

DISSERTATION

Anthropogenic influence on nutrient dynamics in the Kihansi River ecosystem, Tanzania

Verfasserin

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angestrebter akademischer Grad

Doktorin der Naturwissenschaften (Dr.rer.Nat)

Wien, 2011

Studienkennzahl lt. Studienblatt: A 091 444

Dissertationsgebiet lt. Studienblatt: Ökologie

Betreuer: Emer Univ. – Prof Dr Fritz Schiemer

Dedication

To

Husband Miraji

Daughter Rania

Parents Juma Ideva and Hawa Ramadhan

Sisters Ashura, Baby, Saumu and Zaina

Brother Kibo

All the Ideva's and Mkerya's

Acknowledgement

I thank the World Bank through the Lower Kihansi Environmental Management Project for financial support. I am deeply indebted to my supervisors Professor T. Hein for vigilance, guidance and constant support during the course of this study. I am also grateful to Professor F. Schiemer for vigilance and invaluable comments towards completion of this dissertation; and to Professor J Machiwa for the unfailing support and advice. I appreciate the support from the institutions in Austria and Tanzania including the Department of Limnology, University of Vienna; the Interuniversity Center for Aquatic Ecosystems Research, Lunz Am See; the Department of Aquatic Sciences and Fisheries and the Department of Zoology and Wildlife Conservation, both of the University of Dar es Salaam; and the Management of the Tanzania Electric Supply Company-Kihansi hydropower station. I also appreciate the support from fellow colleagues of the Department of Limnology, Irene Zweimueller, Andrea Funk, Birgit, Anna, Evangeline Enriquez, Elizabeth Bondar, and all those who contributed in one way or another towards the fruition of this work. I am wholeheartedly thankful to my parent in law Mr Omar and Mrs Hafsa Othman, the family of Mr Hadad Mvulla and all those who in one way or another took care of my daughter during my absence in the early life milestones. I thank you all relatives and friends who provided moral support and encouragement during the course of this study. Last but not least I am grateful to God for giving me strength to accomplish this work.

Abstract

Rivers provide various ecosystem services including habitat for aquatic communities, nutrient processing and material transport from upstream to downstream areas of their catchments. The changes in environmental conditions due to anthropogenic disturbances consequently affect river ecosystem health ultimately jeopardising the ecosystem services provided. Evaluation of the ecological conditions is crucial due to the fact that some of the effects of degradation take some time until they are noticed. Application of functional indicators including nutrient processes and aquatic productivity in assessing the state of resources in response to land use changes and anthropogenic pressure is imperative.

The agriculture and hydropower production are important economic activities in Tanzania. While 75% of the country population depend on agriculture as their main economic activity, hydro electric power contributes to 60% of the country power supply. The Kihansi River has dual importance. Economically, the river provides water for hydropower production. Ecological importance of this river include provision of habitat for flora and fauna (some of which endemic), nutrient processing and transport. However, the river is vulnerable to anthropogenic perturbation resulting from agriculture and hydropower production in the upper and lower parts of the catchment respectively.

The goal of the study is to understand the impact of anthropogenic activities and pressure on nutrient in the Kihansi River ecosystems. Therefore, this study investigated the influence of changes in land use, effects of a reservoir and of hydrology on N and P concentration and export. In addition, the ecosystem's response to changes in nutrient concentration particularly, on the productivity of the Kihansi reservoir was assessed. Specifically, the water quality status of the Kihansi River before and after the construction of the dam was examined. The nutrient conditions, primary production and respiration were measured both upstream and downstream of the dam to assess the influence of the dam on nutrient concentrations. The influence of agricultural activities on nutrient export from catchment areas was also investigated. In order to assess the sensitivity of the reservoir on elevated N concentration, bacterial secondary production and abundance was determined in an N addition experiment.

Results show that the electrical conductivity and the pH values measured in the river section before construction and after 5 years of the hydropower dam operation showed an increase of 38% and 10% respectively. The increase was associated with increased water residence time in the reservoir compared to the previously free flowing stretch of the river. The data indicate no significant differences in P concentrations upstream and downstream of the LKHP dam. However, elevated concentration of $\text{NO}_3\text{-N}$ was observed in the Kihansi River inflowing to the reservoir compared to the River section downstream the LKHP dam. In general the Kihansi River showed low N: P ratio indicated N limitation. This suggest that the observed low primary productivity compared to respiration was attributed to limited availability of N.

Generally, low variability in P concentration among the land use types and seasons suggests demand for N in the Kihansi catchment. For the N fractions, the results show that $\text{NO}_3\text{-N}$ constitutes about 70% of the sum of dissolved inorganic nitrogen fraction in agricultural areas compared to 43% in forested area. This observation is attributed to agricultural activities especially the use of N fertilizers. In general a dilution effect was the major control factor for the concentration and consequently exports of all nutrient forms in forested area. In the agricultural areas, the concentration-discharge relationship for TN and $\text{NO}_3\text{-N}$ suggests soil activation and dilution effect during high flows, respectively. The observed higher concentration of $\text{NO}_3\text{-N}$ during dry season was associated with fertiliser leaching from agricultural soils, which was ultimately brought to the river through groundwater recharge during low flow. The mean $\text{NO}_3\text{-N}$ export in agricultural areas ranged from 0.20 to 1.65 $\text{kg ha}^{-1} \text{yr}^{-1}$. In forested area the mean export of $\text{NO}_3\text{-N}$ ranged from 0.02 to 0.97 $\text{kg ha}^{-1} \text{yr}^{-1}$. A lower N export was observed downstream of the Lower Kihansi hydropower dam compared to the Kihansi River upstream the Kihansi reservoir. This suggests that the latter is a nutrient sink reducing N export to the river reaches downstream areas of the LKHP dam.

Currently, the Kihansi reservoir is although continued N input can result in a changing status of this N limited ecosystem. Heterotrophic production dominates the reservoir, which is attributed to a more elevated bacterial secondary production compared to riverine sites. However, bacterial secondary production is also N limited evidenced by the stimulated C production after N addition. Due to the N retention nature of the reservoir, agricultural intensification in this river catchment will consequently increase dissolved N input into the reservoir therefore change in aquatic ecosystem function is inevitable.

Given the low N:P ratio of this River ecosystem, there is a potential for an increase in secondary productivity in the case of N enrichment. As a result increase in oxygen demand and associated consequences are inevitable. Therefore the application of the best agricultural management practices needs to be emphasized in order to prevent a further increase in dissolved inorganic N concentration and export from agricultural areas of this catchment. Continuous monitoring of nutrient loading to the reservoir from the catchment is crucial because it will enable for a timely identification of the sources of nutrient to enable the application of proper management actions. The relationship between a decrease in nutrient concentration and export to the aquatic communities downstream of the Kihansi hydropower dam need is recommended.

Key words: hydropower dam, agriculture, land use, nitrogen, phosphorus, concentrations, export, bacterial secondary production, bacterial abundance, tropical, Kihansi, River, reservoir, catchment

Zusammenfassung

Das Ökosystem des Kihansi Flusses bietet, wie andere Flüsse weltweit, verschiedenste Möglichkeiten der Nutzung – unter anderem auch als Habitat für verschiedenste Lebensgemeinschaften (einige Arten davon gelten als endemisch), Nutzung der Wasserkraft, Landwirtschaft und als Transportmittel zu Gebieten flussabwärts. Besonders der untere Teil des Einzugsgebietes gilt durch den anthropogenen Einfluss als gefährdet, wobei hier sowohl Landwirtschaft aus den oberen Teilgebieten und Nutzung der Wasserkraft im unteren Flusslauf vor der Kihansi Schlucht eine entscheidende Rolle spielen. Die Studie untersucht den Einfluss von Veränderungen in der Landnutzung, Nutzung der Wasserkraft und Hydrologie auf die N- und P-Konzentration sowie deren Export, weiters den Einfluss von veränderter Nährstoffzufuhr auf die Produktivität des Kihansi Stausees. Insbesondere wurde die Wasserqualität des Kihansi Flusses vor und nach der Errichtung des Dammes gemessen. Daten zu Nährstoffgehalt, Primärproduktion und Respiration wurden oberhalb und unterhalb des Dammes erhoben, um Aussagen über Veränderungen in der Nährstoffkonzentration treffen zu können. Des weiteren wurde die Frage des Einflusses von Landwirtschaft, Wasserkraft und Hydrologie (Jahreszeiten) auf den Nährstoffexport behandelt. Um die Empfindlichkeit des Reservoirs auf erhöhte N-Konzentration zu beurteilen, wurde anhand eines zusätzlichen N-Experimentes die bakterielle Sekundärproduktion und Abundanz ermittelt

Die Ergebnisse zeigten einen Anstieg der Leitfähigkeit von 37,5% während der pH-Wert um 9,85% anstieg im Vergleich zu der Zeit vor der Errichtung des Dammes. Die erhobenen Daten zeigten keinen signifikanten Unterschied der P-Konzentration oberhalb und unterhalb des LKHP Dammes. Es konnten allerdings erhöhte Werte von $\text{NO}_3\text{-N}$ im Zuflussgebiet oberhalb des Dammes gemessen werden. Allgemein zeigte der Kihansi Fluss ein niedriges N:P Verhältnis. N kann als limitierender Faktor für die Primärproduktion angesehen werden, auch die beobachtete geringe Primärproduktivität im Vergleich zur Respiration könnte sich auf die geringe Verfügbarkeit von N zurückführen lassen.

Auf der anderen Seite bedingen landwirtschaftliche Aktivitäten bis zu 70% der Gesamtkonzentration gelösten Stickstoffes, im Vergleich zu Waldgebieten mit bis zu 43%. Die erhöhte Konzentration von $\text{NO}_3\text{-N}$ während der Trockenzeit steht im Zusammenhang mit der Auswaschung von Düngemitteln, die letztlich durch Grundwasseranreicherung in das Flusssystem während Niedrigwasser eingeschwemmt werden.

Es konnte beobachtet werden, dass Verdünnungseffekte in Waldgebieten die Nährstoffkonzentration im Boden maßgeblich beeinflussen. In landwirtschaftlich genutzten Gebieten zeigt die positive Beziehung von TN und Abfluss eine Aktivierung des Bodens an, während für $\text{NO}_3\text{-N}$ ein Verdünnungseffekt vorliegt. Für gelöste Formen von Stickstoff liegt der $\text{NO}_3\text{-N}$ Export in landwirtschaftlich genutzten Gebieten von 0,20 bis $1,65 \text{ kg ha}^{-1} \text{ yr}^{-1}$. In Waldgebieten hingegen lässt sich ein Export von 0,02 bis zu $0,97 \text{ kg ha}^{-1} \text{ yr}^{-1}$ feststellen. Der Kihansi Stausee agiert dabei als Nährstoffs Senke – die

Konzentration an Stickstoff verringert sich auf dem Weg zum Abschnitt unterhalb des LKHP Dammes.

Derzeit gilt der Kihansi Stausee als oligotrophes Gewässer, zunehmender N-Eintrag könnte allerdings eine Veränderung dieses N-limitierten Ökosystems bedeuten. Heterotrophe Produktion dominiert den Stausee derzeit, welcher sich durch erhöhte sekundäre bakterielle Produktion gegenüber dem Flusslauf auszeichnet. Allerdings ist sekundäre bakterielle Produktion ebenfalls N-limitierend, da eine Erhöhung der N – Konzentration stimulierend wirkt.

Allgemein lässt sich feststellen, dass der Stausee empfindlich gegenüber Veränderungen der N– Konzentration ist. Ausgehend von dem derzeit niedrigen N:P Verhältnis in diesem Ökosystem, ist mit einer Veränderung der Produktivität und des trophischen Status bei Erhöhung der N–Konzentration zu rechnen. Daher muß die Betonung auf bestmöglichem landwirtschaftlichem Management liegen um eine Erhöhung gelösten, anorganischen Stickstoffes im Wasserkörper zu vermeiden. Möglichkeiten müssen gefunden werden um die Nährstoffkonzentration zu verringern und den Export derselben zu den aquatischen Lebensgemeinschaften unterhalb des Staudammes zu vermeiden.

Table of contents

Dedication	2
Acknowledgement	3
Abstract	4
Zusammenfassung	6
1.0. GENERAL INTRODUCTION	9
1.1. Objectives.....	10
1.2. Hypotheses	11
1.3. Significance of the Study	11
1.4. Materials and Methods	13
1.4.1. Description of the Study Area.....	13
1.4.2. Sampling Stations and Sampling Design	13
1.4.3. Laboratory measurements	14
1.4.3.1. Nutrients analyses.....	14
1.4.3.2. Bacterial secondary production and abundance.....	14
2.0. GENERAL RESULTS.....	15
2.1. Summary of the results from Paper 1	15
2. 2. Summary of the results from Paper 2	15
2. 3. Summary of the results from Paper 3	17
3.0. DISCUSSION, CONCLUSION AND RECOMMENDATIONS.....	19
3.1. Discussion.....	19
3.2. Conclusion	24
3.3. Recommendations.....	24
3.4 References	25
4.0. PAPERS	30
4.1. Paper 1.....	30
4.2. Paper 2.....	39
4.3 Paper 3.....	63
<i>Curriculum Vitae</i>	80

1.0. GENERAL INTRODUCTION

Rivers provide various ecosystem services including habitat for flora and fauna, nutrient processing and ultimate material transport from upstream to downstream areas of the catchments. The riverine ecosystems are impacted by anthropogenic perturbations including land use in catchment areas for agriculture (Tilman, 2001 and Vitousek et al., 1997) and hydropower production (Mwaura, 2006; Kemdirim, 2005; Gunkel et al., 2003 and Welcomme, 1985). While agricultural land use results in elevated nutrient amounts in rivers (Gücker et al., 2008; Verstraeten and Prosser, 2008; Howarth et al., 2006; Lehrter, 2006; Brodie and Mitchell, 2005), hydropower dams interrupt nutrient flows (Welcome, 1985) to downstream areas resulting to changes in nutrient biogeochemistry (Elser and Urabe, 1999; Friedl and Wuest, 2002; Vanni et al., 2010) and nutrient limitation patterns (Harven, 2003 and Smith and Bennett, 1999). As a consequence, ecosystems' health is affected (Udy et al., 2006 and von Schiller et al., 2006) ultimately jeopardising the provision of ecosystem services (TEEB, 2009). Therefore, measurement of the ecological condition of the ecosystem needs to be evaluated because degradation may go unnoticed until it triggers substantial disruption of ecosystems functioning.

Forested catchments export less amounts of dissolved inorganic forms of N and P (Graham 2001) compared to organic forms of these nutrients (Lewis et al., 1999). Besides, a positive correlation is found to exist between agricultural activities and NO_3^- -N concentration. This implies that agricultural areas export high NO_3^- -N concentration than forested areas. Similar observation has been made by (Howarth, 1996; Strayer et al., 2003; Donner, 2004; Galloway et al., 2004; Downing et al., 1999 and Austin et al., 2006). However, the quantity of dissolved inorganic N exported in rivers varies due to differences in the inputs from surface runoff and groundwater (Wetzel, 2001). As such, change in discharge is an important factor that controls nutrient export from catchment areas (Saunders and Lewis, 1988). Thus, the concentrations and export of N and P fractions are used as functional indicators of changes in land use. Application of functional indicators is crucial in assessing the state of resources in response to land use changes and anthropogenic pressure imposed to ecosystem (TEEB, 2009).

Agricultural activities increases the amount of dissolved nutrient transported from catchment areas. As a result of hydropower dams, nutrients retention occurs in the reservoirs thus changing the amount of nutrients transported to downstream areas. As nutrients are important for aquatic primary productivity, a source of energy to higher trophic levels, changes in their amount and export along the river continuum will result to changes in ecosystem function.

The influence of land use activities on the Kihansi River ecosystem

Agricultural activities and the construction of a hydropower dam are major environmental management challenges facing the Kihansi River catchment. Inhabitants in the upper parts of the Kihansi River catchment depend on agricultural activities for both food security and income generation. They

cultivate along hill slopes, on the bottom of river valleys as well as along the banks of the river less than 0.5 m from river channel. In intensive cultivation areas the use of fertiliser is inevitable. Slush-and-burn farming method is commonly practiced. These environmentally unfriendly agricultural practices can lead to elevated nutrient inputs in downstream receiving water bodies, particularly in the Kihansi Reservoir.

Changes in nutrient concentration and export can be influenced by changes in the hydrological regimes. The changes in hydrological regime can result from both natural and anthropogenic alterations due to seasonal variability and hydropower dam, respectively. While the resultant reservoir can be either a source or a sink of nutrient, elevated discharge during rainy season can lead to reduced nutrient concentration as a result of dilution effect. Groundwater recharge influences nutrient concentration in rivers especially during low flow. Groundwater constitute elevated amounts of dissolved nutrient forms which previously infiltrated, percolated or leached into soil during rainy season. Thus, understanding the influence of land use activities on amounts of nutrient exported from catchment areas to the river system is crucial in getting an integrated view of tropical riverine ecosystem for the purpose of improving management strategies.

Flow diversion caused the River Kihansi section downstream of the hydropower dam to change from annual average discharge of $16.3 \text{ m}^3 \text{ s}^{-1}$ to $1.5 - 1.9 \text{ m}^3 \text{ s}^{-1}$ (Zilihona et al., 2004). This has far reaching effects on downstream biodiversity, particularly at the Kihansi Gorge ecosystems. Amid is the extinction of the Kihansi spray toad (KST) *Nectophrynoides asperginis* from its endemic habitat at the Kihansi Gorge (Poynton et al., 1998 and Krajick, 2006). Although, the KST is not the focus of this study, knowledge of nutrient which forms the energy base in food webs is important. Changes in nutrient amounts and export as a result of altered flow regime can change nutrient stoichiometry (Elser and Urabe, 1999 and Vanni et al., 2010) in food web interactions (Hoeinghaus et al., 2008).

Following the reported importance of the Lower Kihansi River ecosystem, the Lower Kihansi Environmental Management Project (LKEMP) was initiated. The project formulated the Environmental Management Plan (EMP) for mitigating and monitoring of the project area.

However, it is known that human activities, particularly those occurring in upstream areas of the catchment influences downstream ecosystem health. It is though that both agricultural activities and the hydropower dam can affect not only physico-chemical water parameters, but also nutrient concentration and export to areas downstream of the dam. This formed the basis for this study. Due to paucity of literature regarding water quality, particularly N and P in the investigated river system, literature from other tropical ecosystems was used.

1.1. Objectives

The study aimed at (1) assessing the status of the Kihansi River ecosystem

up- and downstream the Kihansi reservoir after 5 years of LKHP dam operation. (2) investigating spatial and temporal effects of LKHP on the concentration of nitrogen (N) and phosphorus (P) along the Lower Kihansi River ecosystem upstream and downstream of the dam, (3) assessing the influence of agriculture and hydropower on the concentrations and export of N and P in the Kihansi River and (4) investigating the response of excess nutrient enrichment on the bacterial activity in the Kihansi reservoir.

1.2. Hypotheses

It was hypothesised that (1) the electrical conductivity, pH and dissolved oxygen concentration in the Kihansi River are higher than those recorded before the construction of the LKHP dam (2) the N and P concentrations are higher in the Kihansi River upstream than downstream of the LKHP dam (3) Under similar geological conditions, agricultural areas export more N and P than forested ones (4) the LKHP dam can result in elevated N concentration in the reservoir, thus, stimulate bacterial secondary production in the reservoir.

The implication of catchment activities and hydropower dam construction on the concentration and export of N and P nutrients in the Kihansi River and the reservoir itself was studied. The first undertaking was to study the status of the quality water of Kihansi River water quality, while the second was to establish the effects of land use activities in the catchment to the concentration and export of N and P nutrients in the River Kihansi, where as third one was to study the response of bacterial activity to elevated N concentration in the Kihansi Reservoir as a result of agricultural activities and LKHP dam operation. It was expected that bacterial productivity is of major importance in the Kihansi Reservoir. Thus, an N enrichment experiment was carried out to test the response of bacterial activity at increased inorganic N concentrations.

Studying nutrient status and its alteration is a crucial first step in conservation of a fragile riverine ecosystem (Kroeze and Seitzinger, 1998) like the Kihansi River system. Due to similar geological background of the Kihansi catchment, natural spatial variation in nutrient concentration was expected to be minimal. Catchment impacted by land use activities including the agricultural areas and reservoir were expected to have elevated nutrient concentrations. Due to paucity of literature on the present subject in River Kihansi and Tanzanian rivers, the study used information on rivers in other tropical areas.

1.3. Significance of the Study

Ecological studies in the Kihansi River system focused on flora (Quinn et al., 2005 and Lovett et al., 1997) and fauna (Cordeiro et al., 2006; Zillihona et al., 2004 and Poynton et al., 1998) in the Kihansi Gorge ecosystem. Prior to this study, water quality monitoring included physical chemical parameters (electrical conductivity, pH, temperature and dissolved oxygen) which also focused on the Gorge ecosystem. Little was known on how the dam affect the N and P export to downstream areas in African this ecosystem. The ongoing

agricultural activities upstream in the catchment areas provide non point source of N and P nutrient and can be indicated by elevated export rates. The ultimate receiving water body for the nutrient exported from catchment areas is the Kihansi reservoir. It is known that reservoirs alters biogeochemical transport of materials in rivers (Welcome, 1985 and Vörosmary et al., 2003) thus, affecting nutrient transport to the downstream areas of the dam.

This study was commissioned by the Lower Kihansi Environmental Management Project (LKEMP) for the purpose of capacity building in the University of Dar es Salaam. In addition to this main purpose, the knowledge thus gathered during this study will contribute to the freshwater ecological expertise of Tanzanian and tropical rivers in general.

Successful water quality management can be achieved through water quality and pollution monitoring as well as through protection of water sources. Economic activities for a necessary for poverty alleviation such as agriculture and hydroelectric power production threaten the water quality necessary to safeguard ecosystem health and services thereof. Despite this imperative, water quality degradation from agricultural activities in Tanzania seems inevitable so far. This is due to the current promotion of use of agrochemicals to improve harvest in rural areas, where the major part of the river catchment lies, Environmental protection is emphasised in the country's legal framework.

The Water Policy (URT, 2002) The National Environmental Management Act (URT, 2004) and the recent Water Resources Management Act (URT, 2009) emphasizes the protection of water bodies from degradation and preventing adverse ecosystem degradation. These need sound scientific background information for strategic integrated water resources management and governance. Therefore, this study is aimed at contributing to nutrient amounts and export from catchment areas for the conservation and management purposes.

1.4. Materials and Methods

1.4.1. Description of the Study Area

The Kihansi river catchment

Kihansi River catchment is located between 35°44'22"E and 35°53'45"E and latitudes 8°13'08"S and 8°33'12"S and is worldwide known for high biodiversity (LKEMP, 2005). The Kihansi River descends along the eastern scarp of the Southern Udzungwa with a catchment of 688 km² (Poythou et al., 1998). Kihansi River is a tributary to the Kilombero River. The Kilombero River is a sub-basin of Rufiji River Basin, the largest of the river basins in Tanzania. River Kilombero contributes 20% of the Rufiji River flow. Therefore the water quality River Kihansi seems to have little influence to the Rufiji River and thus the coastal ecosystem. However, understanding the effects of land use on the amount and export of nutrients at a local scale is of crucial importance to the management and maintenance of ecosystem integrity.

