WIENER MITTEILUNGEN

WASSER • ABWASSER • GEWÄSSER

Linking Land Use to Stream Pollution: Pollutant Dynamics and Management Implications

Paul T. YILLIA

Band 214 - Wien 2009

WIENER MITTEILUNGEN

WASSER • ABWASSER • GEWÄSSER

Band 214

Linking Land Use to Stream Pollution: Pollutant Dynamics and Management Implications

Paul T. YILLIA

Herausgeber
O.Univ.Prof. Dipl.-Ing. Dr.techn. Dr.h.c. Helmut Kroiss
Technische Universität Wien
Institut für Wassergüte, Ressourcenmanagement
und Abfallwirtschaft

Dissertationsschrift zur Erlangung des akademischen Grades
eines Doktors der technischen Wissenschaften
an der Technischen Universität Wien, Fakultät für Bauingenieurwesen

Institut für Wassergüte,
Ressourcenmanagement
und Abfallwirtschaft
TU- Wien

Karlsplatz 13 / 226
1040 Wien

Institut für Wassergüte, Ressourcenmanagement und Abfallwirtschaft
Karlsplatz 13/226; 1040 Wien
Tel: + 43 1 58801 - 22611
Fax: + 43 1 58801 - 22699
Mail: iwag@iwag.tuwien.ac.at

Druck: Riegelnik
1080, Piaristengasse 19

ISSN 0279 - 5349
ISBN ISBN 978-3-85234-106-4

Zum Geleit

Der vorliegende Band der Wiener Mitteilungen enthält die Dissertation von Paul YILLIA, MSc., aus Sierra Leone, die im Rahmen eines internationalen Forschungsprogrammes entstand. Als Betreuer der Dissertation fungierte Dr. Norbert Kreuzinger vom Institut für Wassergüte, Ressourcenmangement und Abfallwirtschaft der Technischen Universität Wien.

Ziel dieser Arbeit war es mit den am Institut entwickelten Methoden des Flussgebietmanagements einen kleinen Fluss in Kenia zu untersuchen, dessen Wasser für viele verschiedene Zwecke verwendet wird: als Tränke für Nutztiere, als Trinkwasser für die lokale Bevölkerung aber auch für Bewässerung. Das Gewässer wird auch zum Baden und als Kinderspielplatz verwendet. Diese konkurrierenden Nutzungen führen naturgemäß zu Konflikten vor allem in Hinblick auf die hygienischen Belange aber auch hinsichtlich der Gewässergüte.

Dieser Arbeit liegt auch die Fragestellung zugrunde, wie man in Afrika mittels eines umfassenden integrierten Ansatzes an die dort häufig ungelösten Probleme der Wassergütewirtschaft herangehen sollte. Herr Paul Yillia hat sich viele Monate in Österreich aufgehalten um die Untersuchungsmethoden für Fließgewässer und daraus abgeleitete Methoden für ein an die lokalen Gegebenheiten angepasstes Flussgebietsmanagement zu erlernen. Er hat dann mehrere Monate in Kenia verbracht und dort mit den lokal vorhandenen Möglichkeiten für chemische und mikrobiologische Untersuchung und Datenbeschaffung ein kleines Gewässer untersucht, um die Problematik der Nutzungskonflikte sowie Lösungsansätze auszuarbeiten. Er hat dabei nicht nur die wissenschaftliche Untersuchungsmethodik des Limnologen angewendet sondern auch die sozialen und wirtschaftlichen Gegebenheiten analysiert. An Hand dieses Untersuchungsmaterials hat Herr Yillia auch verschiedene Lösungsansätze untersucht, die unter den Randbedingungen in Zentralafrika möglich und sinnvoll erscheinen.

Die vorliegende Arbeit kann als ein wichtiger Beitrag zur Lösung der Wasserprobleme in Entwicklungsländern angesehen werden. Eine langfristig wirksame geordnete Wasserwirtschaft auf Flussgebietsebene muss, so wie überall, auch in Afrika von der dortigen Bevölkerung getragen werden. Dazu sind Experten notwendig, die einerseits in der Lage sind, die spezifische lokale Situation in ihrer ganzen Komplexität zu erfassen und andererseits ein methodisches Rüstzeug beherrschen, das eindeutige Ursache - Wirkungsbeziehungen herzustellen vermag. In der vorliegenden Dissertation hat Herr Yillia diese schwierige Aufgabe mit großem Einsatz verfolgt, um daraus für die Entwicklung einer angepassten Wassergütewirtschaft in Afrika wichtige Schlüsse zu ziehen. Für die Übernahme und konsequente Verfolgung dieser schwierigen Aufgabe soll an dieser Stelle Herrn Yillia und seinem Betreuer Dr. Kreuzinger herzlich gedankt werden.

Wien, am April 2009 Helmut Kroiss

Wiener Mitteilungen (2009) Band 214

Contents

Acknowledgements

I am very grateful to the Austrian Government through the North-South Dialogue Scholarship Programme of the Austrian Development Co-operation for financing this study. Many thanks to the Academic Cooperation and Mobility Unit (ACM) of the Austrian Exchange Service – Agency for International Cooperation in Education and Research (OeAD) for the administrative support I received from various staff members.

Additional financial support and resources were provided by the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology, Austria. I am very grateful for this and would like to thank the Director O.Univ.Prof. Dipl.Ing. Dr.Dr.h.c. Helmut Kroiss and staff for the administrative, academic and technical support they provided.

I wish to express my sincere thanks and gratitude to my examiners Univ.Prof. Dipl.-Ing. Dr.techn. Norbert Matsché, and Ao. Univ. Prof. Dipl. Ing. Dr. Matthias Zessner for the time they found to examine my work.

I particularly indebted to my academic mentor and promoter Mag. Dr. Norbert Kreuzinger for the regular advice and support he consistently offered and for the constructive discussions we had throughout the project and his motivation to carry on.

Many thanks also to Prof. Jude M. Mathooko for making the project possible in Kenya and for serving as my academic mentor during the field and laboratory work in Kenya.

I am very grateful to Dr. Maria Leichtfried for the support she provided during the preparatory phase in Lunz am See, Austria, in particular for the financial grant she provided to develop the proposal and for the link with Prof. Jude M. Mathooko and Dr. Norbert Kreuzinger.

Additional thanks to Dr. Adiel E. M. Magana, Head of Department at the Department of Biological Science at Egerton University, Kenya, where the laboratory work was undertaken. Many thanks also to the staff in particular, Dr. Nzula Kitaka for her support and motivation.

My sincere gratitude to Prof. Ernest Tom Ndomahina, Director of the Institute of Marine Biology and Oceanography and Dean of the Faculty of Pure and Applied

Science at Fourah Bay College, University of Sierra Leone, Freetown for facilitating the scholarship application process, as well as for his unvarying moral and academic support he has always rendered to me.

I want to extend further thanks to the staff of the SUMAWA project at Egerton University, especially Dr. Maina Gichaba for providing useful information on the Njoro River Catchment during the field and laboratory work in Kenya.

I acknowledge and thank Ken Kosimbei and Geoffrey Ongo'ndo of Egerton University, Kenya for the timely technical assistance they provided. Thanks also to the riparian inhabitants of the Njoro River for providing useful indigenous information on the stream and the catchment.

My sincere thanks to all my friends in Austria, at home in Sierra Leone and those who are currently abroad. You stood by me when it mattered. I will remain grateful. To the Sierra Leone community in Vienna, I say thank you very much for making me feel at home in Vienna even though I was away from home.

Finally, I wish to extend my heartfelt gratitude to my parents and siblings for their prayers and support. Mama, I still remember my first day in school with you. I look back in time and I say thank you very much. And to my dear wife and children, Paul and Pauliana, who often asked "daddy when will you finish?" I say thank you for waiting patiently.

Abstract

Njoro River (60 km) is a high altitude second order stream in southwestern Kenya. It is the main source of water for Lake Nakuru National Park, a Ramsar site and a renowned tourist destination for wildlife. The stream is also important for some itinerant herdsmen and the riparian inhabitants that depend on it for their daily water needs. However, considerable land use change has occurred in the catchment within the last three decades with alterations in the water quality, ecology and hydrology of the stream and the receiving lake. But the inherent response by the stream to the interactions between human interventions and the natural landscape variables within the catchment has not been aptly investigated. As a result, the catchment was systematically studied between February 2005 and May 2008 to link land use/cover to pollution in the stream by describing loading, transportation and transformation of pollutants. Eleven sampling sites (3–5 km apart) were routinely monitored in 2005 and 2006 for a suite of water quality indicators. Additional sites were established and appropriate sampling protocols were designed to cater for specific research objectives.

Pollution levels were spatially and temporally variable with the recognition of two significant site clusters for each of three hydrological periods in the region. Analysis of the net flux of pollutants at a reduced spatial scale identified the predominantly forested Upper Njoro River Catchment as the least vulnerable, whereas the densely settled and heavily farmed areas around Egerton University and Njoro Township were the most vulnerable sub-catchments in addition to the Lower Njoro River Catchment, which has no stream flow for most of the year. The potential for self-purification was high especially within the 5 km restricted stream stretch between Egerton University and Njoro Township, in particular during dry weather. This was obliterated as stream flow increased in wet weather due to within-channel sediment mobilization, as well as runoff from commercial farms in the vicinity as was evident with the increase in suspended solids and total P during transient rainstorms. Two forms of transient pollution events were identified. Transients induced by rainstorms yielded significantly (< 0.05) higher levels of pollutants compared to short-lived episodes provoked by the diurnal in-stream activities of people and livestock. The transient yield of suspended solids, BOD_5, total P and total N in excess of base flow during storm-induced transients was particularly striking (780, 8.4, 0.5 and 0.1 t/d, respectively) with all pollutants going through a slight anticlockwise loop of improved water quality within 48–72 hrs of the descending limb of the stream hydrograph.

In-stream activities occurred at several water abstraction points (WAPs) along the stream. They included waste deposal, watering of livestock, washing of clothes and vehicles, swimming, bathing and abstraction of water for domestic use. The daily total abstraction during in-stream activities at the middle reaches was 120–150 $m^3.day^{-1}$ in dry weather, being considerably lower in wet weather. More than 60% of the abstraction was done by adult male water vendors. Vended water from the stream was sold at US$ 3.5–7.5 per cubic meter and vendors earned between US$ 3–6 a day. During dry weather, abstracted water contributed approximately 40–60% of the total daily consumptive water use in the riparian area. However, > 30% of the morning stream flow was abstracted thereby upsetting stream flow in the lower reaches. In-stream activities also affected the water quality of the stream. In particular, the microbial water quality deteriorated significantly ($p < 0.05$) downstream of activities increasing by at least 1–2 log units during in-stream activities. The empirical upstream/downstream site parity/disparity that was observed reflected the diurnal periodicity of in-stream activities and the concomitant pollution they caused. Consequently, the potential health risk (PHR) at the WAPs for bathing and drinking exceeded acceptable health risk levels. PHR was 2–3 times higher with the Cabelli (1983) intestinal enterococci model compared to the U.S. EPA (1994) *Escherichia coli* model.

It was concluded that the response of the stream to various human interventions is principally governed by the current land use/cover, the seasonal and diurnal periodicity of human activities and the seasonality of the hydrological regime. This knowledge could be useful for pollution management in the catchment. Measures may include: (i) improving wastewater treatment efficiency to minimize loading from point sources; (ii) small-scale actions at various locations in the catchment to minimize the transfer of pollutants via surface runoff from diffuse sources; (iii) restricting access within certain stream reaches to control in-stream activities of people and livestock and; (iv) improving water and sanitation facilities in the settled areas of the catchment.

Chapter 1

Introduction

Stream pollution – Perspectives on sub-Saharan Africa

The importance of streams for socioeconomic development and environmental sustainability is recognised throughout sub-Saharan Africa. Streams provide a variety of functions that are valuable to the environment, national economies and the dependent populations (Mbuligwe and Kaseva 2005). And as a matter of fact, many people in the region, in particular those in rural areas live in the proximity of surface water systems for their daily water needs. They are usually shallow streams or ponds. Various studies in sub-Saharan Africa that have monitored the water quality of these systems conclude that many surface water systems are unable to provide basic functions because they are under increasing threat of pollution from various human interventions (Venter *et al*., 1997; Nevondo and Cloete, 1999). These systems receive heavy metals, organochlorides, carbonates, sulphates and several other contaminants that are discharge from industrial areas (Fatoki *et al*., 2001; Mwannuzi, 2000). And runoff from a multitude of disperse sources such as agricultural fields, urban drains, commercial establishments and mining fields introduce soil, organic matter, fertilizers, faecal matter, pesticides, toxic metals and solid waste into streams (Fatoki *et al*., 2001; Dabrowski *et al*., 2002; Mbuligwe and Kaseva 2005).

These contaminants can seriously inhibit stream functions by severely degrading water quality, reducing aesthetic and economic values and rendering them inhospitable to aquatic life with negative consequences on dependent populations. For instance, nutrient enrichment by nitrogen and phosphorus could have irreversible damage on aquatic ecosystems, whereas pathogens and heavy metal contamination of water sources could directly affect human health (Jonnalagadda and Mhere, 2001; Obi *et al*., 2002; Byamukama *et al*., 2005). Of increasing concern are the multiple sources and pathways through which pollutants enter aquatic systems. Industrial effluents and sewage treatment outfalls are still the principal point sources in sub-Saharan Africa (Mbuligwe and Kaseva, 2005). This might be largely due to weaknesses in effluent regulations and inadequate wastewater treatment technologies. Diffuse sources are difficult to detect and isolate but current evidence suggest that human activities within stream channels and surface runoff, as well as subsurface flow from agricultural fields and residential areas are the prime diffuse sources (Dabrowski *et al*., 2002; Mokaya *et al*., 2004; Yillia *et al*., 2007).

Consequently, evidence has increased that aquatic pollution results mainly from inconsiderate land use practices in the vicinity of affected systems with links being made between several land use types to specific contaminants in water. Several studies investigating the consequences of land use on aquatic systems in sub-Saharan Africa have compared different land use types and human activities such as mining, industries, urban development, agriculture and forestry and correlated them to pollution levels in affected streams (Dabrowski *et al*., 2002; Mokaya *et al*., 2004). Others have related high faecal and organic matter loading in streams draining urban catchments to urban storm runoff and inadequate sanitation facilities (Byamukama *et al*., 2005; Mbuligwe and Kaseva 2005). Simple GIS-based runoff models have been used in some places to show that differences in catchment variables in particular land use are responsible for observed differences in contamination of streams (Dabrowski *et al*., 2002). Such studies are indispensable when considering catchment based measures for curbing pollution. However, most reports on stream pollution in sub-Saharan Africa are investigations carried out on streams draining urban or peri-urban areas. Many rural streams have largely been ignored even though information on their pollution status is crucial for pollution management.

Njoro River Catchment, Kenya – An overview

The Njoro River (60 km) is a second order stream in southwestern rural Kenya with the little Shuru as its main tributary (Mathooko, 2001; Shivoga, 2001). The catchment area is approximately 200 km^2. It originates from the Eastern Mau Escarpment at an elevation of 2700 m (a.s.l) and drains into Lake Nakuru at 1700 m (a.s.l) at the floor of the Rift Valley. The lake is an enclosed basin that is protected by the Ramsar Convention and a renowned tourist destination for wildlife (Lelo *et al*., 2005). Stream flow from the Njoro River is the main source of water for Lake Nakuru. The stream is also important for many poor rural riparian inhabitants who depend on it for their daily water needs and the catchment is a major destination for itinerant herdsmen, in particular during dry weather, when large herds of cattle, sheep and goats are led into the catchment in search of pasture and water. Nevertheless, there has been considerable population growth in the catchment area mainly as a result of immigrant farmers and settler pastoralist whose activities have resulted in rapid land use change during the last three decades (Kundu *et al*., 2004; Lelo *et al*., 2005). A significant change in land use from forest and woodland (75% and 12% in 1969) to agriculture and rural built-up land has occurred (Kundu *et al*., 2004). Currently, the predominant land use coverage includes small scale agriculture (82%) woodland/grassland (7%) urban/residential plots (6%) and forest cover (5%). Cultivation is intensive and mainly rain-fed with the growing period coinciding with wet weather conditions.

Problem statement and justification of research

The present land use problems in the Njoro River catchment could be described as a typical manifestation of an immense social and environmental challenge facing authorities, in particular natural resource managers in Kenya and sub-Saharan Africa as a whole. The change in land use particularly during the last two decades is thought to be responsible for alterations in ecology, hydrology and water quality of both the stream and its receiving lake (Mathooko, 2001; Shivoga, 2001; Mokaya *et al*., 2004; Yillia *et al*., 2007). Rapid demographic growth in the catchment has outpaced the development of services and triggered the biophysical alteration of the landscape (Mathooko and Karuiki, 2000). The forest cover has been reduced considerably and agricultural land use has intensified (Kundu *et al*., 2004; Lelo *et al*., 2004). Most of the residents in the catchment do not have access to adequate water supply and, sanitation facilities are dismally poor. Hence, people and livestock visit the stream regularly and undertake a variety of activities within or beside the stream channel (Mathooko, 2001). The riparian buffer strip in most sections of the stream has been destroyed due to these activities (Mathooko and Karuiki, 2000). Surface runoff is though to have increased and the input of sediments, nutrients and faecal contaminants in the stream is reported to be high (Mokaya *et al*., 2004; Yillia *et al*., 2007).

Certainly, the multitude of potential sources of pollutants in the catchment clearly points to both point and diffuse sources. It is therefore necessary to link the various land use types and human activities in the catchment to pollution in the stream. This could form the basis for developing pollution abatement measures. Notwithstanding this need, the processes by which the stream respond to the interactions between human interventions and the natural landscape variables in the catchment has not been aptly investigated. In particular, understanding the loading, transportation and transformation of pollutants, as well as knowledge of the spatial and temporal dynamics of pollutants and the processes, which govern such variations are extremely crucial for developing various management scenarios and implementing measures to curb pollution.

It is worth noting that in-depth and consistent scientific study on the Njoro River and its catchment area started during the Tropical River Ecology Initiative of the mid 1990s with interest on the disturbance of stream biocoenosis (Mathooko, 2001). But the recent increase in the population and the accompanying land use alteration and environmental degradation necessitates a shift in research approach to include livelihoods, stream hydrology and water quality. Therefore, the catchment was methodically studied between February 2005 and May 2008. The study was executed in three phases as follows: (i) six months of preparatory work and literature review in Austria; (ii) fieldwork in Kenya for sixteen months to gather water quality data from the stream and; (iii) sixteen months of data analysis, further literature study and writing-up in Austria.

Aims of the research

The overall objective of this PhD research was aimed at:

(i) linking land use and human activities in the Njoro River Catchment to pollution in the stream;

(ii) describing loading, transportation and transformations of pollutants along the stream and;

(iii) suggesting realistic management measures that may be useful for pollution control in the catchment.

The catchment is predominantly rural with agriculture and pastoral farming dominating industrial or urban activities. Therefore, the choice of pollutants studied was limited to suspended solids, micronutrients (PO_4-P, total P, NH_4-N, NO_2-N, NO_3-N and total N), microbial faecal contaminants (heterotrophic plate counts, total coliforms, *Escherichia coli* and intestinal enterococci) and organic matter, which was measured as BOD_5 and UV_{254}. In addition, stream flow, turbidity, alkalinity, hardness and the physico-chemical parameters (temperature, pH, conductivity, dissolved oxygen and its percent saturation) were investigated.

Scope of the thesis

This thesis is structured such that the main research themes that were investigated are presented in chapters as standalone documents in the manner in which they have been accepted, prepared or submitted for publication in various journals as specified. But cross-referencing of chapters will facilitate reading and comprehension of the overall objective.

Chapter 2 gives a description of the Njoro River Catchment. A systematic review is presented of recent research advancements with special emphasis on evaluating published and unpublished information on the biophysical landscape and the alterations caused by population growth, land use and human activities in the catchment.

The account in *Chapter 3* on the spatio-temporal dynamics of pollutants along the stream reports a routine monitoring approach that was undertaken to provide information on the pollution status of the stream. A suite of traditional water quality indicators was evaluated for associations between indicators, as well as their efficacy to segregate stream sites based on pollution levels. A proposal is presented to optimize the current sampling programme.

A vulnerability assessment of the catchment at a reduced spatial scale was undertaken to link land use variables and various sources of pollutants to pollution levels in the stream. Emissions and riverine loads of pollutants were estimated for five sub-catchments in the catchment to isolate and prioritize specific areas for interim pollution management and remediation. This work is presented in *Chapter 4*.

Two major episodic pollution events that are hardly captured during routine monitoring were recognized during the catchment vulnerability assessment. *Chapter 5* on transient pollution describes the relative contribution of diffuse pollution by storm-induced transients and the diurnal episodes provoked by the in-stream activities of people and livestock.

In-stream activities occurred at several water abstraction points (WAPs) along the stream. They were characterized and reported in two parts. Part I in *Chapter 6* describes the nature of these activities and the effect they have on dry weather stream flow and the chemical water quality. Part II in *Chapter 7* is a description of the effect of in-stream activities on the microbial water quality using pair wise evaluation of stream sites at the two most frequently visited WAPs at the middle reaches.

The high levels of faecal indicator bacteria that were reported at the WAPs necessitated an interim microbial health risk assessment, which followed the observed-adverse-effect-level (OAEL) approach with the aid of two U.S. based models that are often used to characterize recreational water quality. This work is presented in *Chapter 8*.

Chapter 9 concludes with a recapitulation of the main objective of the study, a summary of the main findings and some suggestions of possible catchment-based management measures to curb pollution in the catchment.

References

Byamukama, D., Mach, R. L., Kansiime, F., Manafa, M., Farnleitner, A. H., 2005. Discrimination efficacy of faecal pollution detection in different aquatic habitats of a high-altitude tropical country, using presumptive coliforms, Escherichia coli, and Clostridium perfringens spores. *Applied Environmental Microbiology* 71 (1), 65 – 71.

Dabrowski, J. M., Peall, S. K. C., van Niekerk, A., Reinecke, A. J., Day J. A., Schulz, R., 2002. Predicting runoff-induced pesticide input in agricultural sub-catchment surface waters: linking catchment variables and contamination. *Wat. Res*. 36, 4975 – 4984.

Fatoki, O. S., Muyima, N. Y. O., Lujiza, N., 2001. Situation analysis of water quality in the Umtata River catchment. *Water South Africa* 27 (4), 467 – 474.

Jonnalagadda, S. B., Mhere, G., 2001. Water Quality of the Odzi River in the Eastern Highlands of Zimbabwe. *Wat. Res*. 35 (10), 2371 – 2376.

Kundu, P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. Proceedings - XXth ISPRS Congress. Istanbul, Turkey, 405 – 409.

Lelo F.K., Wanjiku, C., Jenkins, M. W., 2005. Managing Riparian Resources in the River Njoro Watershed in Kenya: The Challenge of Conflicting Laws, Policies and Community Priorities. Paper Presented: International workshop on "African Water Laws - Plural Legislative Frameworks for Rural Water Management in Africa. Guateng, South Africa.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131-139.

Mathooko, J. M., Kariuki, S. T., 2000. Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. *African Journal of Ecology* 38 (2), 123 – 129.

Mbuligwe, S. E., Kaseva, M. E., 2005. Pollution and self-cleansing of an urban river in a developing country: A case study of Dar es Salaam, Tanzania. *Environmental Management* 36 (2), 328–342.

Mokaya, S. K., Mathooko, J. M., Leichtfried, M., 2004. Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *African Journal of Ecology* 42 (4), 281 – 288.

Mwannuzi, F. L., 2000. Assessment of water quality for Pangani River in Tanzania using QUAL2E windows version. Proceedings of the 1st WaterNet/WARFSA Symposium, Maputo, Mozambique.

Nevondo, T. S., Cloete, T. E., 1999. Bacterial and chemical quality of water supply in the Dertig village settlement. *Water South Africa* 25 (2), 215 – 220.

Obi, C. L., Potgieter, N., Bessong, P. O., Matsaung, G., 2002. Assessment of the microbial quality of river water sources in rural Venda communities in South Africa. *Water South Africa* 28 (3), 287 – 292.

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiolgia* 458, 121 – 130.

Venter, S. N, Steynberg, M. C., de Wet, C. M. E., Hohls, D., du Plessis, G., Kfir, R., 1997. A situation analysis of the microbial water quality in a peri-urban catchment in South Africa. *Wat. Sci. Tech.* 35 (11-12), 119–124.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007. In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya. Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium. Lusaka, Zambia.

Chapter 2

Management ineptitude in the Njoro River Catchment: Should we blame it on paucity of information? – A systematic review

Prepared for submission: *African Journal of Ecology*

Management ineptitude in the Njoro River Catchment: Should we blame it on paucity of information? – A systematic review

P. T. Yillia*, N. Kreuzinger** and J. M. Mathooko***

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; E-mail: *paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at*
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; E-mail: *norbkreu@iwag.tuwien.ac.at*
***Egerton University, Department of Biological Sciences, PO Box 563, Njoro, Kenya; Tel: +254 37 61282 or +254 720853844; Fax: +254 37 61055; E-mail: *jmathooko@hotmail.com*

*corresponding author

Abstract
A systematic review is presented of recent research advancements on the Njoro River Catchment (NRC), south-western Kenya. Particular emphasis is placed on evaluating published and unpublished scientific information on the biophysical landscape and the alterations caused by population growth, human activities and land use change. Also the relevance of this knowledge for broader catchment management is examined and an attempt is made to identify possible knowledge gaps that may be hindering management efforts. Undoubtedly, the situation in the NRC is critical – a typical manifestation of the immense social and environmental challenges facing natural resources managers in this part of Kenya. However, substantial information already exists to aid management efforts. Indeed there is knowledge dearth especially on a sustained long-term basis in almost all disciplines but current information gaps need not hinder management efforts as these gaps do not amount to the ostensible general paucity of information that is often widely blamed for the management ineptitude in the catchment.

Keywords
Land use change; management ineptitude; Njoro River Catchment; paucity of information

Introduction

The Njoro River Catchment (NRC) is largely an agro-pastoral catchment in southwestern rural Kenya. The NRC has been in the spotlight in recent times for a number of wrong reasons: (i) extremely flawed and controversial resettlement schemes; (ii) rapid population growth and land use change; (iii) sporadic inter-tribal conflicts; (iv) land and water degradation and; (v) human health risk associated with the use of degraded natural resources, especially, polluted water. Various independent assertions have been made to link some of these issues but there is consensus that the problems were initiated and worsened by repeated actions by successive post-independence governments, particularly in the early 1990s to reverse previous decrees on protected areas and resettle landless farmers and herdsmen in the catchment in an attempt to resolve more than 40 years of land ownership problems and related injustices caused by British colonial rule in the agriculturally fertile areas of central Kenya (Baldyga, 2005; Lelo *et al.*, 2005 and; Krupnik and Jenkins, 2006). It is supposed that since then, the resettlement schemes have been politicized with allegations of political manipulations to redistribute land to certain ethnic groups for political patronage. It is also alleged that politicians have repeatedly capitalized on the situation to incite hatred and violence among ethnic groups. Both phenomena are recurrent in various parts of Kenya and have become the hallmark of politics in post-independent Kenyan.

Notwithstanding these challenges, there is currently no cohesive catchment management framework for the NRC. Yet paucity of information is often blamed for the management problems in the catchment. Almost all research on the catchment was justified on this basic premise. As a result, several independent studies, as well as local and international collaborative research efforts were initiated within the last two decades in an effort to address the inadequacy. While some of the work accomplished on the NRC could be found unpublished on private shelves and those of various academic departments at Egerton University, a substantial amount is available in scientific journals, most of which can be downloaded on the internet without additional costs apart from the usual internet connection fees. Also available on the internet and are articles in proceedings of various scientific symposia and reports of various projects accomplished on the catchment in recent times. A synopsis of this information, in particular the sources can be beneficial to natural resources managers, stakeholders and research groups alike, especially when considering the diversity of sources from which information on the catchment could be obtained and the inherent difficulties associated with accessing and obtaining such information. The current article attempts a systematic review of recent research advancements on the NRC with particular emphasis on those studies that examined the impact of demographic growth and human activities on the biophysical landscape.

Methodology

Literature search

The literature search lasted for slightly over three years from March 2005 to May 2008. It included several computerized databases, in particular, the popular search engines, Google (http://www.google.com), Yahoo (http://www.yahoo.com), msn (http://www.msn.com) and Wikipedia (http://www.wikipedia.com). The search terms were mainly key words such as “Njoro River”, “Njoro”, “Lake Nakuru”, “Egerton University”, and the names of popular authors and/or researchers, as well the names of projects and research initiatives e.g., “SUMAWA” and “Tropical River Ecology Initiative”. In addition, hard copies of published information were obtained from peer-reviewed journals and unpublished information was acquired from departmental libraries, as well as private libraries of staff and researchers at Egerton University. This included MSc. and PhD dissertations. Furthermore, conference proceedings were also sort using the methods listed above. Some undergraduate dissertations were included in the preliminary review but they were not flagged for the final review process. Authors and academic staff were consulted for both published and unpublished information. Lastly, the bibliographies of all published information were reviewed for additional information.

Selection criteria

All reported studies that were accessed were reviewed, whether published or unpublished. Then potentially relevant studies were flagged for further review based on the following criteria: (i) published studies in peer-reviewed journals; (ii) published accounts in books, manuals and newsletters; (iii) unpublished MSc. and PhD dissertations; (iv) reports in the proceedings of various symposia and; (v) unpublished reports of projects and research initiatives. It is worth noting that the selection of flagged articles was based on the primary objective of the review processes and was influence by the obvious limitations of the review exercise such as the discretion of the reviewers. Thus, the choice of a flagged article is by no means an indication of quality or the overall usefulness of the study. Apologies to all authors/researchers that were not contacted but could have provided useful information and/or make their work available had they been approached.

Results and discussion

In total, sixty-seven (67) articles were reviewed for relevance. Out of these, 38 appeared relevant and were flagged for the final review process. Table 1 provides a list of all the studies and reports that were flagged for the final review process. The list is by no mean complete considering the difficulties associated with accessing such information. But as a first step, the review process tried to include all publish and unpublished information that was obtained. Three main research themes were evident: (i) aquatic ecology; (ii) Land use/cover; (iii) Hydrology; (iv) Water use and; (iv) Aquatic pollution. The studies were heavily skewed towards investigations on stream ecology, most of them conducted during the Tropical River Ecology Initiative (TREI) of the 1990s or the follow-up investigations that were associated with this research programme. TREI was a joint programme of the then Departments of Zoology and Botany (now the Department of Biological Science) at Egerton University and the Austrian Academy of Sciences through the then Biological Station at Lunz Am See in Austria. The studies around this theme provided answers to important queries and formed the basis for subsequent research, especially stream biocenosis. However, only a few were interdisciplinary and/or devoted to human interactions with the landscape (Bretschko, 1995; Mathooko and Kariuki, 2000; Mathooko, 2001; Mokaya *et al*., 2004 and; M'Erimba *et al*., 2006). Instead, most were short-term ecological studies at the middle and lower stream reaches that were aimed primarily at describing the biophysical landscape and assessing the dynamic processes in the stream and its receiving basin, Lake Nakuru. Almost all the authors of these studies were either affiliated to the Austrian Academy of Sciences or the then Departments of Botany and Zoology (now the Department of Biological Science) at Egerton University.

In more recent years, there has been a fundamental shift in research approach (Lelo *et*. *al*., 2005; Krupnik, 2004; Krupnik and Jenkins, 2006). The new initiative known as SUMAWA (Sustainable Management of Watersheds) involves research on a broad spectrum of interrelated disciplines ranging from the assessment of the biophysical landscape to social science issues encompassing the entire catchment. Specific research areas include agronomic practices, economic issues, use of local resources, soil management, landscape ecology, hydrology and water quality (Krupnik, 2004). The intension is to link demographic change to biophysical landscape alterations and livelihoods of poor rural inhabitants involving various disciplines with researcher coming from a broad spectrum of research and academic institutions in Kenya and the US. This approach is receiving the attention of natural resources managers and funding agencies alike since current support for research places high premium on partnerships and the applicability of research findings to address pressing environmental and social problems. The SUMAWA studies are still in progress. Excerpts from the studies and other individual research efforts are grouped in the ensuing discussion under various subheadings to provide information on the NRC.

Table 1. NRC studies flagged for final review

Referenced material	Key study theme	Affiliation	Referenced material	Key study theme	Affiliation
Bretschko, 1995	Stream ecology	1	Mainuri, 2005	Soil science	4
Leichtfried & Shivoga, 1995	Stream ecology	1,3	Baldyga, 2005	Hydrology/Land use	16
Mathooko & Kariuki, 2000	Vegetation cover	2	Kundu, 2005	Land use	6
Magana & Bretschko, 2003	Stream ecology	2	Lelo *et al.,* 2005	Resource use	6
Mathooko *et al*., 2000*a*	Stream ecology	2	Mutua & Gichaba, 2006	Hydrology	6
Mathooko *et al*., 2000*b*	Stream ecology	2	Krupnik & Jenkins, 2006	Resource use	5
Magana, 2001	Stream ecology	2	M'Erimba *et al*., 2006	Stream ecology	2
Mathooko, 2001	Water use/ecology	2	Yillia *et al*., 2007a	Water use/Hydrology	7,8,2
Mathooko *et al*., 2001*a*	Stream ecology	2	Yillia *et al*., 2007b	Stream pollution	7,8,2
Mathooko *et al*., 2001*b*	Stream ecology	2	Mokaya *et al*., 2004	Stream pollution	2
Shivoga, 2001	Stream ecology	3	Odero and Peloso, 2000	Hydrology	9,10
Mathooko & Otieno 2002	Stream ecology	2	Raude *et al*., 2007	Land use/Hydrology	11
Mathooko *et al*., 2002	Stream ecology	2	Moturi *et al*., 2002	Water use/Health	4,12
Dobson *et al*., 2003	Stream ecology	2	Baldyga *et al*., 2004	Land use/Hydrology	3,6,16
Morara *et al*., 2003	Stream ecology	2	SUMAWA, 2005	Human interaction	16
Muia *et al*., 2003	Stream ecology	2	Jenkins *et al*., 2005	Water management	5,16
Shivoga *et al.,* 2002	Stream ecology	3	Krupnik, 2004*a*	Resource use	5
Mathooko *et al*., 2004	Stream ecology	2	Kundu *et al.,* 2004	Land use	6
Makoba, *et al*., 2007	Stream ecology	3, 5	Odada *et al*., 1998	Management	13, 14, 15

1: Austrian Academy of Sciences; 2: Department of Biological Sciences, Egerton University, Kenya; 3: Faculty of Environmental Science, Egerton University, Kenya; 4: Department of Soil Science, Egerton University, Kenya; 5: University of California at Davis, USA; 6: Department of Geography, Egerton University, Kenya; 7: University of Sierra Leone, Freetown; 8: Institute for Water Quality Resources and Waste management, Vienna University of Technology, Austria; 9: Department of Geology, University of Nairobi, Kenya; 10: Dipartimento di Scienze della Terra Dell'Universita, via Ferrata, Pavia, Italy; 11: Department of Agricultural Engineering, Egerton University; 12: Moi University, School of Environmental Studies, Kenya; 13: Department of Geology, University of Nairobi, Kenya; 14: World Wildlife Fun for Nature, Nakuru, Kenya; 15: Wetland Programme, Kenya Wildlife Service, Kitengela, Kenya; 16: Department of Renewable Resources, University of Wyoming, USA

Size and location

Two different estimates are given for the size of the NRC (0º 15′ S, 0º 25′ S and 35º 50′ E, 36º 05′ E). The same is equally true for the length of the main Njoro River flow. Both estimates are associated with the two main research groups i.e., the TREI and SUMAWA. Publications and reports by authors and researchers affiliated with the TREI cite 200 km^2 and 50 km for the size and length of the stream, respectively (Mathooko *et. al*., 2000; Mathooko and Kariuki, 2000; Magana, 2001; Mathooko, 2001). Alternatively, more recent estimates by the

SUMAWA research group reported 280 km^2 and 60 km of the same catchment and its main stream (Lelo *et al.*, 2005; Krupnik and Jenkins, 2006, Baldga, 2005, Mainuri, 2005). However, both research groups agree on other aspects of the Njoro River and its catchment area. The Njoro River is a second order high elevation stream. Originating from the eastern segment of Mau Hills (3000 m a.s.l.), the stream flows through indigenous and exotic forests, informally settled areas and cultivated land. It is very shallow and intermittent particularly during dry weather in the lower reaches. NRC is located in Nakuru District, Rift Valley Province, ca. 140 km northeast of the Kenyan capital city Nairobi (Fig. 1). It drains periodically into Lake Nakuru, an endorhic, alkaline and hypereutrophic lake located on the floor of the rift valley (Shivoga, 2001). The lake is within the precinct of Lake Nakuru National Park (LNNP) a designated wildlife sanctuary of international importance (Ramsar site) and a renowned tourist destination notably for its vast flock of flamingos (700,000) that give the lake its characteristic pink shoreline (Leichtfried and Shivoga, 1995).

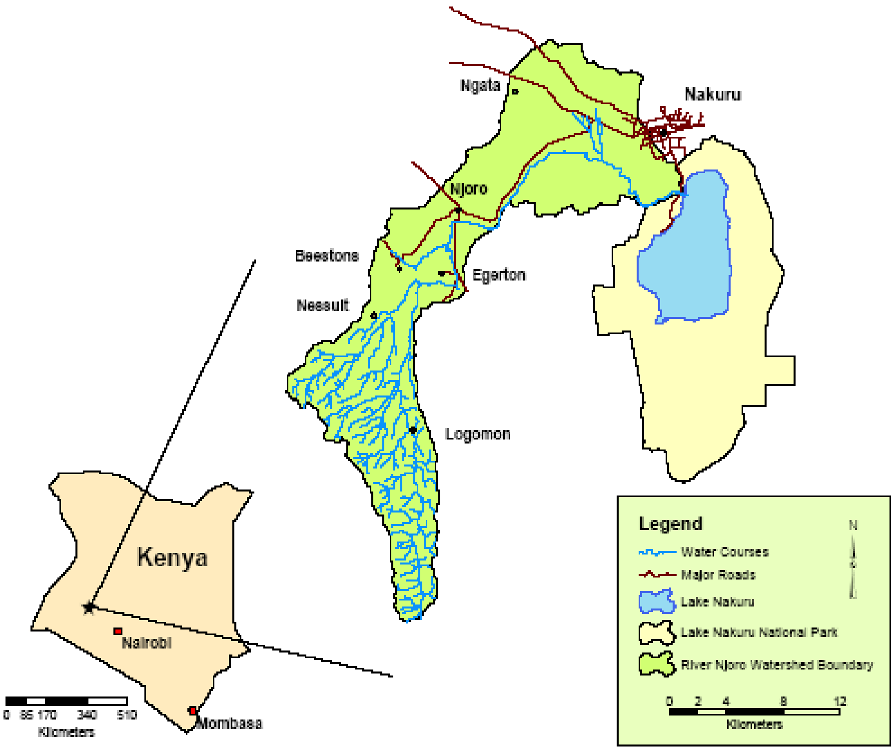

Figure 1. Njoro River catchment. Source: Baldyga, 2005

Landscape and stream morphology

The catchment landscape is structurally heterogeneous and vastly undulating with a steep escarpment in the upper catchment. Residual hills, steep sided valleys, deeply incised gorges, plateaux and rolling plains characterize the middle and lower catchment (Baldyga, 2005, Mainuri, 2005). Slopes are generally steep averaging from 17–30% in the near vertical slopes of the upper mountainous catchment to < 4% in the moderate and gentle slopes, plateaux, plains and peneplains of the middle and lower catchment (Baldyga, 2005; Mainuri, 2005). The altitude declines sharply but uniformly from the peak of the Eastern Mau Escarpment (2800 m a.s.l.) to Lake Nakuru (1700 m a.s.l.) at the floor of the rift valley. The Njoro River is structured in a typical riffle-pool sequence with soft substratum of easily eroded fine sediments in pools and fairly resistant bedrock in the riffle sections (Mathooko and Kariuki, 2000; Mathooko, 2001). This pattern is more evident in the middle reaches where the stream banks in the riffle sections are generally characterised by deeply incised gorges and valleys with very steep sides. The width of the active stream channel may vary with flow but generally it is narrow (0.3–2.3 m). The depth is shallow (0.06–0.1 m) at the riffle sections with exposed bedrock and swirl holes in some places. Swirl holes were probably formed by the scouring action of traction load transported by the stream during high discharge. The surface area of swirl holes can range from 0.15–1.57 m^2 and depths could vary from 0.17–1.35 m (Morara *et al*., 2003). Steep sided banks are not readily accessible to people and livestock. In contrast, pools are visited frequently by people for various activities (abstraction of water for domestic use, watering of livestock, washing of cloths and vehicles, swimming, bathing, waste disposal etc). Where disturbance is high the banks are bare of vegetation (Mathooko *et al*., 2001). Pools are found in stream sections with open and shallow banks that are easily accessible. The active stream channel at most pools is wider (4–10 m), deeper (0.3–0.8 m) and holds slow flowing water (Mathooko *et al*., 2000; Magana, 2001; Dobson *et al*., 2003; Muia *et al*., 2003). In less disturbed areas, pools contribute significantly to the retention and long-term storage of particulate organic matter mostly leaves and twigs derived from the riparian vegetation (Mathooko and Kariuki, 2000; Magana, 2001; Mathooko *et al*., 2001b; Morara *et al*., 2003). Pools and riffles give way to runs as flow increases and the slope diminishes. Hence, runs are particularly evident at the lower reaches, especially during wet weather flow when pools and riffles are connected due to increase in stream flow and transient dams created by obstruction debris. Debris dams are efficient structures for trapping particulate matter mainly falling leaves and twigs of the riparian vegetation and solid waste of human origin (Morara *et al*., 2003). Steps occur in the steep slopes of the high mountain upper reaches where the stream flow over exposed sills and dykes that have resisted abrasion and erosion by the stream.

Geology and soils

The geology of this region consists predominantly of Quaternary volcanic material characterized by porous pumiceous formations and basaltic intrusions that are weakened by fault lines and scarp zones (Baldyga, 2005; Mainuri, 2005). It is thought that these features are in part responsible for the cessation of flow in the lower reach of the stream during dry periods. In recent years the stream bed remains dry for most of the year in the lower reaches with disconnected pools which eventually dry out as the stream flow diminishes and apparently disappears in cracks and fissures mostly along fault lines that are characteristic of the volcanic landscape in this region (Shivoga, 2001). Even though many blame the cessation of flow in the lower reaches on land degradation and abstraction in the upper catchment, early geologic surveys (McCall, 1967) reported loss of stream flow in cracks and fissures on the stream bed. And the recharge of the receiving lake was detailed as a combination of direct rainfall, surface runoff and groundwater seepage from stream losses through porous rocks and fault zones in the landscape (Baldyga, 2005).

The most comprehensive soil study was undertaken by the SUMAWA group and reported in full in the MSc thesis of Mainuri (Mainuri, 2005). The main soil groups display extreme spatial variability (Table 2). They range from ultisols (humic acrisols) on the high mountain region to oxisols (humic ferralsols), mollic andosols and vitric andosols on the hills, slopes and scarps of the upper catchment. On the plateaux and gentle slopes, the soils are mainly humic andosols, vitric andosols and eutric regosols. On the plains in the middle and lower catchment are the phaeozem mollisols, mollic planosols and mollic andosols. Mollic fluvisols and undifferentiated solonetz (entisols and alfisols) have developed in the alluvial and lacrustrine plains at the mouth of the stream and lake edges (Mainuri, 2005). The soils are young and poorly formed being predominantly derived from agglomerates and sediments of recent volcanic activity dating back to the late Tertiary and Quaternary Periods mainly pyroclastic rocks such as pumice, cinders as well as black ash, basaltic tuff and phonolites (Kundu, 2005; Baldyga, 2005). They are formed under tropical rainforest conditions – high seasonal variability in rainfall, heavy leaching of parent minerals and high evaporation rate and the presence of high organic matter. Thus except for those on the plains, the soils are deep and well drained with the humus top soil layer ranging from 20–60 cm (Mainuri, 2005).

