba (K3) for the model period.

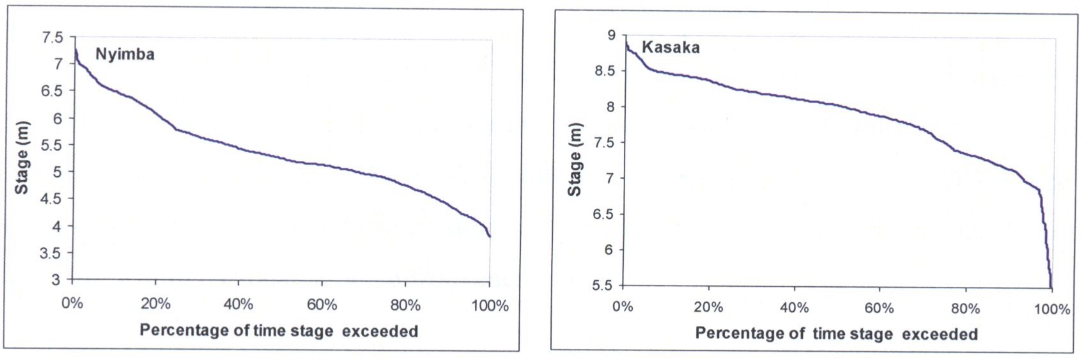


Figure 4.2: Range of stage values at which discharge was measured at Nyimba (K3) and Kasaka (K5) from October 2002 to May 2009 in the Lower Kafue River Basin, Zambia.

A new stage-discharge relationship was also calculated for Kasaka (K5) (Figure 4.1). Approximately 20% of the water levels observed from 2002-2009 were less than the minimum value for which new discharge measurements were available; only ~3% exceeded the maximum level which was observed during the study (Figure 4.2). While a simple linear regression and best-fit power equations yielded reasonable fits to the data (r^2=0.74 for both), both have the potential to substantially overestimate flows when stage is less than ~7.0 m. Therefore, another curve that provided a sharper decrease in Q below water levels of 7.0 m gave a reasonably good fit to the data (r^2=0.69). This latter equation was used for subsequent discharge calculations at Kasaka (K5). Discharge at Kasaka (K5) was quite sensitive to small differences in water elevation (Figure 4.1); given the modest r^2 of the new stage-discharge relationship the estimated flows likely have a higher degree of uncertainty than at other stations.

4.1.2 Correlation of flow data

The flows between the upstream and downstream stations show good correlation (Figure 4.3). The flows at Itezhi Tezhi (K1), Namwala Pontoon (K5) and Nyimba (K5 - stage data) were obtained from ZESCO and DWA. Also the data from various agencies (DWA and ZESCO) showed good correlation and the closeness of the data to the 1:1 line shows that the estimates of flows are within reasonable range from each other.

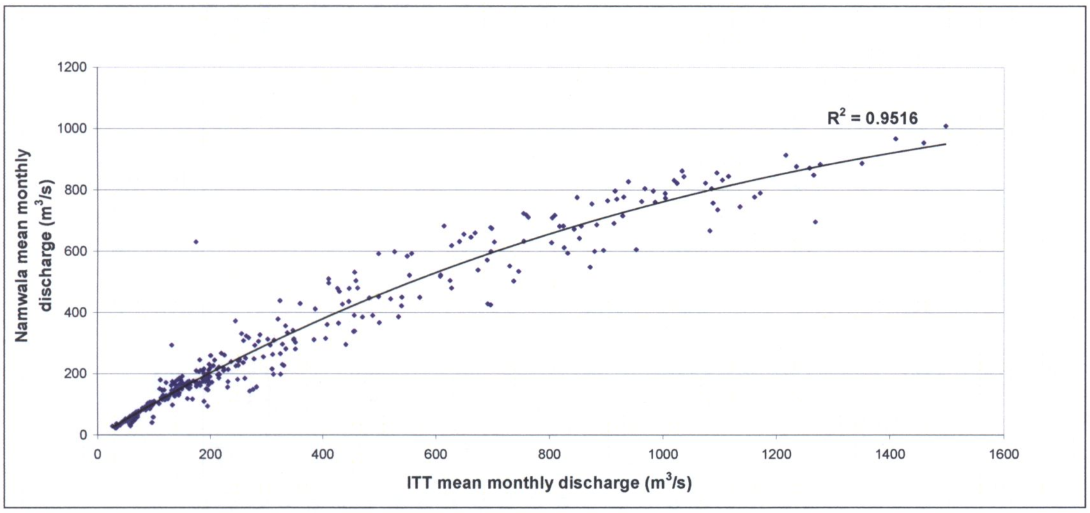
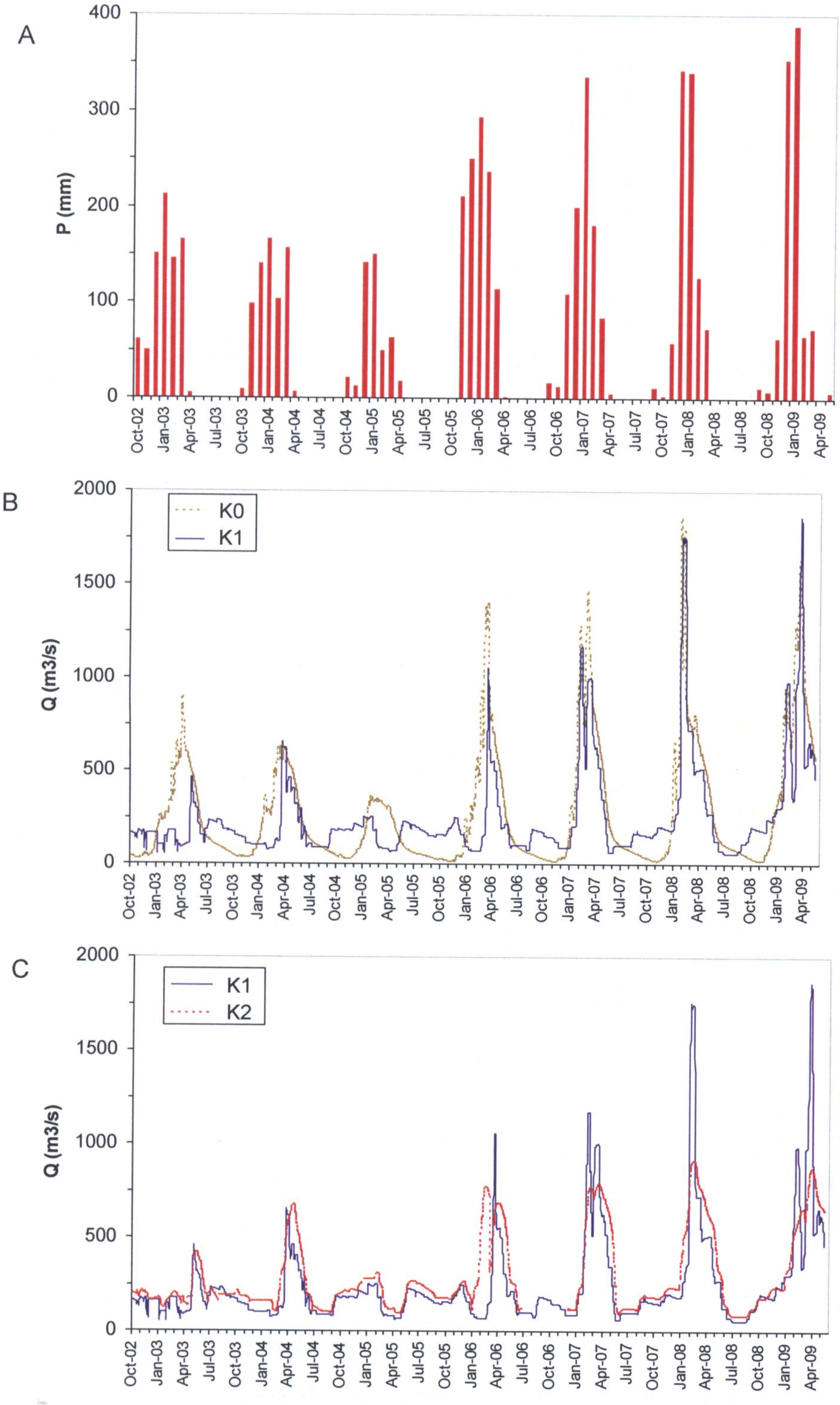


Figure 4.3: Correlation of measurements between flow gauging stations at Itezhi Tezhi (K1) and Namwala Pontoon (K2) in the Lower Kafue River Basin, Zambia, Oct 1960-Sept 1990.

4.1.3 Discharge time series in the middle and lower Kafue River (2002-2009)

Precipitation and discharge time series for several stations along the middle and lower Kafue River are presented in Figure 4.4.


A
P (mm)
0
100
200
300
400
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
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Jan-07
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Jul-07
Oct-07
Jan-08
Apr-08
Jul-08
Oct-08
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K1
K2
Q (m3/s)