The catchment is located on the Udzungwa Mountains which are part of the Eastern Arc Mountains. The mountains are block-faulted and are associated with East African rifting following the break-up of Gondwanaland (Lovett et al., 1997). The Udzungwa escarpment was probably formed by complex interaction of faulting and uplifting associated with the rifting during the Jurassic period and rejuvenated by Tertiary and post-Tertiary rifting. The principal landform features are: (a). the undulating plateau with hill tops and shallow valleys (b) the escarpment cut by the Kihansi gorge and (c) the flat plain. Through these feature runs the River Kihansi.

The Lower Kihansi hydropower dam is built across the Kihansi River and serves as water storage for hydropower production in the Lower Kihansi hydro power plant. The dam is 25 meters high and results in inundation of about 26 ha at its highest water level. From the reservoir, water is diverted to a tunnel, which drops 900 m within 3 km (Zilihona et al., 2004) and after running through the turbine, water is redirected to the Kihansi River again about 6 km downstream of the dam.

Due to engineering design of the Kihansi reservoir, water residence time is about 12 hours. Water for power production is drawn from the bottom of the reservoir enhancing water movement. The bypass flow which provides ecological water for the river downstream of the dam helps to create the current which bring about continuous mixing in the reservoir especially when the power plant is not operating.

1.4.2. Sampling Stations and Sampling Design

The study stations include River Kihansi inflowing to the reservoir, the reservoir and the River Kihansi downstream of the LKHP dam. Other stations include tributaries to the Kihansi River draining agricultural and forested area. The agricultural areas are grouped into scattered, semi-intensive and intensive cultivation. The Kihansi catchment is located 700 km from Dar es

Salaam. Accessibility of catchment presented a challenge to the study design. While road access to Kihansi was close to impossible during rainy seasons, train access was unreliable both due to route cancellation and also infrastructure destruction during the rainy season. This presents a major limitation as samples for nutrient analyses needs immediate analyses. This study was designed to be conducted in periods when the study stations were accessible, while ensuring random representation of data collected. Due to low variability in discharge and geology, representative samples were taken during the rainy and dry seasons. In general sample collection was conducted for a total duration of 14 months. The first six months in 2005 – 2006 (led to publication of the first paper), other six months in 2006 – 2007 (led to the second paper) and 2 months sampling in 2008 (led to the third paper).

1.4.3. Laboratory measurements

1.4.3.1. Nutrients analyses

Nutrient analyses were conducted at the University of Dar es Salaam. Standard methods (APHA, 1998) were used to analyse the dissolved as well as particulate forms of N and P. Primary production and respiration were measured using the Winkler technique.

1.4.3.2. Bacterial secondary production and abundance

Bacterial secondary production was determined by the [3H] thymidine ([methyl-3H] TdR) incorporation technique (Fuhrman and Azam, 1980). About 20 µg of 0.1 mCi ml⁻¹ of was added in each 10 ml of triplicates samples and duplicate controls (killed with 2% final formalin concentration). Bacterial cell production was calculated using a conversion factor of 1.61 x 10¹⁸ cells mol⁻¹ thymidine incorporated (Peduzzi and Schiemer 2004).

For bacterial abundance measurements, 10 ml water sample was fixed with 0.4 ml 37% formalin, before transporting them to Austria for bacteria abundance estimation. In the laboratory, 1 ml of each sample was stained with 100 µl 4, 6-Diamidino-2-phenylindole (DAPI) solution; then incubated in the dark for 10 minutes before counting under the epifluorescence microscope at 1000x magnification. On each filter twenty fields were counted for the determination of the total bacterial number (Weinbauer et al., 1998).

2.0. GENERAL RESULTS

Nitrogen and phosphorus are key nutrients for aquatic primary productivity. Documenting their concentration and exports from catchment areas and assessment of influence of land use on the concentration and export of these nutrients is crucial in integrated watershed management. The major focus of the dissertation was on the amount and export of nitrogen (N) and phosphorus (P) as indicators of anthropogenic activities and pressure. Thus the impact of agriculture and hydropower dam on N and P concentration and export and the ultimate response on reservoir productivity was assessed. The major finding of the study are summarised and presented in this section.

2.1. Summary of the results from Paper 1

Effect of an impoundment on nutrient dynamics in Kihansi River, Tanzania – published in the African Journal of Aquatic Science 33(2): 181-188

A study of the effect of a hydropower dam on nutrient concentration was conducted five years after the commencement of the hydropower dam operation. The study compared the physico-chemical parameters of the river section before (1995) and after dam construction (2005). The latter showed elevated values of electrical conductivity and pH. However, the concentration of dissolved oxygen was lower in 2005. For the 2005 measurements, comparison of nitrogen and phosphorus concentrations as well as primary production rate showed low values at stations downstream of the dam than at upstream stations. Lower primary production rate compared to community respiration was observed in the reservoir. A study of the reservoir's sediment bound phosphorus showed elevated concentration of iron – and manganese-bound phosphorus. Seasonally, elevated concentration of nitrogen and phosphorus along the River Kihansi were observed during the dry season.

2. 2. Summary of the results from Paper 2

Compound effects of land use and hydropower dam on nutrient status of the Tropical Kihansi River ecosystem – a manuscript in review process by the River Systems Journal

In general, the highest mean discharge was observed in the river draining forested area. The lowest mean discharge was recorded downstream of the Lower Kihansi Hydropower (LKHP) dam. Except for the station downstream of the LKHP dam, all other study stations showed higher discharge during rainy season.

For the total nutrient forms, the export of total phosphorus (TP) in forested area ranged from 0.89 to 2.93 kg ha⁻¹ yr⁻¹. In agricultural areas the mean export of TP ranged from 0.36 to 1.51 kg ha⁻¹ yr⁻¹. In forested area the mean export of total nitrogen (TN) ranged from 1.85 to 6.57 kg ha⁻¹ yr⁻¹. In agricultural areas the mean export of TN ranged from 0.08 to 4.08 kg ha⁻¹ yr⁻¹. Among the agricultural areas, a higher export rate for TN was observed in semi intensive cultivation (SIC) areas. However, a significant difference in the

export of TN between forest (F) and scattered cultivation (SC) and between F and intensive cultivation (IC) areas was observed. For dissolved nitrogen (N) forms, the mean $\text{NO}_3\text{-N}$ export in agricultural areas ranged from 0.20 to 1.65 $\text{kg ha}^{-1} \text{yr}^{-1}$. In forested area the mean export of $\text{NO}_3\text{-N}$ ranged from 0.02 to 0.97 $\text{kg ha}^{-1} \text{yr}^{-1}$. In agricultural areas the mean $\text{NH}_4\text{-N}$ export ranged from 0.04 to 0.81 $\text{kg ha}^{-1} \text{yr}^{-1}$ and from 0.16 to 0.67 $\text{kg ha}^{-1} \text{yr}^{-1}$ in forested area.

In general, all the agricultural areas showed elevated concentration of $\text{NO}_3\text{-N}$ compared to other areas (Figure 2). However, lower concentration of $\text{NO}_3\text{-N}$ is observed in the Kihansi River before entering the reservoir (station KBD). Furthermore, the lowest concentration of $\text{NO}_3\text{-N}$ was observed downstream of the hydropower dam (station HP). The highest and lowest concentrations of $\text{NH}_4\text{-N}$ were recorded in intensive cultivation areas, decreased in the river before entering the reservoir and increased again downstream of the hydropower dam. Besides, $\text{NO}_2\text{-N}$ showed lowest concentration at site in the river before entering the reservoir. The concentration of the TN showed a different trend (Figure 3) where the highest concentration is observed in the River Kihansi before flowing to the reservoir.

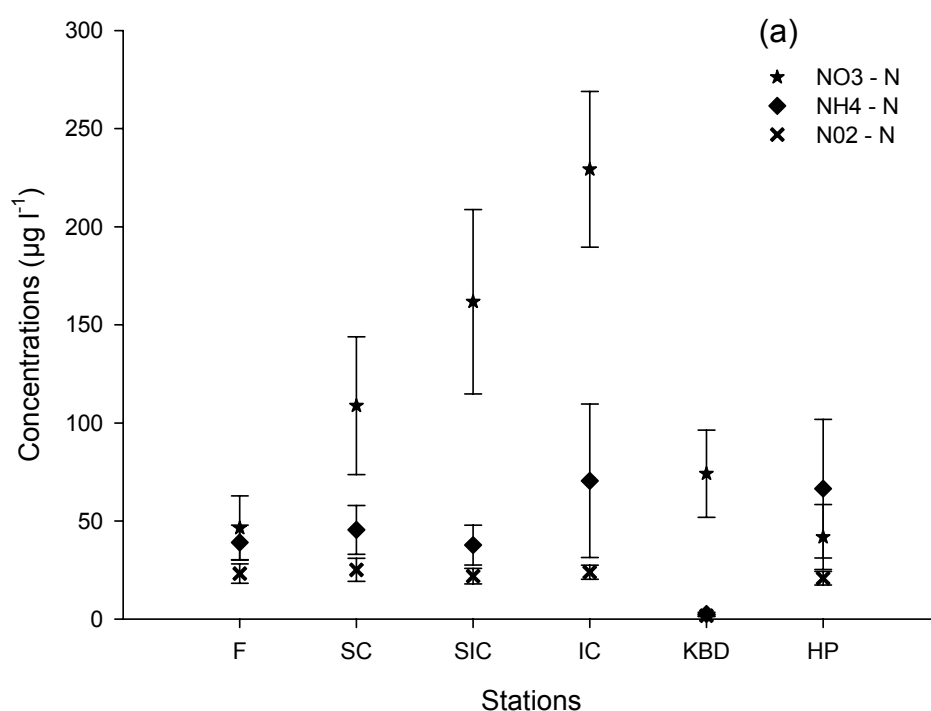


Figure 1. Mean and standard error of the concentration of dissolved forms of N along the Kihansi River catchment. F = Forest, SC = Scattered Cultivation, SIC = Semi Intensive Cultivation, IC = Intensive Cultivation, KBD = Kihansi River before flowing the reservoir and HP = Kihansi River immediately downstream of the hydropower dam (n = 6)

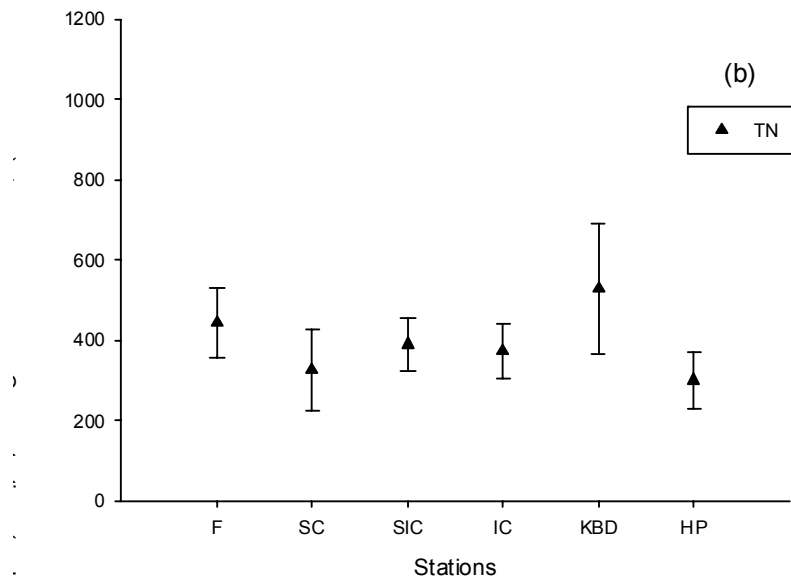


Figure 2. Mean and standard error of the concentration of total N along the Kihansi River catchment. F = Forest, SC = Scattered Cultivation, SIC = Semi Intensive Cultivation, IC = Intensive Cultivation, KBD = Kihansi River before the reservoir and HP = Kihansi River downstream of the hydropower dam. (n = 6)

2. 3. Summary of the results from Paper 3

The influence of elevated nitrogen concentration on bacteria activity in Kihansi Reservoir, Tanzania – in final stage of preparation

The mean concentration of dissolved organic carbon (DOC) in the River Kihansi during the periods of this study ranged from 364.5 to 1202 $\mu\text{g l}^{-1}$. Bacterial secondary production in the River before it enters the reservoir was higher compared to the production in the reservoir and stations downstream of the LKHP dam. Besides, the highest bacterial abundance was observed in River Kihansi before entering the reservoir compared to the reservoir itself.

Compared to in situ measurements, both bacterial secondary production and abundance were higher in an N addition experiment. A significant difference was observed between the bacterial secondary production in time 0 (initial incubation) and after 36 hours of incubation. The highest cell specific production was observed after 12 and 24 hours of incubation.

Decrease in water velocity resulted to elevated bacterial secondary production in the reservoir. In situ bacterial carbon production and bacteria abundance did not correlate, both in situ indicating bacteria responsible for carbon production are site specific. Bacteria can be adapted to differences in environmental variables including the amount of DOC, temperature and hydraulic conditions. Highest bacterial production was observed with low velocity in the reservoir.

N addition experiment suggests that elevated N concentration can result to elevated bacterial production of carbon in the reservoir. This has an implication on changes in dissolved oxygen concentration in the water column

of the reservoir and sediment water interface. Low oxygen conditions in the sediment water interface will result to release of phosphorus bound in iron (Fe) and manganese (Mn) to the water column.

3.0. DISCUSSION, CONCLUSION AND RECOMMENDATIONS

3.1. Discussion

Anthropogenic perturbations in catchment areas affect nutrient amounts occurring in rivers. River discharge is a key factor in nutrient export (Saunders and Lewis, 1988 and Bunn and Arthington, 2002). Thus combined effects of human activities and variation in river discharge define the amount of nutrients exported from catchment areas to receiving water bodies. While agricultural activities have found to increase dissolved N export, hydropower dam retained N in the reservoir reducing nutrient amounts exported to the downstream areas. Thus, the influence of agriculture and hydropower dam on nutrient export from catchment areas is buffered in the reservoir as discussed below.

Effect of the LKHP dam on nutrient concentration in the Kihansi River

The physico-chemical water quality parameter of the River Kihansi is changed compared to periods before the dam construction. The electrical conductivity in this River is less low compared to the other rivers within the River Rufiji Basin, Tanzania. For example, the Little Ruaha River shows electrical conductivity range from 41 – 71 $\mu\text{S cm}^{-1}$. In general, the observed electrical conductivity values are even lower than those recorded in other East African rivers. For example in Uganda, Busulwa and Bailey (2004) and Kasangaki et al. (2008) recorded electrical conductivity values ranging from 12 – 220. Almost neutral range pH values were recorded in the River Kihansi. The values are slightly lower than those recorded in the little Ruaha River (pH ranges from 6.1 – 8.1). The pH values ranging from 6.9-7.9 were recorded also in Sigi River (PRBWO/IUCN, 2007). However, the pH values in Kihansi River are higher than the pH values in other African Rivers. Kasangaki et al., (2008) again recorded pH values ranging from 4.1 – 6.9 in high-altitude stream in Uganda.

Low electrical conductivity indicate low concentration of total ions which is a reflect background geochemistry of catchment. This can be reflected also by the low concentration dissolved N, P and organic carbon. Near neutral pH values suggest the existence of carbon equilibrium which tends to be shifted by photosynthesis processes. Allochthonous input of organic material and biotic consumption results to elevated pH values (Wetzel, 2001). The $\text{NO}_3\text{-N}$ concentration in the River Kihansi is within the average value for the values recorded in other rivers in Tanzania. The $\text{NO}_3\text{-N}$ concentration in the Little Ruaha River range from 0.06 - 1.1 mg l^{-1} , 1 – 1.9 mg l^{-1} in the Sigi River (PRWBO/IUCN/2007), 0.03 – 15 mg l^{-1} in the Wami River (WRBWO/IUCN, 2010a) and 1.6 – 2.4 mg l^{-1} in the Ruvu River (WRBWO/IUCN 2010b).

Significant differences in the concentration of $\text{NO}_3\text{-N}$ between the upstream and downstream areas of the dam suggest that the hydropower dam significance role in controlling dissolved inorganic N concentration. The observed decrease in the concentration of $\text{NO}_3\text{-N}$ and TN in the River Kihansi reach immediately downstream of the dam suggesting that Kihansi reservoir

is a nutrient sink. This is due to increase in water residence time which allows both biotic and chemical transformation of nitrogen in the reservoir.

Pelagic processes are associated with chemical transformation of nutrients, in the reservoir. The processes include settling of particulate matters and sedimentation and are reflected by the concentration of sediment bound phosphorus in the reservoir's sediment (Ideva et al., 2008). The iron (Fe) and manganese (Mn) bound phosphorus implies aerobic conditions in the sediment water interface. This suggests low organic matter content in the reservoir sediment does not lead to oxygen deficit as a result of decomposition. Availability of oxygen in the reservoir sediment water interface is attributed to the water flow as it is abstracted from the reservoir for hydropower production. The reservoir is currently a sink for phosphorus. Anaerobic conditions of the sediment favours phosphorus release to the water column.

Biotic transformation include uptake by organism including bacteria and phytoplankton. However, lower primary production rate compared to community respiration suggests that primary production is limited. The low N:P ratio suggests that primary productivity in this system is N limited, a conditions which favours dominance of nitrogen fixing organisms including cyanobacteria. Currently, there is no indication of excess cyanobacteria growth. This is attributed to other factors including radiation and lack of a stable water conditions. Water residence time in the reservoir is almost 12 hours or less depending on hydropower production rates which draws water from the reservoir to run the turbines in the hydropower plant. Harven et al., (2002) pointed out that factors such as low solar radiation and lack of water column stability may be responsible for observed low productivity in strongly N limited aquatic system. This might also be the case for Kihansi reservoir. Thus in the Kihansi Reservoir, the risk of eutrophication is not immediate compared to the risk associated with reduced nutrient export necessary to maintain aquatic communities downstream of the dam.

Compound effects of agricultural land use and hydropower dam on riverine nutrient exports

The results revealed that agricultural activities are responsible for elevated dissolved inorganic nutrient concentration in the river ecosystem. This is evidenced by elevated concentration of $\text{NO}_3\text{-N}$ concentration in semi-intensive and intensive cultivation areas compared to forested area (Figure 2). The use of inorganic fertilizers in agricultural fields resulted in an increase in reactive nitrogen (Austin et al., 2006; Galloway and Cowling, 2002 and Galloway et al., 2004) and phosphorus export (Bullock et al., 1995 and Tamatamah et al., 2006) into aquatic ecosystems. As primary productivity in this river system is nitrogen limited (Ideva et al., 2008), further addition of dissolved inorganic N from agricultural activities can stimulate reservoir productivity. Although currently the observed concentrations are low compared to the concentrations recorded in other rivers, a risk of $\text{NO}_3\text{-N}$ enrichment will be noticed with time, if appropriate management actions are not taken.

In the agricultural catchments farmers apply fertilizers to increase crop production particular for vegetable including peas, carrots and tomatoes. FAO (2002) reported that in sub-Saharan Africa fertilizer application is on average below 10 kg nutrient ha⁻¹. In Tanzania, the amount of fertilizers application in farms among the farmers depends on the economic status. The amount of fertilizer applied to farms range from 5 to 20 kg nutrient ha⁻¹. Rapid population growth in the country consequently increases in food demand. Therefore, elevated fertilizer application for the purpose of increasing agricultural produced is expected. This poses threat to elevated dissolved inorganic nutrient aquatic ecosystems provided better fertilizer application practices are not applied. Better fertilizer application practices including site specific fertilizer application (Isherwood, 2000) can help in reducing dissolved inorganic N concentration export from agricultural areas.

Elevated total nitrogen and phosphorus nutrients in forested area compared to agricultural areas suggest the importance of allochthonous input of particulate materials from terrestrial vegetation. In general, dissolved inorganic nutrient forms are more important in open canopy rivers draining agricultural areas than closed canopy rivers draining forested area. Similar observation is reported by Lewis et al., (1999) in the undisturbed watersheds. As such conservation of riparian vegetation is important in reducing inorganic N input into rivers.

In the Kihansi River catchment, variation in hydrology is observed to control the nutrient concentration in rivers. During the rainy season, dissolved nutrients infiltrate through the soil to groundwater and some washed out by surface runoff into rivers. Dilution of nutrients in river results in the observed low concentrations during the rainy season. Besides, groundwater recharge during the dry season is attributed to elevated dissolved N concentration, particularly in agricultural areas. Groundwater base flow (Birhanu, 2009) is attributed to river recharge in this catchment expresses elevated dissolved inorganic N previously infiltrated to groundwater during the rainy season. Elevated NH₄-N in agricultural areas compared to forested area further explains the contribution of dissolved N from groundwater sources. Due to limited oxygen conditions in groundwater, dissolved N exists in a reduced form (NH₄-N). However, under high oxygen condition in the river, NH₄-N rapidly oxidises to NO₃-N (Wetzel, 2001). Thus agricultural activities in the Kihansi catchment contribute to elevated dissolved N concentration in the rivers during the dry season.

Flow in River Kihansi River has been assessed by (Birhanu et al., 2009). The simulation model for the River Kihansi catchment indicates reasonable annual water balance (Birhanu et al. 2009). Their simulation results indicated 85% of annual water yield in the Kihansi catchment was contributed to groundwater flow suggesting strong base flow in the catchment. Taking this observation into account, it is suggested that nutrient amount and export in the agricultural areas of the River Kihansi catchment is a factor of groundwater base flow, especially during dry season. This is supported by the observed elevated concentration of NO₃-N in agricultural areas compared to forested area.

Effect of the Reservoir

The Kihansi reservoir is both a sink for TN and $\text{NO}_3\text{-N}$ nutrients and source of $\text{NH}_4\text{-N}$. The latter oxidises easily to $\text{NO}_3\text{-N}$ under oxic condition. $\text{NH}_4\text{-N}$ accumulates from decomposition of particulate and dissolved organic matter. Nitrogen transformation is thus an important subject in the water column, at the water-sediment interface and the groundwater compartment of the river and reservoir, which is beyond the scope of this study. The elevated respiration rates in the water column of the N limited Kihansi reservoir (Ideva et al., 2008) indicated autotrophic production is limited by N, suggesting dominance of heterotrophic production. In tropical freshwater systems like the Kihansi River, heterotrophic bacterial secondary production can also be limited by nutrients. The N addition experiment to test the response of bacteria production and abundance indicate that bacterial production is N limited. Understanding regulatory mechanisms of bacteria productivity is important in studying the response of aquatic water bodies (Schiemer, 2008) from N addition derived from anthropogenic activities and pressures in the river catchments.

Low TN in the reservoir compared to the River Kihansi before upstream is attributed to biological, chemical and physical processes occurring in the water column. Biological processes include uptake by aquatic biota. Chemical processes include N transformation and physical processes including settling of particulate matter, which causes nutrients to be buried in sediment. These processes contribute to nutrient retention phenomenon of the reservoir. Elevated in situ bacterial production supports the hypothesis that microorganisms decompose particulate organic matter for their growth and metabolism, consequently contributing to N cycling. The consequences associated with increase organic matter decomposition includes oxygen depletion and the consequences thereof (Wetzel, 2001).