Table 2. Characteristics of the main soil groups in the NRC

Terrain	Slope (%)	Soil taxa	Soil texture
High Mts	16 ≥ 30	*ultisols*	Clay loam to clay
Hills	>17	*Oxisols*	Clay loam to clay
		mollic andosol	Silt clay loam
		vitric andosols	Clay loam/humic
Plateaux	2 < 6	*humic andosols*	Sandy clay to clay
		eutric regosols	Clay loam
Uplands	1 ≥ 10	*luvic phaeozems*	Clay/humic
		cambisols	Clay/gravely
Plains	0 ≥ 3	*mollic planosols*	Silt clay loam
		mollic fluvisols	Silt loam to clay

Adapted from Mainuri, 2005

The texture of the topsoil layer is mostly silt clay loam in the lower catchment and clay loam to clay in the natural and exotic forests of the upper catchment (Mathooko & Kariuki, 2000). They are largely fine-textured, smeary and friable with a weak to moderate sub-angular blocky structure (Kundu, 2005). The subsoil layer ranges from silt clay loam to clay loam and clay. Generally the soils are weakly acidic with pH ranging from 5.6 to 6.4 (Kundu, 2005). They are largely dark brown to reddish brown and yellowish red to dusky red in colour. However, on the alluvial and lacustrine plains the colour is largely dark grayish brown to dark brown due to the presence of calcareous deposits (Mainuri, 2005). A complex assortment of many soil types occur in the valleys where they are excessively drained and the colour could range from reddish brown to dark brown. The soils are extremely prone to erosion given that they occur mostly on very steep slopes in a catchment that is also heavily altered and degraded (SUMAWA, 2005). Erosion and transport of surface soils from farms, residential plots and degraded areas makes the stream very turbid during rainstorms.

Climate

The Njoro River catchment is in a region of Kenya that is characterized by a continental climate influenced largely by: (i) altitude and topography - a typical characteristic of the Rift Valley and; (ii) movements of the Inter-tropical Convergence Zone (ITCZ) - a frontline of two air masses that bring rain and dry spells to the region. There is considerable seasonal oscillation in precipitation occurring mainly in the form of rain. The pronounced temporal patterns in rainfall account for high annual and seasonal variability in the Njoro River flow (Shivoga, 2001). Rainfall is convective and occurs mainly in the afternoon and late evening in heavy downpours that are highly erosive and short in duration. Mean annual rainfall falls between 600–1200 mm having been described as tri-modal with peaks in April/May, August and November (Mathooko and Kariuki, 2000; Odero and Peloso, 2000; Kundu, 2005). The annual cycle of rainfall is highly variable with the peaks in May and November disappearing in extremely dry years while the peak in November becomes more prominent in some years. There are minimal seasonal thermal oscillations but diurnal and spatial variations are large and dramatic. Atmospheric temperature in the region varies largely with topography and time of day as seasonal differences are not so dramatic. Within short distances, atmospheric temperature could range from 9–24ºC during the day. Night time temperature could drop to 9ºC or even less in the high altitude upper catchment. The annual (potential) evaporation is estimated at 1800 mm (Odada *et al*., 1998). Compared to the annual precipitation, there is a net loss of water from the catchment. But further hydrological consideration may be required to make sound conclusions.

Hydrology

The stream flow is highly variable even within a single season - a response to the annual and inter-annual pattern of rainfall (Table 3). The situation has been exacerbated over the last two decades by deforestation and land degradation in the catchment (Kundu *et al*., 2004; Baldyga *et al*., 2004). High flow variability is accentuated by a number of factors: (i) rain water from the predominantly open agricultural and residential land is rapidly transported to the stream as surface runoff within minutes of a heavy storm; (ii) most of the catchment landscape is very steep with very few areas for depression storage of excess water; (iii) predominantly fine textured clay soils with very little rainwater infiltration and withholding capacity and; (iv) the water storage capacity of the remaining forest and woodland is relatively low (SUMAWA, 2005). The stream flow ranges from very high spates during transient storm events in the wet season to the cessation of flow in the lower reach during dry spells. This annual cycle disrupts the vertical, lateral and longitudinal connectivity in the stream. First the stream width shrinks and depth becomes very shallow. Eventually flow ceases in the lower reaches as flow declines and the stream retreats upstream (Raude *et al*., 2007). The stream bed is then exposed and characterized by a sequence of stagnant and isolated hot pools with a channel that is completely dry and sun-baked (Shivoga, 2001). These are flooded and reconnected again following strong downpour of rain.

Table 3. Records of stream flow at the middle and lower reaches.

Date [mm; year]	Season	Flow x10^{-3} [$m^3.sec^{-1}$]	Source
Jan.–March, 1997	Dry	10–20	Mpawenayo & Mathooko, 2005;
May–Sept., 1998	Wet	200–800	Mathooko *et. al*., 2000*a*
Jan.–March, 1999	Dry	2–9	Muia *et. al*., 2003;
May–Sept., 1999	Wet	40–50	Mathooko *et. al*., 2001
May–Aug., 1999	Wet	5–21	Mathooko *et. al*., 2002
May–Aug., 2000	Wet	5–21	Mokaya *et. al*., 2002

The total annual flow is small as the stream is characterized by low flow for the better part of the year. Major storm events and accompanying increase in stream flow may occur between May and September or for some years in November. There is a clear response of the stream hydrograph to precipitation in the catchment with peak flow coinciding near perfectly with rain storms. In wet periods a reasonable flow is maintained at the middle reach but the stream remains intermittent particularly in the lower reaches being extremely responsive to alternating storms and dry spells. The permanent tributaries of the Njoro River join the main flow largely from the left bank in the upper catchment within 20 km from the source. Others are mostly ephemeral rivulets that are present only during or immediately after rainstorms. The stream's confluence with the Little Shuru - the main tributary - is located approximately midway of the main flow. For the remaining distance to its mouth in Lake Nakuru, no other permanent tributary joins the stream after the confluence. This is very important for the stream's hydrology particularly in the lower reach where flow ceases during dry weather (Raude *et al*., 2007). In summary, the Njoro River flow can be described as partly perennial (upper reaches and permanent tributaries), partly ephemeral (lower reaches and temporary tributaries) with high inter-annual and seasonal variability and low total annual discharge that is intermittent and erratic, in particular at the middle and lower reaches. These characteristics are typical for streams in semiarid regions that are periodically affected by droughts (McMahon and Finlayson, 2003). The NRC constitutes an important water catchment area for Lake Nakuru given that Njoro River is the main stream that flows into the lake. Therefore drainage from the Njoro catchment is crucial for the lake in terms of volume, regularity and water quality (Lelo *et al*., 2005). During periods of intermittent flow when flow ceases in the lower reach of the stream, the lake level falls substantially - sometimes to zero as it were between 1996 and 1998 - with death and migration of wildlife and recession in tourism.

Vegetation cover: distribution and current status

From its source in the Eastern Mau Hills to its mouth in Lake Nakuru, seven vegetation zones along the Njoro River have been described based on current land use practices and the impact of these on the vegetation (Mathooko and Kariuki, 2000). The uppermost mountain region; section of stream between Logoman and Runguma; downstream of Runguma; immediately upstream of Egerton University (EU); section around EU and downstream; section within Lake Nakuru national Park and; the last 200 m to the river mouth. The uppermost mountain region (> 2600 m a.s.l.) consists of open moorland that is extensively grazed by livestock mostly sheep and cattle. The main vegetation types include *Penniseteum clandestium* and *Elensina jaegeri*, which are similar to the disturbed moorlands of Mt. Kenya and the Aberdares, also in Kenya. In some areas the natural vegetation has been cleared for commercial wheat and barley farms and isolated homesteads. Between Logoman and Runguma (2300–2600 m a.s.l.) is indigenous mountain forests through which the stream flows. The forests are dominated by *Juniperus procera*, *Olea europaea africana*, *Olea capensis*, *Podocarpus latiforius*, *Prunus africana*, *Teclea simplicifolia*, *Nuxia congesta*, *Olina usambarensis* and *Rhapanea melanophloes*. In the past, the vegetation was dense with very minimal human disturbance (Mathooko and Kariuki, 2000). At present the original forest has been fragmented into small insular forest blocks with small-scale subsistent farms scattered in between (SUMAWA, 2005). Although officials of the Forestry Department undertake routine patrols and maintain forest guards at strategic locations, widespread poaching for various forest products is clearly evident. Nonetheless, much of the natural vegetation is still present even in altered areas.

The area downstream of Runguma (2000–2300 m a.s.l.) was once covered by large exotic forests of mainly pinewood but today this has been greatly altered. Common plantation forest species remaining include *Cupressus lusitanica*, *Pinus patula*, *Pinus radiate* and *Grevillea robusta*. The herbaceous layer is characterized by *Carex johnstonii*, *Cyathula polycephala* and *Asparagus africana*. A narrow riparian forest of natural vegetation can still be seen in some places and isolated stands of vegetation are present but most of the vegetation has been cleared in most places for pasture and farmland. Immediately upstream of EU (1900–2000 m a.s.l.) the land is used for grazing and maize farming and the area consists mainly of pasture, farmland and residual woodland. In some places, grazing by livestock and farming is practiced close to the stream edge. In such areas no riparian vegetation is present but a small belt of vegetation could be found in areas that are not readily accessible, for instance, at steep stream banks. The riparian vegetation in this reach consist mainly of *Syzygium cordatum*, *Pittospisum abyssinicum*, *Dombeya goetzenii* and *Hibiscus diversifolius*.

The vicinity of EU and downstream (1800–1900 m a.s.l.) is the most populated. It is heavily settled, extensively grazed, largely exposed and the most degraded. It is characterized by emerging and expanding settlements and widespread agriculture and herding of livestock. The riparian vegetation is very scanty due to sustained pressure from people and livestock (Mathooko and Kariuki, 2000). The most common riparian tree species are *Syzygium cordatum*, *Acacia abyssinica* and *Pittospisum viridiflorum* with their characteristic branches spreading over the stream from the banks (Table 4). These plants contribute significantly to leaf litter input in the stream in this reach (Magana, 2001; Mathooko *et al*., 2001b; Morara *et al*., 2003). The herb layer is dominated by *Achyranthes aspera*, *Crassocephalum montuosum*, *Girardinia diversifolia* and *Triumfetta brachyceras* – a probable indication of previous human disturbance (Mathooko and Kariuki, 2000). Others include *Hibiscus diversifolius* and *Panicum hymeniochilum*. The segment within Lake Nakuru National Park (< 1800 m a.s.l.) is protected and managed by the Kenya Wildlife Service (KWS). This stretch is the only stream reach that still receives efficient protection and management. Most of the natural vegetation is still intact. However, the flow is intermittent at this reach and the stream channel remains a dry river bed for most of the year. Within this reach *Acacia abyssinica* is replaced by the fever tree

Acacia xanthophloea as the dominant type of vegetation. Herbaceous vegetation is dominated by *Urtica massaica*. Disturbance within the park is caused mainly by game animals such as buffalos, hippos, warthogs, zebras and waterbucks, which have made deep tracks through the steep sided banks of the stream.

Table 4. Canopy cover of the dominant riparian vegetation at the middle reaches

Riparian vegetation	Canopy cover (%)
Syzygium cordatum	45
Acacia abbysinica	20
Pittospisum viridiflorum	10
Hibiscus diversifolius	8
Rhus natalensis	5
Dombeya goetzenii	3

Adapted from Morara *et al*., 2003

Also within the park and downstream the *Acacia xanthophloea* dominated zone is the last 200 m to the mouth of the stream. It consists of open vegetation dominated by pioneer grass communities mainly *sporobolus* and *Cynodon*. This zone is heavily grazed by wildlife and "naturally" polluted (Leichtfried and Shivoga, 1995). Except for regulated visits by tourists, this region is under very minimal human disturbance. However, the impact of farming activities in the upper catchment is quite evident. Also, it is argued that land use changes in the upper Njoro catchment, abstraction of water from the stream, cessation of flow in the lower reach in recent years and the accompanying drawdown at the lake is disturbing the vegetation within this reach (Mathooko and Kariuki, 2000).

In general, the vegetation in the catchment has been variously disturbed. The riparian vegetation is discontinuous and very scanty in most sections of the stream. At the middle and lower reaches, it has been considerably reduced or completely cleared. The main driving forces generating these alterations have been described - continued pressure from human disturbances for farming and settlements and grazing and watering of livestock. Most stream sections can be easily accessed by livestock and local inhabitants for water, sand and various forest products (Table 5). The extent of damage caused is particularly evident near livestock watering and abstraction points (Mathooko and Kariuki, 2000; Mathooko, 2001). In heavily disturbed sections especially in the middle and lower stream reaches, stream banks have been conspicuously modified and left bare, vegetation growth retarded and the riparian vegetation canopy reduced to zero (Mathooko and Kariuki, 2000; Mathooko, 2001; Morara *et al*., 2003).

Table 5. Main uses of the riparian vegetation along the Njoro River

Uses	No of species
Herbal medicine	102
Edible	20
Timber	22
Fodder	8
Fencing poles	6
Fibre	9
Fuelwood	9
Spiritual/magical	10

Source: Mathooko and Kariuki, 2000

Demography: growth, migration and settlement

Although in decline in recent years, the population growth rate (2.8% per annum) in Kenya is still among the highest in the world and remains significantly high in rural areas. In the Njoro River catchment, this natural growth was considerably enhanced by government decision to resettle immigrant farmers and settler pastoralists in formerly protected areas. Census records in the last two decades indicate a dramatic increase in population in Nakuru District – part of which is in the NRC. The population nearly doubled from ca. 271,000 in 1979 to ca. 414, 000 in 1999 (Baldyga, 2005). This region is among some of the densely populated in Kenya with recent estimates suggesting that there are now over 300,000 inhabitants living at the catchment (Lelo *et al*., 2005). The catchment is mainly rural. Important settlements include Njoro Township (50,000 inhabitants) and the main campus of Egerton University and its environs including Njokerio (20,000) located in the middle catchment. Parts of Nakuru Municipality (300,000) is found in the lower catchment area. Human settlement in the upper catchment is minimal consisting mainly of small isolated homesteads of independent families. In places where communities live together, such as Nessuit and Beeston, the population is < 1000 inhabitants. For a great majority of these inhabitants, daily visit to the stream is indispensable. Along its entire length, the stream is visited for laundry, abstraction of water, watering of livestock, swimming, religious baptism or disposal of waste among others. Such visits are very regular and show diurnal periodicity (Mathooko, 2001; Mathooko *et al*., 2001; Yillia *et al*., 2007a). Since most of the residents do not have adequate water supply and sanitation facilities, the stream is used extensively particularly during dry weather conditions when alternative sources of water are nonexistent or difficult to reach (Yillia *et al*., 2007a). The demand for water and other natural resources to serve basic needs is growing steadily as the population continues to increase. This is putting a lot of pressure on what is already scarce and highly vulnerable. Although there are information gaps for some disciplines on a sustained basis, already links have been suggested between population growth, land cover change, land degradation and the deterioration of water quality in the stream and its receiving basin – Lake Nakuru (Mathooko and Kariuki, 2000; Shivoga, 2001; Mokaya *et al*., 2004; Lelo *et al*., 2005; Krupnik and Jenkins, 2006). For example, it is thought that the cumulative effects of abstraction of water by a chain of rapidly expanding settlements within reach of the stream might influence its hydrology and as the population continues to grow. Also, the input of sediments, organic matter and nutrient could increase consequently (Shivoga, 2001; Mokaya *et al*., 2004; Lelo *et al*., 2005).

Land use/cover change

The catchment area was previously covered by rich vegetation of highland evergreen forest but a significant change in land use has occurred from forest and woodland (75% and 12% respectively in 1969) to agriculture and rural built-up land. The most recent survey on land use (Kundu *et al*., 2004) concludes that predominant land coverage includes small-scale agriculture (82%) woodland/grassland (7%) urban/residential plots (6%) and forest cover (5%). Remote sensing and time series analysis of data over a period of 30 years indicate a shift in land use/cover from predominantly large forests and woodlands in 1969 to small insular forest blocks, small-scale subsistent agriculture and built-up residential areas in 2003 (Table 6).

Table 6. Summary of the main land use change between 1969 & 2003

Land use/cover	Year and % dominance		
	1969	1989	2003
Forests and woodlands	87	60	12
Agriculture and settlements	13	40	88

Adapted from Kundu *et. al.,* 2004

In the 1969 survey, there were large-scale farms (13%), large forest blocks (75%) of both natural and exotic trees and expansive woodland (12%). Land use for residential plots/built-up area was minor and insignificant. During the 1989 survey, a fundamental change was already noticeable – forest and woodland cover had declined to 60% from 87% in 1969 and agriculture and built-up area had risen to 40% from 13% in two decades (Kundu *et al*., 2004). A decade later both forest (5%) and woodland cover (7%) had declined appallingly compared to the 1969 cover while agriculture (82%) mainly small farms and pasture had increased immensely and build-up area (6%) had become conspicuous and significant (Kundu *et al*., 2004; Baldyga *et al*., 2004). Following independence in 1963, land buying organizations mainly citizen's cooperatives and similar entities bought land previously owned by white farmers and redistributed to their members/shareholders (Odero and Peloso 2000; Kundu, *et al*., 2004). As a result large farms were fragmented into small to medium-scale farms and residential plots, some of which are still being further fragmented as the new landlords sell off small portions of land to recent immigrants. Evidently, the major land use types today, in area extent and dominance are: (i) small-scale agriculture; (ii) animal husbandry; (iii) built-up residential plots and; (iv) remnants of forest compartments. Associated with the built-up areas are industries and the activities of the informal sector mainly small-scale industries and commerce which are increasingly becoming important as the population continues to grow. These activities constitute a significant source of both point and non-point input of contaminants (Yillia and Kreuzinger, 2008).

The percentage of land under small-scale mixed agriculture has been increasing steadily in the last two decades as additional woodland and forests are transformed into rural residential plots and fragmented agricultural fields that are under non-fallow cultivation for cereals and vegetables (SUMAWA, 2005). The current estimate for the entire catchment stands at > 80% of land under active cultivation (Kundu *et al*., 2004). Small-scale subsistent farms known locally as *shamba* and backyard gardens are ubiquitous on the landscape (Lelo *et al*., 2005). A few commercial farms are located at the middle and lower catchments. Experimental farms owned by the Kenya Agriculture Research Institute (KARI) and Egerton University are present at the middle catchment. Farming is intensive and largely rain-fed with the growing season coinciding with wet weather conditions. A few farmers irrigate using water from the stream and boreholes during dry spells and periods of uncertainty or failure in rainfall. There are two growing seasons both coinciding with the long and short raining seasons in May–September and November–December respectively. The seasonal agricultural activities are such that maize, wheat and barley are planted in April/May and harvested in August/September, potatoes are planted in November and harvested in early January and vegetables are grown throughout the growing season although this cannot be generalized. With all these crops, both organic (manure) and inorganic fertilizers are applied during sowing with additional "dressing" for most plots during the growing season. Livestock grazing (mainly cattle, sheep, goats and donkeys) is an important activity. It is practiced wherever pasture is present. The catchment falls within the annual migratory route of nomadic herdsmen mainly Maasai tribesmen, who traverse the landscape with their livestock in search of pasture particularly during dry spells. There are a number of slaughter houses, meat and dairy processing units and numerous distribution outlets particularly in settled areas of the middle and lower catchment.

Environmental and social considerations

In recent years the catchment received attention mainly for its environmental and social problems and related political decisions. These problems have been attributed to rapid population growth in the catchment, which was caused mainly by schemes manipulated by the government to relocate and settle migrant pastoralists and farmers in areas that were once protected (Shivoga *et al*., 2002; Lelo *et al*., 2005). The accompanying land ownership problems and intertribal conflict between communities, for example, Ogiek (the indigenous land users, hunters and gatherers) Maasai (nomadic herdsmen) and Kikuyu (settler farmers and business owners) is recurrent and has become a major security concern with fatalities having been reported. It is evident that communities competing over scarce natural resources ignore the norms of civilized behavior and reverence for any legal system. This creates an insecure environment, which results into skirmishes and sometimes death of innocent victims.

Land degradation caused by deforestation and careless land use practices in the catchment is a major concern for the environment with serious threats to public health as well. Communities in the NRC are in constant contact for their daily needs i.e., water, sand, fuelwood, charcoal, timber and a variety of forest products. These products form an important source of livelihood for poor rural inhabitants. Other livelihood practices include small-scale agriculture, animal husbandry, hunting and gathering, bee keeping and commerce (Baldyga, 2005). The stream is an important source of water for over 70,000 poor rural riparian inhabitants whose water needs are met daily or supplemented by the stream, especially during dry weather conditions. Without regulation, communities have become vulnerable to diseases associated with using products from the system. Common ailments among inhabitants include diarrhea, dysentery, typhoid fever, malaria, and sporadic outbreak of cholera, all of which are water related infections (Mokaya *et al*., 2004).

Fertilizers and herbicides are used indiscriminately by farmers on steep slopes that are highly prone to soil erosion (Mokaya *et al*., 2004; Mainuri, 2001). Herding of livestock is quite extensive with little or no regulation for most parts of the catchment. Domestic and industrial effluents from treatment facilities and open drains are discharged with little or no regard for effluent guidelines. In-stream activities mainly abstraction, watering of livestock, washing and disposal of waste are rampant and unregulated. Following the huge population growth and increased revenue from agriculture, the non-formal sector is encouragingly vibrant. Sadly very little or nothing has been done to improve social services in the expanding settlements. With a few exceptions, there are no waste collection facilities for most communities. Sanitation facilities remain miserably poor or still non-existent with uncontrolled disposal of wastes. These factors have resulted in the deterioration of water quality - sedimentation, increased organic matter and nutrient concentration and widespread contamination Lake Nakuru (Shivoga, 2001; Mokaya *et al*., 2004).

Management concerns

There is currently no management authority for the NRC although various institutions and individuals have demonstrated interests in certain sections of the catchment. Three key institutions have stakes and have expressed variable interests in certain sections of the catchment. On its part the Kenya Wildlife Service (KWS) is interested in the section of the catchment that lies within the precincts of the Lake Nakuru National Park. This section of the catchment receives maximum protection but its location makes it highly vulnerable to human activities upstream. In recent years, there is recurrently no water at the lower reaches for most of the year. The Kenya Forest Working Group is more interested in protecting the heavily poached remnant forest blocks of the upper catchment area. The third interested partner, i.e., Egerton University has demonstrated interest in the entire catchment due to its location and research and educational interests. The university is located on the banks of the stream in the middle reaches. Various departments conduct research along the stream, which is also used for various education and training. For example, the stream is the main training site for the annual International Postgraduate Training Course in Tropical Limnology that is organized jointly by the Department of Biological Sciences at Egerton University and the Austrian Academy of Sciences through the Institute for Limnology at Mondsee in Austria. In addition various environmental groups mostly NGOs and CBO's have expressed interest through educational programmes and advocacy. However, neither these interest groups nor the catchment inhabitants are organised into a management body. Catchment-based management is absolutely essential given the wide range of priorities at the national level.

Conclusion

The situation in the Njoro River catchment is a typical manifestation of an immense social and environmental challenge facing authorities in particular natural resource managers in Kenya. There is no doubt that the biophysical landscape has been grossly altered. These alterations have been attributed to rapid population growth following resettlement of migrant herdsmen and farmers and the ensuing land use changes caused by their activities. These are mainly farming, herding of livestock, harvesting of forest products, abstraction of water and commerce. This is impacting negatively on the environment, human health and the livelihood of poor rural communities that are in constant touch with a degraded system. Admittedly, there is indeed some dearths of knowledge in certain disciplines especially on a sustained long-term basis but these gaps do not amount to the ostensible general paucity of information that is often blamed for management ineptitude of the NRC. In fact substantial information already exists on the NRC to compliment management. The task actually lies in utilizing this information properly and garnering stakeholder support to prevent and/or mitigate current environmental problems.

Acknowledgements

The Development Co-operation of the Austrian Foreign Affairs Ministry is acknowledged for financial support through the North-South Dialogue

Scholarship Programme. Thanks to various authors, and staff at Egerton University, Kenya who made their work available for the review.

References

Baldyga, T. J., 2005. Assessing land cover change impact in Kenya's River Njoro watershed using remote sensing and hydrological modelling. M.Sc. Thesis, University of Wyoming, USA.

Baldyga, T. J., Miller, S. N., Shivoga, W., Maina-Gichaba, C., 2004. Assessing the impact of land cover change in Kenya using remote sensing and hydrologic modelling. Proceedings of the ASPRS Annual Conference, Denver, Colorado, USA.

Bretschko, G., 1995. Tropical River Ecology Initiative. First workshop (31 January to 18 February 1994) Egerton University, Njoro, Kenya.

Dobson, M., Mathooko, J. M., Ndegwa F. K., M'Erimba, C., 2003. Leaf litter processing rates in a Kenya highland stream, the Njoro River. *Hydrobiologia* 519, 207–210.

Jenkins, M. W., Marques, G. F., Lelo, F. K., Miller, S. N., 2005. WEAP as a participatory tool for shared vision planning in the River Njoro Watershed, Kenya. Proceedings EWRI: Impacts of Global Climate Change

Krupnik, T. J., 2004. Linking farmer, forest and watershed: Understanding forestry and soil resources management along the Upper Njoro River, Kenya. Centre for African Studies. Breslauer Symposium on natural Resources Issues in Africa (University of California, Berkeley).

Krupnik, T. J., Jenkins, M. W., 2006. Linking Farmer, Forest and Watershed: Agricultural Systems and Natural Resources Management along the Upper Njoro River, Kenya. University of California International and Area Studies, Digital Collection, Article #3. http://repositories.cdlib.org/uciaspubs/articles/3

Kundu, P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. Proceedings - XXth ISPRS Congress. Istanbul, Turkey, 405–409.

Leichtfried, M., Shivoga, W., 1995. The Njoro River – Lake Nakuru ecotonal system in Kenya. *Jber. Biol. Stn Lunz* 15: 67–77

Lelo F.K., Wanjiku, C., Jenkins, M.W., 2005. Managing Riparian Resources in the River Njoro Watershed in Kenya: The Challenge of Conflicting Laws, Policies and Community Priorities. Paper Presented: International workshop on "African Water Laws - Plural Legislative Frameworks for Rural Water Management in Africa. 26 – 28, January 2005, Guateng, South Africa.

Magana, A. E. M., 2001. Litter input from riparian vegetation to streams: a case study of the Njoro River, Kenya. *Hydrobiologia* 458, 141–149.

Magana, A. M., Bretschko, G.,.2003. Retention of coarse particulate organic matter on the sediments of Njoro River, Kenya. *Internat. Rev. Hydrobiol.* 88, (3–4) 414–426.

Mainuri, Z. G., 2005. Land use effects on the spatial distribution of soil aggregate stability within the Njoro River watershed, Kenya. M.Sc. Thesis. Egerton University, Kenya.

Makoba, H., Shivoga, W, Muchiri, M., Miller, S. N., 2007. Use of benthic macroinvertibrates as indicators of water quality in River Njoro Kenya. Taal 2007 12th World Lake Conference

Mathooko, J. M., Kariuki, S. T., 2000. Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. East African Wildlife Society. *Afr. J. Ecol*. 38 (2), 123–129.

Mathooko, J. M., M'Erimba, C. M., Leichtfried, M., 2000. Decomposition of leaf litter of Dombeya goetzenni in the Njoro River, Kenya. *Hydrobiologia* 418, 147–152.

Mathooko, J. M., Magana, A. M., Nyang'au, I., 2000. Decomposition of Syzygium cordatum leaves in a rift valley stream ecosystem. *Afr. J. Ecol*. 38 (4) 365–368.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131–139.

Mathooko, J. M., Morara, G. O., Leichtfried, M., 2001a. The effect of different anthropogenic disturbances on benthic plant coarse particulate organic matter in a tropical Rift Valley stream. East African Wildlife Society. *Afr. J. Ecol*. 39, 310–312.

Mathooko, J. M., Morara, G. O., Leichtfried, M., 2001b. Leaf litter transport and retention in a tropical Rift Valley stream: an experimental approach. *Hydrobiologia* 443, 9–18.

Mathooko, J. M., Otieno, C. O., 2002. Does surface textural complexity of woody debris in lotic ecosystems influence their colonization by aquatic invertebrates? *Hydrobiologia* 489, 11–20.

M'Erimba, C. M., J. M. Mathooko and M. Leichtfried (2006) Variations in coarse particulate organic matter in relation to anthropogenic trampling on the banks of the Njoro River, Kenya. *Afr. J. Ecol*. 44. (2), 282–285.

McCall, G. J., 1967. Geology of the Nakuru Thompson's Falls – Lake Nakuru resources, Geological Surveys of Kenya.

McMahon, T. A., Finlayson, B. L., 2003. Droughts and anti-droughts: the low flow hydrology of Australian rivers. *Freshwater Biology* 48, 1147–1160.

Mokaya, S. K., Mathooko J. M., Leichtfried, M., 2004. Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *Afr. J. Ecol*. 42 (4), 281–288.

Morara, G. O., Mathooko, J. M., Leichtfried, M., 2003. Natural leaf litter transport and retention in a second-order tropical stream: the Njoro River, Kenya. *Afr. J. Ecol*. 41, 278–280.

Moturi, W. K. N., Tole, M. P., Davies, T. C., 2002. The contribution of water towards dental fluorosis: a case study of Njoro Division, Nakuru District, Kenya. *Environmental Geochemistry and Health* 24, 123 – 130.

Mpawenayo, B., Mathooko, J. M., 2005. The structure of diatoms assemblages associated with Cladophora and sediments in a highland stream in Kenya. *Hydrobiologia*, 544, 55–67.

Muia, W. A., Bretschko, G., Herndl, G. J., 2003. A study of biofilm in a second order tropical stream, Njoro River, Kenya: First Results. *Internat. Rev. Hydrobiol*. 88 (3–4), 372–384.

Mutua, B. M., Maina-Gichaba, C., 2006. Effect of land use change on hydrological regime in a rural catchment: A case of River Njoro catchment, Kenya. Proceedings of the international symposium – Soil physics and rural water management (SOPHYWA). Vienna, Austria. 137–142.

Odero, D. O., Peloso, G. F., 2000. A hydrological study of the Njoro area (Rift Valley of Kenya). *Atti Ticinensi di Scienze della Terra* 41, 109 – 131

Odada, E. O., Raini, J., Ndetei, R., 1998. Lake Nakuru - Experience and lessons learned brief.

Raude, J. M., Onyando, J. O, Owino, J. O., 2007. Estimation of soil loss from selected land use practices under varying rainfall intensity in River Njoro Catchment in Kenya. Presented at the 5th International Congress of ESSC. Changing soils and in a changing world: the soils of tomorrow. Palermo, Spain

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiolgia* 458, 121–130.

Shivoga, W.A., Lelo, F.K., Maina-Gichaba, C., Jenkins, M.W., Miller, S.N., 2002. Integrated Stakeholder Participation and Watershed Assessment in the River Njoro Watershed, Kenya. Poster Presentation: Global Livestock Collaborative Research Science Program Annual Conference. October 9–12, 2002. Washington, DC, USA

SUMAWA, 2005. Sustainable Management of Watersheds: Biophysical, livestock and human interactions in the River Njoro Watershed. GL-CRSP, UC, Davis, USA.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007a. Nature of in-stream activities during dry weather flow at the middle reaches of a rural stream in Kenya. Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium, Lusaka, Zambia.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007b. In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya. Proceedings of the 8th WaterNet/ WARFSA Sympossium, Lusaka, Zambia.

Yillia, P. T., Kreuzinger, N., 2008. Net flux of pollutants at a reduced spatial scale - an index of catchment vulnerability. Proceedings of the 11th IWA International Specialized Conference on Watershed and River Basin Management. Budapest, Hungary.

Chapter 3

Spatio-temporal dynamics of pollutants along the Njoro River, Kenya

Prepared for submission: Water Research
Presented at the 2nd Research for Development Young Scientists Forum. 11th June 2007 Vienna, Austria as "Linking land use to stream pollution – Why partnership matters".

Spatio-temporal dynamics of pollutants along the
Njoro River, Kenya

P. T. Yillia*, N. Kreuzinger** and J. M. Mathooko***

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; E-mail: *paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at*
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; E-mail: *norbkreu@iwag.tuwien.ac.at*
***Egerton University, Department of Biological Sciences, PO Box 563, Njoro, Kenya; Tel: +254 37 61282 or +254 720853844; Fax: +254 37 61055; E-mail: *jmathooko@hotmail.com*

*corresponding author

Abstract
To assess the spatio-temporal dynamics of pollutants along the Njoro River, water samples were taken from 11 sites at 14 days interval from January to December, 2006. Samples were processed for microbial indicators, micronutrients, suspended solids, turbidity, BOD_5 and the physico-chemical parameters. Mean (±SD) dry weather levels of conductivity, TSS, BOD_5, total P, NH_4N, and total N increased significantly ($p < 0.05$) from 127±21, 8.7±3.2, 2.9±0.9, 0.1±0.0, 0.1±0.0, and 0.5±0.2 mg.l^{-1}, respectively, at Logoman at the forested upper reaches to 406±106, 14.3±5.1, 17.3±1.3, 1.4±1.1, 0.6±0.3 and 1.0±0.1 at Canning below WTP effluents at the middle reaches. Median indicator bacteria densities were generally within 4–7 log units for HPC and TC and, 2–4 log units for EC and IE with slightly higher levels at the middle and lower reaches. Site specific analysis for seasonal variability of water quality indicators suggested loading as well as dilution during wet weather. Ambient levels of suspended solids, total P and bacteria indicators increased significantly ($p < 0.05$) during wet weather whereas conductivity, total N, PO_4-P, NH_4-N and NO_3-N decreased concurrently. Several parameters displayed strong associations and capacity to segregate sites with the classification of two site clusters for each hydrological period even though clusters for short wet weather were scrambled and indistinct at RDCC (rescaled distance cluster combined) < 6. The observed positive and significant correlations ($R = 0.43$–0.87; $p < 0.05$) between microbial indicators, suspended solids and total P indicated possible common source(s), presumably WTP effluents, runoff from agricultural and residential plots and within channel activities of people and livestock. A reduction of the current number of sampling sites and water quality variables investigated was proposed. This will reduce the cost of sampling and processing by half and the time spent sampling by at least 3 hrs without comprising the value and spatial outlook of the water quality data.

Keywords
Njoro River; pollution; spatio-temporal dynamics; water quality indicators

Introduction

Pollution is a serious threat to aquatic ecosystems and public health in many countries. The situation calls for active management of water quality. Information on the level of pollution and the type of pollutants is often required to identify the major contributing sources and pathways (Venter *et al*., 1997). By measuring as many parameters as possible, it is often less confounding to understand the linkages and interactions between indicators and how well they describe the status of an afflicted system. Therefore, most research efforts aimed at understanding the sources and dynamics of pollutants in aquatic systems are routine monitoring programmes that are designed to collect water samples regularly for analysis of various water quality variables. But the amount of time and money spent on determining the levels of contaminants is often great and could be reduced (Dabrowski *et al*., 2002).

The task lies mainly with the optimization of strategies for sampling and processing during routine water quality monitoring and building a strong framework for long-term monitoring. In some countries, especially in the developing world where essential research tools for advanced water quality monitoring are most often inadequate or even non-existent, this requires careful planning as the strategy must be both cost-effective and well-organized to achieve desired goals. Usually when such strategies are developed, the choice is made to focus resources and time on those areas with the greatest risk of impact on the environment and public health (Venter *et al*., 1997). High priority is often placed on heavily impacted sites, which have clear sources of contamination and associated health risk.

The primary objective of this study was to assess the status of pollution along the Njoro River, Kenya in relation to land use and the chemical response of the stream to anthropogenic impact. The levels of several traditional water quality indicators were evaluated for associations between indicators and their efficacy to segregate stream sites base on relative pollution levels. Both objectives were aimed at providing information for cost reduction and optimization of the current pollution monitoring programme.

Methodology

Njoro River Catchment (NRC)

Njoro River (60 km) is a high altitude second order stream in southwestern Kenya with the Little Shuru as its main tributary (Figure 1). The catchment (280 km^2) is largely rural and agro-pastoral. The altitude declines uniformly from 2800 m (a.s.l) at the Eastern Mau Escarpment to 1700 m (a.s.l) at Lake Nakuru on the floor of the Rift Valley (Mathooko, 2001; Shivoga, 2001). A notable change in land use has occurred in the catchment. The change is largely from forests (75%) and woodlands (12%) in 1969 to agriculture (82%) and settled areas (6%) by 2003 (Kundu *et al*., 2004). Long wet weather is in May–September and short wet weather is in November–December. The total annual rainfall is 600–1200 mm with variable peaks in May, August and November (Mathooko and Kariuki, 2000). Atmospheric temperature is within 9ºC and 24ºC (Baldyga, 2005). Farming is widespread and livestock herding is important especially during dry weather (January–April) when large herds of cattle, sheep and goats are led into the catchment by itinerant herdsmen in search of pasture and water from drier parts in the region (SUMAWA, 2005; Yillia *et al*., 2007). The stream receives intermittent discharge of wastewater from the effluents of the wastewater treatment facilities at Egerton University and Njoro Canning Factory, a vegetable cannery (Mokaya *et al*., 2004). Both of which are located in the same area at the middle reaches.

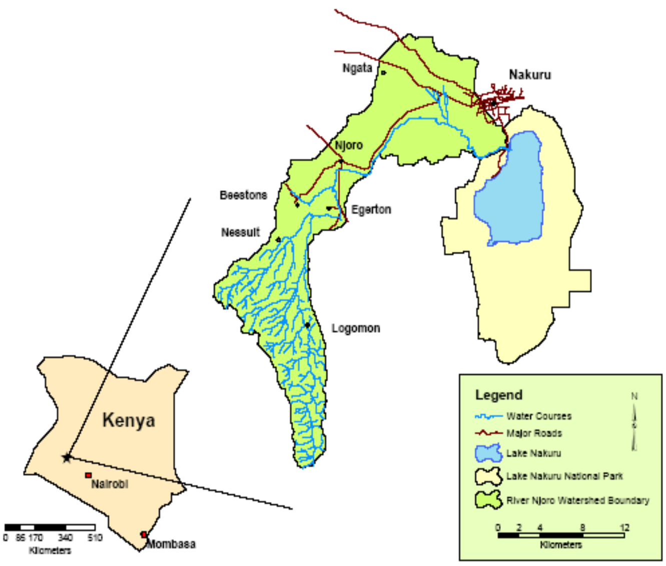

Figure 1. Njoro River Catchment

Table 1. Characteristics of sampling sites along the Njoro River and the main tributary, Little Shuru in 2006

Sampling sites	Longitude [east]	Latitude [south]	Dist. [km]	Height [m]	Bed type	Wet bed width [m]	Depth [cm]	Stream reach and the main land use in the vicinity
Logoman	35º54´09.13″	0º29´12.09″	45	2676	Riffle	0.1–2.1	5–70	A / I, II, IV, VIII
Nessuit	35º53´53.29″	0º23´47.13″	36	2410	Riffle	0.1–1.8	5–50	A / I, II, IV, V, VIII
Segotik	35º54´77.02″	0º24´35.09″	36	2412	Riffle	0.2–2.3	5–100	A / I, II, IV, VIII
Treetop	35º55´63.07″	0º22´51. 02″	32	2277	Riffle	0.2–4.4	10–100	A / II, IV
Turkana Flats	35º56´05.33″	0º22´37.07″	29	2221	Pool	6.4–12.6	50–130	B / II, IV, V, VI
Canning	35º56´04.06″	0º21´89.02″	27	2213	Pool	3.5– 4.2	10–100	B / II, III, IV, V, VI
Njoro Bridge	35º56´06.26″	0º20´27.04″	24	2163	Pool	8.1–10.3	70–150	B / II, III, IV, V, VI,
Kenyatta	35º58´07.85″	0º20´18.05″	21	2134	Riffle	0.1–7.6	5–70	B / II, III, IV, V, VI
Ngatta	35º59´02.31″	0º18´45.02″	16	2047	Pool	6.8–9.6	0–40	C / II, III, IV,
Mogoon	36º01´03.86″	0º17´79.04″	11	1908	Pool	2..3–5.4	0–70	C / II, III, IV
Old sewage	36º03´89.03″	0º19´62.07″	3	1780	Run	0.1–3.8	0–100	C / II, IV, V, VI, VII

A: upper reaches; B: middle reaches; C: lower reaches; I: forest cover; II: small-scale agriculture; III: large-scale agriculture; IV: livestock rearing; V: settlement; VI: commerce; VII: sand mining; VIII: extraction of forest products (firewood, charcoal, timber, poles, herbs etc)

Sampling and site measurements

Regularly spaced semi-monthly and monthly samples were taken from the stream at eleven sites located 3–5 km apart in January through December, 2006 (Table 1). Samples were collected in 500 ml polyethylene containers. Sterile containers were used for microbial indicators. All samples were stored and transported on ice. During sampling, *in-situ* measurements were made for conductivity, temperature, dissolved oxygen and pH with WTW Multiline P4 probes. Stream flow was measured by using two methods recommended for shallow streams (Kitaka *et al*., 2002; Mbuligwe and Kaseva, 2005; UNEP/WHO, 1996). A simplified version of the mean velocity cross-sectional area method was used when flow was substantial and the tipping-bucket method was used when the latter was impractical (Mbuligwe and Kaseva, 2005; UNEP/WHO, 1996). The overt limitations of both methods have been reported (UNEP/WHO, 1996).

Analysis of samples

Water quality analysis was done with standard analytical procedures (APHA, 2002). Turbidity was estimated colorimetrically at UV_{437} with a 5 cm quartz cuvette and reported as $UV_{437}.m^{-1}$. The gravimetric method was used for total suspended solids (TSS). Samples were filtered through rinsed Edorel BM/C glass fibre filters (pore size 0.45 µm). Filtered samples were used to analyze soluble reactive phosphorus (PO_4-P), Ammonium-N (NH_4-N), Nitrite-N (NO_2-N) and Nitrate-N (NO_3-N). PO_4-P was analyzed with the Molybdate blue method. The phenol-hypochlorite method was used for NH_4-N while the 2,6-dimethylphenol method was used for NO_3-N. A modification of the Sulfanil acid method with Naphthylaminsulphonic acid salt NO_2-AN (Merck 1.14776) was used to determine NO_2-N. For total phosphorus (TP) and total nitrogen (TN), 50 ml unfiltered sample was digested with a scoop of Oxisolv powder (Merck F1 369036 528), an oxidizing agent for compounds containing phosphorus and nitrogen. After digestion for 45–60 minutes the samples were analyzed as indicated above for PO_4-P and NO_3-N. BOD_5 was determined with the standard 5 days incubation procedure at 20ºC in darkness. When required, dilutions were made with stream water of lower BOD_5 (< 3 $mg.l^{-1}$ O_2). The salt, allythiourea was used to inhibit oxygen demand due to nitrification. As a result three BOD_5 fractions were separated namely, total BOD_5 (oxygen demand without inhibition) $CBOD_5$ (oxygen demand with inhibition), $NBOD_5$ (total BOD_5 minus $CBOD_5$), which is the oxygen demand due to nitrification.

Samples for microbial analysis were processed within 8 hours of collection. Three appropriate dilutions were made for heterotrophic plate count bacteria (HPC), total coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE). Dilutions were duplicated and drained through sterile membrane filters (0.45 µm; 47 mm) with a vacuum pump. Filters for HPC were placed on solidified Yeast Extract Agar (ISO 6222, OXOID) and all colonies were counted within 24 and 48 hrs of incubation at 37ºC. Filters for TC and EC were incubated on Chromocult Coliform Agar (ISO 6222, OXOID) at 37ºC for 24 hrs. Pink to red colonies and blue colonies were counted for TC and EC respectively. mEnterococcus Agar (ISO 6222, OXOID) was used for EC, the plates were incubated at 37ºC and dark red colonies were counted after 48 hrs. Plates with countable colonies between 20 and 300 were selected for counting. Median values of colony forming units (cfu) were reported per 1 ml for HPC and cfu per100 ml for TC, EC and IE.

Statistical analysis

Statistics was performed with the aid of SPSS (Statistical Package for Social Sciences). Related factor complexes were characterized with Principal Component Analysis (PCA). Components showing Eigen value > 1 were selected to explain associations among water quality indicators. Significant associations were confirmed with uniform certainty at the 95% significant level ($p < 0.05$) using the Wilcoxon test with the Bonferroni correction when required. Cluster Analysis was implemented to detect site linkages based on the prevailing pollution levels. The cluster method used was “between-group linkage”, which was measured by the “squared euclidian distance” with the transformation of values by variable using “z-score standardization”. A rescaled distance cluster combined (RDCC) of 6 was used as the cutoff point on the dendrograms to identify site clusters.

