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Assessment of Pilot Wetland Buffer Strips for Attenuation of Organic Matter and Nutrient Fluxes from Municipal Wastewater Effluents in Urban Environments of East Africa

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Dedication

This Thesis is dedicated to my beloved family in Uganda

Declaration

I declare that the work presented in this thesis is derived from original research and no material has previously been submitted at the University for Natural Resources and Life Sciences (BOKU) and/or any other University.

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Abstract

Developing countries, including East Africa are still grappling with public health and eutrophication challenges due to persistence of pathogens, organic matter, nutrients and other emerging pollutants in municipal wastewater effluents. The overall objective of this study therefore was to assess and elucidate the performance of horizontal (HF) and vertical (VF) subsurface flow (SSF) constructed wetlands (CWs) as buffer systems for enhancing organic matter (OM) and nutrient removal processes between deficient wastewater treatment plants (WWTPs) and receiving urban environments of East Africa. An initial 5 year baseline performance assessment of a typical centralised WWTP in Masaka Uganda indicated 100% non-compliance to the national effluent discharge standards. However, a high pollution attenuation potential by a natural wetland was demonstrated. In addition, an experimental setting using HF and VF CWs planted with *Cyperus papyrus* and operating under batch hydraulic loading conditions exhibited higher efficiency for remediation of OM, N and P effluent pollution loads, with the highest mean reduction efficiencies observed in planted VF CWs due to optimal oxygen supply. The CO_2 fluxes were highest in planted VF and HF CWs. Moreover these systems demonstrated low CH_4 and N_2O emissions hence suitable technological options for low carbon development targets regarding sanitation and wastewater management in East Africa. It was therefore concluded that SSF CWs could be adopted as technologically less intensive interventions at a local scale, to increase the resilience of receiving environments by buffering intermittent and pulse pollution loads from WWTPs.

Key Words: Municipal Wastewater; Pollution Load; Wetland Buffer; Constructed Wetlands; East Africa

Zusammenfassung

In Entwicklungsländern wie in Ostafrika, stellen die Persistenz von pathogenen Erregern, organische Einträge, Nährstoffe und andere Schadstoffe in kommunalen Abwässern Herausforderungen für die öffentliche Gesundheit und die Reinhaltung der Gewässer dar. Das übergeordnete Ziel dieser Studie war es daher, die Leistung von horizontal (HF) und vertikal (VF) angeordneten Bodenfilter Pflanzenkläranlagen (PKA) hinsichtlich der Reduktionseffizienz von organischen Stoff- und Nährstoffeinträgen in einem Versuchsaufbau zu untersuchen und ihre Eignung als Puffersysteme für inefffizient arbeitendende Abwasserreinigungsanlagen (ARA) und damit das Potential für den Schutz urbaner Ökosystemen in Ostafrika zu prüfen. Am Beginn stand eine Beurteilung der Reinigungsleistung einer typischen zentralen Kläranlage in Masaka, Uganda, auf Basis von Messungen über einen Zeitraum von 5 Jahren. Diese erste Untersuchung ergab eine 100% Nichteinhaltung der nationalen ugandischen Abwassereinleitungsstandards, aber auch das Potential eines natürlichen Feuchtgebietes diese Verschmutzung in flussabwärts gelegenen Abschnitten zu reduzieren. Darauf aufbauend zeigte die Verwendung von HF und VF PKA in einem experimentellen Aufbau teilweise mit *Cyperus papyrus* bepflanzt und diskontinuierlich mit Abwasser beschickt eine höhere Effizienz in der Reduktion von Stoffbelastungen aus ungeklärtem kommunalem Abwasser. Darüber hinaus wurde in diesen Systemen bei hoher Reinigungsleistung gleichzeitig geringe CH_4 und N2O-Emissionen ermittelt. Damit sind diese auch eine geeignete Option um bei geringem CO_2-Ausstoß kosteneffizient eine Verbesserung im Abwassermanagement in Ostafrika zu erreichen. Es kann daher der Schluss gezogen werden, dass HF und VF PKA eine praktikable Lösung auf lokaler Ebene sein können, um den Schutz natürlicher Ökosysteme gegenüber stark schwankenden Abwassereinträgen wechselnder Qualität aus Kläranlagen zu erhöhen.

Schlüsselwörter: Kommunales Abwasser; Schadstoffbelastung; Feuchtgebiete; Pflanzenkläranlagen; Ostafrika

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Abbreviations and Acronyms

APHA	American Public Health Association
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CWs	Constructed Wetlands
DO	Dissolved Oxygen
EU-FP7	European Union Seventh Framework Programme for research
GHGs	Green House Gases
HF	Horizontal Subsurface Flow
MDGs	Millennium Development Goals
NWSC	National Water and Sewerage Corporation
OM	Organic Matter
SDGs	Sustainable Development Goals
SSF	Subsurface Flow
TSS	Total Suspended Solids
UNDP	United Nations Development Programme
UNICEF	United Nations Children's Emergency Fund
VF	Vertical Subsurface Flow
WBS	Wetland Buffer Strip
WDS	Wastewater Discharge Standards
WHO	World Health Organisation
WWTP	Wastewater Treatment Plant

PART I

1.0 Introduction

1.1 Contextual Background

Climate change, population pressure, agriculture, industrialisation and urbanisation are key global drivers influencing variability of water quantity due competing demands for available freshwater resources, and water quality deterioration resulting from increasing pollution (Bates et al., 2008). Specifically, increase in industrial and municipal wastewater generation and disposal from urban areas is a major threat to freshwater ecosystems and public health (Bates et al., 2008; Jacobsen et al., 2012). In sub-Saharan Africa, this problem is expected to be exacerbated by the current and projected climate change impacts and rapid urbanisation coupled with industrialisation, high population growth, lack of robust spatial planning, infrastructure deficits, and inadequate investment in sustainable sanitation and wastewater management systems (Jacobsen et al., 2012). The aforementioned notwithstanding, the region has also lagged behind one of the Millennium Development Goals (MDGs) target, for ensuring that half of the population have sustainable access to safe drinking water and basic sanitation by 2015 (UNICEF and WHO 2015).

Removal of pathogens, organic matter and nutrients from municipal wastewater are essential requirements for sanitation and wastewater treatment systems to safeguard environmental pollution and public health (Langergraber 2013; Metcalf and Eddy 2004). In East Africa, inadequate on-site sanitation and discharge of untreated municipal wastewater into the environment has been linked to transport and dispersion of pathogens through both surface and groundwater pathways in urban areas (Howard et al., 2003; Katukiza et al., 2015; Kulabako et al., 2007; Nsubuga et al., 2004) leading to episodic disease outbreaks (Katukiza et al., 2012; Nsubuga et al., 2004) such as cholera and diarrhoea. Another significant consequence of the prevailing deficiency in wastewater treatment, is increased eutrophication of surface waters (Co´zar et al., 2007; Nyenje et al., 2012) due to high nutrient loads (Rast 1996) as has been observed in Lake Victoria (Co´zar et al., 2007; Kivaisi 2001; Machiwa 2003; Nyenje et al., 2012). These challenges are some of the major focus for building resilience through the post 2015 Sustainable Development Goals (SDGs) to reduce vulnerability and disparity of human wellbeing on a global scale (UNDP 2014).

Although developed countries have made progress in elimination of all pollutants through progressive investment in advanced wastewater treatment systems (Shi 2011), developing countries are still grappling with public health and eutrophication challenges due to persistence of pathogens, organic matter and nutrients in wastewater effluents (Kivaisi 2001; Ujang and Henze 2006; von Sperling and Augusto de Lemos Chernicharo 2002). Over the past years, wastewater treatment in developing countries, including East Africa, has relied on natural systems especially wetlands and stabilisation ponds (Babu 2011; Crites et al., 2006b; Kivaisi 2001; Okia 2000; Ujang and Henze 2006). Unfortunately, the rapid degradation and alteration of urban wetlands (Machiwa 2003; Namaalwa et al., 2013; Odada et al., 2009) has impaired their role as pollutants removal and transformation hotspots (Mitsch and Gosselink 2000; Philippe et al., 2010) hence compromising the water quality regulation ecosystem service. In addition, construction of technical conventional wastewater treatment plants (WWTPs) has not been a popular option due to high investment, operation and maintenance

(O&M) costs (Ujang and Henze 2006). Moreover many existing WWTPs have outlived their original design capacity and treatment efficiency due to high pollution loading rates and aging infrastructure coupled with inadequate O&M (Metcalf and Eddy 2004).

The prevailing trends of surface and ground water pollution resulting from municipal wastewater, in rapidly expanding urban systems of East Africa is a major constraint for achieving the proposed post 2015 sustainable development goals (SDGs) related to environment, water, sanitation and health. Moreover, the uncertainty of risks that may emanate from climate change and climate variability can aggravate the situation with stochastic impacts to the urban population, environment and ultimately the economy. Therefore, planning and investment in sustainable technologies for sanitation and wastewater management to enhance the resilience of the urban water cycle is not only necessary, but paramount regarding socio-economic development of urban ecosystems in the region.

1.2 Constructed wetlands as sustainable wastewater treatment systems

Constructed wetlands (CWs) as natural wastewater treatment technologies and sustainable sanitation systems (Langergraber 2013; Zhang et al., 2014) have gained enormous attention across the globe (de Klein and van der Werf 2014; Kadlec and Wallace 2009; Langergraber and Muellegger 2005; Vymazal 2013; Zhang et al., 2014), including East Africa. However, like other regions of the developing world, the application potential of CWs in East Africa (Kivaisi 2001) has not been translated into reasonable technological uptake and adoption (Zhang et al., 2014; Zurita et al., 2009), compared to the research efforts undertaken. This could be attributed to among other reasons, limited focus on contextualization of research to address specific local pressing needs and challenges regarding wastewater management in the region.

With the increasing need to remediate pollution of surface waters, CWs are critically relevant as municipal wastewater treatment buffer systems, since they are efficient in organic matter and nutrients removal (Fisher and Acreman 2004b; Kadlec and Wallace 2009; Langergraber 2013; Wu et al., 2014; Zurita et al., 2012). Sub-surface flow CWs have particularly demonstrated high efficiency regarding elimination of organic matter, Nitrogen and Phosphorus (Boog et al., 2014; Canga et al., 2011; Langergraber et al., 2011; Vymazal 2013; Wu et al., 2014) from municipal or domestic wastewater. Specifically, the vertical sub-surface flow (VF) system, is more robust regarding nitrogen (N) removal (Canga et al., 2011; Langergraber et al., 2008; Langergraber et al., 2011) compared to the horizontal sub-surface flow (HF) system (Vymazal 2007). However, a combination of the VF and HF into hybrid systems (Ãvila et al., 2013; Vymazal 2007; Wu et al., 2014) has been recommended due to the provision of multiple and coupled biophysical and chemical environments which enhance processes for effective elimination of N and P.

1.3 Scope and structure of the thesis

This thesis focusses on the application of wetland buffer strips (WBSs) using HF and VF CWs to address the technical failure of conventional mechanical WWTPs regarding discharge of effluents with high pollution loads in urban environments of East Africa. The main research objective was to assess and elucidate the performance of WBSs in enhancing organic matter and nutrient removal processes between the WWTP and receiving environment to reduce downstream pollution flux. Moreover CWs are envisaged to significantly reduce the carbon foot print of wastewater treatment systems in the region due to the low energy requirements and high carbon sequestration potential. Additionally, they are suitable for low economies because of the low investment costs for construction and O&M compared to the mechanical WWTPs. Moreover they can be easily scaled up as decentralised or onsite sanitation systems to reduce diffuse and point source pollution at an urban ecosystem scale.

The scope of work covered in this thesis describes three major components of the studies undertaken. The three components informed the rationale, objectives, key results and publications presented herein. The three research components included; (i) a baseline study on the performance of Masaka WWTP and effluent pollution attenuation through a natural wetland buffer system (ii) performance of HF and VF CWs as buffer strips for nutrient removal from WWTP effluent at mesocosm scale and (iii) assessment of the carbon and nitrogen gaseous fluxes as fingerprints for CWs microbial mediated processes in the HF and VF mesocosms.

The thesis is structured into five main parts; i.e.

Part I: An Introduction; which highlights the general context of wastewater management and sanitation aspects in line with the sustainable development agenda in developing countries, gives a summary of constructed wetlands as sustainable wastewater treatment technologies, and outlines the general scope and structure of the thesis.

Part II: Describes the overall rationale, objectives and main research questions for the study.

Part III: Presents an overview of the materials and methods used

Part IV: Presents the main research results comprising of publications in peer reviewed journals with an impact factor. In addition, relevant conference papers/articles are also included.

Part V: Gives a general discussion of the key findings, major conclusions and recommendations derived from the study

PART II

2.0 Rationale and objectives of the study

2.1 Rationale and approach

Figure 1 summarises the rationale and approach for the study. Generally, in East African urban environments, wastewater is discharged with limited or no treatment at all, hence creating public and environmental health risks to the population therein. In this study, an initial assessment was therefore undertaken in Masaka municipality, Uganda, to ascertain the performance of a typical conventional municipal wastewater treatment plant (WWTP), regarding effluent pollution flux on a temporal scale. Also, the downstream pollution attenuation through a natural wetland was analysed to establish its role in buffering the WWTP performance deficits on a spatial scale. The results from the initial assessment formed the **1st publication** (Bateganya et al., 2015c) and ultimately informed the design of the pilot HF and VF WBSs at mesocosm scale. These were established to assess their potential application in enhancing organic matter degradation and nutrient removal process from the WWTP effluent before discharge into the natural wetland environment.

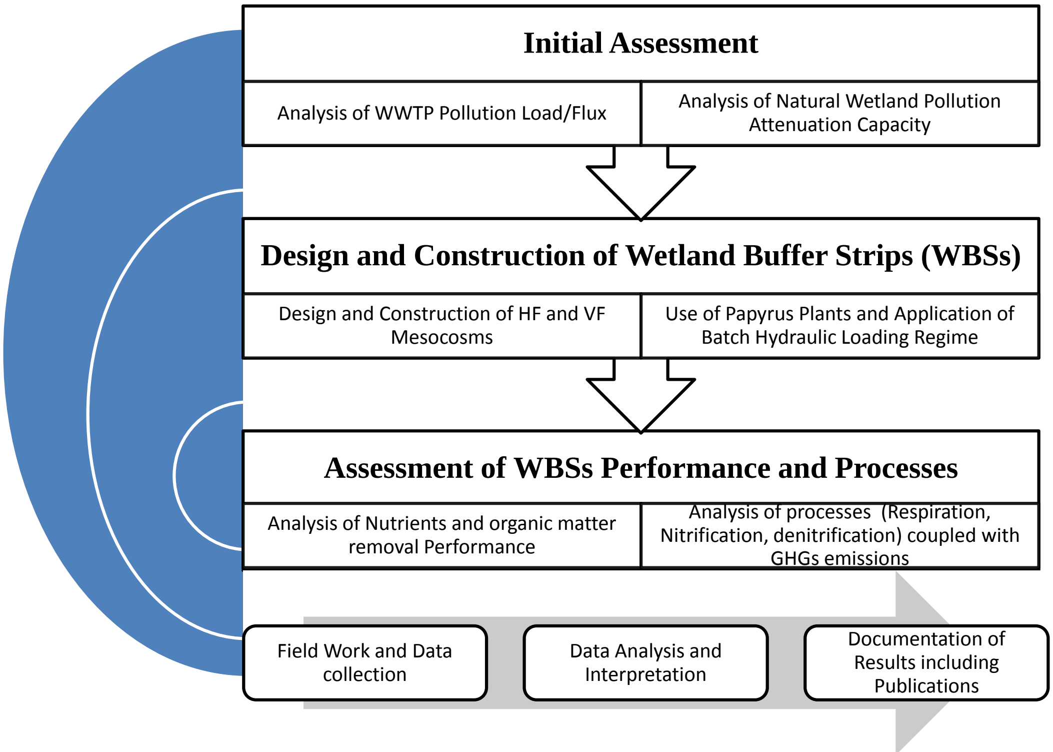

Figure 1: Schematic representation of the study rationale and approach. Illustration by Najib Bateganya

The analysis of the WBSs perfromance regarding nutrients (N and P) transformation and removal from the municipal WWTP effluent before its discharge into the natural (wetland system) environment formed the **2nd Publication** (Bateganya et al., 2015a) of this work. Lastly, the potential respiration, nitrification and denitrification rates for the different WBSs designs were analysed and compared using carbon (CO_2, CH_4) and nitrogen (N_2O) gaseous emissions as fingerprints for microbial mediated wastewater treatment processes. The results of this investigation formed the **3rd Publication** (Bateganya et al., 2015b) for the study.

1.2 Research objectives

The specific objectives for each research component of the study presented in this thesis are stated in the publications in **Part IV**. However, the overall research objective of this work was to assess and elucidate the performance of horizontal and vertical subsurface flow constructed wetlands as buffer systems for enhancing organic matter and nutrient removal processes between deficient WWTPs and receiving urban environments of East Africa. The specific objectives of the study were to;

a) Determine the nutrients, pathogens and organic matter pollution load from the municipal WWTP and its attenuation through a natural wetland buffer system

b) Design and construct horizontal and vertical subsurface flow constructed wetland mesocosms as buffer strips for enhancing organic matter and nutrient removal from WWTP effluent before discharge into the natural environment

c) Characterise the organic matter, N and P elimination rates and removal mechanisms through vegetation accumulation and sediment retention in the different wetland mesocosms

d) Assess and compare the organic matter degradation, nitrification and denitrification rates in the different wetland mesocosm configurations using carbon and nitrogen gaseous fluxes

To investigate each objective, the following research questions were set to guide the field work activities, data collection, analysis and interpretation.

Objective (a)

i. What are the effluent characteristics and pollution load from a typical conventional WWTP into the urban environment?

ii. How does the effluent concentration of selected routine monitoring parameters compare with the Uganda national discharge standards as a treatment efficiency best practice?

iii. Is the natural urban wetland effective in attenuation of a mechanical WWTP effluent pollution load?

iv. How does the effluent pollution removal rate and efficiency vary in the natural wetland on a spatial and temporal scale?

Objective (b and c)

i. Which CW design (HF and VF) offers overall optimal performance regarding organic matter and nutrient elimination

ii. What is the hydrological balance of the HF and VF mesocosms?

iii. What is the appropriate wastewater compensation volume for the water loss fluxes during normal operation of the HF and VF mesocosms?

iv. How does the physical and chemical environment vary in the different mesocosms?

v. Is the presence of *Cyperus papyrus* significant regarding enhancing aerobic conditions in HF and VF mesocosms under the batch loading regime?

vi. How does the organic matter and nutrient removal efficiency (%) and elimination rate vary in the different mesocosms? Is the variation (if any) significant?

vii. What is the potential contribution of *Cyperus papyrus* and treatment bed sediment to the overall nutrient removal and retention?

Objective (d)

i. What is the potential rate of organic matter degradation, nitrification and denitrification in the different treatments of the HF and VF mesocosms?

ii. What environmental factors influence the observed rates of the biogeochemical processes in the different mesocosms?

iii. Are the observed rates for biogeochemical processes correlated with carbon and nitrogen greenhouse gaseous fluxes under warm tropical environments?

PART III

3.0 Methodological approach

The methodology presented in this section gives a general overview and scope of approaches, field and laboratory activities undertaken to achieve the study objectives. The detailed methods and materials for each research component are described in the publications presented in **Part IV** of the thesis.

3.1 Study area

This study was carried out in Masaka municipality (Figure 2), a rapidly developing urban area located in south western Uganda and within the Lake Victoria basin.

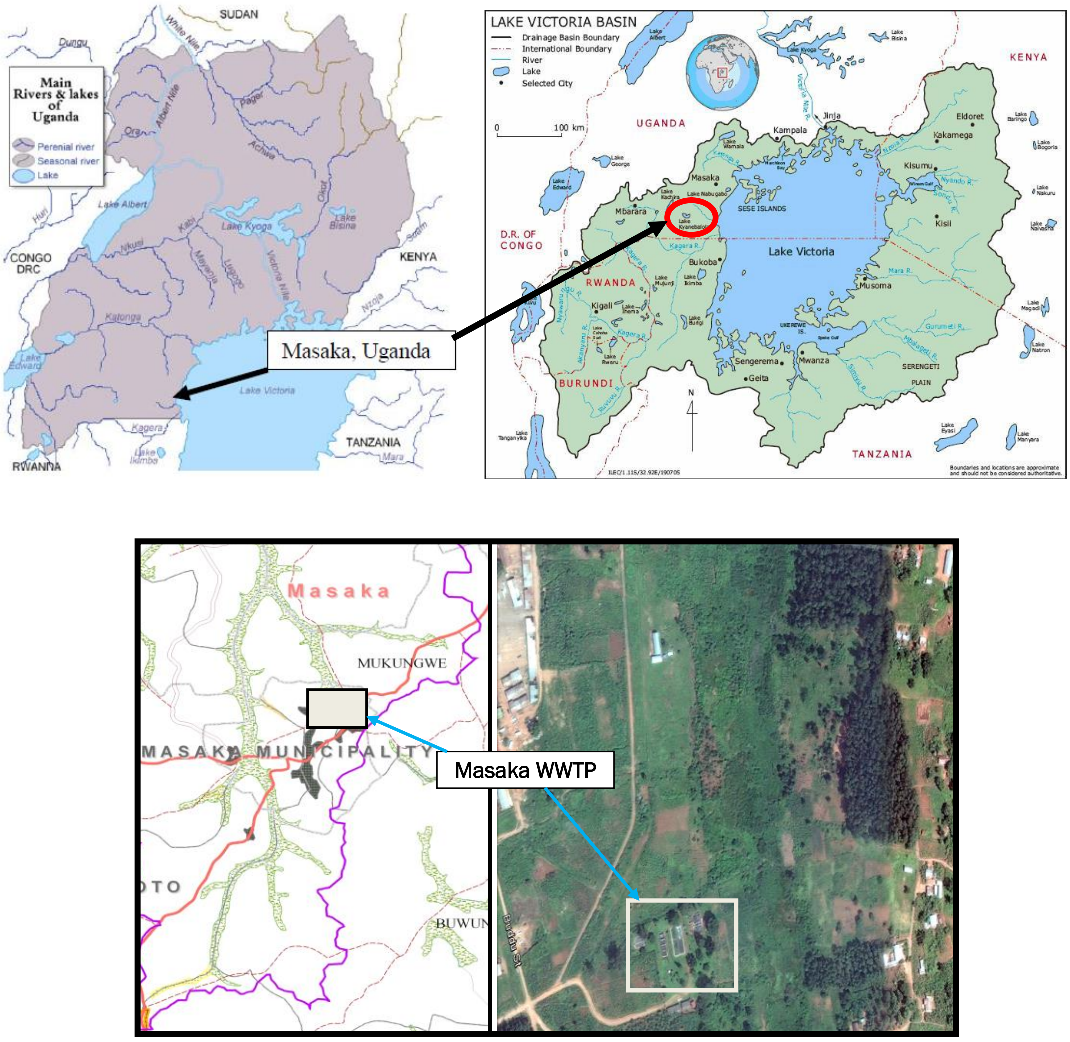

Figure 2: Location of Masaka Municipality and the WWTP, with in the Lake Victoria Basin.