Under low oxygen conditions such as in sediments, microbial decomposition (Wetzel, 2001) results in accumulation of $\text{NH}_4\text{-N}$. Thus, in the sediment of Kihansi Reservoir, TN and $\text{NO}_3\text{-N}$ retention is associated with settling of particles and other pelagic processes, respectively. The reservoir being a source of $\text{NH}_4\text{-N}$ is attributed to microbial processes in the reservoir sediment. Therefore, the N management is important in order to reduce both inorganic N and particulate N input to the Kihansi reservoir.

The Rufiji River Basin where the Kihansi River catchment is part of has both economic and ecological importance. Economically, hydropower contributes to about 1.19 % of the gross domestic per capita income. Hydroelectric power is the major sources of electric power in the country as it contributed about 82 % of total electric power in Tanzania for the period 1993 and 2005. The Rufiji River Basin, including the Kihansi catchment has an average of 66 % of the total electricity generated in country. River Flow diversion for hydropower production purposes changes the hydrological condition posing stress to aquatic communities. Besides, Tanzania signed the UN Convention for biodiversity conservation making biodiversity conservation paramount. The Kihansi River ecosystem is important for both economic development and

ecological conservation. Nevertheless, the economic importance overrides the ecological importance. There is therefore integration of the ecological information in the development plans including land use is called for.

Hydrological alteration including river flow diversion for hydropower production, result of hydropower dam results to complex ecological effects. These effects can be linked with the natural flow regime paradigm (Poff et al., 1997) and flood pulse concept (Junk et al., 1989). The aspects of these concepts include magnitude, frequency, timing and rate of change in flow which are important to maintain downstream aquatic communities. Studies in other river systems have shown that preventing floods through hydropower dam represents ecological disturbance because the aspects of floods and natural flow regimes governs the chemical, physical (Lytle and Poff, 2004) and biological (Bunn and Arthington, 2002) aspects in downstream areas of rivers. Studies in Australia suggested an ecological flow of $1.8 \text{ m}^3 \text{ s}^{-1}$ to maintain aquatic ecosystem health (Bunn and Arthington, 2002).

In Kihansi River, despite the presence of ecological flow of $1.8 \text{ m}^3 \text{ s}^{-1}$ to maintain aquatic communities downstream of the dam, the magnitude and seasonal cycles of inundation and hence N and P export is alienated. The effects of altered flow regime as a result of hydropower dam can be linked to the paradigm of natural flow regime. The consequences of the latter can be associated extinction of the Kihansi Spray Toad, endemic to the Kihansi Gorge ecosystem which is located downstream of the hydropower dam.

The hydrological regime dynamics are important drivers of river ecosystems. Anthropogenic alteration of the hydrological regime can lead to strong and complex ecological impacts (Bunn and Arthington, 2002). In the Kihansi River, the evidence for altering river hydrology on nutrient export includes reduced N export and alienation of seasonal nutrient export. For example, changing nutrient amount and export alters cycles of N, which implies changes in nutrient stoichiometry directly affecting the primary producers. As primary producers form the base of food webs, alteration of N cycle downstream of the dam can affect food chain interaction in river sections.

A study by Hoeinghaus et al., (2008) indicated that rivers have shorter food chains interactions than reservoirs. Thus, anthropogenic alteration of flow regime can further shorten the food chain in the river downstream of the dam due to changes in nutrient supply. In the case of ecological flow left downstream of the Kihansi reservoir was established without considering specific needs of the downstream areas in terms of nutrients. This remains an open question for future research.

The Tanzanian water resources are governed by water policy (URT, 2002) and the Environmental Management Act (URT, 2004), which emphasize on protecting the environment and biodiversity, and the Water Resources Act (URT, 2009), which states the responsibility of River basin offices in water quality management. There are nine water basins in Tanzania, five of which are river basins. However, the water resources governance as stipulated in these legal frameworks is still too general.

Specific management objective and actions need to be established for nutrient management in the each river basin. For example, except for the Pangani and Wami-Ruvu River basins, other river basins have substantial amount of hydrological data with limited information about nutrients. For successful integrated water resources management in the river basin, application of scientific knowledge which integrates ecology and hydrology is crucial for management of riverine resources. It is therefore important to manage the sources of excess N input to the river the effects of an increase in nutrient concentration and export in rivers as the effects can take some time to be evident and costly to restore the natural conditions.

3.2. Conclusion

It is evident that anthropogenic activities including agricultural activities and hydropower dam operation altered nutrient concentration and export, and particularly that of N. In agricultural areas elevated inorganic N is linked to the use of fertiliser. Closely linked to agricultural intensification, N export from catchment areas is inevitable. Therefore taking into account the N limitation of this River ecosystem, the Kihansi reservoir is at the risk of eutrophication provided excess N is received from catchment areas. Currently, seasonal control of N is found to be controlled by groundwater infiltration and dilution effects during rainy season, which are then released to the rivers through groundwater recharge during dry season. The reservoir acts as a sink for N alienating the natural seasonal cycles of N and P in the river reach downstream of the dam.

3.3. Recommendations

Therefore long term monitoring of nutrient concentration and export is recommended for proper and timely management of the effects resulting from changes in nutrient concentration and export from catchment areas. Data from this study will serve as the baseline data for future studies.

Emphasis on the use of best agricultural management practices such as using proper amounts of inorganic fertilizers, stop slash and burn cultivation is recommended. A study on proper N requirement in the soil per unit areas in the Kihansi River catchment is crucial in order to reduce inorganic N export to rivers.

There is a need to establish the optimum nutrients in needs for the aquatic communities in downstream areas of dams before suggesting the amount ecological flow. Some communities are sensitive to changes not only in nutrient amount, but also to nutrient stoichiometry in foods webs.

Specific management objective and actions need to be established for nutrient management in the each river basin in order to understand the trends in ecosystem process and function. This will also reduce the costs for environmental impact assessments, in case of initiating development projects.

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4.0. PAPERS

4.1. Paper 1

Effect of an impoundment on nutrient dynamics in the Kihansi River, Tanzania

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Received 29 March 2008, accepted 15 April 2008

The impact of the Kihansi Dam on electrical conductivity, pH, temperature and dissolved oxygen in the Kihansi River was assessed in 2005 after 85% of the original river flow had been diverted to the Lower Kihansi power plant. The results are compared with the data obtained in 1995 before the dam was constructed. Primary production and nitrogen and phosphorus concentrations from sites upstream and downstream of the dam as well as in the reservoir were compared. Phosphorus fractions were determined in the reservoir's sediment. Electrical conductivity and pH values were higher in 2005 than in 1995, whereas oxygen concentrations were lower. Primary production, nitrogen and phosphorus concentrations were lower at stations downstream of the dam than at upstream stations. High fractions of iron- and manganese-bound phosphorus in the reservoir sediment suggest a potential for phosphorus retention. Concentrations of nitrogen and phosphorus along the Kihansi River were higher during the dry season than in the wet season. These results contribute to the documented baseline data on environmental changes in tropical river systems after flow diversion and reservoir development.

Keywords: environmental impacts, hydropower plants, nitrogen, phosphorus, reservoirs, sediments, tropical rivers

Introduction

Impoundments and hydropower plants impact adversely on rivers and their resultant reservoirs (Kiplagat *et al.* 1999, Mwaura *et al.* 2002, Gunkel *et al.* 2003, Mwaura 2006). The effects include the interruption and blocking of nutrient flows (Welcomme 1985) and the alteration of pH, electrical conductivity and dissolved oxygen levels (Kiplagat *et al.* 1999, Kemdirim 2005, Mwaura 2006). Phosphorus and nitrogen are key nutrients for primary production in aquatic ecosystems (Thomas *et al.* 2001, Doyle *et al.* 2003) and changes in the concentrations and forms of these nutrients can result in altered nutrient limitation patterns (Petr 1978, Hecky 1988, Smith *et al.* 1999, Havens *et al.* 2003) of rivers, reservoirs, lakes and even of coastal areas as shown in temperate rivers (Ittekkot *et al.* 2000). Excess nitrogen or phosphorus causes eutrophication in rivers (Smith *et al.* 1999) which affects the ecological functioning of ecosystems downstream of impoundments.

Increases in hydraulic residence times in reservoirs allows particles to settle and sediments play a critical part in controlling the loading of nutrients, particularly phosphorus, to the water column (Boström *et al.* 1988). Phosphorus concentrations in the sediment are often elevated and its release to the water column depends on the prevailing environmental conditions (Christophoridis and Fytianos 2006).

Quantification of phosphorus fractions in the sediment is important in elucidating the potential of sediment as a source or sink of phosphorus (Ding-Sie and Appan 1996).

The dam across the Kihansi River was closed in 2000. More than 85% of the original river discharge was diverted through an underground tunnel from the reservoir to the Kihansi hydropower plant, bypassing a 4 km stretch of the Kihansi Gorge (Figure 1). Obvious impacts on endemic species downstream at the Kihansi Gorge have since been observed. Many studies have been carried out on the impact of reduced water flow in the Kihansi Gorge, focusing on flora (Lovett *et al.* 1997, Quinn *et al.* 2005) and fauna, such as the Kihansi spray toad *Nectophrynoides asperginis* (Poynton *et al.* 1998, Krajick 2006), and bird assemblages (Cordeiro *et al.* 2006). Nitrogen and phosphorus in the Kihansi River have not been studied, despite their importance to downstream aquatic communities.

The objective of the present study was to examine the status of physico-chemical parameters and nutrients five years after construction of Kihansi Dam and to add to the body of literature on pre- and post-impoundment conditions in tropical African reservoirs. The effect of Kihansi Dam on physical and chemical water parameters was examined by measuring electrical conductivity, dissolved oxygen, pH,

and temperature for the purpose of comparison with pre-impoundment data from 1995. Spatial and temporal variations in nitrogen and phosphorus concentrations in the Kihansi River were explored by determining nitrogen and phosphorus concentrations at stations upstream and downstream of the dam and in the reservoir during both the rainy and dry seasons in 2005. To evaluate the biotic response of nitrogen and phosphorus in the reservoir, primary production and respiration were determined. To determine the potential of the reservoir as a source of phosphorus, its accumulation in the reservoir's sediment was measured.

Materials and methods

Study area

The study was conducted along the upper Kihansi River in the south-western highlands of Tanzania (Figure 1). Climate in the Kihansi catchment is influenced by the Indian Ocean monsoon, which in turn is influenced by the Inter-Tropical Convergence Zone. March and April are the wettest months, whereas August and September are the driest, although rain can fall in any month. Rainfall in the catchment ranges from 1 000–1 600 mm a⁻¹ (Lovett *et al.* 2004). Maximum monthly river discharge of 30.7 m³ s⁻¹ occurs typically in April, and minimum monthly discharge of 10.0 m³ s⁻¹ occurs in September/October.

Sample collection and in situ water quality measurement

A total of eleven sampling stations were located upstream, in the reservoir and its main tributaries, and downstream of

Kihansi Dam (Figure 1, Table 1). Sampling was conducted in 2005, during the rainy (February, April and May), and dry (June, August and September) seasons.

Three 1-litre water samples, collected 30 cm below the water surface in the middle of the river and at two sites in the reservoir, were filtered through glass fibre filters (Whatman GF/F approximately 0.7 µm) and stored in 100 ml polyethylene bottles pre-cleaned by soaking overnight in 10% H₂SO₄ and rinsed three times with distilled water. Total dissolved phosphorus (DP), soluble reactive phosphorus (SRP), nitrate-nitrogen (NO₃-N) and nitrite-nitrogen (NO₂-N) were determined according to standard methods (APHA 1998). Unfiltered water samples were stored in 100 ml polyethylene bottles for determination of total nitrogen (TN) and total phosphorus (TP). To each sample bottle, three drops of chloroform were added and shaken well to prevent bacterial and fungal transformation of nitrogen and phosphorus. Sediment samples were collected using a 5 cm diameter core inserted in a gravity corer, which was released from a boat to the bottom of the reservoir and pulled out with the sediment compacted in it. Approximately 20 g of sediment from the upper 5 cm of the core were put in plastic bags and stored at -20 °C before phosphorus analysis in the laboratory. A total of seven sediment samples were taken on each sampling date at sites located in the reservoir. All sediment and water samples were stored on ice in coolers in the field and transported to the laboratory for storage. In the laboratory, water samples were refrigerated at 4 °C prior to analysis. Sediment samples were analysed within 14 days after sampling.

Data for total monthly discharge (inflow and outflow) at the Kihansi Reservoir were obtained from Tanzania Electric Supply Company (TANESCO) and monthly rainfall data were obtained from the Lower Kihansi Environmental Management Project. Water quality data collected before construction of the dam were obtained from an unpublished report (NORPLAN 1995), there being no published data available. Data for pH, electrical conductivity and temperature obtained in 1995 were used for comparison with data obtained in this study, since measurements made in 1995 and 2005 used similar methods. Nitrogen and phosphorus species data were not used because no documented method was available.

Table 1: Description of sampling stations on the Kihansi River

Station	Area description
1	Main Kihansi River entering the reservoir
2	Stream entering reservoir
3	Stream entering reservoir
4	Stream entering reservoir
6	In reservoir
7	In reservoir
9	Kihansi River upstream of its confluence with the tailrace carrying discharge water from the hydropower plant
11	Udagaji River, a tributary of the Kihansi River
12	Kihansi River below confluence with water exiting the hydropower plant
13	Kihansi River downstream of confluence with water from powerplant tailrace
14	Mgungwe River, a tributary of the Kihansi River

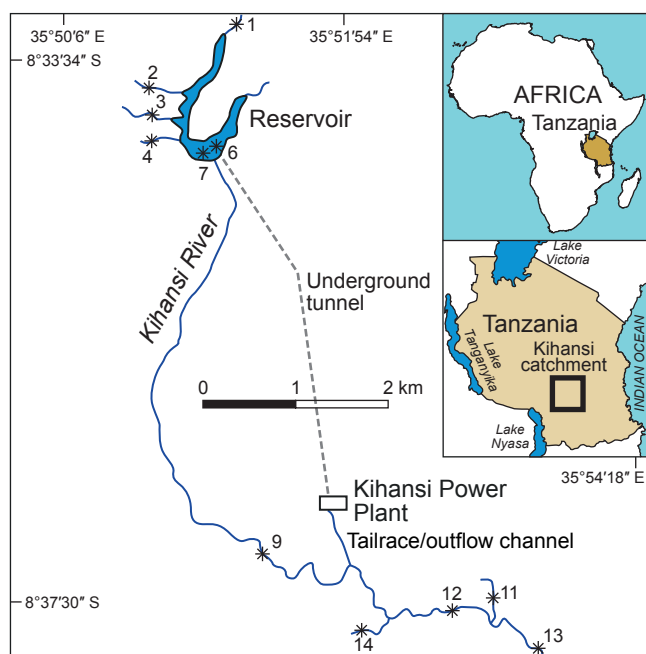


Figure 1: Location of the study area, Kihansi, Tanzania showing 11 sampling stations located upstream, downstream, and within, the Kihansi Reservoir as well as the water diversion associated with the Kihansi Hydropower Plant (see Table 1 for detailed descriptions of sampling stations)

Temperature, pH and electrical conductivity measurements were taken *in situ* using a multi-parameter probe (HORIBA U10, accuracy of ± 0.001 for pH, $\pm 0.1^\circ\text{C}$ for temperature and $\pm 0.001\ \mu\text{S cm}^{-1}$ for electrical conductivity). Dissolved oxygen was measured using a probe (HACH HQ 10 portable LDO, accuracy ± 0.1 at $< 8\ \text{mg l}^{-1}$, ± 0.2 at $> 8\ \text{mg l}^{-1}$ and sensitivity of $\pm 0.05\%$). Primary production and plankton respiration measurements were determined using light and dark bottle methods, respectively (APHA 1998). Oxygen bottles of 250 ml were used and incubated in the water column for two hours before fixation.

Sample analysis

Nutrients were determined spectrophotometrically using a SHIMADZU UV-1601 UV Visible Spectrophotometer (accuracy ± 0.5 Abs and sensitivity of ± 0.0002 Abs at $0.5\ \text{nm}$) with a $10\ \text{cm}$ cell. Concentrations of SRP in the water samples were determined using the tartrate and ascorbic acid method and concentrations of dissolved phosphorus, total phosphorus and total nitrogen were determined by the persulphate autoclave digestion method. Nitrate and nitrite nitrogen concentrations were determined by the sulphanilamide method (in the case of nitrate, after reduction with cadmium to nitrite). Phosphorus fractions in the sediment were determined by hydrolysing to soluble reactive phosphorus according to the method of Murphy and Riley (1962) and differentiating the following fractions: organic-P, soluble-P, Mn- and Fe-bound P and Ca- and Mg-bound P. In each $100\ \text{ml}$ of solvent, $3\ \text{g}$ of sediment sample was dissolved as follows: in H_2O for soluble phosphorus (SP); in HCl for organic phosphorus (OP) and total inorganic-phosphorus (IP); in NaOH for calcium- and magnesium-bound phosphorus (Ca- and Mg-bound P); and in $\text{Na}_2\text{S}_2\text{O}_3$ for iron- and manganese-bound phosphorus (Fe- and Mn-bound P). The same procedure was repeated for all sediment samples. Afterwards, all solutions made from the sediment were shaken for 16 hours for hydrolysis. The samples were

subsequently centrifuged and the supernatant liquid was analysed spectrophotometrically (Ruban *et al.* 2001) for SRP using the molybdate method (APHA 1998). Winkler's method was used for measuring oxygen in light and dark bottles, from which primary production and respiration, respectively, were determined using the method of Wetzel and Likens (1991).

Statistical analysis

The SPSS 12.0 statistical software package (SPSS Inc. 2003) was used for analysis of data. Analysis of Variance was used for comparison of variation in environmental variables between sampling stations and between seasons. Data were grouped for rainy season (February, April and May) and dry season (June, August and September). Analysis of Variance (ANOVA) at the 95% confidence level was performed for nutrient concentrations associated with season.

Results

Hydrology and changes in physico-chemical parameters at sites before and after dam construction

The mean and standard deviation of discharge and rainfall in the Kihansi River are presented in Table 2. Mean monthly discharge was lowest ($8.69 \pm 0.33\ \text{m}^3\ \text{s}^{-1}$) at the end of the dry season (September) and highest ($18.59 \pm 8.84\ \text{m}^3\ \text{s}^{-1}$) during the middle of the rainy season (April). Discharge in the Kihansi River downstream of the dam was approximately 15% of the inflow to the reservoir (Table 2) with approximately 85% of the discharge being diverted to the Lower Kihansi hydropower plant. River flows immediately downstream of the dam had low variability with a mean of $1.83 \pm 0.09\ \text{m}^3\ \text{s}^{-1}$ during the dry season and $1.95 \pm 0.04\ \text{m}^3\ \text{s}^{-1}$ during the wet season. The reduced flow led to a decrease in the variability of flow between the rainy and dry season in the $4\ \text{km}$ stretch of the river downstream of the dam before its confluence with the water exiting from the power plant (see Figure 1 for sample site localities). The 85% decrease in river flow

Table 2: Monthly discharges (mean and SD), and rainfall measured in the Kihansi Gorge (source: TANESCO Head Office, Dar es Salaam)

Date	Mean discharge ($\text{m}^3\ \text{s}^{-1}$) $\pm$ SD			Monthly rainfall (mm)
	Kihansi River inflow to reservoir	Diverted for hydroelectric power	Kihansi River outflow from reservoir	
February	13.19 ± 2.24	11.29 ± 2.47	1.92 ± 0.04	236.7
April	18.59 ± 8.84	15.39 ± 5.52	1.94 ± 0.05	376.3
May	15.93 ± 2.28	14.03 ± 2.25	1.95 ± 0.04	170.3
June	12.93 ± 0.98	11.15 ± 1.74	1.91 ± 0.03	14.5
August	9.81 ± 0.44	8.22 ± 1.78	1.88 ± 0.05	9.0
September	8.69 ± 0.33	6.79 ± 1.30	1.83 ± 0.09	19.5

Table 3: Values of physico-chemical parameters measured in the Kihansi River upstream of the dam site during 1995 (NORPLAN 1995, unpublished environmental impact assessment) and during 2005 ($n = 12$)

Date		pH	Electrical conductivity ($\mu\text{S cm}^{-1}$)	Temperature ($^\circ\text{C}$)	DO (mg l^{-1})
1995	River before dam construction	5.4–7.1	5.0–16.0	15.2–20.8	7.7–10.8
2005	River after dam construction	6.6–7.86	18.0–22.0	15.7–20.0	4.13–10.17
2005	Reservoir	6.76–8.64	18.0–23.0	18.0–25.0	4.47–8.70
2005	River downstream	7.0–8.0	15.5–28.0	19.2–24.3	4.61–9.30

Table 4: Nutrient concentrations (mean and SD) at sampling stations in the Kihansi River upstream of the reservoir, in the reservoir, and downstream of the reservoir ($n = 6$)

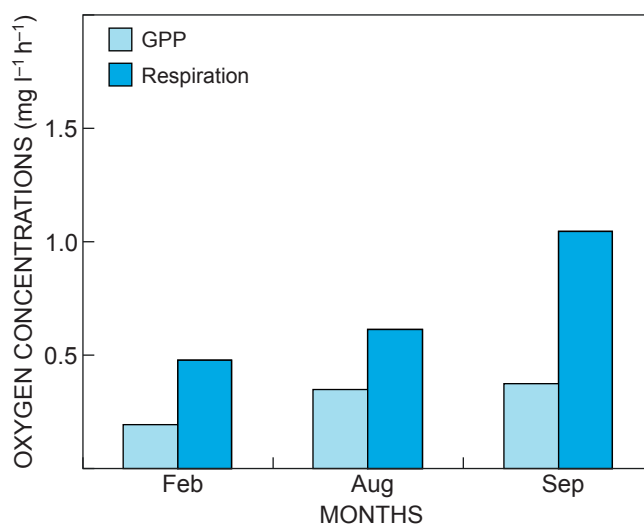
Station	NO ₃ -N ($\mu\text{g l}^{-1}$)	NO ₂ -N ($\mu\text{g l}^{-1}$)	TN ($\mu\text{g l}^{-1}$)	SRP ($\mu\text{g l}^{-1}$)	TP ($\mu\text{g l}^{-1}$)	DP ($\mu\text{g l}^{-1}$)
Upstream of reservoir						
1	19.05 $\pm$ 21.0	4.80 $\pm$ 5.0	34.38 $\pm$ 23.5	11.01 $\pm$ 2.8	44.95 $\pm$ 28.0	23.88 $\pm$ 2.4
In reservoir						
6	7.84 $\pm$ 7.6	7.27 $\pm$ 8.3	31.10 $\pm$ 24.9	13.16 $\pm$ 4.9	49.23 $\pm$ 38.9	27.55 $\pm$ 9.1
7	13.16 $\pm$ 14.2	5.51 $\pm$ 5.1	29.48 $\pm$ 20.4	11.59 $\pm$ 1.6	49.29 $\pm$ 32.6	27.12 $\pm$ 7.6
Downstream of reservoir						
9	10.66 $\pm$ 17.2	5.86 $\pm$ 5.9	38.02 $\pm$ 22.8	11.14 $\pm$ 2.0	46.00 $\pm$ 26.8	25.62 $\pm$ 2.9
12	9.90 $\pm$ 11.9	5.06 $\pm$ 5.5	40.00 $\pm$ 21.5	11.83 $\pm$ 1.8	49.03 $\pm$ 32.6	27.24 $\pm$ 5.0
13	11.36 $\pm$ 14.4	5.22 $\pm$ 5.5	36.86 $\pm$ 22.5	11.45 $\pm$ 1.6	48.05 $\pm$ 30.4	26.80 $\pm$ 5.0

downstream of the dam led to increased pH, electrical conductivity and temperature (Table 3). Electrical conductivity increased by 37.5%, whereas pH values increased by 9.85% to become slightly alkaline. Within the Kihansi River system the highest pH values were found in the reservoir (Station 7: mean = 7.64 ± 0.69) and the lowest mean value was in the Kihansi River upstream of the reservoir (Station 1: mean = 7.18 ± 0.51). The highest electrical conductivity values (mean = $25.03 \pm 4.98 \mu\text{S cm}^{-1}$) were measured at Station 12 (below the confluence with power plant outflows). The lowest electrical conductivity values (mean = $19.45 \pm 1.50 \mu\text{S cm}^{-1}$) were measured at Station 1. The highest water temperature values were measured at Station 9 (mean $22.23 \pm 1.88^\circ\text{C}$) while the lowest values were measured at Station 1 (mean $18.05 \pm 1.61^\circ\text{C}$). The highest dissolved oxygen values were measured at Station 1 (mean $8.32 \pm 2.13 \text{ mg l}^{-1}$) and the lowest values were measured at Station 6 in the reservoir (mean $7.32 \pm 1.42 \text{ mg l}^{-1}$).