Results

Variability of stream flow

Table 2 shows the spatio-temporal matrix of stream flow in 2006. Analysis of the stream hydrograph revealed three flow regimes in response to the monthly variability of rainfall. The mean monthly flow at the middle reaches was < 20 $x10^{-3}$ $m^3.sec^{-1}$ in February through April, 30–50 $x10^{-3}$ $m^3.sec^{-1}$ in May through September and 300–600 $x10^{-3}$ $m^3.sec^{-1}$ in November and December. October was marked by a dramatic decrease in stream flow (< 10 $x10^{-3}$ $m^3.sec^{-1}$) that was analogous to the February–April flow. Even though January 2006 was dry, a relatively high flow was maintained compared to February–April, an outcome of dry weather drawdown following the short wet weather of 2005. Stream flow increased steadily downstream in the upper reaches as smaller tributaries joined the main Njoro flow, decreasing gradually downstream after the confluence with the Little Shuru (river km 29) until it ultimately ceased flowing at the lower reaches. The precise point of cessation fluctuated between 5 and 15 km from the stream mouth. Complete flow was realized during transients (1000–10000 $x10^{-3}$ $m^3.sec^{-1}$) and following increased rainfall in November–December.

Table 2. Spatio-temporal matrix of the mean monthly stream flow (x10^{-3} m^3.sec^{-1}) in 2006 without transients

		Months, 2006											
Stream site	km*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Logoman	45	10	4	4	10	8	20	20	5	15	5	150	175
Nessuit**	36	12	7	7	8	9	8	5	15	10	5	100	200
Segotik	36	30	10	20	20	25	25	25	40	40	6	350	360
Treetop	32	40	15	28	28	30	30	30	55	50	10	400	560
Turkana Flats	29	38	11	22	28	30	24	30	55	50	10	400	550
Canning	27	45	10	18	20	30	20	20	50	50	10	360	560
Njoro Bridge	24	35	8	18	20	25	20	20	50	50	10	350	540
Kenyatta	21	30	2	15	20	18	18	25	50	50	10	350	540
Ngatta	16	20	2	10	15	18	18	30	20	30	5	340	550
Mogoon	11	15	0	8	15	10	10	20	10	20	5	300	400
Old Sewage	3	0	0	0	0	0	0	0	0	0	0	200	300
Rainfall [mm] Egerton***		23	12	90	92	60	74	65	138	25	35	302	219

*km – distance in kilometers from the stream mouth; **located on the Little Shuru, the main tributary; *** Station No. 09035092

Physico-chemical parameters

The physico-chemical parameters are displayed in Figure 2. Stream temperature was lower (11–16ºC) at the forested upper reaches and higher (15–19ºC) at the middle and lower reaches where the landscape was mostly open. Temperature was slightly low during wet weather with Nessuit on the Little Shuru recording the least. Conductivity levels were significantly ($p < 0.05$) higher at the middle and lower reaches. Dry weather levels were generally higher with the lowest conductivity levels recorded during high stream flow in short wet weather. pH was slightly alkaline (7.1–7.8) with no major periodic differences but being slightly lower at the middle and lower reaches. Dissolved oxygen (DO) was fairly stable at the upper reaches (6.6–7.8 mg.l^{-1}) but varied seasonally at the middle and lower reaches. The highest DO levels (8–9 mg.l^{-1}) occurred in short weather with uniform levels along the stream (Figure 2). The lowest DO levels (2.3–4.1 mg.l^{-1}) were recorded at Canning below the WTP effluents during dry weather (Table 3). Both turbidity and suspended solids increased substantially during long wet weather although levels were significantly ($p < 0.05$) lower during short weather.

Micronutrients and organic matter

Total N levels were generally high with a gradual increase downstream and significant ($p < 0.05$) seasonal oscillations for all stream sites. Dry weather total N levels were generally > 0.5 $mg.l^{-1}$. Levels dropped to within 0.2–0.4 $mg.l^{-1}$ as stream flow increased during wet weather. NO_3-N contributed 80–95% of total N with similar spatial and seasonal profiles. NH_4-N increased significantly below settlements at Turkana Flats and Kenyatta and also below the WTP effluents at Canning. The lowest NH_4-N levels were recorded at Logoman at the forested upper reaches (Table 3). Total P levels were relatively high during long wet weather compared to short wet weather increasing gradually downstream between Logoman (0.13±0.03 $mg.l^{-1}$) and Turkana Flats (0.21±0.03 $mg.l^{-1}$) but then abruptly at Canning (0.53±0.21 $mg.l^{-1}$) where 70–80% of total P was PO_4-P. BOD_5 levels were lower (< 3 $mg.l^{-1}$) and fairly uniform during short wet weather compared to long wet weather or dry weather during which significant ($p > 0.05$) differences were observed between sites. The $NBOD_5$ fraction was significantly higher at Canning and Kenyatta where relatively high NH_4-N levels occurred as well but it was hardly detectable during increased stream flow in short wet weather, which coincided with very low NH_4-N levels along the stream (< 0.03 mg NH_4-$N.l^{-1}$, except at Canning with 0.1 mg NH_4-$N.l^{-1}$ of). During this time $CBOD_5$ was equivalent to the total BOD_5 along the stream. The concentration of organic matter (UV_{254}) in the stream was slightly higher at the middle and lower reaches compared to the upper reaches being fairly steady between seasons. The highest levels of organic matter were recorded at Canning, Njoro Bridge and Kenyatta, all of which were located below the WTP effluents.

Bacteria indicator densities

Figure 4 illustrates the median bacteria indicator densities along the stream in 2006. Densities were generally high staying within 4 and 7 log units for HPC ($cfu.ml^{-1}$) and TC (cfu.100 ml^{-1}) and, within 2 and 4 log units (cfu.100 ml^{-1}) for EC and IE. However, bacteria densities were 1–2 log units higher and extremely variable during wet weather with Mogoon at the lower reaches recording the highest densities. HPC densities were similar at Logoman, Segotik, Nessuit, Turkana Flats and Njoro Bridge even though Logoman, Segotik and Nessuit at the forested upper reaches recorded slightly lower densities for TC during wet weather. Segotik and Njoro Bridge had slightly lower wet weather densities for EC, which increased significantly ($p < 0.05$) at Logoman during this period even though Logoman reported significantly ($p < 0.05$) lower IE densities at the same time. Dry weather densities of EC and IE were 1–2 log units lower at Logoman, where the lowest EC and IE densities (2 log units of $cfu.100ml^{-1}$) were observed. Dry weather TC and HPC densities maintained a similar spatial spread as in wet weather being significantly ($p < 0.05$) lower at Logoman and Segotik for HPC and at Logoman only for TC.

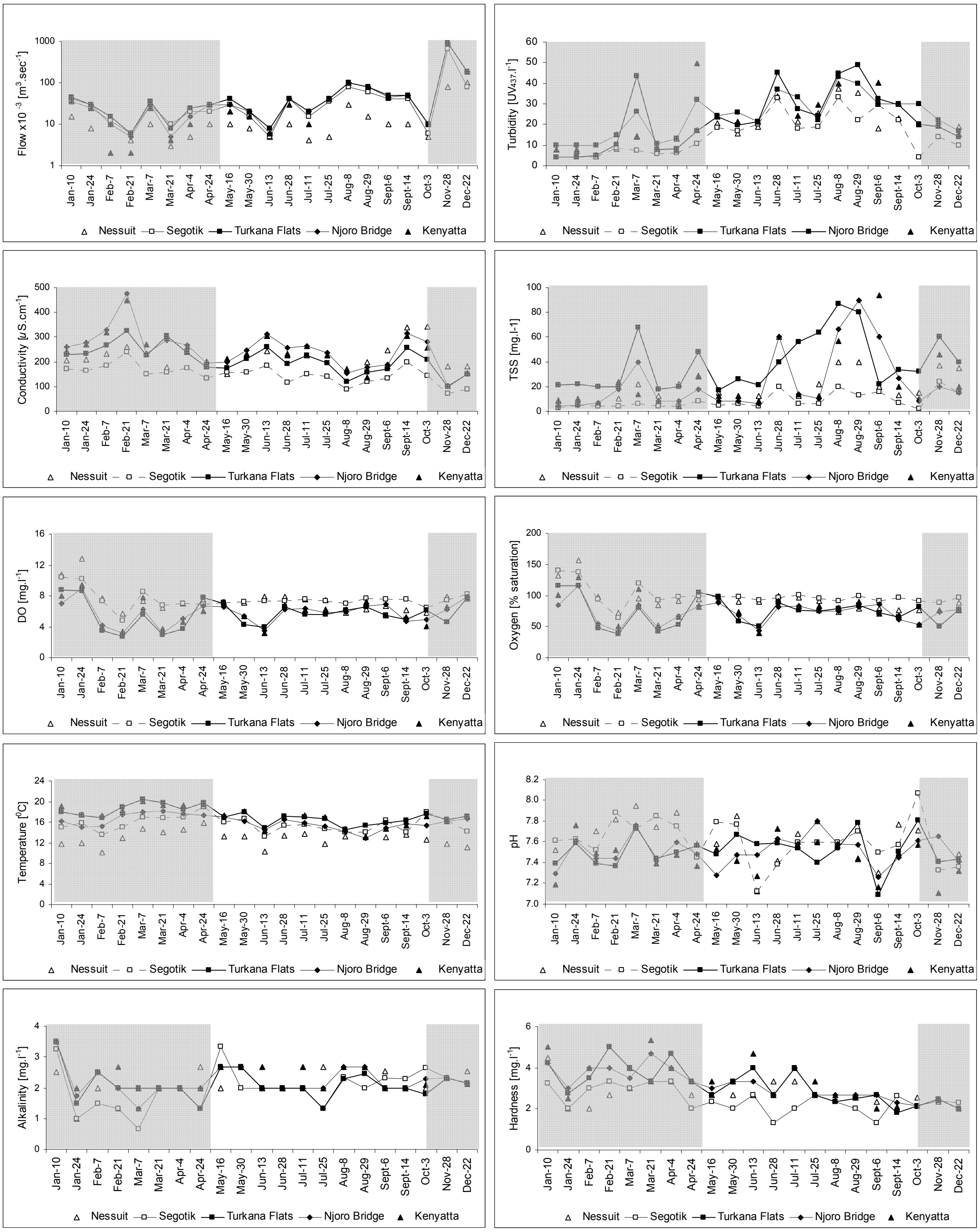

Figure 2. Seasonal variability of stream flow and the physico-chemical parameters at the upper (□ & Δ) and middle reaches (■, ♦ & ▲). Left (shaded) - dry weather; centre (not shaded) - long wet weather; right (shaded) - short wet weather.

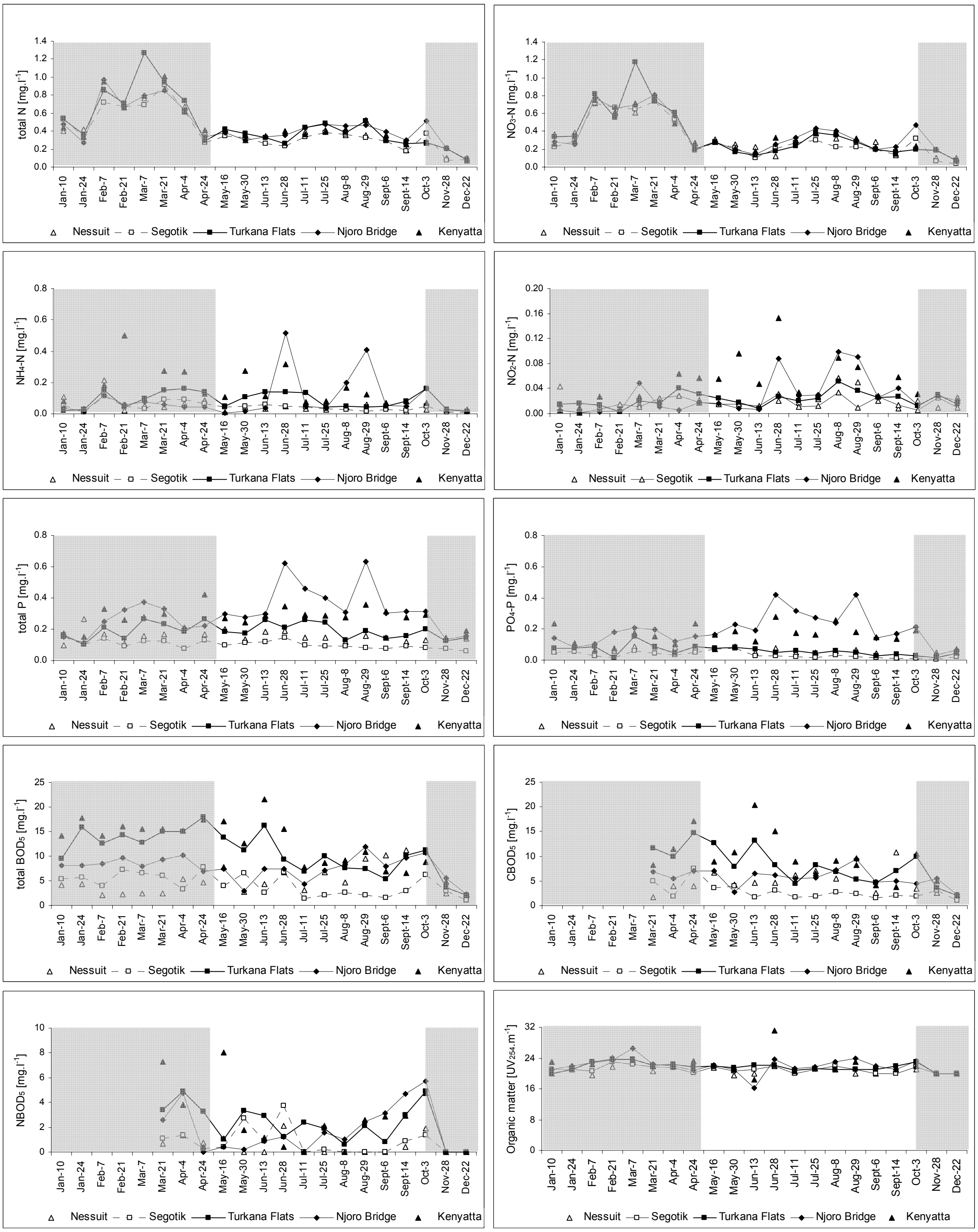

Figure 3. Seasonal variability of nutrients, organic matter and BOD_5 fractions at the upper (□ & Δ) and middle reaches (■, ♦ & ▲). Left (shaded) - dry weather; centre (not shaded) - long wet weather; right (shaded) - short wet weather.

Table 3. Mean (±SD) levels of water quality indicators at Logoman[1], Canning[2] and Njoro Bridge[3] in 2006

Stream site	Flow x10 $^{-3}$ [$m^3.sec^{-1}$]	TSS [$mg.l^{-1}$]	Temp. [°C]	Cond. [$\mu S.cm^{-1}$]	DO [$mg.l^{-1}$]	BOD_5 [$mg.l^{-1}$]	TP [$m.l^{-1}$]	NH_4-N [$mg.l^{-1}$]	TN [$mg.l^{-1}$]
***Dry weather** (January–April, 2006)*									
Logoman[1]	7±3	9±3	12.1±2.0	127±21	8.7±2.2	2.9±0.9	0.1±0.0	0.1±0.0	0.5±0.2
Canning[2]	23±15	14±5	17.2±0.5	406±106	3.9±1.3	17.3±1.3	1.4±1.1	0.6±0.3	1.0±0.1
Njoro Bridge[3]	20±13	13±4	16.9±1.3	291±84	5.6±2.0	8.7±1.1	0.3±0.1	0.1±0.0	0.6±0.3
***Long wet weather** (May–September, 2006)*									
Logoman[1]	11±8	29±30	12.0±0.9	115±10	7.6±0.4	2.4±1.3	0.1±0.0	0.1±0.0	0.3±0.1
Canning[2]	47±35	43±19	15.4±1.0	229±76	5.9±1.1	24.1±7.6	0.5±0.2	0.5±0.3	0.4±0.1
Njoro Bridge[3]	45±28	35±32	15.4±1.3	214±41	6.2±0.5	7.2±2.7	0.4±0.2	0.2±0.2	0.4±0.1
***Short wet weather** (November–December, 2006)*									
Logoman[1]	178±4	23±2	16.1±0.5	59±0.7	8.1±0.7	2.6±0.1	0.1±0.0	0.0±0.0	0.1±0.0
Canning[2]	360±245	30±14	16.8±0.0	132±42	8.4±0.9	2.3±0.3	0.1±0.0	0.1±0.1	0.1±0.1
Njoro Bridge[3]	540±249	18±4	16.4±0.3	126±35	7.1±1.1	3.8±2.3	0.2±0.0	0.0±0.0	0.1±0.3

1: Upper forested reaches; 2: < 200 m below WTP outfalls at the middle reaches; 3: approximately 3 km below WTP outfalls at the middle reaches

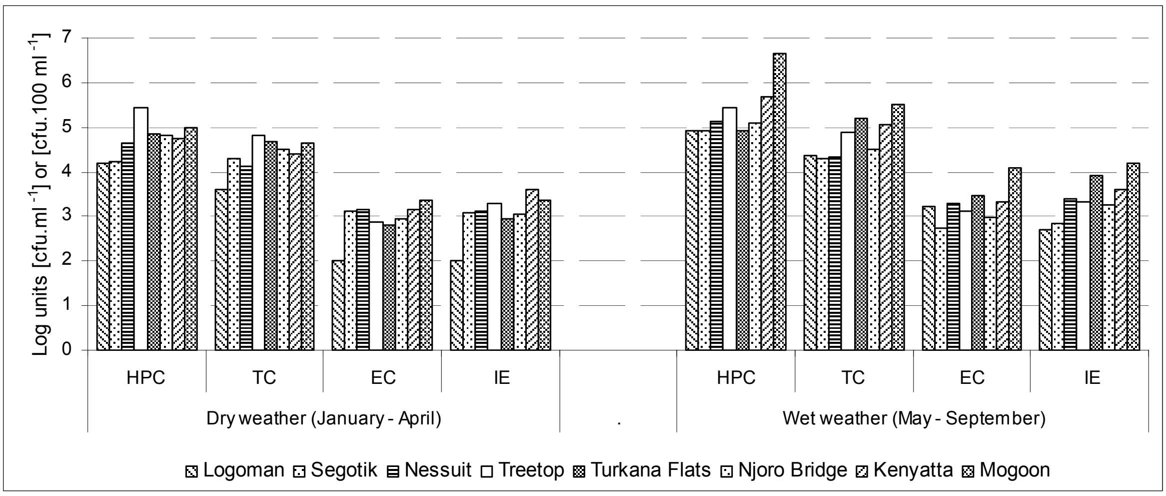

Figure 4. Median densities of Heterotrophic Plate Count [HPC cfu.ml^{-1}]; Total Coliforms [TC cfu.100 ml^{-1}]; *Escherichia coli* [EC cfu.100 ml^{-1}] and; Intestinal Enterococci [IE cfu.100 ml^{-1}] along the Njoro River in 2006.

Principal Component Analysis – Associations among water quality indicators

Site specific analysis of the water quality data showed that, generally, ambient levels of suspended solids, total P and the bacteria indicators increased variably during wet weather whereas conductivity, total N, PO_4-P, NH_4-N and NO_3-N decreased concurrently. Weak to strong positive correlations occurred between stream flow and suspended solids, turbidity and the bacteria indicators ($R = 0.34$–0.89; $p < 0.05$). Alternatively, variable degrees of negative correlations were evident between stream flow and conductivity, total N, PO_4-P, NH_4-N or NO_3-N ($R = 0.43$–0.87; $p < 0.05$). $NBOD_5$ correlated positively and significantly ($R = 0.59$; $p < 0.05$) with NH_4-N at Canning below the WTP effluents. This was unobvious at the other stream sites. The pooled data was explained by three significant principal components, which together accounted for 92% of the total variation even though 68% of the variation was explained by the first principal component (PC1). PC1 correlated variably with all the indicators with the recognition of two major sub-groups namely; (i) water quality indicators which correlated positively (suspended solids, total P and the bacteria indicators) probably due to loading as stream flow increased and; (ii) parameters which correlated negatively (total N, PO_4-P, NH_4-N or NO_3-N) due to dilution as stream flow increased. It therefore seems likely that PC1 was dominated largely by stream flow and it was ascribed to loading and dilution. PC2 accounted for 15% of the total variation and correlated strongly with the indicator bacteria, total P, PO_4-P, total BOD_5, NH_4-N and $NBOD_5$. Due to these associations, PC2 was linked to the loading only. HPC and TC were the only indicators which correlated positively with PC3 possibly an indication of residual pollution as NH_4-N correlated strongly but negatively with this component whereas EC and IE did not correlate with it. Due to the overall dominance of stream flow, the data was filtered and sorted and then ran separately for each hydrological period. Five significant principal components emerged with mixed association for each hydrological period even though the first three components for each explained 79–89% of the total variance with identical associations among water quality indicators as described above for the pooled data.

Cluster Analysis – Segregation of stream sites

Cluster Analysis of the filtered data yielded three distinct outputs of site clusters based on the relative pollution levels during the three hydrological periods (Figure 5). At a rescaled distance cluster combined (RDCC) of 6, the dendrogram of the average linkages between sites for dry weather revealed two pollution related site clusters. Except Canning, which was a “runt” since it was exceptionally polluted (cf. Table 3), all the sites at the biophysically altered middle and lower reaches (Turkana Flats, Njoro Bridge, Kenyatta, Ngatta and Mogoon) were grouped in Cluster 1. Alternatively, Nessuit, Segotik, Treetop and Logoman at the upper predominantly forested reaches clustered in Cluster 2 even though the first three where more closely related. The same site clusters were maintained during long wet weather, except that Mogoon like Canning was a “runt” and detached from the rest since pollution levels were substantially higher at both sites. Clusters 1 and 2, as well as the “runts” were scrambled and dispersed during short wet weather suggesting level associations among sites as indicated by the uniformity of most water quality indicators during this period (cf. Figures 2 and 3). Clusters with at least 3 stream sites were evident only at RDCC > 6 during short wet weather. For instance, Cluster 2 was discernible at RDCC > 12 but without Nessuit, which was during this period closely associated with the sites in Cluster 1 that included Mogoon and even Canning.

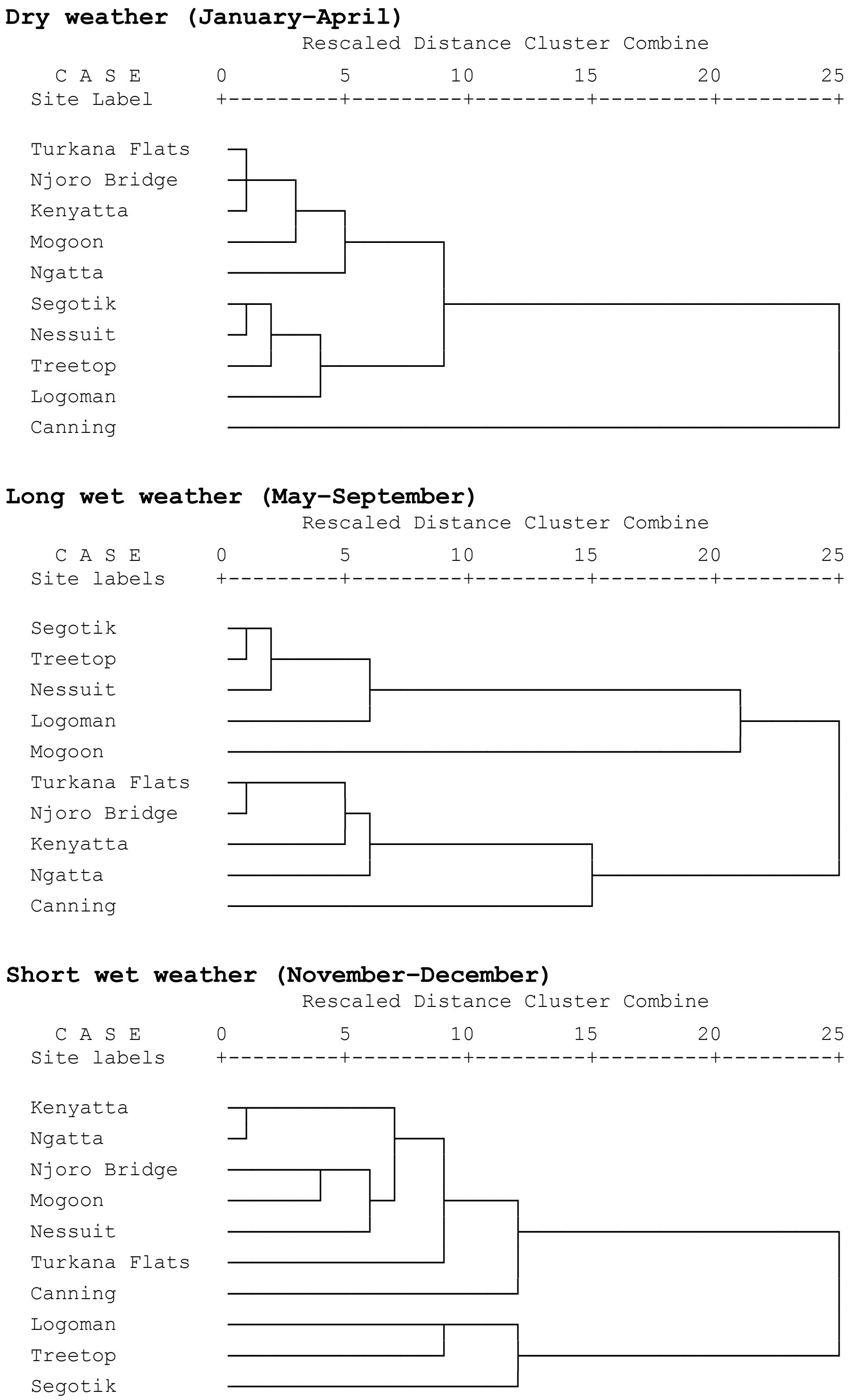

Figure 5. Dendrograms for each hydrological period illustrating the average linkages between sites based on their relative pollution levels.

The outputs of the Cluster Analysis and knowledge of the current land use and stream profile provided an adjunct and an objective basis for grouping the catchment into six sub-catchments. In the upper catchment are: (i) the UNRC (Upper Njoro River Catchment), which includes the sampling sites Logoman and Segotik down to the confluence with the Little Shuru and; (ii) LLS (Lower Little Shuru) – includes the sampling site Nessuit up to the confluence with the main Njoro flow. In the middle section are: (i) EUE (Egerton University & Environs) with the inflow at Treetop and the outflow at Canning and, the sampling site, Turkana Flats in between); (ii) NTA (Njoro Township Area) with the inflow at Njoro Bridge and the outflow at Kenyatta and; (iii) RZ (Restricted Zone), which is a small and largely inaccessible area between EUE and NTA. The Lower Njoro River Catchment (LNRC) with the inflow at Kenyatta and the outflow at the stream mouth at Lake Nakuru, includes the sampling sites Ngatta, Mogoon and Old Sewage. LNRC includes sections of Nakuru Municipality and a segment of Lake Nakuru National Park (LNNP).

Discussion

The increase in stream temperature from relatively low levels in the upper forested catchment to higher levels at the middle and lower reaches is mainly linked to altitudinal variation, which is higher (2300–2800 m a.sl) at the upper stream reaches and lower (1700–2200 m a.sl) at the lower catchment. But also the riparian vegetation at the middle and lower reaches has been heavily modified (Mathooko and Kariuki, 2000). Hence, there is little or no canopy cover at most places along the stream. Vegetated buffer strips are known to prevent stream temperatures from rising by regulating the water temperature as increase in stream temperature is directly related to the amount of water surface exposed to direct sunlight (Ensign and Mallin, 2001). It thus seems reasonable to suggest that forest cover at the upper reaches provided sufficient canopy cover to prevent stream temperatures from rising. This was unlikely at the middle and lower reaches, where the loss of vegetation cover could have far reaching implications not only for regulating stream temperature but also for the transfer of soil and debris. In tropical regions, high intensity rainfall can easily wash away top soil and contaminants via surface runoff (Tondersski, 1996; Dabrowski *et al.*, 2002). The slightly lower temperatures during wet weather may be associated with the increase in cloud cover and the relatively low atmospheric temperatures at this time of the year. Although pH decreased slightly downstream at the middle and lower reaches, no substantial differences were obvious between sites or hydrological periods. Even though no reasonable explanation could be given at the moment for the slightly lower pH levels at the middle and lower reaches, it is possible that pH in the Njoro River is not seriously affected by the current nature of pollution in the catchment.

Dissolved oxygen (DO) was fairly steady at the upper reaches (6.6–7.8 $mg.l^{-1}$) but not so at the middle and lower reaches where the variability in oxygen levels may be associated with the likely depletion of oxygen as organic matter is degraded. Organic matter in the stream could be released from farmland and residential areas but also from the activities of people and livestock within the stream channel. DO is usually depressed downstream of impacted sites (Ensign and Mallin, 2001). This was evident for Canning which was located downstream the WTP effluents of the Egerton University and Njoro Canning Factory. Low DO at Canning corresponded to high levels of total BOD_5, $CBOD_5$ and even $NBOD_5$ as NH_4-N levels were correspondingly high. Alternatively, high DO levels in the forested upper catchment, especially at Logoman matched low/undetectable levels of the BOD_5 fractions. The high DO levels that were reported following the increase in stream flow during short wet weather may be associated with turbulent mixing and oxygenation while the relatively high and fairly uniform levels of DO and the correspondingly low levels of BOD_5 fractions suggested minimum human disturbances during this period. Compared to dry weather, the visit made by people and livestock to the stream during wet weather was low given that residents access other sources of water (cf. Chapter 7).

The increase in conductivity levels at the middle and lower reaches was certainly pollution related since conductivity reflects the status of dissolved inorganic constituents in the water (Jonnalagadda and Mhere, 2001). Conductivity levels increased concurrently with NO_3-N, PO_4-P and NH_4-N. High stream flow corresponded with generally relatively low levels during short wet weather. This was attributed to dilution caused by rain water which flowed quickly into the stream during wet periods. The generally high total N (80–90% of which was NO_3-N) at all the sites may be associated with the consistent input or waste from farm animals as livestock grazing is widespread (Mokaya *et al*., 2004). Like BOD_5, the increase in total P at Canning could be linked to effluent discharge from the WTPs in the area. Other likely sources for total P input were non-point surface runoff of sediments from agricultural land

and residential plots. Sediments are known to play an important role in the transfer of particulate P (Kitaka *et al*., 2002). This is often associated with the increase in both turbidity and suspended solids during wet weather in biophysically altered catchments (Ensign and Mallin, 2001; Dabrowski *et al*., 2002; Jain, 2002; Trevisan *et al*., 2002). The noticeable decrease in suspended solids and turbidity during short wet weather may be connected to antecedent conditions. During dry weather, which precedes long wet weather, there is a huge buildup of loose materials and debris on residential plots and farmland. These materials including contaminants are easily washed into the stream as runoff in wet weather (SUMAWA, 2005). The dry spell in October between long wet weather and short wet weather was short. Therefore, it is possible that sediment accumulation was small for subsequent transportation in short wet weather as much of it may have been removed by the rains and runoff in long wet weather. Alternatively, it could be that the monthly sampling protocol that was employed during this period captured the descending limb of the stream hydrograph after transient rainstorm events. Anticlockwise depressions of the concentration-discharge relationship for pollutants were observed before base flow condition was reestablished after storm-induced transients (cf. Chapter 5).

The status of the microbial water quality of the stream was generally poor with the levels of faecal indicator bacteria in excess of acceptable water quality guidelines for surface water intended for bathing or drinking (U.S. EPA, 1986; WHO, 2001, 2003). The increase in ambient levels during wet weather may be attributed to increased storm runoff and leaching in a manner that has been linked to land use and human activities (Jagals, 1997; Crowther *et al*., 2001; Trevisan *et al*., 2002). During dry weather, it is expected that organic matter and faecal input may be limited mainly to point source emissions and within channel activities. But during storms, diffuse input increase as contaminants including bacteria are washed into the stream via surface runoff or sub-surface flow (Jagals, 1997; Crowther *et al*., 2001). Actually, diffuse sources have been recognized as being of greater importance than point source in streams draining rural catchments (Jain, 2002). In the NRC, most of the residents do not have access to proper sanitation facilities and livestock grazing is widespread (Mokaya *et al*., 2004). It is therefore very likely that surface runoff from farmland and residential areas will contain faecal matter of high bacteria density. In this respect, storm runoff could act as the dominant pathway for the input of faecal matter during wet weather. This was most likely the case for almost all the stream sites, in particular, Mogoon and Kenyatta where wet weather bacteria densities increase substantially compared to the dry weather densities. The high bacteria densities reported at Treetop during dry weather may be associated with livestock activities one kilometer upstream at this time of the year. The same was evidently true for Kenyatta below Njoro Town and Turkana Flats below Njokerio. Both were regular livestock watering points for migrating herds and resident livestock, respectively.

Routine monitoring of pollution does not necessarily identify the specific sources of pollutants (Bowes *et al*., 2005). Nonetheless, the information accrued may provide the basis for reasonable inferences and establishing the framework for subsequent source tracking studies. In particular, associations among water quality variables may be useful for site characterization. This might prove useful for cost optimization. Also, associations among water quality parameters may help characterize the processes that govern pollution levels in aquatic systems even though most associations are often too complex to be interpreted by simple linear regressions (McCarthy *et al*., 2007). In the present study, strong associations were evident among bacteria densities, stream flow, turbidity, suspended solids and BOD_5. This was illustrated vividly by the strong correlation of the water quality indicators in the first principal component suggesting possible common sources. Nonetheless, most of the associations were inconsistent among sites, which is an indication of the mixture of potential sources in the catchment and the large number of natural variables that govern stream processes. Analysis of the present data shows that regular monitoring of the stream flow and the physico-chemical parameters (Conductivity, temperature, pH, dissolved oxygen and oxygen % saturation) is justifiable. But one measure each of particulate matter (turbidity, suspended solids), organic matter (total BOD_5, $CBOD_5$, $NBOD_5$), the physical variables (Hardness, Alkalinity) and two or three each of micronutrients (NH_4-N, NO_3-N, NO_2-N, total N, PO_4-P, total P) and the microbial indicators (HPC, TC, EC, IE) may be adequate for characterizing the water quality of the stream without compromising the quality and interpretation of the data. The current practice of measuring all at the same time at thirteen stream sites is expensive and unnecessarily. Sampling sites could be reduced to seven, especially during increased stream flow without distorting the spatial outlook of the water quality data. Consequently, the cost of sampling and processing can be reduced by more than half while the time spent sampling will be at least 3 hrs less. Subsequent routine sampling could target the outlets of the identified sub-catchments above (cf. Cluster Analysis).

Conclusion

The spatial and temporal variability of pollution levels along the Njoro River was evaluated with the aid of a suite of traditional water quality indicators. Pollution levels increased significantly from relatively low levels in the forested upper reaches to high levels at the predominantly settled and farmed areas of the middle and lower reaches. Spatial variability was more obvious during dry weather and less evident during short wet weather. Site specific analysis for temporal variability revealed loading, as well as dilution during wet weather. The observed linear associations among water quality indicators was useful for site segregation based on pollution levels with the inference of likely common sources of pollutants even though the total variability in the water quality data was not completely explained by the associations. The study provided an objective basis to redesign the sampling framework to minimize sampling and processing costs and optimize resource use for subsequent source tracking studies.

Acknowledgements

The research was funded by the Austrian Development Co-operation through the North-South Dialogue Scholarship Programme with additional funding from IWAG at TU-Wien, Austria. Ken Kosimbei and Geoffrey Ongo'ndo at Egerton University and PSR are acknowledged for their technical assistance.

References

APHA, 1995. Standard methods for the examination of water and wastewater, 19th ed. American Public Health Association, Washington, D.C.

Baldyga, T. J., 2005. Assessing land cover change impact in Kenya's River Njoro watershed using remote sensing and hydrological modelling. M.Sc. Thesis, University of Wyoming, USA.

Bowes, M. J., 2005. Phosphorus-discharge hysteresis during storm events along a river catchment: the River Swale, UK. *Wat. Res.* 39, 751–762.

Crowther, J., Kay, D., Wyer, M. D., 2001. Relationship between microbial water quality and environmental conditions in coastal recreational waters: The Fylde Coast, UK. *Water Res.* 35 (17), 4029–4038.

Dabrowski, J. M., Peall, S. K. C., van Niekerk, A., Reinecke, A. J., Day J. A., Schulz, R., 2002. Predicting runoff-induced pesticide input in agricultural sub-catchment surface waters: linking catchment variables and contamination. *Wat. Res.* 36, 4975–4984.

Ensign, S. H., Mallin, M. A., 2001. Stream water quality changes following timber harvest in a coastal plain swamp forest. *Wat. Res.* 35 (14), 3381–3390.

Jagals, P., 1997. Storm water runoff from typical developed and developing South African urban developments: definitely not for swimming. *Wat. Sci. Tech.* 35 (11–12), 133–140.

Jain, C. K., 2002. A hydro-chemical study of a mountainous watershed: the Ganga, India. *Wat. Res.* 36, 1262–1274.

Jonnalagadda, S. B., Mhere, G., 2001. Water Quality of the Odzi River in the Eastern Highlands of Zimbabwe. *Wat. Res.* 35 (10), 2371 – 2376.

Kitaka, N., Harper, D. M., Maviuti, K. M., Pacini, N., Chemical characteristic, with particular reference to phosphorus, of the rivers draining into Lake Naivasha, Kenya. *Hydrobiologia* 488, 57–71.

Kundu, P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. Proceedings - XXth ISPRS Congress. Istanbul, Turkey, 405 – 409.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131–139.

Mathooko, J. M., Kariuki, S. T., 2000. Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. East African Wildlife Society. *Afr. J. Ecol.* 38 (2), 123–129.

Mbuligwe, S. E., Kaseva, M. E., 2005. Pollution and self-cleansing of an urban river in a developing country: A case study of Dar es Salaam, Tanzania. *Environmental Management* 36 (2), 328–342.

McCarthy, D. T., Mitchell, V. G., Deletic, A., Diaper, C., 2007. Escherichia coli in urban stormwater: explaining their variability. *Wat. Sci. Tech.* 56 (11), 27–34.

Mokaya, S. K., Mathooko, J. M., Leichtfried, M., 2004. Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *Afr. J. Ecol.* 42 (4), 281–288.

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiolgia* 458, 121–130.

SUMAWA, 2005. Sustainable Management of Watersheds: Biophysical, livestock and human interactions in the River Njoro Watershed. GL-CRSP, UC, Davis, USA.

Tonderski, A., 1996. Landuse-based non-point source pollution. A threat to water resources in developing countries. *Wat. Sci. Tech.* 33 (4-5), 53–61.

Trevisan, D., Vansteelant, J. Y., Dorioz, J. M., 2002. Survival and leaching of fecal bacteria after slurry spreading on mountain hay meadows: consequences for the management of water contamination risk. *Water Res.* 36, 275–283.

U.S. EPA, 1986. Ambient water quality criteria for bacteria – 1986. Office of the Regulations and Standards Criteria and Standards Division, Washington, DC 20469. EPA440/5-84-002, 1–18.

UNEP/WHO (1996) Water Quality Monitoring – A practical guide to the design and implementation of freshwater quality studies and monitoring programmes.

WHO, 2001. Water Quality: Guidelines, Standards and Health (ed.) Fewtrell, L. Bartram, J. WHO Water Series: IWA Publishing, London, UK. 1–422.

WHO, 2003. Guidelines for safe recreational waters. Vol. 1, Coastal and fresh waters. WHO Library cataloguing-in-publication Data, Geneva, Switzerland. 1–32.

Venter, S. N, Steynberg, M. C., de Wet, C. M. E., Hohls, D., du Plessis, G., Kfir, R., 1997. A situation analysis of the microbial water quality in a peri-urban catchment in South Africa. *Wat. Sci. Tech.* 35 (11-12), 119–124.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007. Nature of in-stream activities during dry weather flow at the middle reaches of a rural stream in Kenya. Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium, Lusaka, Zambia.

Chapter 4

Net flux of pollutants at a reduced spatial scale - an index of catchment vulnerability

Submitted: *Water Science and Technology*
Accepted April, 2008 for oral presentation and publication in the proceedings of the *IWA 11th International Specialized Conference on Watershed and River Basin Management*, 4-5 September 2008, Budapest, Hungary

Net flux of pollutants at a reduced spatial scale - an index of catchment vulnerability

P. T. Yillia* and N. Kreuzinger**

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; E-mail: *paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at*
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; E-mail: *norbkreu@iwag.tuwien.ac.at*

*for correspondence

Abstract
Emissions and riverine loads of pollutants were estimated for five sub-catchments in the Njoro River Catchment, Kenya to isolate specific areas for interim pollution management. The most vulnerable sub-catchments were the densely settled and heavily farmed areas around Egerton University and Njoro Township with the restricted area between them demonstrating a remarkable potential to retain/remove most of the pollution emitted in the Egerton University area. The least vulnerable sub-catchment was the predominantly forested Upper Njoro River Catchment whereas the recently settled and increasingly farmed Lower Little Shuru was moderately vulnerability. The method provided a scientific framework for the rapid assessment of catchment vulnerability to prioritize areas for remediation.

Keywords
Catchment vulnerability; land use; net flux of pollution; rural stream; sub-catchments

Introduction

Considerable land use change has occurred in the last three decades within the Njoro River Catchment (NRC), Kenya (Kundu *et al*., 2004). The consequences on water quality, stream ecology and hydrology are severe particularly at the middle and lower reaches, where the stream is seriously polluted and flow is now intermittent (Mathooko, 2001; Shivoga, 2001; Mokaya *et al*., 2004; Yillia *et al*., 2007). The rise in pollution levels in the Njoro River and the recurrent cessation of flow in the lower stream reaches has consequently affected water quality and water levels in the receiving Lake Nakuru, a Ramsar site and a renowned tourist destination for wildlife (SUMAWA, 2005).

The complex nature of many pollution problems usually requires complete knowledge of the various sources and pathways through which pollutants enter aquatic systems. Catchment scale studies are very relevant in this respect but the interactions between human interventions and numerous landscape variables are often indistinct and extremely complex to analyze (Sliva and Williams, 2001). Therefore, many catchment scale studies are usually long-term evaluations of land use and the related pollution status of afflicted aquatic systems. This is normally time consuming, expensive and simply unachievable when resources are limited.

Alternatively, an interim catchment vulnerability assessment (CVA), especially, when undertaken at a reduced spatial scale offers the prospect for a rapid and diagnostic appraisal that may highlight specific areas for urgent intervening actions. At this scale, there is less chance for confounding sources of pollutants such as agricultural runoff and point sources, which could confuse management decisions (Zielinski, 2002).

This study describes a provisional CVA that was undertaken in the NRC in 2006. The main objective was to estimate emissions and riverine loads of pollutants at a reduced spatial scale to isolate specific areas for interim pollution management.

Methodology

Njoro River Catchment

The NRC (280 km^2) is largely rural in southwestern Kenya (Figure 1). The altitude declines uniformly from the peak of the Eastern Mau Escarpment at 2800 m (a.s.l.) to Lake Nakuru at 1700 m (a.s.l.) on the floor of the Rift Valley (Shivoga, 2001). The soils are predominantly volcanic and highly prone to erosion. Farming is largely rain fed and the main growing season coincides with the long wet weather (May–September). The short wet weather is usually in November–December. Rainfall (600–1200 mm) is variable with peaks usually in May, August and November. Temperature is generally within 9ºC and 24ºC and the main dry weather occurs in January–April during which livestock herding can be widespread (SUMAWA, 2005).