The main focus of the study was the municipal WWTP which discharges its effluent into Nakayiba wetland system (Figure 3) flowing through Masaka urban landscape (Bateganya et al., 2015c). Based on the baseline data collected under the EU-FP7 WETwin project (Zsuffa et al., 2010), the WWTP effluent was found to be non-compliant with the Uganda national discharge standards. These results formed a benchmark for undertaking a detailed study on assessing the WWTP performance (Bateganya et al., 2015c) to inform the development of a sustainable ecological sanitation approach (Bateganya et al., 2015a) for optimising its efficiency, as well as enhancing the resilience of the receiving natural wetland to mitigate environment and public health risks due to pulse and intermittent pollution exposure.

Figure 3: Dilapidated Masaka WWTP (left) and WWTP effluent-wetland stream confluence (right). The WWTP effluent is characterised by the black colour at the effluent-wetland stream confluence. Source: Field photos by *Najib Bateganya*

3.2 Characterisation of Municipal WWTP performance

The detailed methodology for assessment of the Masaka WWTP performance is described in Bateganya et al., 2015c (**Part IV**). Two approaches for the assessment were adopted; first, secondary data (2008-2012) using selected routine monitoring parameters were used to analyse long term WWTP performance and ascertain the seasonal dynamics of pollution fluxes. Secondly, primary data through field and laboratory measurements was undertaken for one year (2012-2013) to ascertain the consistence of secondary data and minimise any potential uncertainties of operational monitoring. Field and laboratory procedures followed standard methods for examination of water and wastewater (APHA 1992). The WWTP influent and effluent flow and quality data was analysed by (i) quantification of the WWTP suspended solids, organic matter, nutrients and pathogens mass balance and removal efficiency and (ii) comparison of the effluent characteristics with the Uganda National wastewater (effluent) discharge standards (WDSs) to verify the level of WWTP compliance.

3.3 Natural wetland effluent pollution buffering capacity

To assess the removal rate and efficiency of the WWTP effluent pollution through a natural urban wetland environment, five sampling sites (points) along the main wetland stream were selected. The criterion for selection of wetland monitoring sites was primarily based on upstream-downstream changes in hydrological characteristics and WWTP effluent flow gradient. The study area map and detailed methodology for water flow and quality to assess the pollution attenuation through the wetland is given in Bateganya et al., 2015c (**Part IV**). An upstream reference sampling site was identified 0.25km before the WWTP effluent-wetland confluence. The confluence formed the second site to capture the upstream and WWTP effluent pollution flux impact. The downstream pollution removal rate and efficiency was monitored at wet 1 (0.35km from confluence), Wet 2 (0.75km from the confluence) and the main outflow downstream 2.15km (from the confluence) of the delineated study area.

Wet 1 and Wet 2 were identified closer to the confluence compared to downstream to capture initial impact of pollution attenuation processes especially dilution effects. To quantify the pollution removal rate and efficiency as a function of wetland distance, mathematical models in equation 1 and 2 (Howard-Williams et al., 2010; Mander et al., 2005) were applied, considering the predominantly low base flow (< 0.5 m^3/s) in-stream conditions (Howard-Williams et al., 2010) through Nakayiba wetland system.

$$Change\ in\ concentration\ (\%) = (1 - e^{-KL}) \times 100 \qquad \textit{Equation (1)}$$

Where L = Distance of sampling site from the confluence (m); K = Removal rate coefficient (m-1), calculated from equation 2.

$$K = \frac{(In\ C_0 - In\ C_L)}{L} \qquad \textit{Equation (2)}$$

Where C_0 = Concentration at the confluence; C_L = Concentration at distance L from the confluence

3.4 Design and construction of wetland buffer strips

VF and HF SSF CWs configurations were used to design single stage WBS mesocosms (Figure 3) planted with *Cyperus papyrus* as described in Bateganya et al., 2015a and 2015b, following the Masaka WWTP effluent pollution load baseline assessment (Bateganya et al., 2015c). Both HF and VF WBS mesocosms were constructed using plastic drums (0.9m height and Ø 0.5m) and setup at Bugolobi WWTP, Kampala Uganda in January 2013. Duplicate treatment units were adopted; i.e. two (2) planted VF and HF mesocosms and two (2) unplanted HF and VF control treatments respectively, making a total of eight (8) treatment units.

Figure 4: Horizontal (left) and Vertical (right) subsurface flow constructed wetland mesocosms designed as buffer strips for organic matter and nutrient removal from municipal WWTP effluents. Source: Field photos by *Najib Bateganya*

Generally, the design criteria and application of SSF CWs buffer system was based on the following assumptions. (i) The buffer system does not function as an independent wastewater treatment unit, but an integral part of the cleaning cascade to reduce downstream pollution

(ii) on the SSF CW buffer system could function as an ecotone (Co´zar et al., 2007) and biogeochemical hotspot (Philippe et al., 2010) to provide a continuum of treatment processes between the WWTP and receiving natural (wetland) environment (iii). Although natural wetlands provide both aerobic and anaerobic environments (Gutknecht et al., 2006; Mitsch and Gosselink 2000) due to a fluctuating hydrological regime (Mitsch et al., 2010), the soils (hydric) are predominantly anaerobic or anoxic (Mitsch and Gosselink 2000). As a result, with constant supply of carbon from decaying macrophytes (Mitsch et al., 2010; Mitsch and Gosselink 2000), anaerobic microbial nutrient transformation processes such as denitrification (Gutknecht et al., 2006; Venterink et al., 2002) are found to be significant especially in frequently flooded systems (Mitsch et al., 2010; Venterink et al., 2002; Welti et al., 2012). Consequently, establishment of SSF CWs was primarily targeting enhancing aerobic processes, especially nitrification. This was envisaged to facilitate a coupled N elimination with anaerobic mediated processes in a natural wetland.

3.4 Water loss fluxes and compensation volume

Water loss fluxes and compensation volume were estimated using the water balance approach (equation 3) as described in Bateganya et al., 2015a. Each mesocosm was loaded with wastewater (between 50 mm d^{-1} to 80 mm d^{-1}) and held for 48hrs. After the holding period, each mesocosm was completely drained into plastic basins. The collected effluent was transferred into 1 Litre measuring cylinders for determining the residual volume. In case of any rains, precipitation was established using a rain gauge installed on site, at the Bugolobi WWTP. Whereas gross water loss in unplanted control units was assumed to be due to direct evaporation, water loss in planted mesocosms was attributed to ET. ET (and direct evaporation for unplanted units) was estimated using the water balance equation (3).

$$Q_{in} = Q_{out} + ET - P \qquad \textit{Equation (3)}$$

Where Q_{in} is the amount of wastewater loaded at the beginning of the experiment (mm d^{-1}), Q_{out} is the amount of the effluent drained after the holding period (mm d^{-1}), ET is evapotranspiration (for planted systems) or direct evaporation (from unplanted systems), P is amount of water added to the mesocosm (mm d^{-1}) due to precipitation. It was also assumed that the difference between ET in planted and unplanted systems was due to water uptake and storage by plants.

3.5 Physical-chemical and nutrient performance analysis

Wastewater samples (0.5 L) of the influent from the distribution reservoir and effluent from each mesocosm were taken bi-weekly for 16 months from March 2013 to June 2014. During sampling, on-site measurements were also taken using portable meters for; temperature and electrical conductivity (EC) (WTW Cond 3301-WTW GmbH, Weilheim, Germany), pH (WTW pH 3301-WTW GmbH, Weilheim, Germany) and DO (Model HACH, HQ40d). Filtration was done using 0.45µm glass fiber filters and suspended solids determined by the gravimetric method. Organic matter was analyzed using biochemical oxygen demand (BOD_5) (by Winkler's method) and chemical oxygen demand (COD) (by closed reflux-titrimetric method). All colorimetric measurements for nutrient analysis were done using the HACH DR 5000 spectrophotometer. Ammonium-nitrogen (NH_4^+) was determined by direct nesslerization, nitrite-nitrogen (NO_2^-) by diazotisation using sulphanilamide and N-(1-napthyl) ethylenediaminedihydrochloride, nitrate-nitrogen (NO_3^-) by sodium salicylate method and total nitrogen (TN) by sodium salicylate method after persulphate digestion (APHA 1992; Johnes and Heathwaite 1992; Raveh and Avnimelech 1979). Both total phosphorus (TP) (after persulphate digestion) and orthophosphate (PO_4^{3-}) were determined by the ascorbic acid method (APHA 1992; Johnes and Heathwaite 1992).

3.6 Vegetation biomass and nutrient analysis

Above ground biomass of *Cyperus papyrus* was harvested every 6 months during the 18 months study period. The harvesting activity only targeted the above ground plant biomass for two main reasons; (i) removal of rhizomes every 6 months could result into extreme disturbance of the established substrate and rhizosphere and (ii) regarding routine operation and maintenance, it is more feasible and less expensive to regularly remove above ground biomass than uprooting the entire system. During each harvesting campaign, all above ground standing biomass in each mesocosm was cut (at about 0.1m from ground level) and weighed to determine fresh weight (kg). A 1 kg fresh weight sub-sample (Mugisha et al., 2007) (composite sample consisting of umbels and culms of the papyrus plant) was taken from each mesocosm for sun drying (until no further change in weight). The dry weight was then used to estimate total productivity (biomass) (kg DW m^{-2}). For nutrient analysis, the dry sample was crushed into powder form for P and N nutrient analysis (Kyambadde et al., 2005; Mnaya et al., 2007; Mugisha et al., 2007) at the Soil Laboratory, College of Agricultural and Environmental Sciences, Makerere University, following the multi-element plant analysis technique after digestion (Novozamsky et al., 1983).

3.7 Sediment analysis

To characterise the potential retention of N and P in the treatment media of the mesocosms, substrate samples were collected from the VF and HF mesocosms, respectively. The sampling was done at the same time as the vegetation harvesting following the 6 months cycle. The collection of samples was done using a hand held simple PVC plastic core (5cm diameter, 50cm length) at a maximum depth of 15cm and 10cm for VF and HF mesocosms, respectively. All samples were immediately transported in polyethylene bags to the Soil Laboratory, College of Agricultural and Environmental Sciences, Makerere University. In the laboratory, replicate samples from each mesocosm were manually sorted to form a homogenous silt-sand grain size sediment range for easy homogenisation and further processing. For course gravel sizes from the HF, biofilm, silt and other trapped suspended materials were scraped off manually to form the main sediment sample. All replicate samples from each mesocosm were then combined as a single sample following compositing standard procedures (Sheppard and Addison 2006). The sediment samples were gradually oven dried at 45^{o}C for a week to preserve the original chemical composition, which would otherwise be altered if rapidly exposed to excessive heat. A dry composite sediment sample of 0.3g each was then processed by digestion for nutrient extraction before colorimetric analysis for determination of TN and TP following standard methods for soil chemical analysis (Bremner 1996; Kuo 1996).

3.7 Gas sampling and analysis

Measurement of gaseous emissions was carried out weekly for a period of three months from April, 2014 (the 16th month of operation) until June 2014 (the 18th Month of operation). The timing and duration for gas sampling was justified by two main factors: (i) the gas measurement period covered peak rainy events in April, a wet-dry transition period in May, and a typical dry period in June. Therefore, the potential influence of seasonal changes regarding gaseous emissions (Mitsch et al., 2010) from the treatment beds was captured. (ii) After 14 months of operation, the microbial community structure in the mesocosms treatment beds was assumed to have been fully established and attained approximate equilibrium conditions (Ramond et al., 2012; Samsó and García 2013).

The closed gas chamber method (Weishampel and Kolka 2008) widely used in previous studies (Mander et al., 2008; Picek et al., 2007; Teiter and Mander 2005) was applied, with chamber size modifications to suite the mesocosms scale. A closed gas chamber with approximate dimensions of height 19cm, diameter 7.3cm, and volume of 4.2 liters was locally fabricated from white PVC plastic to minimize internal heating during measurement (Mander et al., 2008; Teiter and Mander 2005). The top closed part of the chamber was fabricated with a sampling port with a septum which would facilitate gas extraction with a syringe needle (Picek et al., 2007; Weishampel and Kolka 2008). A PVC plastic collar with fitting dimensions as the chamber was used. The collar was permanently inserted (approximately 5cm depth) in the treatment bed 24 hours before sampling to avoid influence of extreme substrate disturbance on gaseous fluxes (Weishampel and Kolka 2008). Due to the small surface area of the mesocosms, only one collar could be accommodated especially in planted WBS. Whereas the collar was inserted in the middle part of the unplanted treatment beds, available space besides the vegetation was utilized for the planted mesocosms (Picek et al., 2007).

To capture variations during each sampling day, two sampling campaigns where adopted i.e. 1 hour after wastewater loading in the morning (between 5 - 7am), and then repeated 8-10 hours after the morning sampling campaign, just before the next loading regime. During each sampling campaign, a 20 minutes interval was adopted after installation of the gas chamber i.e. gas extraction was done at 0, 20, 40 and 60 minutes. Gas extraction from the chamber head space was done using 60ml plastic gas syringes and 25 gauge needles. Prior to gas extraction, chamber flushing with a gas syringe was carried out 3-4 times to reduce potential stratification due to the difference in target gas densities. The flushing was envisaged to enhance homogenization by induced air circulation and localized turbulence effects within the chamber. Gas samples were extracted into pre-evacuated 10ml vials with an airtight septum and an aluminium 20mm unlined crimp seal. Air temperature was always taken before and after each sampling campaign using a potable thermometer. All samples were stored in a hard paper box maintained at room temperature and in a non-illuminated environment prior to transportation for analysis at the Institute of Soil Research, University for Natural Resources and Life Sciences, BOKU, Vienna, Austria. Gas samples were analyzed using an automated 7697A headspace sampler and 7890A Gas Chromatography System (Agilent technologies, USA). Prior to analysis, a calibration ($R^2 \geq 0.99$) was prepared for CO_2, CH_4 and N_2O. The flame ionization detector was used for analysis of CH_4 and CO_2 concentration equivalent (after conversion to CH_4), whereas N_2O was analyzed using an electron capture detector.

3.8 Data analysis

Physical and chemical variables were primarily summarised in tables and compared between mesocosms based on descriptive statistics in MS Excel 2010. Descriptive comparison graphs were developed using Sigma plot 12.5. Coefficient of variation (CV) was calculated to determine the variability (fluctuation) of wastewater quality during the entire study period. The BOD_5/COD ratio was calculated to determine the biodegradability (Metcalf and Eddy 2004; Saeed and Sun 2012) of organic matter. Comparison of mesocosms performance regarding reduction of influent concentrations was done by analysis of variance (ANOVA, significance level $\alpha = 0.05$), assuming homogeneity of variances after Bartlett's test. Tukey's test was used to elucidate differences between means of treatments. All statistical analyses were performed using the R-console (Version 3.0.2).

Removal efficiency of suspended solids, organic matter (BOD_5 and COD) and nutrients (TN, NH_4-N, NO_3-N, and TP) was quantified based on mesocosms influent and effluent loads using equation (4)

$$Removal\ efficiency\ \% = \frac{(Q_{in} \times C_{in}) - (Q_{out} \times C_{out})}{(Q_{in} \times C_{in})} \times 100 \qquad \textit{Equation (4)}$$

Where Q_{in} and Q_{out} are influent and effluent volumetric loads ($m^3\ d^{-1}$) respectively, whereas C_{in} and C_{out} are influent and effluent concentrations ($kg\ m^{-3}$), respectively. In addition, areal based elimination rate ($g\ m^{-2}\ d^{-1}$) for organic matter and nutrients was calculated as a ratio of the load removal ($g\ d^{-1}$) to the loading surface area (m^2) of the mesocosm.

This criterion was also used to calculate the *C. Papyrus* nutrient removal rate after establishing the N and P content of the harvested dry biomass. Means of N and P content were compared to establish mesocosms performance regarding sediment nutrient retention. The gas flux quantification was implemented using a mathematical model represented by equation 5 (Metcalfe et al., 2007), taking into account the chamber dimensions, temperature and pressure.

$$F = \frac{\Delta C}{\Delta t} \times \frac{P}{1000} \times \frac{273}{t + 273} \times \frac{M}{V_m} \times \frac{V_{ch}}{A} \qquad \textit{Equation (5)}$$

Where F is the gas flux ($kg\ m^{-2}\ s^{-1}$) which was converted to $g\ m^{-2}\ h^{-1}$ for presentation and comparison with literature values; $\frac{\Delta C}{\Delta t}$ was derived from the slope of the linear regression model (general equation 6) (Chunming et al., 2010), and represents change in concentration of the gas ΔC (ppm) with change in time Δt (seconds); P is atmospheric pressure (*Pa*) based on Kampala conditions from the Meteorological Department, Ministry of Water and Environment; t is the average air temperature of the chamber (^0C); M is molar mass of the gas ($g\ mol^{-1}$) (CH_4 = 16.04; CO_2= 44.01; N_2O = 44.01); V_m is molar gas volume (22.4l); V_{ch} gas chamber internal volume (m^3); and A the substrate bed area covered by the gas chamber (m^2).

$$C_t = a_o + a_1 t \qquad \textit{Equation (6)}$$

Where C_t is the concentration of the gas (ppm) measured at time t (seconds); a_o is a regression parameter representing the concentration (ppm) of a gas at time t = 0 (seconds); a_1 is a regression parameter ($ppm\ sec^{-1}$) representing the slope, and was used to substitute $\frac{\Delta C}{\Delta t}$ in equation 2 for flux calculations.

PART IV

4.0 Key Publications submitted in Peer Reviewed Journals

1. Bateganya, N.L.; Nakalanzi, D.; Babu, M.; Hein, T., 2015. *Buffering municipal wastewater pollution using urban wetlands in sub-Saharan Africa: A case of Masaka Municipality, Uganda*. Environmental Technology:1-35 (**Published**)

2. Bateganya, N.L.; Kazibwe, A.; Langergraber, G.; Okot-Okumu, J.; Hein, T., 2015. *Performance of subsurface flow constructed wetland mesocoms in enhancing nutrient removal from municipal wastewater in warm tropical environments*. Environmental Technology (**Under final review for publication after minor revisions**)

3. Bateganya, N.L.; Mentler, A.; Busulwa, H.; Langergraber, G.; Hein, T., 2015. *Carbon and nitrogen gaseous fluxes from subsurface flow wetland buffer strips at mesocosm scale in East Africa*. Ecological Engineering (**Submitted manuscript under peer review**)

Other Relevant Publications, articles and conference papers

1. A.Y. Katukiza, K. Musabe, S. Nsubuga, J.T. Tukahirwa, J. Byansi, **N.L. Bateganya.,** 2015. *A Business model approach for sustainable faecal sludge management in a typical Sub-Saharan Africa city: the Case of Kampala in Uganda*. (**Under peer review**)

2. Tukahirwa T.J and **Bateganya L.N.,** 2015. *The Role of Policy and Institutional Reform in Enhancing the Technical Efficiency of Urban Authorities: Reference to Solid Waste Management in Kampala City, Uganda*. In Future Directions of Municipal Solid Waste Management in Africa. African Institute of South Africa, Pretoria, South Africa. http://www.africanbookscollective.com/books/future-directions-of-municipal-solid-waste-management-in-africa

3. **Najib Lukooya Bateganya** and Anna Kristina Kanathigoda 2015. *Strengthening pit emptying through private sector led service delivery in Kampala City, Uganda*. Conference paper; proceedings of the 3rd International Faecal Sludge Management Conference, Hanoi, Vietnam, January 2015. http://www.susana.org/en/resources/conference-materials-2/2015/259-fsm3

4. **Najib Lukooya Bateganya**, 2014. *The Kampala city transformation process: Some experiences and challenges in improving sanitation*. Conference paper; proceedings of the Unclogging of Blockages in Sanitation Conference; Kampala, Uganda; February 18-20 2014. http://forum.susana.org/forum/categories/142-upscaling-sanitation-governance-institutional-aspects-sanitation-policies/6467-unclogging-the-blockages-in-sanitation-meeting-uganda-february-17-20-2014-feedback-about-the-event

5. **Najib Lukooya Bateganya**, Diana Nakalanzi, Mohammed Babu, Thomas Hein., 2013.*Wastewater pollution attenuation in a tropical urban wetland system: Nakayiba,*

Masaka, Uganda. Conference paper (O.132); proceedings of the 5th International Symposium on Wetland Pollutant Dynamics and Control, WETPOL 2013, co-organized by the Ecole des Mines de Nantes and GEPEA, Nantes, France, October 13-17, 2013. http://www.emn.fr/z-ener/wetpol2013/

6. **Bateganya, L. N**; Tukahirwa, T.J; Busulwa, H; Hein, T.; 2013. *Integrating wetland ecosystem services into the planning of urban landscapes in developing cities of East Africa: Lessons from European riverine wetlands and floodplains*. In Urbanisation and Global Environment Change – Emerging scholars Edition, No. 9 July 2013. https://ugec.org/docs/ugec/viewpoints/Viewpoints9-July2013.pdf

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Buffering municipal wastewater pollution using urban wetlands in sub-Saharan Africa: a case of Masaka municipality, Uganda

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Buffering municipal wastewater pollution using urban wetlands in sub-Saharan Africa: a case of Masaka municipality, Uganda

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In many sub-Saharan Africa municipalities and cities, wastewater is discharged with limited or no treatment at all, thus creating public and environmental health risks. This study assessed the performance of a conventional municipal wastewater treatment plant (WWTP), based on effluent pollution flux, in Masaka Municipality, Uganda. Also, the downstream pollution attenuation through a natural wetland was analysed to ascertain its role in buffering the WWTP performance deficits. Generally, there was deficiency in WWTP performance, with 100% failure over a five-year assessment period, for example, the mean effluent biochemical oxygen demand $(BOD)_5$ and chemical oxygen demand (COD) concentrations (mg l^{-1}) were found to be 316 ± 15 and 582 ± 28 compared with 50 and 100 maximum permissible environment discharge limits, respectively. Despite these deficits in WWTP performance, the wetland buffer effectively reduced pollutant loads for suspended solids (73%), organic matter (BOD_5, 88% and COD, 75%), nutrients (total nitrogen, 74% and total phosphorus, 83%) and pathogens (*faecal coliforms*, 99%). These findings underpin the challenge of managing municipal wastewater using centralized mechanical WWTPs in the region. However, the wetland buffer system demonstrated a critical role these ecosystems play in abating both pulse and intermittent pollution loads from urban environments of sub-Saharan Africa whose sanitation systems are defective and inadequate. Therefore, it was concluded that integrating wetland ecosystems in urban planning as natural landscape features to enhance municipal wastewater management and pollution control is paramount.

Keywords: municipal wastewater; wastewater treatment plant; pollution; wetland buffer; mass removal efficiency

1. Introduction

Although Africa is the least urbanized, it currently has the highest rate of urban population growth estimated to be 3.9% per year.[1] Rapid urbanization, especially in tropical regions,[2] has been linked to intense degradation of the landscape and aquatic ecosystems [3–6] including wetlands. One important aspect concerns the negative impacts on public health and environmental quality due to increasing pollution from inadequate urban sanitation and improper wastewater management.[3,6–11]. This situation is exacerbated by the high population density, unplanned settlements and uncontrolled industrial development, which contribute to the large quantities of indiscriminately discharged wastewater and high pollution loads [4,6,8] into the environment.

In Masaka Municipality (Uganda), like many other urban areas and cities of East Africa, municipal and industrial wastewater is frequently discharged into the environment untreated or partially treated.[8,12] It is estimated that in East Africa, approximately 80% of wastewater is discharged untreated.[6,8,12–14] This is due to inadequate or no access to appropriate on-site sanitation or centralized wastewater treatment systems.[14,15] Consequently, water quality has grossly deteriorated, as observed in Lake Victoria,[4,6,12,16–18] East Africa.