Spatial and seasonal variations in nutrient concentrations and biotic responses in the Kihansi River

The concentrations of the different phosphorus and nitrogen species upstream and downstream of the reservoir are presented in Table 4. High concentrations of nitrogen species were found in samples from Station 1, upstream of the reservoir, compared to that at sites located immediately downstream of the reservoir. Higher concentrations of nitrate were found at Station 1 than at Stations 6 and 7 in the reservoir (Table 4). Sampling sites located downstream of the dam showed a continued decrease in nitrate concentrations, with the lowest concentrations being found at Station 9, before increasing again further downstream at Station 13. The same trend was observed for total nitrogen. The concentrations of soluble reactive phosphorus, dissolved phosphorus, total phosphorus and nitrite were found to be higher in the reservoir than at any of the river sites (Table 4). However, analysis of variance showed no significant difference in nutrient concentration among the sampling stations ($p > 0.05$).

Respiration and primary production measurements indicated low productivity and the heterotrophic state of this ecosystem. Respiration and gross primary production were high in September and low in February (Figure 2).

**Figure 2:** Respiration and gross primary production in the Kihansi River. $n = 23$ measurements, obtained from sampling stations 6, 7, 9, 11, 12, 13 and 14

Concentrations of nitrate nitrogen were lowest during the middle of the rainy and dry seasons and more variable during transition periods between the seasons. However, nitrate nitrogen concentrations of less than $0.1 \mu\text{g l}^{-1}$ were observed at the peak of the rainy season. On the other hand, nitrite nitrogen concentrations were found to be high during the dry season. Total nitrogen concentrations were observed to be high during rainy seasons (Figure 3). Highest total phosphorus concentrations were obtained during the dry season (Figure 4). The observation that nitrate and total nitrogen concentrations were higher at Station 1 and were low downstream of the dam (Station 9) suggests that the Kihansi Reservoir is a nutrient retention site. Nitrate concentrations continued to decrease at Stations 9 and 12, before increasing at Station 13. In contrast to the nitrate concentrations, total nitrogen concentrations continued to increase at Stations 9 and 12 before decreasing again at Station 13, below the confluence with the power plant outflows.

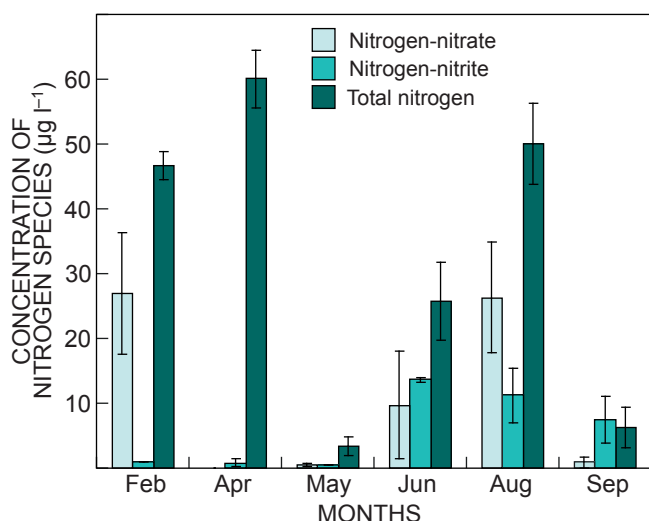


Figure 3: Nitrate, nitrite and total nitrogen concentrations (mean and SD) in different months in the Kihansi River (sampling stations 1, 2, 3, 4, 6, 7, 9, 11, 12, 13 and 14; $n = 6$)

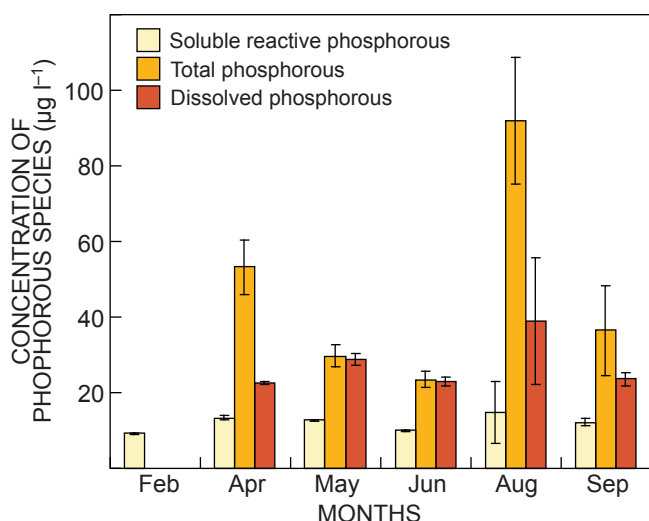


Figure 4: Soluble reactive phosphorus, total dissolved phosphorus and total phosphorus concentrations (mean and SD) in different months in the Kihansi River (sampling stations 6 and 7; $n = 6$)

Sediment phosphorus concentrations

High concentrations of iron, manganese-bound phosphorus and organic phosphorus varied between rainy and dry seasons. Greater variation was observed in the dry season. Soluble phosphorus, as well as calcium- and magnesium-bound phosphorus, showed less variation and both fractions were approximately of equal concentration throughout the study (Figure 5).

Discussion

Status before dam construction and after five years of dam operation

The observed higher values of electrical conductivity after

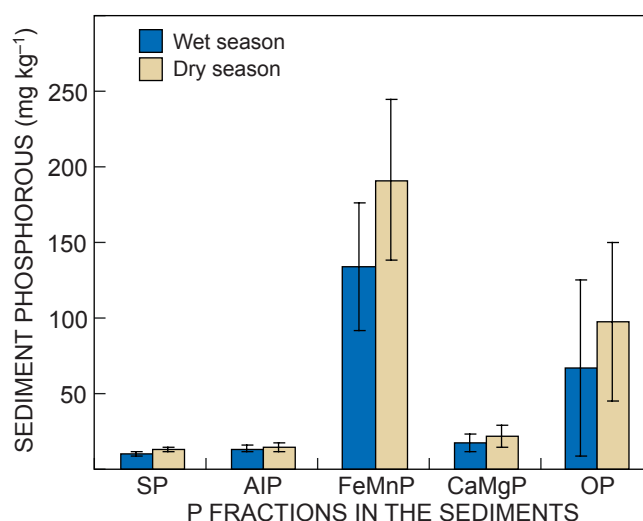


Figure 5: Seasonal variations in sediment phosphorus species (mean and SD) in the Kihansi Reservoir ($n = 6$) (SP = soluble phosphorus; AIP = aluminium-bound phosphorus; FeMnP = iron- and manganese-bound phosphorus; CaMgP = Ca- and Mg-bound phosphorus; OP = organic phosphorus)

dam construction compared to before dam construction is one of the effects of the impoundment. The increased hydraulic retention time resulted in some degree of evaporative concentration, resulting in elevated electrical conductivity values. This can also explain the slightly elevated pH values, which show that the Kihansi river system has low buffering capacity.

Higher values of these parameters were observed in the reservoir. Compared to other African reservoirs (Kiplagat *et al.* 1999, Kemdirim 2005) the Kihansi Reservoir has low electrical conductivity values. A decrease in dissolved oxygen content was also observed in the reservoir and downstream of the dam. Decomposition of organic matter together with the observed higher respiration contributed to the observed lower dissolved oxygen concentrations in the reservoir. Low concentrations of nitrogen and phosphorus in the reservoir compared to those in the inflowing river, indicate nutrient retention. Thus the Kihansi Reservoir is a sink for both nitrogen and phosphorus. In parallel with the amount of water diverted for power production, the availability of nitrogen and phosphorus decreased by 85% in the river reaches downstream of the dam.

Spatial and seasonal impacts on nutrient concentration and their biotic response in the Kihansi River

The Kihansi River and reservoir have low nitrate and phosphate concentrations compared to other African streams and reservoirs. Mokaya *et al.* (2004) found phosphate concentrations of up to 0.3 mg l^{-1} and nitrate concentrations of up to 0.38 mg l^{-1} in the Njoro River in Kenya. Devi *et al.* (2008) recorded 952 mg l^{-1} of phosphate and $0.165952 \text{ mg l}^{-1}$ of nitrate in Gilbe Dam, Ethiopia. Kemdirim (2005) recorded phosphate values of $0.02\text{--}3.0 \text{ µg l}^{-1}$ and nitrate concentrations ranging between 0.03 and $1.98 \text{ ppm (mg l}^{-1})$ in Kangimi Reservoir, Nigeria.

Kiplagat *et al.* (1999) found phosphate concentrations of 5.3 to 8.9 $\mu\text{g l}^{-1}$ and nitrate concentrations ranging between 16.0 $\mu\text{g l}^{-1}$ and 57.8 $\mu\text{g l}^{-1}$ in Turkwel Reservoir, Kenya.

The calculated N:P ($\text{NH}_4^+ + \text{NO}_3^- + \text{NO}_2^-$:SRP) mean ratio of 3:1 by weight in the water of the Kihansi River indicates nitrogen limitation (Hecky 1988, Smith *et al.* 1999). This suggests that there is potential for noxious nitrogen-fixing cyanobacteria to proliferate (Havens *et al.* 2003). Munn and Meyer (1990) showed that nitrate retention is highest in streams with a low nitrogen to phosphorus ratio. Mulholland *et al.* (2008) indicated that streams and rivers can be important sinks for bioavailable nitrogen due to their higher rates of biological activity. In contrast, higher phytoplankton respiration in the Kihansi River indicates that biological activity other than primary production is responsible for nitrogen retention. Mulholland *et al.* (2008) also suggest that, at moderate nitrogen loading, larger streams respond to nitrogen removal and hence limit nitrogen export to downstream ecosystems.

Further downstream of the dam there is a decrease in the mean concentrations of nitrate at Stations 9 and 12. This is attributed to uptake by microorganisms and abundant macrophytes that are found on the river banks from Station 9. Retention in the stream or river can be the result of hydrological processes, as detailed by Thomas *et al.* (2001), and biological processes such as respiration and primary production, as well as chemical processes (Valett *et al.* 1997). However, further downstream, below the confluence with power plant outflows (Station 13), all nitrogen and phosphorus concentrations are elevated. This indicates that there might be a recovery of both nutrients due to inputs from the tributaries (Stations 11 and 14). It can also be argued that reduced river flow rates, as the river starts meandering, allows time for the processing of organic matter. This argument supports the model suggested by Mulholland *et al.* (2008) that high nitrogen loading in all sizes of streams exports virtually all catchment-derived nitrogen.

Seasonally, increasing retention time in the dry season resulted in higher concentrations of both nitrogen and phosphorus (Figures 4 and 5 respectively). In the American tropics Lewis *et al.* (1999) found that the concentrations of all N species increased with decreasing water supplies from the catchment. During the rainy season, increased flow and runoff in the Kihansi River led to an increase in the loading of allochthonous materials exported from the catchment. This is evidenced by increased concentrations of total nitrogen and phosphorus during the peak of the rainy season. This has also been found in other studies (Kiplagat *et al.* 1999). As observed in other tropical rivers, elevated amounts of material are transported during high flows (Brodie and Mitchell 2005). Similar to the reservoirs, are the tropical floodplain lakes, which retain nutrients during periods of low water but release nutrients during the rainy season (Furch and Junk 1993). In the Kihansi River the lowest mean river flow of 1.9 $\text{m}^3 \text{s}^{-1}$ downstream of the dam is lower than the natural minimum flow (mean 8.69 $\text{m}^3 \text{s}^{-1}$) during the dry season. In parallel to this decrease in flow is the decrease in nutrient supply and availability to the aquatic communities previously adapted to seasonal inundation.

In the Australian tropics Downing *et al.* (1999) suggest that the pre-impoundment nitrogen concentrations have

been controlled by surface water runoff patterns. Post impoundment nitrogen concentrations in the Kihansi River are high at the peak of the rainy season (April). This suggests that, seasonally, nitrogen concentrations are controlled by surface water runoff. Agricultural activity in the Kihansi catchment, which coincides with the rainy season, contributes to elevated concentrations of total nitrogen and phosphorus. Burning of fields before cultivation also contributes to the elevated total nitrogen and total phosphorus in the Kihansi River during the rainy season.

Role of sediment in phosphorus dynamics in the reservoir

Trivalent iron and manganese ions (Fe^{3+} and Mn^{3+}) form complex compounds with $(\text{PO}_4)^{3-}$ under oxic conditions, decreasing phosphorus in the water column (Ding-Sie and Appan 1996, Christophoridis and Fytianos 2006). High concentrations of iron- and manganese-bound phosphorus in the sediment of the Kihansi Reservoir suggest immobilisation of inorganic phosphorus. A high percentage of iron- and aluminium-bound phosphorus was observed in sediments of Kranji Reservoir, Singapore (Ding-Sie and Appan 1996), indicating dominance of iron in binding to inorganic phosphorus. Phosphorus concentration in the sediment is highly dependent on organic matter accumulation (Jorcin and Nogueira 2005). Rivers and their small tributaries are the source of allochthonous organic materials (Cummings *et al.* 1989) that decompose to fine particulate matter, releasing inorganic phosphorus (Christophoridis and Fytianos 2006). Decomposition of organic matter in the Kihansi Reservoir is demonstrated by the elevated soluble reactive phosphorus and decreased oxygen concentrations in the water column. There were higher concentrations of iron- and manganese-bound phosphorus in the sediment in the dry season than in the rainy season. Low flow during the dry season is associated with minimum sediment disturbance, which allowed more phosphorus to be immobilised.

Conclusion

The construction of Kihansi Dam resulted in changes in the water quality of the Kihansi River (monitored five years after its construction). The Kihansi Reservoir is considered a sink for both nitrogen and phosphorus, thus interrupting the flow of these nutrients to downstream river reaches. Despite elevated nitrogen and phosphorus concentrations in the reservoir, primary production there remains low. Reservoir sediment does not contribute to the elevated phosphorus concentrations, on account of the prevailing oxic conditions. The low N:P ratio indicates that nitrogen is a limiting nutrient. Further studies on nutrient limitation are recommended to investigate whether nitrogen — alone or in combination with another nutrient besides phosphorus — limits primary production in the Kihansi River system. Seasonally, nitrogen and phosphorus concentrations are high during the dry season and thus are a function of river flow. Nitrogen concentrations are controlled by surface water runoff, with higher concentrations observed during the peaks of the rainy and dry seasons.

Acknowledgements — The Lower Kihansi Environmental Management Project is especially thanked for funding this research and supporting the thesis of the senior author. Two anonymous reviewers are thanked for comments that helped to improve this manuscript, which is partly a fulfilment of the PhD requirements. We gratefully acknowledge assistance, during fieldwork in Tanzania, by S Mukama and R Ngunda.

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4.2. Paper 2

Compound effects of land use activities and a hydropower dam on the nutrient status of the tropical Kihansi River system.

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Abstract

Human pressure poses environmental challenges to tropical rivers. This study investigated the influence of agriculture and hydropower production on nutrient concentration and export in a tropical river system. Specifically, the study aimed at understanding how different dominant land use types, seasons and a reservoir affect nitrogen (N) and phosphorus (P) concentration and export. Water samples for analysis of various forms of N and P were collected in tributaries of the Kihansi River draining forested, scattered cultivation, semi-intensive cultivation, and intensive cultivation areas during dry and rainy seasons; as well as in the River Kihansi entering inflowing to the reservoir and downstream of the Lower Kihansi Hydropower (LKHP) dam.

High concentration and export of total inorganic N and P was observed in forested area, while elevated dissolved inorganic N was observed in agricultural areas ($p < 0.05$). In agricultural areas, $\text{NO}_3\text{-N}$ contributed about 70 % of the total dissolved inorganic N export of the total export compared to 43 % in forested area. The observation was attributed to application of fertilizers, especially in intensive cultivation areas. Except for TN, the dilution effect resulted in reduced nutrient concentration during rainy season. The TN export was related to soil activation associated with slush and burn agricultural practice. Thus, vegetation cover and use of best agricultural management practices is important in order to control dissolved inorganic N in rivers. Regarding the effect of the hydropower dam, the reservoir is a sink of N, but a source of P. However, elevated $\text{NH}_4\text{-N}$ and reduced DO concentration downstream of the dam suggest that organic matter degradation gets an increased importance in the reservoir.

Key words: agriculture, nitrogen, phosphorus, export, tropical River, reservoir.

Introduction

Land use change in river catchment including forest, agriculture and dam construction for hydropower production (Howarth et al. 1996, Welcome et al.

1995 & Lewis et al. 1999) can affect nutrient cycling in river systems (Gücker et al. 2008, Tamatamah et al. 2006, Faithful and Finlayson 2005, Meybeck 1982). As a consequence, these changes affect ecosystem productivity, aquatic food webs and ecosystems health (Friedl and Wüest 2002) in general.

Forested catchment with less human activities, for example, are known to export little amounts of dissolved inorganic forms of N and P (Austin et al. 2006, Boyer et al. 2002, and Graham 2001) and particulate and organic forms of these nutrients become more important (Lewis et al. 1999). Agricultural activities in the catchment areas contribute to elevated nutrient exports in rivers (Verstraeten and Prosser 2008, Howarth et al. 2006, Brodie and Mitchell 2005, Vanni et al. 2001, Carpenter et al. 1998, Howarth et al. 1996) and consequently to receiving water bodies (Downing et al. 1999) including reservoirs.

In addition, hydropower dam construction in river catchments and the resultant reservoir prevents nutrient from flowing to downstream areas. The nitrogen (N) and phosphorus (P) are key nutrient for aquatic primary productivity and their concentrations and export can be used as indicators of land use change. In aquatic ecosystems the N: P ratio for primary productivity is 16:1. Thus rivers play a role in the transport of these nutrients along the river continuum to the receiving water bodies, dams they can lead to changes in the nutrient stoichiometry (Harven et al. 2003, Vanni et al. 2010).

In Tanzania, 75% of the country population depend on agriculture as their main economic activity (URT 2006). Likewise, hydro electric power contributes to 60% of the country power supply. Together agriculture and hydropower production poses challenges to the River Kihansi ecosystem, located on the western block of the Udzungwa Mountains, a part of Eastern Arc Mountain range. While agricultural land use is thought to increase nutrients export in the river, the hydropower dam is thought to retain nutrients from flowing to downstream areas. In River Kihansi, the effects of the Lower Kihansi hydropower (LKHP) dam are recognized through loss of downstream biodiversity as evidenced by extinction of the endemic Kihansi Spray Toad (Poynton et al. 1998).

Under similar geological conditions, elevation and geomorphology, anthropogenic activities can play a decisive role in changing nutrient concentration and export into rivers and receiving water bodies. In addition, changes in hydrology can pronounce the anthropogenic effects of land use on nutrient concentration and export.

The goal of this study is to understand the influence of land use in tropical soft water highland rivers. Three questions are answered in this study; the first is the extent to which agriculture contributes to elevated nutrient concentration and export in river systems. It is expected that elevated nutrient concentrations and export to be higher in agricultural than in forested area. The second question is how the change in hydrological conditions affects nutrient concentration and export in catchments with different land use while

the third question is how the reservoir influences nutrient export to areas downstream of the dam.

To answer these questions, the concentration and export of N and P was determined in forested and agricultural areas. The N and P export within agricultural areas were categorised according to the areal coverage and agricultural intensification including use of agrochemicals. Therefore, three agricultural land use categories including scattered cultivation, semi-intensive cultivation and intensive cultivation were studied. The effect of hydrology was established by determining the N and P concentrations and export during dry and rainy seasons. The export of N and P was determined upstream and downstream of the reservoir to evaluate the influence of a hydropower dam on downstream nutrient export.

MATERIALS AND METHODS

Study Area

Kihansi River catchment is located on the western part of Udzungwa Mountain block, a part of Eastern Arc Mountains between 35°44'22"E and 35°57'45"E and latitudes 8°13'08"S and 8°33'12"S. The catchment covers an area of approximately 582.5 km² upstream of the hydropower dam. The geology of the catchment is similar mostly to precambrian rocks overlain by deep weathered rocks formed during the Quaternary and Neogene periods (Lovett 1990 and Lovett et al. 2004). The rocks are made of red clay soils of dark or humic top soils. Elevation in the catchment is categorized into four main elevation units including highlands (> 1700 m.a.s.l), hills (1400 – 1700 m.a.s.l), low hills (500 – 1400 m.a.s.l) and low land (< 500 m.a.s.l). The slope of the catchment is categorized as flat to gentle slope (0 – 7%), gentle to moderate slope (8-13%) and moderately steep to very steep slope (>14%).

The total population in the upper Kihansi River catchment was 35,177 people (NBS, 2002). The land uses include forest, bush and grassland, complex of bushes, grassland and agriculture. Agriculture is the major economic activity of the people of Kihansi River catchment. About 85% of the population in Kihansi catchment are involved in crop production. However, agriculture accounts for about 48% only of the land use whereas about 52% of the catchment is dominated by natural to semi-natural vegetation. The major crops produced include maize, beans, vegetables, tea, coffee and pyrethrum. The River Kihansi has five major tributaries, namely Muhu, Mkalasi Mnyazungwa and Lower Ruaha. These tributaries join the River Kihansi before the dam. Mhalala River joins the Kihansi River at the lower part of the Kihansi Gorge. For this study (Figure 1), sampling stations included Station SC (River Kihansi upstream draining scattered cultivation area), Station IC (River Muhu draining intensive cultivation area), Station SIC (River Mkalasi draining semi intensive cultivation area) Station F (River Ruaha draining forested area), Station KBD (Kihansi River after collecting water from major tributaries and before it enters the reservoir) and Station HP (River Kihansi downstream of the LKHP dam before falling into the Gorge).