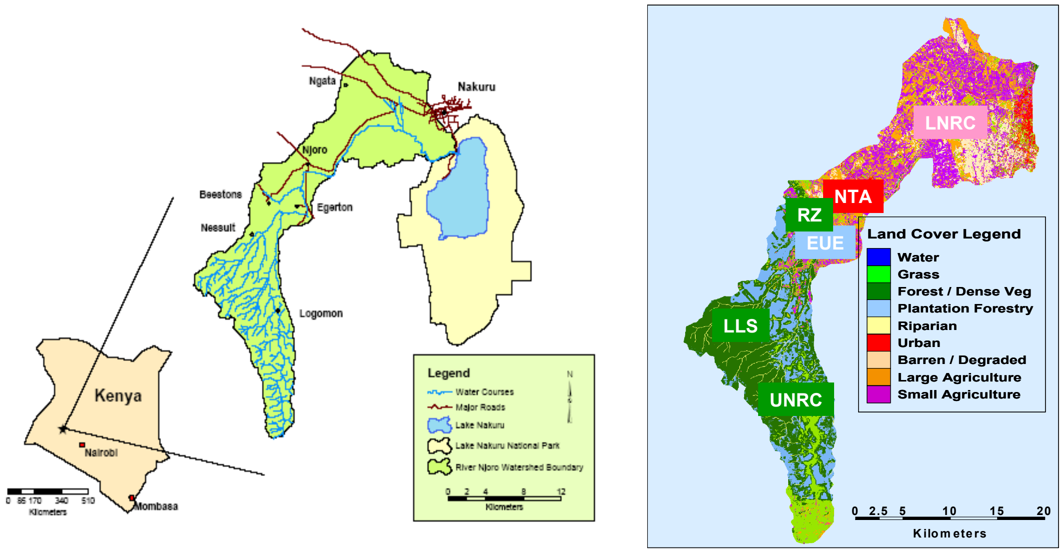

Figure 1. Njoro River with sub-catchments and recent (2003) land use cover. Acronyms are explained in the text below

Data acquisition

Six sub-catchments were delineated based on the results of recent spatial analysis of land use/cover and the spatial dynamics of pollutants in the stream (Kundu, *et al*., 2004; cf. Chapter 3). In the upper catchment are the UNRC (Upper Njoro River Catchment) and LLS (Lower Little Shuru). In the middle section are EUE (Egerton University & Environs), NTA (Njoro Township Area) and RZ (Restricted Zone), the largely inaccessible area between EUE and NTA. The Lower Njoro River Catchment (LNRC) which includes sections of Nakuru Municipality and part of Lake Nakuru National Park (LNNP) was not included in the study due to the cessation of stream flow at the lower reaches.

Samples were collected at the inflow and outflow of the six sub-catchments in 2006 (Table 1). Four regularly spaced monthly samples were collected in January–April (pre-growing season/dry weather) and May–September (growing season/long wet weather) and three semi-monthly samples were collected in November–December (post-growing season/short wet weather). Additional samples were collected from WTP and open sewer outfalls within EUE, and also from the stream at Turkana Flats, < 0.5 and < 1 km before the WTP outfalls of Egerton University and Njoro Canning Factory, respectively. Flow was estimated using the mean velocity cross-sectional area method and the tipping-bucket method (UNEP/WHO, 1996; Mbuligwe and Kaseva, 2005).

Standard analytical procedures were followed for BOD_5, TSS, PO_4-P, NH_4-N, NO_2-N, NO_3-N, TN, TP and Turbidity. Loads were estimated for the inflow and outflow of each sub-catchment from the instantaneous stream flow and specific concentrations (UNEP/WHO, 1996). The net flux ($kg.day^{-1}$), the difference between loads at inflow and outflow was expressed over sub-catchment area to estimate the net emission or potential retention ($kg.ha^{-1}.day^{-1}$), which was used to index vulnerability. Daily loads were preferred over annual loads given the relatively short duration of the study and the requisite to compare different seasons.

Statistics was performed with SPSS (Statistical Package for Social Sciences).

Table 1. Sub-catchments and location of sampling sites along the Njoro River and its main tributary, the Little Shuru

Sub-catchments	Area (%) [Hectares]	Density [pop/ha]	Sampling sites	Popular reference	Longitude [East]	Latitude [South]	Dist. * [km]	Height [m a.s.l]
UNRC	8.3 (29.6)	1	*inflow*	Logoman	35º54´09.13″	0º29´12.09″	45.0	2676
			outflow	Confluence **	35º55´10.04″	0º22´58.02″	32.5	2299
LLS	4.3 (15.3)	7	*inflow*	Nessuit	35º53´53.29″	0º23´47.13″	35.6	2410
			outflow	Confluence**	35º55´11.00″	0º22´55.08″	32.5	2289
EUE	4.2 (14.8)	77	*inflow*	Treetop	35º55´63.07″	0º22´51. 02″	31.5	2277
			outflow	Below Canning	35º56´04.06″	0º21´89.02″	27.3	2185
RZ	0.6 (2.0)	0	*inflow*	Below Canning	35º56´04.06″	0º21´89.02″	27.3	2185
			outflow	Njoro Bridge	35º56´06.26″	0º20´27.04″	23.7	2162
NTA	1.4 (4.9)	399	*inflow*	Njoro Bridge	35º56´06.26″	0º20´27.04″	23.7	2162
			outflow	Kenyatta	35º58´07.85″	0º20´18.05″	20.7	2138
LNRC	9.3 (33.3)	107	*inflow*	Kenyatta	35º58´07.85″	0º20´18.05″	20.7	2138
			outflow	Lake Nakuru	36°05´32.01″	0°19´41.08″	<0.5	1762

*Distance (River kilometres) from stream mouth at Lake Nakuru; **20 m before confluence of the main Njoro flow with Little Shuru

Results and Discussion

Loads from sub-catchments

An overview of pollution loads from each sub-catchment during the three farming/hydrological periods is illustrated in Table 2. Generally, loads increased significantly ($p < 0.05$) with increase in stream flow during the growing/post-growing periods. For example, BOD_5 and TSS loads at the outflow of UNRC increased by > 2 and > 10 folds, respectively, between pre-growing and the growing season, and between the later and post-growing season by > 3 and > 6 folds, respectively. This was also true for P & N loads although the magnitude of increase differed. A similar trend was observed for NTA and LLS.

Table 2. Loads of pollutants at the outflow of sub-catchments for the three farming periods in 2006

Sub-catchments		Flow(10^3) [m^3/day]	BOD_5 [kg/day]	TSS [kg/day]	PO_4-P [kg/day]	TP [kg/day]	NH_4-N [kg/day]	NO_2-N [kg/day]	NO_3-N [kg/day]	TN [kg/day]
***Pre-growing season/Dry weather** (January–April, 2006)*										
UNRC	mean	**1.3**	**4.1**	**5.0**	**0.1**	**0.2**	**0.1**	**0.01**	**0.6**	**0.8**
	min–max	0.4–3.0	1.2–10.1	1.4–10.1	0.02–0.2	0.05–0.5	0.01–0.2	0.00–0.02	0.3–1.2	0.3–1.8
LLS	mean	**0.6**	**8.5**	**15.3**	**0.1**	**0.1**	**0.1**	**0.02**	**0.3**	**0.4**
	min–max	0.3–1.3	2.9–18.5	6.9–30.2	0.03–0.2	0.04–0.3	0.04–0.2	0.01–0.05	0.2–0.4	0.3–0.5
EUE	mean	**1.8**	**31.6**	**32.1**	**1.8**	**3.6**	**1.7**	**0.11**	**1.1**	**1.4**
	min–max	0.7–3.9	11.1–70.9	6.9–77.8	0.2–4.4	0.3–8.7	0.05–4.2	0.01–0.24	0.6–2.0	0.7–2.7
RZ	mean	**1.5**	**12.5**	**6.3**	**0.2**	**0.3**	**0.1**	**0.02**	**0.7**	**1.0**
	min–max	0.4–3.5	4.2–27.9	2.9–11.5	0.1–0.5	0.1–0.7	0.02–0.2	0.01–0.03	0.3–1.1	0.4–1.8
NTA	mean	**1.4**	**23.9**	**15.3**	**0.3**	**0.4**	**0.1**	**0.03**	**0.7**	**1.0**
	min–max	0.4–3.0	7.3–53.9	6.9–30.2	0.03–0.6	0.2–0.8	0.03–0.3	0.01–0.06	0.4–1.1	0.4–1.7
***Growing season/Long wet weather** (May–September, 2006)*										
UNRC	mean	**4.2**	**9.7**	**59.5**	**0.1**	**0.3**	**0.1**	**0.08**	**0.8**	**1.1**
	min–max	1.3–6.9	1.9–17.7	7.8–138.2	0.03–0.2	0.1–0.7	0.05–0.2	0.08–0.2	0.3–1.5	0.5–2.4
LLS	mean	**0.9**	**10.9**	**41.8**	**0.1**	**0.2**	**0.1**	**0.05**	**0.3**	**0.3**
	min–max	0.4–1.7	4.3–16.3	11.5–69.1	0.02–0.2	0.1–0.3	0.02–0.1	0.01–0.1	0.1–0.6	0.1–0.6
EUE	mean	**5.4**	**134.3**	**269.3**	**1.7**	**2.3**	**3.2**	**0.43**	**1.6**	**1.9**
	min–max	1.7–8.6	51–225	69–461	1.0–2.3	1.3–3.3	1.4–4.6	0.3–0.6	0.7–3.2	0.7–3.4
RZ	mean	**5.4**	**50.6**	**334.4**	**1.6**	**2.2**	**1.2**	**0.42**	**1.7**	**2.0**
	min–max	1.7–8.6	7.3–82.6	24–622	0.5–2.9	0.7–4.4	0.1–2.8	0.05–0.9	0.6–3.5	0.8–3.9
NTA	mean	**5.2**	**47.3**	**478.2**	**1.1**	**1.6**	**0.7**	**0.39**	**1.4**	**1.7**
	min–max	0.9–8.6	6.7–78.6	12–1382	0.2–2.2	0.2–2.5	0.06–1.4	0.03–0.8	0.3–3.3	0.3–3.7
***Post-growing season/Short wet weather** (November–December, 2006)*										
UNRC	mean	**22.8**	**31.6**	**395**	**0.5**	**1.8**	**0.2**	**0.3**	**1.8**	**2.1**
	min–max	6.9–31.7	7–46	104–634	0.1–0.8	0.5–2.5	0.1–0.4	0.1–0.4	0.3–2.5	0.6–3.0
LLS	mean	**12.6**	**30.2**	**419**	**0.6**	**1.8**	**0.4**	**0.3**	**2.1**	**2.2**
	min–max	8.6–16.2	18–38	302–566	0.4–0.7	1.2–2.2	0.3–0.5	0.2–0.4	0.9–2.9	0.9–3.1
EUE	mean	**35.3**	**84.2**	**1314**	**1.6**	**4.9**	**1.7**	**0.7**	**5.8**	**6.2**
	min–max	15.6–46.7	33–117	311–1866	1.0–1.9	2.5–6.3	1.5–2.0	0.3–1.1	1.1–8.3	1.5–8.8
RZ	mean	**35.4**	**81.9**	**1212**	**1.7**	**5.1**	**1.0**	**0.8**	**5.8**	**6.2**
	min–max	15.6–46.7	34–117	233–1866	1.0–2.1	2.4–7.0	0.4–1.4	0.3–1.1	1.0–8.4	1.2–9.1
NTA	mean	**34.0**	**80.1**	**1364**	**1.8**	**5.7**	**1.0**	**0.8**	**5.7**	**6.4**
	min–max	15.6–43.2	35–104	311–2052	1.1–2.2	2.9–7.7	0.4–1.3	0.3–1.1	1.1–8.2	1.1–9.6

UNRC: Upper Njoro River Catchment; LLS: Lower Little Shuru; EUE: Egerton University & Environs; RZ: Restricted Zone; NTA: Njoro Township Area

Elsewhere, the elevation of loads during wet weather is ascribed to increase storm runoff and leaching in a manner that links both to land cover and human interventions (Jagals, 1997). Because agriculture in the NRC is small-scale and predominantly rain fed, the growing seasons coincides with wet weather (SUMAWA, 2005). This is also the period when a large proportion of the annual stream flow occur (Figure 2). Given that fertilizers are applied on soils that are easily eroded and cultivation is largely on steep terrain (slopes are within 7–30%), surface runoff is typically laden with sediments, organic matter and nutrients (SUMAWA, 2005). The resultant pollution load is expectedly high even though it may be influenced by several landscape variables which affect runoff (Jagals, 1997). In the NRC, the most striking are perhaps; (i) antecedent weather; (ii) location, intensity and duration of rainfall; (iii) limited depression storage; (iv) low infiltration/withholding capacity and; (v) low water storage capacity of remnant forests.

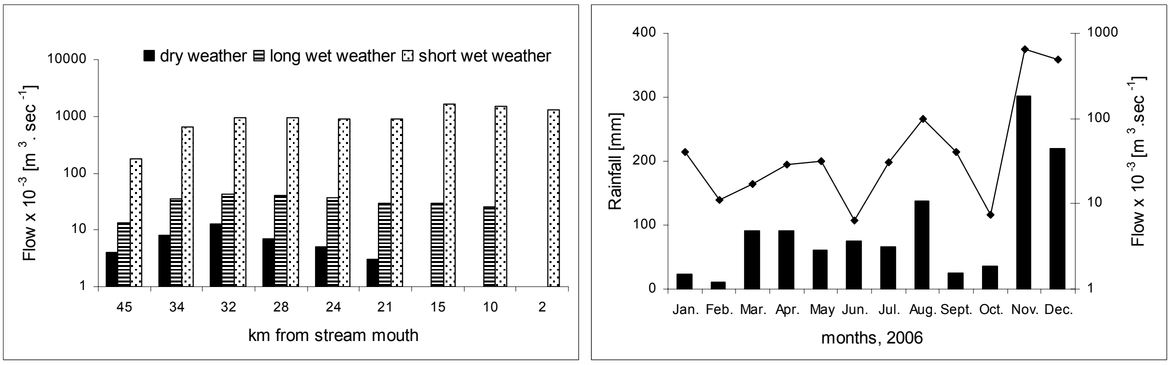

Figure 2. Left: Seasonal variability of stream flow along the Njoro River in 2006. Right: Total monthly rainfall (bars) and the monthly flow at the middle reaches (y-axis log-scale except for rainfall)

Table 3. Daily loads of pollutants from wastewater outfalls at Egerton University & Environs (EUE) in 2006

Sub-catchments		Flow [$m^3.d^{-1}$]	BOD_5 [$kg.d^{-1}$]	TSS [$kg.d^{-1}$]	PO_4-P [$kg.d^{-1}$]	TP [$kg.d^{-1}$]	NH_4-N [$kg.d^{-1}$]	NO_2-N [$kg.d^{-1}$]	NO_3-N [$kg.d^{-1}$]	TN [$kg.d^{-1}$]
Dry weather *(January–April, 2006)*										
WTP*	mean	**130**	**12**	**5**	**0.9**	**1.0**	**0.3**	**0.01**	**0.1**	**0.1**
	min–max	86–173	5–18	3–7	0.6–1.2	0.6–1.4	0.2–0.5	0–0.01	0.06–0.1	0.07–0.2
OS**	mean	**345.6**	**48.4**	**122.6**	**0.3**	**0.6**	**0.001**	**0.001**	**0.02**	**0.04**
	min–max	259–432	34-63	72–173	0.3–0.4	0.4–0.8	0–0.001	0–0.001	0.02–0.02	0.03–0.05
Long wet weather *(May–September, 2006)*										
WTP*	mean	**202**	**22**	**12**	**1.6**	**1.7**	**0.2**	**0.1**	**0.05**	**0.1**
	min–max	173–259	13–28	6–17	1.4–1.8	1.4–2.0	0.1–0.2	0.1–0.2	0.03-0.1	0.1–0.1
OS**	mean	**302**	**32**	**63.4**	**0.3**	**0.5**	**0.01**	**0.001**	**0.001**	**0.01**
	min–max	259–234	28–37	35–92	0.2–0.3	0.2–0.6	0–0.01	0–0.001	0–0.001	0.01–0.01
Short wet weather *(November–December, 2006)*										
WTP*	mean	**66**	**2**	**3**	**0.5**	**0.6**	**0.5**	**0.03**	**0.01**	**0.02**
	min–max	26–86	1–3	1–4	0.2–0.7	0.2–0.8	0.1–0.7	0.01–0.1	0–0.02	0.01–0.03
OS**	mean	**302**	**9**	**90**	**0.4**	**1.4**	**0.3**	**0.01**	**0.001**	**0.02**
	min–max	259–346	7–10	41–138	0.3–0.6	0.7–2.1	0.1–0.6	0–0.01	0–0.001	0.02–0.02

*WTP outfall at Egerton University; **Open Sewer outfall from hostels at Egerton University

The general wet weather increase in loads was unattainable for some loads at the EUE outflow, where for example, the daily total P load significantly ($p < 0.05$) decreased by > 40% of the dry weather load. In addition to diffuse sources, EUE received wastewater chiefly via WTP and open sewer outfalls (Table 3). The contribution of these sources was significant with respect to BOD_5, phosphorus and ammonium. For instance, the daily P load during the growing season/long wet weather increased from 0.6 kg at the EUE inflow to 0.9 kg at Turkana Flats (before outfalls) but then abruptly to 2.3 kg after the outfalls downstream of Njoro Canning Factory. Similarly, the daily NH_4-N load increased from 0.1 kg, to 0.3 kg and then 3.2 kg while the observed daily BOD_5 load rose from 41 kg to 43 kg and then abruptly to 132 kg at the same locations during the same period. The observed increase in loads before the outfalls was associated with agricultural runoff and other diffuse sources from residential areas mainly Njokerio (20,000 inhabitants) but the increase below Njoro Canning was certainly due to point source emissions from the outfalls.

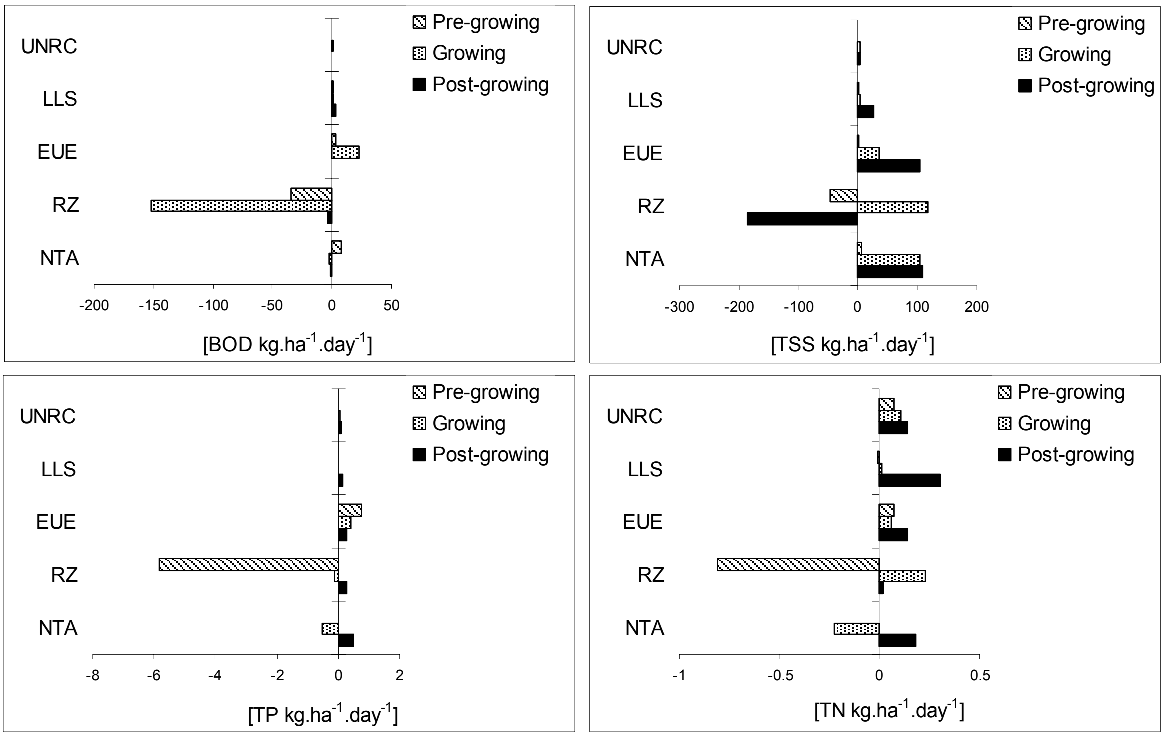

Figure 3. Net emissions (+ve) and retentions (-ve) by sub-catchments during the three farming periods

Emissions by sub-catchments

The densely settled EUE and NTA were notable emitters of pollutants (Figure 3). Like Njokerio, the informal sector in Njoro Township (50,000 inhabitants) constituted small-scale artisan works and a progressively vibrant commercial sector which included bars, restaurants, street markets, slaughter houses and meat distribution outlets. The type of waste generated from these enterprises is unique to developing countries and constitute a major source of pollution (Mbuligwe and Kaseva, 2005). Furthermore, because water and sanitation facilities are inadequate, people visit the stream regularly and the activities they undertake pollute the stream (Yillia *et al*., 2007). Dry weather load increase at the outflows of UNRC, NTA and LLS was attributed to these activities as runoff from agricultural fields and residential areas was minor at this time of the year.

All sub-catchments emitted N although RZ and NTA retained/removed N during pre-growing and growing seasons, respectively. This was unexpected for NTA but given the gentle slopes (< 4%) in the area and the impact the 2006 drought had on long wet weather, the contribution of surface runoff was probably low as evident in the stream hydrograph below km 28 (Figure 2). Otherwise, N loads increased slightly downstream but emissions were consistent as ambient N levels were generally high (0.1–1.3 $mg.l^{-1}$). The whole catchment (except RZ and the section within LNNP) was affected by livestock grazing, a likely source for the consistent N emissions. P emissions were generally higher during the growing/post-growing periods as wet weather runoff increased from agricultural fields and residential areas except for EUE where point sources were located and the explained incongruity at NTA during long wet weather.

EUE emissions were considerably removed or retained within RZ during dry weather/pre-growing period. Due to restrictions, the stream stretch within RZ was largely inaccessible and the riparian vegetation was still intact. Also flow was low (0.01–0.04 $m.sec^{-1}$) in dry weather and travel time was long, 2–6 days for 5 km. This is sufficient time for sediment-water-atmosphere exchanges (Stow *et al*., 2001). Additionally, the stream is generally shallow with a high wetted-zone to depth ratio (20–30) especially in the pools that characterize the streambed at the middle reaches (Mathooko, 2001). This should provide extensive sediment-water interface for P adsorption, and denitrification in oxygen-deficient pockets given the low oxygen levels (< 4 $mg.l^{-1}$; < 50% saturation) after the outfalls. But due to the considerable increase in flow in short wet weather, steam velocity increased (0.2–0.5 $m.sec^{-1}$) and the travel time was reduced accordingly. Thus, retention within RZ was obliterated and the area became a net emitter of both P and N. Perhaps the emissions came from sediment wash-out, as well as runoff from commercial farms in the vicinity as was evident with the increase in TSS, P & N loads at the RZ outflow during this period. Sediment wash-out especially during high stream flow could have major impact on water quality at Lake Nakuru given that stream flow is usually complete during such events.

Pollution management in the NRC

The prospect for pollution control in the NRC is high given that the catchment is constantly under critical media attention. Some recent media reports even blame the environmental problems in the NRC for the death and migration of wildlife at Lake Nakuru and the recent plummet in tourism in the region. Some of the allegations lack scientific evidence but encouragingly they highlight the crucial nature of the catchment for the environment and the regional economy. Obviously, some problems such as land ownership conflicts in the upper catchment are more complex and require long-term management but others are far less intricate and could be tackled in the interim. For instance, addressing point sources by improving wastewater treatment efficiency and adherence to effluent regulations at EUE could bring down P, N and BOD_5 loading dramatically. It is estimated that without point sources, the restricted area (RZ) could maintain pollution levels at the middle reaches below EUE inflow levels especially during dry weather flow.

Diffuse sources in the NRC are far more complex to address given their widespread nature. But some such as in-stream activities of people and livestock have been previously isolated as an important contributor to diffuse pollution in the stream (Mathooko, 2001; SUMAWA, 2005; Yillia *et al*., 2007). The regulation of these activities has proved beneficial at RZ and the section of the stream within LNNP. Other measures to control diffuse sources will require a variety of small-scale management actions at various locations. They may include: (i) restraining the use of fertilizers (ii) maintain the riparian strip; (iii) preserving the remnant forests; (iv) interrupting the slope on farms and grazing fields and; (v) increasing the infiltration capacity on farmlands. Additional measures will require more elaborate planning such as improving the general water and sanitation situation in settled areas.

Nevertheless, even the best measures will fail without the cooperation of important actors and the support of regional and local administrators. The present Water Act provides for catchment-based management but this is currently wanting for the NRC. Regional experience shows that catchment-based management is indispensable for any local effort given the different management priorities at the national level. For the time being, public expectations must be realistic given that the NRC will require a lot of time to recover even if correct measures are implemented immediately to address the current environmental problems.

Conclusion

The vulnerability of sub-catchments was indexed by the net flux of pollutants responded to present land use/cover and the specific human interventions that characterize each. The largely forested UNRC was the least vulnerable. In contrast, the densely settled and heavily farmed EUE and TNA were extremely vulnerable although the restricted area (RZ) between them showed some potential to retain or remove pollution. The inherent response by the stream to human actions and natural landscape variables was primarily governed by the seasonality of the hydrological regime.

Acknowledgements

The research was funded by the Austrian Development Co-operation. Prof. J. M. Mathooko, Ken Kosimbei and Geoffrey Ongo’ndo at Egerton University are acknowledged.

References

Jagals, P., 1997. Storm water runoff from typical developed and developing South African urban developments: definitely not for swimming. *Wat. Sci. Tech*. 35 (11–12), 133–140.

Kundu P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. In O. Altan (Ed.) 20th ISPRS Congress. Istanbul, Turkey, 37 (B7), 1 – 5.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131-139.

Mbuligwe, S. E., Kaseva, M. E., 2005. Pollution and self-cleansing of an urban river in a developing country: A case study of Dar es Salaam, Tanzania. *Environmental Management* 36, (2) 328 – 342.

Mokaya, S. K., Mathooko, J. M., Leichtfried, M., 2004. Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *Afr. J. Ecol*. 42, (4) 281 – 288.

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiolgia* 458, 121 – 130.

Sliva, L., Dudley Williams, D., 2001. Buffer zone versus whole catchment approaches to studying land use impact on river water quality. *Wat. Res*. Vol. 35, (14) 3462 – 3472.

Stow, C. A., Borsuk, M. E., Stanley, D. W., 2001. Long-term changes in watershed nutrient inputs and riverine exports in the Neuse River, North Carolina. *Wat. Res*. Vol. 35, (6) 1489 – 1499.

SUMAWA, 2005. Sustainable Management of Watersheds: Biophysical, livestock and human interactions in the River Njoro Watershed. GL-CRSP, UC, Davis, USA.

UNEP/WHO, 1996. Water Quality Monitoring – A practical guide to the design and implementation of freshwater quality studies and monitoring programmes.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007. In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya. Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium. Lusaka, Zambia.

Zielinski, J., 2002. Watershed Vulnerability Analysis, Centre for Watershed Protection, Ellicott City, MD 21043, USA.

Chapter 5

Transients and the temporal dynamics of diffuse pollution in a pastoral stream

Prepared for submission: *Water Research*

Transients and the temporal dynamics of diffuse pollution in a pastoral stream

P. T. Yillia*, N. Kreuzinger** and J. M. Mathooko***

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; E-mail: *paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at*
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; E-mail: *norbkreu@iwag.tuwien.ac.at*
***Egerton University, Department of Biological Sciences, PO Box 563, Njoro, Kenya; Tel: +254 37 61282 or +254 720853844; Fax: +254 37 61055; E-mail: *jmathooko@hotmail.com*

*corresponding author

Abstract
Two contrasting transient pollution events were monitored at the middle reaches of the Njoro River in Kenya to evaluate the dynamics of diffuse pollution related to such events. Peak loads during storm-induced transients were within 3–4 orders of magnitude higher than short-lived (30–60 minutes) diurnal transients caused by in-stream activities of people and livestock. Clockwise concentration-discharge hysteresis were observed for Turbidity, TSS, DO, BOD_5, total P and the faecal indicator bacteria whereas anticlockwise loops were detected for conductivity and total N. Transient yield of TSS; BOD_5; P and N in excess of wet weather base flow during storm-induced transients was striking (780; 8.4; 0.5 and 0.1 t/d, respectively) with all pollutants going through a slight anticlockwise circle of improved water quality within 48–72 hrs of the descending limb of the stream hydrograph. It was concluded that even though both transient events are symptomatic of within-channel processes, storm-induced transients are exceedingly important for catchment mobilization of pollutants from diffuse sources. Hence measures are required control in-stream activities and limit the rapid transfer of pollutants from diffuse sources through surface runoff.

Keywords:
Diffuse pollution; in-stream activities; pastoral stream; rainstorms; transient events

Introduction

Transient pollution events are isolated episodes that occur occasionally in addition to the observed temporal variations of pollutants in streams. They may be driven by natural phenomena like sporadic rainstorms and/or regular human induced perturbations such as recreational activities or accidental spillage of pollutants (Jacobsen *et al*., 1996; Schreiber *et al*., 2001). Transients are detected more frequently in small streams than in large rivers but they can occur on all spatial scales from small plots and watersheds to large drainage basins (Schreiber *et al.*, 1996). Depending on the type of land use in the surrounding area and the forces that generate them, large quantities of pollutants can be produced and transported downstream (Schreiber *et al.*, 2001).

Transients provide an exceptional opportunity to evaluate the magnitude and dynamics of diffuse pollution in biophysically altered catchments. Thus most transient studies try to capture episodic pollution events that are often associated with diffuse sources (Beck *et al.*, 1991; Schreiber *et al.*, 2001; Beck, 1996). However, transients are difficult to monitor because they are generally short-lived and could pass easily unnoticed, which makes hysteresis in the concentration-discharge relationship difficult to observe. But data loggers equipped with water quality sensors are recommended for obtaining continuous online information particularly for low frequency events although spot sampling at short time intervals is also possible (Whitefield and Wade, 1992; Whitefield and Wade, 1996; Bowes *et al.*, 2005).

A special spot sampling programme was designed to monitor two forms of transient events in a pastoral stream in southwestern Kenya. Transients have not been studied in the Njoro River although this knowledge could be useful for addressing diffuse pollution which is currently a major concern. The stream is the main source of water for over 70,000 riparian inhabitants and the main drainage area for Lake Nakuru, a Ramsar site and a renowned tourist destination for wildlife that is imperil of siltation and eutrophication (SUMAWA, 2005; Yillia *et al.*, 2007; cf. Chapter 6). Sediment and nutrient mobilization from diffuse sources is expectedly high in the Njoro River given the immense land use change that has occurred in the catchment (Kundu *et al.*, 2004; SUMAWA, 2005).

The main objective of this study was to evaluate the relative contribution of diffuse pollution by storm-induced transients and the diurnal episodes provoked by in-stream activities of people and livestock.

Materials and methods

The study stream – Njoro River

Njoro River originates from the Eastern Mau Escarpment at 2800 m (a.s.l) and flows northwards until it joins the main tributary, Little Shuru almost midway

(Figure 1). For the remaining 30 km after the confluence, the stream follows a north-east course through farmland and settlements including Njokerio, Egerton University and Njoro Township in the middle reaches and then southwards through parts of Nakuru Municipality in the lower reaches before discharging intermittently into Lake Nakuru at 1700 m (a.s.l) on the floor of the Rift Valley (Shivoga, 2001).

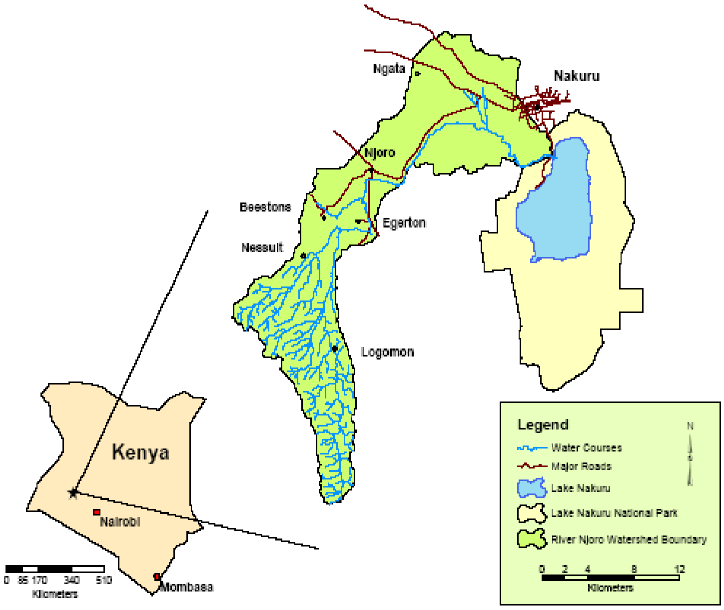

Figure 1: Njoro River Catchment

The soils in the Njoro River Catchment (NRC) were developed from sediments and agglomerates of Quaternary volcanic activity (Mainuri, 2005; Baldyga, 2005). They are shallow and extremely prone to erosion during long (May–September) and short (November–December) wet weather. Both periods are characterized by an increase in surface runoff (Shivoga, 2001). The main dry weather is in January–April but dry spells could occur during wet weather. Additional information of the NRC is given in Table 1.

Table 1. Supplementary information on the Njoro River Catchment

Stream length	60 km	Arable land	80%
Total drainage area	280 km^2	Forest/woodland	12%
Drainage area at Turkana Flats	120 km^2	Residential area	6%
Kilometres from stream mouth	28 km	Riparian population	70,000
Slopes (upper catchment)	7–27%	Pop. density (upper catchmeent)	< 50/km^2
Slopes (lower catchment)	< 4%	Pop. density (lower catchmeent)	> 2000/km^2
Annual rainfall	800–1200 mm	Temperature	9–24ºC

The study site – Turkana Flats

Turkana Flats (a disturbed pool) was the ideal choice for the transient study because of its location in an area dominated by farmland and residential plots at the middle polluted reaches. At this site, the stream drains approximately 43% of the total catchment area but it was uninfluenced by point source input from WTP outfalls which were at least 500 m downstream. In addition, the pool at Turkana Flats was visited regularly by people and livestock especially during dry weather.

Sampling

Weekly sampling for transients caused by in-stream activities was undertaken at 6 hrs intervals starting at 06:00 hrs on two successive days in dry weather. Samples were collected upstream and downstream of activities. The schedule was repeated four times. For storm-induced transients, four such events were sampled at peak flow with three more samples taken at 24 hrs interval after each storm. Additional water quality data was obtained from a routine monitoring programme at the site. Storm induced flow was monitored at Egerton Gate Bridge, < 100 m downstream of Turkana Flats at 3 hrs interval during the ascending and descending limb of the stream hydrograph using the mean velocity cross-sectional area method (UNEP/WHO, 1996).

Laboratory analysis

Standard analytical procedures were followed for Turbidity, BOD_5, TSS, PO_4-P, NH_4-N, NO_2-N, NO_3-N, TP and TN (APHA, 2002). Loads were estimated from the instantaneous stream flow and the concentration of pollutants (UNEP/WHO, 1996). The standard membrane filtration technique was used for faecal indicator bacteria (FIB) i.e. Total Coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE) (Yillia *et al*., 2007).

Results

Response of the steam hydrograph

The stream hydrograph at Egerton Gate Bridge recorded at least five transient flow events in 2006 (Figure 2). Compared to wet weather base flow, transients were characterized by soaring spikes in stream flow with storm water accounting for 99% of stream flow at the peak of the ascending limb of the stream hydrograph. This was largely the product of the duration and location of the inciting storm (Table 2). Whereas short duration rainstorms nearby produced short-lived transients with the stream reaching peak flow in less than 30 minutes, the stream required 1–2 hrs to peak during long duration storms that affected the whole catchment. But the resultant transients yielded superior peaks and the descending limbs of the hydrograph lasted longer (72–120 hrs).

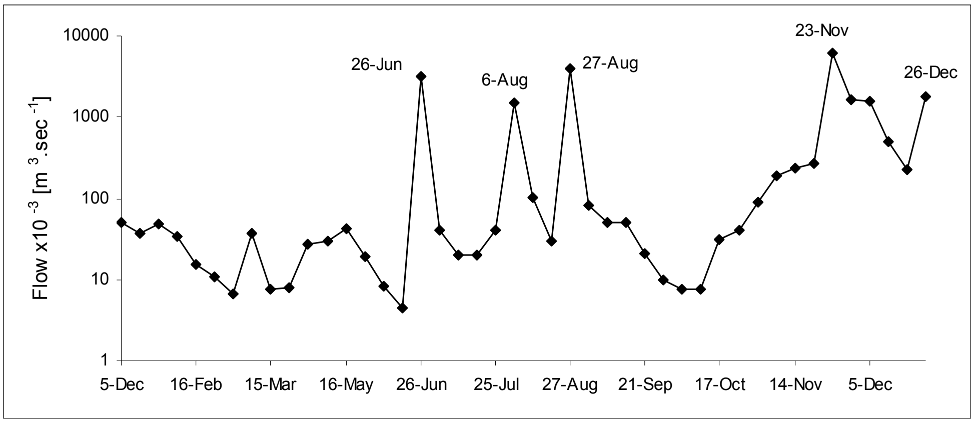

Figure 2. The 2006 stream hydrograph at Egerton Gate Bridge indicating transient spikes

Table 2. Hydrological characteristics of transients in 2006 and details of the inciting rainstorms

Date when storm occurred	Type of storm	Duration of storm	Location of storm in the catchment	Response time to reach peak flow	Peak flow achieved	Duration of the descending limb
June 26, 2006	rainstorm	3 hrs	middle reaches	< ½ hr	3.2 $m^3.sec^{-1}$	< 48 hrs
August 6, 2006	rainstorm	1 hr	middle reaches	< ¼ hr	1.5 $m^3.sec^{-1}$	< 10 hrs
August 27, 2006	hailstorm	4 hrs	whole catchment	> 1 hr	3.9 $m^3.sec^{-1}$	> 72 hrs
November 23, 2006	rainstorm	6 hrs	whole catchment	> 2 hrs	6.2 $m^3.sec^{-1}$	> 120 hrs
December 26, 2006	rainstorm	4 hrs	whole catchment	> 1 hrs	1.8 $m^3.sec^{-1}$	< 72 hrs

Storm-induced transients

Two types of concentration-discharge response curves were observed during storm-induced transients. A clockwise hysteresis characterized by a dramatic rise in pollutant concentration as the stream attained peak flow and an anti-clockwise response with a unexpected decrease in concentration at peak flow. The clockwise response was typical for TSS, BOD_5, DO and total P (Figure 3). A similar response was observed for TC, EC and IE, which were 2–3 orders of magnitude higher than pre-storm base flow levels (Figure 4). On the contrary, anti-clockwise loops were identified for conductivity & total N (Figures 5). Generally, the degree of hysteresis produced decreased in succession with transients in the latter part of wet weather producing the least hysteresis. Both clockwise and anticlockwise hystereses were characterized by a small anticlockwise circle at the base of the descending limb of the stream hydrograph after each storm. This trend was distinctive around 48-72 hrs of recession during which ambient levels were significantly ($p < 0.05$) lower than pre-storm base flow levels (Table 3). Concentrations increased steadily afterwards pending the establishment of post-storm base flow or interruption by subsequent transients.

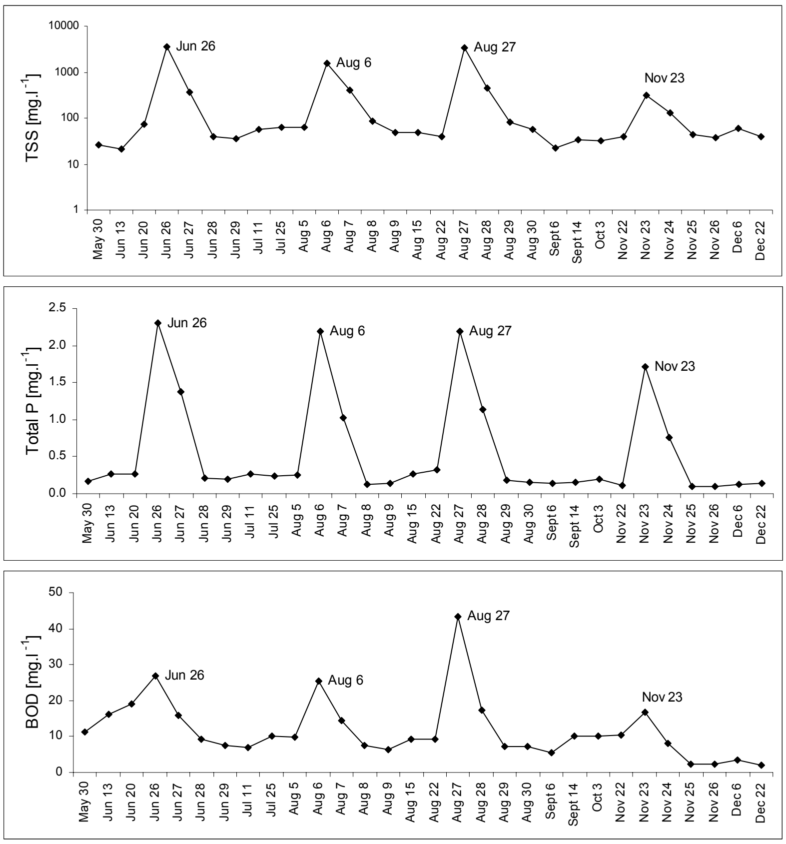

Figure 3. Storm induced clockwise hysteresis for TSS, total P and BOD_5

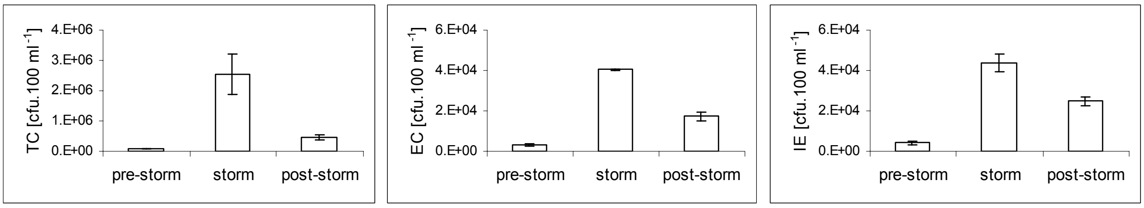

Figure 4. Mean Total Coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE) at Turkana Flats during storm induced transients (storm), < 7 days before (pre-storm) and 24 hrs after (post-storm)

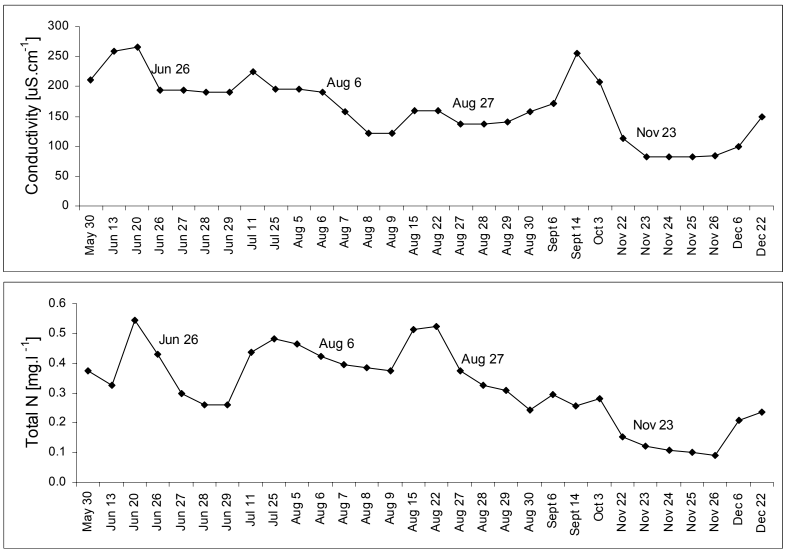

Figure 5. Storm induced anticlockwise hysteresis for conductivity and total N

Table 3. Mean levels of pollutants illustrating post-storm recovery 3 days after storm-induced transients

Period	Flow x10^{-3} [$m^3.sec^{-1}$]	BOD_5 [$mg.l^{-1}$]	TSS [$mg.l^{-1}$]	PO_4-P [$mg.l^{-1}$]	TP [$mg.l^{-1}$]	NH_4-N [$mg.l^{-1}$]	NO_3-N [$mg.l^{-1}$]	TN [$mg.l^{-1}$]
Pre-storm (< 7 days before)	30	12.8	60	0.06	0.28	0.13	0.31	0.51
Transient (storm-induced)	2900	31.9	2850	-	2.32	-	-	0.41
Post-storm (3 days after)	50	7.0	47	0.04	0.17	0.08	0.22	0.29
Post-storm (> 7 days after)	35	9.1	50	0.05	0.23	0.09	0.27	0.42

Transients provoked by in-stream activities

Transient peaks produced by in-stream activities were strongly associated with the diurnal pattern of visits by people and livestock at the pool (Figures 6, 7 & 8). In-stream activities started with human visits at 07:00 hrs and peaked twice at 10:00 and 18:00 hrs before subsiding around 19:00 hrs. The transients produced were short-lived lasting for a couple of minutes only and compared to storm-induced transients, they were generally characterized by smaller amplitudes and smaller pollution loads. Nevertheless, they were an important source and pathway of diffuse pollution during dry weather as they yielded significantly ($p < 0.05$) higher loads of pollutants compared to dry weather base flow levels even though storm-induced transient yields were the most striking (Table 4). The difference in levels between dry weather base flow and transients provoked by in-stream activities was especially evident with the FIB, Turbidity, TSS and BOD_5. Ambient P and N levels increased slightly downstream during in-stream activities but spatial (upstream/ downstream) and temporal (before/during/after) disparities with respect to in-stream activities were not significantly different ($p > 0.05$). N levels in particular did not correspond well to the diurnal pattern of in-stream activities while both upstream and downstream P levels increased slightly in the morning and afternoon during activities even though mean levels downstream were a little higher.