The limnological dynamics of Lake Victoria over the last three to four decades have been characterized by elevated nutrient concentrations and intense eutrophication regimes [4,17] due to excessive pollution especially from urban areas. This situation has also been extricably linked to massive encroachment on wetlands which have over the past acted as natural pollution buffer zones.[6,12,16,18–20] Studies have demonstrated that the water quality regulation function, a key ecosystem service of natural wetlands, is essential [5,21,22] especially in developing countries where technological fixes for advanced wastewater treatment systems are expensive, lacking and/or dilapidated.[12,14,23] The dynamic nature of wetland hydraulics and hydrology influences the transport, dispersion and transformation of wastewater (including stormwater) through multiple, complex physical and biogeochemical processes.[22,24–26] These processes

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enhance water quality regulation and attenuation of floods especially during rainy seasons in tropical environments.

In wastewater management, public health, environmental quality and community concerns are of paramount importance.[7,27–33] In line with the aforementioned, developed countries have invested and gradually overcome the basic stages of wastewater pollution problems.[11,27,28,30,34,35] On the contrary, developing countries are still grappling with protection of public health through control of pathogens and eutrophication of surface waters [12,23] due to wide spread point and diffuse pollution sources. Besides concerns over sustainability in terms of operation and maintenance of existing centralized wastewater treatment systems,[15,31,32,36] other factors such as unprecedented population growth, governance, inadequate financing and social acceptance are critical barriers to implementation of sustainable sanitation and appropriate wastewater management technologies [11,32,37] in developing countries.

The adequacy and hence reliability of wastewater treatment systems can be analysed based on the level of compliance to specified discharge standards and/or treatment targets.[30,38] These standards or targets are primarily developed to safeguard public and environmental health.[11,27,31,36,39] Unfortunately, conventional technical wastewater treatment plants (WWTPs) exhibit numerous uncertainties regarding design and operation which are ultimately associated with performance failure risks,[15,30,38] if not well managed. Therefore, measures to address WWTP treatment performance deficits are not only necessary, but also an essential obligation for urban authorities and utilities to safeguard public health and control of environmental pollution.

Like in Masaka Municipality, old-dilapidated municipal centralized WWTPs continue to operate, hence discharging inadequately treated wastewater into the environment. The situation is made worse by cases of unregulated industrial wastewater discharge into the sewer system. This makes WWTPs major sources of highly concentrated pollutants, which can potentially induce high public and environmental health risks. In Uganda, although Wastewater Discharge Standards (WDS) exist, monitoring compliance of existing treatment systems is very limited. Consequently, routine effluent quality monitoring data are scarce, and detailed treatment performance analysis of these systems is rare or inadequate to inform long-term planning and decision-making regarding investments in sustainable sanitation technologies and other appropriate wastewater management options.

In this paper, performance failure of municipal WWTPs in terms of effluent quality and associated environmental pollution is demonstrated in Uganda. The study focussed on the performance assessment of Masaka Municipal WWTP, which is among the emerging cities in the region due to its current and projected rapid development. Masaka Municipal WWTP is among the many remnants of centralized treatment systems developed during colonial times in 1954 and has never undergone any major refurbishments since then. The aim of this paper was twofold; first, to provide an empirical analysis of long term (2008–2012 secondary monitoring data) and current performance (2012–2013 – field-based monitoring) of a centralized mechanical WWTP against the national WDS as a local reference for treatment performance. This was expected to form a benchmark for rethinking approaches and options for managing centralized municipal wastewater treatment systems regarding sanitation management and pollution control. Secondly, the potential WWTP pollution (organic matter, and inorganic nutrients and pathogens) flux and removal efficiency through Nakayiba wetland, the immediate WWTP effluent discharge point to the environment was assessed.

The specific objectives of the study included: (1) characterizing the effluent flow and quality of the WWTP, (2) quantifying the WWTP pollution flux into Nakayiba wetland and (3) determining the pollution removal rate and efficiency through Nakayiba wetland.

2. Materials and methods

2.1. Study area

Masaka Municipality is located in south western Uganda within the Nabajuzi riverine wetland catchment (31°33″ – 31°49″ E and 00°27″ S – 00°05″ N), which is part of the Lake Victoria basin, East Africa. This rapidly expanding urban system covers an area of about 46 km^2, with the current population estimated to be over 100,000. From an urban landscape perspective, Masaka is endowed with extensive natural wetlands which provide key ecosystem services and functions, especially; water supply (from Nabajuzi wetland), urban drainage and flood control (Nabajuzi and Nakayiba wetlands) and wastewater treatment (Nakayiba wetland).

Regarding water and sanitation services coverage, water supply is approximately 80%, whereas only about 2% of the municipality is served by the sewer network, connected to the WWTP. Over 98% of the other areas rely on on-site sanitation, that is, septic tank for middle to high-income settlements and pit-latrines for the urban poor (low income) communities.

The Masaka municipal WWTP was designed as a simple mechanically aerated bioreactor but differs from a conventional activated sludge system because it has no option for sludge return. The main treatment units include primary screens, a settlement tank (for primary sedimentation) and an aeration tank (for aerobic microbial processes) which is mechanically aerated using electric power supply. The sludge produced is pumped into drying beds for treatment prior to final disposal and reuse especially in agriculture. The effluent of the WWTP is discharged into Nakayiba wetland which is characterized by a perennial stream (Figure 1).

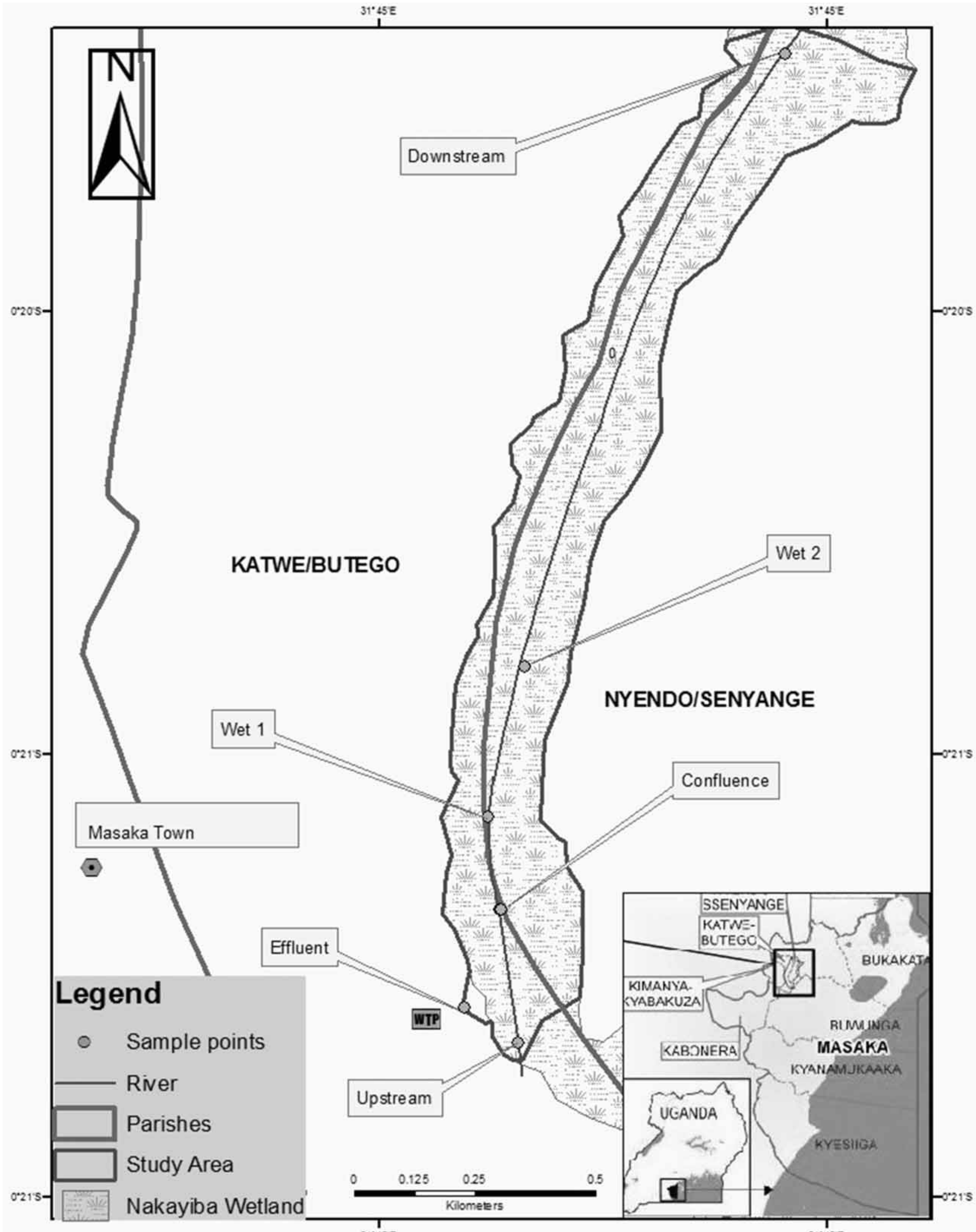

Figure 1. Study area showing Nakayiba wetland. The inset shows the region including Masaka Town. The WWTP effluent discharge point and the sampling points along the upstream–downstream flow gradient within the main wetland stream are also indicated.

2.2. Monitoring (sampling) sites

To assess the pollution flux from the WWTP and its attenuation through the environment, the WWTP effluent and five sampling sites (points) along the main wetland stream (Figure 1) were selected. One year monthly water quality monitoring campaign was conducted from October 2012 to September 2013. The effluent sampling site (outflow point) followed the same monthly monitoring schedule and protocol used by National Water and Sewerage Corporation (NWSC) for comparison with long-term monitoring data.

The criterion for selection of wetland monitoring sites was primarily based on upstream–downstream changes in hydrological characteristics and WWTP effluent flow gradient. Upstream of the WWTP effluent discharge, a small stream flows into the wetland area. Towards the WWTP effluent discharge point (confluence), the narrow wetland stretch is characterized by permanent inundation and high stream discharge due to ground water recharge (influenced by steep slopes), surface run-off and diffuse wastewater overflow especially during rainy events. However, at the main effluent–wetland stream confluence, a surface flow convergence zone is established. As a result, from this point, flow is predominantly confined in the stream channel with some isolated cases of lateral dispersion and diversion (due to vegetation) towards the downstream outflow point.

Sampling sites (points) were therefore identified in areas where surface flow was predominantly confined in the stream channel. An *upstream* reference sampling site was identified 0.25 km before the WWTP effluent–wetland *confluence*. The *confluence* formed the second site to capture the upstream and WWTP effluent pollution flux impact. The downstream pollution removal rate and efficiency were monitored at *Wet 1* (0.35 km from confluence), *Wet 2* (0.75 km from the confluence) and the main outflow *downstream* 2.15 km (from the confluence) of the delineated study area. *Wet 1* and *Wet 2* were identified closer to the confluence compared with downstream to capture initial impact of pollution attenuation processes especially dilution effects.

2.3. WWTP and wetland flow (discharge) measurements

Flow measurements were required to quantify instantaneous pollution fluxes from the WWTP and a mass removal efficiency of the wetland area. In addition, flow data were used to assess the WWTP and Nakayiba wetland response to seasonal changes as a function of precipitation. This was critically relevant in understanding the dynamics of potential pollution mobilization, transport and removal. Precipitation (rainfall) data for the local meteorological station (Kitovu and Masaka) were obtained from the Department of Meteorology (Ministry of Water and Environment) to characterize seasonal patterns.

Due to infrastructure degradation, the WWTP flow measurement system broke down hence long-term and current flow data were scanty. For this study, flow measurements of the WWTP effluent were done using the bucket and stop watch technique [40] due to the relatively low flows. This was done bi-weekly alongside wetland flow measurements for a period of one year (October 2012 to September 2013) and thus captured flow data for the different seasons. Diurnal wastewater flow fluctuations were also captured by taking measurements at 6:00 a.m., 12:00 noon and 6:00 p.m. A 100-l capacity plastic drum was placed at the final effluent outflow point. The time taken to fill a known volume of the drum was noted using a digital watch. The procedure was repeated three times and the average flow rate ($m^3\ s^{-1}$) was calculated.

The wetland stream flow measurements were carried out using the velocity-area method [40–42] as a function of channel morphology (stream water depth and wetted width). This was done at the upstream, confluence and downstream sampling sites where water flow was confined in the stream channel. Flow velocity and depth-width measurements were carried out using a propeller current flow meter ((Wading set model 001, Valeport Ltd., Devon, UK)) and a calibrated metallic rod, respectively.

2.4. Wastewater quality monitoring data

Both primary and secondary data (long term) were collected for the WWTP effluent quality analysis, whereas wetland monitoring was only based on primary data (following field and laboratory measurements) since secondary data were rarely available for majority of the parameters.

2.4.1. Secondary data

To assess the long-term performance of the Masaka WWTP (based on effluent quality), secondary data obtained from NWSC database were used for further analysis. Parameters considered include pH, electrical conductivity (EC), temperature, total suspended solids (TSS), Five-day Biochemical Oxygen Demand (BOD_5), chemical oxygen demand (COD), ammonia nitrogen (NH_4-N), total nitrogen (TN), dissolved inorganic phosphorus-phosphate (PO_4-P), total phosphorus (TP) and *faecal coliforms* (FC). However, due to laboratory analytical limitations, there were numerous data gaps especially for nutrients and FC. Therefore, parameters with consistent data (for the entire study period) were prioritized for further processing and analysis. These included EC, TSS, BOD_5, COD and NH_4-N.

2.4.2. Field sampling and measurements

Wastewater samples were taken monthly for a period of one year (October 2012 to September 2013) from all sampling points described in Section 2.2 and illustrated in Figure 1. Portable meters were used for on-site measurement of EC (WTW Cond 3301-WTW GmbH, Weilheim, Germany) and pH (WTW pH 3301-WTW GmbH, Weilheim, Germany). For laboratory analysis, separate samples were collected for BOD_5, physical–chemical and FC analysis. Sample collection and storage were conducted using standard procedures for the various parameters as described in APHA (1992). All collected samples were kept in cooling boxes at about 1–4 °C, and transported to the NWSC central laboratories, Bugolobi, Kampala, for analysis within 12 h after collection.

2.4.3. Laboratory analysis

Processing and preparation of samples were done immediately on arrival at the laboratory; BOD_5, COD, NH_4-N, PO_4-P, TN and TP were analysed according to standard methods.[43] For physical–chemical analysis, the samples that required filtration were filtered using glass fibre filters (0.45 μm). TSS was determined by the gravimetric method. Nutrient analysis for nitrogen (TN and NH_4-N) and phosphorus (TP and PO_4-P) was carried out using the HACH DR 5000 spectrophotometer. TN was determined by the sodium salicylate method after persulphate digestion, whereas NH_4-N was determined by the direct nessslerization method. TP (after persulphate digestion) and PO_4-P were determined by the ascorbic acid method from the unfiltered and filtered samples, respectively. FC was determined using lauryl sulphate broth stained on an adsorbent pad and incubated at 44 °C for 16 h. Yellow colonies that developed were counted and expressed as CFU per 100 ml.

2.5. *Data analysis*

2.5.1. *WWTP effluent performance*

The five-year secondary monitoring data were summarized in an Excel spread sheet for further analysis. The minimum (Min.), maximum (max.), mean and standard error of the mean (SEM) were determined for each parameter. To ascertain overall WWTP performance, mass removal (%) of suspended solids, organic matter and ammonia was analysed using mean influent and effluent flow and concentration. WWTP effluent quality compliance or performance failure to WDS per parameter was calculated as a percentage of number of months per year in which the standard value was exceeded. In addition, coefficient of variation (CV) was calculated to determine and compare the level of monthly variability of each parameter from the annual mean performance. Seasonal variation (dry and wet season) of effluent quality was done by analysis of variance (one-way ANOVA and significance level $\alpha = 0.05$), assuming homogeneity of variances after Bartlett's test. All statistical analysis was performed using the *R*-console (Version 3.0.2).

2.5.2. *Wetland pollution removal capacity*

Pollution attenuation capacity was defined and determined in this study as the efficiency of pollution removal relative to the wetland distance [33] from the confluence. A mathematical model developed for estimating the percentage change in concentration of pollutants as a function of distance (Equations 1 and 2) [44,45] was used, considering predominantly low base flow ($< 0.5\ m^3\ s^{-1}$) in-stream conditions [45] through Nakayiba wetland system.

$$\text{Change in concentration (\%)} = (1 - e^{-KL}) \times 100, \quad (1)$$

where L is the distance of the sampling site from the confluence (m) and K is the removal rate coefficient (m^{-1}), calculated from the following equation:

$$K = \frac{(\ln C_0 - \ln C_L)}{L}, \quad (2)$$

where C_0 is the concentration at the confluence and C_L is the concentration at distance L from the confluence.

The COD to BOD_5 ratio was also used as an indicator for biodegradation.[29,34] This ratio significantly increases (above 3.0) when the biodegradable fraction of organic matter decreases [34] as was assumed to be the case in Nakayiba wetland. Pollution fluxes (except FC quantified as log cfu/100 ml and log removal, respectively) from the WWTP effluent, confluence and downstream were calculated as a product of discharge ($m^3\ d^{-1}$) and concentration ($kg\ m^{-3}$) for each date of flow rate measurement. Using the quantified pollution fluxes, the wetland mass removal efficiency/capacity from the confluence (main inflow) to downstream (main outflow) of the study area was determined. ANOVA and simple linear regression analysis were performed in *R*-console (Version 3.0.2) to ascertain the significance of variation or direct dependence of pollution fluxes with seasonal regimes and/or at different sampling sites, respectively. In all cases, the level of significance was set at $\alpha = 0.05$ and homogeneity of variances checked prior to *ANOVA* test.

3. Results

3.1. *Flow (discharge) dynamics*

Rainfall distribution exhibited a typical bi-modal seasonal pattern, similar to the wider Lake Victoria basin. Considering a seven-year meteorological data set (2007–2013), the mean ($\pm$SEM) annual rainfall was found to be 1018.3 $\pm$ 76.6 mm (min = 822.3 mm and max = 1383 mm). Typical dry seasons were observed in January (41.7 $\pm$ 12.4 mm) – February (48.7 $\pm$ 12.2 mm) and June (21.4 $\pm$ 9.1 mm) through July (28.2 $\pm$ 7.7 mm) to August (52.6 $\pm$ 12.9 mm). March (113.6 $\pm$ 14.6 mm) to May (96.7 $\pm$ 11.9 mm) was the first rainy season, with a peak observed in April (170.5 $\pm$ 20.8 mm). The second rainy season was observed from September (108.1 $\pm$ 29.8 mm) through October (128.3 $\pm$ 16.3 mm), November (130.7 $\pm$ 23.3 mm) to intermittent rains in December (77.3 $\pm$ 17.5 mm). The monthly rainfall trend during the study period exhibited a similar pattern (Figure 2), and thus was used as a criterion for characterizing the seasonal flow variability for the WWTP effluent and Nakayiba wetland stream.

Flow variability of the WWTP effluent and wetland stream (Figure 2) was generally influenced by seasonal changes. The WWTP effluent ($R^2 = 0.77, p = .002$), confluence ($R^2 = 0.78, p = .001$) and downstream (outflow) ($R^2 = 0.69, p = .006$) flow rates all showed a significant strong linear regression ($n = 12$) with mean monthly rainfall. Although the upstream site showed a similar trend, the response was statistically weaker ($R^2 = 0.53, p = .040$).

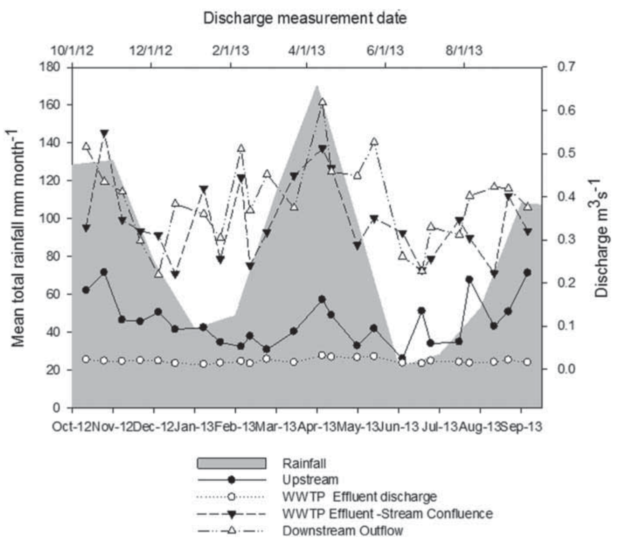

Figure 2. Seasonal variability of WWTP discharge and wetland stream flow; upstream, at the confluence and the main outflow downstream during the study period (October 2012–September 2013).

The surface flow contribution of the WWTP effluent and upstream discharge to the total discharge measured at the confluence was found to be 40.0 ± 13.5%. Consequently, ground water and surface run-off (overland flow) especially during rainy periods were assumed to have a remarkable impact on the difference in discharge. On the contrary, although discharge recorded at the downstream monitoring site was slightly higher in comparison with the confluence site, no significant difference ($p = .90$) was found.

3.2. *WWTP effluent quality performance*

Generally, the WWTP exhibited low removal efficiency (below 50%) for TSS, BOD_5, COD and NH_4-N. Consequently, the system was defective in meeting the maximum permissible WDS for all parameters during the entire study period (Table 1). The annual performance analysis for all parameters gave a 100% failure against the WDS except for pH (7.3 ± 0.7 compared with 6.0–8.0 WDS) and EC (1905.9 ± 63.1 compared with 1500 WDS). The CV indicated a low deviation for all parameters from the annual mean performance, that is, the CV values for all parameters and entire study period ranged from 0.2 (20% minimum deviation from the mean) to 0.5 (50% maximum deviation from the mean). Also, ANOVA showed no significant annual variation ($p > .05$) in effluent quality for pH, EC, BOD_5, and NH_4-N, although COD ($p = .009$) and TSS ($p = .042$) significantly differed between the different years.

3.3. *WWTP pollution flux*

WWTP effluent pollution flux (Table 2) into the wetland was generally influenced by rainfall. Temporal analysis (Figure 3) showed that the maximum pollution load for organic matter, suspended solids, nutrients and pathogens was recorded during the peak rainy season (April) and varied at different intensities in other months. The CV (%) indicated that pollution flux variation during the dry and rainy seasons was more pronounced for FC (63%), TP (56%) and TSS (47%), compared with BOD_5 (23%), COD (28%) and TN (19%), whose fluctuations were quite unpredictable (Figure 3).

The high pollution load during rainy events was strongly associated with mobilization of suspended solids from the WWTP hence significant delivery of particulate-bound pollutants into Nakayiba wetland. A significant increase ($n = 12$) in pollution flux with rainfall for TSS ($R^2 = 0.58$, $p = .04$) and FC ($R^2 = 0.79$, $p = .0001$) was observed. Consequently, increase in TSS flux ($n = 12$) was strongly correlated and hence accounted for increased load of TP ($R^2 = 0.65$, $p = 0.001$), TN ($R^2 = 0.59$, $p = .003$), FC ($R^2 = 0.48$, $p = .013$) and BOD_5 ($R^2 = 0.62$, $p = .002$).