The major land uses compared were natural forest, natural bush/grassland and agriculture. The agricultural areas were mixed with natural vegetation, and the agricultural areas were classified according to the area share. The Kihansi River (Station 1) which is covered dominantly by grass and bush land, has < 25 % of the area used for agriculture and was classified as scattered cultivation agricultural land use (SC). The Muhu River (Station 2), which is covered by grassland, has > 75 % of the land used for agriculture and was classified as intensive cultivation agricultural land use (IC). The Mkalasi River (Station 3) which is covered by grass and bush land, has about halve of the land used for agriculture and was classified as semi intensive cultivation agricultural land use (SIC). The Ruaha River (Station 4) was classified as forest land use (F). The Kihansi River inflowing to the reservoir was named KBD (Station 5) and Kihansi downstream the dam (Station 6) was classified impacted by hydropower dam (HP). Other physiographic characteristics of all the stations are shown in Table I.

Sample collection

All samples were collected once a month during dry (August, October and November of 2006) and rainy (December, January and February of 2007) seasons. In situ measurements for temperature, pH and electrical conductivity (EC) were taken using a multi-parameter probe (HORIBA water quality checker U10). Dissolved oxygen was determined using a HACH-Lange probe (HQ 10 Hach portable LDO).

Water samples were collected for dissolved and particulate forms of N and P concentration once a month. Water samples, collected 30 cm below the water surface in the middle of the rivers and in the reservoir. Water sample for determination of soluble reactive phosphorus (SRP), nitrate-nitrogen ($\text{NO}_3\text{-N}$), nitrite-nitrogen ($\text{NO}_2\text{-N}$) and ammonium – nitrogen ($\text{NH}_4\text{-N}$) were filtered through glass fibre filters (Whatman GF/F approximately 0.7 μm). Unfiltered water sample from each station was collected for determination of total inorganic nitrogen (TN) and total phosphorus (TP). All samples were stored in 100 ml polyethylene bottles pre-cleaned by soaking overnight in 10% H_2SO_4 and rinsed three times with distilled water.

In the laboratory, SRP was determined using the sodium tartarate–ascorbic acid method. Concentration of $\text{NO}_3\text{-N}$ (which is the total $\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$) was determined using cadmium reduction technique, where as $\text{NO}_2\text{-N}$ was determined in unreduced sample. Ammonium was determined using the indo phenol technique. Light absorbance (λ) of the water sample was measured using a spectrophotometer (APHA, 1998). A standard curve was established for SRP, $\text{NO}_2\text{-N}$ and $\text{NH}_4\text{-N}$ concentration to obtain a slope. The concentration of $\text{NO}_3\text{-N}$ was taken as the difference between $\text{NO}_3\text{-N}$ ($\text{NO}_3\text{-N} + \text{NO}_2\text{-N}$) and $\text{NO}_2\text{-N}$ concentration. The slope and the wavelength were used to calculate nutrient concentration of each sample. The concentrations of TN and TP were obtained by the persulfate oxidation method (APHA, 1998). The concentration of TN was determined as $\text{NO}_2\text{-N}$ after reduction using the cadmium reduction column method where as the concentration of TP was determined as orthophosphate.

The measured nutrient concentration in each station for the duration of the study was used as the basis for N and P export calculation applying the following formula: $e = c \times q / A$

where e = export of a particular nutrient form (monthly sample), c = nutrient concentration $\mu\text{g l}^{-1}$, q = average daily discharge of each month of the study ($\text{m}^3 \text{s}^{-1}$), and A = area of the catchment (ha). Nutrient export from each station was standardized by dividing with the total area of the catchment. Seasonal nutrient export was calculated using individual nutrient concentrations in each season by using the same formula.

Statistical Analysis

Statistical data analysis was done using SPSS 16.0. Datasets were not normally distributed and were thus log transformed. While the multivariate analysis of variance (ANOVA) at 95% confidence level followed by a detailed post hoc test was performed to assess variation in the concentration and export of N and P nutrient forms among the land use types, univariate analysis of variance tested the variation in nutrient concentration and exports between the seasons. Linear regression analysis was performed to test the variation of nitrogen export among the land use types.

RESULTS

Hydrology

Discharge is one of the key factors in nutrient export from catchment areas to receiving water bodies. Variation in discharge was observed among the studied catchments. In general, the highest mean discharge was observed in the river draining the forested subcatchment. The mean discharges for the other study areas are presented in Table II. The lowest mean discharge was recorded downstream of the LKHP dam (Station HP). There was no significant difference in discharge between the agricultural areas. Higher discharge in all stations was observed during rainy season. The ANOVA showed a significant difference in the mean discharge between the station F and station SIC ($p = 0.009$) and between F and SC ($p = 0.016$).

Physicochemical parameters

Electrical conductivity ranged from 11 – 45 $\mu\text{S cm}^{-1}$ with the average of 25.96 ± 2.11 . In general agricultural areas, stations SC and IC had higher and similar electrical conductivity compared to station SIC (Table III). Water temperature ranged from 18.1 – 24 °C. While high temperature was observed at station HP, lowest temperature was found at station SC.

The mean DO concentration in the catchment ranged from 6.8 – 9.5 mg l^{-1} . The highest and lowest DO concentration was recorded in stations F and SC, respectively (Table III). The water pH values did not vary among the land use types. A weak negative correlation was found between electrical conductivity

and discharge. However, there was no other significant relationship among other parameters.

The concentration and export of N and P in catchments with different land use

N and P concentrations

No particular trend in the concentration of TN among the land use types was observed despite the observed higher TN concentrations in the forested area (Station F) than in the agricultural areas (SC, SIC and IC) as shown in Figure 2(a). Contrary to this observation, a higher mean concentration of $\text{NO}_3\text{-N}$ was observed in the agricultural areas than in the forested area. However, among the agricultural dominated subcatchments there was an increasing trend in the concentration of $\text{NO}_3\text{-N}$ agricultural intensity increase (Figure 2(a)). The highest mean concentration ($196 \pm 86 \mu\text{g l}^{-1}$) of $\text{NO}_3\text{-N}$ was observed in the catchment with intensive cultivation. There was a significant difference in the mean concentration of $\text{NO}_3\text{-N}$ between F and IC ($p=0.023$). The concentration of $\text{NO}_3\text{-N}$ was the highest of the dissolved inorganic N ($\text{NH}_4\text{-N}$ and $\text{NO}_2\text{-N}$). The lowest mean concentration of all N forms studied was that of $\text{NO}_2\text{-N}$ which ranged from $21 \pm 9 - 25 \pm 14 \mu\text{g l}^{-1}$. There was no significant difference in the concentration of both $\text{NO}_2\text{-N}$ and $\text{NH}_4\text{-N}$ among the land use types ($P > 0.05$).

The TP concentration increased slightly in semi intensive ad intensive cultivation areas compared to forested and scattered cultivation areas. However, there was no significant variation in both SRP and TP concentration among the land use types (Figure (2b)). According to the Redfield's N: P weight ratio of 1:7, the Kihansi catchment has a higher concentration of P than the concentration that of N. The analysis of variance showed no significant difference in the concentration of both SRP and TP among the land use types ($p>0.05$).

In agricultural areas the mean $\text{NO}_3\text{-N}$ export ranged from 0.20 to $1.65 \text{ kg ha}^{-1} \text{ yr}^{-1}$ where as in the forested area it ranged from 0.02 to $0.97 \text{ kg ha}^{-1} \text{ yr}^{-1}$. The mean export of $\text{NH}_4\text{-N}$ export ranged from 0.04 to $0.81 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and 0.16 to $0.67 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in the agricultural and the forested areas, respectively. For SRP, the export ranged from 0.15 to $0.31 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and 0.02 to $0.27 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in the forested and in agricultural areas, respectively. For the total N form, the mean export of TN ranged from 1.85 to $6.57 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and 0.08 to $4.08 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in forested area and agricultural areas, respectively. The export of TP ranged from 0.89 to $2.93 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and 0.36 to $1.51 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in the forested area and agricultural areas, respectively.

The rate of TN export in forested area was triple the rate of TN export from agricultural areas. Among the agricultural areas, a higher export rate for TN was observed in the SIC areas compared to the TN export rate in the SC and IC areas. However, the IC area exported less proportion of TN compared to the SC and SIC areas (Figure 3(a)). There was no significant difference in TN export among the land use types. The analysis of variance showed a

significant difference in the export of TN between F and SC ($p = 0.005$) and between F and IC ($p = 0.005$). There was a significant difference in the mean export of $\text{NO}_3\text{-N}$ between F and IC ($p = 0.044$). Besides, there was no significant variation in $\text{NH}_4\text{-N}$ among the land use types ($P > 0.05$).

A higher TP export rate was observed in the forested than in agricultural areas. Among the latter, a higher TP export was observed in catchment with semi-intensive cultivation. The analysis of variance showed a significant difference in the export of TP between F and IC ($p = 0.002$). The SRP export showed significant differences between the forested and agricultural areas ($p = 0.046$).

Seasonal variation in the concentration and export of N and P among the land use types

Seasonal variation in N and P concentration

An elevated TN concentration was observed in station F during the dry season (Figure 4a). In agricultural areas (SC, SIC and IC) lower TN concentration was observed in the dry season compared to the rainy season. However, the forested catchment showed higher proportions of TN in both dry and rainy season. To the contrary, agricultural areas showed low proportion of TN during the dry season than in the rainy season.

For $\text{NO}_3\text{-N}$, lowest concentration was observed in forested catchment in both seasons. In this catchment, no significant difference in mean concentration of $\text{NO}_3\text{-N}$ between the dry and the rainy season was observed. In the agricultural areas, the concentration of $\text{NO}_3\text{-N}$ increased with increase in agricultural intensity especially during the dry season. The highest mean concentration of $\text{NO}_3\text{-N}$ was observed during the dry season (Figure 4a). In the rainy season, the mean concentration of $\text{NO}_3\text{-N}$ in scattered and semi intensive cultivation areas was similar but was lower than the concentration observed in intensive cultivation area (Figure 4b). The concentration of $\text{NH}_4\text{-N}$ in all land use types was higher in the dry season than in the rainy season (Figure 4a and Figure 4b). However, the highest concentration of $\text{NH}_4\text{-N}$ was observed in the intensive cultivation area. The highest concentration of TP (Figure 4c) was observed in semi-intensive and intensive cultivation areas during the dry season. In general, there is no variation in the concentration of TP between the seasons. Elevated SRP concentration was observed in all land use types during the dry season (4d).

Variation in discharge is among the factors controlling nutrient export from catchment areas. In Kihansi River catchment, elevated discharge is observed during the rainy season. This coincided with elevated concentration on total inorganic forms (TN and TP). The TN export was lower during the dry season than during the rainy season. However, higher amounts of TN were exported from forested area compared agricultural areas to during both seasons. For $\text{NO}_3\text{-N}$, low export was observed in forested catchment in both seasons. In the agricultural areas, the highest mean export of $\text{NO}_3\text{-N}$ was observed during the dry season (Figure 5(a)) where as during the rainy season the export of

NO₃-N increased with increase in agricultural intensity (Figure 5(b)). During the dry season, the export rate for NH₄-N was slightly elevated in both forested and intensive cultivation catchments. In general, there was no significant difference in the export of NH₄-N between the dry and the rainy seasons. High export rate of both SRP and TP was observed in the rainy season (Figure 5(c)) compared to the dry season (Figure 5(d)). However, in both seasons higher TP export was observed in forested catchment. In general, there is no variation in the export of SRP between the seasons.

Figure 6 presents the relationship between nutrient concentration and river discharge. In the forested area (Figure 6 a), there is a weak trend of decrease in concentration of NO₃-N and NH₄-N as discharge increases. In the intensive agricultural area (Figure 6 b), there is a pronounced increasing trend in the concentration of NO₃-N and a weak decreasing trend in the concentration of NH₄-N as discharge increases. In contrast, the concentration of TN showed an increasing trend as discharge increases. In general, elevated TN concentration was observed during the onset of the rainy season.

Influence of the reservoir on the concentration and export of N and P

Higher concentration of TN and TP are observed in the river inflowing to the reservoir compared to the downstream of the reservoir. On the contrary, the station downstream of the reservoir showed reduction of the concentration of TN by 200% (Figure 7 (a)). In addition, the concentration of NO₃-N was higher upstream of the reservoir than downstream the reservoir. The latter showed elevated concentrations of NH₄-N compared to that of NO₃-N. On the other hand, the concentration of TP and SRP was low upstream of the reservoir and increased downstream of the dam.

Furthermore, the export of TN and NO₃-N was higher entering the reservoir compared to the export observed downstream of the dam. To the contrary, NH₄-N was lower upstream of the reservoir than the export observed downstream of the reservoir as shown Figure 8 (a). However, the export of TP was higher upstream of the dam than in the downstream station (Figure 8 (b)). The lowest concentration of NO₃-N and the highest concentration of NH₄-N was recorded downstream the LKHP dam. Regardless of the season, the lowest N and P export was observed in the River Kihansi reach downstream of the LKHP dam.

Discussion

The concentration and export of N and P in the Kihansi River catchment are affected by anthropogenic activities and pressure. The effects can be enhanced or reduced by the local hydrology. The impact of the agricultural activities, seasons and reservoir on the concentration and export of N and P in the Kihansi catchment are discussed.

Influence of agricultural land use to nutrient concentration and export

The dissolved and total forms of P showed no significant differences among the land use types. Similar geology of the Kihansi River catchment explains lack of variability in the concentration of SRP among the land use types. However, land cover is responsible for variation in the concentration of TP between the forested and agricultural areas. Among the agricultural areas, elevated concentration of TP in areas with semi-intensive and intensive cultivation indicates soil erosion taking place in these areas.

For the N nutrient forms, significant variation in dissolved inorganic forms, particularly $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ was observed in the agricultural areas compared to forested area. The observation supports the hypothesis that the agricultural activities are accountable for the elevated concentration of dissolved N concentration in rivers. Similar observation was reported from other catchments of the world (Verstraeten and Prosser 2008, Howarth et al. 2006, Brodie and Mitchell 2005, Vanni et al. 2001, Carpenter et al. 1998, Howarth et al. 1996).

In Kihansi River catchment, the concentration of $\text{NO}_3\text{-N}$ contributes about 70% of the sum of the concentration of dissolved inorganic N in the intensive cultivation area while contribute about 43 % only in forested area. Low concentration of $\text{NO}_3\text{-N}$ in forested area compared to all agricultural areas suggest that agriculture, regardless of intensity, contributes to elevated dissolved inorganic nitrogen concentration in aquatic systems. The observation from this study agrees with the assumption under similar that dissolved inorganic nitrogen is the main form of nitrogen in agricultural catchments. The observation has also been reported elsewhere (Howarth et al. 2006, Lehrter 2006, Bramley and Roth 2002, Galloway et al. 2004, Downing et al. 1999). The highest concentration of $\text{NO}_3\text{-N}$ observed in intensive agriculture compared to semi intensive and areas with scattered cultivation are an indication that agricultural intensification enhances the occurrence of dissolved inorganic N in rivers.

Agricultural practice in the semi-intensive and intensive cultivation areas include unregulated use of fertilizers, cultivation on hill slopes, slash and burn farming methods and cultivating close to river banks. Cultivation in less than 1 m away from the river banks is also a common phenomenon in these areas. The application of fertilizer contributes to elevated inorganic N concentration through seepage and leaching as water infiltrates to the ground. Surface runoff washes out the surface nutrients in areas in farms located on hills slopes where as cultivating close to river banks results to increase in nutrients input into rivers.

It is a known phenomenon that riparian areas provide a buffer zone enhances nutrient uptake by riparian vegetation consequently reduce nutrient inputs into rivers. The width of the riparian zone is important to allow the effective interception of nutrients, especially in zones with no efficient uptake from the riparian zone (Lowrance 1998). In the United States for example, Karr et al. (2001) reported that a buffer zone of 7.6 m was not enough to prevent

leaching of $\text{NO}_3\text{-N}$ to the river systems. In this study, a riparian buffer zone of 1 m might be less to allow interception of nutrients from the farms. This implies that the insufficient buffer zone can cause increases in inorganic N concentration and ultimately increased N export in rivers. The consequences of elevated N concentration and export include alteration of the N cycle thus impair the aquatic productivity and potential impacts on downstream areas (Gruber and Galloway 2008 and Udy et al. 2006).

In the Kihansi River catchment the regression analysis indicates that 66% of $\text{NO}_3\text{-N}$ variability is controlled by other factors. In this case, the factors include hydrology and land cover. The latter is also a function of land use, considering that open land cover is a result of agricultural expansion. Nevertheless, low $\text{NH}_4\text{-N}$ concentration in all land use types is a common phenomenon in running waters, especially at high oxygen concentration.

The highest concentration of TN observed in forested area suggests input from forest vegetation. This attributed to contribution from falling litter and logs in the forested area catchment compared to open canopy in agricultural catchments. This has also been reported by other studies in other areas that particulate forms of nutrients are important in forested catchment (Lewis et al. 1999). Therefore further conversion of forests to farmlands in (Holmgren 2006) is thought to result in an increase in both, dissolved and particulate forms of N in receiving water bodies.

Among the agricultural areas, a higher concentration of TN in semi intensive and intensive cultivation areas compared to scattered cultivation is attributed to soil erosion effects (Lufafa et al. 2003). Slush and burn and cropping on hill slopes result in elevated total N forms in soils in the semi intensive and intensive cultivation areas (Giardina et al. 2000) leads to accumulation of undissolved N containing particulate matter.

Nutrient export is a function of nutrient concentration which can be used as a water quality indicator to changes resulting from human perturbation in catchment areas (Udy et al. 2006). In general, the differences between N and P export are attributed to the fact that N is transported in dissolved forms where as P is transported in particulate forms. This is observation is similar to observation made in Lake Michigan watersheds (Han et al. 2011). Agricultural areas of the Kihansi River catchment have shown to export elevated proportions of $\text{NO}_3\text{-N}$ compared to the forested area. Therefore agricultural activities enhance dissolved inorganic N input and their export to rivers and ultimately to receiving water bodies.

The N export from agricultural areas of the Kihansi River catchment is approximately $2 \text{ kg ha}^{-1} \text{ yr}^{-1}$. This is however low compared to exports reported in other areas (Austin et al. 2006, Howarth et al 2006, Boyer et al. 2002, Vanni et al. 2001 Saunders and Lewis 1988). This study provides evidence that intensifying agricultural activities can result in an increase in $\text{NO}_3\text{-N}$ export in rivers. Nutrient management strategies in this catchment need to focus on the management of dissolved inorganic N. However, apart from enforcing the application of best agricultural management practices in

the catchment, continuous monitoring is crucial for timely management of excess nutrient transport. This is because, the effects of excess nutrient export and loading on receiving water bodies take sometime to be realised. Even once realised reversing the situation be costly and may also take a long time.

Effect of season on N and P concentration and export among the land use types

This study found that the concentration and export of N and P nutrient were affected by hydrology. In forested area, the relationship between nutrient concentration and discharge show that dilution effects control the concentration of TN, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$ and SRP. In agricultural areas, the relationship between nutrient concentration and discharge show that dilution effect controls the concentration of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$ and TP. On the other hand, a positive trend of increasing TN with increasing discharge suggests soil activation, especially at the onset of the rainy season. Thus, this confirms the finding that agricultural activities result in soil erosion particularly with respect to the poor agricultural management practices applied by farmers in the area. Slush and burn agricultural practice, for example causes burnt crop remains to be buried as farms are tilled. When rain falls, the loose soil with accumulated particulate materials is swept to the rivers resulting in elevated TN. However, some of the organic N might be lost to the atmosphere leading to elevated TP compared to TN export.

Besides, the observed higher concentration of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ during the dry season suggests leaching and seepage of inorganic N fertilizers from agricultural areas. The fertilizers which are applied during the rainy season infiltrate to the groundwater. The observed elevated concentration of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ during the dry season is a result of river recharge from groundwater. Birhanu et al. (2009) reported strong base flow due to the fact that 85% of the annual water yield in the Kihansi catchment was contributed to groundwater flow. Taking this observation into account, it is deduced that nutrient concentration in the Kihansi catchment during the dry season results from groundwater during river recharge. Nevertheless, elevated discharge during the rainy season results in the observed low concentration of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$.

As nutrient exports are a function of discharge, lower exports of dissolved inorganic nutrients in the Kihansi River catchment was expected during the dry season. In contrast, elevated dissolved inorganic N during the dry season is associated with leaching of fertilizer application from farmlands during the rainy season. As fertilisers were applied during rainy season, the leached nutrient was stored in groundwater and brought to the river as groundwater recharge the river during the dry season.

Effect of the reservoir on N and P concentration and export downstream of the dam

Results show that the reservoir affects nutrient export to the river reach downstream of the dam. A reduction in N concentration and export in downstream areas suggests enhanced reduction in the N:P ratio, pronounces further the N limitation. The change in N forms downstream of the dam is attributed to more effective N transformation in the reservoir. Less TN and TP export suggest pelagic processes and sedimentation as a consequence of retentive nature of the reservoir.

An increase in the concentration of $\text{NO}_3\text{-N}$ from agricultural areas poses risk for eutrophication of the reservoir. The Kihansi River system has a low N: P ratio (Ideva et al. 2008). Smith et al., 1995 indicated that DIN: SRP ratio < 10:1 by mass indicates strong nitrogen limitation, a condition which favours proliferation of N_2 fixing cyanobacteria (Smith et al. 1995). Despite the presence of the favourable conditions for cyanobacteria growth, there is no indication of excess cyanobacteria growth as the Kihansi reservoir still displays low primary productivity (Ideva et al. 2008). Harvens et al. (2002) pointed out that factors such as low radiance and lack of water column stability may be responsible for observed low productivity in strongly N limited aquatic system. This might also be the case for Kihansi reservoir where currently other factors which inhibit excess plankton growth save the reservoir from eutrophication. Among the factors is lack of water column stability caused by as water is abstracted to run the turbines of the hydropower plant. As such, in the Kihansi reservoir, the risk of eutrophication is not immediate compared to the risk associated with reduced nutrient export necessary to maintain aquatic communities downstream of the dam. It has been reported elsewhere that changes in nutrient ratios may lead to shifts in aquatic community composition as a result of contrasting nutrient requirement (Seitzinger & Vörosmary 2005, Harven et al. 2003).

Conclusion

The Kihansi River ecosystem is in threat due to multiple pressures from land use. Agriculture contributes to elevated concentration and export of inorganic N, particularly $\text{NO}_3\text{-N}$. Although elevated N is associated with the application of fertilizers, the N occurrence is also controlled by local hydrology. However, the capacity of the soil to retain inorganic nutrient ($\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$) in this catchment is high causing nutrient release to the river during the dry season as groundwater recharges the river system. Increasing the width of the riparian zone as well as afforestation in agricultural areas of the Kihansi River catchment is recommended in order to reduce inorganic N export into rivers. There is also a need to investigate the amount fertiliser unit area needed in order to maximize both agricultural production and reduction of inorganic nitrogen export to river. There is a need to understand nutrient transformation in the reservoir in order to choose appropriate management action to combat changes in nutrient export downstream of the dam.