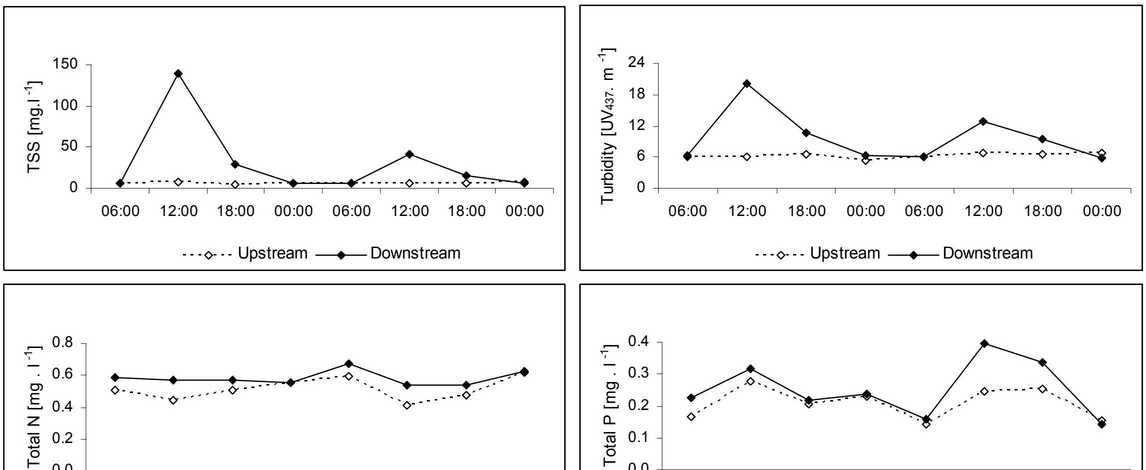

Figure 6. Diurnal transients provoked by in-stream activities on two consecutive days for TSS, Turbidity, TP and TN at Turkana Flats in dry weather (January–April)

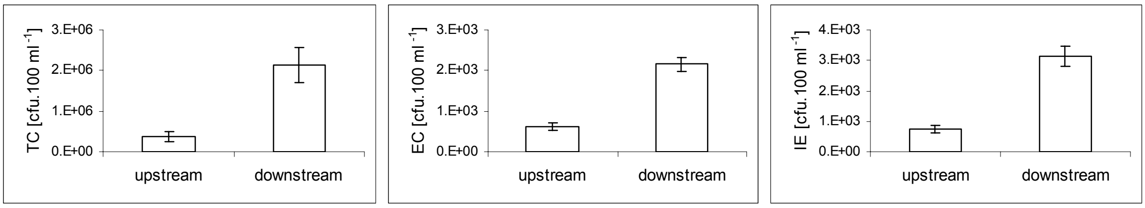

Figure 7. Mean levels of Total Coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE) upstream and downstream of in-stream activities at 11:00–12:00 at Turkana Flats in dry weather

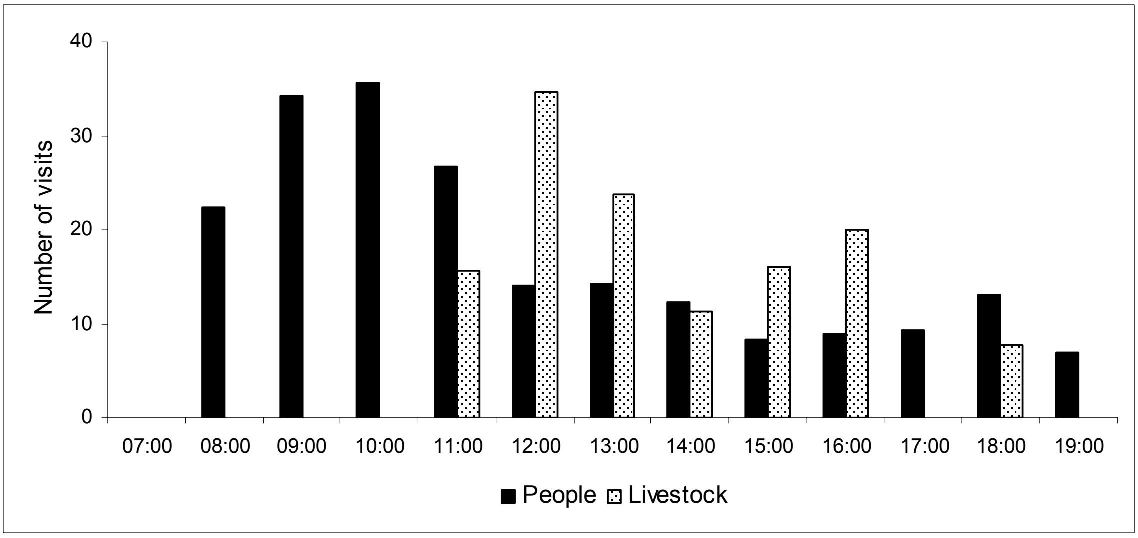

Figure 8. Diurnal variation of visits by people and livestock at Turkana Flats during dry weather

Table 4. Pollution loads at Turkana Flats during transient events and base flow conditions

Events	Flow [$m^3.day^{-1}$]	BOD_5 [$kg.day^{-1}$]	TSS [$kg.day^{-1}$]	TP [$kg.day^{-1}$]	TN [$kg.day^{-1}$]
Transients (rainstorms)	247000	8400	778000	550	100
Base flow (wet weather)	2800	30	150	0.8	1.4
Transients (In-stream activities)	890	20	50	0.3	0.6
Base flow (dry weather)	890	10	10	0.2	0.5

Discussion

Njoro River can be described as an event response stream due to the sudden reaction of the stream hydrograph to surface runoff. The fairly swift hydrograph response is accentuated by a number of factors. Storm water reaches the stream via surface runoff within minutes because most of the catchment landscape is steep with limited depression storage (SUMAWA, 2005). Furthermore, the generally thin soils that are underlain by a crystalline basement complex lessen the infiltration capacity (Mainuri, 2005; Baldyga, 2005). Also the water holding capacity of the remnant forests could be low as the catchment has undergone biophysically alteration (Kundu *et al.*, 2004). Hence, the contribution of subsurface flow does not maintain a reasonable base flow during dry weather. Actually, base flow accounts for a very small fraction of the annual stream flow which means the contribution of storm water is easily manifested during rainstorms as the hydrograph is largely dominated by storm runoff.

Clockwise hysteresis during transient storms is typical for streams draining biophysically altered catchments that are dominated by agricultural activities. It results from the rapid delivery of pollutants during the rising limb of the stream hydrograph (Iqbal, 2002; Bowes *et al.*, 2005). The sources of mobilized pollutants are usually within reach of the stream for them to be transported quickly (Bowes *et al.*, 2005). The most likely sources in the NRC are farmlands and residential areas where loose soil and debris accumulate during antecedent dry weather (SUMAWA, 2005). But the unexpected anticlockwise loops for conductivity and nitrogen suggest dilution of within-channel soluble constituents as stream flow increased. Unlike phosphorus which is largely (> 80%) in the particulate/adsorbed form and correlates well with suspended solids, 80–95% of total nitrogen in the Njoro River exist mainly as NO_3-N or NH_4-N. It might be reasonable to suggest that within-channel processes override catchment mobilization for nitrogen speciation in the Njoro River as indicated previously (Yillia and Kreuzinger, 2008).

The small anticlockwise circles which occurred between 48 and 72 hrs at the base of the descending limb of the stream hydrograph may be considered as a short transient post-disturbance recovery period of improved water quality before the next base flow is established. It is thought that delayed intrusion of low conductivity sub-surface flow from the crystalline basement of recent volcanic activity in the predominantly forested upper catchment brings with it dilution water to the middle and lower reaches after precipitation and surface runoff has subsided. In addition, wash-out by high velocity discharge during increased stream flow has previously been associated with within-channel mobilization of pollutants in the stream (Yillia and Kreuzinger, 2008; cf. Chapter 4). Furthermore, within-channel diffuse loading of pollutants by in-stream activities is low at this time as visits by people and livestock is infrequent during and/or immediately after rainstorms. It was observed that residents accessed other water sources in the area as the increase in suspended solids and turbidity during rainstorms dissuaded people from visiting the stream.

The diurnal transients produced by in-stream activities were typically short-lived and smaller in scale compared to storm-induced transients. They dissipated within a few minutes and often easily pass unnoticed. However, they are important forcing factors for within-channel mobilization of pollutants especially during low dry weather flow as observed previously at the middle polluted reaches of the stream (Yillia *et al*., 2007; cf. Chapter 6). Activities could include watering of livestock, washing of clothes and vehicles and abstraction of water for domestic use (Mathooko, 2001). Animals watering within the stream channel and cars or carts driven on the streambed agitated and mobilize sediments and attached or adsorbed pollutants. Similarly, phosphorus may be introduced during washing and pathogens, micronutrients and organic matter are released in waste from people and animals during in-stream activities (Yillia *et al*., 2007; cf. Chapter 6).

The present analysis suggests that the two most important diffuse pollution problems currently in the NRC are in-stream activities of people and livestock especially during dry weather and surface runoff of sediments and pollutants from farmlands and residential areas during wet weather. Therefore, measures are needed to control the transfer of diffuse pollution via these pathways. In particular, in-stream activities ought to be regulated given their widespread nature and the development of innovative strategies related to land use in the entire catchment area will be required to restrict surface runoff. It may be necessary to protect and maintain the remnant vegetation cover as vegetated buffer strips effectively reduce pollutants in surface runoff by trapping sediments, stabilizing stream banks and improving the infiltration capacity (Dabrowski *et al*., 2002). Also, the impact of slope on runoff is greatly restrained by the presence of vegetation cover on steep slopes as sheet-flow is enhanced with generally lower flow rate compared to rapid channel-flow in the absence of vegetation cover (Dabrowski *et al*., 2002).

Conclusion

Transient pollution events in the Njoro River are important driving forces producing and aiding the transport of pollutants from diffuse sources in the catchment. Storm-induced transients lasted longer and yielded considerably more loads compared to short-lived diurnal episodes provoked by in-stream activities of people and livestock. Both events are symptomatic of within-channel processes even though storm-induced transients are exceedingly important for catchment mobilization of pollutants. Measures are required to regulate in-stream activities and minimize the transfer of pollutants via surface runoff.

Acknowledgements

The research was funded by the Austrian Development Co-operation with additional support from IWAG, TU-Vienna, Austria. Ken Kosimbei and Geoffrey Ongo'ndo of Egerton University, Kenya are acknowledged.

References

Baldyga, T. J., 2005. Assessing land cover change impact in Kenya's River Njoro watershed using remote sensing and hydrological modelling. M.Sc. Thesis, University of Wyoming, USA.

Beck, M. B., 1996. Uncertainty, risk, and transient pollution events: a survey. *Wat. Sci. Tech.* 33, 34–41.

Beck, M. B., Adeloye, A. J., Finney, B. A., Lessard, P., 1991. Operational water quality management: transient events and seasonal variability. *Wat. Sci. Tech.* 24, 257–265.

Bowes, M. J., 2005. Phosphorus-discharge hysteresis during storm events along a river catchment: the River Swale, UK. *Wat. Res.* 39, 751–762.

Dabrowski, J. M., Peall, S. K. C., van Niekerk, A., Reinecke, A. J., Day, J. A., Schulz R., 2002. Predicting runoff-induced pesticide input in agricultural sub-catchment surface waters: linking catchment variables and contamination. *Wat. Res.* 36, 4975–4984.

Iqbal, M. Z., 2002. Nitrate flux from aquifer storage in excess of baseflow contribution during a rain event. *Wat. Res.* 36, 778–792.

Jacobsen, J. L., Madsen, H., Harremoës, P., 1996. Modelling the transient impact of rain events on the oxygen content of a small creek. *Wat. Sci. Tech.* 33 (2), 177–185.

Kundu P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. Proceedings of the 20th ISPRS Congress. Turkey, 37 (B7), 1–5.

Mainuri, Z. G., 2005. Land use effects on the spatial distribution of soil aggregate stability within the Njoro River watershed, Kenya. M.Sc. Thesis. Egerton University, Kenya.

Schreiber, J. D., Smith, Jr. S., Cooper, C. M., 1996. The occurrence, distribution, and remediation of transient pollution events in agricultural environments. *Wat. Sci. Tech.* 33, 17–26.

Schreiber, J. D., Rebich, R. A., Cooper, C. M., 2001. Dynamics of diffused pollution from US southern watersheds. *Wat. Res.* 35 (10), 2534–2542.

SUMAWA, 2005. Sustainable Management of Watersheds: Biophysical, livestock and human interactions in the River Njoro Watershed. GL-CRSP, UC, Davis, USA.

UNEP/WHO, 1996. Water Quality Monitoring – A practical guide to the design and implementation of freshwater quality studies and monitoring programmes.

Whitfield, P. H., Wade, N. L., 1996. Transient water quality events in British Columbia coastal stream. *Wat. Sci. Tech.* 33 (2), 151–161.

Whitfield, P. H., Wade, N. L., 1992. Monitoring transient water quality events electronically. *Wat. Res. Bull.* 29, 703–711.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007. In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya. Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium. Zambia.

Yillia, P. T., Kreuzinger, N., 2008. Net flux of pollutants at a reduced spatial scale - an index of catchment vulnerability. Proceedings of the 11th IWA International Specialized Conference on Watershed and River Basin Management. Budapest, Hungary.

Chapter 6

The effect of in-stream activities on the Njoro River, Kenya - Part I: Stream flow and chemical water quality

Accepted March, 2008: *Physics and Chemistry of the Earth*
Presented at the *8th WaterNet/ WARFSA Sympossium*, 31 October - 2 November 2007 Lusaka, Zambia as "Nature of in-stream activities during dry weather flow at the middle reaches of a rural stream in Kenya" and published in the proceedings.

The effect of in-stream activities on the Njoro River, Kenya - Part I: Stream flow and chemical water quality

P. T. Yillia*, N. Kreuzinger** and J. M. Mathooko***

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; E-mail: *paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at*
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; E-mail: *norbkreu@iwag.tuwien.ac.at*
***Egerton University, Department of Biological Sciences, PO Box 563, Njoro, Kenya; Tel: +254 37 61282 or +254 720853844; Fax: +254 37 61055; E-mail: *jmathooko@hotmail.com*

*corresponding author

Abstract
For shallow streams in sub-Saharan Africa, in-stream activities could be described as the actions by people and livestock, which take place within or besides stream channels. This study examined the nature of in-stream activities along a rural stream in Kenya and established the inequality in water allocation for various livelihood needs, as well as the negative impact they have on dry weather stream flow and chemical water quality. Seven locations along the stream were studied in wet and dry weather of 2006. Enumeration consisted of making head counts of people and livestock and tallying visitors at hourly intervals from 6 a.m. to 7 p.m. To estimate water abstraction, filled containers of known volume were counted and the stream was sampled to examine the impact on water quality. Water samples were obtained upstream and downstream of in-stream activities before (6 a.m.) and during (11 a.m., 6 p.m.) activities. Samples were analyzed for suspended solids, turbidity, BOD_5, total nitrogen and total phosphorus. The daily total abstraction at the middle reaches during dry weather was 120–150 $m^3.day^{-1}$. More than 60% of abstraction was done by water vendors. Vended water from the stream was sold at US$ 3.5–7.5 per cubic meter and vendors earned between US$ 3–6 a day. Abstracted water contributed approximately 40–60% of the total daily consumptive water use in the riparian area during dry weather but > 30% of the morning stream flow was abstracted thereby upsetting stream flow in the lower reaches. The daily total water abstraction correlated positively (R2, 0.98) and significantly ($p < 0.05$) with the daily total human visit, which was diurnally periodic with two peaks, occurring between 9 a.m. and 10 a.m. and from 4 p.m. to 5 p.m. This diurnal pattern of visits and the corresponding in-stream activities affected water quality. In particular, suspended solids, turbidity and BOD_5 levels increased significantly ($p < 0.05$) downstream during in-stream activities. It was concluded that the positive contribution of in-stream activities, in particular, water abstraction to livelihoods and the daily water needs was overshadowed by the apparent disregard of the impact on stream flow and water quality. Therefore, measures are required to control in-stream activities along the stream but authorities should be mindful of the implications of any management strategy on the livelihoods of the riparian inhabitants.

Keywords:
Abstraction; in-stream activities; people and livestock; stream flow; water quality

Introduction

Many people in rural sub-Saharan Africa have strong cultural and socioeconomic ties with surface water systems and live close to them as a matter of necessity. In essence, most settlements in rural sub-Saharan Africa have developed near lakes or streams because these systems have always played a fundamental role in these communities (Obi *et al*., 2002). Nearly all the inhabitants in such communities are poor and lack adequate access to basic services like pipe-borne water and/or proper sanitation facilities (Nevondo and Cloete, 1999; Fatoki *et al*., 2001; Venter, 2001; Obi *et al*., 2002). Although some progress has been made in recent years in some parts of rural sub-Saharan Africa to achieve the water and sanitation targets of the Millennium Development Goals (MDGs), the high proportion of rural populations that are still without adequate water and sanitation facilities implies that many people rely on readily accessible surface water systems as direct and untreated sources for domestic use (Nevondo and Cloete, 1999; Zamxaka *et al*., 2004). Usually, these sources i.e. small stream, lakes, ponds or springs are highly polluted (Venter *et al*., 2001; Obi *et al*., 2002; Byamukama *et al*., 2005). Nonetheless, they are used for a variety of functions, which could involve a wide range of activities that take place within or beside the water source.

For shallow streams in sub-Saharan Africa, in-stream activities may include water abstraction (also called withdrawal) for domestic use, washing of clothes and vehicles, swimming and bathing, waste deposal and watering of livestock (Nevondo and Cloete, 1999). They are very common in developing countries and occur on a daily basis (Mathooko, 2001). But they can be periodic, happening at various intensities during the day and may vary with the local weather conditions, as well as with the characteristics of the stream such as flow and turbidity. During activities, people and livestock are in regular physical contact with the stream and in so doing, they dislodge sediments and stream biota, which could be transported downstream (Mathooko, 2001). In water scarce regions, in-stream activities could have serious repercussions on shallow streams with low flow regimes particularly during dry weather flow. However, they have not received much scientific attention (Mathooko, 2001).

Scientific study on in-stream activities along the Njoro River started during the Tropical River Ecology Initiative of the mid 1990s with interest mainly on the disturbance caused by these activities on the stream biocoenosis (Mathooko, 2001).

However, the recent increase in the riparian population and the accompanying impact this increase might have on the biophysical and hydrological landscape has necessitated a shift in research approach to include aspects of stream hydrology and water quality, as well as issues of livelihood of the catchment inhabitants. It is generally thought that the cumulative impact of various activities along the stream, for instance, the abstraction and allocation of water for various needs may affect stream hydrology and water quality, which may in consequence distress the ecological functions of the stream, as well the livelihoods of the riparian inhabitants who depend on it for their daily water needs (Shivoga, 2001; Mokaya *et al*., 2004; Lelo *et al*., 2005).

The objective of this study was to evaluate the nature of in-stream activities along the Njoro River and assess the allocation of abstracted water for various livelihood activities in particular, water vending, livestock watering and domestic water use. In addition, the consequences of in-stream activities on dry weather stream flow and the chemical water quality of the stream was examined.

Materials and methods

Description of the study area

Njoro River (approximately 60 km) is an event response mountain stream in southwestern rural Kenya with a catchment area of approximately 280 km^2 (Figure 1). It lies between latitudes $0^{\circ}15'$S, $0^{\circ}25'$S and longitudes $35^{\circ}50'$E, $36^{\circ}05'$E (Mathooko, 2001). The stream originates from the Mau Hills (2800 m a.s.l) and flows mainly through farmland and settlements before draining intermittently into Lake Nakuru (1700 m a.s.l) at the floor of the Rift Valley (Shivoga, 2001).

The main tributary of the Njoro River is the Little Shuru, a small permanent stream that joins the main flow halfway at the upper reaches. Below the confluence, there is no other permanent tributary and the stream flows through a string of densely settled areas which do not have adequate access to water and sanitation facilities (Mokaya, *et al*., 2004). The settlements include Njokerio and Njoro Town with approximately, 20,000 and 50,000 inhabitants, respectively. Stream flow is intermittent below Njoro Town and there is often no flow in the lower reaches during dry periods (Shivoga, 2001). In general, the stream hydrograph displays considerable temporal and spatial fluctuations even within a single season in response to the annual and inter-annual variability of rainfall and the land use changes that have taken place in the last three decades (Shivoga, 2001; Kundu *et al*., 2004).

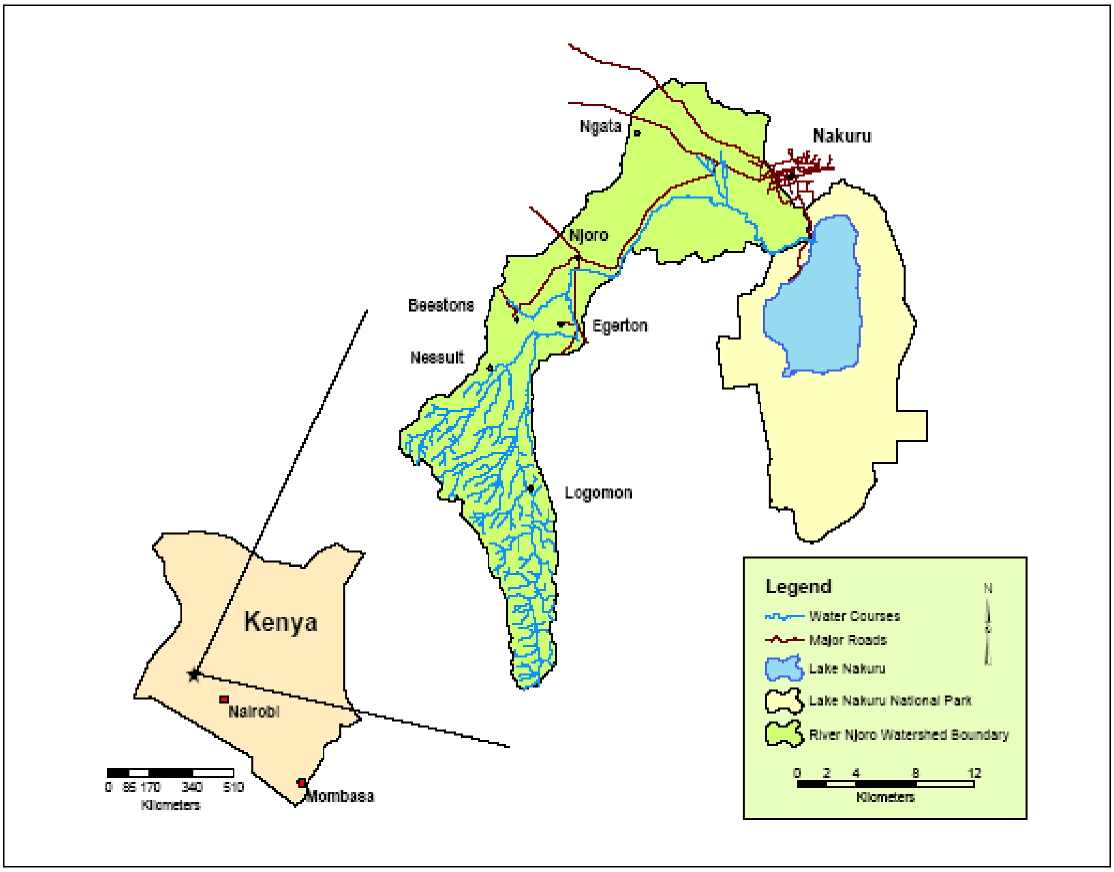

Figure 1. Map showing the catchment of Njoro River and its receiving basin, Lake Nakuru

Rainfall in the region is generally within 600–1200 mm per annum with most of it usually occurring in May–September (long wet period) and November–December (short wet period) (Mathooko and Kariuki, 2000). The main dry period occurs in January–April and the average annual minimum and maximum atmospheric temperature lies within 9ºC and 24ºC (Baldyga, 2005). Farming in the area is predominantly rain fed. Therefore, the growing seasons coinciding with the long and short wet periods. The main crops cultivated are maize, potatoes and vegetables. Cultivation is done on steep slopes in most parts of the catchment on soils that are predominantly volcanic and highly prone to erosion (Mainuri, 2005). Livestock herding is important and particularly widespread during dry weather when large herds of cattle, sheep and goats are led into the catchment by itinerant herdsmen from drier areas in search of pasture and water (personal observation).

Njoro River is structured in a typical riffle-pool sequence (Mathooko, 2001). This pattern is particularly evident at the moderate bed slopes of the middle reaches. Pools are generally attractive for human activities given that they are broad, relatively deep and are easily accessible. The vicinity of frequently visited pools is usually characterized by degraded stream banks that have little or no vegetation cover because the riparian vegetation has been heavily modified (Mathooko and Kariuki, 2000).

Characterization of in-stream activities

General information on the nature and duration of in-stream activities was obtained at seven locations along the stream during dry and wet weather in 2006. Logoman, Segotik, Nessuit and Treetop are located in the upper reaches of the stream, whereas Turkana Flats, Njoro Bridge and Kenyatta are found at the middle and lower reaches. Additional data was acquired at the two most frequently visited pools i.e. Turkana Flats and Njoro Bridge, during dry weather (January–April) of 2006. It was presumed that the repercussion of water abstraction on dry weather stream flow and water quality would be evident during this period because of the low steam flow (10–20 x 10^{-3} $m^3.sec^{-1}$) at this time of the year. Turkana Flats is close to Egerton University and a few meters downstream of a sequence of recently settled areas including Njokerio whereas Njoro Bridge is approximately 5 km further downstream near Njoro Town on the main road linking the town and the university.

Enumeration consisted of making head counts of people and livestock as they passed through an enumeration post after visiting the stream. At Njoro Bridge and Turkana Flats, head counts of people and livestock were tallied at hourly intervals from 6 a.m. to 7 p.m. (± 15 minutes) and information was obtained on the age/sex composition of human visitors; the mode of transport used to carry abstracted water and; the composition of livestock watered.

In addition, a stratified random sample of human visitors aged 18 years and above was targeted for a semi-structured interview on water abstraction. 25 men and 15 women were interviewed at Njoro Bridge while 15 men and 10 women were interviewed at Turkana Flats. The sample size and composition of the respondents was a function of the preliminary disaggregated data on the gender composition of human visitors at the two pools. None of the respondents was informed prior to the interview although the questions were prepared in advance.

The interviewers sort additional information mainly on: household consumption of water; reason(s) why the respondents were involve in water abstraction; cost of abstracted water if intended for sale; number of trips made to the stream per day; use of abstracted water; methods (if any) used to purify abstracted water from the stream if it was intended for domestic use and; knowledge of any other possible sources of water in the vicinity.

Estimation of water abstraction

Estimate of water abstracted from the stream was achieved by counting known volumes of filled containers passing through the enumeration post. These were mainly 10-litre jerry cans, 20-litre jerry cans and 200-litre metal containers. The amount of water ingested by livestock was estimated through computerized simulations of the equivalents of Livestock Unit (LU) developed by the European Commission (RDS, 2006). 1 LU is equivalent to cattle aged 2 years and above, whereas cattle aged between 6 months and 2 year is equivalent to 0.6 LU. And 0.15 LU is equivalent to one sheep or goat (RDS, 2006). Estimates for the average volume of water ingested by livestock vary. An ingestion rate of 9×10^{-3} m^3 within 1–3 minutes drinking session by 1 LU was used (RDS, 2006). The duration of a watering session of livestock along the Njoro River was estimated at 5–10 minutes. Therefore, 1 LU could possibly ingest between 15–90 x 10^{-3} m^3 of stream water per watering session. The drawbacks associated with this type of estimate have been documented (RDS, 2006).

Sampling for chemical water quality

A total of 36 water samples were obtained from the pools at Turkana Flats and Njoro Bridge. On each day of sampling, three trips were made in response to the diurnal rhythm of in-stream activities at the two pools. One trip was made before in-stream activities at 6 a.m., another during the morning peak session at 11 a.m. and one after the evening peak session at 6 p.m. This schedule was repeated three times, all of which were on Saturdays, being the day with the highest number of human visits at the stream. During each sampling trip, a sample each was obtained upstream and downstream of in-stream activities at each pool. The rationale for this sampling procedure and the suitability of the study period has been described (Yillia *et al*., 2007; cf. Chapter 7). Before sampling, *in-situ* measurement of the physico-chemical parameters was made with WTW multimeter probes.

Measurement of stream flow and rainfall

Data on stream flow was acquired from December 2005 to December 2006 at several locations along the stream including the pools at Turkana Flats and Njoro Bridge. Two methods recommended for estimating flow in shallow streams were used (UNEP/WHO, 1996). The mean velocity cross-sectional area method was used when flow was substantial and the tipping-bucket method was used when stream flow was very low (Mbuligwe and Kaseva, 2005). Flow data was evaluated for temporal and spatial incongruity. In particular, the dry weather flow data upstream (Treetop, km 32) and downstream (Kenyatta, river km 21) of the densely settled areas of the middle reaches was scrutinized. The rainfall data for 2006 was acquired from the meteorological station at Egerton University (Station No. 09035092).

Analysis of water samples

Standard analytical procedures were used to analyze water samples (APHA, 2002). Turbidity was estimated colorimetrically at UV437 with a 5 cm glass cuvette and the results expressed as $UV_{437}.m^{-1}$, whereas the standard gravimetric method (Edorel BM/C 0.45 µm glass fibre filters) was used for total suspended solids (TSS). For total phosphorus (total P) and total nitrogen (total N), 50 ml of the unfiltered sample was treated with a scoop of *Oxisolv* powder (*Merck F1 369036 528*) and autoclaved for 45–60 minutes. Digested samples were then analyzed using the Molybdate blue method for total P and the 2,6-dimethylphenol method for total N. The standard 5 days determination was used for BOD_5 with incubation at 20ºC in darkness. Dilutions were made with stream water of lower BOD_5 (< 2 $mg.l^{-1}$) that was obtained in the upper reaches. The BOD_5 of the sample ($sBOD_5$) was then calculated using the following expression.

$$sBOD_5 = tDO \times (sV + dV) / sV \quad \text{.. (1)}$$

where, *tDO*, is change in DO (Dissolve Oxygen) of the incubated sample after 5 days; *sV,* is the volume (ml) of sample incubated and; *dV*, is the volume (ml) of dilution water used.

Data analysis

All statistical analyses were performed with the aid of Microsoft Excel. The least-squares regression test was made to ascertain relationships between data sets. Site pairs were compared with; t-Test: Paired two-sample for means and, t-Test: two samples assuming equal or unequal variances. The F-test: two-sample for variances was performed prior to the t-Test for equal or unequal variances. Site parity/disparity was confirmed with uniform certainty at the 95% significant level ($p < 0.05$) with the Bonferroni correction when necessary.

Results and analyses

Visits made by people and livestock

Njoro Bridge was by far the most frequently visited pool with an average 1000 people on a single day. Next was Turkana Flats with < 200 (Table 1). The least visited location was Logoman in the upper reaches with < 10 people per day. The number of human visits during wet weather declined to < 10% of the dry weather estimates as access to other sources in the area increased. Visits to the stream were far more frequent at Njoro Bridge compared to Turkana Flats with at least six times more human visits occurring at the former. The highest human visits were recorded on Saturdays (Figure 2).

Table 1. Range of visits by people and livestock and the corresponding water abstracted (abs.) at various points along the stream during dry weather

Parameters	Logoman	Segotik	Nessuit [1]	Treetop	Turkana Flt.	Njoro Bridge	Kenyatta
Longitude [East]	35º54´09″	35º54´46″	35º53´53″	35º55´37″	35º56´31″	35º56´37″	35º58´07″
Latitude [South]	0º29´12´	0º24´11″	0º23´47″	0º22´30″	0º22´22″	0º20´16″	0º20´18″
Elevation [m]	2676	2412	2425	2271	2214	2160	2130
Distance [km] [2]	45.1	33.5	45.5	31.5	28.5	23.7	20.7
People living nearby [3]	0	< 1000	> 2000	> 3000	> 20000	> 50000	> 5000
Visit [people/day]	0 – 10	10 – 50	25 – 100	25 – 100	100 – 200	600 – 1500	10 – 50
Abs. people [m^3/day]	0 – 0.5	0.5 – 2	1 – 5	1 – 5	10 – 25	50 – 100	0.5 – 10
Visit [livestock/day]	0 – 50	10 – 557	50 – 557	10 – 20	50 – 200	300 – 557	50 – 557
Abs. livestock [m^3/day]	0 – 0.8	0.1 – 16.7	0.3 – 16.7	0.1– 0.6	0.3 – 6.0	9.0 – 16.7	0.3 – 16.7

1: *Nessuit* was on Little Shuru, the main tributary of Njoro River; 2: River kilometres from the mouth of the stream at Lake Nakuru; 3: < 1 km from the WAP

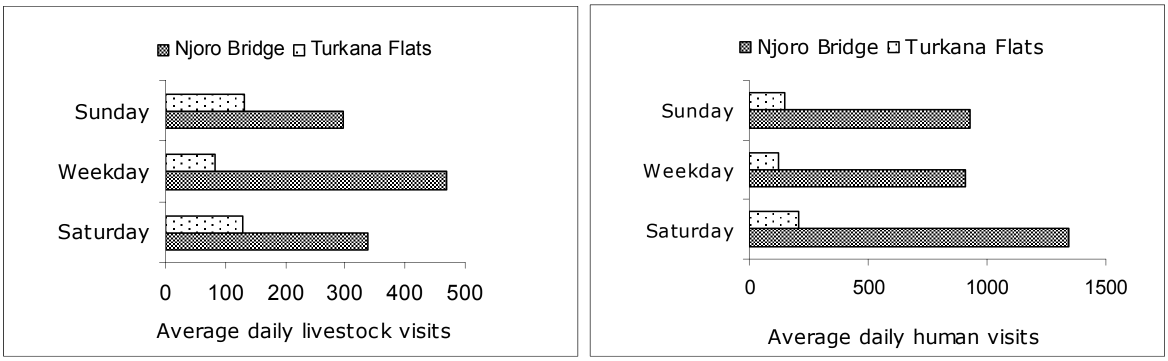

Figure 2. Average daily visits by people (left) and livestock (right) at Turkana Flats and Njoro Bridge (n=3).

The diurnal rhythm of visits at the middle reaches is illustrated in Figure 3. Visits by people started at sunrise roughly at 6 a.m. and stopped at sunset around 7 p.m. Peak human visits occurred between 9 a.m. and 10 a.m. and also between 4 p.m. and 5 p.m. These two periods were spaced by a brief period of low activity around 2 p.m. The evening peak was typically brief and smaller compared to the morning peak. First to visit the stream were women, followed by men, who made more visits during the day and contributed more than 50% of the daily total visits (Figure 4). Children were less than 15% of the morning total on weekdays but increased close to 40% in the late afternoon. They went to the stream mainly in the afternoon to water livestock or to play and swim. Occasionally, children assisted in washing of clothes by fetching water for adult females who did most of the washing at the banks of the stream. Washing was an important activity on Saturday, starting in the morning and lasting until early in the afternoon. Vehicles were cleaned in the evening mainly at Turkana Flats and sometimes Christian baptism occurred at Njoro Bridge.

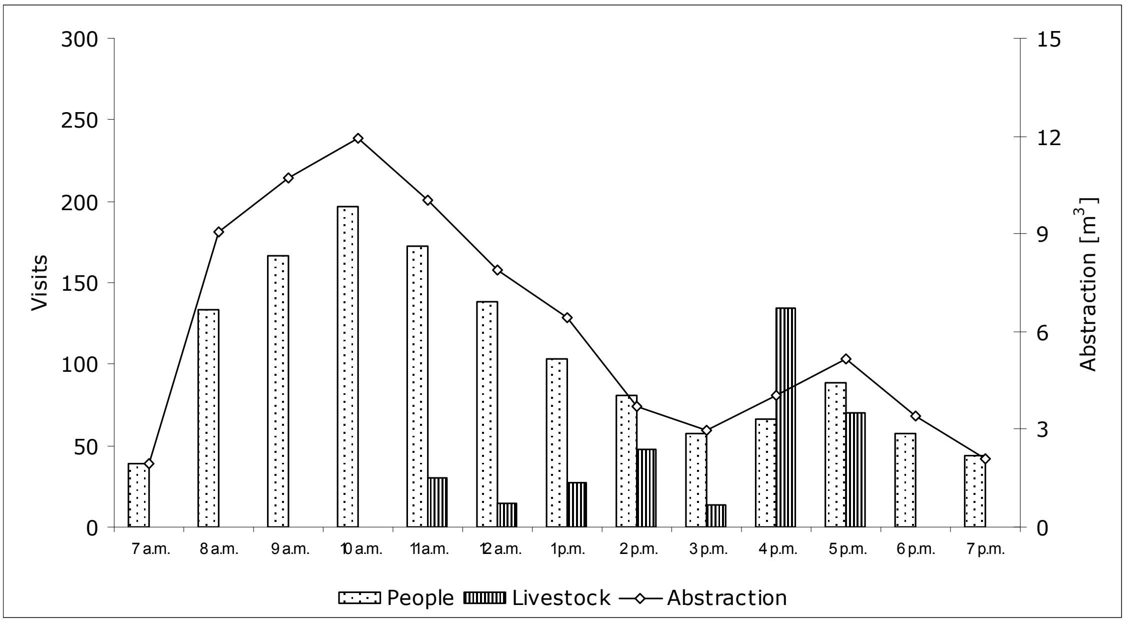

Figure 3. Average diurnal frequency of visits and average volume of water abstracted by people and livestock at Njoro Bridge on Saturday (n=3).

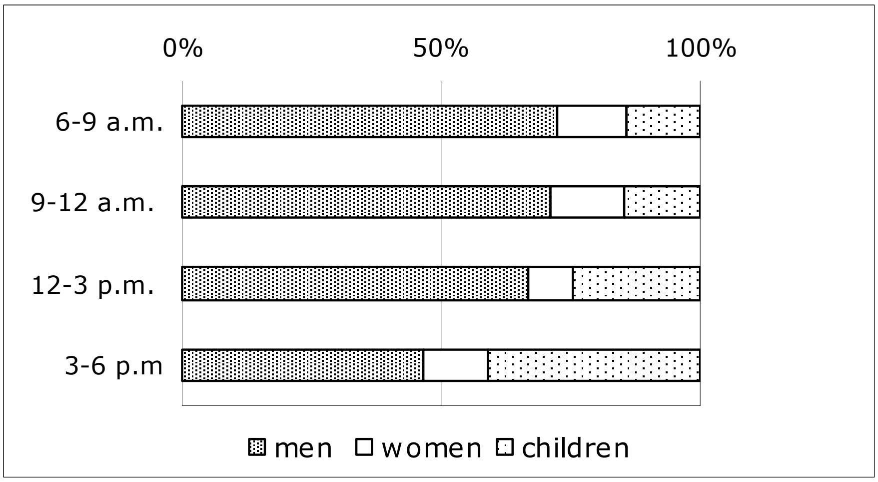

Figure 4. Average gender composition of visitors on weekdays at the middle reaches

Almost all pools that were easily accessible were important watering holes for livestock. Segotik, Nessuit, Njoro Bridge and Kenyatta were on the main migration route. Watering began in the morning after 10 a.m. and peaked between 3 p.m. and 4 p.m. (Figure 3). The main livestock watered were cattle (53%), sheep (41%), goats (4%) and donkeys (1%). They included animals in the neighbourhood as well as herds of migrating pastoralist.

Allocation of abstracted water

People visited the stream primarily to abstract water. The daily total abstraction correlated positively (R^2, 0.98) and significantly ($p < 0.05$) with daily total human visits. The daily total abstraction in the middle reaches during dry weather ranged from 120–150 $m^3.day^{-1}$. More than 60% of the total water abstraction was done by water vendors and approximately 30% was abstracted by non-vendors. These were mainly women and children. Less than 10% of the water abstracted was used onsite on the banks of stream for bathing and washing of clothes or vehicles. More water was abstracted on Saturday (23 and 79 $m^3.day^{-1}$ at Turkana Flats and Njoro Bridge, respectively) compared to weekdays (17 and 65 $m^3.day^{-1}$) or Sunday (8 and 48 $m^3.day^{-1}$). The daily total abstraction due to watering of livestock at the middle reaches was extremely variable, ranging from 10–50 m^3 per day. Most of this abstraction occurred during the afternoon accounting for between 8% and 25% of the daily total water abstracted by livestock in the middle reaches.

Several containers were used to abstract and transport water from the stream but 20-litre polyethylene jerry-cans and 200-litre metal containers were frequently used. Bicycles were the preferred mode of transport at Njoro Bridge accounting for at least 60% of water transported daily. Carts pulled by donkeys were frequently used at Turkana given that 73% of the water abstracted at this pool was transported in 200-litre metal containers. Human portage was common at all locations among women and children carrying 20-litre and 10-litre polyethylene containers, respectively. Donkeys (without carts) were used for carrying abstracted water in the hilly and steep sites of the upper stream reaches.

Variability of stream flow

The seasonal and spatial variability of stream flow along the Njoro River, and the total monthly rainfall in the middle reaches is illustrated in Figure 5. Three distinct flow regimes were evident in direct response to the seasonal pattern of rainfall in 2006. Generally, stream flow increased gradually in the upper reaches until the confluence with the main tributary Little Shuru. Downstream of the confluence, which is < 1 km upstream of Treetop (32 km from stream mouth), flow declined steadily especially during dry weather. Further downstream after Kenyatta (21 km), the stream was intermittent until it eventually stopped flow just upstream of Ngatta (15 km) although the precise point of cessation of flow was unfixed. The spatial variation was substantial between Treetop (upstream of Njokerio) and Kenyatta (downstream of Njoro Town). For instance, the total daily stream flow during dry weather in February 2006 declined from 1.3 $m^3.day^{-1}$ at Treetop to less than 0.2 $m^3.day^{-1}$ at Kenyatta. Conversely, during periods of heavy rainfall and relatively high discharge as it happened in short wet weather (November–December, 2006), stream flow extended further downstream and reached the mouth at Lake Nakuru. During this period, the spatial flow variability at the middle and lower reaches (i.e., downstream of Treetop) was to a large extent imperceptible (Figure 5).

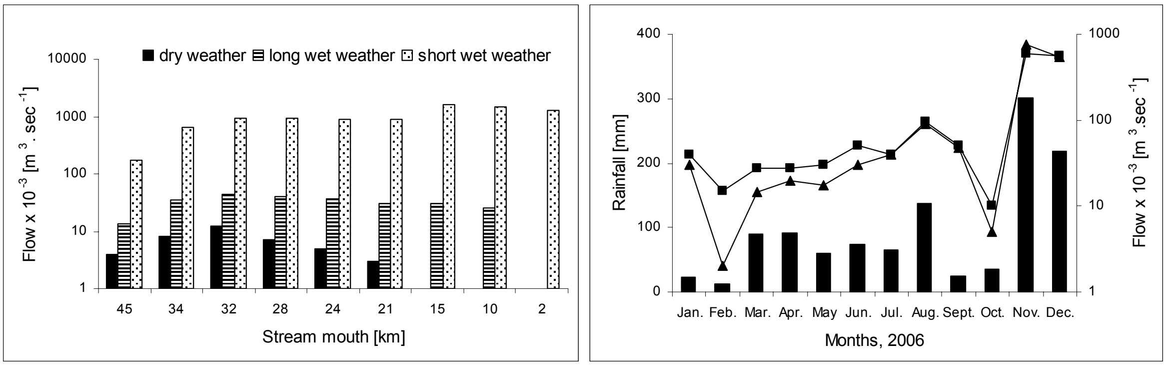

Figure 5. Left: Seasonal flow variability along the Njoro River in 2006. Right: Total monthly rainfall (bars), and the average flow upstream (squares) and downstream (triangles) of settlements at the middle reaches.