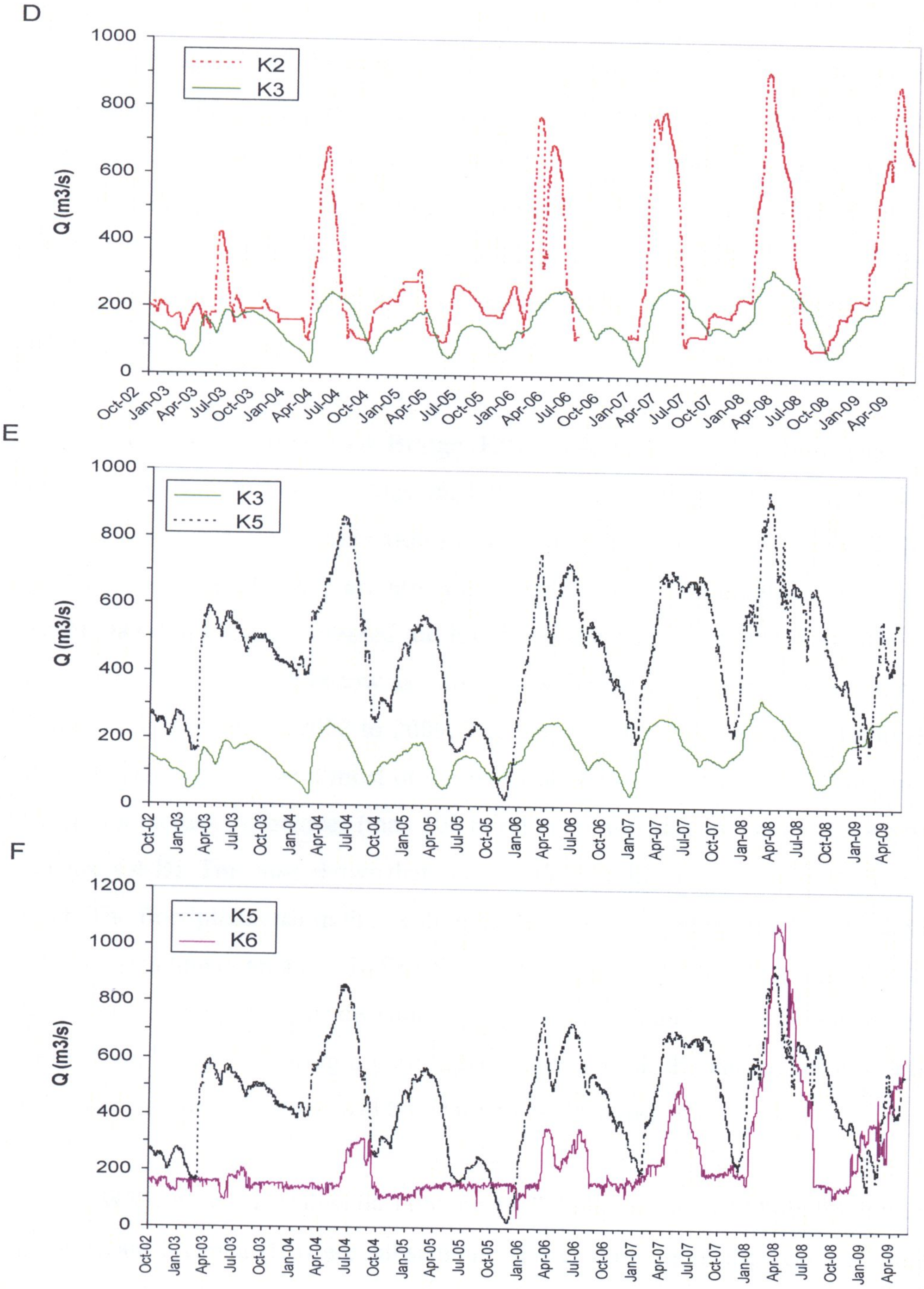

Figure 4.4: (A) Cumulative monthly precipitation at Itezhi-Tezhi, and (B-F) daily discharge at Hook Bridge (K0), Itezhi Tezhi (K1), Namwala Pontoon (K2), Nyimba (K3), Kasaka (K5), and Kafue Gorge (K6), Kafue River Basin, Zambia. P = precipitation and Q = Discharge.

The flows at Itezhi Tezhi and Kafue Gorge dams were based on reported daily flows by ZESCO, the dam operators. At the other river stations, discharges were calculated from daily water level data using previously established stage discharge curves that were verified with ADCP measurements (Kafue Hook Bridge, Namwala Pontoon), or using newly established stage-discharge relationships (Figure 4.1). Continuous data sets were available for all stations from 2002-2009, except for ~6 months of missing data at Namwala Pontoon (K2) (28.06.2006 to 01.12.2006).

Comparing Kafue Hook Bridge (K0) and Itezhi Tezhi (K1) flow data, it is observed that in general between December - May the dam is filling up and from June to December, the Itezhi Tezhi Dam is releasing excess flows downstream. The peak flows between Kafue Hook Bridge (K0) and Itezhi Tezhi (K1) are also well synchronized. The graph shows as expected that Itezhi Tezhi Dam has greatly increased the low flows downstream of the dam. The low flows at Kafue Hook Bridge (K0) reach as low as ~20 m^3/s while the flows at the dam outlets are always above 110 m^3/s for the period 2002 to 2009. The very similar flows at Itezhi Tezhi (K1) and Namwala Pontoon (K2) indicate that most of the water at Namwala Pontoon (K2) originates from the dam, except for modest differences (max 100 m^3/s) in the wet season that must arise from lateral inflows (Figure 4.4 B). This also shows that channel flow is the dominant flow type in this stretch of the river. The floodplain area in this section is also relatively small (~544 Km^2) compared to the large total sub-catchment area of ~10,986 Km^2. The relative importance of lateral inflows to the overall flow depends on operating decisions at Itezhi Tezhi Dam; for example, if releases from Itezhi Tezhi Dam are small during a particularly rainy period, the lateral inflows between Itezhi Tezhi Dam and Namwala Pontoon will be relatively more important.

While flows at Namwala Pontoon (K2) range from 110-880 m^3/s (Figure 4.4C), flows at downstream Nyimba (K3) are substantially lower throughout the year and limited to a range of 100-300 m^3/s. There is a large sub-catchment (~13,400 Km^2) between Namwala Pontoon (K2) and Nyimba (K3) that should contribute more water; thus the consistently dramatically lower flow rates at Nyimba (K3) are surprising. This reduction is attributed to the channel's geomorphology in this section of the river. Substantially smaller channel areas at and upstream of Nyimba (K3) were observed during ADCP measurements in 2009 and 2010 (Zurbrügg et al., in preparation). In addition, a detailed survey of cross sections along the Kafue River conducted in 1980 (DHV, 1980) helped to verify that pronounced channel constrictions exist in this area. Scott Wilson Piésold (2003) estimated the channel capacity between Itezhi Tezhi (K1) and Namwala Pontoon (K2) to be ~250 m^3/s. Other authors have observed that channel capacity of the river in the middle of Kafue flats (i.e., near Nyimba) reduces to ~170 m^3/s (Mumba and Thompson, 2005; Obrdlik et al. 1989).

Flow estimates at Kasaka (K5) substantially exceed those at Nyimba (K3) for the period 2002-2009, except for a few instances. While the new stage discharge relationship developed for Kasaka (K5) has more associated uncertainty than the new relationship at Nyimba (K3), it still seems to provide a reasonably good fit to the data. Its accuracy seems most uncertain at low stage (below ~7.0 m; Figure 4.1) and not at higher stages; thus a high bias, based on the discharge measurements, seems unlikely. When flows at Nyimba (K3) are compared with flows at Kafue Gorge Dam (K6) during the period 2002 - 2009 the flows are closer in magnitude except for 2008 - 2009. In this period the flows at Kafue Gorge Dam substantially exceeded those at Nyimba (K3). The large differences between calculated discharge at Kasaka (K5) and reported discharges at Kafue Gorge (K6) appear suspicious (Figure 4.4F). A possible explanation for the disparity between the two curves is an unaccounted for change in storage in Kafue Gorge Reservoir. Kasaka (K5) is quite close to the outlet of the Kafue Gorge Dam (K6), where flow is known with a higher degree of certainty. Therefore, the discharge from Kafue Gorge station (K6) was assumed to be the flow leaving the Kafue flats, which should be reasonably accurate especially at monthly time scales.

4.1.4 Physically measured and Remote Sensed precipitation

To assess spatial variations in precipitation at the scale of the Kafue flats, a comparison was made using Famine Early Warning System (FEWS) remote-sensed precipitation data set within the flooded area (Figure 4.5). Comparisons between CV1, CV2 and CV3 were made using both 1 day and 10-day cumulative data. CV1 and CV2 agreed reasonably well for both 1 day and 10 day data (Figure 4.5 A and B). For 1-day FEWS data, CV3 had poor agreement with CV1 and CV2 (Figure 4.5 C and E) with relatively low r^2 (0.54 and 0.66, respectively), and slopes of the best fit line substantially different from 1 (0.65 and 0.73, respectively). Using the 10-day FEWS data, there was better agreement between all three control volumes, including slopes between 0.9 and 1.0 (Figure 4.5 B, D, F), and using 30-day data the slopes were all >0.95 and $r^2 > 0.9$ (not shown). Thus, at the time scale of 10-days, the FEWS data indicates that there is low spatial variability in precipitation (within 10%) across the Kafue flats. A similar comparison was performed with the Tropical Rainfall Measuring Mission (TRMM) data. Using TRMM there was good agreement between CV1 and CV2 for 1 day and 10 day cumulative data ($r^2 = 0.8$, slope = 0.92). Similar to FEWS, using TRMM (for 1 day) CV3 had moderate agreement with CV1 and CV2, with relatively low r^2 values (0.61and 0.75) and slopes of the best fit line were 0.74 and 0.80 respectively. A time scale of 10 days CV3 had better agreement with CV1 and CV2 with the r^2 values of 0.87 and 0.92 and slopes of the best fit line were 0.94 for both.

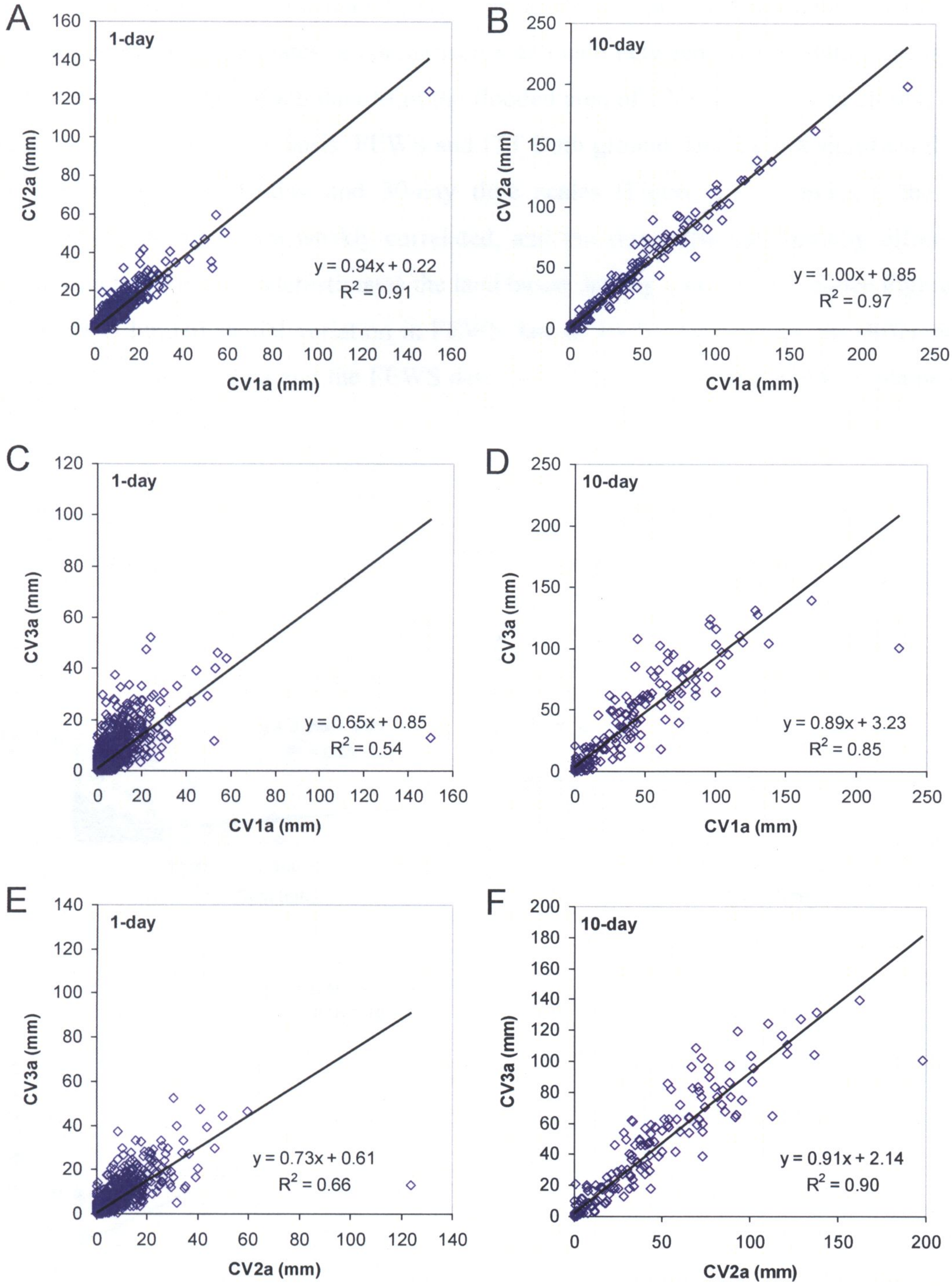

Figure 4.5: Comparison of spatial variation in remote sensed precipitation over the flooded area in CV1, CV2 and sub-catchments of the Kafue flats, Southern Province, Zambia, at 1 and 10 day time steps.