3.4. *Wetland pollution attenuation*

3.4.1. *Pollution concentration gradients*

The concentration for all pollution parameters from the WWTP effluent was significantly higher ($p < .05$) compared with the upstream source. Consequently, WWTP effluent discharge was found to be the major pollution source into the wetland hence influence on its water quality (Table 3). This was also verified by EC and FC values

Table 1. Mean WWTP influent and effluent concentration, load and overall mass removal efficiency based on NWSC monthly monitoring data for the period 2008–2012 ($n = 60$; mean flows ($m^3\ d^{-1}$) for influent = 1634.0 ± 135.2 and effluent = 1602.0 ± 132.6).

	Mean concentration ± SEM ($mg\ l^{-1}$)			Mean load ± SEM ($kg\ d^{-1}$)		
Parameter	Influent	Effluent	WDS	Influent	Effluent	Mass removal efficiency (%)
TSS	437 ± 22	268 ± 14	100	714 ± 37	421 ± 22	40
BOD_5	574 ± 22	316 ± 15	50	937 ± 36	506 ± 24	47
COD	1040 ± 45	582 ± 28	100	1700 ± 78	932 ± 45	46
NH_4-N	83.0 ± 3.3	54.7 ± 2.5	10.0	136.2 ± 5.4	87.6 ± 4.1	37

Table 2. Mean (±SEM) ($n = 12$), Min. and Max. WWTP effluent pollution load and FC concentration based on field flow rate and concentration measurements from October 2012 to September 2013.

	TSS (kg d^{-1})	BOD (kg d^{-1})	COD (kg d^{-1})	TP (kg d^{-1})	TN (kg d^{-1})	FC (cfu/100 ml)
Mean	549	516	915	50.1	103.9	3.36E + 08
SEM	75	36	75	8.1	5.8	6.07E + 07
Min.	266	352	621	25.2	81.8	9.50E + 07
Max.	1089	704	1413	118.0	140.7	8.20E + 08

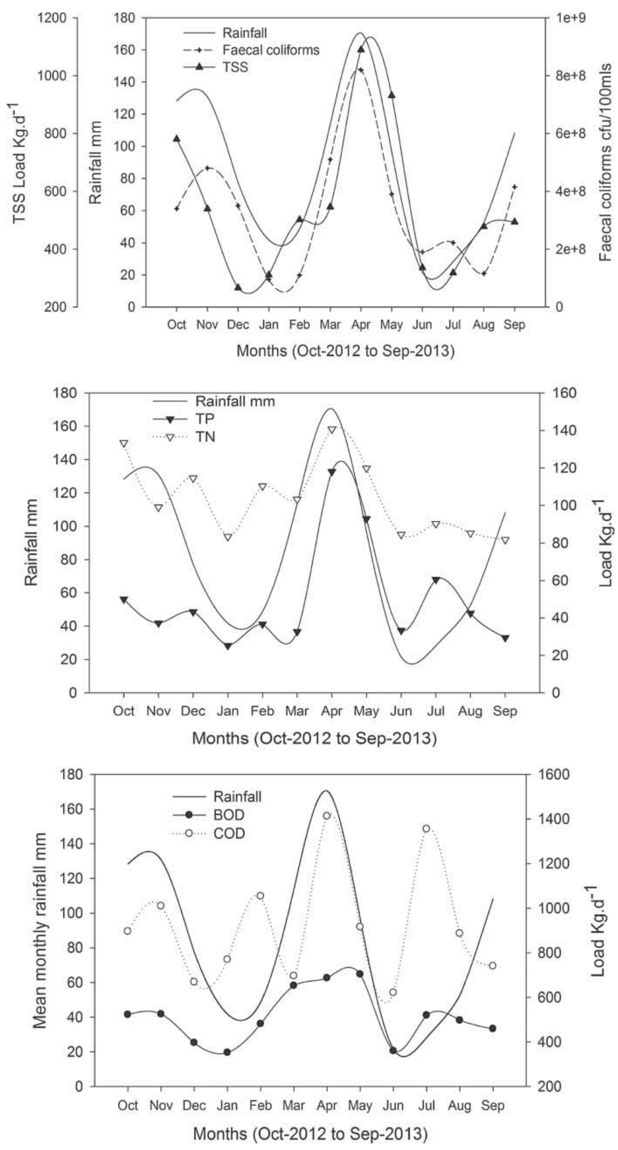

Figure 3. Seasonal variation of the WWTP effluent pollution load for: TSS and FC concentration, nutrients (TN and TP) and organic matter (COD and BOD_5) as a function of rainfall during the October 2012–September 2013 monthly monitoring ($n = 12$) period.

as indicators for wastewater flow.[13] A significant strong linear regression ($p < .05$; $n = 12$; EC, $R^2 = 0.796$; FC, $R^2 = 0.858$) was found for both parameters between the WWTP effluent and confluence. However, the high concentration of organic matter, pathogens, suspended solids, nutrients and EC measured at the confluence significantly decreased ($p < .05$, $n = 12$) downstream through *Wet 1* and *Wet 2*. Despite this remarkable reduction in pollution levels for all parameters, the downstream concentration was still found to be significantly higher ($p < .05$) than the background concentration measured upstream except for TP ($p = .151$) and FC ($p = .183$).

3.4.2. *Pollution removal rate and efficiency*

The majority of the pathogens (FC 98%), organic matter (COD 51% and BOD_5 74%) and suspended solids (TSS 62%) were removed in the first 750 m section (at *Wet 2*), which is approximately 35% of the total wetland stream length considered for this study (Table 4). On the contrary, besides PO_4-P whose removal efficiency was 56% at *Wet 2*, the removal efficiency for inorganic nutrients (TN, TP and NH4-N) was generally lower ($\leq 40\%$) in the same section. In agreement with the removal efficiency trends along the wetland gradient, the removal rate coefficient (m^{-1}) for nutrients was lower compared with the pathogens, organic matter and suspended solids. Overall, a significant ($p = < .05$) reduction in the concentration of all pollutants was achieved downstream.

3.4.3. *Mass removal*

Generally, the wetland inflow pollution load at the confluence was significantly higher ($p < .05$) than the downstream outflow. Overall, the mass removal efficiency was high ($> 65\%$) for all pollutants during the entire study period (Table 5). However, there was no significant difference ($p > .05$) in removal efficiency for all categories of pollutants (individual parameters) between dry and wet season. FC log removal was also high (4.0–5.0), regardless of inflow concentration and flow regime. On the contrary, despite the statistical insignificance, it was observed that organic matter (COD and BOD_5) removal was more efficient during the dry season, whereas suspended solids (TSS) and nutrients (except PO_4-P) were removed more efficiently during the wet season.

4. Discussion

4.1. *WWTP-Nakayiba wetland hydrological dynamics*

As observed in major tropical river systems,[41,46] rainfall is the main factor that determines seasons, and

Table 3. Mean (±SEM) concentrations for the WWTP effluent and wetland sampling sites for the monthly monitoring period (October 2012 to September 2013), $n = 12$.

	EC (μs cm^{-1})	TSS (mg l^{-1})	BOD (mg l^{-1})	COD (mg l^{-1})	TN (mg l^{-1})	NH_4-N (mg l^{-1})	TP (mg l^{-1})	PO_4–P (mg l^{-1})	FC (cfu/100 mls)
Upstream	104.2 ± 11.1	48 ± 4	20 ± 3	47 ± 3	1.9 ± 0.2	1.1 ± 0.1	3.5 ± 0.4	1.9 ± 0.2	5.0E + 03 ± 1.0E + 03
Effluent	1803.6 ± 93.0	331 ± 21	328 ± 14	592 ± 50	66.8 ± 3.2	37.6 ± 2.2	30.0 ± 2.5	24.1 ± 1.8	3.4E + 08 ± 6.1E + 07
Confluence	1656.4 ± 86.5	273 ± 23	282 ± 18	446 ± 28	52.7 ± 2.9	35.1 ± 2.9	26.0 ± 2.6	21.7 ± 1.5	2.4E + 08 ± 4.7E + 07
Wet 1	1136.2 ± 97.8	155 ± 19	106 ± 14	256 ± 20	45.7 ± 3.3	27.1 ± 2.5	19.6 ± 2.7	10.9 ± 0.9	8.5E + 06 ± 3.5E + 06
Wet 2	920.7 ± 62.7	101 ± 9	69 ± 7	205 ± 15	32.5 ± 2.6	20.6 ± 2.5	15.2 ± 1.5	9.1 ± 1.1	7.4E + 05 ± 3.2E + 05
Downstream	416.2 ± 64.4	72 ± 6	31 ± 2	107 ± 11	13.0 ± 0.8	6.2 ± 0.7	4.4 ± 0.5	2.1 ± 0.3	2.6E + 04 ± 1.5E + 04

Table 4. Removal efficiency (%) and removal rate coefficient K (m^{-1}) as a function of distance from the confluence to downstream.

	Removal efficiency (%)			
Sampling site	Wet 1	Wet 2	Downstream	
Distance L from the confluence	350 m	750 m	2150 m	Removal rate coefficient K (m^{-1})
TSS	42	62	73	0.0013
BOD_5	62	74	88	0.0020
COD	40	51	75	0.0011
TN	13	37	74	0.00063
NH_4-N	19	36	82	0.00077
TP	26	40	83	0.0008
PO_4-P	48	56	90	0.0014
FC	94	98	99	0.0082

Table 5. Seasonal comparison of mass flow (kg/day) and removal (%) of pollutants through Nakayiba Wetland.

Season	Parameter	TSS	BOD	COD	TN	NH_4-N	TP	PO_4-P	FC[a]
Dry	Confluence	7672	11514	18419	1617.6	1041.7	839.1	679.8	8.0
	Downstream	2421	1018	3892	452.2	232.2	177.7	57.2	3.0
	Mass removal %	68.0	91.2	78.9	72.0	77.7	78.8	91.6	5.0
Wet	Confluence	8111	6384	10142	1510.8	1045.8	732.7	613.0	8.6
	Downstream	2389	1030	3522	419.5	204.4	139.3	79.4	4.2
	Mass removal %	70.0	83.9	65.3	72.2	80.5	81.0	87.1	4.4

[a]FC is represented as log (cfu/100 mls) and log removal, respectively.

ultimately the hydrological regime of tropical wetland ecosystems.[47] Masaka WWTP effluent and Nakayiba Wetland stream discharge varied on a temporal scale and generally increased with an increase in monthly rainfall. This hydrological behaviour is also in tandem with observations in other tropical riverine–wetland systems [41,46–48] and conventional WWTP with inadequate stormwater flow separation and or retention systems.[30]

The wetland upstream flow regime exhibited a pulse response [41,49] to rainy events, which is typical of first-order streams with relatively short residence times.[49] Although, such short-term variations can best be measured with high-resolution data logging (in-situ methods) or spatial data interpolation of similar gauged streams/rivers,[50] the velocity-area method gave a good indication of the upstream temporal flow characteristics. At the confluence, about 50% of the surface flow could be accounted for, based on surface flow contributions from upstream and wastewater effluent from the WWTP. This was expected for this area characterized by steep topographic gradients, which normally have complex surface, subsurface and ground water hydrological exchanges.[49] Studies on wetland hydrology [51,52] under similar hydrogeomorpholocal characteristics have demonstrated that steep-slope topographic settings have significant influence on ground water discharge into wetland areas and stream channels.

The confluence–downstream wetland section exhibited a relatively balanced inflow–outflow discharge including attenuation of peak flow events during the rainy season. Like other studies on East African wetlands have demonstrated,[6,16,53] the hydro-geomorphological scale of tropical wetlands especially due to vegetation and topography is essential in regulating hydrological balance including but not limited to flood control. Therefore, the observed dampening of high flows in this section could be attributed to the relatively wide and long wetland section, also characterized by heterogenious vegetation type and structure.

4.2. Dynamics of WWTP pollution flux

The impact of rainfall onto the WWTP effluent flow rate (discharge) was particularly essential in understanding the effluent pollution load into the wetland. Although the WWTP was not designed as a combined sewerage treatment system,[30,34] the dilapidated municipal sewer infrastructure and poor drainage culminated into a combined flow system. Heavy rain events generally imposed pulse hydraulic loading [30,34] into the WWTP, whose impact according to the findings of this study was twofold: (1) an increase in total wastewater volumes beyond the capacity of the WWTP leading to overflows hence short circuiting [54] of untreated wastewater into the wetland and (2) enhanced massive mobilization and flush out of suspended solids and accumulated sludge,[30,54] hence high load of particulate-bound pollutants and pathogens into the receiving wetland buffer system.

The highest WWTP effluent concentration and pollution loads for suspended solids (TSS), organic matter (COD and BOD_5), nutrients (TN and TP) and pathogens (FC) were measured after peak rain events in April which is typical of combined sewerage systems.[30] Apart from precipitation, other factors that were observed to have influenced the poor effluent quality performance of the WWTP, based on Masaka local context include: (1) high WWTP influent concentration and load (Table 1), (2) inadequate development and separation of municipal sewerage and drainage infrastructure to regulate hydraulic loading of the WWTP,[30,49] (3) lack of combined sewerage storm water storage system to reduce the impact of high flows during peak rain events [30,49,55] and (4) inadequate operation and maintenance of the WWTP system, such as mechanical repairs and regular de-sludging to optimize wastewater hydraulics and treatment processes.[30,34,54]

4.3. WWTP performance against WDS

Generally, Masaka municipal WWTP performance in terms of effluent quality demonstrates some of the typical challenges of wastewater management not only in Uganda, but also other urban areas in sub-Saharan Africa.[8,12,23] Although the WWTP was designed as a centralized conventional mechanically aerated bioreactor system, to provide primary and secondary treatment to municipal wastewater prior to discharge, the effluent concentrations were in the range of raw or pre-settled sewage with minimum treatment.[28,30,33,56] Additionally, despite the fact that effluent quality depends on many other factors including influent characteristics, the operation and maintenance of the WWTP are paramount [11,30] and was particularly inadequate in Masaka. Therefore, low sustainability of centralized mechanical wastewater treatment technologies in developing countries [12,15,23,31] is critically highlighted from this research. In addition, the effluent quality performance pinpoints a major capacity gap not only in terms of utility investment is sewerage infrastructure hence compliance to WDS, but also inadequate monitoring and enforcement of WDS by the relevant government regulatory agencies [11] to ensure reliability of treatment [38] and public health/environmental safety.

4.4. Nakayiba wetland pollution buffering capacity

Despite the deficiency in the performance of Masaka WWTP, Nakayiba wetland provided an effective buffer for attenuation of downstream environmental pollution. Overall, the wetland pollution removal for suspended solids, pathogens, organic matter and nutrients were found to be over 65% reduction compared with the inflow load. Many other studies have demonstrated that wetland ecosystems in the Lake Victoria region play a major role in pollution abatement and water quality regulation [6,13,16,19,20,53] as exhibited in Nakayiba wetland. The natural wetland wastewater treatment processes including the physical, hydrological and biogeochemical dynamics are also well documented.[22,24] The heterogeneous vegetation structure, soil and stream–wetland hydrological exchange processes coupled with various hydraulic retention opportunities [22,24,26,57] are vital pathways for effective mass removal of pollutants in both natural and constructed wetlands.

The microbial activity, which is a key driver in processing and transformation of nutrients and carbon sequestration,[22,29,30,47,58] was particularly exhibited by the effective degradation of organic matter. With a mean WWTP effluent BOD_5 of $328 \pm 14\ \mathrm{mg\ l^{-1}}$, the biodegradable organic matter input (organic pollution) into the wetland at the confluence site was very high. Also, the COD/BOD_5 ratio (Figure 4) at the confluence was below 2.0 and within the range of raw or primary settled sewage.[30,34] Although dilution may have been a key factor, a general increase in the COD/BOD_5 ratio from the confluence through *Wet 1*, *Wet 2* to the downstream outflow was indicative of remarkable organic matter degradation hence potentially high microbial activity in the wetland system.

It was also observed that the first 750 m section of the wetland (35% of the total length of the study area) was found to be more efficient in pollution removal. This is in agreement with the non-linear behaviour of riparian buffer zones, which generally show a higher removal efficiency of materials in the first sections compared with the remote parts.[44] It was also observed that the downstream residual concentration was generally higher compared with

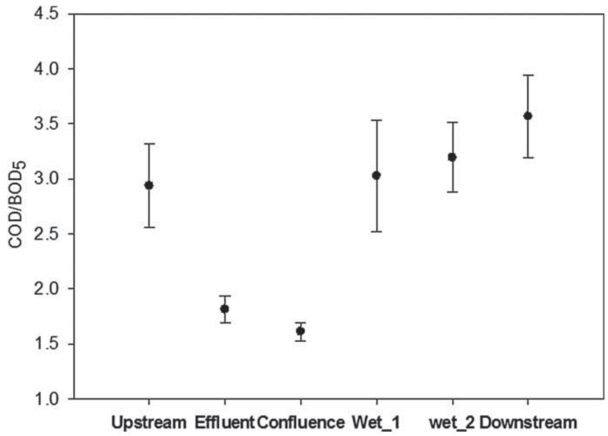

Figure 4. Variation of COD/BOD_5 ($n = 12$) ratio for the WWTP effluent along the wetland flow gradient.

the upstream reference sampling site for nutrients and organic matter. This may be expected due to internal physical and biogeochemical processes which can influence mobilization and release pathways.[13,24,33,47,58]

5. Conclusions and recommendations

The deficiency in performance of Masaka WWTP showed a great challenge of wastewater management in sub-Saharan Africa in terms of environmental pollution. Remnants of such centralized wastewater systems and technologies in municipalities and cities of this region are wide spread, but are overloaded, dilapidated and with significant operation and maintenance deficits.

The Masaka case clearly demonstrated that even when monitoring data indicated consistent poor performance and operational failure of the effluent quality against the WDS, the status has been maintained over the years. This is indicative of lack of investment and/or inadequate capacity to operate and maintain such technologies.

Although the natural wetland buffer offered a robust opportunity for wastewater treatment and downstream pollution control (for pathogens, organic matter, suspended solids and nutrients) to NWSC and Masaka Municipality, the long-term response of the system to high pollution loads is not certain and provides future environmental and public health risks

It can therefore be recommended from this study that

(1) The existing WWTP need to be refurbished to optimize its treatment capacity/efficiency and reduce downstream pollution.
(2) Locally sustainable on-site sanitation and decentralized wastewater treatment systems such as constructed wetlands need to be explored and tested for long-term sanitation planning and investment in Masaka Municipality.
(3) Nakayiba wetland needs to be integrated in the long-term municipal physical development plan to safeguard its landscape functions especially enhancing wastewater treatment and sanitation management of Masaka Urban area.

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Disclosure statement

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Performance of subsurface flow constructed wetland mesocoms in enhancing nutrient removal from municipal wastewater in warm tropical environments

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Nutrient rich effluents from municipal wastewater treatment plants (WWTPs) have significantly contributed to eutrophication of surface waters in East Africa. We used vertical (VF, 0.2m^2) and horizontal (HF, 0.45m^2) subsurface flow (SSF) constructed wetland (CW) configurations to design single stage mesocosms planted with *Cyperus papyrus*, and operating under batch hydraulic loading regime (at mean organic loading rate of 20 g COD m^{-2} d^{-1} for HF and 77 g COD m^{-2} d^{-1} for VF beds). The aim of the investigation was to assess the performance of SSF CWs as hotspots of nutrient transformation and removal processes between the WWTP and the receiving natural urban wetland environment in Kampala, Uganda. *C. papyrus* coupled with batch loading enhanced aerobic conditions and high efficiency regarding elimination of suspended solids, organic matter and nutrients with significant performance ($P < 0.05$) in VF mesocosms. The mean N and P elimination rates (g m^{-2} d^{-1}) were 9.16 **N** and 5.41 **P** in planted VF, and 1.97 **N** and 1.02 **P** in planted HF mesocosms, respectively. The lowest mean nutrient elimination rate (g m^{-2} d^{-1}) was 1.10 **N** and 0.62 **P** found in unplanted HF controls. Nutrient accumulation in plants and sediment retention were found to be essential processes. It can be concluded that whereas the SSF CWs may not function as independent treatment systems, they could be easily adopted as flexible and technologically less intensive options at a local scale, to increase the resilience of receiving environments by buffering peak loads from WWTPs.

Key words: Municipal wastewater, Constructed wetland mesocosms, Nutrient elimination, Batch hydraulic loading, Cyperus papyrus

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1.0 Introduction

Existing urban sanitation systems and wastewater treatment technologies in developing countries are largely inadequate and deficient [1, 2]. One of the most significant consequences of the prevailing inadequate sanitation and deficiency in wastewater treatment, is increased eutrophication of surface waters [3, 4] due to high nutrient loads [5] as has been observed in the East African region [3, 4, 6, 7]. The rapid urbanization trend in sub-Saharan Africa [8], has been associated with the exacerbation of the eutrophication problem, due to; (i) increased generation and disposal of nutrient rich untreated wastewater [3, 6, 8, 9] (ii) inadequate development of appropriate technologies and infrastructure to suit wastewater management challenges at a local scale [1, 10, 11, 12] and (iii) rapid degradation of natural ecosystems in urban landscapes [7, 13, 14], especially with regard to wetlands and floodplains which act as nutrient removal and transformation hotspots [15, 16].

Constructed wetlands (CWs) as natural wastewater treatment technologies and sustainable sanitation systems [1, 11] have gained enormous attention across the globe [1, 10, 17, 18, 19], including East Africa. However, like other regions of the developing world, the application potential of CWs in East Africa [6] has not been translated into reasonable technological uptake and adoption [1, 20], compared to the research efforts undertaken. This could be attributed to among other reasons, limited focus on contextualization of research to address specific local pressing needs and challenges regarding wastewater management in the region.

With the increasing need to remediate eutrophication of surface waters, CWs are critically relevant as municipal wastewater treatment buffer systems, since they have exhibited high efficiency in nutrients removal [11, 19, 21, 22, 23]. Various studies have demonstrated effective nutrients removal by subsurface flow (SSF) CWs with more focus on nitrogen elimination [17, 21, 24, 25, 26] from municipal or domestic wastewater. Specifically, the vertical subsurface flow (VF) system, with an effective oxygen transfer mechanism, has exhibited more efficiency regarding removal of nitrogen (N) [25, 26, 27] compared to the horizontal subsurface flow (HF) system [28]. However, a combination of the VF and HF into hybrid systems [21, 28, 29] has been recommended due to the provision of multiple and coupled biophysical and chemical environments which enhance processes for effective elimination of N and P.

The warm climate in the East African region also provides a conducive environment for higher performance of CWs compared to the cold temperate regions [30, 31]. This is mainly due to the high temperature distribution throughout the annual cycle [32] which; (i) enhances faster rate of microbial growth hence higher intensity of biogeochemical processes [6, 31, 32, 33] and (ii) promotes high plant biomass production hence efficient nutrient uptake by a variety of macrophytes [34, 35, 36, 37, 38]. Besides provision of optimum conditions for effective nutrient removal, CWs in East African environments, especially VF systems, offer design flexibility in terms of space utilization [1, 19, 39] for sanitation systems in congested urban areas. This is an essential factor for; (i) integration of CWs into existing or planned wastewater treatment systems [1, 10, 11] (ii) provision of an option for sustainable urban onsite sanitation [11, 40] and (iii) use and integration into urban landscaping, aesthetics and drainage infrastructure [1, 22, 41].