Diurnal changes in water quality

Table 2 illustrates the diurnal fluctuations in water quality variables with respect to in-stream activities. Of striking importance was the effect of in-stream activities on the levels of suspended solids, turbidity, and BOD_5. Before in-stream activities (6 a.m.), the ambient levels of these parameters at the upstream and downstream locations at both pools were not statistically significant ($p > 0.05$). But ambient levels downstream increased significantly (< 0.05) during in-stream activities in the morning (11 a.m.) and later in the evening (6 p.m.). For instance, at Njoro Bridge, the concentration of suspended solids increased from 7 $mg.l^{-1}$ upstream of activities to 118 $mg.l^{-1}$ downstream of activities at 11 a.m. while turbidity levels rose from 7 to 29 $UV_{437}.m^{-1}$ during the same period. BOD_5 levels were three times more downstream compared to upstream levels, whereas, the corresponding DO levels dropped from 4.2 mg.l^{-1} upstream, to 3.5 mg.l^{-1} downstream during activities at the same pool. The evening increases downstream were less dramatic at both pools and the fluctuations in the levels of conductivity, total N and total P were less evident even though on some occasions the mean total N and total P concentrations increased downstream during in-stream activities but the differences were not statistically significant ($p > 0.05$). Stream temperature at the pools fluctuated with the time of day increasing from 15ºC at 6 a.m. to 20 ºC at 11 a.m. and decreasing slightly to 19 ºC at 6 p.m. The pH of the stream was generally slightly alkaline ranging from 7.1–7.8 without any discernible spatial or diurnal variability that may be associated with in-stream activities.

Table 2. Mean ± SD of water quality variables upstream and downstream of in-stream activities at the middle reaches during dry weather flow

		Temp. [°C]	Cond. [µS.cm^{-1}]	DO [mg.l^{-1}]	BOD_5 [mg.l^{-1}]	TSS [mg.l^{-1}]	Turbidity [UV_{437}.l^{-1}]	TN [mg.l^{-1}]	TP [mg.l^{-1}]
Turkana Flats									
6 a.m.	*Upstream*	15.5±1.0	301±4.2	4.7±1.1	6.9±0.8	6.3±0.5	6.0±0.6	0.5±0.1	0.2±0.0
	Downstream	15.0±0.8	300±5.0	4.0±0.9	8.2±0.5	6.3±0.5	6.2±0.5	0.6±0.1	0.2±0.1
11a.m.	*Upstream*	20.0±0.1	299±6.4	5.6±0.1	8.7±1.0	8.3±2.4	6.1±0.2	0.5±0.1	0.3±0.0
	Downstream	20.1±0.6	306±0.7	4.2±1.3	24.3±1.7	140.0±28	20.1±10.9	0.6±0.1	0.3±0.0
6 p.m.	*Upstream*	19.5±0.4	299±7.1	5.3±1.1	9.5±1.3	5.0±2.4	6.5±0.9	0.5±0.0	0.2±0.0
	Downstream	18.5±0.1	300±6.4	5.3±0.6	17.6±1.3	28.3±16.5	10.7±1.0	0.6±0.0	0.2±0.0
Njoro Bridge									
6 a.m.	*Upstream*	15.2±0.9	443±43	4.5±0.9	8.5±1.2	7.0±4.2	7.1±1.2	0.7±0.1	0.5±0.2
	Downstream	15.1±0.5	441±43	4.0±0.6	9.2±0.7	9.0±1.4	7.2±1.2	0.7±0.0	0.4±0.1
11a.m.	*Upstream*	20.8±0.1	448±41	4.2±0.1	7.1±1.7	6.7±4.7	6.8±0.8	0.5±0.0	0.5±0.1
	Downstream	21.8±0.4	447±40	3.5±0.9	21.6±1.5	118.3±15	28..6±27	0.6±0.1	0.6±0.1
6 p.m.	*Upstream*	19.9±0.4	449±42	4.9±0.8	8.3±2.0	8.3±2.4	6.8±0.9	0.5±0.0	0.4±0.1
	Downstream	19.1±0.1	452±38	3.7±0.8	19.3±1.7	41.7±16	20.8±12	0.6±0.0	0.5±0.1

Discussion

The allocation of water for domestic needs particularly during dry weather was substantial even though the precise contribution of water from the stream for all the water needs in the riparian area was less certain. Based on average estimates for developing countries and inference from prevailing estimates for poor households in Nairobi (Gleick, 1996; Gulyani *et al*., 2005), abstracted water accounted for 40–60% of the daily water consumption in the Njoro Town area during dry weather. The corresponding per capita consumption in the area was approximately 10 litres per capita per day. Generally, consumptive use of water in many areas of Kenya is low compared to other countries and previous use levels in Kenya itself (Thompson *et al*., 2000; Gulyani *et al*., 2005). For domestic needs, this may vary with the availability of water, as well as the ease of access to a water source (Gleick, 1996). In the Njoro area as in many other parts of Kenya, these two factors are seriously influenced by weather conditions (UN-WATER, 2006). There is no reliable rainfall during dry weather in the Njoro area. Therefore, rainwater is barely harvested during this period. Also many boreholes dry out and pipe-borne water is supplied occasionally (Moturi, 2004; Odero and Peloso, 2000). In addition, the weather related scarcity in water supply is compounded by the generally high levels of fluoride in the groundwater sources in the region (Odero and Peloso, 2000; Moturi *et al*., 2002; Moturi, 2004).

As a result, the stream was the main source of readily available water during dry weather. People and livestock visited the stream on a daily basis to primarily to abstract water. Water abstraction was dominated by adult mail water vendors. The role of water vendors in providing services in rural and peri-urban area is increasingly being recognized. Water vendors are often flexible and offer convenient services that are perfectly tailored to the needs of diverse clientele (Collignon and Vézina, 2000). As a vital non-formal economic activity in many towns and cities in sub-Saharan Africa, water vending provides a means of livelihood for the unemployed. (Whittington *et al*., 1989; Thompson *et al*., 2000; Gulyani *et al*., 2005). In the Njoro area, some vendors were engaged in the practice either as an off-farm activity during dry period or as a periodic means of livelihood when they need arose. Abstracted water from the stream was vended at Ksh 5–10 per 20-litre jerry-can (Ksh 250–500 per cubic meter or US$ 3.73–7.46 per cubic meter) and vendors earned from Ksh 200–450 (US$ 3–6) daily during dry weather. This is substantial considering the fact that most people in rural sub-

Saharan Africa earn < US$1 a day. However, because the cost of vended stream water was pegged to the cost of vended tap water, vended water was unaffordable by some residents. They included the non-vendors at the stream who abstracted approximately 30% of the daily total abstraction. Tap water in the Njoro area was vended at Ksh 10–15 (US$ 0.15–0.22) per 20-litre jerry-can or US$ 7.5–11.0 per cubic meter. The cost of vended tap water in Njoro Town was higher than what is reported for Nairobi, where households pay, on average, Ksh 4.1 per 20-litre jerry-can (approximately, Ksh 205 per cubic meter or US$ 2.7 per cubic meter) for delivered water at the homes of customers (Colligton and Vézina, 2000; Gulyani *et al*., 2005). It is worth noting that the vended cost of tap water in both Nairobi and Njoro Town is high when compared to the prevailing utility tariffs charged by water utilities in Kenya. The average fee charged by water utilities in Kenya is US$ 0.40 per cubic meter (Gulyani *et al*., 2005). This is 15–30 times less than the vended price of tap water in Njoro Town. The assertion that poor residents in rural and peri-urban areas pay more for water even though the water is usually of poor quality and difficult to obtain is perhaps correct for the Njoro area.

Although the water abstracted from the stream contributed substantially to the daily water needs and livelihoods of riparian residents, the present data suggest that water abstraction intermittently interrupted stream flow at the middle and lower reaches. Analysis of the water abstraction data from various locations at the middle reaches revealed that around 120–150 $m^3.day^{-1}$ of stream water was abstracted during dry weather flow. At the same time, stream flow was as low as 1000 $m^3.day^{-1}$. As a result, roughly 15% of the daily dry weather flow was abstracted at the middle reaches during the day. This is seemingly insignificant but given that over 60% of the daily total abstraction took place between 7 a.m. and 12 a.m., it was estimated that approximately 70–90 m^3 was abstracted within five hours each morning. This is one third of the morning flow and certainly noteworthy given that no tributaries join the main Njoro flow in dry weather after the confluence with the Little Shuru in the upper reaches. Therefore, flow diminished steadily downstream as the stream flowed through the densely settled areas in the middle reaches. It is though that even if the natural losses through evaporation, seepage and uptake from the riparian vegetation is significant, it seems these losses were confounded by abstraction given the erratic nature of the stream downstream of Njoro Town in the lower reaches.

The cessation of stream flow in the lower reaches has far reaching implications for the environment, as well as the lives of the riparian inhabitants in the area. The stream is the main source of water for Lake Nakuru, a designated Ramsar site and a renowned tourist destination for wildlife (Baldyga, 2005; Lelo *et al*., 2005). The recent and reoccurring fall in water levels in the lake and the corresponding death and migration of wildlife has been blamed by the public and various media establishments on the land degradation problems within the Njoro River catchment. Although these allegations require in-dept study, there is evidence that fundamental land use changes have occurred in the catchment within last three decades (Kundu *et al*., 2004). The consequences of these alterations are currently being investigated by various research groups but it is clear from historic records and indigenous knowledge that the stream flow has changed dramatically in recent years particularly in the middle and lower reaches with negative consequences on stream ecology, agricultural productivity and the general water security situation in the area (Mathooko, 2001; Shivoga, 2001; Baldyga, 2005).

Furthermore, the water quality of the stream has deteriorated considerably over the years (Mokaya *et al*., 2004). This is supported by the current data, which provide evidence that in-stream activities of people and livestock in the Njoro River affected chemical water quality. During abstraction, carts and vehicles were pulled or driven into the stream channel while people waded upstream to abstract water. Animals were led into the stream to water, during which, they urinated and defecated (Yillia *et al*., 2007; cf. Chapter 7). Whereas grazing and tramping by animals in the vicinity of watering areas affect the natural vegetation cover and the soil structure, which may in turn influence surface runoff and the infiltration capacity, urine and faeces are established sources of microbial pollutants, nutrients and easily degradable organic matter for surface water sources in densely settled catchments (Venter *et al*., 2001; Nevondo and Cloete, 1999; Obi *et al*., 2002; Vinneras, *et al*., 2003; Byamukama *et al*., 2005). Also, washing of clothes introduces eutrophying substances in the form of phosphorus, which was high in the stream and noticeably present in the detergents that were used as was observed from the discarded wrappings in the surrounding area. The use of phosphorus as a softener in detergents has been banned in some countries and its use in this part of Kenya may be unnecessary as the geology is typically volcanic in nature with associated soft waters, in contrast to limestone areas which have characteristically hard waters, for which softeners may be required in detergents. Polluted stream water could have health consequences on the exposed population in the area because most of the water abstracted was used for domestic needs, usually without purification. It is thought that much of the water quality problems caused by in-stream activities may be transient in nature and usually flows downstream without much notice. This could be challenging for monitoring pollution and attributing sources. For example, the time of sampling, the choice of sampling points at a disturbed site, and the number of representative samples will require careful consideration during sampling to optimize results.

Conclusions and recommendations

1. This study investigated the contribution of the Njoro River flow to the daily water needs of the riparian communities, as well as the impact of in-stream activities on dry weather stream flow and water quality.
2. In-stream activities contributed to livelihoods of the riparian inhabitants along the Njoro River especially during dry weather. However, the haphazard nature of in-stream activities and the apparent disregard for the environmental negatively affected on stream flow and water quality.
3. The effect was particularly evident during dry weather at the middle and lower reaches where the chemical water quality deteriorated significantly and stream flow was intermittent with total cessation of flow at the lower reaches.
4. It is absolutely necessary to restrain in-stream activities to control the effect they have on the stream but authorities should be mindful of the implications on the lives of riparian inhabitants given that most people in the area do not have access to adequate water and the fact that the region recurrently experience inter-tribal conflicts over dwindling natural resources.

Acknowledgements

This study was financed by the Austrian Government through the North-South Dialogue Scholarship Programme of the Austrian Development Co-operation. The authors wish to thank PSR for collecting some of the enumeration data and the riparian residents of the Njoro River for providing useful information.

References

APHA, 1995. Standard methods for the examination of water and wastewater, 19th edition. American Public Health Association, Washington, D.C.

Baldyga, T. J., 2005. Assessing land cover change impact in Kenya's River Njoro watershed using remote sensing and hydrological modelling. M.Sc. Thesis, University of Wyoming, USA.

Byamukama, D., Mach, R. L., Kansiime, F., Manafa, M., Farnleitner, A. H., 2005. Discrimination efficacy of faecal pollution detection in different aquatic habitats of a high-altitude tropical country, using presumptive coliforms, Escherichia coli, and Clostridium perfringens spores. *Applied Environmental Microbiology* 71 (1), 65–71.

Collignon, B., Vézina, M., 2000. Independent water and sanitation providers in African cities: full report of a ten-country study. Water and Sanitation Programme, World Bank. Washington, DC. 1–64.

Fatoki, O. S., Muyima, N Y. O, Lujiza, N., 2001. Situation analysis of water quality in the Umtata River catchment. *Water South Africa* 27 (4), 467–474.

Gleick, P. H., 1996. Basic water requirements for human activities: meeting basic needs. Water International 21, 83–92.

Gulyani, S., Talukdar, D., Kariuki, R. M., 2005. Universal (non)service? Water markets, household demand and the poor in urban Kenya. *Urban Studies* 42 (8), 1247–1274.

Kundu, P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. Proceedings - XXth ISPRS Congress, 12-23 July 2004. Istanbul, Turkey, 405–409.

Lelo F.K., Wanjiku, C., Jenkins, M. W., 2005. Managing riparian resources in the River Njoro watershed in Kenya: The challenge of conflicting laws, policies and community priorities. International workshop on "African water laws - plural legislative frameworks for rural water management in Africa. 26 – 28, January 2005, Guateng, South Africa.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131–139.

Mathooko, J. M., Kariuki, S. T., 2000. Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. East African Wildlife Society. *African Journal of Ecology* 38 (2), 123–129.

Mainuri, Z. G., 2005. Land use effects on the spatial distribution of soil aggregate stability within the Njoro River watershed, Kenya. M.Sc. Thesis. Egerton University, Kenya.

Mbuligwe, S. E., Kaseva, M. E., 2005. Pollution and self-cleansing of an urban river in a developing country: A case study of Dar es Salaam, Tanzania. *Environmental Management* 36, (2) 328–342.

Mokaya, S. K., Mathooko, J. M., Leichtfried M., 2004. Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *African Journal of Ecology* 42 (4), 281–288.

Moturi, W. K. N., Tole, M. P., Davies, T. C., 2002. The contribution of water towards dental fluorosis: a case study of Njoro Division, Nakuru District, Kenya. *Environmental Geochemistry and Health* 24, 123–130.

Moturi, W., 2004. Household water sources and their contribution towards fluoride consumption in Njoro Division, Nakuru, Kenya. *African Journal of Aquatic Sciences* 29 (2), 275–277.

Nevondo, T. S., Cloete, T. E., 1999. Bacterial and chemical quality of water supply in the Dertig village settlement. *Water South Africa* 25 (2), 215–220.

Obi, C. L., Potgieter N., P., Bessong, O., Matsaung, G., 2002. Assessment of the microbial quality of river water sources in rural Venda communities in South Africa. *Water South Africa* 28 (3), 287–292.

Odero, D. O., Peloso, G. F., 2000. A hydrological study of the Njoro area (Rift Valley of Kenya). *Atti Ticinensi di Scienze della Terra* 41, 109–131.

RDS, 2006. Revised calculation of Livestock Units for higher stewardship agreements. *Rural Development Service (RDS) Technical Advice Note* 33. 2nd Edition. Published 2006.

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiologia* 458, 121–130.

Thompson, J., Porras, I. T., Wood, E., Tumwine, J. K., Mujwahuzi, M. R., Katui-Katua, M., Johnstone, N., 2000. Waiting at the tap: changes in urban water use in East Africa over three decades. *Environment and Urbanization* 12 (2), 37–52.

UNEP/WHO (1996) Water Quality Monitoring – A practical guide to the design and implementation of freshwater quality studies and monitoring programmes.

UN-WATER, 2006. Kenya national water development report 2005. Prepared for the 2nd UN World Water Development Report. UN-WATER/WWAP/2006/12.

Venter, S. N., 2001. Microbial water quality in the 21st century. *Water South Africa* 27 (1), 16–17.

Vinneras, B., Holmqvist, A., Bagge, E., Albihn, A., Jonsson, H., 2003. The potential for disinfection of separated faecal matter by urea and by peracetic acid for hygienic nutrient recycling. *Bioresource Technology* 89, 155–161.

Whittington, D., Lauria, D. T., Okun, D. A., Mu, X., 1989. Water vending activities in developing countries – A case study of Ukunda, Kenya. *International Journal of Water Resources Development* 5 (3), 158–168.

Zamxaka, M., Pironcheva, G., Muyima, N Y. O., 2004. Microbiological and physico-chemical assessment of the quality of domestic water sources in selected rural communities of the Eastern Cape Province, South Africa. *Water South Africa* 30 (3), 333–340.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007. In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya. Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium. Lusaka, Zambia.

Chapter 7

The effect of in-stream activities on the Njoro River, Kenya - Part II: Microbial water quality

Accepted March, 2008: Physics and Chemistry of the Earth
Presented at the 8th WaterNet/ WARFSA Sympossium, 31 October - 2 November 2007 Lusaka, Zambia as "In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya" and published in the proceedings.

The effect of in-stream activities on the Njoro River, Kenya - Part II: Microbial water quality

P. T. Yillia*, N. Kreuzinger** and J. M. Mathooko***

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; E-mail: *paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at*
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; E-mail: *norbkreu@iwag.tuwien.ac.at*
***Egerton University, Department of Biological Sciences, PO Box 563, Njoro, Kenya; Tel: +254 37 61282 or +254 720853844; Fax: +254 37 61055; E-mail: *jmathooko@hotmail.com*

*corresponding author

Abstract
The influence of periodic in-stream activities of people and livestock on the microbial water quality of the Njoro River in Kenya was monitored at two disturbed pools (Turkana Flats and Njoro Bridge) at the middle reaches. A total of ninety-six sets of samples were obtained from the two pools in six weeks during dry weather (January–April) in 2006. On each sampling day, two trips were made before and during in-stream activities and on each trip, two sets of samples were collected upstream and downstream of activities. This schedule was repeated four times each for Wednesday, Saturday and Sunday. Samples were processed for Heterotrophic Plate Count bacteria (HPC), Total Coliform (TC), presumptive Escherichia coli and presumptive Enterococci. Additional samples were analysed for Total Suspended Solids (TSS), Turbidity, BOD_5 and Ammonium-N. The microbial water quality deteriorated significant ($p < 0.05$) downstream during activities at both pools. A similar trend was observed with the chemical indicators (TSS, Turbidity, BOD_5 and Ammonium-N). The two groups of indicators demonstrated high capacity for site segregation based on pollution levels. Pollution levels for specific days were not significantly different ($p > 0.05$). This was incompatible with the variability of in-stream activities with specific days. The pooled data was explained largely by three significant principal components - recent pollution (PC1), metabolic activity (PC2) and residual pollution (PC3). It was concluded that the empirical site parity/disparity in the levels of microbial and non-microbial indicators reflected the diurnal periodicity of in-stream activities and the concomitant pollution they caused. However, microbial source tracking studies are required to distinguish faecal sources. In the meantime, measures should be undertaken to regulate in-stream activities along the stream and minimize the movement of livestock in the catchment.

Keywords:
Dry weather flow; faecal indicators; in-stream activities; microbial water quality; people and livestock; rural stream

Introduction

Visits by people and livestock to surface water systems are common in developing countries, particularly in poor rural communities where most residents lack access to portable clean water. As a result, they usually obtain water for their daily needs from surface water systems that are often contaminated (Venter *et al*., 2001; Nevondo and Cloete, 1999; Obi *et al*., 2002). Visits are periodic and frequent, especially during dry periods when other sources of water such as pipe-borne water, rainwater or groundwater are irregular, lacking or inaccessible. During visits, livestock may be watered, people bath or swim, waste is disposed of, clothes and vehicles may be washed and water is usually abstracted for domestic needs (Nevondo and Cloete, 1999; Mathooko, 2001, Yillia *et al*., submitted). Since these activities occur largely within and beside stream channels, they are collectively called in-stream activities and could constitute a major source of diffuse pollution, especially in shallow water systems. Specifically, in-stream activities may influence microbial water quality as faecal matter is deposed of during visits and the surrounding area is usually littered with faeces (Fatoki *et al*., 2001; Zamxaka *et al*., 2004).

Unsanitary means of disposing human waste and faecal droppings from livestock are routes through which faecal matter may enter aquatic systems. Faecal matter degrades water quality due to the possible introduction of pathogens, nutrients and organic matter (Vinneras *et al*., 2003; Langergraber and Muellergger, 2005; Vikaskumar *et al*., 2007). Degraded water quality may result in increase in cost of drinking water treatment or loss of opportunities for recreation, aquaculture and fishing (Sinton *et al*., 1998; Parveen, *et al*., 2001; Ebdon *et al*., 2007; Edge and Hill, 2007). Prominently, pollution with faecal matter may present significant health risk to the public (Sinton *et al*., 1998; Byamukama *et al*., 2005). The level of risk will depend considerably on the origin and level of contamination (Scott *et al*., 2002). In particular, contamination from human excreta is of greater risk to public health as it is more likely to contain human-specific enteric pathogens although reliable epidemiological evidence is lacking (Sinton *et al*., 1998). To minimize health risk, it is often required to undertake regular monitoring of indicator parameters in aquatic systems (Kong *et al*., 2002; Wheeler *et al*., 2002; McLellan and Salmore, 2003; Noble *et al*., 2003; Shah *et al*., 2007). Such assessment studies are useful not only for evaluating health risk, but also for determining the course of action that may be required to solve the problem (Parveen *et al*., 2001; Ahmed *et al*., 2007; Graves *et al*., 2007).

The nature of in-stream activities and the likely influence they have on stream water quality is currently the subject of discussions on mitigating pollution in the Njoro River. The stream drains the western steep slopes of the East African Rift Valley in southwestern rural Kenya. The catchment (280 km^2) is mostly agro-pastoral but the stream flows through densely populated areas at the middle and lower reaches before draining periodically into Lake Nakuru (Shivoga, 2001; Lelo *et al*., 2005). The riparian population is largely poor and inadequately provided with basic sanitation or portable clean water (Mokaya *et al*., 2004). As a result, most riparian inhabitants and itinerant herdsmen depend largely on the stream for their daily water needs. People and livestock visit the stream regularly and undertake activities within or beside the stream (Mathooko, 2001). The main objective of this study was to assess the short-term influence of periodic in-stream activities of people and livestock on the microbial water quality of the stream using classical microbial indicators. The presence and numbers of Heterotrophic Plate Count bacteria, Total Coliform, presumptive *Escherichia coli* and presumptive *Enterococci* were determined at the middle polluted reaches of the stream. Parallel determinations were made of Total Suspended Solids, Turbidity, BOD_5, Ammonium-N and the physico-chemical parameters (Temperature, pH, Dissolved Oxygen and Conductivity).

Materials and Methods

Description of the study area

The Njoro River (60 km) originates from the Mau Escarpment – part of the western rim of the East African Rift Valley in Kenya – and flows through predominantly farmland and residential areas before discharging intermittently into Lake Nakuru at the floor of the Rift Valley (Figure 1). The stream descends from > 2800 m (a.s.l) at its source in the Mau Hills to about 1700 m (a.s.l) at its mouth in Lake Nakuru (Mathooko, 2001). The terrain is structurally heterogeneous with slopes within 17–30% in the upper mountainous escarpment but mostly < 4% in the moderate and gentle slopes that characterize the plains around the middle and lower reaches (Baldyga, 2005; Mainuri, 2005). Njoro River is structured in a typical riffle-pool sequence especially at the moderate bed slopes of the middle reaches (Mathooko, 2001). The pools are generally very attractive for human activities given that they are broad and easily accessible. The region is characterized by two wet periods in May–September and November–December and a dry period in January–April but there are huge seasonal, as well as inter-annual variations in rainfall (Mathooko and Kariuki, 2000; Shivoga, 2001). The mean annual rainfall is 600–1200 mm per annum and the atmospheric temperature is typically between 9°C and 24°C (Baldyga, 2005).

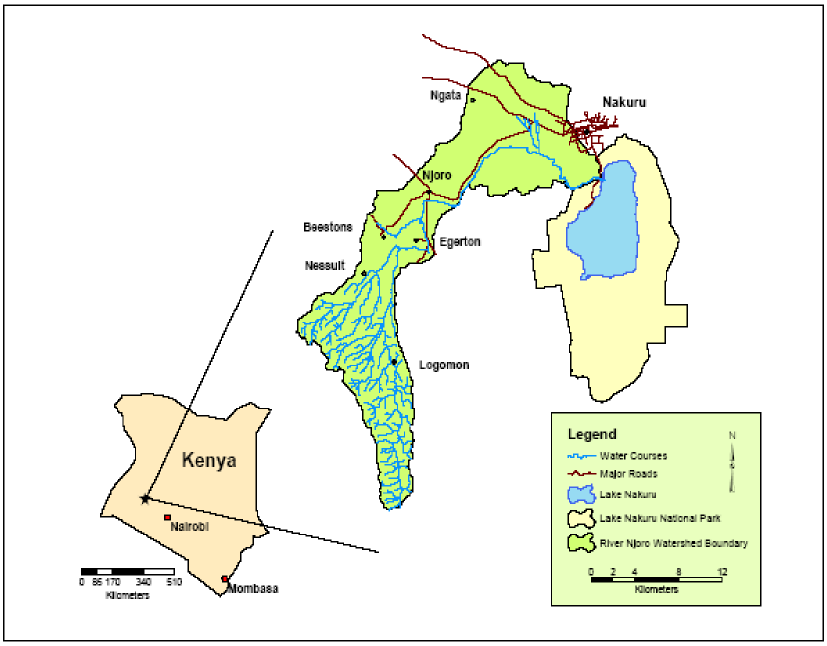

Figure 1. Map showing the catchment of Njoro River and its receiving basin, Lake Nakuru

Sampling sites

Two pools frequently visited by people and livestock were selected at the middle reaches of the Njoro River. The pool at Turkana Flats (TF) is in the vicinity of Njokerio (approximately, 20,000 residents), close to Egerton University. The pool at Njoro Bridge (NB) is 5 km downstream of TF and very close to Njoro Town (approximately, 50,000 residents). Between TF and NB, the stream flows through farmland and intermittently receives wastewater from Egerton University and a vegetable cannery but access to the stream is limited due to restrictions by farm owners. A pair of sites – upstream and downstream of activities – was selected each at TF and NB for sampling before and during activities. This arrangement facilitated same-site as well as between-sites comparisons at each pool for parity or disparity in pollution levels before and/or during in-stream activities.

Sampling procedure

Sampling occurred during the hydrological recession phase in March – April, 2006 in the absence of precipitation. The period was ideal since in-stream activities are frequent in dry weather and stream velocity is very low during this period (Mathooko, 2001; Shivoga, 2001). Thus, a reasonable duration of stream flow was guaranteed in the pools and temporary contamination generated by surface runoff and resuspension of contaminated sediments by turbulent flow was low. Samples were obtained from the site-pairs at TF and NB during twelve sampling events within six weeks. The short duration reduced variations between sampling events as flow in the Njoro River is extremely variable (Shivoga, 2001). On each sampling day, two trips were made – before (5–6 a.m.) and during (11–12 a.m.) in-stream activities. This schedule was repeated four times each for Wednesday, Saturday and Sunday, being days on which the pools were variously disturbed (cf. Chapter 6). Samples for the microbial indicators were collected in sterile 500 ml polyethylene containers and transported on ice. The physico-chemical parameters were measured *in-situ* with *WTW multimeter* probes.

Processing of samples

Samples were processed within two hours of collection. Three appropriate dilutions were made for each microbial parameter. Dilutions were duplicated and drained through sterile membrane filters (0.45 μm; 47 mm) with a vacuum pump. For Heterotrophic Plate Count bacteria (HPC), filters were placed on solidified *Yeast Extract Agar (ISO 6222, OXOID)* and all colonies were counted within 24 and 48 hrs of incubation at 37°C. Filters for Total Coliforms (TC) and presumptive *Escherichia coli* (*E. coli*) were incubated on *Chromocult Coliform Agar (ISO 6222, OXOID)* at 37°C for 24 hrs. Pink to red colonies and blue colonies were counted for TC and *E. coli* respectively. *mEnterococcus Agar (ISO 6222, OXOID)* was used for presumptive *Enterococci*. Plates were incubated at 37°C and dark red colonies were counted after 48 hrs. Plates with countable colonies between 20 and 300 were selected for counting. Median values of colony forming units (cfu) were reported per 1 ml for HPC and 100 ml for TC, *E. coli* and *Enterococci*. Standard analytical procedures (APHA, 1995) were followed for Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD_5) and Ammonium-N. Direct determination with a spectrophotometer at UV_{437} was made for Turbidity, using 5 cm quartz cuvette and the results reported as Absorbance per meter [Abs. m^{-1}].

Data processing

The data was analyzed in SPSS (Statistical Package for Social Sciences). Principal Component Analysis (PCA) was applied on the data to characterize related factor complexes. Components showing an Eigen value > 1 were selected to explain associations among indicator parameters. Cluster Analysis was performed to establish site segregation and desegregation. Cluster Analysis was based on *z*-score standardization with squared Euclidian distances between sites. Site segregation and desegregation were confirmed with uniform certainty at the 95% significant level ($p < 0.05$) using the Wilcoxon test with the Bonferroni correction where applicable. The level of significance with the Wilcoxon test was also used to deduce the site segregation capacity of the indicators.

Results and analyses

A total of 96 sets of samples were obtained from the pair of sites at the pools. Non-parametric analysis of the data for variations between specific days was not statistically significant ($p > 0.05$). Hence the data for specific days was pooled and analyzed for site parity or disparity at each pool separately. Figure 2 displays the median levels and variations of the physico-chemical parameters. Except for temperature, the physico-chemical parameters were fairly uniform and showed no capacity to segregate sites. Generally, pH was slightly alkaline ranging from 7.4–7.8. Dissolved Oxygen concentration ranged from 4.2–6.1 $mg.l^{-1}$ while the percent saturation generally exceeded 75% but never up to 100%. Conductivity was slightly higher at NB (270 $\mu S.cm^{-1}$) compared to TF (250 $\mu S.cm^{-1}$) but no site disparity was evident at the two pools. Stream temperature increased from < 15°C before 6 a.m. preceding in-stream activities to > 20°C around midday coinciding with increase in activities. But the increase occurred at the pair of sites so no upstream-downstream disparity was evident during in-stream activities at the pools.

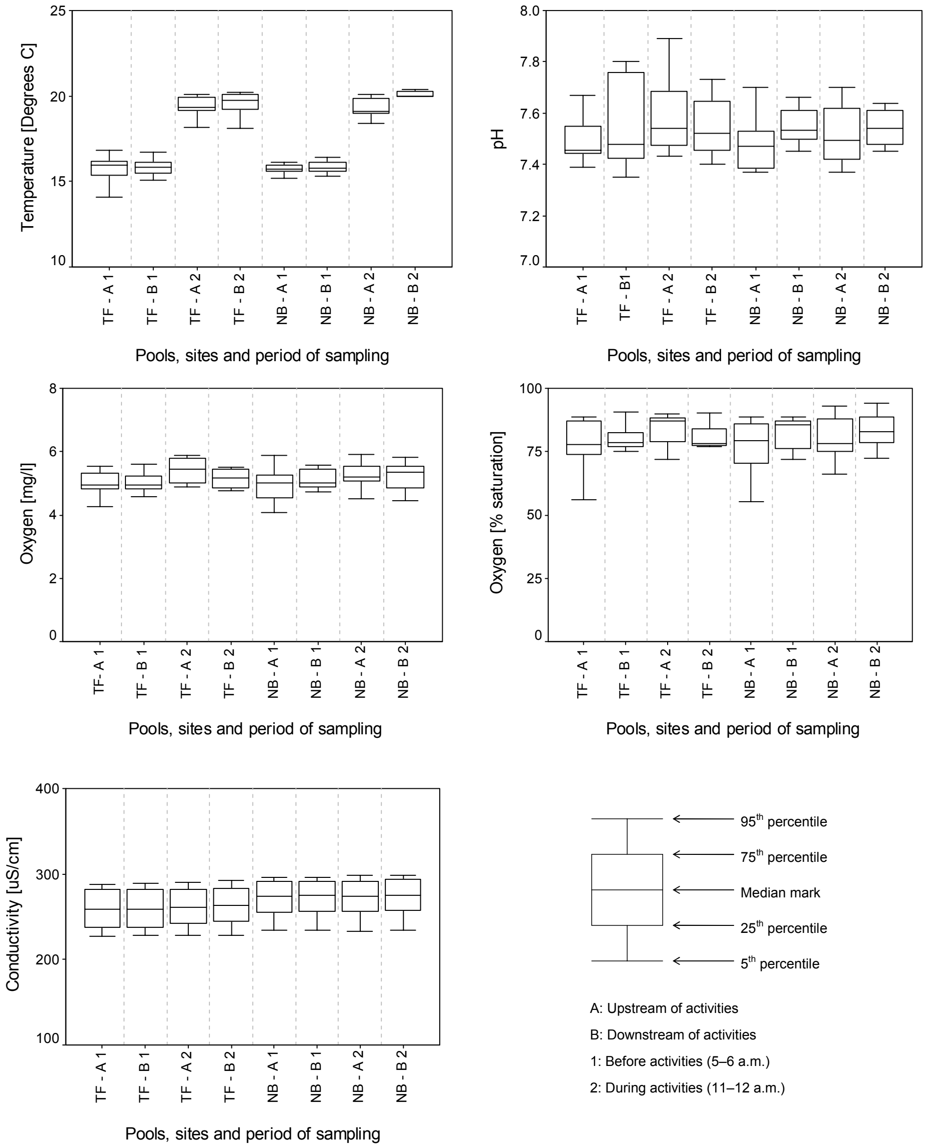

Figure. 2: Box-whisker plots of the physico-chemical parameters at Turkana Flats (TF) and Njoro Bridge (NB) during dry weather. The legend describes the box-whisker plot, the sites and the sampling period.

All the sites had high levels of microbial indicators, which ranged from 2.8–3.5 $\log_{10}$ cfu.100 ml $^{-1}$ for *E coli* or *Enterococci*, and between 4.5–6.2 $\log_{10}$ cfu.100 ml $^{-1}$ and 3.2–4.5 $\log_{10}$ cfu.ml^{-1} for TC and HPC respectively. TC and HPC levels were compatible but HPC is traditionally reported in cfu.ml^{-1}. The median levels and the variations of the microbial indicators are displayed in Figure 3. Before in-stream activities, microbial levels downstream were within the same range as the respective levels upstream. Since they were not statistically different ($p > 0.05$), this trend was called upstream/downstream site parity. Alternatively, median levels of microbial indicators downstream were higher and statistically different (p < 0.05) from upstream levels during in-stream activities causing upstream/downstream site disparity. Similarly, downstream levels during in-stream activities were statistically different from levels at the same site before activities (downstream/downstream site disparity). The two site disparities resulted from increases downstream in indicator bacteria levels during in-stream activities by > 1 $\log_{10}$ cfu.ml^{-1} for HPC and TC and > 0.5 $\log_{10}$ cfu.100 ml^{-1} for *E coli* and *enterococci*. The microbial levels during in-stream activities at the upstream sites at both pools remained within the same range as the respective levels before activities at the same site (upstream/upstream site parity).

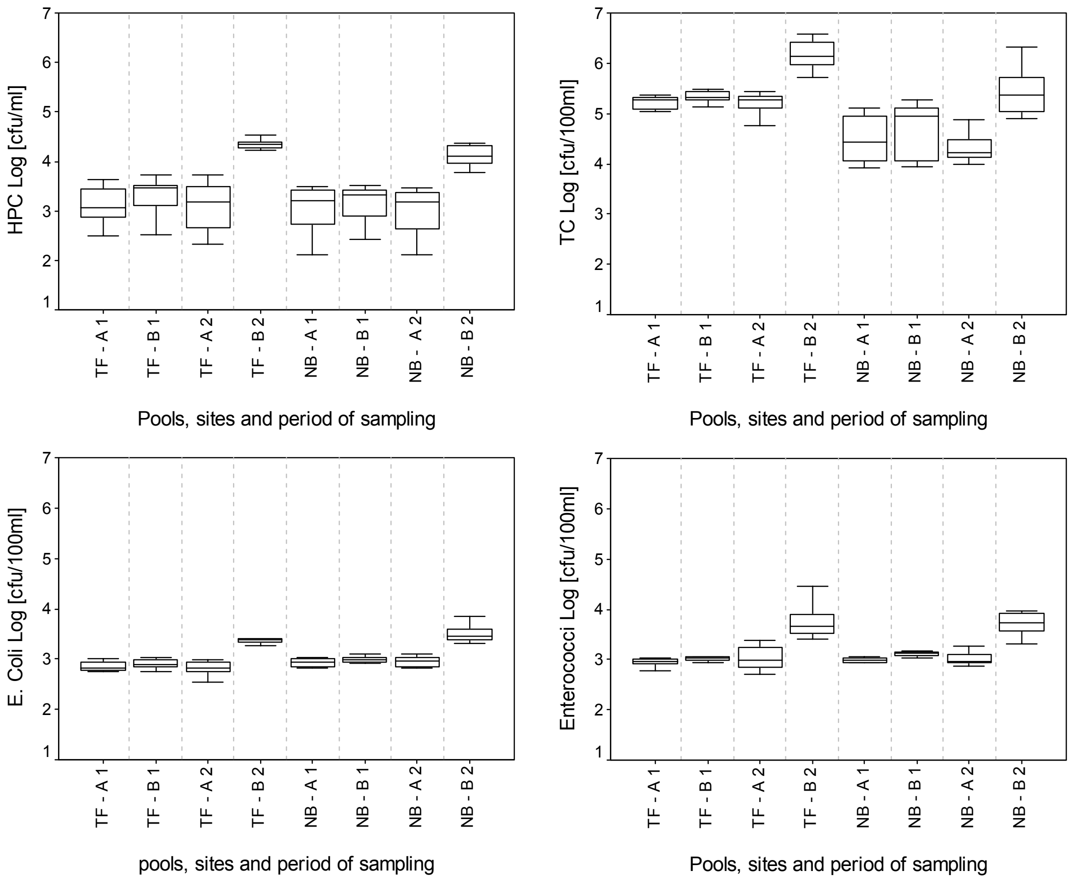

Figure. 3: Box-whisker plots illustrating the site segregation capacity of the microbial indicators at Turkana Flats (TF) and Njoro Bridge (NB). Note a significant (p < 0.05) increase in downstream levels during in-stream activities (TF-B2 & NB-B2). The legend in Fig. 2 gives a description of the box-whisker plot, the sites and the sampling period.

The chemical indicators (TSS, Turbidity, BOD_5 and Ammonium-N) showed similar capacity for site segregation as the microbial indicators (Figure 4). Samples collected before in-stream activities were generally clear as both TSS and Turbidity levels were relatively low (< 10 $mg.l^{-1}$ and < 10 $Abs.UV_{437}.m^{-1}$, respectively). But TSS and Turbidity levels downstream were respectively, 6 and 2 times higher during in-stream activities at both pools while upstream values remained unaltered. BOD_5 levels downstream were generally higher than upstream levels where a pooled median 10 $mg.l^{-1}$ was recorded. But during in-stream activities significant ($p < 0.05$) downstream increase by an average 5 times was recorded. Similarly, Ammonium-N levels increased downstream during in-stream activities from < 30 $\mu g.l^{-1}$ to > 40 $\mu g.l^{-1}$ and from < 40 $\mu g.l^{-1}$ to > 50 $\mu g.l^{-1}$ at TF and NB, respectively, although these increases were not statistically significant ($p > 0.05$).

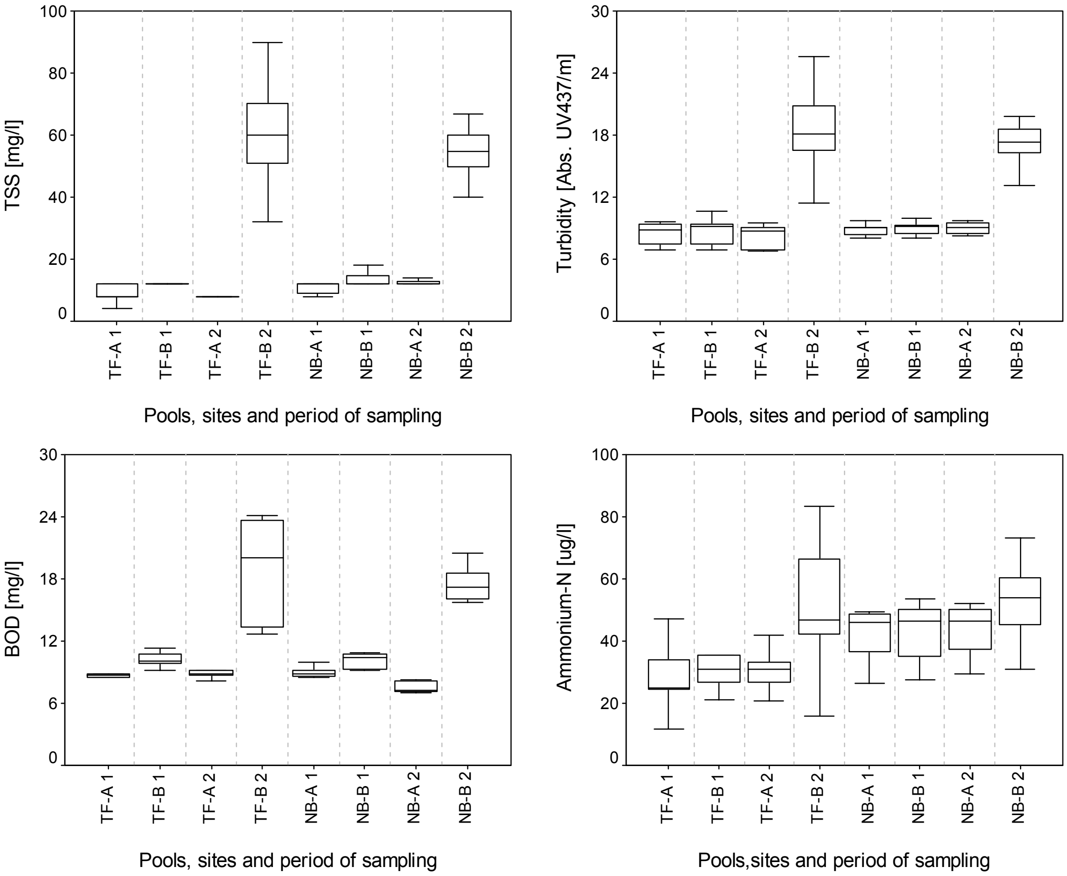

Figure 4: Box-whisker plots illustrating site segregation with the non-microbial indicators at Turkana Flats (TF) and Njoro Bridge (NB). Note (except for Ammonium-N) a significant ($p < 0.05$) increase in downstream levels during in-stream activities (TF-B2 & NB-B2). The legend in Fig. 2 gives a description of the box-whisker plot, the sites and the sampling period.

The output of the PCA is displayed in Table 1. The data was explained largely by three principal components (PC1, PC2 & PC3), which together explained 66% of the total variation. The microbial indicators (HPC, TC, *E coli* and *Enterococci*) as well as the chemical indicators (TSS, Turbidity, BOD_5 and Ammonium-N) correlated positively with PC1. PC1 was ascribed to recent pollution since these indicators had a strong capacity to segregate sites based on the pollution status of the sites. PC1 accounted for 42.6% of the total variation. Except temperature, the physico-chemical parameters did not correlate with PC1. Instead they were more associated with PC2, which accounted for 14.8% of the total variations. None of the indicators in PC1 correlated with PC2. Apparently, PC2 could not explain pollution in the data set and since it was associated with oxygen, pH and temperature, it was distinguished as the metabolic activity component. PC3 contributed to 8.6% of the total variations and conductivity, pH, HPC, TC and *Enterococci* correlated weakly with this component. In contrast, TSS, Turbidity, Dissolved Oxygen and *E. coli* did not correlate with PC3 while BOD_5 and Ammonium-N correlated negatively with it. The mixed associations suggested that PC3 might explain pollution but not recent pollution. It was ascribed to the residual pollution status of the stream, which could have resulted from previous pollution and the stream's inherent response through self-purification.