To evaluate the agreement between ground-based precipitation data and FEWS remote-sensed precipitation estimates, a comparison was made between ground station measurements at Itezhi Tezhi Dam and FEWS data from the flooded area of CV1, i.e., the area closest to the Itezhi Tezhi Station. On a daily basis, FEWS and ITT Dam ground data are not significantly correlated (Figure 4.6 A). On 10-day and 30-day time scales (Figure 4.6 B and C), the cumulative precipitation estimates are weakly correlated, and the slopes are substantially different from 1, suggesting that FEWS underestimates the land based data by a factor of 2. Since Figure 4.5 shows that there is limited spatial variation in FEWS data at 10-day time scales, the difference between the ITT Dam ground data and the FEWS data for CV1 can not be reasonably explained by spatial variations in precipitation.

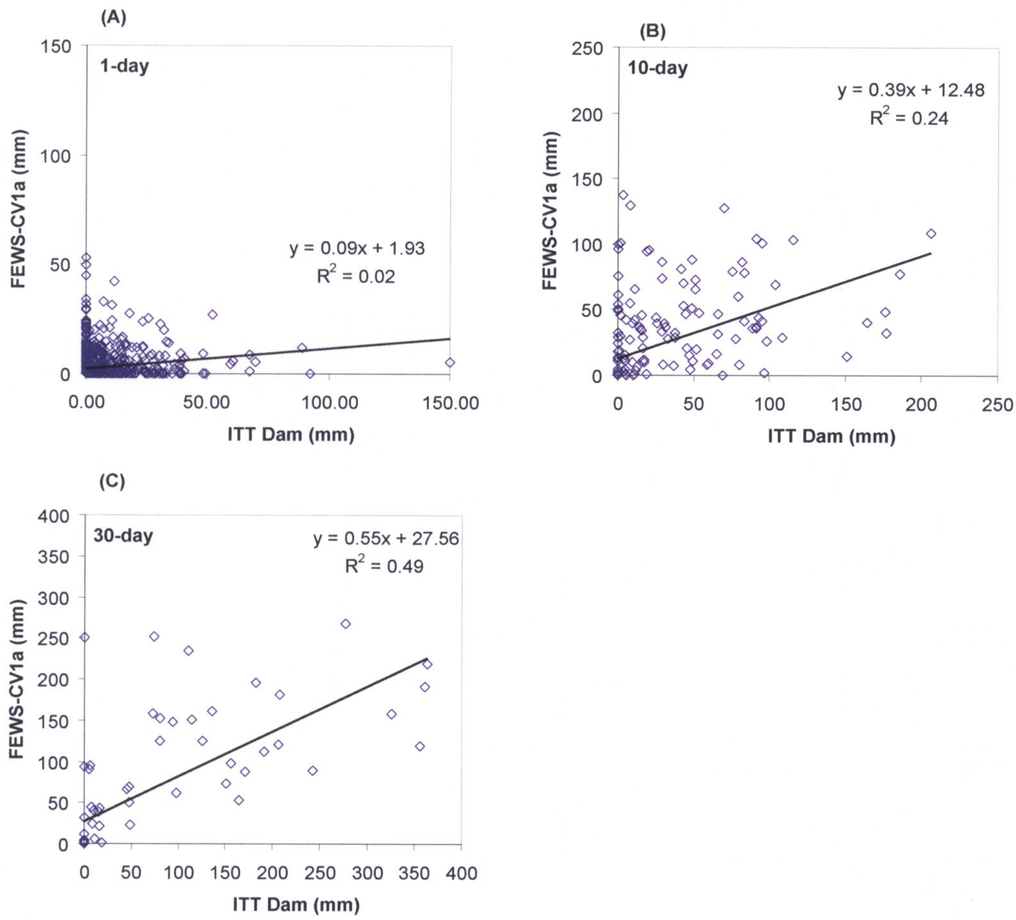

Figure 4.6: Precipitation data, comparing ground station measurements at Itezhi Tezhi and FEWS data from the flooded area of CV1, Southern Province, Zambia. (a) 1- day time (b) 10 - days and (c) 30 - day time steps.

Given that there is limited ground-truthing of the FEWS data in this region, and the poor agreement between FEWS and ITT Dam physical data, the assumption made is that the ITT Dam data likely provides more accurate information. Thus ITT Dam physically measured data was used for the water balance model over the entire Kafue flats. The FEWS data indicates that there is small spatial variation in precipitation in the west-east direction at the scale of the entire flats at time-scales of 10-days (Figure 4.5). Therefore applying the ITT precipitation measurements over the entire Kafue flats is reasonably accurate and should introduce an acceptable level of uncertainty (e.g., in the order of 10%).

4.1.5 Water Balance for the Lower Kafue River Basin

As a starting point for exploring the water balance of the individual sub-catchments, long term (2002-2009) mean annual water balances were calculated for the control volumes depicted in Figure 3.4. Because of the relatively high uncertainty associated with some of the variables (E_t, Q_{lat}, $\Delta S/\Delta t$), the balances were approached in three ways. First, best estimates were used for all input and output terms, and the water balance equation (Equation 4) was solved for the change in storage within the control volume ($\Delta S/\Delta t$) (Figure 4.7 A). For the second and third approaches (Figures 4.7 B and C), an assumption was made that the change in storage within each control volume over an annual cycle was small relative compared to the major input and output terms, and used the water balance equation to solve for either E_t or Q_{lat}. While the assumption of zero annual change in storage is not entirely accurate (e.g., change in storage could differ substantially from zero due to relatively dry or wet years), it is a reasonable first approximation, and may have less uncertainty associated with it than the uncertainty associated with some of the water inflow or outflow parameters. The water balance parameters that are known with the highest degree of confidence are Q_{in}, Q_{out}, and P. However, there is no measured data available on lateral inputs from tributaries (Q_{lat}) to the flooded areas of the Kafue flats. Nonetheless, Q_{lat} can be reasonably well-constrained, especially over an annual time-scale, using a realistic runoff coefficient (e.g., 10-20%). The amount of water lost from the sub-catchments (CVs) due to E_t is also subject to substantial uncertainty due to temporal variations in flooded area and spatial variations in land cover.

Figure 4.7 presents the mean annual magnitudes (2002-2009) of the principal inflows and outflows in the three sub-catchments (CV1 to CV3) of the Kafue flats. In most cases, evapotranspiration exceeds direct precipitation over the floodplain on an annual time step. Depending on the approach used to close the water balance, evapotranspiration from the floodplain accounts for 4-8%, 42-56% and 19-42% of total outflows in CV1, CV2 and CV3 respectively. The different approaches to closing the water balance identified some physical limitations that can better constrain the E_t and Q_{lat}. In CV1, the results do not change substantially across the three approaches, because E_t and Q_{lat} are of only minor importance to the budget. However, when solving for $\Delta S/\Delta t$, CV2 and CV3 have relatively large annual changes in storage that

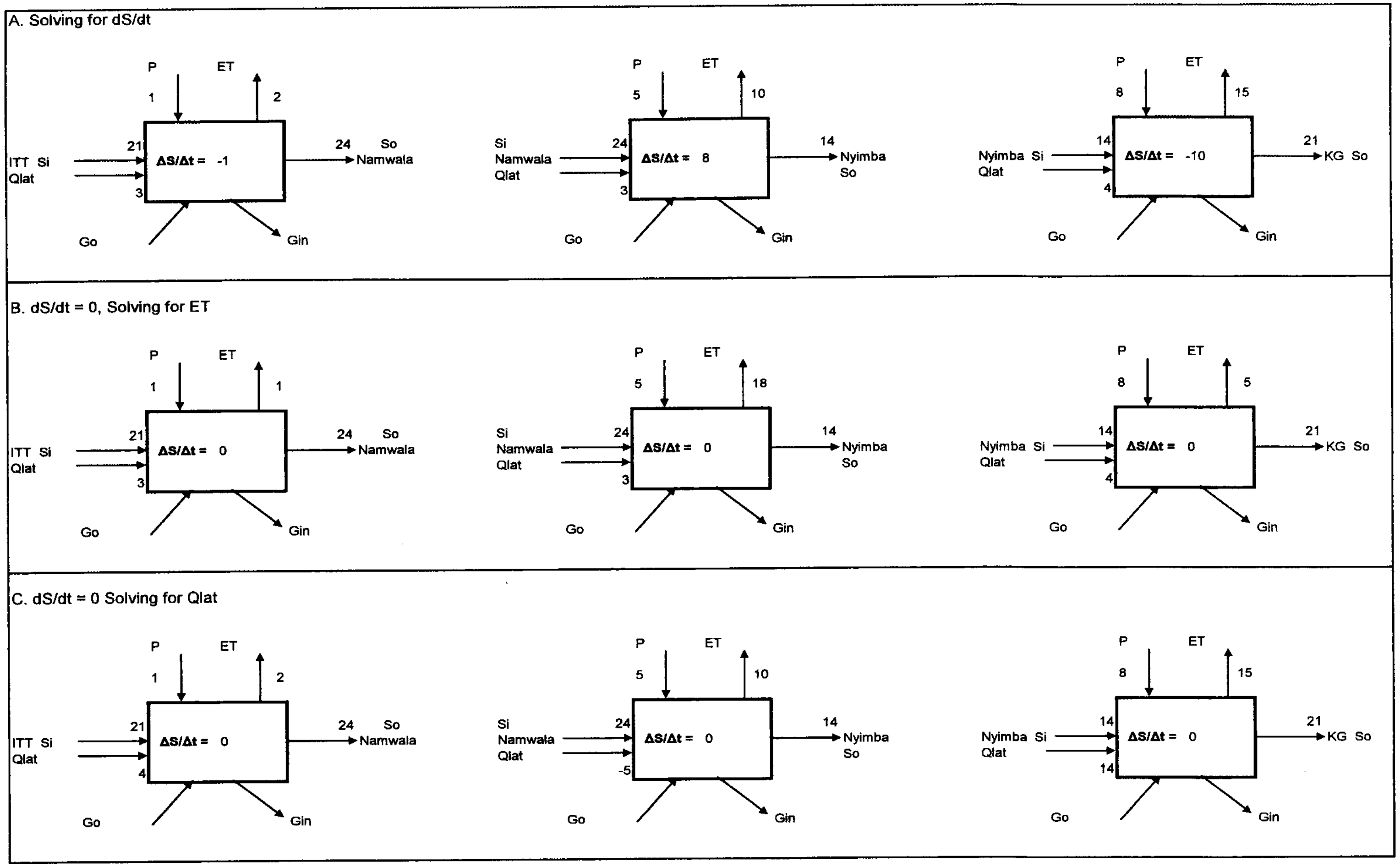

Figure 4.7: The water balance of the Kafue Flats Floodplain, South Central Zambia (October 2002 to June 2009). (A) Solving for $\Delta S/\Delta t$, (B) solving for E_t and (C) solving for Q_{lat}. Where P= precipitation, E_t = evapotranspiration, Q_{in} is the inflow and Q_{out} is the surface outflow. Q_{gwo} and Q_{gwi} are exfiltration and infiltration are assumed to be equal over an annual cycle in this analysis. All values expressed in Mm^3/yr.

unrealistically imply that CV2 and CV3 experience net retention and net loss of water, respectively, each year. This imbalance suggests that E_t or Q_{lat} are being inaccurately quantified. The third approach for CV2 yielded a negative Q_{lat}, thus it appears that E_t was being underestimated and may be 50% higher than suggested by original calculated value (i.e., first approach). On the other hand, if only Q_{lat} is allowed to vary in CV3 (third approach) to compensate for the negative change in storage found, the calculated Q_{lat} requires a runoff coefficient >30% to achieve. Thus, for CV3, a more realistic balance may represent higher Q_{lat} (~8 Mm^3 y^{-1}) and lower E_t (~9 Mm^3 y^{-1}).