This study therefore applied the concept of VF and HF CWs as a buffer for addressing the technical failure of conventional mechanical wastewater treatment systems in tropical East Africa focusing on enhancing nutrient removal processes. A one year WWTP effluent monitoring for Masaka municipality, Uganda (East Africa) [42], indicated 100% failure of the system in meeting the wastewater (effluent) discharge standards (WDS) for Uganda. Consequently, high nutrient (TN, 66.8±3.2 mgl^{-1} and TP, 30.0±2.5 mgl^{-1}) and organic matter (BOD_5, 328±14 mgl^{-1} and COD, 592±50 mgl^{-1}) effluent pollution delivery into a natural wetland system (natural environment) was found. This formed the basis for developing a buffer system which is an integral part of the WWTP to address treatment performance deficits, and also act as a continuum for the biogeochemical processes in the natural environment (rivers and wetland ecosystems).

Generally, the design criteria and application of SSF CWs buffer system for this study was based on the following assumptions. (i) The buffer system does not function as an independent wastewater treatment unit, but an integral part of the cleaning cascade to reduce downstream pollution (ii) on the SSF CW buffer system could function as an ecotone [4] and biogeochemical hotspot [15] to provide a continuum of treatment processes between the WWTP and receiving natural (wetland) environment (iii). Although natural wetlands provide both aerobic and anaerobic environments [16, 33] due to a fluctuating hydrological regime [32], the soils (hydric) are predominantly anaerobic or anoxic [16]. As a result, with constant supply of carbon from decaying macrophytes [16, 32], anaerobic microbial nutrient transformation processes such as denitrification [33, 43] are found to be significant especially in frequently flooded systems [32, 43, 44]. Consequently, establishment of SSF CWs was primarily targeting enhancing aerobic processes, especially nitrification. This is envisaged to facilitate a coupled N elimination with anaerobic mediated processes in a natural wetland.

Based on the assumptions, VF and HF mesocosms planted with *C. papyrus* and operating under batch hydraulic loading conditions were designed and constructed. It was hypothesized that the use of local *C. papyrus*, a highly productive macrophyte species [34, 37, 38, 45, 46] in the region, coupled with batch loading for both systems would enhance efficient oxygen transfer [9, 21, 30] and nutrient uptake [35, 37, 47]. The general objective of the study therefore, was to investigate the performance of VF and HF CWs as wastewater treatment buffer systems, for nutrients (N and P) transformation and removal from the municipal WWTP effluent before its discharge into the natural (wetland system) environment. The specific objectives included: (i) Physical and chemical characterization of the effluent from the different mesocosms including potential enrichment in dissolved oxygen (DO) and organic matter degradation, and (ii) Determining the N and P elimination rates, including removal processes by plant accumulation (*C. papyrus*) and sediment retention pathways.

2.0 Materials and Methods

2.1 Experimental set-up

2.1.1General Lay-out of the design

The mesocosms were set up in January 2013 and allowed to stabilize (for two months), to facilitate establishment of vegetation and microbial community. VF and HF CW designs at mesocosm scale were constructed using plastic drums (0.9m length and 0.5m diameter) at Bugolobi WWTP, Kampala Uganda. Each design comprised of four units, two planted with *C. papyrus* to enhance oxygen transfer and nutrient uptake, and the other two as controls without any plants except the substrate media as summarized in Table1 and illustrated in Figure 1.

2.1.2 HF mesocosm structural design

The HF mesocosm was constructed out of a drum, cut horizontally to make a total loading surface area of $0.45m^2$ (0.9m length x 0.5m width). Each HF mesocosm comprised of 0.1m inlet and outlet sections packed with substrate in the range of 16mm - 32mm grain size. The main treatment medium was packed with coarse gravel aggregates, with a grain size range of 4mm-8mm. The treatment bed was curved and generally shallow with a maximum depth of 0.3m along the central axis of the drum.

2.1.3 VF mesocosm structural design

The VF mesocosm with a loading surface area $0.2m^2$ (diameter = 0.5m), was packed with a main treatment media (0.4m depth) comprising of sand with a grain size range of 0.6-4mm (d_{10} = 0.35mm, d_{60} = 0.85mm). The treatment media was covered with a 0.1m surface layer of coarse gravel aggregates, with size range of 4mm-8mm to minimize surface erosion. The treatment media drainage was aided by a 0.2m bottom layer comprising of gravel with a size range of 16mm-32mm. To ensure even effluent outflow, and also reduce internal short circuiting, four equidistant outlets were bored around the circular bottom of the drainage layer and connected to a single PVC drainage pipe. To capture a homogenized sample of the effluent from the VF unit, a single outflow (tap) was connected to the PVC drainage pipe.

2.1.4 Wastewater loading and flow distribution

2.1.4.1 Estimation of water loss flux and compensation volume

Due to high temperatures typical in the tropical East African region, water loss by evapotranspiration (*ET*) can be significant [46] hence affecting the hydrology and treatment performance [48] of the SSF CW mesocosms. Therefore, preliminary water loss experiments were carried out to estimate the compensation volume for water loss fluxes, especially *ET*. The preliminary hydrological investigations were carried out in the 1^{st}- 3^{rd} week of March 2013, after establishment of the mesocosms. Each mesocosm was loaded with wastewater (between 50 mm d^{-1} to 80 mm d^{-1}) which was held for 48hrs. After the holding period, each mesocosm was completely drained into plastic basins. The collected effluent was transferred into 1 Litre measuring cylinders for determining the residual volume. In case of any rains, precipitation was established using a rain gauge installed on site, at the Bugolobi WWTP. Whereas gross water loss in unplanted control units was assumed to be due to direct evaporation, water loss in planted mesocosms was attributed to *ET*. *ET* (and direct evaporation for unplanted units) was estimated using the water balance equation (1).

$$Q_{in} = Q_{out} + ET - P \qquad (1)$$

Where Q_{in} is the amount of wastewater loaded at the beginning of the experiment (mm d^{-1}), Q_{out} is the amount of the effluent drained after the holding period (mm d^{-1}), ET is evapotranspiration (for planted systems) or direct evaporation (from unplanted systems), P is amount of water added to the mesocosm (mm d^{-1}) due to precipitation. It was also assumed that the difference between ET in planted and unplanted systems was due to water uptake and storage by plants.

2.1.4.2 Loading and flow distribution

Treated wastewater (effluent) from the WWTP was pumped into a $1m^3$ reservoir tank elevated at a 10m rooftop base. The reservoir tank was then used to supply wastewater to the mesocosms by gravity through a pipe distribution network (Figure 1). Both the VF and HF mesocosms were loaded batch wise, twice a day, i.e. at 6:00am and 6:00pm. The volume of wastewater loaded in each mesocosm was manually controlled using a tap. Pressure loss in the distribution pipe system had negligible impact on the hydraulic experimental set-up, since the loading regime was intermittent and controlled manually at the inlet of each mesocosm.

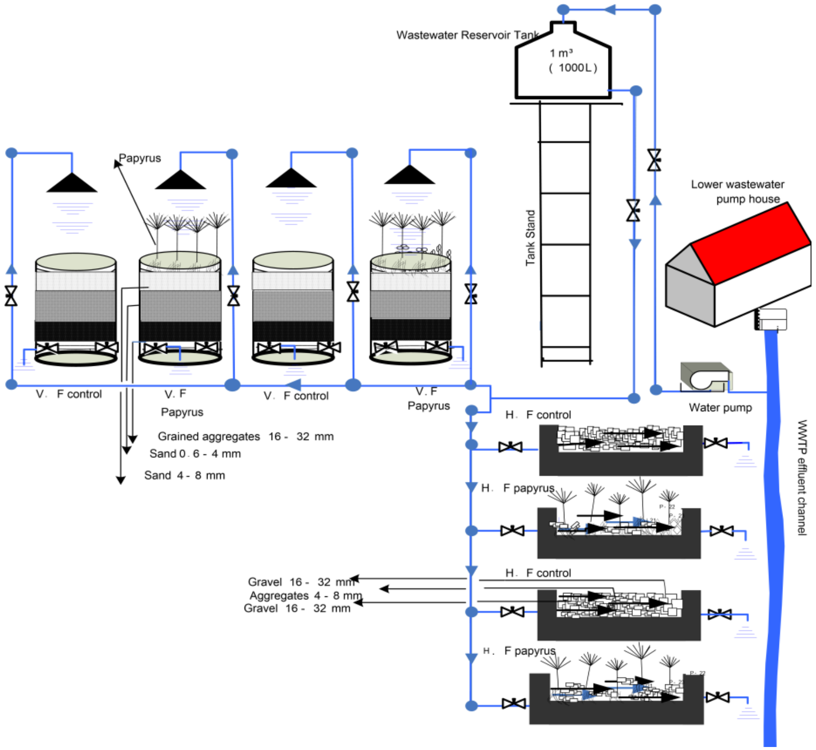


Figure 1: General Layout and design of the WBS mesocosms set at Bugolobi WWTP, Kampala, Uganda.

Table 1: Characterization of the mesocosms design and set-up

Mesocosm Unit ***V***= *Vertical Flow*, ***H***=*Horizontal Flow*	Plants	Surface Area (m^2)	Main Treatment media (**V**, 0.4m depth; **H**, 0.5m length)	Volumetric Load $m^3\ d^{-1}$	Theoretical **COD** Loading Rate (mean conc. 582 mgl^{-1}) g **COD** $m^{-2}\ d^{-1}$	Theoretical **BOD** Loading Rate (mean conc. 316 mgl^{-1}) g $\mathbf{BOD_5}$ $m^{-2}\ d^{-1}$
H1 and H2	No Plants	0.45	Coarse grained aggregates, 4-8mm	0.035	45	25
H3 and H4	*C. Papyrus*	0.45	Coarse grained aggregates, 4-8mm	0.035	45	25
V1 and V2	No Plants	0.20	Sand, 0.6-4mm (d_{10} = 0.35mm, d_{60} = 0.85mm)	0.055	160	90
V3 and V4	*C. Papyrus*	0.20	Sand, 0.6-4mm (d_{10} = 0.35mm, d_{60} =	0.055	160	90

0.85mm)

The VF mesocosms were irrigated with 55l d^{-1} ($0.055m^3d^{-1}$) of wastewater using a plastic shower head, whereas the HF mesocosms were loaded with 35l d^{-1} ($0.035m^3d^{-1}$) through a perforated PVC pipe at the inlet. Effluent flow in both the VF and HF mesocosms was controlled using taps at an average outflow rate of 50l d^{-1} ($0.05m^3d^{-1}$) and 30l d^{-1} ($0.03m^3d^{-1}$), respectively. A hypothetical residual volume of 5 l d^{-1} to compensate for plant uptake and *ET* (section 3.1) was maintained.

2.1.5 Papyrus planting

Considering the high growth rate of *C. papyrus* characterized by extensive rhizomes and above ground biomass accumulation [35, 37] compared to the mesocosm loading surface area, only one shoot was planted per experimental unit in January 2013. The planted mesocosms were then loaded with wastewater as described in section 2.1.4.2 for 8 weeks to allow for full system establishment.

2.2 Wastewater quality monitoring

Wastewater samples (0.5 L) of the influent from the distribution reservoir and effluent from each mesocosm were taken bi-weekly for 16 months from March 2013 to June 2014. To obtain a representative sample, a plastic container was placed at the outlet of each mesocosm unit and the effluent allowed to flow at the set experimental flow rate described in section 2.1.4.2. During sampling, on-site measurements were also taken using portable meters for; temperature and electrical conductivity (EC) (WTW Cond 3301-WTW GmbH, Weilheim, Germany), pH (WTW pH 3301-WTW GmbH, Weilheim, Germany) and DO (Model HACH, HQ40d). All collected samples were transported in a cold box maintained at about 4^oC, to the National Water and Sewerage Corporation (NWSC) central laboratories, Bugolobi for analysis within 12 hours. All samples were prepared and analyzed in the laboratory following standard methods for examination of water and wastewater [49]. Filtration was done using 0.45μm glass fiber filters and suspended solids determined by the gravimetric method. Organic matter was analyzed using biochemical oxygen demand (BOD_5) (by Winkler's method) and chemical oxygen demand (COD) (by closed reflux-titrimetric method). All colorimetric measurements for nutrient analysis were done using the HACH DR 5000 spectrophotometer. Ammonium-nitrogen (NH_4^+) was determined by direct nesslerization, nitrite-nitrogen (NO_2^-) by diazotisation using sulphanilamide and N-(1-napthyl) ethylenediaminedihydrochloride, nitrate-nitrogen (NO_3^-) by sodium salicylate method and total nitrogen (TN) by sodium salicylate method after persulphate digestion [49, 50, 51]. Both total phosphorus (TP) (after persulphate digestion) and orthophosphate (PO_4^{3-}) were determined by the ascorbic acid method [49, 50].

2.3 Vegetation biomass and nutrient analysis

Permanent removal of nutrients due to vegetation uptake from CWs can only be achieved with a regular harvesting regime [19, 28, 34, 36, 52]. Various studies on *C. papyrus* indicated that nutrient uptake is highest during the maximum growth phase (about 2-5 months growing period) [52, 53]. As a result, 3 harvesting cycles of 6 months each, were adopted during the 18 months study period. The harvesting activity only targeted the above ground plant biomass for two main reasons; (i) removal of rhizomes every 6 months could result into extreme disturbance of the established substrate and rhizosphere and (ii) regarding routine operation and maintenance, it is more feasible and less expensive to regularly remove above ground biomass than uprooting the entire system.

During each harvesting campaign, all above ground standing biomass in each mesocosm was cut (at about 0.1m from ground level) and weighed to determine fresh weight (kg). A 1 kg fresh weight sub-sample [53] (composite sample consisting of umbels and culms of the papyrus plant) was taken from each mesocosm for sun drying (until no further change in weight). The dry weight was then used to estimate total productivity (biomass) (kg DW m^{-2}). For nutrient analysis, the dry sample was crushed into powder form for P and N nutrient analysis [47, 53, 54] at the Soil Laboratory, College of Agricultural and Environmental Sciences, Makerere University, following the multi-element plant analysis technique after digestion [55].

2.4 Sediment nutrient analysis in the treatment media

To further characterise the potential retention of N and P in the treatment media of the mesocosms (planted and unplanted), four (4) and six (6) substrate replicate samples (based on mesocosm differences in surface area) were collected from the VF and HF mesocosms, respectively. The sampling was done at the same time as the vegetation harvesting following the 6 months cycle. The collection of samples was done using a hand held simple PVC plastic core (5cm diameter, 50cm length) at a maximum depth of 15cm and 10cm for VF and HF mesocosms, respectively. All samples were immediately transported in polyethylene bags to the Soil Laboratory, College of Agricultural and Environmental Sciences, Makerere University. In the laboratory, replicate samples from each mesocosm were manually sorted to form a homogenous silt-sand grain size sediment range for easy homogenisation and further processing. For course gravel sizes from the HF, biofilm, silt and other trapped suspended materials were scraped off manually to form the main sediment sample. All replicate samples from each mesocosm were then combined as a single sample following compositing standard procedures [56]. The sediment samples were gradually oven dried at 45^{o}C for a week to preserve the original chemical composition, which would otherwise be altered if rapidly exposed to excessive heat. A dry composite sediment sample of 0.3g each was then processed by digestion for nutrient extraction before colorimetric analysis for determination of TN and TP following standard methods for soil chemical analysis [57, 58].

2.5 Data analysis

Physical and chemical variables were primarily summarised in tables and compared between mesocosms based on descriptive statistics in MS Excel 2010. Descriptive comparison graphs were developed using Sigma plot 12.5. Coefficient of variation (CV) was calculated to determine the variability (fluctuation) of wastewater quality during the entire study period. The BOD_5/COD ratio was calculated to determine the biodegradability [9, 59] of organic matter of the influent wastewater. Comparison of mesocosms performance regarding reduction of influent concentrations was done by analysis of variance (ANOVA, significance level $\alpha = 0.05$), assuming homogeneity of variances after Bartlett's test. Tukey's test was used to elucidate differences between means of treatments. All statistical analyses were performed using the R-console (Version 3.0.2). Removal efficiency of suspended solids, organic matter (BOD_5 and COD) and nutrients (TN, NH_4-N, NO_3-N, and TP) was quantified based on mesocosms influent and effluent loads using equation (2)

$$Removal\ efficiency\ \% = \frac{(Q_{in} \times C_{in}) - (Q_{out} \times C_{out})}{(Q_{in} \times C_{in})} \times 100 \qquad (2)$$

Where Q_{in} and Q_{out} are influent and effluent volumetric loads ($m^3\ d^{-1}$) respectively, whereas C_{in} and C_{out} are influent and effluent concentrations ($kg\ m^{-3}$), respectively. In addition, areal based elimination rate ($g\ m^{-2}\ d^{-1}$) for organic matter and nutrients was calculated as a ratio of the load removal ($g\ d^{-1}$) to the loading surface area (m^2) of the mesocosm. This criterion was also used to calculate the *C. Papyrus* nutrient removal rate after establishing the N and P content of the harvested dry biomass. Means of N and P content were compared to establish mesocosms performance regarding sediment nutrient retention.

3.0 Results

3.1 Water loss flux and compensation volume

A comparison of water fluxes in the different mesocosms is summarized in Table 2. It was observed that although all precautions were taken to ensure accuracy of measurements, some errors in the water balance were encountered due to (i) residual volume retained in treatment media and rhizosphere and (ii) inaccuracies due to effluent transfer from the collection basin into the measuring cylinders (indirect measurement method).

Generally, the planted mesocosms exhibited higher water loss than the unplanted ones due to *C. papyrus* contribution to *ET*. In addition, water loss from the VF systems was greater than that of the HF systems due to the higher above ground *C. Papyrus* production (section 3.5). The average water loss due to *ET* and plant uptake was estimated to be 10.8mm d^{-1} (or ≈ 2.16 l d^{-1}). Therefore to cater for potential water losses and maintain a reasonable residual volume for the *C. papyrus* plants, a compensation volume of 5 l d^{-1} (approximately double the average water loss) was used for subsequent volumetric loading during the entire study period (section 2.1.4.2) .

Table 2: Precipitation, gross water loss, evapotranspiration (*ET*), and estimated plant contribution to *ET* for the different mesocosms. ** Not applicable

Mesocosms	Q_{in} mm d^{-1}	Q_{out} mm d^{-1}	*P* mm d^{-1}	*ET* mm d^{-1}	Plant contribution to *ET* mm d^{-1}
HF-unplanted	75.16±0.11	67.23±1.86	5.10±4.50	3.50±1.10	**
HF-planted	76.42±1.05	58.11±2.07	5.10±4.50	8.10±1.60	4.60±0.90
VF-unplanted	50.38±1.07	47.92±0.80	5.10±4.50	5.80±1.30	**
VF-planted	53.47±1.12	47.48±0.85	5.10±4.50	13.50±2.10	7.70±1.50

Table 3: Physical and chemical characterization (Mean ± SEM, n=32) of the influent and mesocosms effluent from March 2013 to June 2014. Uganda WDS for EC, TSS, BOD_5 and COD are 1500 µS/cm, 100 mgl^{-1}, 50 mgl^{-1} and 100 mgl^{-1} respectively.

Mesocosm Unit	*pH*	Temp ºC	EC µS/cm	DO mgl^{-1}	TSS mgl^{-1}	BOD_5 mgl^{-1}	COD mgl^{-1}
Influent	7.5 ±0.1^a	24.3 ±0.2^a	1645 ±94^a	1.1 ±0.1^a	179 ±11^a	218 ±56^a	303 ±16^a
H1^{NP}	7.4 ±0.1^a	22.1 ±0.2^a	1184 ±61^b	1.3 ±0.1^a	73 ±5^b	68 ±4^b	143 ±5^b
H2^{NP}	7.6 ±0.1^a	23.2 ±0.2^a	1180 ±52^b	1.4 ±0.2^a	71 ±4^b	66 ±4^b	136 ±6^b
H3^{P}	6.9 ±0.1^a	24.0 ±0.2^a	1257 ±56^c	2.4 ±0.2^b	55 ±3^b	57 ±5^b	120 ±7^c
H4^{P}	7.3 ±0.1^a	23.5 ±0.2^a	1353 ±58^c	2.7 ±0.2^b	56 ±4^b	62 ±4^b	128 ±7^c
V1^{NP}	7.5 ±0.1^a	23.1 ±0.2^a	1198 ±63^b	1.6 ±0.1^a	43 ±3^c	48 ±3^c	119 ±6^c
V2^{NP}	7.1 ±0.1^a	23.2 ±0.2^a	1178 ±61^b	3.2 ±0.2^b	43 ±3^c	52 ±4^c	121 ±5^c
V3^{P}	7.4 ±0.1^a	23.6 ±0.3^a	1312 ±64^c	4.6 ±0.3^c	33 ±3^d	34 ±3^d	83 ±4^d
V4^{P}	7.2 ±0.1^a	24.7 ±0.2^a	1375 ±53^c	4.5 ±0.2^c	39 ±3^d	39 ±3^d	85 ±4^d

^{NP} Not planted; ^{P} Planted; for each variable, values with similar superscripts are not significantly different (P > 0.05) whereas non uniform superscripts indicate significant difference (P < 0.05).

3.2 Influent-Effluent Physical and Chemical characteristics

The basic physical and chemical characteristics of the influent and effluent of the mesocosms are summarized in Table 3. Overall, there was no significant difference (*P>0.05*) in pH and temperature between each mesocosm influent and effluent values, and between the different mesocosms. The pH value was generally above 7.0 (slightly alkaline), except for H3 were slightly acidic conditions were encountered. Influent *EC* was significantly higher (*P<0.05*) than the effluent from all mesocosms, with lower values recorded in unplanted mesocosms compared to the planted, for both HF and VF CW mesocosms. All mesocosms achieved the *EC* WDS for Uganda. The effluent DO concentration in planted HF and VF mesocosms was significantly higher (*P<0.05*) than the influent, hence indicating efficient oxygen transfer into the treatment bed. On the contrary, for unplanted HF mesocosms, the observed slight increment in effluent DO concentration was statistically insignificant (*P>0.05*).

The Coefficient of variation (CV) analysis for TSS, BOD_5 and COD influent concentration depicted a fluctuation of 34%, 23% and 30%, respectively. Regardless of this fluctuation, the influent suspended solids and organic matter concentrations were beyond the WDS for Uganda, during the entire study period. The mean influent (±SEM) BOD/COD ratio was 0.59±0.03 and within the range of raw or pre-settled domestic/municipal wastewater. However, all mesocosms significantly reduced (*P<0.05*) influent TSS, BOD_5 and COD. Generally, planted VF and HF mesocosms were significantly (P<0.05) more efficient in reduction of TSS, BOD_5 and COD concentration. The TSS effluent concentration met the WDS for Uganda in all mesocosms. On the contrary, only planted VF mesocosms achieved the WDS for both BOD_5 and COD. The quantified mass (load), elimination rates and removal efficiency for suspended solids and organic matter are presented in Table 4. Although the VF mesocosms were subjected to higher loading rates, they exhibited higher elimination rates and hence greater removal efficiency for TSS (≥ 76%), BOD_5 (≥ 70%) and COD (≥ 60%) compared to the HF mesocosms with TSS (≤ 70%), BOD_5 (≤ 74%) and COD (≤ 60%). In addition, the planted mesocosms performed more efficiently compared to the unplanted, for both HF and VF.