Acknowledgement

The World Bank funded Lower Kihansi Environmental Management Project under the National Environmental Management Council of the United Republic of Tanzania through the IDA credit No. 3625 is acknowledged for funding this study.

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List of Tables

Table I Landscape characteristics, altitude, land cover and land use in the Kihansi River catchment

Name of the station (River)	Station Code	Landscape type	Altitude (m.a.s.l)	Land cover	Land use
Kihansi	1	Highlands with complex of flat to gently sloping terrain	1700	Bush/Grassland, farm lands	Scattered cultivation (SC),
Muhu	2	Highlands with complex of flat terrain; gently, moderate to very steep sloping terrain	1700	Farm lands	Intensive cultivation (IC)
Mkalasi	3	Hills with complex of flat and gently sloping terrain	1600	Scattered bush/grassland and farmlands	Semi intensive cultivation (SIC)
Ruaha	4	Hills with complex of flat and gently sloping terrain	1500	Forest	Forest (F)
Kihansi	5				
Kihansi	6	Low hill with complex of flat terrain, gently, moderate to very steep terrain	1400	Dense bushland	Hydropower dam (HP)

Table II. Mean variation of discharge (m^3s^{-1}) measurements in the studied rivers draining the Kihansi River catchments

	August	October	November	December	January	February
Rivers	n= 31	n=31	n=30	n=31	n=31	n=28
1 (SC)	0.29 ± 0.02	0.24 ± 0.00	0.43 ± 0.18	0.89 ± 0.13	1.04 ± 0.18	1.40 ± 0.28
2 (IC)	1.08 ± 0.04	0.99 ± 0.04	1.05 ± 0.08	1.13 ± 0.22	1.40 ± 0.08	1.27 ± 0.04
3 (SIC)	0.90 ± 0.03	0.74 ± 0.11	0.87 ± 0.20	1.17 ± 0.58	1.65 ± 0.19	1.38 ± 0.03
4 (F)	3.34 ± 0.26	2.34 ± 0.32	2.51 ± 1.07	3.90 ± 3.66	4.62 ± 1.50	5.12 ± 1.00
KBD						
5 (HP)	1.25 ± 0.05	1.26 ± 0.07	1.27 ± 0.05	1.33 ± 0.04	1.35 ± 0.03	1.33 ± 0.04

Table III. Mean variation and standard deviation in physico-chemical parameter among the land use types in Kihansi River catchment (n = 6, description of station see Table I)

Station	Electrical conductivity ($\mu\text{S cm}^{-1}$)	Temperature ($^{\circ}\text{C}$)	Dissolved oxygen saturation (%)	pH
SC	38.33 ± 11.58	19.32 ± 0.39	57.49 ± 11.59	7.05 ± 0.94
IC	36.00 ± 3.39	19.28 ± 1.07	76.29 ± 7.22	6.68 ± 0.48
SIC	18.67 ± 3.67	19.42 ± 0.10	83.37 ± 4.10	6.67 ± 1.43
F	15.00 ± 4.21	20.10 ± 2.10	87.14 ± 9.74	6.33 ± 1.18
KBD				
HP	21.83 ± 9.98	23.40 ± 1.09	83.32 ± 9.43	6.76 ± 1.14

List of Figures

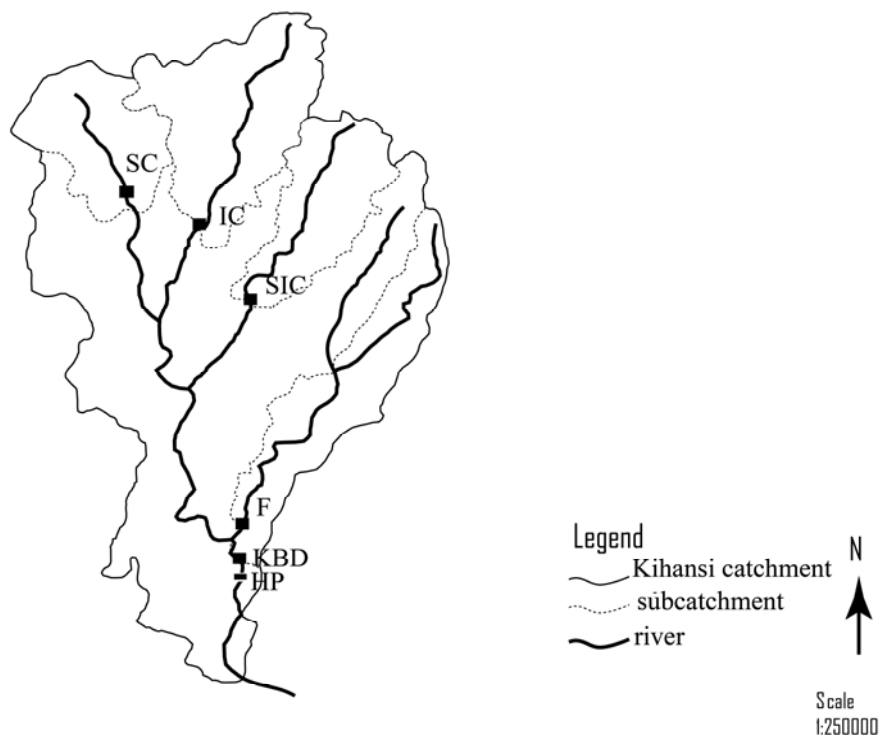


Figure 1. Kihansi catchment showing the sampling stations. 1 – = SC (Bush/grassland with scattered cultivation), 2 – IC = Intensive Cultivation, 3 – SIC = Grassland with semi intensive cultivation 4 – F = Forested 5 – HP = Downstream the hydropower dam

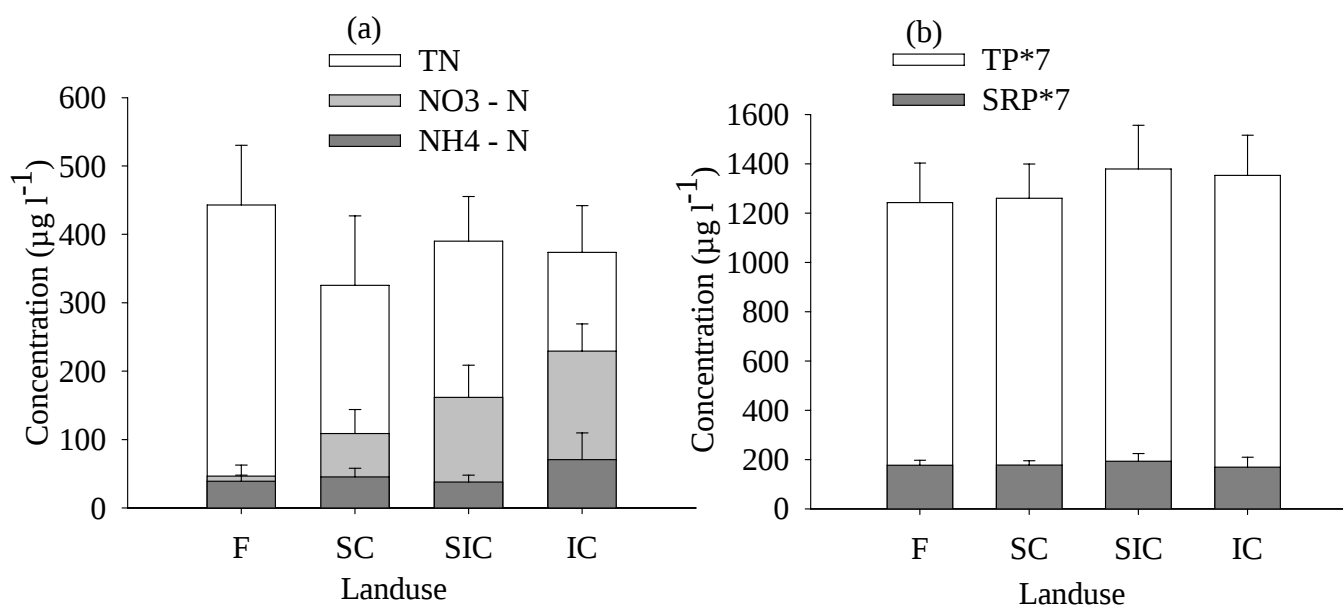


Figure 2 a & b (F= Forested, SC = scattered cultivation, SIC = Semi intensive cultivation and IC = Intensive cultivation). The scale for SRP and TP is computed to fit the Redfield's N:P ratio by weight in comparison to N.

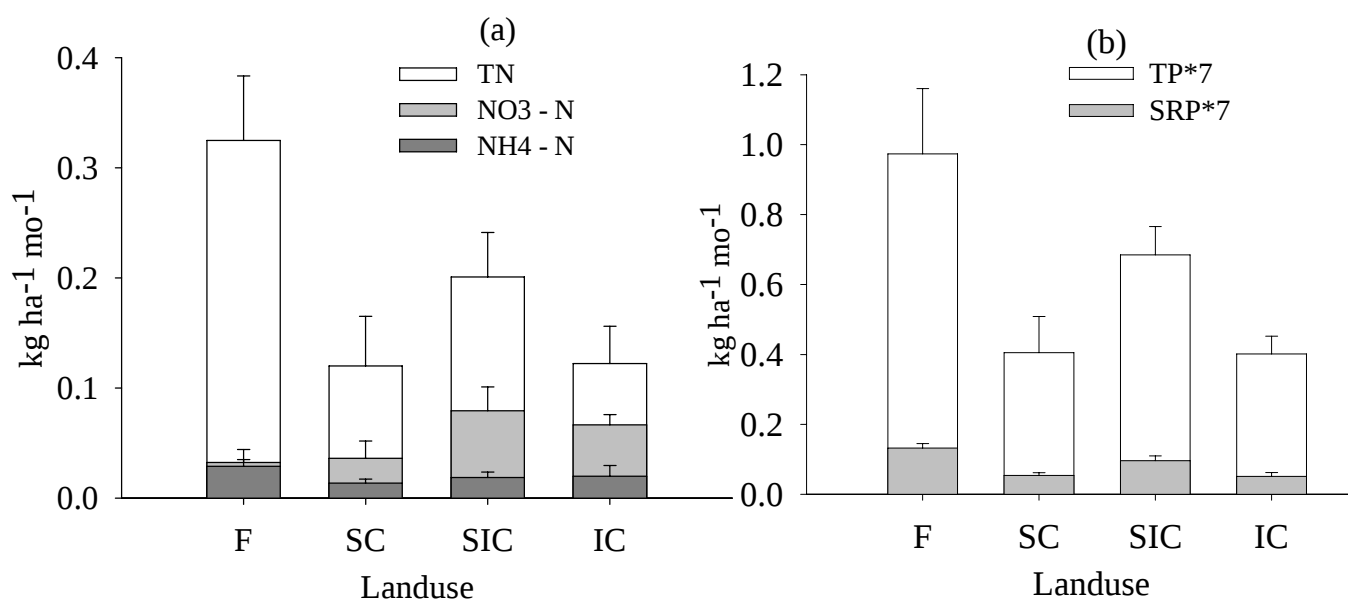


Figure 3 a & b. (F= Forested, SC = scattered cultivation, SIC = Semi intensive cultivation and IC = Intensive cultivation). The scale for SRP and P is computed to fit the Redfield's ratio N:P by weight in relation to N.

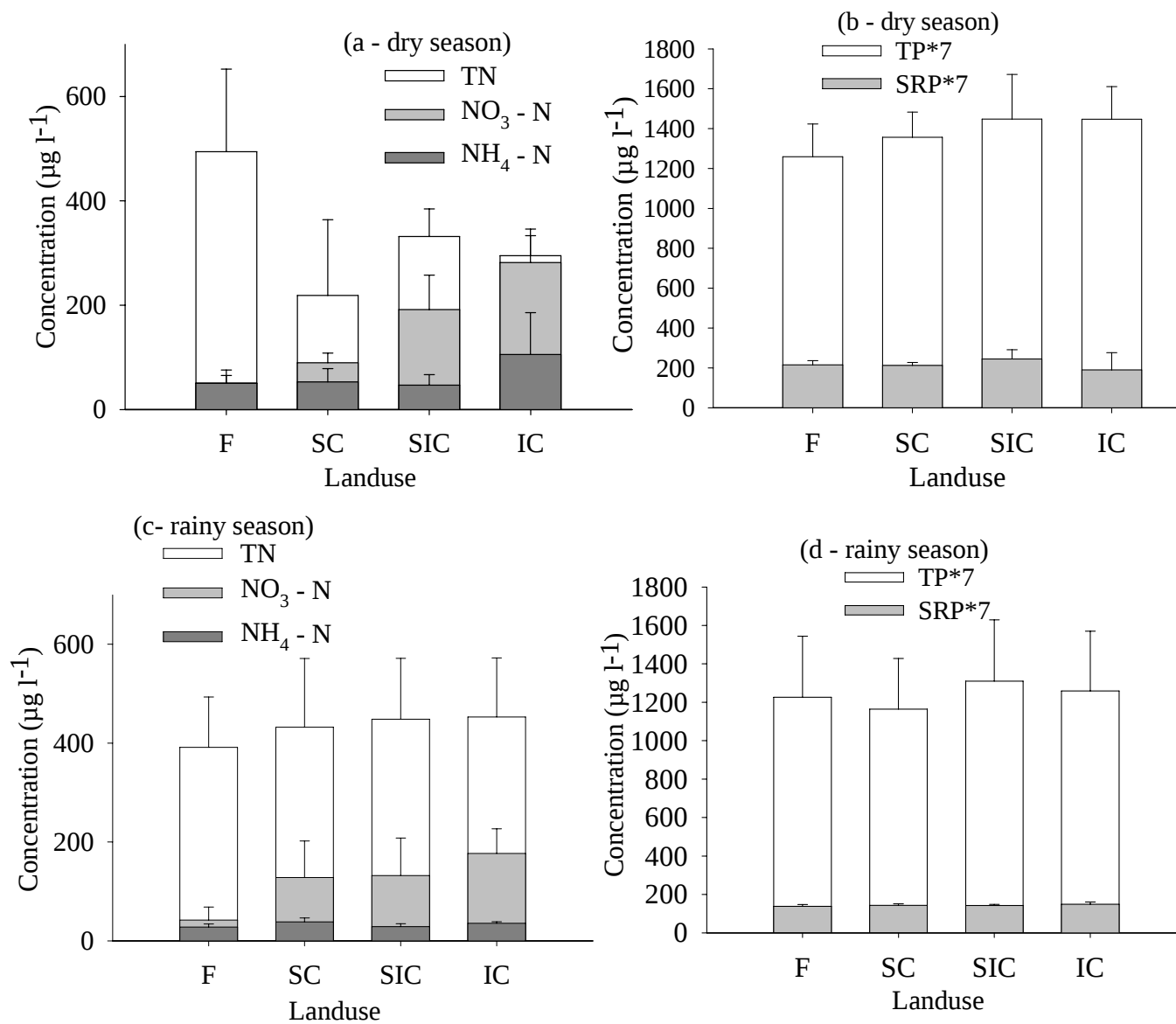


Figure 4 a –d. (F= Forested, SC = scattered cultivation, SIC = Semi intensive cultivation and IC = Intensive cultivation). The scale for SRP and P is computed to fit the Redfield's ratio N:P by weight in relation to N.

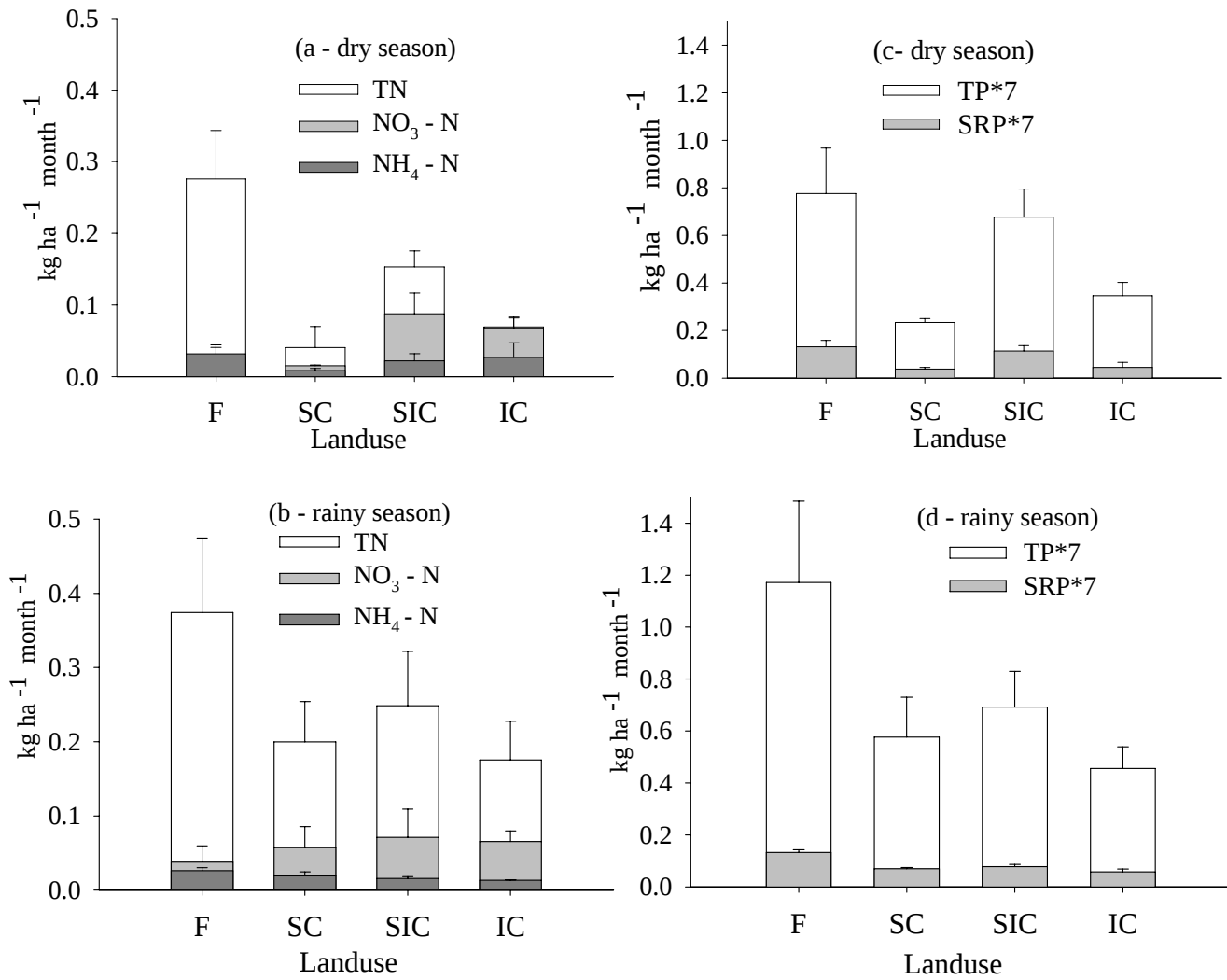


Figure 5 a – d. (F= Forested, SC = scattered cultivation, SIC = Semi intensive cultivation and IC = Intensive cultivation). The scale for SRP and P is computed to fit the Redfield's ratio N:P by weight in relation to N.

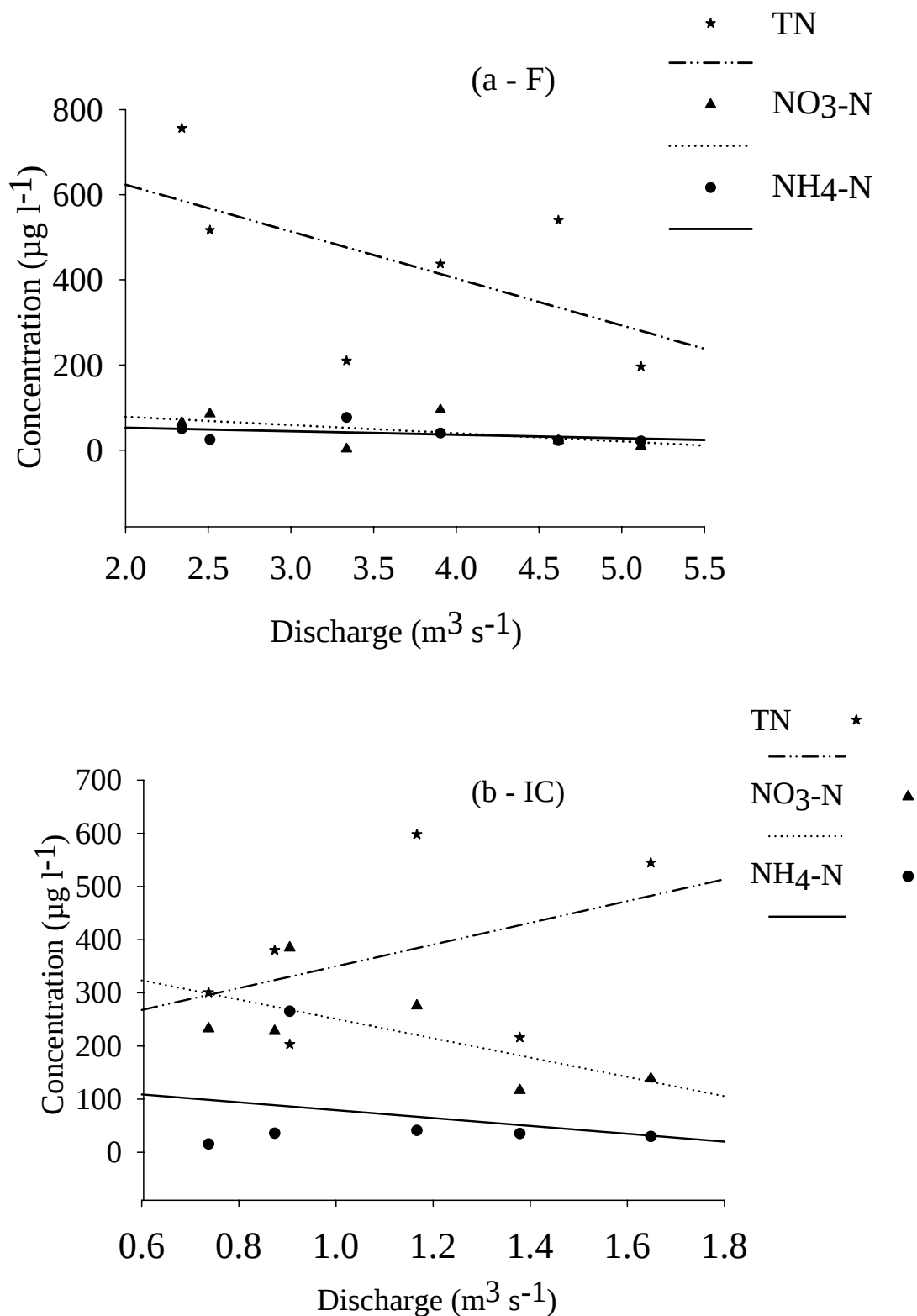


Figure 7 a & b. Relationship between nutrient concentration and discharge in forested (F) (left graph) and intensive agricultural (IC) area ($n = 6$, $p > 0.05$)