Local precipitation (Q_{lat} and P) plays an important role in the hydrology of the Kafue flats, accounting for on average 15, 29 and 46 % of the inflows in CV1, CV2 and CV3 respectively. At the scale of the entire Kafue flats, the inflow from ITT Dam (21 Mm^3/y) accounts for ~45% of the total inflow to the flats with the remaining ~55% coming from direct precipitation to the floodplain and lateral inflows.

Estimates of river inputs, direct precipitation and lateral inflows to each of the sub-catchments are presented on a monthly basis from 2002-2009 in Figure 4.8 to illustrate how the relative importance of these inputs vary seasonally, interannually and by sub-catchment. While this information could also be calculated on a daily basis, monthly comparisons are more relevant considering the water travel times along the main channel (5 - 10 days for each sub-catchment; average velocity (v_{avg}) ~ 0.5 m/s) and the inability to accurately account for time-lag of the lateral inflow on daily time scales. River inputs at ITT Dam are the dominant source of water to CV1 with only limited contributions from direct-P and lateral inflows. CV2 has slightly larger contributions from direct precipitation and lateral inflows to the floodplain. CV3 appears quite different from CV2 and CV1, with direct precipitation and lateral inflows to the floodplain taking on relatively larger importance. This difference is due to two factors: i) the smaller river inputs along the main channel (low flows at Nyimba); and ii) the larger floodplain area compared to CV1 and CV2. Thus, during the wet months of the year (Nov-Mar), more than 50% of the total inputs to CV3 enter via the floodplain, which may exert a substantial influence on the characteristics of the water leaving the system, i.e., the water has spent a substantial amount of time in the floodplain as opposed to traveling along the river's main channel. The water volumes in Figure 4.8 do not take into account any exchange of water from the river into the floodplain (i.e., overbank flow).

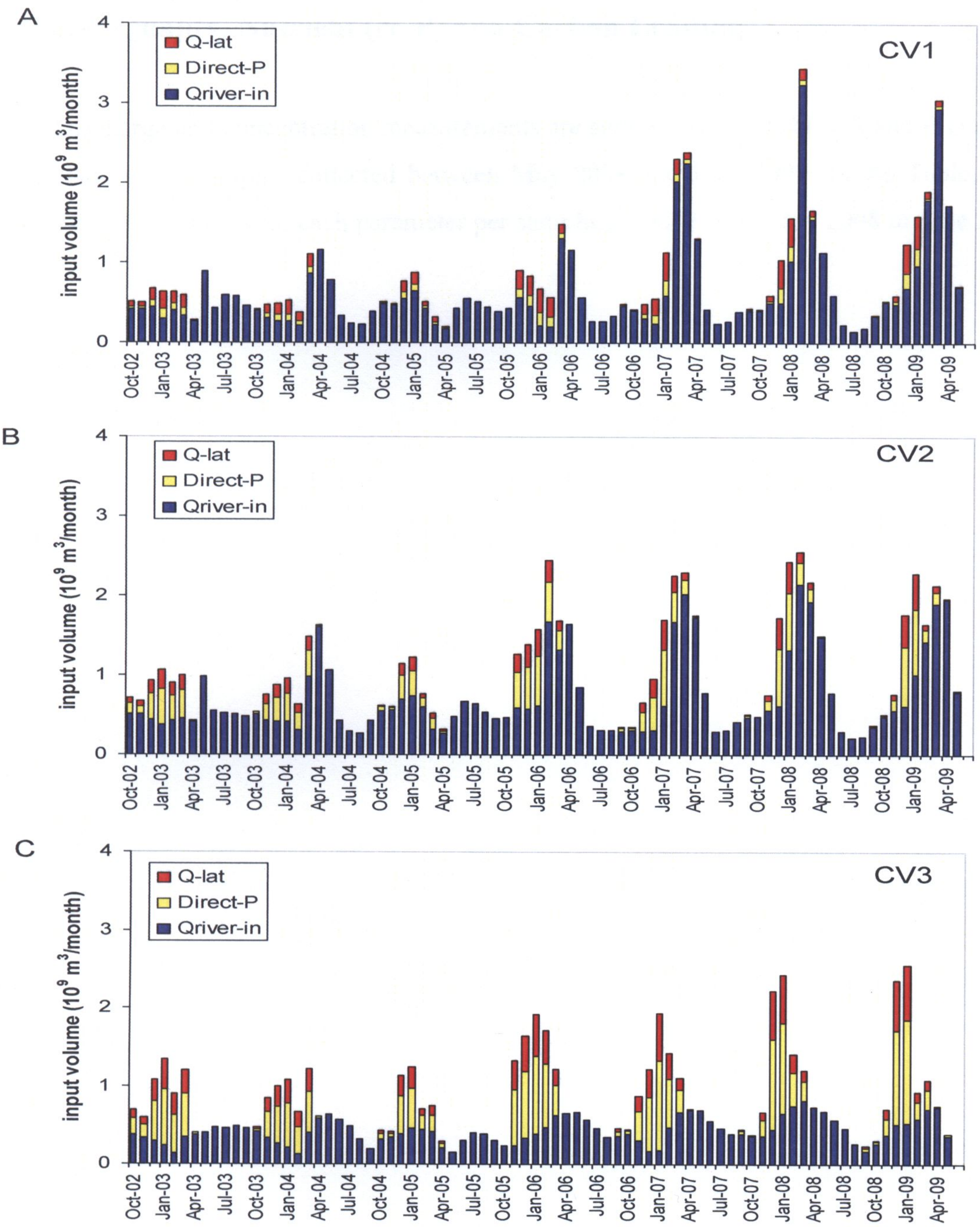

Figure 4.8: Seasonal variation of relative inputs into the Kafue flats Southern Province, Zambia, in CV1, 2 and 3 sub-catchments.

4.2 Water Quality, Nutrient (N, P) and Carbon Loading

Discharge and concentration measurements are summarized in Table 4.2 and Figure 4.9 for all the stations for samples collected between May 2008 and June 2009. In the Table, n is the number of samples taken for each parameter per sampling station from May 2008 to June 2009.

Table 4.2 Physical and chemical parameters of the middle and lower Kafue River, Southern Province, Zambia (2008-2009 sampling campaigns). TN = Total Nitrogen, TP = Total Phosphates and TOC = Total Organic Carbon.

Parameter		**K0**	**K1**	**K2**	**K3**	**K4**	**K5**	**K7**
Discharge (m^3/s)	Mean	201	286	315	174	346	422	406
	Range	30-674	78-490	62-778	55-246	159-660	259-724	280-589
	n	5	6	7	6	6	5	4
Dissolved Oxygen	Mean	7.05	8.57	6.94	5.36	2.62	4.07	8.52
	Range	5.65-8.40	7.8-11	5.21-8.35	4.65-7.55	1.08-3.68	2.72-5.63	7.17-11.84
	n	5	6	7	6	7	7	5
Specific conductanc [µS/cm]	Mean	334	171	178	194	197	195	201
	Range	172-451	114-220	102-218	159-220	165-220	168-225	180-221
	n	5	7	7	6	7	7	5
pH	Mean	8.17	8.2	7.96	7.72	7.32	7.4	8.11
	Range	7.62-8.42	7.97-8.67	7.38-8.37	6.92-8.26	7.02-7.94	7.03-7.94	8.08-8.17
	n	5	7	7	6	7	7	5
NO_3^- (µg/L)	Mean	25.85	52.16	42.51	15.75	21.92	32.87	
	Range	14.80-31.89	19.26-109.60	11.52-90.14	16.53-29.57	23.00-36.57	9.25-56.44	
	n	3	6	6	5	6	6	
$NH4^+$ (µg- N/L)	Mean	80.54	18.93	15.35	58.95	50.89	6.41	44.36
	Range	5.58-290.32	1.28-56.23	2.49-43.07	6.92-214.27	0.62-204.74	0.82-11.22	12.55-64.24
	n	4	5	6	4	6	5	4
PO_4^{3-} (µg - P/L)	Mean	30.57	18.01	22.59	29.66	34.48	43.11	37.88
	Range	21.86-52.94	14.80-26.06	16.61-30.60	4.66-51.56	12.25-63.30	15.22-86.78	27.73-55.54
	n	5	6	7	6	6	6	4
TN (µg- N/L)	Mean	299.26	353.72	334.52	391.87	449.64	462.6	518.73
	Range	210.67-375.24	264.43-411.63	236.78-457.58	305.88-505.27	287.60-620.74	300.65-553.86	340.14-609.88
	n	6	7	7	6	7	7	5
TP (µg-P/L)	Mean	10.69	12.19	13.49	17.95	13.08	12.54	24.94
	Range	3.93-15.52	7.16-16.06	11.94-15.52	7.88-22.43	9.30-19.64	10.17-19.28	11.01-51.78
	n	6	7	7	5	7	6	5
TOC (mg-C/L)	Mean	13.431	8.53	8.95	10.38	12.01	12.83	9.8
	Range	6.79-23.68	3.0-13.66	2.98-14.53	2.78-18.54	2.87-22.33	5.63-17.88	4.41-18.18
	n	4	5	5	5	6	6	3

Where K0 = Kafue Hook Bridge, K1 = downstream Itezhi Tezhi Reservoir, K2 = Namwala Pontoon, K3 = Nyimba, K5 = Sable Sugar, K6 = Kafue Gorge and K7 = Chiawa Pontoon

In Figure 4.9 discharge and various water quality measurements as a function of distance on the seven sampling dates are presented in Figure 4.9 with distance = 0 Km corresponding to the Itezhi-Tezhi Dam (K1), and -120 Km corresponding to Kafue Hook Bridge (K0). The station at ~ 475 Km is Chiawa Pontoon (K7), which is downstream of Kafue Gorge Dam (K6) and just upstream of the Kafue and Zambezi confluence. Data from Chiawa Pontoon (K7) are not used for subsequent calculations but are presented here nonetheless for completeness. Kafue Gorge Dam (K6) was not accessible for water sample collection, but it is included here because daily discharge data is available from the Kafue Gorge Dam operators.