3.4 N and P dynamics

Analysis of mesocosms influent and effluent concentrations for N and P parameters is summarized in Figure 2. The effluent concentrations for NH_4^+, TN, PO_4^{3-} and TP from all mesocosms were significantly lower (P<0.05) compared to the influent, although none of these parameters met the WDS for Uganda i.e. $NH_4^+ \leq 10$ mgl^{-1}, TN ≤ 10 mgl^{-1}, $PO_4^{3-} \leq 5$ mgl^{-1}and TP 10 mgl^{-1}, respectively. On the contrary, NO_3^-significantly increased (P<0.05) in the effluent except for H1, H2 and V1 mesocosms where no significant difference (*P>0.05*) with the influent concentration was found. It was observed that NO_3^-increased more significantly (*P<0.05*) in both HF and VF planted mesocosms compared to the unplanted control units. Also, the increase in NO_3^-in the planted mesocosms followed a significant reduction (*P<0.05*) in effluent NH_4^+ concentration. Moreover, the significant decrease in $NH_4^+$and increase in NO_3^-in Planted HF and VF WBS was in tandem with the high DO effluent concentration (Table 3) for these mesocosms. Regarding NO_2^-, although in general terms no significant difference (*P>0.05*) was found between the effluent and influent concentration, significantly higher mean effluent concentration (*P<0.05*) was found in planted VF mesocosms compared to other experimental units.

The results for nutrient concentrations were in agreement with mass (load) removal efficiencies and elimination rates for NH_4^+, NO_3^-, TN and TP as summarized in Table 5. Generally, planted HF and VF mesocosms exhibited remarkable N and P removal efficiency and elimination rates compared to the unplanted control experimental units. The mean N and P elimination rates (g m^{-2} d^{-1}) were 9.16 **N** and 5.41 **P** in planted VF; 6.75 **N** and 3.54 **P** in unplanted VF control; 1.97 **N** and 1.02 **P** in planted HF; and 1.10 **N** and 0.62 **P** in unplanted HF control mesocosms. Despite the higher loading rate, VF mesocosms performed better regarding N and P elimination. Planted VF mesocosms achieved the highest average mass removal efficiency of 77% for NH_4^+, 62% TN, and 60% TP compared to 67% for NH_4^+, 51% TN, and 43% TP determined in planted HF mesocosms. The lowest mass removal efficiency was found in HF unplanted control mesocosms.

Table 4: Suspended solids (TSS) and organic matter (BOD_5 and COD) influent and effluent loads, loading and elimination rates, and removal efficiencies for the HF and VF mesocosms (average values, n=32). [NP] Not Planted; [P] Planted

	TSS			BOD_5			COD		
	Load g d^{-1}	Loading/Elimination rate g TSS m^{-2} d^{-1}	Removal efficiency %	Load g d^{-1}	Loading/Elimination rate g BOD_5 m^{-2} d^{-1}	Removal efficiency %	Load g d^{-1}	Loading/Elimination rate g COD m^{-2} d^{-1}	Removal efficiency %
HF influent	**5.4**	**11.9**		**6.5**	**14.5**		**9.1**	**20.2**	
H1[NP]	2.2	7.1	59	2.0	10.0	69	4.3	10.7	53
H2[NP]	2.1	7.2	60	1.9	10.1	70	4.1	11.1	55
H3[P]	1.6	8.3	70	1.7	10.8	74	3.6	12.2	60
H4[P]	1.7	8.2	69	1.9	10.4	72	3.8	11.7	58
VF influent	**9.0**	**45.7**		**10.9**	**55.6**		**15.2**	**77.3**	
V1[NP]	2.1	34.8	77	2.4	43.3	73	5.9	47.0	61
V2[NP]	2.2	34.7	76	2.6	42.4	70	6.0	46.8	60
V3[P]	1.7	37.2	80	1.7	46.8	80	4.2	56.1	71
V4[P]	1.9	35.8	78	2.0	45.6	78	4.1	55.8	73

Table 5: NH_4^+-N, NO_3^--N, TN and TP influent and effluent loads, loading and elimination rates, and removal efficiencies for the HF and VF mesocosms (average values, n=32).

	NH_4^+-N			**NO_3^--N**		**TN**			**TP**		
	Load g d^{-1}	Loading/Elimination rate g m^{-2} d^{-1}	Removal efficiency %	Load g d^{-1}	Loading/Elimination rate g m^{-2} d^{-1}	Load g d^{-1}	Loading/Elimination rate g m^{-2} d^{-1}	Removal efficiency %	Load g d^{-1}	Loading/Elimination rate g m^{-2} d^{-1}	Removal efficiency %
HF influent	**1.40**	**3.17**		**0.08**	**0.17**	**1.80**	**3.94**		**1.10**	**2.38**	
H1^{NP}	0.82	1.32	42	0.06	0.04	1.30	1.05	27	0.80	0.66	28
H2^{NP}	0.83	1.30	41	0.07	0.00	1.30	1.10	28	0.83	0.58	24
H3^{P}	0.42	2.23	70	0.15	-0.16	0.87	2.00	52	0.54	1.18	50
H4^{P}	0.52	1.98	63	0.14	-0.14	0.90	1.94	50	0.70	0.85	36
VF influent	**2.40**	**12.14**		**0.13**	**0.64**	**3.00**	**15.07**		**1.80**	**9.10**	
V1^{NP}	1.00	6.93	58	0.18	-0.27	1.70	6.66	43	1.20	3.14	34
V2^{NP}	0.94	7.35	61	0.22	-0.51	1.60	6.83	46	1.00	3.93	44
V3^{P}	0.49	9.61	79	0.41	-1.44	1.20	8.95	60	0.70	5.54	61
V4^{P}	0.60	9.04	75	0.38	-1.31	1.10	9.36	63	0.75	5.28	58

^{NP} Not Planted; ^{P} Planted. Negative elimination values indicate increment in effluent nutrient load compared to the influent.

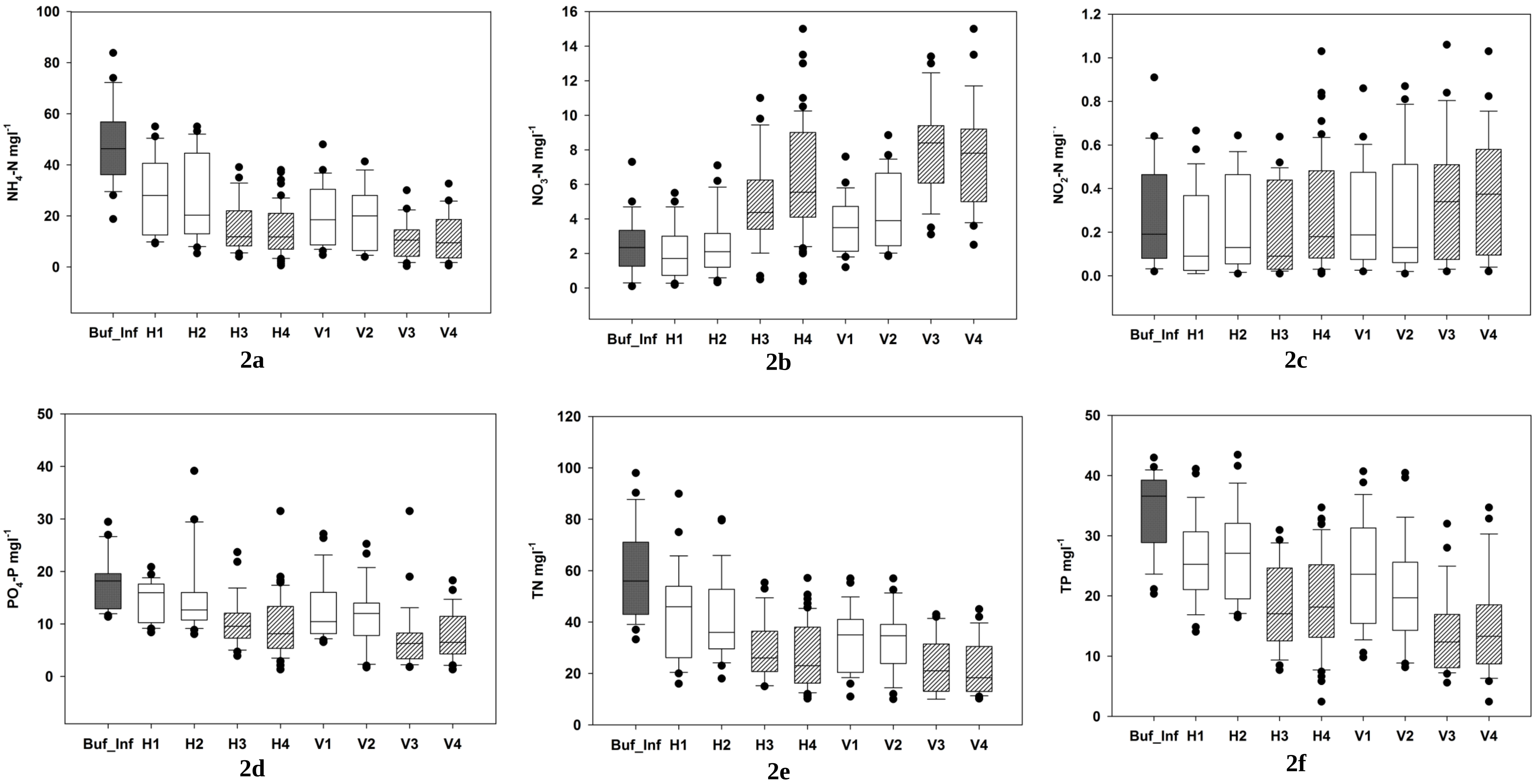


Figure 2: NH_4^+-N (2a), NO_3^--N (2b), NO_2^--N (2c), PO_4^{3-}-P (2d), TN(2e) and TP (2f) concentrations for the mesocosms Influent and Effluent (n=32). Box lines indicate upper and lower quartiles. Whiskers extend to the 95th and 5th percentiles.

3.5 Biomass production and plant nutrient content

Generally, higher biomass production of papyrus was achieved in the VF compared to the HF mesocosms (Figure 3a). This was consistent with the higher nutrient loading rate in VF (15.1 g N m^{-2} d^{-1} and 9.10 g P m^{-2} d^{-1}) compared to HF (3.94 g N m^{-2} d^{-1} and 2.38 g P m^{-2} d^{-1}) (Table 5) and the impact on water loss flux (Table 2). The VF mesocosm treatment-V4 exhibited the highest mean biomass production of 33.0 kg DW m^{-2} compared to the lowest, 14.0 kg DW m^2 measured in H4. Although there was no clear biomass production trend from the 1st to the 3rd harvesting cycle in all mesocosms, generally the 1st harvest showed a relatively lower biomass production compared to the 2nd and 3rd harvesting cycles.

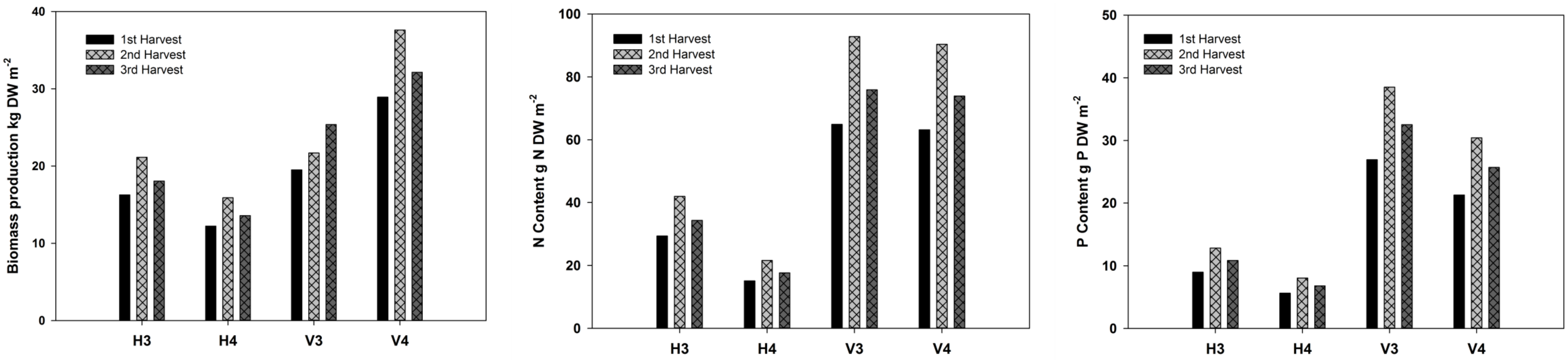
Table 5: A comparison of N and P content in harvested plant biomass compared to the overall TN and TP elimination performance in the planted mesocosms.

Mesocosm Unit	Overall TN Elimination rate g N m^{-2} d^{-1}	N removal by plant biomass harvesting g N m^{-2} d^{-1}	Contribution to TN removal %	Overall TP Elimination rate g P m^{-2} d^{-1}	P removal by plant biomass harvesting g P m^{-2} d^{-1}	Contribution to TP removal %
H3	2.00	0.20	10.0	1.18	0.06	5.1
H4	1.94	0.10	5.2	0.85	0.04	4.7
V3	8.95	0.43	4.8	5.54	0.18	3.3
V4	9.36	0.42	4.5	5.28	0.14	2.7

The N and P plant nutrient content hence accumulation in above ground tissues followed a similar trend for biomass production (Figure 3a and b). The highest N and P content were measured in VF mesocosms, where biomass production was highest. The average N and P content in V3 were 78.0 g N DW m^{-2} and 32.0 g P DW m^{-2}, respectively. This was also comparable with V4 which achieved 77.0 g N DW m^{-2} and 26.0 g P DW m^{-2}. HF mesocosm H4 recorded the lowest nutrient content of 18.0 g N DW m^{-2} and 7.0 g P DW m^{-2}, respectively. Based on the plant nutrient content, N and P elimination through harvesting of above ground biomass was quantified to elucidate plant removal contribution as summarized in Table 5. The VF mesocosms had the highest contribution to N and P elimination by above ground biomass harvesting, with an average of 0.43 g N m^{-2} d^{-1} and 0.16 g P m^{-2} d^{-1}, respectively. In comparison, the average biomass nutrient elimination from HF mesocosms was 0.15 g N m^{-2} d^{-1} and 0.05 g P m^{-2} d^{-1}. It was however noted that on average, the percentage contribution of biomass harvesting to the total N and P elimination was lower in VF (5% N and 3% P) compared to HF (8% N and 5% P) mesocosms.

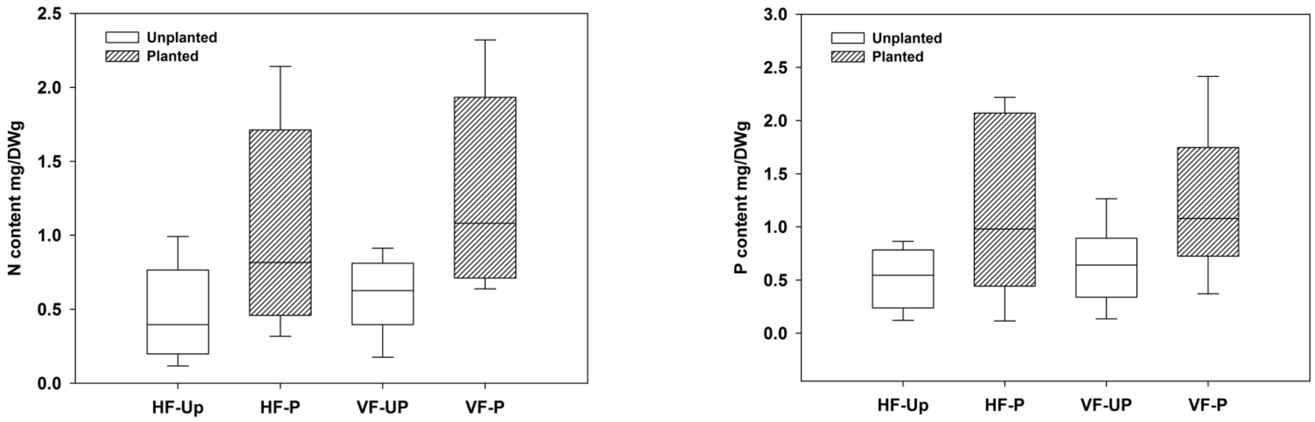
3.6 N and P sediment retention

A comparison of mean N and P content in the sediment of the VF and HF mesocosms is presented in Figure 4. Overall, sediment N (Figure 4a) and P (Figure 4b) content was significantly higher (*P<0.05*) in the planted mesocosms than the unplanted. However, despite the higher mean **N** (1.26 ±0.23 mg N /DW g) and **P** (1.22 ±0.24 mg P /DW g) content measured in planted VF compared to the planted HF (**N**, 1.02 ±0.24 mg N /DW g ; **P**, 1.99 ±0.29 mg P /DW g), no significant difference in sediment nutrient content (*P>0.05*) was found between the two mesocosm configurations. The lowest mean N and P sediment content was established in the unplanted HF (**N**, 0.46 ±0.11 mg N /DW g; **P**, 0.52 ±0.10 mg P /DW g), which was however not significantly (P>0.05) different, compared to the unplanted VF (**N**, 0.59 ±0.09 mg N /DW g); **P**, 0.66 ±0.13 mg P /DW g).



3a **3b** **3c**

Figure 3: Comparison of C. papyrus total biomass production (Dry Weight-DW) (3a), total Nitrogen content (3b) and total Phosphorus content (3c) during the three (3) 6 months harvesting/growing cycles for the study period january 2013 to June 2014.



4a **4b**

Figure 4: Mean N (4a) and P (4b) content in the sediment of the planted and unplanted mesocosms treatment bed (n= 6). Box lines indicate upper and lower quartiles. Whiskers extend to the 95th and 5th percentiles.

4.0 Discussion

4.1 Physical chemical environment characteristics

The physical-chemical environment of the mesocosms regarding pH and temperature did not vary significantly, and was within the optimum range for most microbial mediated biogeochemical processes for wastewater treatment [9, 59, 60]. Influent and effluent pH was in the range of 6.5-8.5, whereas temperature varied from a minimum of 20 ºC to a maximum of about 27 ºC. Under these environmental conditions, essential microbial driven biogeochemical processes such as ammonification, nitrification, and denitrification have been found to be efficient [9, 15, 28, 59, 60, 61] provided other performance factors are favorable.

Besides pH and temperature, the dynamics of DO in CWs is a key driver of N and P cycling processes [9, 28], hence was a critical parameter for the design and performance assessment of the mesocosms in this study. The batch loading method provided a drying and rewetting regime [43] in all mesocosms hence periodic influx of atmospheric oxygen [21, 25, 30, 62]. Consequently, all mesocosms showed higher DO concentration ($\geq$ 1.3 mg l^{-1}) in the effluent, with the highest mean DO of 4.25 ±0.25 mg l^{-1} attained in planted VF mesocosms. Although effluent DO does not necessarily fully explain the coupled heterogeneous substrate aerobic-anaerobic zones [9, 28], the observed significantly higher effluent DO concentration in planted mesocosms could be attributed to efficient transfer of oxygen into the rhizosphere by *C. papyrus* [35, 37]. Moreover, even predominantly anaerobic HF systems [17, 19, 28] exhibited high aerobic effluent in the planted mesocosms. An HF CW planted with *C. papyrus* in similar tropical conditions of Kenya [63] under continuous loading was found to be predominantly anaerobic with a mean effluent DO concentration of $\leq$ 0.6 mgl^{-1} compared to $\geq$ 2.0mgl^{-1} measured in the planted HF mesocosms for this study. Although the difference could be explained by other factors such as organic loading rate [19], it could be concluded that the observed high DO effluent concentration in the planted HF mesocosms for this study was a coupled role of papyrus plants, batch feeding mode and a shallow substrate bed.

The role of plants regarding enhancing aerobic conditions in the treatment media as demonstrated in this study has been reported by other studies on CWs [20, 21, 34, 37]. Specifically, studies comparing planted VF and HF systems have reported increased performance regarding aerobic processes, especially nitrification in contrast to the non-planted systems [9, 21, 28, 37, 39]. For example, a study on substrate free constructed wetland in Uganda [37], showed that efficient oxygen transfer in the *C. papyrus* (used in this study) root structures enhanced establishment of epiphytic nitrifiers hence high nitrification rates compared to other macrophytes and unplanted experimental units.

4.1 Suspended solids and organic matter removal performance

Suspended solids and organic matter are essential routine parameters for assessing performance in wastewater treatment systems [2, 30, 31, 59, 64] since they are indicators of treatment efficiency regarding physical and biodegradation processes [9, 19, 59, 65]. Although, WWTP effluent was used as the influent for the mesocosms in this study, its quality regarding TSS, BOD_5 and COD was found to be within the range of raw or pre-settled sewage. Similar municipal wastewater treatment deficiency has been found in Masaka municipality, Uganda [42] and elsewhere in developing countries [2, 12]. However, results from this study indicated that the WBS significantly reduced the inflow mass loads for TSS, BOD_5 and COD by over 50%, with TSS effluent concentrations achieving the WDS ($\leq$100mgl^{-1}) for Uganda in all mesocosms.

Based on reviews [1, 9, 21, 66] and studies [20, 39, 63, 67, 68, 69] on municipal and domestic wastewater treatment using CWs worldwide, HFs and VFs have demonstrated efficient removal of suspended solids and organic matter in the range of 45% - 95%. Although not encountered in the mesocosms for this study, high suspended solids influent loads and retention rates in the treatment media can significantly affect CWs hydraulics due to clogging [19, 63, 69, 70]. Despite the high TSS concentration (179 ±11 mgl^{-1}) in the effluent, no clogging in all mesocosms was encountered during the study period, and this could be explained by the high biodegradability of the suspended solids after conventional pretreatment [59, 70]. The high influent BOD_5 and BOD_5/COD ratio ($\geq$ 0.5) indicated predominance of biodegradable matter [9, 59, 64] including organic particulate solids [70] and less of non-biodegradable materials. As a result, under induced aerobic conditions in the mesocosms, the filtered organic particulate solids were potentially, aerobically biodegraded by microbial processes [9, 60] leading to low TSS accumulation rate in the treatment media, as well as achieving significant reduction in effluent BOD_5. However, it has been observed that with persistent high influent TSS, the clogging problem cannot be avoided in sub-surface CWs on a long term scale (over 10 years) [70] depending on the operation and maintenance regime [30, 64].

Influent biodegradable organic matter (BOD_5 , 218 ±56 mgl^{-1}; COD, 303 ±16 mgl^{-1}; BOD5/COD ≥ 0.5) was high and provided organic carbon [31, 59, 64] that was degraded aerobically at high rates [9, 60]. This could therefore explain the high elimination rates for organic matter especially in VF mesocosms (Table 4). Removal of organic matter through the SSF CW mesocosms in this particular study was essential in addressing challenges of organic pollution [31, 62] from municipal wastewater in receiving environments which may result into (i) depletion of DO in surface waters, (ii) accumulation of organic suspended solids and associated public nuisances such as odour, and (iii) public health risks due to proliferation of pathogens in surface and ground water [11, 40, 59].

4.3 Nutrients removal efficiency

The removal of nutrients was generally high considering the fact that; (i) the influent concentrations (Figure 2) and load (Table 5) especially for NH_4^+, TN and TP were high (ii) the mesocosms were designed as single stage VF and HF systems (Figure 1), which have been found to be limited regarding nutrient removal [28] especially for N elimination [17, 21, 26]. However, based on the primary goal of enhancing the aerobic mediated processes especially nitrification, the mesocosms performance was satisfactory in the planted VF and HF experimental units.