Table 1. Output of the Principal Component Analysis (PCA)

Parameters	Extracted components		
	PC1[a]	PC2[a]	PC3[a]
HPC	0.72	—[b]	0.23
TC	0.76	—[b]	0.16
E. coli	0.88	—[b]	—[b]
Enterococci	0.86	—[b]	0.11
TSS	0.97	—[b]	—[b]
Turbidity	0.96	—[b]	—[b]
BOD	0.75	—[b]	-0.35
Ammonium-N	0.47	—[b]	-0.68
Temperature	0.53	0.34	0.12
Conductivity	—[b]	0.43	0.56
pH	—[b]	-0.63	0.30
Oxygen	—[b]	0.67	—[b]
Percent of total variance	42.6	14.8	8.6

[a]PC1, PC2 & PC3 are the extracted principal components 1, 2 & 3, respectively
[b] excluded values that did not contribute significantly to the total variance.

Table 2. Spearman's rank correlation matrix of the pooled data.

Parameters	HPC	TC	*E. coli*	*Entero.*	TSS	Turb.	BOD_5
TC	0.65[a]						
E. coli	0.52[a]	0.67[a]					
Entero.	0.55[a]	0.57[a]	0.83[a]				
TSS	0.67[a]	0.67[a]	0.87[a]	0.82[a]			
Turbidity	0.64[a]	0.65[a]	0.87[a]	0.82[a]	0.98[a]		
BOD_5	0.43	0.45	0.57[a]	0.50[a]	0.72[a]	0.69[a]	
NH_4-N	0.17	0.23	0.26	0.36	0.40	0.38	0.56[a]

[a] Significant correlation ($p < 0.05$). n = 96, *Entero* (*Enterococci*), Turb. (Turbidity)

In general, very strong associations existed among the parameters in PC1 as shown by the Spearman's rank correlation matrix of the pooled data (Table 2). In particular, TSS and Turbidity correlated positively and significantly with HPC, TC, *E. coli* and *Enterococci*. Specifically, *E. coli* and *Enterococci* correlated very strongly while TC correlated well with HPC. BOD_5 correlated moderately with HPC, TC, *E. coli* and *Enterococci* but strongly with TSS, Turbidity and Ammonium-N, which correlated weakly with the other parameters. Cluster Analysis confirmed that the capacity for site segregation was very strong with the microbial indicators as well as the chemical indicators. When data of these indicators was applied in Cluster Analysis, the sites segregated and desegregated with respect to pollution levels that depicted the specific location of the sites and the alleged influence of in-stream activities at the pools (Figure 5). The downstream sites during in-stream activities were closely associated and segregated from the rest. A similar assessment proved futile with the physico-chemical parameters, which failed to correlate with the other parameters.

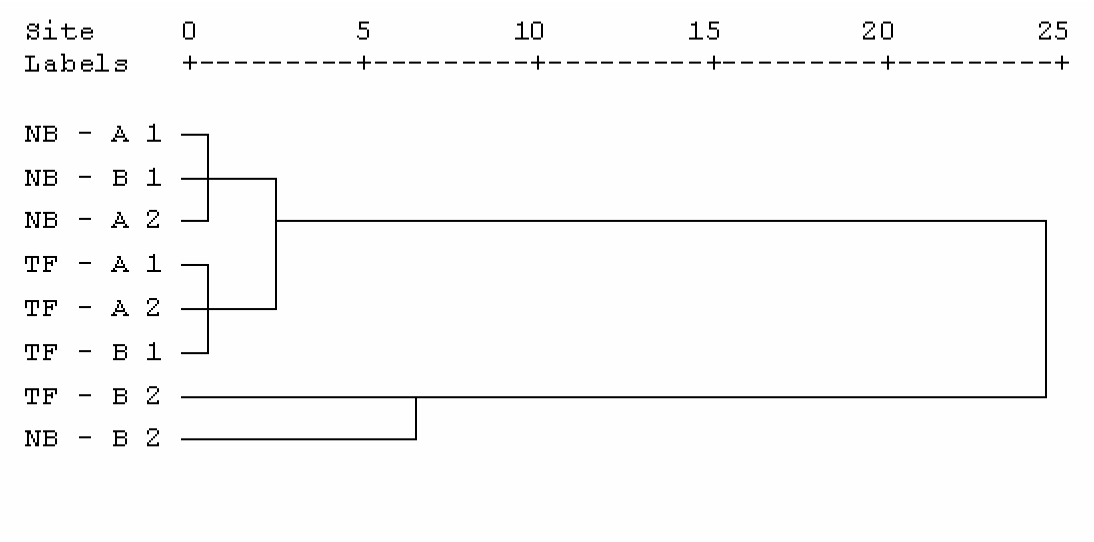

Figure 5. Dendrogram illustrating the average linkages between sites at Turkana Flats (TF) and Njoro Bridge (NB). Note in particular the segregation of the downstream sites during in-stream activities (TF – B2 & NB – B2). The legend in Fig. 2 gives a description of the sites and the period of sampling.

Discussion

As noted in the past, in-stream activities are widespread at the middle reaches of the Njoro River (Mathooko, 2001). However, they are intentionally concentrated in isolated spots along the stream channel, usually around pools since pools are relatively broad and easily accessible compared to riffles. Pools and riffles are dominant bedforms in gravel and mixed bedded stream channels (Emery *et al*., 2003). At moderate slopes, pools alternate in sequence with riffles, where stream flow is relatively high compared to pools (Emery *et al*., 2003; Richards, 2007). In the Njoro River, riffle-pool sequences are typical features at the middle reaches with soft substratum of easily eroded fine sediments in pools and fairly resistant bedrock in the riffle sections (Mathooko and Kariuki, 2000; Mathooko, 2001). Most pools at the middle reaches could be described as diffuse pollution hotspots since they are regularly visited by people and livestock and the surrounding area is usually littered with faeces and solid waste. Visits have been reported to vary seasonally and diurnally but they may vary with specific days as well (cf. Chapter 6). As a result, relative pollution levels downstream of activities were anticipated to vary with days accordingly. But specific days were indistinguishable with the water quality data. It is thought that the array of in-stream activities that took place simultaneously, made it unattainable to define “intensity” or “frequency” of activities unambiguously. For instance, a few livestock watering in the middle of the stream may stirrup more sediments than many people abstracting water from the stream bank and visits by people may not necessarily coincide with visits by livestock. In addition, several external factors could have influenced visits, which in turn affected “intensity” or “frequency” of activities. For example, a sudden failure of a public standpipe to supply water or a change in weather could influence human visits in particular, irrespective of which day of the week it was.

Nevertheless, the indicators detected significant variations in pollution levels between upstream and downstream sites during in-stream activities although BOD_5 detected subtle differences before activities. The consistency by the indicators to segregate sites during in-stream activities pointed to a pollution factor and confirmed the assertion that in-stream activities influenced pollution levels at the pools. Site segregate capacity was strong with the microbial indicators, as well as the chemical indicators. This was confirmed with Cluster Analysis using both groups of indicators to segregate dissimilar sites and desegregate similar sites based on their relative pollution status. On the other hand, it was impossible to group sites into similar and dissimilar pollution clusters accordingly with data of the physico-chemical parameters. Thus, it was reasonable to classify the microbial indicators and the chemical indicators in the pollution component while the physico-chemical parameters were grouped into the metabolic activity component (cf. PCA results). The physico-chemical parameters were fairly uniform without any distinctive pattern or consistency to segregate sites and there was no evidence that they influenced indicator levels. Nevertheless, environmental factors may affect the presence and die-off of microbes in aquatic systems (Wilkinson *et al*., 1995; Beaudeau *et al*., 2001; Nola *et al*., 2002; Noble *et al*., 2003; Byamukama *et al*., 2005).

The observed associations between the microbial indicators and chemical indicators were useful in linking microbial pollution to in-stream activities. For instance, there was close coupling between faecal indicator bacteria and suspended sediments. This phenomenon is fairly well understood and has been explained by some authors (Wilkinson *et al*., 1995; Edberg *et al*., 2000; Beaudeau *et al*., 2001; McLellan and Salmore, 2003; Byamukama *et al*., 2005). During in-stream activities sediments are disturbed and resuspended. As a result, bacteria levels increase by concomitant resuspension with sediments and/or resuspension of sediments with attached bacteria (Edberg *et al.*, 2000; Byamukama *et al.*, 2005). Resuspension of sediments with attached bacteria was probably more important since it is unlikely that unattached bacteria will settle unaided in running waters. Co-sedimentation, *i.e.* the joint deposition of sediment particles and bacteria is most likely the only way bacteria will settle in running waters (Wilkinson *et al.*, 1995). It is known that when viable bacteria attach to sediments, they are protected and their survival is enhanced (McLellan and Salmore, 2003). Attached bacteria will sediment in undisturbed segments particularly in pools or other stream reaches where stream velocity may be low because such areas are ideal for preferential accumulation of bacteria even though washout during disturbance or increased flow may result in irregular bacteria peaks immediately downstream (Wilkinson *et al.*, 1995; Beaudeau *et al.*, 2001). It will be recalled that indicator bacteria levels upstream and downstream were compatible before in-stream activities when the pools were undisturbed. But during in-stream activities, the levels increased substantially downstream. Certainly, this increase was associated with the washout of bacteria that resulted from disturbances caused by activities in the pools. At the same time, direct input of excreta by people or livestock during in-stream activities could have increased pollution levels immediately downstream. This form of pollution is a familiar cause of water quality deterioration in developing countries (Nevondo and Cloete, 1999; Fatoki *et al.*, 2001; Mathooko, 2001; Zamxaka *et al.*, 2004). In addition to pathogens, urine and faeces contain organic matter as well as eutrophying substances in the form of phosphorus and nitrogen compounds (Vinneras *et al.*, 2003; Langergraber and Muellergger, 2005). Ideally, heterotrophic bacteria will respond to pollution of this nature by decompose organic matter to release energy and nutrients (van Veen and Kuikman, 1990). Usually, this response is rapid and useful when monitoring the input of organic matter and the corresponding bacteria increase in aquatic systems (Ramaiah *et al.*, 2002).

It was evident that the stream at the middle reaches was polluted with faecal matter and easily degradable organic matter. However, the stream demonstrated a considerable capacity to recover from pollution between Turkana Flats and Njoro Bridge. Pollution levels at the upstream site at Njoro Bridge (NB-A1 or NB-A2) were compatible with the levels observed at the corresponding site at Turkana Flats (TF-A1 or TF-A2). Except for Ammonium-N and Conductivity levels, the stream recovered from the pollution generated at Turkana Flats and the additional input it received intermittently from the wastewater outfalls at Egerton University and a vegetable cannery, both of which were located between the two pools. This remarkable self-purification capacity by the stream may be linked to the internal metabolic processes occurring in the stream alongside with the riffle-pool sequences that are typical at the middle reaches and the flow dynamics that are often associated with this configuration (Emery *et al*., 2003; Richards, 2007). It should be noted that the intrinsic capacity of streams to recover from pollution is essential for restoring water quality to pre-pollution status (Vagnetti *et al*., 2003). In the Njoro River catchment, this may be particularly useful for downstream residents who depend on the stream for their daily water needs even though riparian communities upstream may be contaminating the stream.

When faecal contamination is established, it may be required in certain cases to attribute contamination to specific contributing sources. This may arise in places where discrete faecal sources occur simultaneously and/or remediation measures require prioritization or legal backing for sharing remediation cost (Ebdon *et al*., 2007). It is challenging at present to attribute faecal pollution to specific sources in the Njoro River Catchment although people and livestock could be the main contributing sources since sanitation facilities are inadequate and livestock grazing is widespread. The present unavailability of adequate diagnostic tests makes it impossible to trace faecal pollution to any specific source in the catchment. It is well known that classical faecal indicators alone do not precisely distinguish between specific sources of faecal pollution (Gauthier and Archibald, 2001 Field and Samadpour, 2007; Shah *et al*., 2007). This is because indicator bacteria have a wide host range occurring in nearly all warm-blooded animals (Leeming *et al*., 1996; Hoglund *et al*., 1998; Scott *et al*., 2002; Ahmed *et al*., 2007). Alternatively, various analytical procedures have been proposed to identify the host or environment from which faecal indicators may originate (Sinton *et*. *al*., 1998; Scott *et al*., 2002; Field and Samadpour, 2007). These methods, collectively known as microbial (or bacterial) source tracking techniques offer various diagnostic possibilities for distinguishing specific faecal sources. They are currently in use in developed countries but are not yet available in most developing countries because most of them are technically complex and unaffordable (Byamukama *et al*., 2005). It might take some time before they are included in routine water quality monitoring in developing countries.

Conclusions and recommendations

1. This study demonstrated that the in-stream activities of people and livestock at the middle reaches of the Njoro River significantly affected the microbial water quality of the stream immediately downstream of activities.
2. The observed site parity/disparity in the levels of indicators before/during in-stream activities reflected the diurnal periodicity of activities and the concomitant pollution they caused.
3. Although the frequency of visits by people and livestock and the intensity of in-stream activities may vary with specific days, such differences were indistinct with the water quality data.
4. The procedure adopted provided a pragmatic way to isolate and assess diffuse pollution of this nature and stressed the merit of using microbial indicators concurrently with chemical indicators in routine assessment of microbial water quality. However, microbial source tracking studies are required to attribute faecal contamination to specific contributing sources.
5. Meanwhile pollution control measures are necessary to regulate in-stream activities along the stream and minimize the movement of livestock in the catchment.

Acknowledgements

This study was supported by the Austrian Government through the North-South Dialogue Scholarship Programme of the Austrian Development Co-operation. The authors are grateful for the additional support received from the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology in Austria and the Department of Biological Sciences at Egerton University in Kenya.

References

Ahmed, W., Stewart, J., Gardner, T., Powell, D., Brooks, P., Sullivan, D., Tindale, N., 2007. Sourcing faecal pollution: A combination of library-dependent and library-independent methods to identify human faecal pollution in non-sewered catchments. *Water Res*. 41, 3771–3779.

APHA, 1995. Standard methods for the examination of water and wastewater, 19th edition. American Public Health Association, Washington, D.C.

Baldyga, T. J., 2005. Assessing land cover change impact in Kenya's River Njoro watershed using remote sensing and hydrological modelling. M.Sc. Thesis, University of Wyoming, USA.

Beaudeau, P., Tousset, N., Bruchon, F., Lefevre, A., Taylor, H. D., 2001. In situ measurement and statistical modelling of Escherichia coli decay in small rivers. *Water Res*. 35 (13), 3168–3178.

Byamukama, D., Mach, R. L., Kansiime, F., Manafa, M., Farnleitner, A. H., 2005. Discrimination efficacy of faecal pollution detection in different aquatic habitats of a high-altitude tropical country, using presumptive coliforms, Escherichia coli, and Clostridium perfringens spores. *Applied Environmental Microbiology* 71 (1), 65–71.

Ebdon, J., Muniesa, M., Taylor, H., 2007. The application of a recently isolated strain of Bacteroides (GB-124) to identify human sources of faecal pollution in a temperate river catchment. *Water Res*. 41, 3683–3690.

Edberg, S. C., Rice, E. W., Karlin, R. J., Allen, M. J., 2000. Escherichia coli: the best biological drinking water indicator for public health protection. *Applied Environmental Microbiology* 88, 106–116.

Edge, T. A., Hill, S., 2007. Multiple lines of evidence to identify the sources of fecal pollution at a freshwater beach in Hamilton Harbour, Lake Ontario. *Water Res*. 41, 3585–3594.

Emery, J. C., Gurnell, A. M., Clifford, N. J., Petts, G. E., Morrissey, I. P., Soar, P. J., 2003. Classifying the hydraulic performance of riffle-pool bedforms for habitat assessment and river rehabilitation design. *River Research and Applications* 19 (5-6), 533–549.

Fatoki, O. S., Muyima, N. Y. O., Lujiza, N., 2001. Situation analysis of water quality in the Umtata River catchment. *Water South Africa* 27 (4), 467 – 474.

Field, K. G., Samadpour, M., 2007. Fecal Source tracking, indicator paradigm, and managing water quality. *Water Res*. 41, 3517 – 3538.

Graves, A. K., Hagedorn, C., Brooks, A., Hagedorn, R. L., Martin, E., 2007. Microbial source tracking in a rural watershed dominated by cattle. *Water Res*. 41, 3729–3739.

Gauthier, F., Archibald, F., 2001. The ecology of "fecal indicator" bacteria commonly found in pulp and paper mill water systems. *Water Res*. 35 (9), 2207–2218.

Hoglund, C., Stenstrom, T. A., Jonsson, H., Sundin, A., 1998. Evaluation of faecal contamination and microbial die-off in urine separated sewage systems. *Wat. Sci. & Tech*. 38, 17–25.

Kong, R. Y. C., Lee, S. K. Y., Law, T. W. F., Law, S. H. W., Wu, R. S. S., 2002. Rapid detection of six types of bacterial pathogens in marine waters by multiplex PCR. *Water Res*. 36, 2802–2812.

Langergraber, G., Muellergger, E., 2005. Ecological sanitation – a way to solve global sanitation problems? *Environment International* 31, 433–444.

Leeming, R., Ball, A., Ashbolt, N., Nichols, P., 1996. Using faecal sterols from humans and animals to distinguish faecal pollution in receiving waters. *Water Res*. 30 (12), 2893–2900.

Lelo F.K., Wanjiku, C., Jenkins, M. W., 2005. Managing Riparian Resources in the River Njoro Watershed in Kenya: The Challenge of Conflicting Laws, Policies and Community Priorities. Paper Presented: International workshop on "African Water Laws - Plural Legislative Frameworks for Rural Water Management in Africa. Guateng, South Africa.

Mainuri, Z. G., 2005. Land use effects on the spatial distribution of soil aggregate stability within the Njoro River watershed, Kenya. M.Sc. Thesis. Egerton University, Kenya.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131–139.

Mathooko, J. M., Kariuki, S. T., 2000. Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. *African Journal of Ecology* 38 (2), 123 129.

McLellan, S. L., Salmore, A. K., 2003. Evidence for localized bacterial loading as the cause of chronic beach closings ion a freshwater marina. *Water Res*. 37, 2700–2708.

Mokaya, S. K., Mathooko, J. M., Leichtfried, M., 2004. Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *African Journal of Ecology* 42 (4), 281–288.

Nevondo, T. S., Cloete, T. E., 1999. Bacterial and chemical quality of water supply in the Dertig village settlement. *Water South Africa* 25 (2), 215–220.

Noble, R. T., Moore, D. F., Leecaster, M. K., McGee, C. D., Weisberg, S. B., 2003. Comparison of total coliform, faecal coliform, and enterococcus bacterial indicator response for ocean recreational water quality testing. *Water Res*. 37, 1637–1643.

Nola, M, Njine, T., Djuikom, E., Foko, V. S., 2002. Faecal coliform and faecal streptococci community in the underground water in an equatorial area in Cameroon (Central Africa); the importance of some environmental chemical factors. *Water Res*. 36, 3289–3297.

Obi, C. L., Potgieter, N., Bessong, P. O., Matsaung, G., 2002. Assessment of the microbial quality of river water sources in rural Venda communities in South Africa. *Water South Africa* 28 (3), 287–292.

Parveen, S., Hodge, N. C., Stall, R. E., Farrah, S. R., Tamplin, M. l., 2001. Phenotypic and genotypic characterization of human and nonhuman Escherichia coli. *Water Res*. 35 (2), 379 – 386.

Ramaiah, N., Kenkre, V. D., Verlecar, X. N., 2002. Marine environmental pollution stress detection through direct viable counts of bacteria. *Water Res*. 36, 2383 – 2393.

Richards, K. S., 2007. Simulations of flow geometry in a riffle-pool stream. *Earth Surface Processes and Landforms*. 3 (4), 345–354.

Scott, T. M., Rose, J. B., Jenkins, T. M., Farrah, S. R., Lukasik, J., 2002. Microbial source tracking: current methodology and future directions. *Applied Environmental Microbiology* 68 (12), 5796–5803.

Shah, V. G., Dunstan, R. H., Geary, P. M., Coombes, P., Roberts, T. K., Nagy-Felsobuki, E. V., 2007. Evaluating potential applications of faecal sterols in distinguishing sources of faecal contamination from mixed faecal samples. *Water Res*. 41, 3691–3700.

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiolgia* 458, 121–130.

Sinton, L. W., Finlay, R. K., Hannah, D. J., 1998. Distinguishing human from animal contamination in water: a review. *New Zealand Journal of Marine and Freshwater Research* 32, 323–348.

Vagnetti, R., Miana, P., Fabris, M., Pavoni, B., 2003. Self-purification ability of a resurgence stream. *Chemosphere* 52, 121–130.

van Veen, J. A., Kuikman, P. J., 1990. Soil structural aspects of decomposition of organic matter by micro-organisms. *Biogeochemistry* 11 (3), 213 – 233.

Venter, S. N., 2001. Microbial water quality in the 21st century. *Water South Africa* 27 (1), 16–17.

Vikaskumar, G. H., Dunstan, R. H., Geary, P. M., Coombes, P., Roberts, T. K., Rothkirch, T., 2007. Comparison of water quality parameters from diverse catchments during dry periods and following rain events. *Water Res*. 41, 3655–3666.

Vinneras, B., Holmqvist, A., Bagge, E., Albihn, A., Jonsson, H., 2003. The potential for disinfection of separated faecal matter by urea and by peracetic acid for hygienic nutrient recycling. *Bioresource Technology* 89, 155–161.

Wheeler, A. L., Hartel, P. G., Godfrey, D. G., Hill, J. L., Segars, W. I., 2002. Potential of Enterococcus faecalis as a human faecal indicator for microbial source tracking. *Journal of Environmental Quality* 31, 1286–1293.

Wilkinson, J., Jenkins, A., Wyer, M., Kay, D., 1995. Modelling faecal coliform dynamics in streams and rivers. *Water Res*. 29 (3), 847–855.

Zamxaka, M., Pironcheva, G., Muyima, N Y. O., 2004. Microbiological and physico-chemical assessment of the quality of domestic water sources in selected rural communities of the Eastern Cape Province, South Africa. *Water South Africa* 30 (3), 333–340.

Chapter 8

Evaluation of microbial health risk at water abstraction points along a rural stream

Prepared for submission: *Applied Environmental Microbiology*
Accepted for oral presentation at the *9th WaterNet/WARFSA Sympossium*, 29 – 31 October 2008 Johannesburg, South Africa. To be published in the proceedings

Evaluation of microbial health risk at water abstraction points along a rural stream

P. T. Yillia*, N. Kreuzinger** and J. M. Mathooko***

*University of Sierra Leone, Fourah Bay College, Freetown, Sierra Leone; Tel.: +232 30 226296; e-mail: paulyillia@yahoo.com; pyillia@iwag.tuwien.ac.at
**Vienna University of Technology, Institute for Water Quality, Resources and Waste Management, Karlsplatz 13/226, Vienna, Austria; Tel.: +43 1 58801 22622; Fax: +43 1 58801 22699; e-mail: norbkreu@iwag.tuwien.ac.at
***Egerton University, Department of Biological Sciences, PO Box 563, Njoro, Kenya; Tel: +254 37 61282 or +254 720853844 ; Fax: +254 37 61055; e-mail: jmathooko@hotmail.com

*for correspondence

Abstract
U.S. based models for recreational water quality were applied to characterize the potential health risk (PHR) of infection with gastroenteritis (GI) and highly credible gastroenteritis (HCGI) illnesses from single exposure at several water abstraction points (WAP) along the Njoro River in rural Kenya. Ambient geometric mean densities of Escherichia coli (EC) and intestinal enterococci (IE) were generally high (2–4 log units/100 ml) and risk levels were grossly in excess of acceptable health risk (AHR) levels for bathing and drinking. PHR was 2–3 times higher with the Cabelli (IE) model compared to the U.S. EPA (EC) model. Risk levels varied among WAPs in association with the spatial and seasonal variability of ambient EC and IE densities. With the Cabelli (1983) IE model, PHR of HCGI illness on single exposure to the dry weather 95th percentile IE densities for bathing was 2.5% of the exposed population at Logoman compared to 5.2% at Turkana Flats, 4.9% at Kenyatta or Nessuit and 4.6%, 4.5% and 4.2% at Treetop, Segotik and Njoro Bridge, respectively. PHR was ≥ 5% on exposure to the wet weather 95th percentile IE densities at the WAPs, excepting Treetop with 4.3%. Relative risk levels increased by at least 30 and 70 times for GI and HCGI illnesses, respectively, from drinking (250 ml) untreated stream water rising erratically in wet weather by > 80% of the dry weather risk at Logoman, > 30% at Njoro Bridge and Kenyatta and 10–15% at Segotik, Nessuit and Turkana Flats. By stipulating freshwater bathing water quality guidelines of 126 and 33 cfu/100 ml for EC and IE, respectively, U.S. EPA upholds maximum AHR levels at 0.7% and 1.9% for EC and IE, respectively. Reducing current PHR levels at the WAPs to the U.S. EPA bathing AHR levels would require at least 2–4 log reductions of IE and EC densities and further log reductions to achieve the WHO recommended drinking water AHR level of 0.1%. This would necessitate specialized treatment techniques and comprehensive catchment management measures to protect WAPs.

Keywords
Faecal indicator bacteria; microbial health risk; water abstraction points; water quality

Introduction

Exposure to contaminated water has been associated with illnesses such as gastroenteritis and infections of the skin, eyes, ears, nose and throat (Cabelli *et al*., 1982; Cabelli, 1983, 1989; Dufour, 1984). The threat of microbial pollution-related illnesses is predictable with microbial risk assessment (MRA). In particular, MRA can function as a valuable tool for risk identification and management in situations where epidemiological investigations are lacking (Gale, 2004; Gibson *et al*., 2002; Westrell *et al*., 2004). With the observed adverse effect level (OAEL) approach, the level of faecal contamination is indicated by the presence of an indicator organism (Steyn *et al.*, 2004). A negative health effect can be expected if the indicator is present and the level of risk increases with increase in the indicator density (Wade *et al*., 2003). The common bacteria indicators currently in use are total coliforms (TC), faecal coliforms (FC), faecal streptococci (FS), Escherichia coli (EC) and intestinal enterococci (IE). Most regulatory agencies are interested in EC and IE given that they correlate well with the rate of gastrointestinal (GI) illnesses in recreational waters (Cabelli *et al*., 1982; Cabelli, 1983, 1989; Dufour, 1984; Fattal *et al*., 1986; Medema *et al*., 1997; Haile *et al*., 1999; Turbow *et al*., 2003; Wade *et al*., 2003; Dwight *et al*., 2004). This correlation has been useful for the development of microbial water quality guidelines. Notably, the bathing water guidelines of the United States (US) Environmental protection Agency (U.S. EPA, 1986) and the European Union (EU) Bathing Water Directive (Anon, 1976) were adopted on the basis of measured levels of faecal indicator bacteria in recreational waters. Similarly, regulatory institutions in many countries are aided by WHO guidelines (WHO, 2001, 2003) that were developed on the same basic principle.

A guideline value stipulates a theoretical health safety limit that is often associated with the maximum acceptable health risk. It is usually the tolerable concentration of an indicator rather than the detectable harmful dose of infectious pathogens (Salas, 1986, Steyn *et al.*, 2004). The choice of indicator over pathogen is largely due to methodological problems (Cabelli, 1983). A lot of time and resources may be needed to adequately detect any type of pathogen and because they are diverse and occur in low numbers in the environment, large errors and costs may be incurred in sampling and enumeration (Rose and Gerba, 1991; Kong *et al*., 2002; Wade *et al*., 2006). Also, many pathogenic bacteria could be described as viable but non-culturable and the densities of most pathogens in environmental waters are unpredictable (Cabelli, 1983; Kong *et al*., 2002). As a result, bacteria indicators such as EC and IE are used during routine microbiological assessment. However, both indicators have been criticized for not being representative enough, especially, for viral and protozoan pathogens (Barrell *et al*., 2000; Skraber *et al*., 2002; Noble *et al*., 2003). Pathogens may be present where bacteria indicators are shown to be absent (Barrell *et al*., 2000; Donaldson et al., 2002). Also, there is substantial evidence that natural systems with no established faecal input may harbour some bacteria indicators. For example, IE has been associated with soil, insects, plants, aquatic organisms and other natural sources where faecal contamination is not expected (Anderson *et al*., 1997; Gauthier and Archibald, 2001; Signoretto *et al*., 2005). Similarly, EC may occur in non-faecal environments and its persistence and potential to multiply in the environment has been demonstrated (Byappanahalli and Fujioka, 1998; Rajala and Heinonen-Tanski, 1998; Anderson *et al*., 2005).

Despite these limitations, tests for faecal indicator bacteria are accepted for assessing the hygienic quality of environmental waters. Because a complete epidemiological investigation is normally expensive and time consuming, public health authorities and water quality managers are inclined to follow the OAEL approach, which is usually integrated into the routine water quality monitoring programme. OAEL requires testing the water for the presence of a preferential faecal indicator bacterium at the point of exposure, usually a recreational site or a water source. When the indicator bacterium is present in excess of referential water quality guidelines and the tolerable risk threshold is breached, a sanitary survey is executed to detect faecal sources (WHO, 2003). This may be undertaken concurrently with an assessment of physical water quality parameters such as suspended solids, turbidity and colour, in tandem with chemical constituents like BOD, oxygen and ammonia or chloride levels to verify any external input that may be associated with faecal contamination. The research aspect of this study was aimed at following a similar MRA framework at several water abstraction points (WAP) along the Njoro River, Kenya to characterize the potential health risk of infection with gastroenteritis (GI) and highly credible gastroenteritis (HCGI) illnesses that may be attributed to bathing or drinking. Four related questions were addressed: (i) Are U.S. based recreational water quality models useful in characterizing the potential health risk of water sources in rural Kenya? (ii) Are risk levels above or below referential threshold levels for bathing and drinking? (iii) How do risk levels vary seasonally and among WAPs along the stream? (iv) How efficient are water quality parameters in indicating potential health risk of gastrointestinal illness?

Materials and methods

Njoro River

Njoro River (60 km) drains a small predominantly rural catchment (280 km^2) in southwestern Kenya, approximately 180 km northeast of Nairobi (Figure 1). It is a high altitude stream with its source at the eastern segment of the Mau Hills at about 2700 m (a.s.l) (Mathooko, 2001). The stream is very narrow, shallow, and intermittent in the lower reaches. When flowing at full length, Njoro River drains into Lake Nakuru approximately 1700 m (a.s.l) at the floor of the Rift Valley (Shivoga, 2001). Its main tributary is the Little Shuru, which joins the main Njoro River flow in the lower segment of the Upper Njoro River Catchment (UNRC). Below the confluence, the stream flows through largely poor rural communities that lack adequate sanitation and access to clean water.

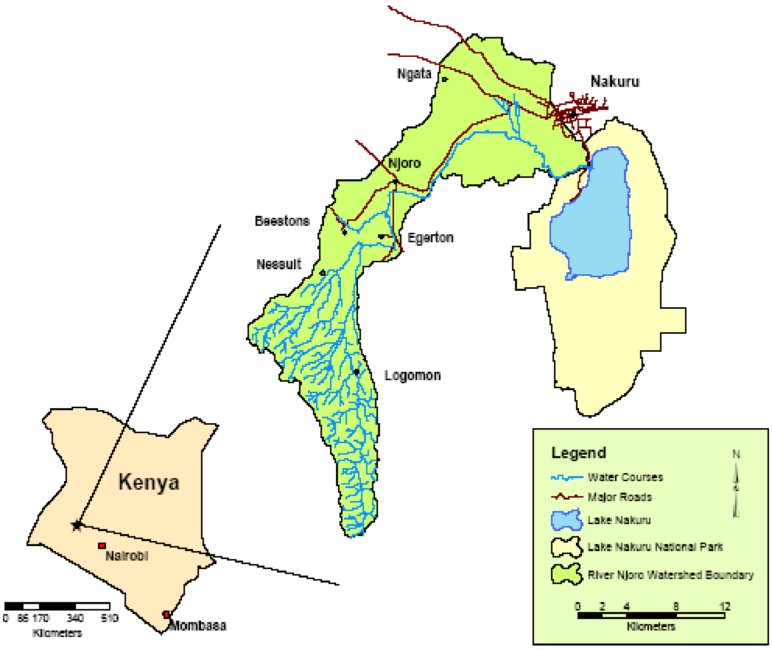

Figure 1: Njoro River Catchment

The water abstraction points (WAPs)

The relative downstream order of the WAPs is shown in Table 1. In the UNRC are Logoman, Segotik and Nussuit. The vicinity of Logoman consisted of grazing land in open areas with exotic and natural trees in the forested area. At Segotik, a narrow riparian strip was evident along the stream but the nearby area was used for grazing and farming. On the Little Shuru is Nessuit, the main WAP for Nessuit Village a pastoral and farming community with approximately 2000 inhabitants. Treetop, Turkana Flats, Njoro Bridge and Kenyatta are at the middle reaches. Treetop is near the supplementary drinking water intake of Egerton University, 1 km downstream the confluence with Little Shuru. Although the nearby area was under cultivation and grazing, the riparian vegetation was vividly present. In contrast, the vicinity of Turkana Flats was densely settled with much of the riparian vegetation destroyed. Njoro Bridge (4 km downstream of the outfalls of the wastewater treatment facilities at Egerton University and Njoro Canning Factory) was the main WAP for Njoro Town with about 50000 inhabitants. At Kenyatta (2 km downstream of Njoro Town), the riparian vegetation was very scanty with farming and grazing in the surrounding.

Table 1. The WAPs along the Njoro River in sequence downstream

Parameters	Logoman	Segotik	Nessuit [1]	Treetop	Turkana Flats	Njoro Bridge	Kenyatta
Longitude [East]	35º54´09.13″	35º54´46.59″	35º53´53.29″	35º55´37.92″	35º56´31.27″	35º56´37.09″	35º58´07.85″
Latitude [South]	0º29´12.09´	0º24´11.12″	0º23´47.13″	0º22´30.49″	0º22´22.71″	0º20´16.19″	0º20´18.05″
Elevation [m]	2676	2412	2425	2271	2214	2160	2130
Distance [km] [2]	45.1	33.5	45.5	31.5	28.5	23.7	20.7

[1] Nessuit was on the main tributary, Little Shuru; [2] River kilometres from the mouth of the stream at Lake Nakuru.

Data acquisition

Water quality data was acquired at monthly intervals from September 2005 through October 2006. Water samples were collected from the upstream segments of WAPs between 8 a.m. and 2 p.m. Sterile polyethylene containers (500 ml) were used for microbial parameters with appropriate dilutions drained through sterile membrane filters (0.45 µm; 47 mm). Filters for *E. coli* (EC) and Total Coliforms (TC) were placed on Chromocult Coliform Agar (ISO 6222, OXOID) and incubated at 37ºC for 24 hrs. The medium mEnterococcus Agar (ISO 6222, OXOID) was used for intestinal enterococci (IE) with incubation at 37ºC for 48 hrs. Filters for Heterotrophic Plate Count bacteria (HPC) were incubation on solidified Yeast Extract Agar (ISO 6222, OXOID) at 37ºC for 48 hrs. Countable colonies were reported in colony forming units (cfu) per 100 ml for EC, IE and TC and cfu per 1ml for HPC. Standard analytical procedures were followed for BOD_5, NH4-N, total nitrogen (TN), PO4-P, total phosphorus (TP) and total suspended solids (TSS) and direct spectrophotometer determination at UV_{437} was made for turbidity (APHA, 1995). Direct *in-situ* determinations were made of Conductivity, Temperature, pH and Dissolved Oxygen with the aid of WTW multi-meter probes. Estimates were made of daily water abstraction and visitation of people and livestock at each WAP.

Health risk analysis

U.S. EPA (1994) offered a regression model to quantify the potential health risk (PHR) of illness attributable to full-body submersion during swimming in recreational waters. Gastrointestinal (GI) illness could increase if water with E. coli (EC) >1000 cfu/100 ml is utilized based on the following linear relationship.

$$y = -150.5 + 423.5(\log x) \qquad \text{.......1}$$

where, (y) is PHR per 100000 bathers given that log x ≥ 3, (x) is the number of EC (cfu) per 100 ml (Steyn et al., 2004).

The U.S. EPA model (U.S. EPA, 1994) was compared to the Cabelli model (Cabelli, 1983), which is a similar procedure developed earlier from the relationship between intestinal enterococci (IE) density in recreational waters and the associated rates of illness with highly credible gastroenteritis (HCGI).

$$y = 0.20 + 12.17(\log x) \qquad \text{.......2}$$

where, (y) is the rate of illness per 1000 bathers and (x) is the mean IE (cfu) density per 100 ml of recreational water (Salas, 1986).

GI symptoms include diarrhoea, vomiting, nausea, or stomachache, plus fever for HCGI (Turbow *et al*., 2003). The PHR of infection with these illnesses was calculated at single exposure to the geometric mean as well as the upper 95th percentile EC and IE densities from the following expression.

$$95\,percentile = anti\log(\mu + 1.65\sigma) \qquad \text{.......3}$$

where, (μ) and (σ) are the arithmetic mean and the standard deviation, respectively, of the log10 values (Chawla *et al*., 2005).

Acceptable health risk (AHR) levels were derived from the U.S. EPA freshwater bathing guidelines, i.e. 126 cfu/100 ml for EC and 33 cfu/100 ml for IE (U.S. EPA, 1986). The probable illness rate in excess of AHR denotes the unacceptable health risk (UHR). Discrete dry and wet weather odds ratios (OR) at the WAPs were derived from the expression, [UHR/AHR], on the assumption that infection is unlikely at the AHR level. The natural log of OR was taken to represent the relative risk of illness, which was correlated with each water quality parameter to determine the predictive capacity of the later. Dose-response models for recreational water are based on the assumed unintentional ingestion of 100 ml of contaminated water during full-body submersion (Steyn *et al*., 2004). This is described as the infective dose, (λ) (Benke and Hamilton, 2007). Conventionally, it is the product of the bacteria density per unit volume (mi), and the volume of contaminated water ingested (V).

$\lambda_i = m_i V$ 4

Based on linear interpolations of ambient EC/IE densities, specific dose-response relative risk levels were derived for intentionally drinking (250 ml) untreated stream water using 0.1% (WHO, 2001) as the referential AHR value – a reasonable level based on protozoan pathogens causing GI symptoms in drinking water (WHO, 2001).

The limitations and uncertainties of the OAEL approach are discussed afterwards.

Results

Visits by people and livestock

Visits made by people and livestock at the WAPs during dry weather (January–April) in 2006 are summarized in Table 2. Njoro Bridge was by far the most frequently visited WAP with the average human visits exceeding 1000 per day. Next in order of decreasing importance were Turkana Flats, Nessuit and Treetop, which jointly, accounted for barely 25% of the average dry weather human visits at

Njoro Bridge. Logoman was the least visited WAP with < 10 people per day and no visits on some days even during dry weather when the stream was frequently visited. People rarely visited the WAPs during wet weather (May–September) with the wet weather estimates for human visits ranging from 0–10% of the dry weather estimates. All WAPs were important watering points for resident and/or migrating livestock, which were mainly cattle, sheep, goats and donkeys. The lower limit of livestock visits per day in Table 2 indicates the visits made by resident livestock in the neighbourhood of each WAP. Njoro Bridge had six times more resident livestock visits per day compared to Kenyatta, Turkana Flats or Nessuit, each with five times more visits than Treetop or Segotik. There were no resident livestock visits at Logoman since the nearest resident livestock were > 5 km away but the surrounding area was frequently visited by itinerant livestock. The highest head count of itinerant livestock that passed through Segotik, Nessuit, Njoro Bridge and Kenyatta during dry weather in 2006 is shown by the upper limit of visiting livestock at these WAPs in Table 2. Visits made by livestock during wet weather were mostly residential herds in the neighbourhood.

Table 2. Range of daily visits by people and livestock plus water abstracted in dry weather (Jan.–Apr.) 2006

Parameters	Logoman	Segotik	Nessuit[1]	Treetop	Turkana Flats	Njoro Bridge	Kenyatta
Visit [people/day]	0 – 10	10 – 50	25 – 100	25 – 100	100 – 200	600 – 1500	10 – 50
Visit [livestock/day]	0 – 50	10 – 557	50 – 557	10 – 20	50 – 200	300 – 557	50 – 557
Abstraction [m^3/day]	0 – 0.5	0.5 – 2	1 – 5	1 – 5	10 – 25	50 – 100	0.5 – 10
Inhabitants nearby [2]	0	< 1000	> 2000	> 3000	> 20000	> 50000	> 5000

[1] Nessuit was on the main tributary, Little Shuru; [2] < 1 km from the respective water abstraction point

Ambient water quality

Ambient EC and IE densities at the WAPs were generally high with geometric mean densities within 2.0–3.5 log cfu/100 ml (Table 3). Both were in excess of the drinking water guideline (zero EC/IE cfu/100 ml) as well as the referential freshwater bathing water quality guidelines (126 EC and 33 IE cfu/100 ml; U.S. EPA, 1986 and 100 EC/IE cfu/100 ml; Anon, 1976). The most serious breaches occurred at Turkana Flats, Kenyatta and Nessuit. Wet weather was characterized by extremely variable and relatively high bacteria densities especially after rainfall when ambient densities exceeded 4 log units. Dry weather geometric mean EC and IE densities were 2–3 log units higher at

Kenyatta and Turkana Flats compared to Segotik or Logoman, where the lowest EC (190cfu/100 ml) and IE (110cfu/100 ml) mean densities occurred. But densities at Logoman increased significantly ($p < 0.05$) during wet weather. Dry weather mean TC and HPC densities ranged from 9–91x10^3 cfu/100 ml and 15–248x10^3 cfu/ml, respectively, being relatively high at Kenyatta, Turkana Flats, Nessuit and Treetop compared to Logoman, Segotik or Njoro Bridge. TC and HPC densities were higher than EC/IE densities and were also extremely variable during wet weather (Table 3).

TSS and Turbidity levels increased 2–3 times during wet weather at Logoman, Segotik, Nessuit and Njoro Bridge and 10 times at Kenyatta. There was no major increase at Treetop and Turkana Flats (Table 4). BOD_5 levels increased downstream from 1.6±0.1 and 2.7±1.7 mg/l at Logoman during dry and wet weather, respectively, to 14.7±4.1 and 15.5±2.6 mg/l at Kenyatta, excepting Njoro Bridge, where the dry and wet weather levels (5.8±2.4 and 3.9±1.6 mg/l, respectively) were compatible to the levels at Segotik and half the levels at Turkana Flats even though the two WAPs were located 10 and 5 km upstream, respectively. Dry weather TN levels were generally > 0.5 mg/l, being higher at Turkana Flats (0.75±0.37 mg/l) and declining to within 0.2–0.4 mg/l as stream flow increased during wet weather. A significant seasonal disparity was unobvious with TP levels but all weather mean TP concentrations increased gradually downstream between Logoman (0.13±0.05 mg/l) and Turkana Flats (0.21±0.03 mg/l) and then abruptly at Njoro Bridge (0.36±0.14 mg/l) but decreased again afterward about 3 km downstream at Kenyatta (0.27±0.03 mg/l). Stream temperature was at all times relatively low (12–16ºC) at Logoman, Segotik and Nessuit in the high altitude UNRC compared to Turkana Flats, Njoro Bridge and Kenyatta (18–20ºC) in the much lower altitudes of the middle reaches. Alternatively, oxygen levels were much higher at the WAPs in the UNRC (> 7 mg/l) compared to those in the middle reaches (< 5 mg/l) with no discernible seasonal pattern. Conductivity increased downstream with lower levels during wet weather and ranged from 126±5 and 121±1 µS/cm at Logoman to 246±10 and 223±6 µS/cm at Kenyatta during dry and wet weather respectively. Generally, pH levels showed no distinct seasonal or spatial variability, being circum-neutral or slightly alkaline (7.1–7.8) at all times.