In stations downstream of K1, the maximum observed specific conductance (SpC) was measured in December 2008, except for K7 which had its maximum in October 2008 (Figure 4.9 B). The highest value observed overall was 451 μS/cm at K0 in October 2008. This relatively high value occurred when discharge at K0 was at its lowest (~30 m^3/s) and thus solutes were dissolved in a relatively small amount of water. In the stretch where the river flows through the Kafue flats, the highest observed value was 225 μS/cm at station K4 in October, 2008. Lower conductivity readings were observed in May both in 2008 and 2009. These observations are consistent with other studies in the Kafue flats.

Dissolved oxygen (DO) levels varied systematically as the Kafue River flowed through the Kafue flats (Figure 4.9 C). In all months, dissolved oxygen concentrations were highest after the turbulent flow from the spillway at Itezhi Tezhi Dam and the turbines and steep slopes after Kafue Gorge Dam (K7). Dissolved Oxygen (DO) concentrations consistently dropped to their minimum levels ~300 km downstream of Itezhi Tezhi Dam at station K4 and then start to slightly rise again by station K5. The overall maximum concentration of 11.8 mg/l was measured at K7 in June 2008. The minimum DO was 1.1 mg/l measured in February 2009 at K4, and values ranged from 1.1 to 3.7 mg/l at this station throughout the study period. These hypoxic conditions (i.e., < 2 mg/l) correspond to levels that have been shown in other systems to adversely impact ecosystem function, including fisheries productivity (Mitsch and Gosselink, 2007).

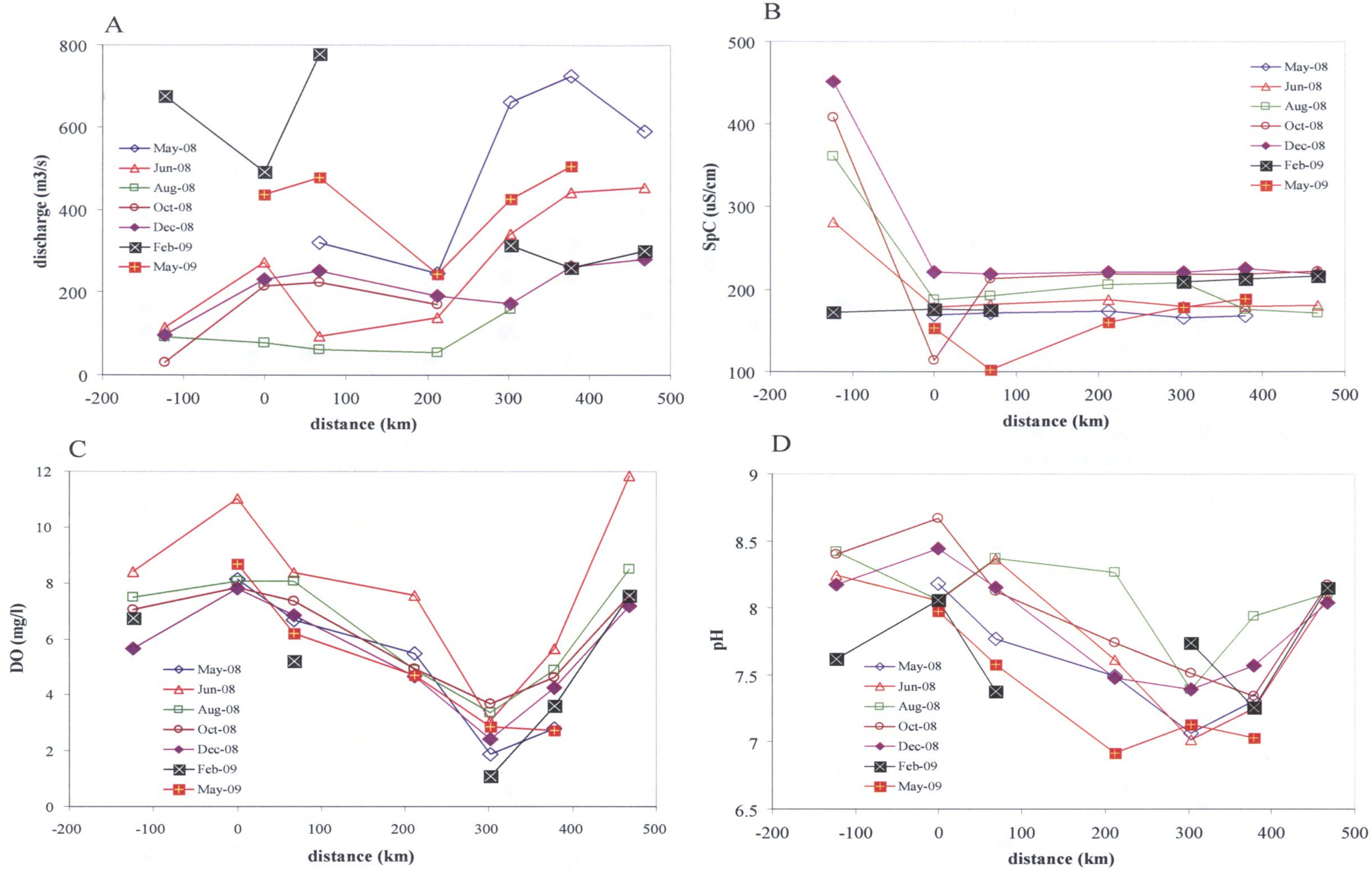

Figure 4.9 Discharge and water quality parameters measured along the Kafue River between May 2008 and May 2009. A = Discharge, B = Specific Conductance, C = Dissolved Oxygen, D = pH, E = Orthophosphates, F = Nitrate, G = Ammonium, H = Total Nitrogen, I = Total Organic Carbon. Distance = 0 corresponds to the Itezhi Tezhi Dam (K1).

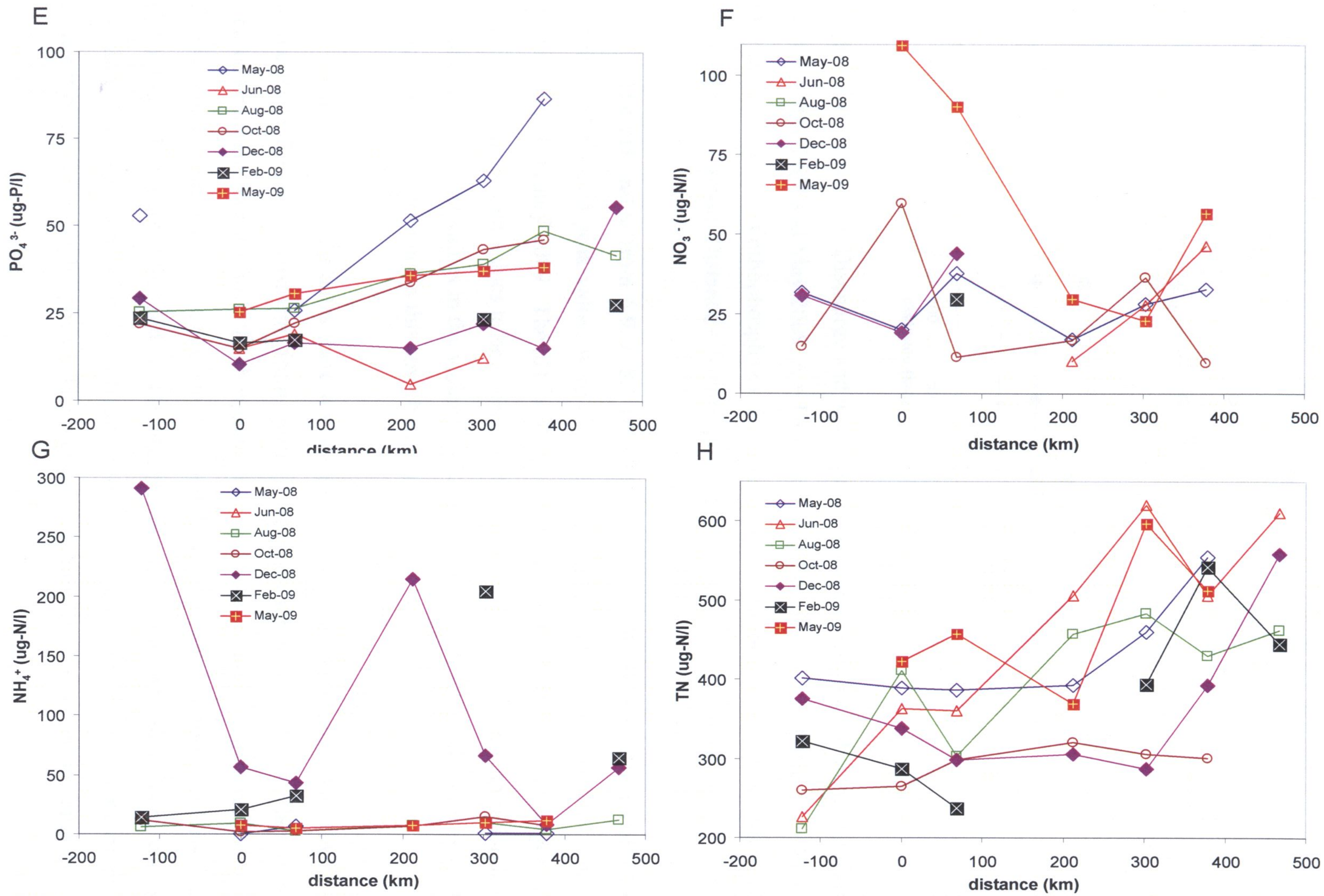

Figure 4.9 (continued)

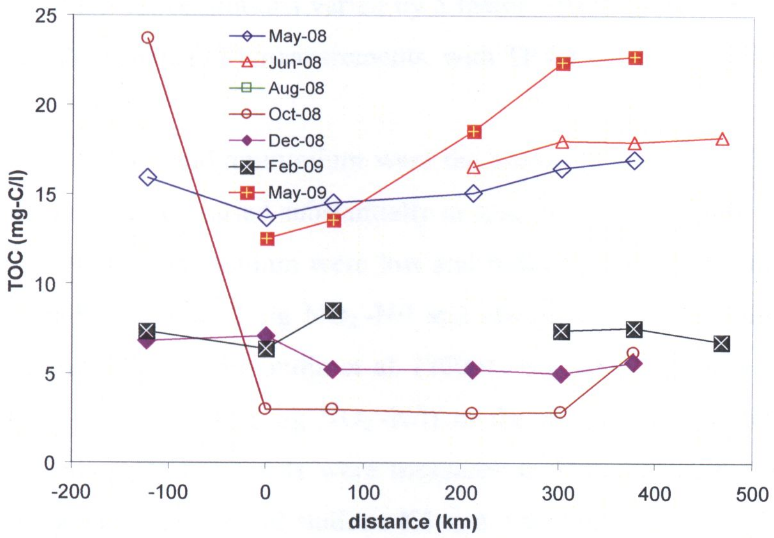

Figure 4.9: (continued) Discharge and water quality parameters measured along the Kafue River between May 2008 and May 2009. A = Discharge, B = Specific Conductance, C = Dissolved Oxygen, D = pH, E = Orthophosphates, F = Nitrate, G = Ammonium, H = Total Nitrogen, I = Total Organic Carbon. Distance = 0 corresponds to the Itezhi Tezhi Dam (K1).