Regarding N transformation and removal processes, all VF and planted HF mesocosms exhibited significant ($P<0.05$) reduction in NH_4^+ (hence high removal efficiencies as shown in Table 5) and increased NO_3^- concentrations (Table 3) in the effluent. Moreover these changes were also concomitant with the elevated DO effluent concentration in the same mesocosms compared to the unplanted HF control experimental units (Table 3). Therefore, it was evident from these findings that VF mesocosms effectively enhance nitrification, which is well documented from other studies [20, 25, 39] and performance reviews of CWs [21, 26, 28]. However, one remarkable observation from these findings was the enhanced nitrification process in planted HF mesocosms which could be explained by multiple oxygen influx options described in section 4.1. Unfortunately, it can be noted that use of the batch loading mode for HF could further reduce the typical low hydraulic loading rate [19, 26, 30, 64], hence increase in the area requirements for high municipal wastewater pollutant loads [19].

Although nitrification does not lead to total nitrogen removal [28], the planted mesocosms especially VF experimental units registered remarkable TN (≥ 60%) mass removal efficiency which could be attributed to processes applicable for the experimental set up, such as; biomass assimilation reported in VF CWs [9] and plant uptake by *C. papyrus* ([6, 35, 37]. Other processes that could potentially have a minor role but reported in similar systems include; completely autotrophic nitrite removal over nitrate [9], ammonia volatilization [28] and denitrification which is reported to occur in some substrate patches even when aerobic conditions dominate [9, 33, 60].

The Total N elimination rates especially in VF mesocosms were high compared to other documented systems treating municipal wastewater [26]. The elimination rate from the VF mesocosms ranged between 7-9 g N m^{-2} d^{-1}, which is in close range with some of the highest N elimination rates (up to 15 g N m^{-2} d^{-1}) from single stage VF systems documented in Thailand [26]. Systems with high N elimination rates have been significantly correlated with high organic loads [26, 31, 59] within the range of 86-167 g COD m^{-2} d^{-1} for CWs [26] coupled with high TN concentration as established in our experimental units. In addition, although *C. papyrus* N removal by above ground biomass harvesting was low compared to the overall TN removal (Table 5), its root system (which was not assessed) could potentially accumulate significant nutrient stocks as reported by other studies in the region [37, 38, 45, 53]. Another N retention pathway, which was remarkably more efficient in planted HF and VF mesocosms, was sediment retention (Figure 4) through effective filtration and settlement by C. papyrus roots. Although vulnerable to remobilization, removal of N by elimination of particulate and suspended organic matter through filtration and settlement processes has been reported to be essential in treatment wetlands [16, 30, 31, 52, 64].

Removal processes of P are more stochastic than N due to influence of multiple dynamic physical and chemical processes including but not limited to temperature, pH, redox potential, DO, COD [31, 59] and many others. However, based on the mesocosms design, physical and chemical characteristics in comparison to other studies regarding P removal processes from treatment wetlands [9, 19, 28, 37, 39, 45, 47, 60, 63, 71, 72], the significant overall P elimination rate (Table 5) especially in planted VF mesocosms could be attributed to (i) plant uptake and accumulation (Table 6) of regularly harvested above ground biomass including significant storage by below ground biomass [37, 38, 45, 47], which was not assessed in this study; (ii) high rate of aerobic microbial assimilation [9, 31, 59, 60], which could be significantly enhanced in planted VF mesocosms; (iii) particulate bound P removal through TSS (sediment) retention, which was efficiently exhibited in planted mesocosms [19, 35, 37, 72] and (iv) potential precipitation under aerobic conditions in the rhizosphere which has been reported in papyrus treatment systems [37, 47].

5.0 Conclusions

Generally, the study demonstrated the feasibility of using CWs as buffer systems for remediation of high organic and nutrient (N and P) pollution loads from deficient municipal wastewater treatment systems.

Planted VF and HF mesocosms were found to be more efficient regarding removal of suspended solids, organic matter and nutrients. HF systems were limited in efficiency regarding treating wastewater with high hydraulic loading rates compared to VF mesocosms.

Use of *C. papyrus* with batch hydraulic loading mode in both HF and VF mesocosms enhanced; (a) oxygen transfer in the treatment beds hence creating aerobic conditions suitable for efficient microbial processes with high metabolic rates, (b) aerobic organic matter degradation hence significant reduction of COD and BOD_5 loads to the natural environment, (c) NH_4^+removal through nitrification which provides a great opportunity for facilitating coupled denitrification with the receiving natural wetland, and (d) high TN and TP elimination rates through plant uptake and sediment retention

The use of CWs as wastewater treatment buffer systems can be easily adopted as flexible and technologically less intensive options at local scale to provide a natural continuum for nutrient removal processes from effluents of deficient WWTPs in East Africa. This can increase the resilience and overall buffering capacity of the receiving environment.

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Carbon and nitrogen gaseous fluxes from subsurface flow wetland buffer strips at mesocosm scale in East Africa

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This study investigated the carbon (CH_4, CO_2) and nitrogen (N_2O) gaseous fluxes as finger prints for microbial wastewater treatment processes in vertical (VF) and horizontal (HF) subsurface flow mesocosms, planted with *Cyperus papyrus* and operated under batch hydraulic loading. The closed chamber method was used to measure gaseous emissions for 12 weeks (April-June 2014) in Kampala, Uganda. Organic matter (OM) (BOD_5 and COD) and inorganic nitrogen (NH_4-N and NO_3-N) nutrient concentrations were monitored to estimate OM degradation rates and potential nitrification and denitrification. The highest mean CH_4 flux (mg CH_4-C m^{-2} h^{-1}) was 38.3 ± 3.3 in unplanted HF compared to the lowest (3.3 ± 0.4) established in planted VF mesocosms. CO_2 fluxes (mg CO_2-C m^{-2} h^{-1}) were significantly higher ($P < 0.05$) in planted mesocosms, with no significant difference ($P > 0.05$) between the planted HF (2213.5 ± 122.4) and VF (2272.8 ± 191.0) mesocosms. The high CO_2 flux was attributed to sufficient dissolved oxygen concentration which suggested high rates of aerobic OM degradation in planted mesocosms. On the contrary, N_2O fluxes were relatively low and did not vary significantly ($P > 0.05$) in all treatments. This could be attributed to the inhibition of denitrification under aerobic conditions, which however enhanced significant nitrification, especially in the planted mesocosms. Generally, in this study CO_2 gaseous flux, compared to CH_4 and N_2O fluxes, was the most significant under induced aerobic conditions enhanced by use of papyrus plants and an intermittent loading regime.

Key words: Wetland buffer strips, subsurface flow, organic matter, nitrogen, gas fluxes, East Africa

1.0 Introduction

Use of subsurface flow (SSF) constructed wetlands (CWs) regarding removal of organic matter (OM) and nitrogen (N) from wastewater has attracted enormous research attention with varying degree of full scale application on a global scale (Kivaisi 2001; Vymazal 2007; Wu et al., 2014). The OM degradation from wastewater is essential in mitigating the effects of organic pollution (Metcalf and Eddy 2004), especially oxygen depletion in receiving aquatic environments (Saeed and Sun 2012). On the other hand, N removal is critical to abate the increasing eutrophication problem (Rast 1996; Srivastava et al., 2008) as observed in the East African region (Co´zar et al., 2007; Machiwa 2003; Nyenje et al., 2012).

The role of microbial activity in SSF CWs as the main driver for OM degradation and nutrient removal processes especially N elimination, has been demonstrated by various studies (Faulwetter et al., 2009; Saeed and Sun 2012; Yeh et al., 2010). Consequently, technological innovations focused on optimizing environments which promote microbial mediated processes to enhance treatment efficiency have been prioritized (Saeed and Sun 2012; Wu et al., 2014). For example, oxygen availability and distribution as a function of hydraulics and hydrology (Kadlec and Wallace 2009; Langergraber et al., 2009), in the treatment beds of horizontal flow (HF) and vertical flow (VF) SSF-CWs is of great interest, since it influences the prevalence of aerobic or anaerobic conditions (Maltais-Landry et al., 2009b; Wu et al., 2014), with significant implications to the development of microbial communities and dominant processes therein (Langergraber et al., 2009; Meng et al., 2014; Saeed and Sun 2012; Samsó and García 2013).

Whereas aerobic environments and processes are predominant in VF beds, HF systems are mainly anaerobic (Kadlec and Wallace 2009; Langergraber et al., 2009; Vymazal 2007). Therefore, in order to enhance aerobic microbial processes which are considered to be limiting regarding N transformation through nitrification (Faulwetter et al., 2009; Meng et al., 2014; Saeed and Sun 2012), interventions such as; effluent recirculation, artificial aeration, tidal operation, drop aeration and the traditional use of macrophytes have been tested and implemented (Vymazal 2013; Wu et al., 2014). Moreover the current priority is focused on advancement in coupling aerobic-anaerobic environments to optimize N elimination through nitrification and denitrification processes (Ãvila et al., 2013a; Ãvila et al., 2013b; Langergraber et al., 2011; Meng et al., 2014; Vymazal 2013).

Nitrification mainly proceeds in presence of oxygen under aerobic environments (Crites et al., 2006; Metcalf and Eddy 2004), and forms the main mechanism for ammonia nitrogen (NH_4-N) removal from wastewater. This process is aided by a synergy of microbial mediated processes leading to the transformation of NH_4-N to nitrate nitrogen (NO_3-N) (Faulwetter et al., 2009; Saeed and Sun 2012; Wu et al., 2014). On the other hand, denitrification is regarded as the main total N elimination mechanism in CWs (Kadlec and Wallace 2009; Saeed and Sun 2012; Vymazal 2007). It generally proceeds under anaerobic conditions in which NO_3-N is converted to nitrogen gaseous products, mainly N_2 (nitrogen gas) and N_2O (nitrous oxide) (Faulwetter et al., 2009; Gutknecht et al., 2006; Huang et al., 2013; Metcalfe et al., 2007).

The OM degradation also occurs in both aerobic and anaerobic environments facilitated by a consortium of microbial species through different biogeochemical pathways. Under aerobic environments, OM degradation by aerobic heterotrophic bacteria proceeds faster through oxidation to release carbon dioxide (CO_2) as one of the main by-products (Faulwetter et al., 2009; Saeed and Sun 2012; Wu et al., 2014). On the contrary, anaerobic heterotrophic bacteria dominate anaerobic SSF beds (Faulwetter et al., 2009), and gradually degrade OM through coupled fermentation and methanogenesis processes to release methane (CH_4) as one of the main carbon gaseous by-products (Gutknecht et al., 2006; Liikanen et al., 2006; Mitsch et al., 2010).

The intensification of full scale SSF CWs performance has ultimately resulted into increased efficiency (Meng et al., 2014; Wu et al., 2014) regarding N and OM removal especially in Europe and North America (Canga et al., 2011; Vymazal 2007; Wu et al., 2015), with only a few cases of progress reported in other regions such as Asia (Canga et al., 2011; Jin et al., 2014) and South America (Zurita et al., 2012). With the current global agenda towards low carbon development as a mechanism for climate change mitigation and adaptation (Mulugetta and Urban 2010), CWs are vital wastewater treatment technological options especially in developing countries, since they are less energy intensive compared to the conventional technical systems (Langergraber 2013; Saeed and Sun 2012). Besides the limited external energy inputs, SSF CWs provide other complementally benefits for low economies like East Africa. These include among others; the low investment and operational costs (Langergraber 2013; Langergraber and Muellegger 2005) and abatement of the increasing surface and ground water pollution especially in urban areas (Bateganya et al., 2015; Katukiza et al., 2015; Kulabako et al., 2007; Nsubuga et al., 2004).

The aforementioned benefits notwithstanding, various studies have indicated that CWs can potentially be carbon sinks due to efficient sequestration mechanisms or sources with significant CO_2 and CH_4 emissions (de Klein and van der Werf 2014; Mander et al., 2008) depending on the hydrological regime and ultimately oxygen dynamics. Moreover CO_2 and CH_4 coupled with N_2O are major GHGs (de Klein and van der Werf 2014; Huang et al., 2013; Maltais-Landry et al., 2009b; Mander et al., 2014b), which can potentially offset the benefits of low cost pollution control of CWs, due to their potential impacts on the global climate (Maltais-Landry et al., 2009b). Investigation on GHG fluxes from SSF CWs have mainly been carried out in Europe and North America (Mander et al., 2008). Comparative studies in the tropics especially East African region are very scanty, if any at all.

The high nutrient and organic pollution loads (Bateganya et al., 2015; Machiwa 2003; Namaalwa et al., 2013; Nyenje et al., 2012) encountered in this region, coupled with high temperatures can potentially lead to high rates of microbial N and OM transformation processes with significant influence on release of CO_2, CH_4 and N_2O (de Klein and van der Werf 2014; Faulwetter et al., 2009; Huang et al., 2013; Mander et al., 2014b; Teiter and Mander 2005). The main objective of this study therefore, was to elucidate the potential rate of carbon (CO_2, CH_4) and nitrogen (N_2O) gaseous emissions as fingerprints for microbial wastewater treatment processes in VF and HF mesocosms under warm tropical environments of East Africa. The significance of this investigation was twofold; (i) contributing to the slim knowledge base of GHGs flux from SSF CWs in East Africa and (ii) providing an initial step for evidence based information on CWs as an input to the technological development shift regarding wastewater treatment, in tandem with the low carbon development agenda within the region.

2.0 Materials and Methods

2.1 Rationale of the Wetland Buffer strips design

The HF and VF mesocosms were designed as wetland buffer strips (WBSs), operated and monitored for 18 months (January 2013-June 2014) at Bugolobi WWTP, Kampala, with the overall goal of assessing their potential for attenuation of high organic and nutrient load from the effluents of deficient conventional wastewater treatment plants (WWTPs) (Bateganya et al., 2015) in the region. The WBS mesocosms were planted with *Cyperus papyrus*, a local macrophyte species and operated using a batch feeding mode to (i) promote oxygen transfer hence aerobic conditions into the treatment beds (Kadlec and Wallace 2009; Maltais-Landry et al., 2009c), (ii) enhance plant nutrient uptake as demonstrated in previous studies in the region (Kansiime et al., 2007a; Kansiime et al., 2007b; Kyambadde et al., 2004; Mugisha et al., 2007; Odong et al., 2013), and (iii) provide plant roots attachment and exudates in the rhizosphere (Wu et al., 2014) for enhancing microbial growth and activity (Saeed and Sun 2012; Srivastava et al., 2008).

2.2 HF and VF mesocosms structural design and operation

Both HF and VF WBS mesocosms (Fig. 1) were constructed using plastic drums (0.9m height and Ø 0.5m) and setup at Bugolobi WWTP, Kampala Uganda in January 2013. Duplicate treatment units were adopted; i.e. two (2) planted VF and HF mesocosms and two (2) unplanted HF and VF control treatments respectively, making a total of eight (8) treatment units. The HF mesocosms were made by cutting the drum horizontally to make a total surface area of 0.45m^2 (0.9m length x 0.5m width). The substrate bed comprised of 0.1m inlet and outlet sections, all packed with 16mm - 32mm gravel stones. The main treatment media had a total length of 0.5m and was packed with coarse gravel aggregates, with a grain size range of 4mm-8mm. The treatment bed had a curved bottom with a maximum depth of 0.3m along the central axis of the drum. The VF mecosoms were made by vertical orientation of the drum, which was cut at the top to make a total loading surface area of 0.2m^2 (Ø 0.5m). The main treatment media had a total depth of 0.4m comprising of sand with a grain size range of 0.6-4mm (d_{10} = 0.35mm, d_{60} = 0.85mm). To prevent surface erosion, the treatment media was covered with a 0.1m depth surface layer of coarse gravel aggregates, with a size range of 4mm-8mm. In addition, drainage of the VF system was aided by a 0.2m depth bottom layer comprising of gravel stones with a size range of 16mm-32mm. Effluent outflow was facilitated by four equidistant outlets bored around the circular bottom of the drainage layer and connected to a single PVC drainage pipe. A single outflow (tap) was connected to the PVC drainage pipe to enable sampling of a homogenized effluent.

Both VF and HF WBS mesocosms were operated under a batch hydraulic loading regime, at a mean organic loading rate of 20 g COD m^{-2} d^{-1} for HF and 77 g COD m^{-2} d^{-1} for VF beds respectively. Loading of the mesocosms was by gravity aided by a 1m^3 reservoir tank elevated at a 10m rooftop base. Both the VF and HF WBS mesocosms were loaded twice a day, i.e. at 6:00am and 6:00pm. The VF WBSs were irrigated with 55l d^{-1} (0.055m^{3}d^{-1}) of wastewater using a plastic shower head, whereas the HF was loaded with 35l d^{-1} (0.035m^{3}d^{-1}) through a perforated PVC pipe at the inlet. The volumetric inflow and outflow in each mesocosm was manually controlled using installed plastic taps. For general characterization of seasonal changes during WBSs monitoring, precipitation was also recorded using a rain gauge installed at the Bugolobi WWTP, Kampala.

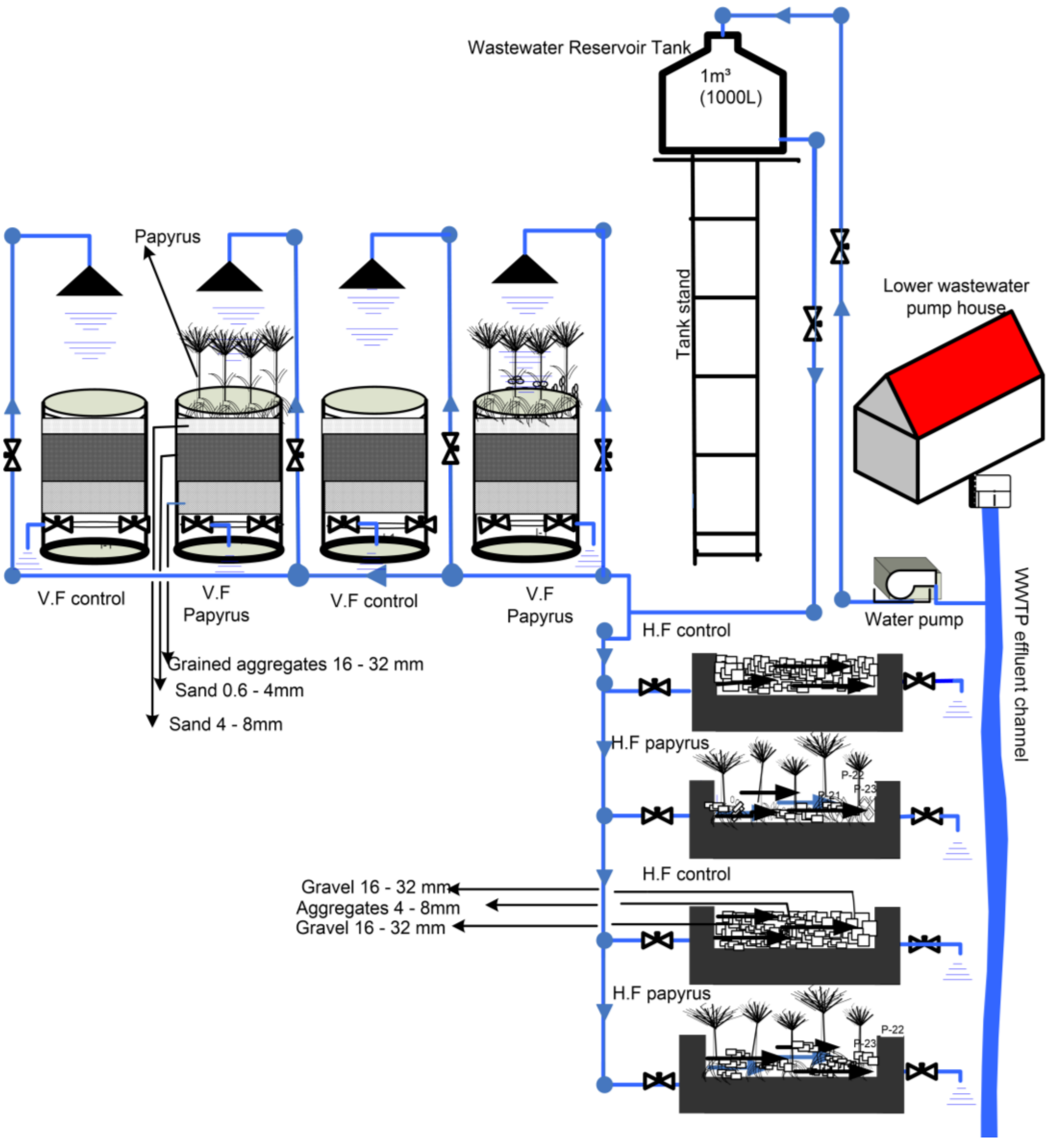


Figure 1: General layout of the HF and VF wetland mesocosms

2.3 Organic matter, ammonia and nitrate-nitrogen monitoring

To ascertain OM degradation efficiency, potential nitrification (by ammonia oxidation) and denitrification (by nitrate removal) in relation to gaseous fluxes, monitoring data for BOD_5, COD, NH_4-N and NO_3-N was obtained for a 16 months (March 2013-June 2014) period of WBS mesocosms operation. During the monitoring period, wastewater samples of the influent and effluent were taken bi-weekly and analyzed for physical, chemical and biological parameters at the National Water and Sewerage Corporation (NWSC) central laboratories, Bugolobi within 12 hours, following standard methods (APHA 1992). The OM content was analyzed as biochemical oxygen demand (BOD_5) (by Winkler's method) and chemical oxygen demand (COD) (by closed reflux-titrimetric method) respectively. Colorimetric measurements for NH_4-N and NO_3-N analysis were done using the HACH DR 5000 spectrophotometer. The NH_4-N concentration was determined by direct nesslerization, whereas NO_3-N was analyzed using the sodium salicylate method (APHA 1992; Johnes and Heathwaite 1992; Raveh and Avnimelech 1979). In addition, on-site measurements were taken using portable meters for temperature, dissolved oxygen (DO) (Model HACH, HQ40d) and pH (WTW pH 3301-WTW GmbH, Weilheim, Germany).

2.4 Gas sampling and analysis

Measurement of gaseous emissions was carried out weekly for a period of three months from April, 2014 (the 16th month of operation) until June 2014 (the 18th Month of operation). Apart from logistical limitations for undertaking continuous gaseous emissions monitoring, the timing and duration for gas sampling was justified by two other factors: (i) the gas measurement period covered peak rainy events in April, a wet-dry transition period in May, and a typical dry period in June. Therefore, the potential influence of seasonal changes regarding gaseous emissions (Mitsch et al., 2010) from the treatment beds was captured. (ii) After 14 months of operation, the microbial community structure in the mesocosms treatment beds was assumed to have been fully established and attained approximate equilibrium conditions (Ramond et al., 2012; Samsó and García 2013).

The closed gas chamber method (Weishampel and Kolka 2008) widely used in previous studies (Mander et al., 2008; Picek et al., 2007; Teiter and Mander 2005) was applied, with chamber size modifications to suite the mesocosms scale. A closed gas chamber with approximate dimensions of height 19cm, diameter 7.3cm, and volume of 4.2 liters was locally fabricated from white PVC plastic to minimize internal heating during measurement (Mander et al., 2008; Teiter and Mander 2005). The top closed part of the chamber was fabricated with a sampling port with a septum which would facilitate gas extraction with a syringe needle (Picek et al., 2007; Weishampel and Kolka 2008). A PVC plastic collar with fitting dimensions as the chamber was used. The collar was permanently inserted (approximately 5cm depth) in the treatment bed 24 hours before sampling to avoid influence of extreme substrate disturbance on gaseous fluxes (Weishampel and Kolka 2008). Due to the small surface area of the mesocosms, only one collar could be accommodated especially in planted WBS. Whereas the collar was inserted in the middle part of the unplanted treatment beds, available space besides the vegetation was utilized for the planted mesocosms (Picek et al., 2007).