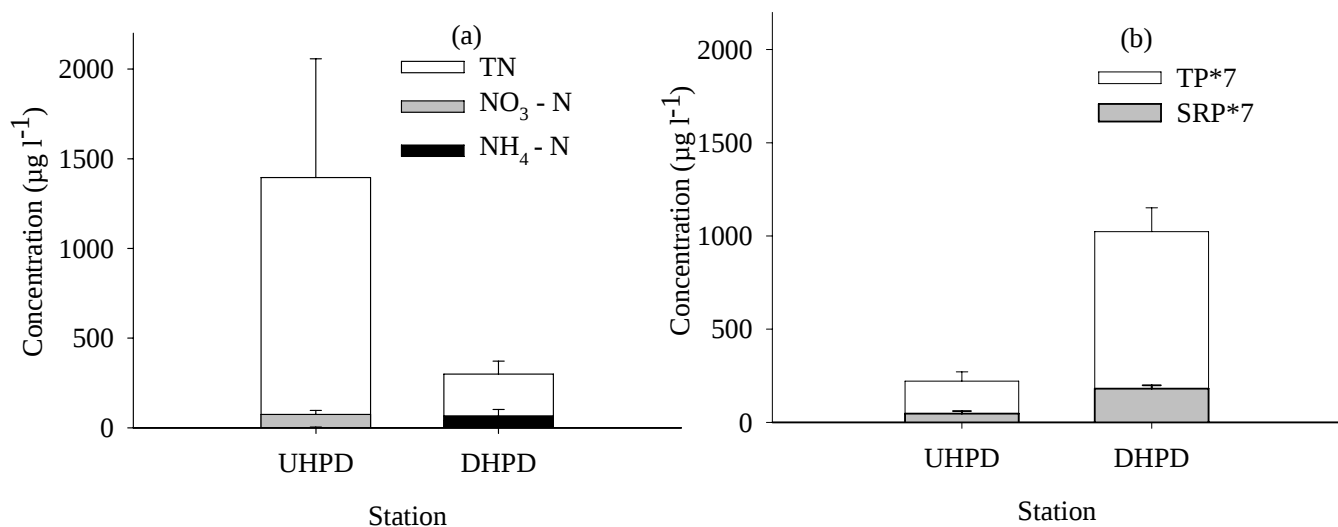


Figure 7 a & b. (UHPD= Upstream the hydropower dam, DHPD = Downstream the hydropower dam. The scale for SRP and P is computed to fit the Redfield's ratio N:P by weight in relation to N

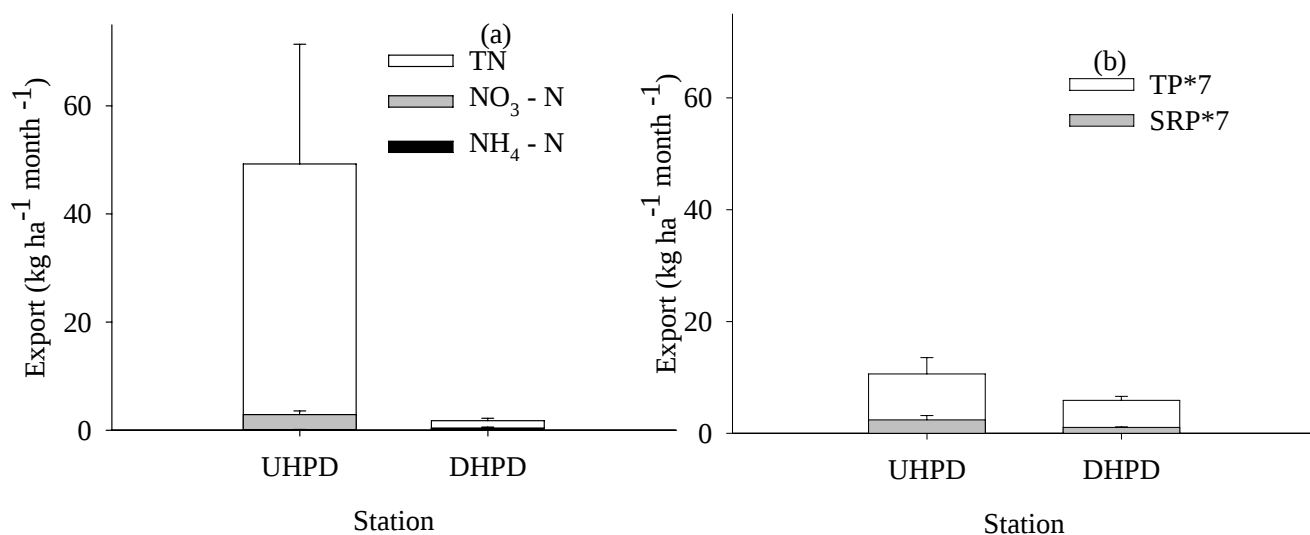


Figure 8 a –b. (UHPD= Upstream the hydropower dam, DHPD = Downstream the hydropower dam. The scale for SRP and P is computed to fit the Redfield's ratio N:P by weight in relation to N

4.3 Paper 3

Bacterial activity under altered hydrology and nutrient in the Kihansi River and reservoir, Tanzania

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Abstract

Reservoirs resulting from hydropower dams act as retention sites for nutrients. Increased residence times and decreased turbulence due to altered river flow changes nutrient conditions consequently affecting reservoir productivity. Where primary productivity is N limited, bacterioplankton activity can be used as an indicator of impacts of anthropogenic activities on aquatic ecosystem functioning. The major goal of this paper is to understand the ecosystem response to changes in both hydrological and nutrient conditions. This will enable development of appropriate management objective and actions in response to nutrient export as a result of anthropogenic perturbation in catchment areas. Specifically, the study aimed to assess influence of the reduced river flow on secondary production and also to test the sensitivity of the reservoir on the elevated dissolved inorganic nitrogen input. Therefore, bacterial secondary production in the reservoir was compared to bacterial secondary production in riverine sites upstream and downstream of the dam. In the laboratory experiment using water obtained from the reservoir, the bacteria secondary production and abundance in response to dissolved N addition were determined.

Results from in situ measurements showed elevated bacteria secondary production values in the reservoir compared to riverine samples upstream and downstream of the dam. In an N addition experiment, a significant difference in bacterial secondary production and abundance between N added and control samples suggests bacteria production responded to N addition in the reservoir. Lack of correlation between bacterial secondary production and abundance suggests that the process is performed by specialised bacteria communities, which are also site specific. Therefore, the reservoir is a vital site of bacterial production and a further increase in N loading in the Kihansi reservoir will change the current ecosystem metabolism.

Key words: Bacterial secondary, production, bacterial abundance, Kihansi River, tropical, River, Reservoir, nitrogen, limitation

Introduction

The consequences of altered river flow and its implication in nutrient conditions can affect ecosystem productivity (Friedl and Wüest, 2002, Gücker et al., 2008). In aquatic systems where phytoplankton production is limited by nutrients, bacterioplankton production can be an important source of energy to higher trophic levels (Wetzel, 2001).

Bacterioplankton assimilate dissolved organic carbon they produce through enzymatic degradation of organic matter. In this sense, they play a role in the transformation of organic matter by producing new biomass while decomposing organic carbon (Castillo *et al.*, 2004; Pace, 1993 and Kirchman *et al.*, 1982). Bacteria production is thus important in the trophic dynamics of aquatic food webs (Peduzzi and Schiemer, 2008). However, bacterioplankton is also often limited by nutrient availability (Farjalla et al., 2002). Thus bacterial activity can be used as an indicator of changes in nutrient concentration resulting from anthropogenic activities and pressure (Schiemer, 2008).

The Kihansi Reservoir in Tanzania is both economically and ecologically important. Economically, the reservoir stores water to run the turbines of a Lower Kihansi Hydropower Plant. This power plant provides electric power necessary for economic development in Tanzania. Ecologically, the reservoir retains nutrient, reducing their export to the river section downstream of the dam. The ecological importance of the reservoir is taken into account in this paper.

Potential of elevated dissolved N concentration in the reservoir exists (Ideva et al, in review process in the River Systems journal) due to application of poor agricultural management practices in upstream areas of the catchment. There is limited knowledge on the manner in which these anthropogenic perturbations affect aquatic ecosystem function in this tropical N-limited riverine ecosystem. Understanding the aquatic productivity of water bodies in response to changes hydrological conditions and nutrients is important to enable formulation of appropriate management objectives and actions necessary for conservation and restoration purposes.

Differences in bacterial activity can be contributed by the bacterial community structure. However, the scope of this study was not to identify the types of bacteria involved in bacterial secondary production rather characterise the pattern of bacterial activity with respect to the changes in flow conditions and nutrients concentrations. It is hypothesised that bacteria secondary production in the Kihansi reservoir can be stimulated by reduced river flow and elevated dissolved inorganic N concentration.

The major goal of this paper is to understand the ecosystem response to changes in both hydrological and nutrient conditions. This will enable

development of appropriate management objective and actions in response to elevated nutrient export as a result of anthropogenic perturbation in catchment areas. Specifically, the study aimed to assess influence of the reduced river flow on secondary production and also to test the sensitivity of the reservoir on the elevated dissolved inorganic nitrogen input. To test the impact of altered river flow on activity, bacterial secondary production and abundance was determined in reservoir and in riverine sites upstream and downstream of the reservoir. To test sensitivity of the reservoir on changes elevated dissolved nitrogen concentrations, the response of bacterial secondary production and abundance were determined in an N addition experiment in the laboratory.

Materials and Methods

Sampling station, sampling and sample analysis

Water samples for in-situ measurements of bacterial secondary productivity and abundance and dissolved inorganic carbon (DOC) were collected upstream and downstream of the hydropower dam (Figure 1). Station 1 is River Kihansi inflowing to the reservoir, station 2 is located in the mid of the reservoir where 3 denotes the station where ecological water flows from the reservoir. Station 4 is situated downstream the Kihansi dam before confluence with water exiting the hydropower plant after running the turbines, station 5 Udagaji River after passing through the wetlands/rice farms and station 6 is located in the Kihansi River downstream after confluence with water exiting LKHP and River Udagaji. Samples were collected at 0.5 m depth except for station 5 where the depth of water was below 0.5 m. During field work, samples were stored temporarily in a cooler before further processing.

For DOC measurements, samples were filtered through GFF (Millipore glass fibre, 47 mm diameter, APFF) pre-combusted at 500 °C for 4h then acidified with a solution of 2.7 mM sodium azide for a final concentration of 13.5 µM (Kaplan, 1994), which were stored in combusted (at 500 °C for 4 hours) glass tubes. Filtered water sample was stored in pre-combusted glass tubes prior to analysis.

Laboratory analyses

The DOC concentration in the samples was determined by high temperature combusting method with a Shimadzu TOC 5000 C - analyser according to (Benner *et al.* (1993).

Determination of bacterial production

Bacterial secondary production was measured by the [³H] thymidine ([methyl-³H] TdR) incorporation method according to Fuhrman and Azam (1980) at an ambient temperature. Measurements were performed in triplicates for experimental samples and duplicate controls (formaldehyde-killed). After every 12 hours, 10 ml of the sample was put in 5 vials of which were 3 triplicate samples and 2 controls (in the controls 0.5 ml of formalin (2% final

concentration) was added and left to stay for 10 minutes to ensure that bacterial metabolism was inhibited). In each vial 20 μl of 0.1 mCi ml^{-1} was added and incubated for 30 minutes at room temperature (25°C). Incorporation was stopped by addition of 0.5 ml formalin (2% final concentration) in the triplicates. All samples (triplicate and control) were filtered through 0.45 μm cellulose nitrate filters (Millipore HAWP, 25 mm diameter) using a filtration manifold (Millipore 25 mm diameter). While still in the funnel of the filtration manifold, filters were washed 2 times for 10 minutes with ice cold 5 % TCA. Dry filters were taken into the scintillation vials and stored at temperature of 4°C in the dark and transported to Austria for analysis.

To calculate bacterial cell production, we used a conversion factor of 1.61×10^{18} cells mol^{-1} thymidine incorporated determined by Peduzzi and Schiemer (2004) for tropical freshwater reservoirs. The specific BSP (production biomass ratio) was calculated by dividing bacterial production by bacterial abundance. The enrichment experiment was conducted in the Lower Kihansi Environmental Management Project laboratories in Kihansi Tanzania. Bacterial secondary production and bacteria abundance determination were conducted at the Wassercluster Lunz, an Interuniversity Center for Aquatic Ecosystem Research laboratories, Lunz am See, Austria.

Determination of bacterial abundance

Each water sample amounting to 10 ml was fixed with 0.4 ml 37% formalin, transferred to Greiner tubes and stored at 4°C before transporting to Austria for bacteria abundance estimation. In the laboratory, 100 μl of DAPI solution was put into 1 ml of sample and incubated in the dark for 10 minutes to stain. Under the fume chamber, a supporting filter was put in the lower part of the filtration device, followed by a black polycarbonate filter (Millipore, GTBP, 25 mm diameter, 0.2 μm) on which a filter funnel was fitted. Samples were then poured into the funnel and filtered in a vacuum filtration unit (< 200 mbar). After a concentration of microbial cells on the filters, the filter was carefully removed using forceps, while still applying pressure, and placed over a drop of paraffin oil on the slide, covered with cover slip ready for counting under the epifluorescence microscope (Weinbauer et al, 1998). On each slide 20 fields were counted to determine the total number of bacteria.

The bacterial community structure was determined according to (Muyzer et al, 1993). The microbial community structures in the different samples were analysed through comparisons of community fingerprints obtained by denaturing gradient gel electrophoresis (Muyzer et al. 1995). A DGGE (denaturing gel gradient electrophoresis) analysis was performed with a Dcode Universal Mutation Detection System (Bio-Rad, Hercules, CA) under the following conditions: 1-mm thick 8% polyacrylamide gels, a denaturant gradient of 30%-60% urea-formamide (where 100% denaturant contained 7M urea and 40% formamide) at 60°C , 150 V for 6 hours.

Gels were stained with SybrGreen for 1 hour and photographed on a UV transilluminator table with a digital camera. A clearly visible band was

determined as present or absent. The software Primer 5.2.2 (Primer-E Ltd., UK) was used for determining the band pattern similarities (Bray-Curtis similarity matrix) among DGGE fingerprints of microbial communities and for subsequent cluster analyses and dendrogram reconstruction (group average linking method).

Experimental design for N enrichment experiment

The response of bacterial growth rates to enrichment of N was compared between diluted whole water samples and diluted fractionated water similar to the procedure followed by (Rejas *et al.*, 2005). Diluted fractionated water served as bacteria free water whereas diluted whole water served as bacteria inoculum. Bacteria free (BF) water was obtained by filtering water through the 0.2 μm filters. Cultures were prepared using 900 ml of 0.2 μm filtrate and 100 ml bacterial cultures. Triplicate samples were enriched with 20 μg ammonium chloride per litre in order to increase nitrogen concentration to ensure higher nitrogen levels compared to background level. Replicate samples without addition of ammonium chloride served as control. Cultures were placed in the dark at 24 °C to prevent accumulation of autotrophic and enable bacterial community to acclimatize, respectively. Samples of bacterial secondary production and abundance were taken after every 12 hours over a period of 5 days. The response of bacterial carbon production and bacterial growth in the treatment compared to the control sample was expected to indicate that bacterial growth is stimulated by addition of N.

Results

Bacterial activity in in-situ conditions

Bacterial activity is known to be controlled by physiographic factors, organic matter and nutrients. Whereas altitude ranged from 287 - 1249 m.a.s.l, temperatures ranged from 15.7 - 20.4 °C. Compared to high altitude stations, higher temperatures were observed in low altitude site. The concentration of DOC ranged from 364.5 to 1202 $\mu\text{g l}^{-1}$. Except for site 5, which is located in River Udagaji, a decreasing trend in the concentration of DOC was observed (Table 1). River Kihansi inflowing the reservoir had the highest concentration of DOC whereas the lowest concentration was observed immediately downstream of the dam. The concentration of DOC picked up further downstream after confluence with water from the hydropower plant.

Determination of bacterial secondary production and abundance was conducted in years 2005 and 2008. In general, along the studied section of the Kihansi River, bacterial secondary production was high in the reservoir compared to the Kihansi River flowing into the reservoir (Figure 2). However, bacterial secondary production decreased downstream of the dam before increasing again in the River section after confluence with water from the power plant. While, highest bacteria production was observed in the reservoir the lowest bacterial secondary production was observed in the Kihansi River (site 4) before the water exiting the power plant adjoins.

The observed trend for bacterial abundance did not follow the trend of bacterial secondary production. Bacterial abundance (Figure 3) showed higher cell counts in the Kihansi River before entering the reservoir compared to the reservoir. However, the lowest cell counts were observed immediately downstream of the dam. In general, bacterial abundance was observed to be higher in lower altitude compared to higher altitude. Udagaji River passing through rice farms showed the highest bacterial abundance. The analysis of variance showed a significant difference in bacterial secondary production between sites 1 and 5; 2 and 4 as well as sites 4 and 6. Bacterial abundance was significantly different between sites 1 and 5, 2 and 4, 3 and 5 as well as between sites 4 and 5.

The highest cell specific production was observed immediately downstream of the dam. In general, cell specific production was inversely proportional to bacterial abundance (Figure 4). The lowest cell specific bacterial production was recorded in the lower Udagaji River (site 5).

Bacterial activity in an N addition experiment

In general, the bacterial secondary production in control samples were similar to those recorded in situ, but lower compared to productivity observed after N addition. The highest bacterial secondary production was observed after 36 hours of incubation. At this incubation time, bacterial production rate was higher by almost two orders of magnitude compared to the production observed in control samples (Figure 5). Lowest bacterial production in both experimental and control samples was observed after 60 hours of incubation. The highest bacterial abundance (Figure 6) was observed after 24 hours of incubation.

The analysis of variance indicated a significant difference in bacterial secondary production between 0 hour (initial incubation) and after 36 hours of incubation ($p = 0.044$). Likewise, bacterial secondary production between 36 hours and 60 hours of incubation ($p = 0.045$) was also significantly different. Moreover, there is a significant difference between bacterial secondary production at 36 hours of incubation and in situ bacterial production observed in the reservoir.

The initial specific bacterial production rates were similar to the in situ growth rates. High cell specific bacterial production was observed in the N enrichment experiment. Highest specific growth rates were observed at 12 and 24 hours of incubation before declining to initial rates after 36 hours of incubation. However, the rates increased again at 48 hours and declined at 60 hours.

Bacterial community composition was conducted as supplement information on the variation in bacterial activity as a result of changing flow conditions. The DGGE of PCR-amplified 16S rDNA fragments (Figure 7) showed different bacterial community structures upstream and downstream of the dam. The bacterial community in site 1 was different from those in other sites by almost 40%. Bacterial community in site 2 and 3 were similar compared to the communities in the riverine sites 4, 5 and 6.

Discussion

The influence of reduced river flow to bacterial secondary production and abundance

The elevated bacterial secondary production in the reservoir suggests presence of favourable condition for bacterial activity. This is linked with reduced flow in the reservoir compared to free flowing conditions in the riverine stations. Therefore, change in hydraulic condition is observed to affect bacterial utilisation of dissolved nutrients.

In Kihansi River system, the DOC concentration from $350 \mu\text{g l}^{-1}$ to 1.6 mg l^{-1} is similar to the DOC concentration recorded in high altitude rivers (particularly alpine ones). The DOC concentration in Kihansi River system is low compared to other African rivers. The Orange River in Zaire has mean DOC concentration of 8.5 mg l^{-1} (Martins 1991) and $> 20 \text{ mg l}^{-1}$ were found in some tropical or polluted rivers and rivers draining swamps and wetlands (Malcolm and Durum 1976, Naiman and Sedell 1979).

In-situ bacterial secondary production and abundance recorded in this study is lower compared to other tropical systems. For example, an average bacteria production between $0.13 - 0.27 \mu\text{g C l}^{-1}\text{h}^{-1}$ was recorded by Farjalla *et al.* (2002), whereas $1.16 \mu\text{g C l}^{-1}\text{h}^{-1}$ was recorded by Benner *et al.* (1995) and $0.14 - 26.2 \mu\text{g C l}^{-1}\text{h}^{-1}$ were reported from other tropical clear water ecosystems (Tórreton *et al.*, 1994; Lindell and Edling, 1996; Bouvy *et al.*, 1998; Peduzzi and Schiemer, 2004). In terms of bacterial abundance, data from the Amazon indicated $\sim 0.1 \times 10^{10}$ cells per liter $^{-1}$ – 0.294×10^{10} cells per liter $^{-1}$ (Benner *et al.*, 1995, Farjalla *et al.*, 2002). In other areas bacterial abundance ranging from $0.026 - 2.38 \times 10^{10}$ cells per liter $^{-1}$ (Tórreton *et al.*, 1994; Lindell and Edling, 1996; Bouvy *et al.*, 1998; Peduzzi and Schiemer, 2004) was recorded.

The observed low DIN (Ideva *et al.*, 2008) and DOC concentrations in the reservoir compared to the riverine station in station 1 due to nutrient transformation associated with pelagic processes in this semi-lentic environment. The processes include biological uptake (during mineralisation of organic matter) and chemical transformation can lead to decreased nutrient levels.

High cell specific bacteria production and DOC in sites 2 and 6 is an evidence that elevated bacterial productivity occurs in areas with reduced water flow. In other systems, Rejas (2004) found that in carbon limited systems bacteria are directly stimulated by the phytoplankton development due to bacterial dependence on algal exudates. This is contrary to the observation made in the Kihansi River system (Ideva *et al.*, 2008). According to Lennon and Pfaff (2005), the sources and supply of organic matter affects aquatic microbial metabolisms in these systems. For the Kihansi River system, it implies that bacteria utilise allochthonous sources of organic matter for their growth meanwhile releasing dissolved carbon.

The observed differences in bacterial community structure shown by the DGGE indicate that the bacterial production and growth rates are controlled by environmental parameters. In general, bacteria in the Kihansi River ecosystem are adapted to an low nutrient environment, thus changes in environmental factors and nutrient supply have impacts on their activity. Similar trends were observed by White et al., (1991). The observed change in bacterial secondary production in the reservoir compared to upstream and downstream riverine sites is an evidence of the impact of altered river flow on ecosystem functioning. Bacterial metabolism is recognised as a key ecosystem function in the reservoirs (Schiemer, 2008, Pedduzi and Schiemer, 2004). Its disruption by hydropower production will also influence carbon processing in river reaches downstream of the dam.

The sensitivity of the reservoir to elevated dissolved N concentration

In an experiment to test the sensitivity of the reservoir to changes in landuse and nutrient inputs, stimulation of bacterial activity was observed after addition of dissolved inorganic N. In the N addition treatment bacterial secondary production was stimulated by elevated N concentrations, whereas bacterial abundance was not affected by N addition. The observation indicates that highest bacterial biomass was obtained before maximum carbon production was attained evidenced by lack of similar trends between bacterial production and bacterial abundance. However, the coincidence between low bacterial biomass and highest carbon production suggests the existence of few bacteria which were efficient in carbon production (Rejas et al., 2005).