The pH varied from 6.9 to 8.7 (Figure 4.9D). Low pH values were recorded during the February-March and peak values were observed in August with exception of K4 where the peak value was in February 2009. The pH exhibited a pattern similar to Dissolved Oxygen (DO) with a tendency for minimum values to be observed at K4. Since organic matter respiration leads to a pH decrease, the low pH values in the vicinity of K4 likely resulted from similar processes that caused the low DO concentrations in this stretch of river.

On most sampling dates there was a trend of increasing orthophosphate (PO_4^{3-} - P) as the Kafue River flowed downstream from Itezhi-Tezhi Dam through the Kafue flats (Figure 4.9E). The downstream increase in orthophosphate concentrations could be partly related to its release during organic matter mineralization in the floodplain, which the variations in Dissolved Oxygen (DO) and pH (Figure 4.9C and 4.9D) suggest are important. Although there was substantial variation between months, it is difficult to discern a clear seasonal pattern of high or low concentrations for orthophosphate. The highest variability was observed in samples collected at

K3, where concentrations varied by a factor ~10 (Figure 4.9E). A discrepancy was observed with Total Phosphate (TP) measurements, with TP frequently lower than PO_4^{3-} - P.

Nitrate and ammonium were the dominant forms of Dissolved Inorganic Nitrogen (DIN), and both species varied substantially in space and time (Figure 4.9F and 4.9G). Overall, the levels of nitrate and ammonium were low and indicative of a fairly uncontaminated system. Nitrite was generally less than 2 μg NO_2^--N/l and always less than 10 μg NO_2^--N/l, and thus was a minor portion of DIN. Muvundja et al. (2009) also found insignificant values of nitrite (average 8 μg NO_2^--N/l, range: 0-21 μg NO_2^--N/l) in the rivers draining into Lake Kivu. Relatively elevated ammonium (NH_4^+) levels were measured in December 2008 at several locations, indicating an ammonium peak around stations K3 and K4. On other dates, NH_4^+ concentrations (Figure 4.9G) were ~20 times lower than the peak values, and on some dates (August 2008, October 2008, May 2009) there was a slight trend toward increasing NH_4^+ downstream of K2. Nitrate concentrations ranged from 10 to 110 μg NO_3^--N/l, with most values falling between 10 and 50 μg NO_3^--N/l. The highest values were observed during peak flooding in May 2009. Whereas clear patterns in nitrate levels are not evident on most dates, in May 2009 NO_3^- decreased from a maximum of 110 μg/l at K1 to 25 μg/l at K4, and then increased further downstream at K5. These observations are supported by spatially intensive measurements in May 2009 (Zurbrügg et al., in preparation). In general, Total Nitrogen (TN) concentrations (200-600 μg N/l; Figure 4.9H) exceeded DIN (nitrate + ammonium + nitrite) by more than a factor of 10. Spatially intensive measurements along the river in May 2009 found that ~50% of TN were dissolved (passing a 0.7 μm glass fiber filter). These observations indicate that most of TN in the river was Dissolved Organic Nitrogen (DON) and Particulate Organic Nitrogen (PON) as opposed to DIN. There was a tendency for TN concentration to increase over the stretch from K1 to K5.

Total Organic Carbon (TOC) exhibited clearer temporal and spatial patterns than the nitrogen species or phosphate (Figure 4.9I). TOC concentrations were relatively higher (12-23 mg C/l) in May 2008, June 2008 and May 2009, and increased between K1 and K5. In October 2008, December 2008, and February 2009, TOC concentrations were lower (3-8 mg C/l) and fairly constant over the 400 Km stretch of river downstream of Itezhi Tezhi Dam (K1). These values are similar for Dissolved Organic Carbon (DOC) in the Okavango Delta on average 10.7 mg C/l (Mladenov et al., 2005), although these values are a little higher than in the Kafue flats. Mladenov et al. (2005) noted that Dissolved Organic Matter (DOM) transport was controlled by slow movement of an annual flood pulse.

Chapter 5.0 Discussion

5.1 Water balance and river- floodplain exchange

While river inputs are the dominant source of water year round to CV1, direct precipitation and lateral inputs are increasingly more important sources of water to CV2 and CV3. This is evident in the long-term annual water balances (Figure 4.7), where direct precipitation and lateral inputs comprise nearly 50% of all inputs to CV3. The importance of direct precipitation and lateral inputs in CV2 and CV3 is also clear in monthly data over 2002-2009 (Figure 4.8), where they represent substantially more than 50% in certain months. Chimatiro (2004) also documents that in the wet season, rainfall and lateral inputs accounts for important supply of water to the Shire Floodplain in Malawi.

The comparison of daily discharge data (2002-2009) at the upstream and downstream ends of CV2 and CV3 indicate that there is exchange between the river and the floodplain (Figure 4.4 D). Dissolved oxygen data along the main stem of the river suggests that this exchange may have a substantial influence on river biogeochemistry (Figure 4.9 C)

To characterize river-floodplain exchange in each sub-catchment (CV) using water balance constraints, monthly flow rates were used to calculate a fractional exchange ratio (FE):

If $Q_{out} - Q_{in} \geq 0$ $\quad$ $FE = (Q_{out} - Q_{in})/Q_{out}$ .... *(7a)*

If $Q_{out} - Q_{in} < 0$ $\quad$ $FE = (Q_{out} - Q_{in})/Q_{in}$ .... *(7b)*

The ratio FE ranges between -1 and +1. When monthly outflow exceeds monthly inflow (FE >0), the difference is divided by Q_{out} and FE quantifies the fraction of Q_{out} that must have entered the river from the floodplain along that stretch, either through disperse lateral inputs or tributaries draining the floodplain. When outflow is less than inflow (FE<0), the difference is divided by Q_{in} and FE quantifies the fraction of Q_{in} that must have entered the floodplain along that stretch of river, as opposed to flowing directly out along the river channel downstream. Because travel times along the main channel of the river are in the order of several days, monthly flows were used for this calculation in order to limit the influence of short-term fluctuations in flows.

As the Kafue River flows through CV1, it generally gains some water (average 15%, FE= +0.15; Figure 5.1A). A substantial portion of this water likely comes from Nanzhila River, a tributary that enters the Kafue River ~30 km downstream from Itezhi Tezhi Dam (K1). The effect of peak discharges at Itezhi Tezhi Dam (K1) (Figure 4.4B) is indicated as a local minima in FE (-0.2 to -0.3; Figure 5.1A) in September 2006, February 2006, February 2007 and March 2009. During this time period, 20-30% of the discharge from the dam entered the floodplain, likely through overbank flow. Some of this water underwent evapotranspiration in the floodplain, whereas the remainder flowed back into the Kafue River during flood recession contributing to a positive FE during subsequent months.

In contrast, CV2 has an average FE of approximately -0.3 (Figure 5.1B), indicating that ~30% of the water that enters CV2 as river flow at Namwala Pontoon (K2) is forced out into the floodplain before it reaches Nyimba (K3). During peak flow periods at Namwala Pontoon (K2), (e.g., Jan-May), FE is typically between -0.4 and -0.6, and thus indicating that 40%-60% of the flow is forced out into the floodplain during this time. Positive peaks in FE from (Jun-Oct 2006, Jun-Jul 2007 and Jun-Aug 2008) suggest that some of the water that was forced into the floodplain during peak flows was flowing back into the river channel during flood recession. Chimatiro (2004) also observed similar trends in the Lower Shire Floodplain where water seems to be retained in the floodplain. But as Chimatiro (2004) also noted few studies have been conducted in tropical floodplains that quantify the flooding mechanisms and dynamics, thus only a few are cited in this section.

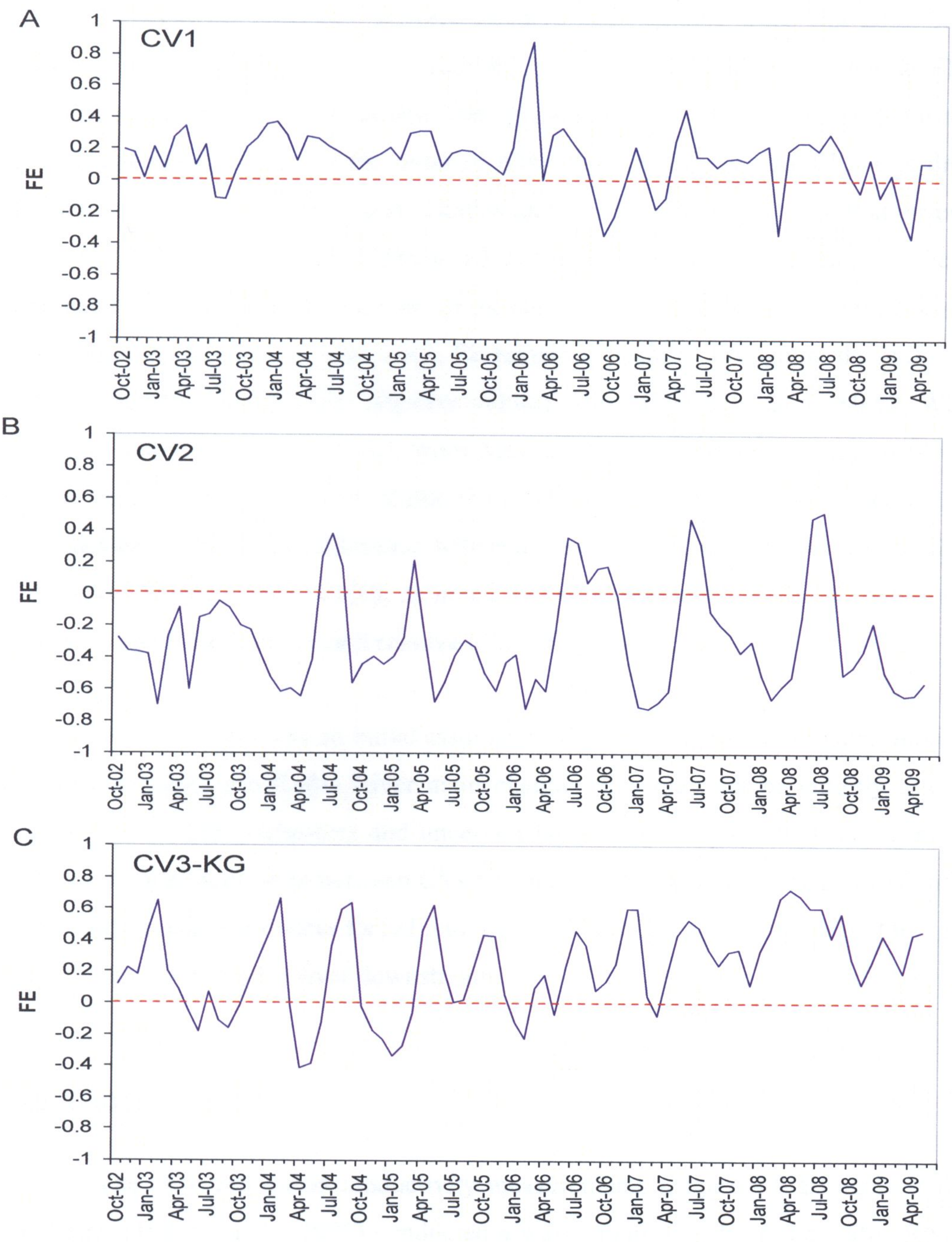

Figure 5.1: Fractional exchange ratio (Equation 7a and 7b) on monthly time scales in the Kafue flats, CV1 to CV3 sub-catchments, Southern Province, Zambia.