Table 3. Geometric mean (95th percentile) densities (x 10^3) of bacteria indicators at the WAPs in 2006 (n = 12).

Indicator bacteria	Logoman	Segotik	Nessuit	Treetop	Turkana Flats	Njoro Bridge	Kenyatta
Dry weather flow (January – April 2006)							
EC [cfu/100ml]	0.2 (0.9)	0.7 (4.8)	1.6 (5.1)	0.8 (1.6)	1.2 (10.0)	0.7 (1.3)	1.2 (3.6)
IE [cfu/100ml]	0.1 (0.2)	0.7 (4.5)	1.5 (10.2)	1.9 (5.8)	1.7 (17.5)	0.9 (2.6)	2.5 (9.6)
TC [cfu/100ml]	9 (53)	15 (37)	15 (44)	52 (144)	91 (809)	27 (88)	37 (98)
HPC [cfu/ml]	15 (17)	28 (250)	80 (345)	248 (457)	64 (302)	78 (394)	132 (1521)
Wet weather flow (May – September 2006)							
EC [cfu/100ml]	1.7 (50.6)	0.5 (6.8)	1.9 (7.1)	1.3 (3.5)	2.9 (4.9)	1.0 (5.3)	2.2 (26.8)
IE [cfu/100ml]	0.5 (12.8)	0.7 (13.8)	2.5 (42.1)	2.1 (3.2)	8.4 (48.4)	1.8 (30.4)	3.9 (112.3)
TC [cfu/100ml]	22 (35)	20 (151)	21(42)	75 (67)	162 (1079)	32 (137)	116 (656)
HPC [cfu/ml]	86 (5977)	84 (1148)	135 (440)	265 (687)	84 (294)	127 (292)	477 (3274)

EC: *Escherichia coli*; IE: Intestinal enterococci ; TC: total coliforms: HPC: heterotrophic plate count

Table 4. Mean levels ± standard deviation of the physical & chemical characteristics at the WAPs in 2006 (n=12)

Parameters	Logoman	Segotik	Nessuit[1]	Treetop	Turkana Flats	Njoro Bridge	Kenyatta
Dry weather flow (Jan. – April, 2006)							
Flow [litres/sec]	6.0 ± 2.8	16.4 ± 9.1	6.2 ± 2.8	21.4 ± 12.0	20.6 ± 12.9	16.0 ± 9.4	10.8 ± 6.7
BOD_5 [mg/l]	1.6 ± 0.1	4.4 ± 1.8	4.5 ± 1.8	7.4 ± 2.3	9.3 ± 1.9	5.8 ± 2.4	14.7 ± 4.1
TSS [mg/l]	11.0 ± 4.2	5.0 ± 1.0	16.6 ± 5.1	12.4 ± 7.7	29.8 ± 21.6	14.4 ± 14.3	10.0 ± 4.0
Turbidity [Abs_{437}/m]	15.3 ± 10.4	10.9 ± 6.3	14.1 ± 4.6	16.0 ± 6.3	20.0 ± 7.6	20.6 ± 14.6	15.0 ± 7.5
NH_4-N [mg/l]	0.02 ± 0.00	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.03	0.11 ± 0.04	0.04 ± 0.03	0.20 ± 0.09
TN [mg/l]	0.49 ± 0.35	0.58 ± 0.25	0.61 ± 0.24	0.54 ± 0.29	0.75 ± 0.37	0.59 ± 0.24	0.63 ± 0.27
TP [mg/l]	0.14 ± 0.07	0.11 ± 0.02	0.17 ± 0.03	0.16 ± 0.03	0.21 ± 0.04	0.30 ± 0.06	0.26 ± 0.03
Wet weather flow (May – September, 2006							
Flow [litres/sec]	14.0 ± 8.5	28.3 ± 12.6	9.3 ± 1.2	36.7 ± 15.3	33.3 ± 11.6	30.0 ± 10.0	21.7 ± 7.6
BOD_5 [mg/l]	2.7 ± 1.7	5.8 ± 1.6	5.1 ± 2.1	6.7 ± 2.5	8.1 ± 0.8	3.9 ± 1.6	15.5 ± 2.6
TSS [mg/l]	39.0 ± 35.5	10.3 ± 8.4	29.0 ± 26.9	12.0 ± 6.9	27.7 ± 11.6	25.3 ± 30.0	94.7 ± 143.2
Turbidity [Abs_{437}/m]	33.2 ± 14.8	22.7 ± 8.7	23.3 ± 9.4	23.4 ± 5.3	29.1 ± 7.0	29.5 ± 13.6	76.4 ± 93.1
NH_4-N [mg/l]	0.03 ± 0.00	0.05 ± 0.00	0.03 ± 0.02	0.05 ± 0.04	0.10 ± 0.05	0.18 ± 0.29	0.23 ± 0.11
TN [mg/l]	0.23 ± 0.01	0.30 ± 0.06	0.33 ± 0.08	0.31 ± 0.07	0.35 ± 0.08	0.35 ± 0.04	0.39 ± 0.03
TP [mg/l]	0.12 ± 0.04	0.12 ± 0.02	0.17 ± 0.03	0.15 ± 0.03	0.19 ± 0.02	0.40 ± 0.20	0.29 ± 0.05

[1] Nessuit was on the main tributary, Little Shuru

Table 5. PHR per 1000 people attributable to bathing on single exposure to the geometric mean (95th percentile)

Model	Illness	Logoman	Segotik	Nessuit	Treetop	Turkana Flats	Njoro Bridge	Kenyatta
Dry weather (January – April 2006)								
U.S. EPA (EC)	GI [1]	8 (11)	11 (14)	12 (14)	11 (12)	11 (15)	11 (12)	12 (14)
Cabelli (IE)	HCGI [2]	25 (27)	35 (45)	39 (49)	40 (46)	39 (52)	36 (42)	42 (49)
Wet weather (May – September 2006)								
U.S. EPA (EC)	GI [1]	12 (18)	10 (15)	12 (15)	12 (13)	13 (14)	11 (14)	13 (17)
Cabelli (IE)	HCGI [2]	33 (50)	35 (51)	42 (56)	41 (43)	48 (57)	40 (55)	44 (62)

[1] GI: gastrointestinal symptoms; [2] HCGI: highly credible gastroenteritis; U.S. EPA acceptable risk for bathing: HCGI = 19, GI = 7 per 1000

Potential health risk

Table 5 displays the PHR attributable to bathing at the WAPs. PHR was 3–4 times higher with the Cabelli (1983) IE model compared to the U.S. EPA model. Risk levels from single exposure to the 95th percentile dry or wet weather bacteria density were at least 30% higher than those derived with the geometric mean densities. Risk levels varied seasonally in concomitance with ambient EC and IE densities. For example, PHR at single exposure to the dry weather 95th percentiles IE densities with the Cabelli model yielded an illness rate of 25 per 1000 people at Logoman compared to 52 at Turkana Flats or 49 at Kenyatta or Nessuit and 46, 45 and 42 at Treetop, Segotik and Njoro Bridge, respectively. On exposure to the wet weather 95th percentile IE densities, PHR exceeded 50 at all WAPs, excepting Treetop, where an illness rate of 43. The increase in the PHR of HCGI illness during wet weather corresponded to an increase in risk by > 80% of the dry weather estimate at Logoman, 10–15% at Segotik, Nessuit and Turkana Flats and > 30% at Njoro Bridge and Kenyatta. But risk levels remained fairly stable at Treetop although a slight decrease occurred with the Cabelli model on exposure to the 95th percentile IE density.

Relative risk

Table 6 displays the relative risks of GI/HCGI illnesses from bathing at single exposure. As expected, the trends were similar to those reported for PHR. The relative risks of GI and HCGI illnesses increased by at least 30 and 70 times, respectively, for drinking untreated stream water (250 ml) at single exposure to the geometric mean dry weather EC/IE densities (results not shown). This risk increased erratically during wet weather especially with the 95th percentile EC/IE densities. The potential of water quality parameters to predict relative risks of GI/HCGI illnesses for bathing are illustrated in Table 7. The results confirmed strong associations between EC/IE densities and illness risks with both bacteria indicators demonstrating significant ($p < 0.05$) efficacy to predict risks. IE was a better predictor of both GI and HCGI illnesses, displaying slightly higher regression coefficients, smaller 95th percentile confidence intervals and lower p-values compared to EC. Among the supplementary water quality parameters, only TC and stream flow demonstrated significant ($p < 0.05$) predictive capacity for indicating illness risks. Both parameters correlated significantly with EC and IE. But HPC, TSS, Turbidity and BOD could not significantly ($p > 0.05$) predict illness risks even though they correlated significantly with EC and IE at some WAPs. TN and TP, as well as the physico-chemical parameters did not correlate significantly ($p > 0.05$) with EC/IE nor were they capable of predicting risk of GI/HCGI illnesses.

Table 6. Relative risk of illness for bathing on single exposure to the geometric mean (95th percentile)

Model	Illness	Logoman	Segotik	Nessuit	Treetop	Turkana Flats	Njoro Bridge	Kenyatta
Dry weather (January – April 2006)								
U.S. EPA (EC)	GI [1]	1.1 (1.6)	1.5 (2.5)	1.9 (2.5)	1.6 (1.9)	1.7 (3.0)	1.5 (1.8)	1.7 (2.3)
Cabelli (IE)	HCGI [2]	1.4 (1.5)	2.4 (4.0)	2.9 (5.1)	3.2 (4.3)	3.0 (4.6)	2.6 (3.4)	3.4 (5.0)
Wet weather (May – September 2006)								
U.S. EPA (EC)	GI [1]	1.9 (4.4)	1.4 (2.7)	2.0 (2.7)	1.8 (2.3)	2.2 (2.5)	1.7 (2.5)	2.0 (3.7)
Cabelli (IE)	HCGI [2]	2.1 (5.2)	2.3 (5.3)	3.3 (7.2)	3.1 (3.5)	4.6 (7.5)	3.0 (6.6)	5.0 (9.4)

1 GI: gastrointestinal symptoms; 2 HCGI: highly credible gastroenteritis

Table 7. Predictive potential of water quality parameters to indicate relative risk of GI/HCGI illnesses

	GI illness					HCGI illness				
Parameter	R^2	IR	95% CI	Slope	p-value	R^2	IR	95% CI	Slope	p-value
EC	0.6	1.3	0.8 – 1.7	5×10^{-4}	0.002*	0.5	1.8	0.6 – 3.0	1×10^{-3}	0.005*
IE	0.6	1.5	1.2 – 1.8	2×10^{-4}	0.002*	0.6	2.4	1.7 – 5.1	5×10^{-4}	0.001*
TC	0.3	1.6	1.2 – 1.9	6×10^{-6}	0.028*	0.5	2.5	1.6 – 3.3	2×10^{-5}	0.007*
HPC	0.1	1.8	1.3 – 2.2	1×10^{-6}	0.374	0.2	2.7	1.7 – 3.8	5×10^{-6}	0.076
Flow	0.2	1.5	0.9 – 2.1	2×10^{-2}	0.108	0.3	2.1	0.6 – 3.6	7×10^{-2}	0.045*
Turbidity	0.2	1.6	1.2 – 2.1	1×10^{-2}	0.171	0.2	2.6	1.2 – 3.9	3×10^{-2}	0.130
TSS	0.1	1.7	1.3 – 2.1	7×10^{-3}	0.228	0.1	2.9	1.8 – 4.0	2×10^{-2}	0.205
BOD_5	0.1	1.6	1.1 – 2.2	4×10^{-2}	0.264	0.3	2.3	0.9 – 3.7	2×10^{-1}	0.068
TN	0.2	2.6	1.7 – 3.4	-1.42	0.102	0.1	4.7	2.3 – 7.1	-2.77	0.243
TP	0.0	1.9	1.1 – 2.7	2×10^{-1}	0.931	0.0	2.8	0.8 – 4.9	32×10^{-1}	0.486

IR: intercept of relative risk; CI: lower – upper 95% confidence interval of IR; * significant $p \leq 0.05$

Discussion

In general, the results showed that the water quality at the WAPs was very poor during the study. An accompanying sanitary survey identified several potential sources of faecal contamination. Prominent among point sources were the outfalls of open sewers and wastewater treatment facilities at the middle reaches in the Egerton University area. Given that a large proportion of the population in the NRC lacks access to basic sanitation, unsanitary disposal of waste is widespread. As a result non-point source contamination is extremely likely. Some residents defecate in the open and human excreta could be found in areas very close to the stream. Besides, NRC is a major destination for migrant herdsmen especially during dry weather when most livestock are relocated in search of pasture and water. Livestock are allowed to graze freely in most places and watering takes place in the stream at watering points that are often littered with feaces. Both human and animal feaces are established sources of EC and IE as well as GI pathogens (Fisher and Endale, 1999). The stream is visited regularly for bathing, washing of clothes and vehicles, abstraction of water and recreation among others (Mathooko, 2001; Yillia *et al.*, 2007a; cf. Chapter 6). Some of these activities have been linked to poor water quality at the middle reaches (Yillia *et al.*, 2007b; cf. Chapter 7). Most visits occur during dry weather because the stream is often turbid in wet weather and residents could access alternative sources of water. Due to their propinquity to densely settled areas, Njoro Bridge, Turkana Flats and Nessuit were the most visited WAPs and all were in serious breach of referential EU and US water quality threshold levels for bathing and drinking. However, although Njoro Bridge was < 5 km downstream of the wastewater outfalls, it recorded relatively low EC/IE densities. It seems EC and IE densities decreased substantially between the outfalls and Njoro Bridge below upstream outfall levels at Turkana Flats. This occurrence could be attributed to die-off, sedimentation and/or attachment within a restricted stretch that is relatively undisturbed. But the relatively low risk levels at Njoro Bridge is perhaps an underestimation given the differential die-off of EC/IE compared to GI causing pathogens in wastewater (Cabelli, 1983). Actually, public health authorities in nearby Njoro Town observed that GI symptoms are among illnesses reported frequently at health care units in the area and outbreaks of cholera and typhoid fever occur recurrently.

Associations among water quality parameters may help characterize the processes that govern bacteria density in aquatic systems. However, bacteria populations depend on a variety of factors that are not wholly explained by simple regression models alone (McCarthy *et al*., 2007). Most associations are often too complex and non-linear making data interpretation a complicated matter. Nevertheless, the elevation of indicator bacteria during wet weather and the corresponding increase in illness risk has been attributed to storm runoff and leaching in a manner that is linked to land use and human activities (Jagals, 1997; Crowther *et al*., 2001; Trevisan *et al*., 2002; Howard *et al*., 2003; Vinten *et al*., 2004; Chawla *et al*., 2005; Godfery *et al*., 2005; Vikaskumar *et al*., 2007). In the present study, strong associations were evident among bacteria densities, stream flow, turbidity, suspended solids and BOD_5. However, most of the associations were inconsistent among WAPs, probably a manifestation of the mixture of the potential sources of contaminants in the NRC, and possibly due to the variability of the natural processes that influence bacteria density. But it seems storm runoff was the overriding factor during wet weather, the impact of which was evident particularly at Logoman, where wet weather bacteria densities increase substantially compared to the dry weather densities. The area was an important destination for livestock even though it was fairly protected, largely forested and mostly uninhabited. EC/IE at Logoman could have originated from nearby grazing fields given that both are always found in the feaces of farm animals (Anderson *et al*., 1997). Risk levels at Logoman could have been overestimated since faecal matter from non-human sources and storm runoff from fairly protected areas may carry much lower risk (Cabelli, 1983; Cinque *et al*., 2004). Alternatively, runoff may be deterred by riparian vegetation (Sukias and Nguyen, 2003). This was partly evident at Treetop where relatively lower risk levels were observed during wet weather. It is noteworthy given that the supplementary drinking water intake for Egerton University is located in the vicinity of Treetop. Runoff and leaching are reported to be negligible during dry weather and bacterial populations may decline upon exposure to UV irradiation as the vegetation cover is reduced (Trevisan *et al*., 2002; Noble *et al*., 2003). In the present study, although bacteria densities in the stream were relatively low during dry weather, they remained high owing to the increase of in-stream activities at this time of the year and the intermittent input from wastewater outfalls.

The OAEL approach has several caveats besides the overt limitations of the common bacteria indicators. The popular one-dimensional linear relationship between bacteria density and illness risk does not directly account for viral or protozoan pathogens even though they are the leading etiological agents for acute GI illnesses (Cabelli, 1983; Wade *et al*., 2006; van Lieverloo *et al*., 2007). Because of this limitation, various pathogen-based dose-response models have been developed for drinking water and selected recreational waters (Haas, 1996; Gale, 2001; Benke and Hamilton, 2007). Yet many sources of uncertainty exist. Besides computational problems such as the averaging procedure for microbial density, dose-response relationships are complicated by many extrinsic factors such as individual susceptibility, medical history or secondary transmissions of GI illness, all of which vary with region, race, age, culture, environment, economic status and diet (Salas, 1986; Haas, 2002; Turbow *et al*., 2003). Consequently, the derivation of the perceived infective dose is often problematic. With bathing water models, full-body submersion is used to characterize dose and an unintentional ingestion of 100 ml is assumed at single exposure (Steyn *et al*., 2004). However, there is no experimental evidence for a minimum infective dose and no reason why a single pathogen should not be able to cause illness (Gale, 2001). Certainly, illness risk would increase with frequency of exposure but the duration and intensity of exposure may vary among exposed individuals who may partake in several activities with unpredictable dose levels (Turbow *et al*., 2003; Wade *et al*., 2003). In the present study, most visitors at the WAPs undertook activities that did not entail full-body submersion e.g. water abstraction and washing of clothes or vehicles.

Activities such as swimming, bathing, playing and baptism, which may involve full-body submersion, occurred infrequently. Moreover, an undisputable threshold risk level for microbial induced illness from water has not been achieved. For example, guidelines for drinking water recommend zero cfu/100 ml of EC/IE but the acceptable threshold risk is imprecise as the obscured zero is not risk free. Nevertheless, WHO sets a threshold at 0.1% of the exposed population based on the presence of infectious protozoan pathogens in drinking water (WHO, 2001). But the concept is misleading because it suggests zero risk of infection at low pathogen dose (Gale, 2001). For recreational waters, a significant attack rate (1.0%) with IE density was detected at 10 cfu/100 ml (Cabelli *et al*., 1982). Later Cabelli (1983) reported an increase in risk at 12 cfu/100 ml (1.3%) while Haile *et al*. (1999) subsequently reported an elevated increase at ≥ 104 cfu/100 ml (2.5%). The latter is currently the U.S. single sample beach closure guideline even though 35 and 33 cfu/100 ml (1.90% and 1.87%) are the stipulated IE thresholds for US marine and freshwater recreation, respectively (Turbow *et al*., 2003; Wade *et al*., 2003). A critical scrutiny by Fleisher (1991) of the supporting data suggested a possible underestimation of the true HCGI risk level (Turbow *et al*., 2003). However, more recent studies uphold current U.S. EPA threshold levels even if uncertainty remains over acceptability.

As a result of these limitations and given that the present study did not measure the actual illness response after exposure, the reported risk levels ought to be interpreted cautiously. Potential risk does not essentially translate into actual incidence of pollution-related gastrointestinal illness (Steyn *et al*., 2004). Nevertheless, the overall data depicts an unsanitary situation in the NRC and brings to light an urgent need for pollution control and health risk management. Both would require comprehensive catchment management measures, as well as site specific protective actions. Measures are needed to limit the movement of faecal matter from residential areas, farmlands and grazing fields. Thus, improving sanitation facilities could be important in addition to controlling point sources such as wastewater outfalls. Diffuse sources could be minimized considerably through appropriate land use planning and application of best management practices (BMPs). For example, maintaining an undisturbed riparian vegetation corridor along the stream may be significant in reducing surface runoff from residential areas or farmlands. Similarly, restricting public access and the movement of livestock in certain stream reaches is demonstrably a good management practice that appears to be working in certain reaches e.g., some sections in the fairly protected UNRC, a large portion of the stretch between Turkana Flats and Njoro Bridge and the stretch of the stream within the Lake Nakuru National Park. However, restriction may deprive public use, which is contrary to the overall goal of the Kenya Water Policy. It might also have unhelpful ramifications in an already volatile region that has recurrently experienced inter-communal conflicts over natural resources mainly land and water. As a means of dissuading visitors, signposts have been strategically installed to caution visitors on the poor water quality situation of the stream. But such warnings are mostly unheeded given that many residents depend entirely on the stream for their daily water needs (Mathooko, 2001; Yillia *et al*., 2007a; cf. Chapter 6). Pipe-borne water supply is unreliable and groundwater sources contain high levels of fluoride (Moturi, 2004). Current data suggests that abstracting water from the stream for domestic use would require specialized treatment to achieve acceptable threshold levels. At least 2–4 log reductions of IE and EC densities may be needed for bathing with additional reductions for drinking to reduce current risk levels at the WAPs. Meanwhile, current water use could be limited to low health risk functions such as construction work or irrigation of low-risk crops while enlightening residents on the benefits of environmental sanitation.

Conclusion

Evaluation of the microbial health risk associated with using polluted stream water from various water abstraction points along the Njoro River revealed that the potential health risk of contracting GI/HCGI illness seriously exceeded acceptable threshold levels for bathing and drinking. Health risk varied seasonally among WAPs in association with the ambient EC/IE densities, which were extremely variable and relatively high during wet weather. The unsanitary situation in the NRC and the potential health risk necessitate public health surveillance and comprehensive measures to abate pollution in order to reduce current risk levels. But further research is needed in the following areas: (i) A complete epidemiological study; (ii) Source tracking experiments to distinguish faecal sources; (iii) Field experiments on the adaptability and efficacy of BMPs in the NRC.

Acknowledgements

The authors acknowledge the support of the Austrian Development Co-operation (OAD) and the Institute for Water Quality Resources and Waste Management at Vienna University of Technology, Austria. Ken Kosimbei and Geoferry Ogo'ndo of the Department of Biological Sciences at Egerton University in Kenya provided technical assistance.

References

Anderson, K. L., Whitlock, J. E., Harwood, V. J., 2005. Persistence and differential survival of faecal indicator bacteria in subtropical waters and sediments. *Appl. Environ. Microbiol.* 71 (6), 3041–3048.

Anderson, S. A., Turner, S. J., Lewis, G. D., 1997. Enterococci in the new Zealand environment: implications for water quality monitoring. *Wat. Sci. Tech.* 35 (11–12), 325–331.

Anon, 1976. Council Directive 76/160/EEC concerning the quality of bathing waters. *Official Journal of the European Communities*. L31, 1–7.

APHA, 1995. Standard methods for the examination of water and wastewater, 19th ed. American Public Health Association, Washington, D.C.

Barrell, R. A. E., Hunter, P. R., Nicholas, G., 2000. Microbiological standards for water and their relationship to health risk. *Communicable Diseases and Pubic Health* 3 (1), 8–13.

Benke, K. K., Hamilton, A. J., 2007. Quantitative microbial risk assessment: uncertainty and measures of central tendency for skewed distribution. *Stoch. Environ. Res. Risk Assess.* DOI 10.1007/s00477-007-0171-9, 1–7.

Byappanahalli, M. N., Fujioka, R. S., 1998. Evidence that tropical soil environment can support the growth of *Escherichia coli*. *Wat. Sci. Tech.* 38 (12), 171–174.

Cabelli, V., 1983. Health effects criteria for marine recreational waters. *U.S. EPA Report EPA-600/1-80-031*. Cincinnati, OH: U.S. Environmental Protection Agency. 1–98.

Cabelli, V. J., 1989. Swimming associated illness and recreational water quality criteria. *Wat. Sci. Tech.* 21 (2), 13–21.

Cabelli, V., Dufour, A. P., McCabe, L. J., Levin, M. A., 1982. Swimming-associated gastroenteritis and water quality. *American Journal of Epidemiology* 115, 606–616.

Chawla, R., Real, K., Masterson, B., 2005. An assessment of the impact of the proposed EU bathing water directive on Irish coastal bathing area compliance. *Wat. Sci. Tech.* 51 (3-4), 225–230.

Cinque, K., Stevens, M. A., Roser, D. J., Ashbolt, N. J., Leeming, R., 2004. Assessing the health implications of turbidity and suspended particles in protected catchments. *Wat. Sci. Tech.* 50 (1), 205–210.

Crowther, J., Kay, D., Wyer, M. D., 2001. Relationship between microbial water quality and environmental conditions in coastal recreational waters: The Fylde Coast, UK. *Water Res.* 35 (17), 4029–4038.

Donaldson, K. A., Griffin, D. W., Paul, J. H., 2002. Detection, quantification and identification of enteroviruses from surface waters and sponge tissue from the Florida Keys using real-time RT-PCR. *Water Res*. 36, 2505–2514.

Dufour, A. P., 1984. Health effects criteria for freshwater recreational waters. *EPA-600/1-84-004*. 1–33.

Dwight, R. H., Baker, D. B., Semenza, J. C., Olson, B. H., 2004. Health effects associated with recreational coastal water use: urban versus rural California. *Am. J. Public Health* 94 (4), 565–567.

Fattal, B., Peleg-Olevsky, E., Yoshpe-Purer, Y., Shuval, H. I., 1986. The association between morbidity among bathers and microbial quality of seawater. *Wat. Sci. Tech.* 18 (11), 59–69.

Fleisher, J. M., 1991. A reanalysis of data supporting US federal bacteriological water quality criteria governing marine recreational waters. *Res. J. Water Pollut. Control Fed. 6*3 (3), 259–265.

Fisher, D. S., Endale, D. M., 1999. Total coliform, E. coli, and enterococci bacteria in grazing and wooded watersheds of the southern Piedmont. *Proceedings of the Georgia Water Resources Coference*. 30th–31st March 1999, Athens, Goergia.

Gale, P., 2001. A review: developments in microbiological risk assessment for drinking water. *Journal of Applied Microbiology* 91, 191–205.

Gauthier, F., Archibald, F., 2001. The ecology of "fecal indicator" bacteria commonly found in pulp and paper mill water systems. *Water Res*. 35 (9), 2207–2218.

Godfery, S., Timo, F., Smith, M., 2005. Relationship between rainfall and microbiological contamination of shallow groundwater in northern Mozambique. *Water South Africa* 31 (4), 609–614.

Haas, C. N., 1996. How to average microbial densities to characterize risk. W*ater Res.* 30 (4), 1036 – 1038.

Haas, C. N., 2002. Progress and data gaps in quantitative microbial risk assessment. W*at. Sci. Tech. 46* (11-12), 277–284.

Haile, R., Witte, J., Gold, M., Cressey, R., McGee, C., Millikan, R., Glasser, A., Harawa, N, Ervin, C., Harmon, P, et *al.*, 1999. The health effects of swimming in ocean water contaminated by storm drain runoff. *Epidimiology* 10 (4), 355–363.

Howard, G., Pedley, S., Barrett, M., Nalubega, M., Johal, K., 2003. Risk factors contributing to microbial contamination of shallow groundwater in Kampala, Uganda. W*ater Res*. 37, 3421–3429.

Jagals, P., 1997. Storm water runoff from typical developed and developing South African urban developments: definitely not for swimming. *Wat. Sci. Tech.* 35 (11–12), 133–140.

Kong, R. Y. C., Lee, S. K. Y., Law, T. W. F., Law, S. H. W., Wu, R. S. S., 2002. Rapid detection of six types of bacterial pathogens in marine waters by multiplex PCR. *Water Res*. 36, 2802–2812.

McCarthy, D. T., Mitchell, V. G., Deletic, A., Diaper, C., 2007. *Escherichia coli* in urban stormwater: explaining their variability. *Wat. Sci. Tech.* 56 (11), 27–34.

Medema, G. J., van Asperen, I. A., Havelaar, A. H., 1997. Assessment of the exposure of swimmers to microbiological contaminants in freshwater. *Wat. Sci. Tech.* 35 (11–12), 157–163.

Mathooko, J. M., 2001. Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* 458, 131–139.

Moturi, W., 2004. Household water sources and their contribution towards fluoride consumption in Njoro Division, Nakuru, Kenya. *African Journal of Aquatic Sciences* 29 (2), 275–277.

Noble, R. T., Moore, D. F., Leecaster, M. K., McGee, C. D., Weisberg, S. B., 2003. Comparison of total coliform, faecal coliform, and enterococcus bacterial indicator response for ocean recreational water quality testing. W*ater Res*. 37, 1637–1643.

Rajala, R. L., Heinonen-Tanski, H., 1998. Survival and transfer of faecal indicator organisms of wastewater effluents in receiving lake waters. *Wat. Sci. Tech.* 38 (12), 191–194.

Rose, J. B., Gerba, C. P., 1991. Use of risk assessment for development of microbial standards. *Wat. Sci. Tech.* 24 (2), 29–34.

Salas, H. J., 1986. History and application of microbiological water quality standards in the marine environment. *Wat. Sci. Tech.* 18 (11), 47–57.

Shivoga, W. A., 2001. The influence of hydrology on the structure of invertebrate communities in two streams flowing into Lake Nakuru, Kenya. *Hydrobiolgia* 458, 121–130.

Signoretto, C., Burlacchini, G., Pruzzo, C., Canepari, P., 2005. Persistence of *Entrococcus faecalis* in aquatic environments via surface interactions with copepods. *Applied Environmental Microbiology* 71 (5), 2756–2761.

Skraber, S., Gantzer, C., Maul, A., Schwartzbrod, L., 2002. Fates of bacteriophages and bacterial indicators in the Moselle River (France). *Water Res.* 36, 2629–2637.

Steyn, M., Jagals, P., Genthe, B., 2004. Assessment of microbial infection risks posed by ingestion of water during domestic water use and full-contact recreation in a mid-southern African region. *Wat. Sci. Tech.* 50 (1), 301–308.

Sukias, J. P. S., Nguyen, M. L., 2003. Inactivation of *E. coli* in the riparian and non-riparian soils. *Proceedings: Diffuse Pollution Conference*, 2003, Dublin, 3D: Agriculture, 3-82–3-87.

Trevisan, D., Vansteelant, J. Y., Dorioz, J. M., 2002. Survival and leaching of fecal bacteria after slurry spreading on mountain hay meadows: consequences for the management of water contamination risk. W*ater Res*. 36, 275–283.

Turbow, D. J., Osgood, N. D., Jiang, S. C., 2003. Evaluation of recreational health risk in coastal waters based on enterococcus densities and bathing patterns. *Environmental Health Perspectives* 111 (4), 598–603.

U.S. EPA, 1986. Ambient water quality criteria for bacteria – 1986. Office of the Regulations and Standards Criteria and Standards Division, Washington, DC 20469. EPA440/5-84-002, 1–18.

U.S. EPA, 1994. National primary drinking water regulation: enhanced surface water treatment requirements; proposed rule. *Fed. Reg.*, 59, 38,832–38,858.

van Lieverloo, J. H. M., Mesman, G. A. M., Bakker, G. L., Baggelaar, P. K., Hamed, A., Madema, G., 2007. Probability of detecting and quantifying faecal contaminations of drinking water by periodically sampling for *E. coli*: a simulation model study. W*ater Res*. 41, 4299–4308.

Vikaskumar, G. H., Dunstan, R. H., Geary, P. M., Coombes, P., Roberts, T. K., Rothkirch, T., 2007. Comparison of water quality parameters from diverse catchments during dry periods and following rain events. *Water Res*. 41, 3655–3666.

Vinten, A. J. A., Lewis, D. R., McGechan, Duncan, A., Aitken, M., Hill, C., Crawford, C., 2004. Predicting the effect of livestock inputs of *E. coli* on microbiological compliance of bathing waters. *Water Res*. 38, 3215–3224.

Wade, T. J., Pai, N., Eisenberg, J. N. S., Colford, Jr., 2003. Do U.S. environmental protection agency water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic review and meta-analysis. *Environmental Health Perspectives* 111 (8), 1102–1109.

Wade, T. J., Calderon, R. L., Sam, E., Beach, M., Brenner, K. P., Williams, A. H., Dufour, A. P., 2006. Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. *Environmental Health Perspectives* 114 (1), 24–28.

Westrell, T. Schönning, C., Stenström, T. A., Ashbolt, N. J., 2004. QMRA (quantitative microbial risk assessment) and HACCP (hazard analysis and critical control points) for management of pathogens in wastewater and sewage sludge treatment and reuse. *Wat. Sci. Tech*. 50 (2), 23–30.

WHO, 2001. Water Quality: Guidelines, Standards and Health (ed.) Fewtrell, L. Bartram, J. *WHO Water Series*: *IWA Publishing*, London, UK. 1–422.

WHO, 2003. Guidelines for safe recreational waters. Vol. 1, Coastal and fresh waters. *WHO Library cataloguing-in-publication Data*, Geneva, Switzerland. 1–32.

Wong, T. W., 1994. Swimming-related illnesses in Hong Kong beaches: an epidemiological perspective. *J. Hong Kong Med. Assoc*. 46 , 27–30.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007a. Nature of in-stream activities during dry weather flow at the middle reaches of a rural stream in Kenya. *Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium*. Lusaka, Zambia.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M., 2007b. In-stream activities influence microbial water quality of a shallow mountain stream in rural Kenya. *Proceedings of the 8th WaterNet/WARFSA/GWP-SA IWRM Symposium*. Lusaka, Zambia.

Chapter 9

Conclusions

Recapitulation

Streams are important for socioeconomic advancement and environmental sustainability. As a result, many people in sub-Saharan Africa depend directly on surface water systems and live close to them as a matter of necessity. But many aquatic systems in the sub-region are under increasing threat of pollution from various human interventions (Venter *et al*., 1997; Nevondo and Cloete, 1999; Fatoki *et al*., 2001; Jonnalagadda and Mhere, 2001; Byamukama *et al*., 2005; Mbuligwe and Kaseva 2005).

Several research efforts in sub-Saharan Africa have succeeded in drawing attention to the deteriorating state of streams and rivers in the sub-region. However, most of the investigations were undertaken on urban and peri-urban systems. This is largely because these systems attract more media publicity and research funding. Little attention is given to streams draining rural areas even though knowledge of their pollution status is relevant for pollution management.

Njoro River Catchment (NRC), a predominantly rural catchment in southwestern Kenya was systematically studied for three years. The stream is important for Lake Nakuru, a wetland site of international importance and a major tourist destination for wildlife (Lelo *et al*., 2005). The stream is also important to the riparian inhabitants and some itinerant herdsmen. But there has been considerable population growth in the catchment, mainly as a result of the resettlement of farmers and pastoralists whose activities have resulted in rapid land use change during the last three decades (Kundu *et al*., 2004; Lelo *et al*., 2005).

Therefore, it was absolutely necessary to provide information on the linkages between land use in the catchment and the status of pollution in the stream for management purposes.

Consequently this study tried to:

i. link land use and various human activities in the catchment to pollution in the stream;
ii. describe loading, transportation and transformations of pollutants in the stream and;
iii. suggest management measures for pollution control in the catchment.

Several specific objectives were derived from these and developed into research themes. Investigations were designed accordingly and a range of pollutants in the stream were evaluated. The choice of pollutants examined was limited to organic matter, suspended solids, micronutrients and faecal contaminants given that farming and livestock rearing dominate other human activities in the catchment. This was achieved through standard analytic procedures for a suite of water quality indicators at several points along the stream from its source in the Mau Hills to its mouth at Lake Nakuru.

PhD Research – Main findings

1) The systematic review of research reports on the NRC showed that knowledge on a sustained long-term basis in almost all disciplines is needed. However, this constraint need not hinder management effort given that the knowledge gaps do not amount to the general paucity of information that is most often blamed for management ineptitude in the catchment.
2) The stream is seriously polluted, especially at the middle and lower reaches, which are characterized mainly by settlements, farmland and grazing fields. Pollution levels increased significantly from relatively low levels at the forested upper reaches to high levels at the middle and lower reaches.
3) The spatial variability was clear during dry weather and less evident during increased stream flow in short wet weather. Analysis of the temporal data specifically for each stream site revealed loading, as well as dilution during wet weather with significant associations among water quality indicators and the stream sites, as well. This provided an objective basis for dividing the catchment into six sub-catchments.
4) Estimates of emissions and riverine loads of pollutants for five of the six sub-catchments revealed that the predominantly forested Upper Njoro River Catchment was the least vulnerable, whereas the most vulnerable sub-catchments were the densely settled and heavily farmed areas around Egerton University and Njoro Township in addition to the Lower Njoro River Catchment, where there is no stream flow for most of the year.

5) The self-purification capacity of the stream via reduction and retention processes was remarkable, in particular within a restricted stream stretch between Egerton University and Njoro Township during dry weather. Dilution was important during increased stream flow in wet weather but the concomitant loads of pollutants transported by the stream increased substantially.
6) Two contrasting transient pollution events were recognized at the middle polluted reaches – transients generated by rainstorms in wet weather and the relatively short-lived episodes provoked by the in-stream activities of people and livestock. Both transients were symptomatic of within-channel processes but storm-induced transients were far more important for catchment mobilization of pollutants.
7) In-stream activities occurred at several water abstraction points (WAPs) along the stream. They contributed to livelihoods of the riparian inhabitants but the haphazard nature of these activities negatively affected stream flow and water quality, as well. Both the chemical and microbial water quality of the stream was affected in rhythm with the seasonal and diurnal periodicity of in-stream activities.
8) Evaluation of the microbial health risk at several WAPs showed that the densities of faecal indicator bacteria were high. Correspondingly, the potential health risk of contracting gastrointestinal illnesses seriously exceeded acceptable threshold levels for bathing and drinking with clear temporal, as well as spatial variations in risk levels among WAPs.
9) The research methods employed provided a scientific framework for the rapid evaluation of vulnerability of the catchment and the stream to prioritize areas for interim pollution remediation. They also provided an objective basis to redesign the sampling framework in order to minimize sampling and processing costs and optimize resource use for subsequent source tracking studies.

Njoro River Catchment (NRC) – Prospects for management

Undoubtedly, the pollution situation in the NRC is critical and constitutes an immense environmental challenge facing natural resources managers in this part of Kenya. Yet there is currently no catchment management authority even though several institutions have vested interests in certain sections of the catchment. For instance, the Kenya Wildlife Service (KWS) protects the Lake Nakuru National Park (LNNP), a certain segment of which is within the Lower Njoro River Catchment and heavily impacted by various human interventions upstream. The Kenya Forest Working Group is more interested in the remnant forest blocks of the upper catchment area. For its part, Egerton University has demonstrated considerable interest in the catchment mainly for research, training and education purposes. In addition, various environmental groups mostly NGOs and CBO's have expressed interest through educational programmes and advocacy. Therefore, the prospects for pollution control in the catchment are high. This is underscored by the fact that the catchment is constantly under critical media attention due to its significance for tourism, livelihoods and environmental sustainability. The task lies in organizing the interest groups and the catchment inhabitants to constitute a workable catchment management entity. Experience in the sub-regional has shown that catchment-based management is indispensable for any local effort because there are many different management priorities that need attention at the national level.

Njoro River Catchment (NRC) – Possible management measures

Certainly, some of the problems, such as, land ownership conflicts in the upper catchment are very complex and require long-term management (Yillia and Kreuzinger, 2008). But others are less intricate and could be tackled in the interim. Possible management measures could include:

a) Addressing point sources by improving wastewater treatment efficiency and adhering to effluent regulations at the middle polluted reaches
b) Regulating in-stream activities and restricting the movement of livestock in the catchment.

c) Restraining the use of fertilizers and pesticides on agricultural fields in the catchment.

d) Maintain a riparian buffer strip along the stream.

e) Site specific measures to interrupt the slope on farms and grazing fields and increase the infiltration capacity of rain water.

f) Additional effort to protect and preserve the remnant forests in the upper catchment area.

However, even the best management measures are likely to fail without the co-operation of important stakeholders. This highlights the significance of constituting a catchment management authority with the involvement of key interest groups and soliciting the support of authorities at the local, regional and national level. This should be possible at the administrative level given that the current Water Act makes provisions for catchment-based management.

Conclusion

The main findings of this PhD thesis indicate that the water quality and hydrology of the Njoro River in Kenya is critically affected by various human interventions within the catchment. The response of the stream to the interventions is governed principally by the existing land use/cover, the seasonal and diurnal periodicity of human activities and the seasonality of the hydrological regime. This knowledge could be useful for pollution management in the catchment. But the main task lies in constituting a unified catchment management entity of stakeholders.

References

Byamukama, D., Mach, R. L., Kansiime, F., Manafa, M., Farnleitner, A. H., 2005. Discrimination efficacy of faecal pollution detection in different aquatic habitats of a high-altitude tropical country, using presumptive coliforms, Escherichia coli, and Clostridium perfringens spores. *Applied Environmental Microbiology* 71 (1), 65 – 71.

Fatoki, O. S., Muyima, N. Y. O., Lujiza, N., 2001. Situation analysis of water quality in the Umtata River catchment. *Water South Africa* 27 (4), 467 – 474.

Jonnalagadda, S. B., Mhere, G., 2001. Water Quality of the Odzi River in the Eastern Highlands of Zimbabwe. *Wat. Res.* 35 (10), 2371 – 2376.

Kundu, P. M., China, S. S., Chemelil, M. C., Onyando, J. O., 2004. Detecting and quantifying land cover and land use change in Eastern Mau by Remote Sensing. Proceedings - XXth ISPRS Congress. Istanbul, Turkey, 405 – 409.

Lelo F.K., Wanjiku, C., Jenkins, M. W., 2005. Managing Riparian Resources in the River Njoro Watershed in Kenya: The Challenge of Conflicting Laws, Policies and Community Priorities. Paper Presented: International workshop on "African Water Laws - Plural Legislative Frameworks for Rural Water Management in Africa. Guateng, South Africa.

Mbuligwe, S. E., Kaseva, M. E., 2005. Pollution and self-cleansing of an urban river in a developing country: A case study of Dar es Salaam, Tanzania. *Environmental Management* 36 (2), 328–342.

Nevondo, T. S., Cloete, T. E., 1999. Bacterial and chemical quality of water supply in the Dertig village settlement. *Water South Africa* 25 (2), 215 – 220.

Venter, S. N, Steynberg, M. C., de Wet, C. M. E., Hohls, D., du Plessis, G., Kfir, R., 1997. A situation analysis of the microbial water quality in a peri-urban catchment in South Africa. *Wat. Sci. Tech.* 35 (11-12), 119–124.

Yillia, P. T., Kreuzinger, N., 2008. Net flux of pollutants at a reduced spatial scale - an index of catchment vulnerability. Proceedings of the 11th IWA International Specialized Conference on Watershed and River Basin Management. Budapest, Hungary.

Résumé – Paul T. Yillia

Paul T. Yillia was born on the 16th of May, 1968 in Yengema, Kono District, Sierra Leone. He completed his secondary school education in 1988 at Christ the King College, Bo and worked for two years as Laboratory Technician in the Production Laboratory at Sierra Rutile Limited. In 1990, he was admitted to Fourah Bay College, University of Sierra Leone to study Marine Science. He graduated in 1995 with BSc. (honours) and was awarded the Faculty of Science Prize for Best Dissertation. The dissertation was titled "*A Study of the Ichthyoplankton of the Sierra Leone Continental Shelf*". He was employed by the University of Sierra Leone as Research and Teaching Assistant from 1995 until 2000 when he left for the Netherlands to pursue a Master of Science degree in Environmental Science and Technology with specialty in Limnology and Wetland Ecosystems at the UNESCO-IHE Institute for Water Education in Delft, The Netherlands. The study involved education, training and research in Austria, Czech Republic, The Netherlands and Uganda. His MSc. thesis was titled "*Performance of Cocoyam (Colocasia esculenta) in Polishing Municipal Wastewater*". The study was financed jointly by the Governments of Austria and The Netherlands through the Austrian Development Co-operation and Netherlands Fellowship Programme, respectively. Upon graduation in 2002, he undertook various assignments with UNESCO-IHE, Cap-Net and WA-Net, which involved training materials development, training, research, partnership, as well as networking in capacity building for Integrated Water Resources Management. He returned to Sierra Leone in 2004 as Lecturer and Research Fellow in Aquatic Systems at the University of Sierra Leone, Fourah Bay College and was Head of Office, Water Initiative – Sierra Leone, a national network for capacity building in the water sector. In 2005, he received a three year scholarship award from the Austrian Government through the North-South Dialogue Scholarship Programme of the Austrian Development Co-operation to pursue a PhD research in Austria and Kenya in partnership with the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology, Austria; The Department of Biological Sciences at Egerton University Kenya and; Fourah Bay College, University of Sierra Leone, Freetown, Sierra Leone. The dissertation of the PhD research is titled "*Linking Land Use to Stream Pollution: Pollutant Dynamics and Management Implications*".