Contrary to observations made in the N addition experiment during this study, Benner *et al.* (1995) showed that the addition of ammonium or phosphate alone had no significant effect on leucine incorporation rates in the Amazon River. Glucose additions and addition of all three substrates (Glucose, ammonium and phosphate) stimulated leucine incorporation and therefore bacterial production. Another study by Carlson *et al.* (2002) in the north western Sargasso Sea showed no increase in bacterial production nor utilization of DOC (by the bacteria) by the addition of inorganic N or P (alone or in combination).

Therefore increasing export from agricultural activities with subsequent retention in the reservoir will change bacterial secondary production. Elevated N loading into the Kihansi reservoir (both internal and external loading) can stimulate heterotrophic bacterial production consequently resulting in changes in ecosystem function. In the N-limited River system, bacteria activity indicates a change in ecosystem function in response to anthropogenic perturbation.

Conclusion

It is observed that altered river flow and nutrient conditions results in change in ecosystem productivity. High bacterial secondary production is a result of

reduced flow giving enough time for bacterial activity to take place. Stimulation of bacterial secondary production in an N addition experiment provides evidence that excess N loading due to both elevated N exports from agriculture and processes occurring in the reservoir. Although the reservoir is currently a sink for N, there is a need to prevent excess input of dissolved inorganic N from catchment areas in order to conserve this ecosystem from changes in its productivity and the associated consequences. Future studies involving molecular techniques are recommended for identification of the bacterial communities involved and their relation to DIN and DOC uptake.

Acknowledgement

Thanks to the Lower Kihansi Environmental Management Project for funding the Radhia Ideva.

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Table 1. DOC concentration in the study stations

	DOC 2008	($\mu\text{g l}^{-1}$)	DOC ($\mu\text{g l}^{-1}$) 2005	mean DOC ($\mu\text{g l}^{-1}$) (n=2)
1	1567		837	1202
2	379		350	364.5
3	815		867	841
4	635		575	605
5	681		729	705
6	757		658	707.5

List of Figures

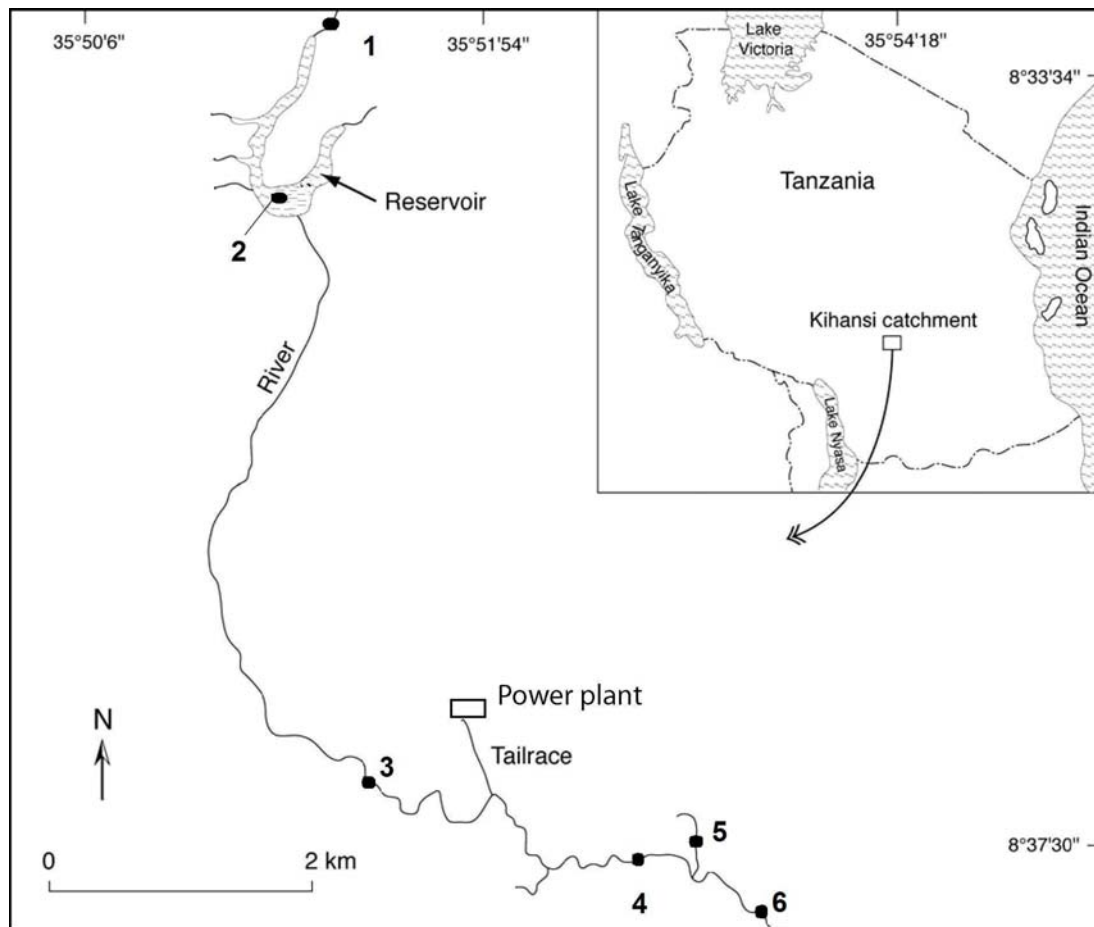


Figure 1. Study stations along the Kihansi River and reservoir

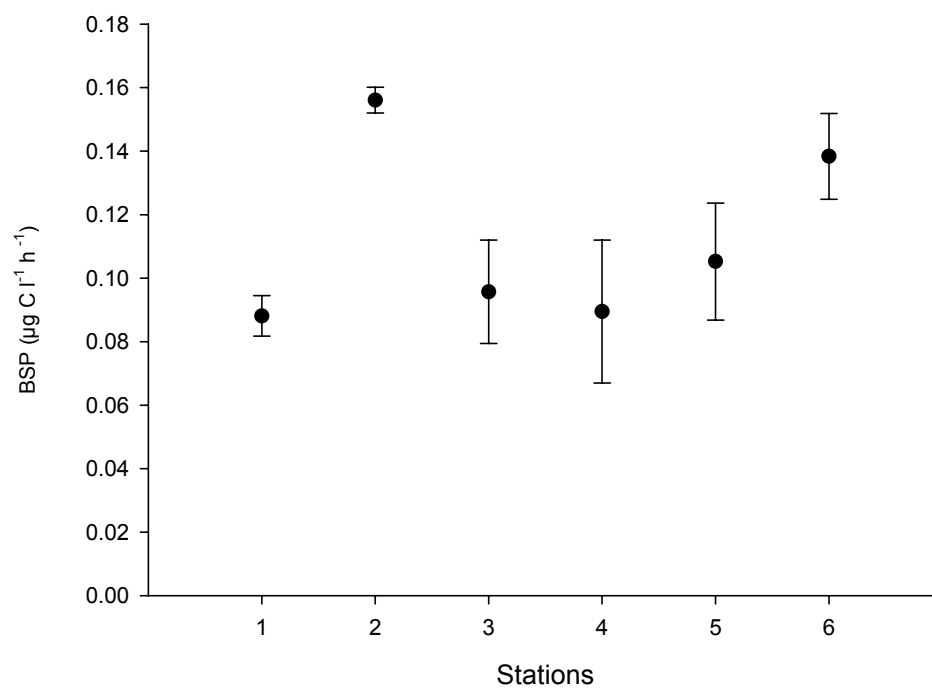


Figure 2. The mean bacterial secondary production in the Kihansi River (n=3)

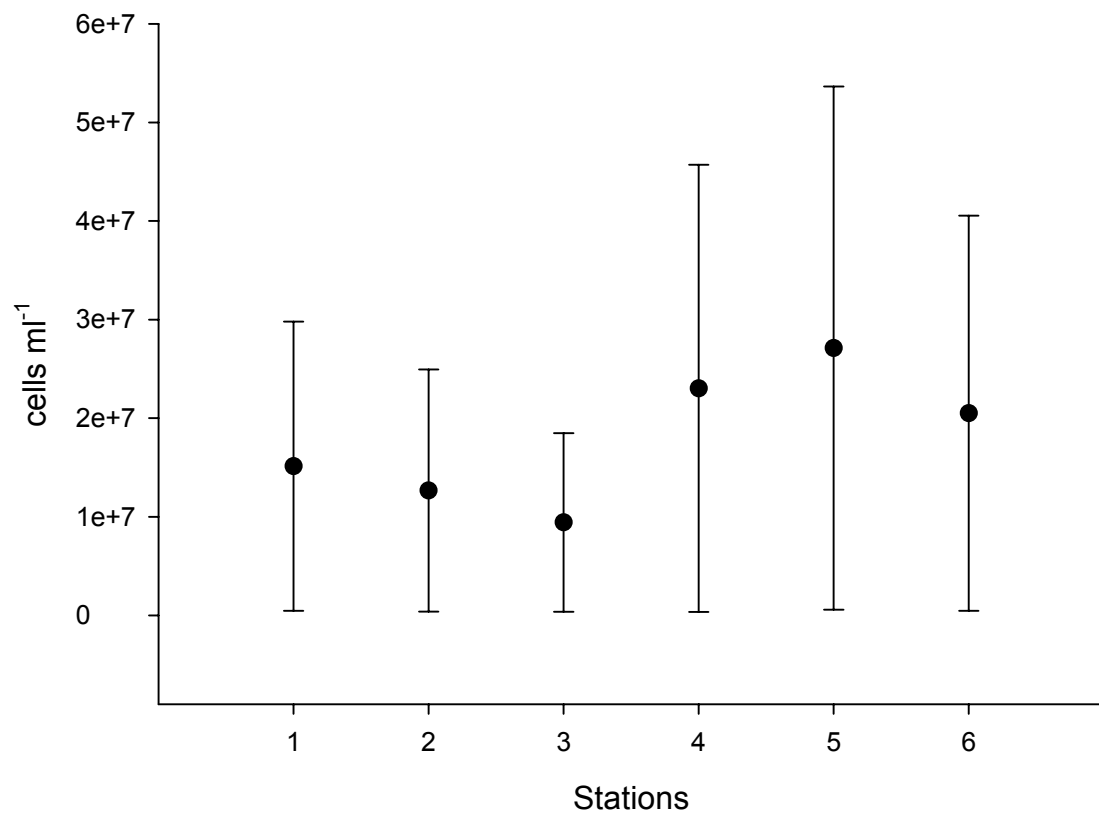


Figure 3. The mean bacterial abundance in different sites along the Kihansi River (site 1- 2 are located upstream of the dam, sites 3-6 are located downstream of the dam; n = 3)

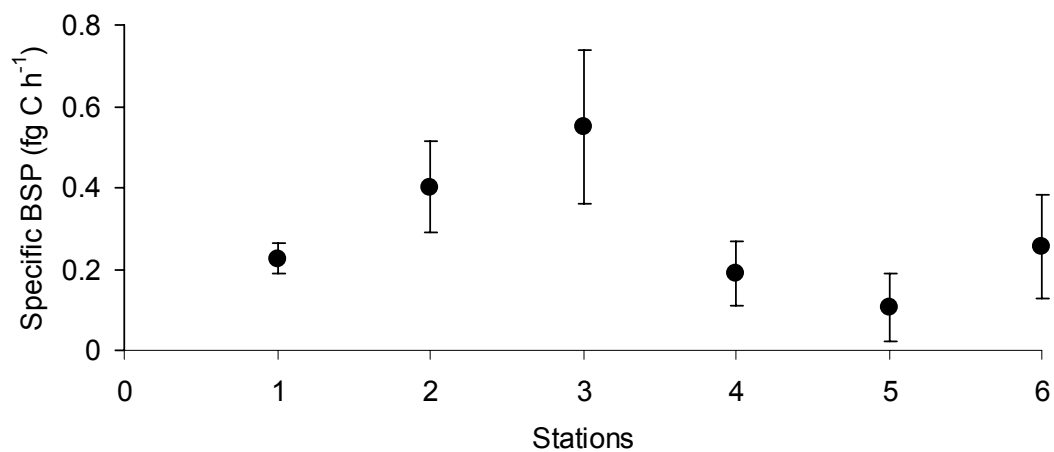


Figure 4. The mean specific bacterial secondary production rate in Kihansi River system (n=3)

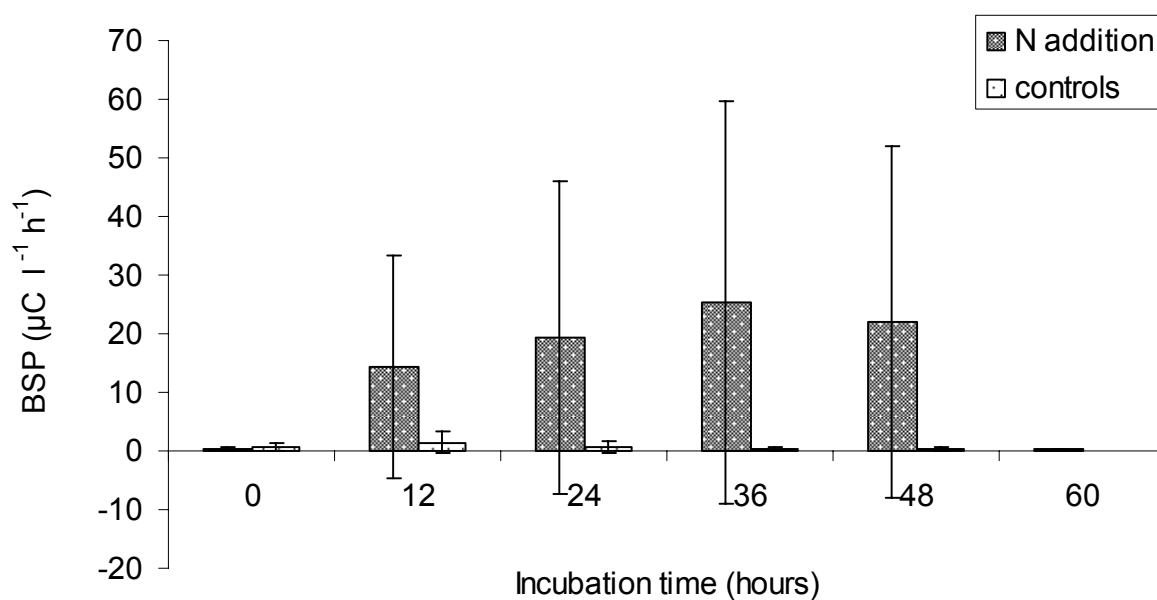


Figure 5. The mean bacterial secondary production in an N addition experiment (n=3)

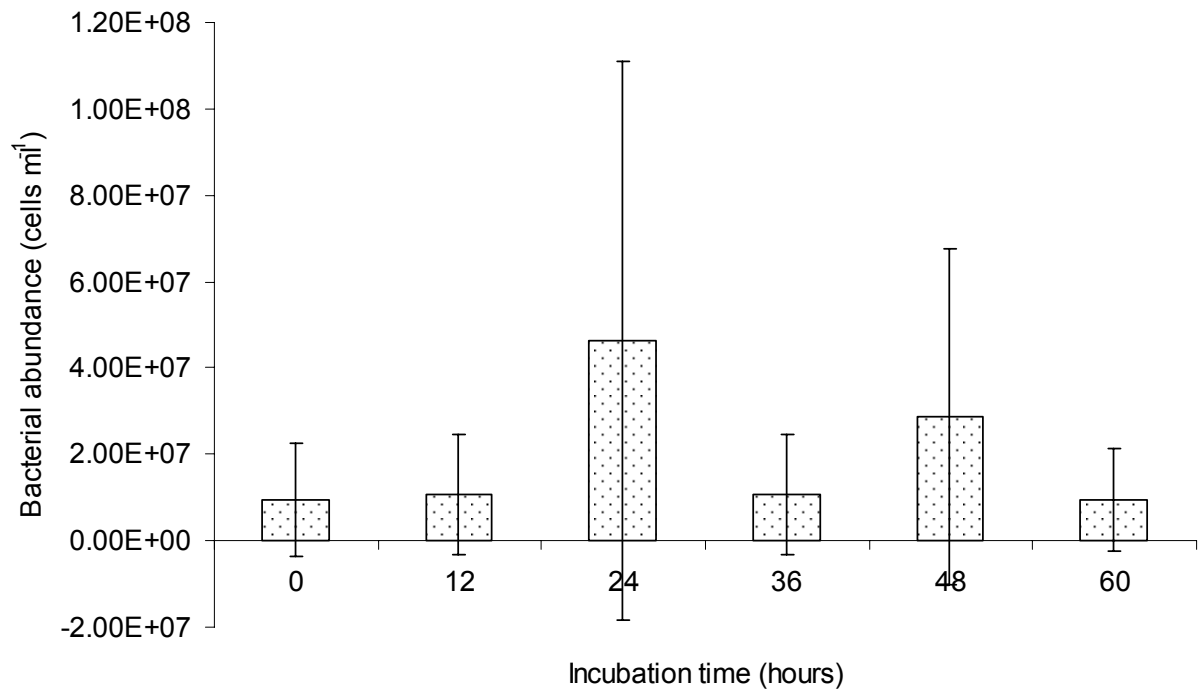


Figure 6. The mean bacterial abundance in an N addition experiment (n = 3)

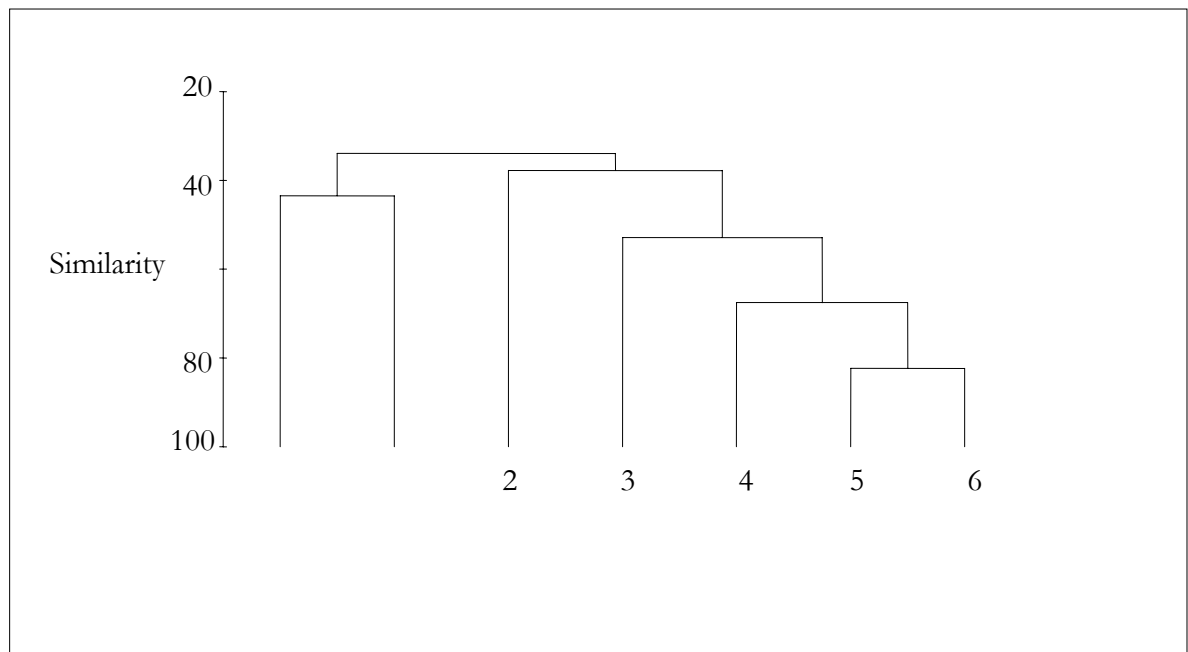


Figure 7. A dendrogram showing bacterial community similarity among sites in the Kihansi River system

Curriculum Vitae

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Educational Background

2004: MSc Environmental Sciences - University of Dar es Salaam, Tanzania

2001: BSc (General majoring Marine Biology and microbiology) - University of Dar es Salaam, Tanzania

1997: Advanced Level Certificate for Secondary Education at Msalato High School, Dodoma Tanzania

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2004 – Short course on Lake Ecology. Mondsee, Austria.

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Research Experience

2009: Ecological monitoring of the Lower Kihansi Environmental Management Project: Water quality monitoring component

2008: Effects of land use and hydropower plant on nutrient dynamics of the Kihansi River and Reservoir

2002: The Hydrogeochemistry of Fluoride in the groundwater of Northern Iramba District, Singida Region

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Work Experience

2011: Assistant Lecturer at the Department of Aquatic Sciences and Fisheries, University of Dar es Salaam teaching 'water quality and pollution control' and 'watershed management' to undergraduate students

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Consultancy

June – October 2010. Sub-consultancy to the SMEC Consultant Company to

establishing water quality and pollution control strategy in Tanzania: A consultancy to the Ministry of Water and Irrigation.

Publication

Ideva RJ, Machiwa J, Schiemer F and Hein T (2008). Effect of an impoundment on nutrient dynamics in the Kihansi River, Tanzania. *African Journal of Aquatic Science* 33 (3) 181 - 188.

Ideva R. J. (2004). Hydrogeochemistry of Fluoride in the groundwater of Northern Iramba District, Singida Region, MSc Dissertation, University of Dar es Salaam.

Ideva R.J. and Nkotagu, H. H. (2004). Fluoride in the groundwater of Northern Iramba District, Singida Region, Proceeding of Annual Water Experts Conference, 19th to 23rd January 2004, Arusha, Tanzania

Reports

Ideva R (2008). Nitrogen and phosphorus nutrient status in Kihansi Reservoir and Gorge. In: The Lower Kihansi Environmental Monitoring report. Lower Kihansi Environmental Management Project, National Environmental Management Council. Dar es Salaam, Tanzania.

Ideva R (2007). Nitrogen and phosphorus nutrient status in the Kihansi Reservoir and Gorge. In: Ecological Monitoring of the Kihansi Gorge Lower Kihansi Environmental Management Project, National Environmental Management Council. Dar es Salaam, Tanzania

Conferences/workshops attended

UNESCO-IHP workshop on addressing water quality challenges in Africa, 14th – 16th March 2011, UN Gigiri, Nairobi, Kenya.

Water quality monitoring trends in Kihansi Gorge. Ecological Monitoring Trends in the Kihansi Gorge Ecosystem. 27th -29th January 2010. Kiromo Beach Resort, Bagamoyo, Tanzania.

Strengthening Local Agricultural Innovations to Adapt to Climate Change through networking in Tanzania, Botswana and Malawi. 24th – 26th August 2009, Kunduchi Beach Hotel, Dar es Salaam Tanzania

International Limnology Austria. Fresh blood for Fresh water. 16th – 18th May 2008. Wassercluster Lunz, Austria

Membership to Organisations

1. Member of the East Africa Water Association
2. Member of the University of Dar es Salaam Alumni Association
3. Member of the Germany Exchange Programme (DAAD) alumni Association
4. Member of the Western Indian Ocean Marine Science Association