In CV3, FE oscillates between positive and negative from Oct 2002-Sep 2005 (Figure 5.1C). Pinay (1988) also reports that the hydrological cycle of the Kafue Floodplain varies tremendously. The average over this time period is +0.13 with peaks of +0.6 during the high-flow season indicating that up to the order of 60% of the water leaving CV3 was draining from the floodplain. Welcomme (1975) and Dudley and Scully (1979) also noted that water recedes slowly from the Kafue flats. Pinay (1988) noted that high water levels (flooding) in the Kafue flats are maintained for 6-7 months. But none of the studies quantified the approximate proportions that are retained in the floodplain. After 2005, FE remained positive throughout the entire year (except for a few modest excursions into negative values) with values as high as +0.68. While the average over the entire period was +0.22, from May 2007-May 2009 the average was +0.42, indicating wetter years. Reported flows at Kafue Gorge (K6) were used instead of Kasaka (K5) to calculate FE because of the large difference between Kasaka (K5) and Kafue Gorge (K6) flows during 2002-2005 (Figure 4.4F), which, as noted above, is reasonable because change in storage in the Kafue Gorge Reservoir is small relative to monthly flows.

Whereas there was an initial assumption that the only route for water moving between CVs is via flow along the Kafue River main channel, this may not be entirely true considering the extremely flat sub-catchments and uncertain boundaries (in particular during high water levels), and some water may cross between CVs through the floodplain. Thus, some of the positive FE for CV3 could result from water forced into the floodplain from CV2, traveling through the floodplain to CV3, and entering the river downstream.

5.2 Water Quality

The observations of conductivity measurements (Figure 4.9 B) agree with measurements by Salter (1985). Salter (1985) conducted a water quality study in the Kafue River between June 1978 and May 1979, with two sampling stations close to station K3. The study found that the average conductivity was 172 μS/cm with a range of 110 to 260 μS/cm. Salter (1985) also observed that the seasonal variation of conductivity presented two peaks, one between August and October (230 μS/cm) and the other between January and June (260 μS/cm). Salter (1985) attributed the elevated conductivity in dry season to greater evaporation.

Depletion of oxygen in the Kafue River and Kafue flats has been noted by other authors. Welcomme (1975) noted that small pools, depressions and lagoons in the floodplain may become completely deoxygenated in the dry season. Welcomme (1975) thus suggested that lower oxygen levels can occur in the river early in the flooding period by the flushing out of stagnant waters from the swamps and lagoons. Salter (1979) also observed that low dissolved oxygen can occur during floods due to high biochemical demand of oxygen by decomposition processes. Dudley and Scully (1980) observed low DO values in the main river channel in the same period of the year (January -March). Dudley and Scully (1980) observed these low values in the main river upstream of Chunga lagoon or K3. The findings in this study generally agree with the observations of Welcomme (1975), Salter (1979) and Dudley and Scully (1980). Station K4, where the DO minimum was consistently observed, is a zone of the river where discharge is consistently higher than at upstream stations (i.e., K3, where the discharge is minimum, Figure 4.9 A). The increase in flow observed between K3 and K4 resulted from low-oxygen floodplain water entering the river channel, and that this led to the persistent low-oxygen levels at K4. The importance of the floodplain water contribution along this stretch of the Kafue River is consistent with spatially intensive chemical measurements (SpC, $\delta^{18}O$) made in this area in May 2008 and May 2009 (Zurbrügg et al., in preparation) and it is supported by the water balance.

5.3 Nutrient speciation and loading (P, N) and Carbon Loading

It is difficult to attribute many of the observed spatial and temporal variations P, N or C concentrations in the Kafue River to individual processes, especially when considering the spatial and temporal variations in discharge and therefore loading (kg/d). Nitrogen undergoes complex natural cycling in river-floodplain ecosystems, with numerous routes for transformations, loss, and gain (Mitsch and Gosselink, 2007). According to Mitch and Gosselink (2007) sinks for ammonium (NH_4^+) include plant or microbial uptake, oxidation of NH_4^+ to NO_3^- (nitrification) and immobilization by negatively charged soil particles. Nitrate (NO_3^-) losses can also occur by microbial or plant uptake and by reduction of nitrate to Nitrogen (N_2) under low oxygen conditions (denitrification). Mineralization of organic matter is a potential source of Dissolved Inorganic Nitrogen (DIN), as is nitrogen fixation (Mitsch and Gosselink, 2007). In addition, anthropogenic inputs, such as human wastewater, fertilizer and livestock excrement can be substantial in certain systems. Although the generally low DIN levels in the lower Kafue River suggest those human activities are not currently having a major impact. Mumba and Thompson (2005) noted that one of the major changes due to the construction of Kafue Gorge (KG) Dam has been the permanent flooded areas (1100 km^2) on the eastern part of the Kafue flats due to the back water effects from KG Dam. These conditions, along with additional flooding throughout the flats during and after the wet season, would thus favour denitrification and tend to decrease nitrate concentrations (Mitsch and Gosselink, 2007). Organic matter mineralization in the floodplain would lead to gross production of partially degraded Dissolved Organic Nitrogen (DON) and Dissolved Organic Carbon (DOC) along with NO_3^-, NH_4^+ or PO_4^{3-} - P. The fraction of these compounds that was not recycled or otherwise lost in the floodplain would undergo seasonal flushing from the floodplain into the river channel, as suggested by the discharge and dissolved oxygen measurements (Figure 4.9A and 4.9C). Although few chemical measurements were undertaken, the calculations offer some valuable inferences from the results.

CV1 had small positive net phosphate export rates in May-December 2008 and small negative net export rates between January and June 2009 (Figure 5.2). Over the entire year, the cumulative negative net export (i.e., area under the curve) was 680 kg, but this was less than 1% of total phosphate entering CV1 from Itezhi-Tezhi Dam, thus inputs and outputs appeared to be approximately balanced during that year. In CV2, inputs and outputs were also fairly well-balanced from May-December 2008 (Figure 5.2). From January-June 2009, however, there were more substantial negative net export rates of TP (200-800 kg P/d). Summed over the entire year, there was a negative net export of 78 tons of total phosphate (TP), which was approximately 30% of TP inputs into CV2. This negative net export likely resulted in a large part due to water leaving the river and entering the floodplain in CV2 (Figure 5.1B). CV3 exhibited relatively large positive net export rates throughout most of the year that resulted in a cumulative net export of +360 tons TP, with annual gross export exceeding input by a factor of ~2. At the scale of the entire Kafue flats (input at K1, export at K5), the floodplain appears to be a net source of TP, exporting 220 tons/yr or ~ 4 Kg P Km^{-2}/yr. The specific loads compare well other areas in East Africa and Lake Malawi. Muvundja et al. (2009) determined on average 110 tons P/yr corresponding to areal ~ 26 Kg P Km^{-2}/yr for the rivers that drain in to Lake Kivu. These estimates are five fold the values in Kafue Floodplain. This is due to the fact that the areas where the rivers draining Lake Kivu flow are more highly populated and have more intense land use than the Kafue Floodplain.

In CV1, TN and TOC net exports appear similar to that of TP with fairly well-balanced inputs and outputs (Figure 5.2). In January through May, the negative TN net exports are relatively larger than for phosphate or TOC. However, the cumulative net TN export from CV1 for the year was in the order of 500 tons, which was only ~10% of the total input at Itezhi Tezhi K1 (~ 4000 tons/yr). The negative net exports of both TN and TOC were more pronounced from CV2. From May 2008-May 2009, TN output from CV2 was 1100 tons lower than TN input, which represented a decrease of approximately 30% of the input load. TOC output was also ~30% lower than input with a negative net export of 27,000 tons. In CV3, the opposite was true for both TN and TOC. Outputs of TN and TOC were double inputs with positive net exports of 2,900 tons and 72,000 tons, respectively. At the scale of the entire Kafue flats (input at K1, export at K5), TN and TOC export exceeded input by 30% and 50%, respectively, positive net exports were 1,300 tons N/yr or ~ 28 Kg N Km^{-2}/yr and 50,000 tons C/yr or ~ 1086 Kg C Km^{-2}/yr. The TN is ~ 16 times lower compared to the average for the rivers that drain in to Lake Kivu with loading of ~ 450 Kg N Km^{-2}/yr (Muvundja et al. 2009). This is expected as the Lake Kivu drainage area has more intense land use activities. Mladenov et al. (2005) also noted increasing TOC concentration in the Okavango as the river flowed downstream. The similar shape for TP, TN and TOC net export curves for each of the control volumes, especially CV2 and CV3, suggests that the balances were largely dictated by the flow rate.

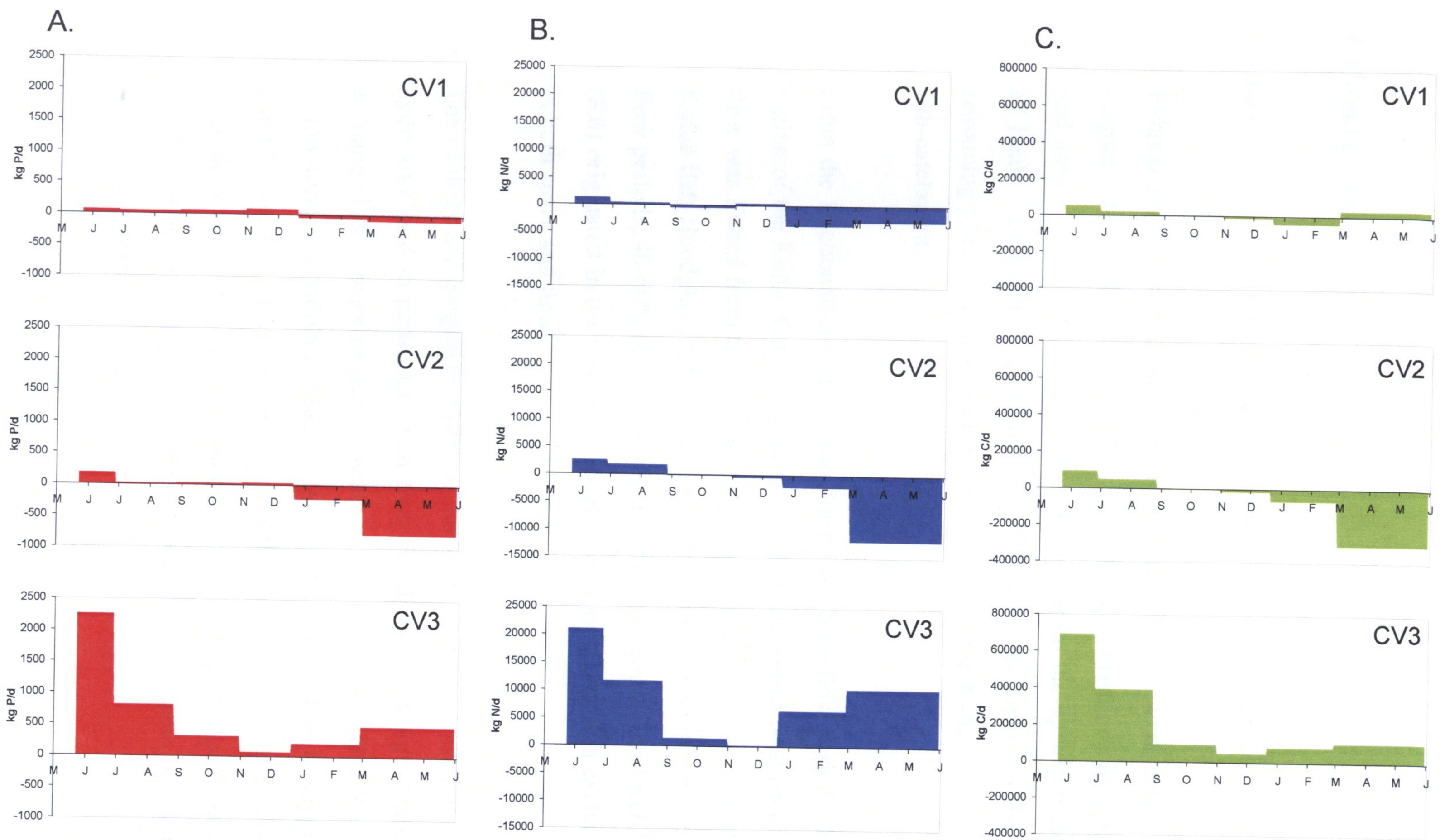

Figure 5.2: Nutrient (N, P) and Carbon loading over the sub-catchments (CV1, CV2 and CV3) in the Lower Kafue River Basin May 2008 - May 2009), Southern Province, Zambia, A. Total Phosphates, B. Total Nitrogen (TN) and C. Total Organic Carbon (TOC).

Chapter 6.0 Conclusions and Recommendations

6.1 Conclusions

From the study the following set of distinct conclusions can be drawn:

- Evapotranspiration accounted for approximately 6%, 49%, and 30% of total hydrologic outputs from CV1, CV2 and CV3, respectively. Direct precipitation accounted for 15, 29 and 46%, respectively, of the inputs. Runoff from the upstream catchment (i.e., upstream of Itezhi Tezhi Dam) accounted for 45% of water inputs to the Kafue flats, while the remaining 55% came from direct precipitation to the Kafue flats and lateral inputs from its sub-catchment.

- From the fractional exchange ratio during the high-flow periods (Feb-May) in the central region of the Kafue flats floodplain (CV2) a substantial fraction (up to ~60%) of the river flow was forced from the river into the floodplain. Conversely, in the eastern region of the Kafue flats floodplain (CV3), water moved from the floodplain into the river. During high flow periods, 40-60% of the water that left the system at Kasaka (K5) or Kafue Gorge Dam (K6) originated in (or traveled through) the floodplain. This exchange varies considerably in both space and time.

- The ecology and biogeochemistry of the Kafue flats are inextricably linked to the system's hydrology, and in particular, with river-floodplain exchange. During flood recession this exchange has a major impact on water chemistry in the Kafue River. Within CV3, inputs of low-oxygen floodplain water during flood recession lead to suppressed oxygen levels (< 2 mg/l) over long stretches of the river that persisted for several months. In addition, the floodplain was a net source of phosphate (220 tons/yr), total nitrogen (1300 tons/yr, of which ~90% was organic nitrogen) and total organic carbon (50,000 tons/yr) to downstream systems.

6.2 Recommendations

The following recommendations are made from the study:

- Whereas existing stage-discharge curves appear to be accurate at some stations (K0, K1, and K2), other downstream stations (K3 and K5) have experienced substantial changes due to backwater effects from Kafue Gorge Dam. The new stage-discharge curve developed for Nyimba (K3) appears to be reasonably accurate; however, large discrepancies between calculated flows at Kasaka (K5) and reported discharges from near-by Kafue Gorge Dam (K6) suggest that more information is needed to better predict flows at Kasaka (K5). The Department of Water affairs in the Ministry of Energy and Water Development and ZESCO need to correct the rating curves at Nyimba (K3) and Kasaka (K5).

- The groundwater and surface water interactions have not been documented in detail in the Kafue flats. The Department of Water Affairs in the Ministry of Energy and Water Development and the University of Zambia Integrated Water Resources Management Centre need to conducted a detailed study in this area to help understand the river floodplain exchange and to improve the water balance.

- This study carried out a nutrient and carbon loading estimates over a period of one year, Department of Water in the Ministry of Energy and Water Development, ZESCO and Zambia Environmental Management Agency need to collect more data over a longer period of time to further help understand the temporal and spatial variation in nutrient and carbon loading over the Kafue flats floodplain.

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Appendix A: Procedure for Catchment Delineation

A) ---- Creation of subbasin outlet shape file ----

1. Corrected coordinates in "Sampling points LKFB.xls" of Hook Bridge and Kafue Gorge Dam with the help of Google Earth.
2. Corrected coordinates in "Sampling points LKFB.xls" of Kasaka with the help of the Zamwis "zam_flow_stations.shp".
3. Converted coordinates in "Sampling points LKFB.xls" to decimal degrees.
4. Read "Sampling points LKFB.xls" into Arc SWAT by using menu "Tools"-->"Add XY Data" (Geogr. projection: WSG 1984)
5. Exported as "Points_Layer1.shp".

B) ---- Preparation of the DEM (Shuttle Radar Topography Mission, V4, 90m, http://srtm.csi.cgiar.org/)----

1. Determined which DEM tiles to download by opening mask layer from http://www.ambiotek.com/topoview.
2. Downloaded DEM tiles srtm_42_16 and srtm_42_15 from ftp://srtm.csi.cgiar.org/ as GeoTiff images.
3. Opened the two images in ArcGIS and converted them (context menu "Data"-->"Export") and saved as img files (16bit).
4. Merged the two new img files by executing "Mosaik to new raster" from ArcGIS toolbox using "16-bit signed" depth setting.

C) Initial run of Arc SWAT to determine whether DEM-created streams match reality.

D) ---- Creation of burn-in layer for the correction of DEM-created stream network ----

1. Cut "Zam_Rivers.shp" from ZAMWIS with ArcGIS editor tool "Split" to extract Kafue Flats stretch.
2. Exported selected stretch (context menu "Data"-->"Export") to

"BurnInZamwisFinal.shp".

E) Second run of Arc SWAT with burn-in layer.

F) ---- Preparing Matlab input in ArcGIS (HowTo) ----

--Create Subbasin Raster---

1. [OLD]Open the subs.shp file from your Arc SWAT project (is found somewhere in the project directory) in ArcMAP.[OLD]
UPDATE: Open a subbasin shapefile you've either created in the above steps or derived from elsewhere in ArcMAP.
1.1 Copy the shapefile and reproject it to WGS 1984.
2. Open Toolbox and "search" for "Polygon to Raster"
3. Execute "Polygon to Raster" tool with a cell size of 0.25 and cell centers being used for the conversion. Choose the subasin field as the "value field". IMPORTANT: Go to "Environments..."(at the bottom of the dialog)--> "General Settings"-->"Extent" --> "As specified below" and choose exactly the same coordinates you used to extract the TRMM data (in this case: "Top": -9, "Bottom": -20.25, "Left": 18.5, "Right": 36.25)

--Export Subbasin Raster---

4. Open Toolbox again and "search" for "Raster to ASCII"
5. Execute "Raster to ASCII" with the before generated Raster file. Name: "SubGRID.dat". Save it together with your yearly .mat files in one folder and delete the first six rows in the file.

Appendix B: Procedure for Extracting Rainfall in Gis and Matlab

THE STEPS BELOW ARE NEEDED FOR PREPARING RAINFALL FOR ARCSWAT.

--Create Centroid table--

1. Open Toolbox again and "search" for "Zonal Geometry As Table"
2. Execute "Zonal Geometry As Table" with the before generated subbasin Raster file (not the ASCII one). And save the "Output Table" together with your yearly .mat files in one folder as: "SubGRIDCentroid.dbf".

--Create Elevation table---

3. Add the digital elevation model (dem) into the map with your created subbasin raster layer. The dem is located in."ArcSWAT Projectname"/"RasterStore.mdb"/"ClipDem". See if they overlay. If not, open ArcCatalog and change the projection of your created subbasin raster from "Unknown" to "WGS 1984". Then they should match.
4. Open Toolbox again and "search" for "Zonal Statistics As Table"
5. Execute "Zonal Statistics As Table" with the before generated subbasin Raster file (not the ASCII one) as "Input raster of feature zone data" and choose as "Input value raster" the ClipDem. Save the "Output Table" together with your yearly .mat files in one folder as: "SubGRIDElevation.dbf".
6. Execute matlab script

Each of the matlab project folders (see Folder "Matlab Input Project Folders") contains some key files:

- SubGRID.dat (different for each project): The ASCII raster exported from ArcGIS (see Folder "Log and HowTo")
- pf1998-2009 (same for each project): Matlab file which can be loaded into the matlab workspace. It contains yearly variables (pfyyyy) which are needed by the script:

- average.m (same for each project) which must be run to extract the time series for the subbasins based on the yearly variables. In the script, one can choose the start- and end year of the time series. It creates the matlab file PAVG.mat in the project folder.
- MakeAvgStat.m (same for each project) is automatically executed by average.m. It creates a subfolder called SWATin. The text files created in this subfolder are numbered according to the subbasin numbers from ArcGIS and contain on each line one day of precipitation with the first line being the start date of the time series.

BASIC PROCEDURE:

I) To start a new rainfall extraction project, just copy-paste one of the old project folders, delete PAVG.mat and the folder SWATin and copy a SubGRID.dat into the folder. The SubGRID.dat is created according to the manuals in the folder "Log and HowTo".
II) Run averag.m
III) Find extracted time series for each subbasin in folder SWATin (one file per subbasin).

Appendix C: Field Data Sheet

Sample sheet

Date	22.4.08
Time	8:22

Site Description

GPS	S 14° 56.971' EO 25° 54.929' Accuracy: 10m
Near town/city/village	Between Kaoma and Mumwa
Short description	Name: Hook Bridge, Middle of the bridge across the Kafue.
Picture	
Remarks	Brownish color of the water.
Site- Name	K1

Parameter Description

Parameter taken (incl. comments)	TN & TP (A, 50 ml PE, unfiltered), O,H,DIC-Isotopes (B, Septum-bottle, poisoned, filtered), 2 x Dissolved Nutrients (C, D, 15 ml cent-tube, 50 ml PE, both filtered), Ions (F,

	15ml cent-tube, filtered), Other (G, 15 ml cent-tube, filtered), TSS (J, 2.3 L filtered).
Neglected parameters (incl. reason)	None
Remarks	During TSS filtering, settlement of particle was noticed (after approx. 0.5 L filtered). After noticing, bucket water was occasionally mixed by shacking.

Storage Description

1. Storage (incl. time and temp)	Cold-box (8:30,close to 0°C until 24:00,close to 0°C)
2. Storage (incl. time and temp)	CYPAC-Freezer (24:00 until 23.4, 9:00)
3. Storage (incl. time and temp)	UNZA- Freezer (23.4, 9:00 on, incl. 10 min transport in a small ice filled Cold-box)
4. Storage (incl. time and temp)	

General remarks/problems

- Two 0.45 um filters used.
- Both, filtered and unfiltered sample containers were 3 times rinsed (as well bucket and syringe)
- Septum bottles were contaminated before in a wet plastic bag but were used anyway
- Weather: Sunny and windy.
- After returning home, septum bottle had a bubble inside.