To capture variations during each sampling day, two sampling campaigns where adopted i.e. 1 hour after wastewater loading in the morning (between 5 - 7am), and then repeated 8-10 hours after the morning sampling campaign, just before the next loading regime. During each sampling campaign, a 20 minutes interval was adopted after installation of the gas chamber i.e. gas extraction was done at 0, 20, 40 and 60 minutes. Gas extraction from the chamber head space was done using 60ml plastic gas syringes and 25 gauge needles. Prior to gas extraction, chamber flushing with a gas syringe was carried out 3-4 times to reduce potential stratification due to the difference in target gas densities. The flushing was envisaged to enhance homogenization by induced air circulation and localized turbulence effects within the chamber. Gas samples were extracted into pre-evacuated 10ml vials with an airtight septum and an aluminum 20mm unlined crimp seal. Air temperature was always taken before and after each sampling campaign using a potable thermometer.

All samples were stored in a hard paper box maintained at room temperature and in a non-illuminated environment prior to transportation for analysis at the Institute of Soil Research, University for Natural Resources and Life Sciences, BOKU, Vienna, Austria. Gas samples were analyzed using an automated 7697A headspace sampler and 7890A Gas Chromatography System (Agilent technologies, USA). Prior to analysis, a calibration ($R^2 \geq 0.99$) was prepared for CO_2, CH_4 and N_2O. The flame ionization detector was used for analysis of CH_4 and CO_2 concentration equivalent (after conversion to CH_4), whereas N_2O was analyzed using an electron capture detector.

2.5 Data analysis

Operational conditions of the mesocosms were characterized by calculating mean ± Standard error of the mean (SEM) for the influent-effluent pH, Temperature and Dissolved Oxygen (DO) considering the entire study period, using Microsoft Excel (2010) spread sheets. The minimum, maximum and coefficient of variation were also determined to ascertain the range and variability of the physical and chemical parameters during the investigation period. Rainfall was used as a descriptor of seasonal variation with a time series graphical analysis using sigma plot 12.5.

The biodegradability of OM in the influent and effluent was calculated using the BOD_5/COD ratio(Saeed and Sun 2012). The difference in OM biodegradation between the mesocosms was then determined by analysis of variance (one way ANOVA followed by Tukey's test, significance level was set as $\alpha = 0.05$) of the influent-effluent OM biodegradability. Comparison of WBS mesocosms performance regarding reduction of influent BOD_5, COD, NH_4-N and NO_3-N concentrations was done by analysis of variance (one way ANOVA followed by Tukey's test, significance level was set as $\alpha = 0.05$). OM and nutrients elimination rates were quantified as a difference between the influent and effluent loading rates (g m^{-2} d^{-1}). Consequently, removal efficiency was estimated using equation (1)

$$Removal\ efficiency\ \% = \frac{\left(\frac{L_{in}}{SA}\right) - \left(\frac{L_{out}}{SA}\right)}{\left(\frac{L_{in}}{SA}\right)} \times 100 \qquad \textit{Equation (1)}$$

Where L_{in} and L_{out} are influent and effluent loads (g d^{-1}) respectively, whereas SA represents the mesocosm surface area (m^2). Gas fluxes were calculated based on a linear regression model approach (Nakano et al., 2004; Parkin et al., 2012; Pihlatie et al., 2007) assuming linear change in concentration of the gases in the chamber with time (Chunming et al., 2010; Parkin et al., 2012) during a four interval, time-step measurement (0-20-40-60 minutes). Consequently, the gas flux quantification was implemented using a mathematical model represented by equation 2 (Metcalfe et al., 2007), taking into account the chamber dimensions, temperature and pressure.

$$F = \frac{\Delta C}{\Delta t} \times \frac{P}{1000} \times \frac{273}{t + 273} \times \frac{M}{V_m} \times \frac{V_{ch}}{A} \qquad \textit{Equation (2)}$$

Where $\boldsymbol{F}$ is the gas flux (kg m^{-2} s^{-1}) which was converted to g m^{-2} h^{-1} for presentation and comparison with literature values; $\frac{\boldsymbol{\Delta C}}{\boldsymbol{\Delta t}}$ was derived from the slope of the linear regression model (general equation 3) (Chunming et al., 2010), and represents change in concentration of the gas $\boldsymbol{\Delta C}$ (ppm) with change in time $\boldsymbol{\Delta t}$ (seconds); $\boldsymbol{P}$ is atmospheric pressure (Pa) based on Kampala conditions from the Meteorological Department, Ministry of Water and Environment; $\boldsymbol{t}$ is the average air temperature of the chamber (ºC); $\boldsymbol{M}$ is molar mass of the gas (g mol^{-1}) (CH_4 = 16.04; CO_2= 44.01; N_2O = 44.01); $\boldsymbol{V_m}$ is molar gas volume (22.4l); $\boldsymbol{V_{ch}}$ gas chamber internal volume (m^3); and $\boldsymbol{A}$ the substrate bed area covered by the gas chamber (m^2).

$$C_t = a_o + a_1 t \qquad \textit{Equation (3)}$$

Where $\boldsymbol{C_t}$ is the concentration of the gas (ppm) measured at time $\boldsymbol{t}$ (seconds); $\boldsymbol{a_o}$ is a regression parameter representing the concentration (ppm) of a gas at time $\boldsymbol{t}$ = 0 (seconds); $\boldsymbol{a_1}$ is a regression parameter (ppm sec^{-1}) representing the slope, and was used to substitute $\frac{\boldsymbol{\Delta C}}{\boldsymbol{\Delta t}}$ in equation 2 for flux calculations. Analysis of variance (one way ANOVA followed by Tukey's test, significance level was set as $\alpha = 0.05$) was used to establish differences in gas fluxes between treatments. For all ANOVA tests, homogeneity of variances was checked using Bartlett's test. All statistical analyses were performed using the R-console (Version 3.0.2).

3.0 Results

3.1 WBSs physical and chemical environment

The WBS mesocosms operation period (January 2013- June 2014) was characterised by a bi-modal seasonal pattern of wet and dry periods (Fig. 2) typical of equatorial regions. Specifically, during the gas flux assessment period in 2014, daily mean precipitation exhibited high values in April (12.8 ± 3.4 mm day^{-1}), a wet-dry transition period in May (6.2 ± 1. 5 mm day^{-1}), and a dry period in June (0.2 ± 0. mm day^{-1}). Influent and effluent temperature, pH and DO are summarised in Table 1. Despite the seasonal variations characterized by wet and dry periods, influent and effluent temperature remained relatively stable, within a range of 20-27 ºC in all mesocosms. As a result, no significant difference ($P > 0.05$) was found in mean temperature between the influent and effluent or between WBS mesocosms. Regarding pH, a slight reduction in alkaline conditions of the influent was observed in all mesocosms. However, this reduction was found to be insignificant ($P > 0.05$). The low variation in temperature and pH was also further confirmed by CV values for both parameters that did not exceed 10%.

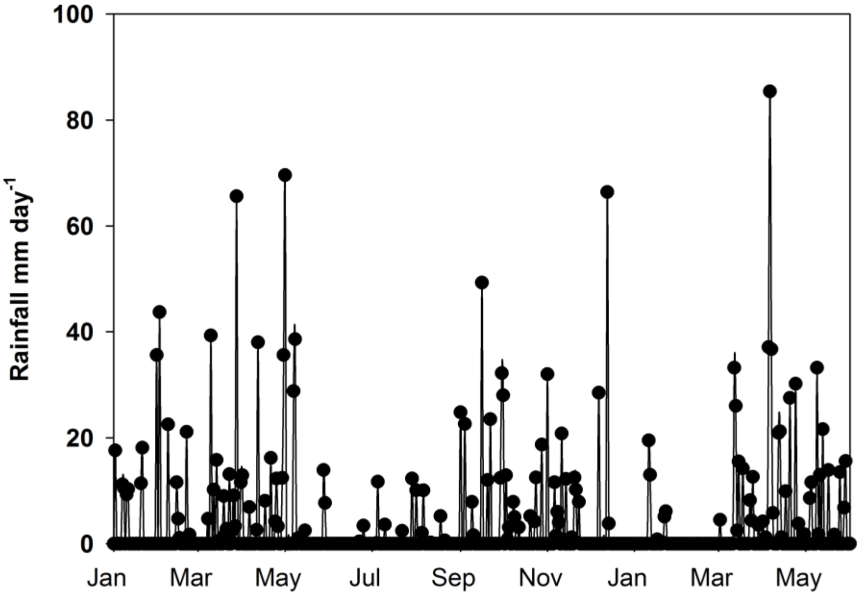


Figure 2: A time series graphical display of daily precipitation as a descriptor of seasonal variation during the study period (January 2013-June 2014)

Influence of *C. Papyrus* plants on the aerobic conditions of the treatment beds was observed by a significant increment ($P > 0.05$) of DO concentration in the planted HF and VF mesocosms. In addition, an induced aerobic environment in VF was demonstrated compared to the HF treatment beds. Whereas no significant difference ($P > 0.05$) was found between the influent and effluent DO concentration in the unplanted HF mesocosms, unplanted VF registered a significant increase in effluent DO ($P < 0.05$) comparable to the planted HF mesocosms ($P > 0.05$) (Table 1), but significantly lower ($P < 0.05$) than planted VF. The Min-Max range and CV analysis indicated that DO concentration exhibited high fluctuation in the influent and effluent compared to temperature and pH.

3.2 Organic matter, NH_4-N and NO_3-N dynamics

The influent and effluent concentration, loading/elimination rates and mass removal efficiency for organic matter (BOD_5 and COD), NH_4-N and NO_3-N, in all mesocosms are presented in Table 2. All mesocosms significantly reduced ($P < 0.05$) influent BOD_5 and COD concentrations, with planted VF mesocosms exhibiting the lowest ($P < 0.001$) effluent concentrations compared to the planted HF and unplanted control treatments. This observation was consistent with the mass removal efficiency in which planted VF mesocosms were the most effective in reduction of both BOD_5 (86%) and COD (71%) compared to the unplanted VF (with the same organic loading rate) and HF mesocosms (with a lower organic loading rate).

Analysis of BOD_5/COD ratio (Fig. 3) indicated that highly biodegradable OM in the effluent (0.60 ± 0.02) was significantly degraded ($P < 0.001$) in all treatment beds to 0.46 ± 0.02 in planted HF, 0.48 ± 0.02 in unplanted HF, 0.35 ± 0.01 in planted VF and 0.39 ± 0.02 in unplanted VF mesocosms. However, VF beds were significantly ($P < 0.05$) more efficient than the HF mesocosms, with planted VF being the most effective ($P < 0.001$) overall. On the contrary, a comparison of planted HF mesocosms with unplanted controls was statistically insignificant ($P > 0.05$).

Regarding inorganic nitrogen dynamics, NH_4-N concentration and load was significantly reduced ($P < 0.05$) in all mesocosms with the highest mass removal efficiency (78%) achieved in planted VF mesocosms ($P < 0.001$). Although NH_4-N reduction in the unplanted HF mesocosms was significant ($P < 0.05$), the mass removal efficiency was the lowest (<40%) compared to the planted HF and VF mesocosms. A significant reduction of NH_4-N in planted HF, unplanted VF and planted VF treatment beds' effluent was also reflected in the significant increment ($P< 0.05$) of NO_3-N concentration in the effluent, hence negative elimination rates, compared to unplanted HF ($P > 0.05$).

Table 1: Variation of WBSs influent and effluent Temperature, pH and Dissolved Oxygen (DO) during the entire study period (n=32).

	Temperature °C				pH				DO mg l^{-1}			
	Mean ± SEM	Min	Max	CV %	Mean ± SEM	Min	Max	CV %	Mean ± SEM	Min	Max	CV %
Influent	24.3 ±0.2[a]	22.5	26.5	5.7	7.5 ±0.1[a]	7.4	8.3	8.4	1.1 ±0.1[a]	0.4	2.6	62.0
HF Planted	23.5 ±0.2[a]	21.5	25.8	5.4	6.9 ±0.1[a]	5.8	8.2	10.0	2.7 ±0.2[b]	0.2	4.7	52.0
HF Unplanted	23.8 ±0.1[a]	21.0	27.0	4.7	7.0 ±0.1[a]	6.2	8.2	8.2	1.4 ±0.1[a]	0.0	3.3	67.0
VF Planted	23.3 ±0.2[a]	20.5	25.9	5.5	7.2 ±0.1[a]	6.1	8.6	8.0	4.6 ±0.1[c]	1.8	7.1	40.0
VF Unplanted	23.7 ±0.2[a]	20.5	26.5	5.5	7.1 ±0.1[a]	6.0	8.4	7.3	3.1 ±0.2[b]	0.4	4.9	39.4

Mean values with similar superscripts are not significantly different ($P > 0.05$) whereas non uniform superscripts indicate significant difference ($P < 0.05$).

Table 2: Mean concentration, mass loading/elimination rate and removal efficiency for BOD_5, COD, NH_4-N and NO_3-N from WBS mesocosms bi-weekly monitoring (March 2013-June 2014) (n=32).

	BOD_5			**COD**			**NH_4-N**			**NO_3-N**	
	Concentration mg l^{-1}	Loading/ Elimination rate g m^{-2} d^{-1}	Average mass removal %	Concentration mg l^{-1}	Loading/ Elimination rate g m^{-2} d^{-1}	Average mass removal %	Concentration mg l^{-1}	Loading/ Elimination rate g m^{-2} d^{-1}	Average mass removal %	Concentration mg l^{-1}	Loading/ Elimination rate g m^{-2} d^{-1}
HF-Influent	218 ±56$^{\mathbf{a}}$	14.5		303 ±16$^{\mathbf{a}}$	20.0		47.69±2.80$^{\mathbf{a}}$	3.2		2.37±0.31$^{\mathbf{a}}$	0.2
HF Planted	59±3$^{\mathbf{bc}}$	10.6	73	129±5$^{\mathbf{b}}$	11.5	58	15.26±1.78$^{\mathbf{c}}$	2.2	68	4.68±0.41$^{\mathbf{b*}}$	-0.2
HF Unplanted	67±2$^{\mathbf{b}}$	10.0	69	141±4$^{\mathbf{b}}$	10.7	54	29.04±3.10$^{\mathbf{b}}$	1.2	39	2.14±0.29$^{\mathbf{a}}$	0.0
VF- Influent	218 ±56$^{\mathbf{a}}$	55.6		303 ±16$^{\mathbf{a}}$	77.0		47.69±2.80$^{\mathbf{a}}$	12.0		2.37±0.31$^{\mathbf{a}}$	0.6
VF Planted	31±1$^{\mathbf{d}}$	47.8	86	87±3$^{\mathbf{c}}$	55.0	71	10.49±1.50$^{\mathbf{d}}$	9.3	78	7.83±0.51$^{\mathbf{c*}}$	-1.4
VF Unplanted	50±2$^{\mathbf{c}}$	43.0	77	124±4$^{\mathbf{b}}$	45.5	61	19.00±2.15$^{\mathbf{c}}$	7.2	60	4.05±0.33$^{\mathbf{b*}}$	-0.4

Mean values with similar superscripts are not significantly different ($P > 0.05$) whereas non uniform superscripts indicate significant difference ($P < 0.05$); ***** represents increment in effluent concentration compared to the influent; negative elimination rate represents increase in effluent loading relative to the effluent.

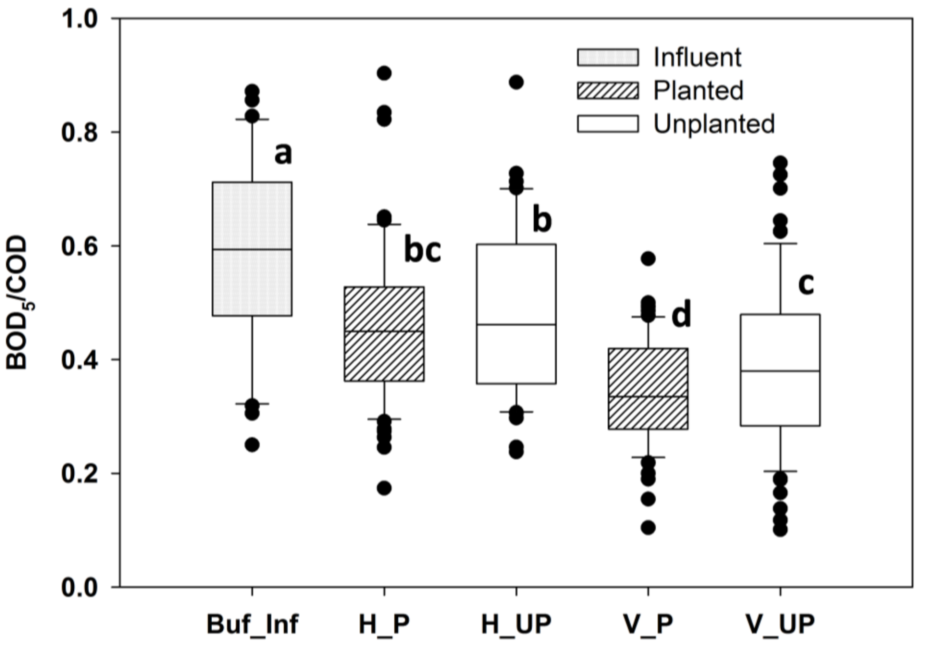


Figure 3: Variation of influent and effluent biodegradable OM estimated using the BOD_5/COD ratio, n=32. Box lines indicate upper and lower quartiles. Whiskers extend to the 95th and 5th percentiles. Letters indicate significance level; similar letters, if $P > 0.05$ and different letters, if $P < 0.05$ between treatments.

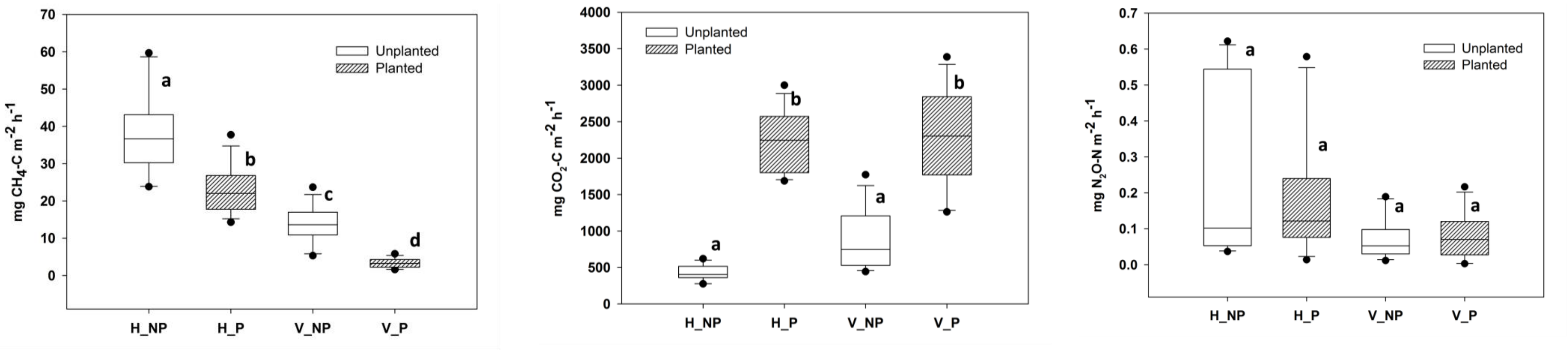
3.2 Carbon and nitrogen gaseous fluxes

A comparison of gaseous fluxes for the three months monitoring period in the HF and VF mesocosms is presented in Fig. 4. Generally, carbon gaseous fluxes, CH_4 and CO_2 significantly differed (P < 0.05) between treatments (Figure 4A and 4B). The mean CH_4 flux (mg CH_4-C m^{-2} h^{-1}) was significantly higher (P < 0.001) in the unplanted HF (38.3 ± 3.3) compared to planted HF (22.7 ± 1.9), unplanted VF (13.6 ± 1.4) and the planted VF (3.3 ± 0.4) with the lowest mean flux. A separate comparison of HF and VF mesocosms between planted and unplanted control mesocosms indicated that planted treatments had significantly lower (P < 0.05) CH_4 flux compared to the unplanted. Moreover HF mesocosms gave significantly higher (P < 0.05) CH_4 fluxes compared to the VF treatment units.

On the contrary, mean CO_2 flux (mg CO_2-C m^{-2} h^{-1}) was found to be significantly higher (P < 0.001) in the planted mesocosms compared to the unplanted controls for both VF and HF mesocosms (Figure 3b). In addition, no significant difference (P > 0.05) in mean CO_2 flux was found between the planted HF (2213.5 ± 122.4) and planted VF (2272.8 ± 191.0) mesocosms. Similarly, despite the fact that unplanted VF had a higher mean CO_2 flux (874.0 ± 116.3) compared to the unplanted HF (428.0 ± 30.7), no significant difference (P > 0.05) between the two treatments was found.

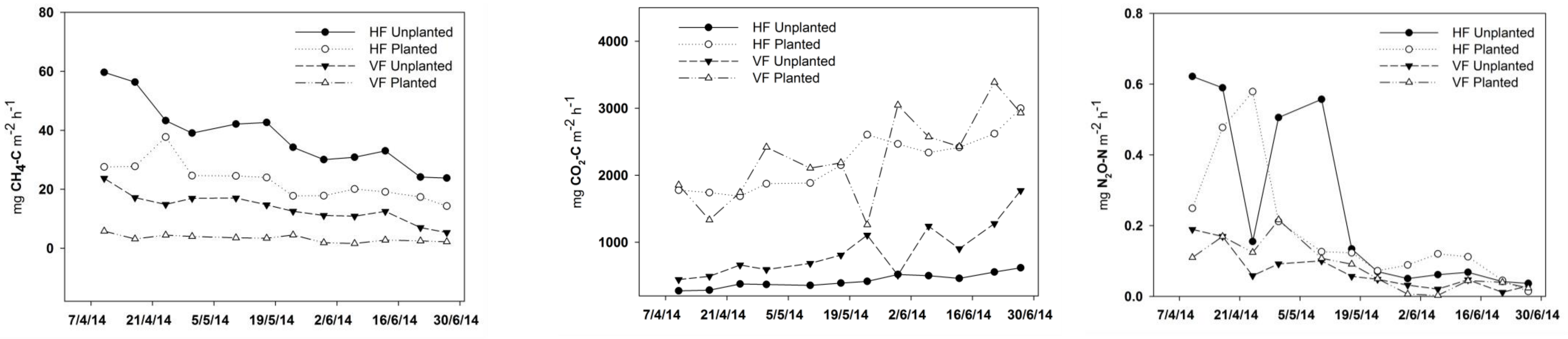
Compared to CH_4 and CO_2, the N_2O flux (Fig. 4C) was found to be insignificant (P > 0.05) in all treatments. However, despite the statistical insignificance, mean N_2O fluxes (mg N_2O-N m^{-2} h^{-1}) in HF mesocosms tended to be higher than in VF treatment units. The highest N_2O flux was measured in unplanted HF (0.24 ± 0.07) compared to 0.19 ± 0.05 in the planted HF, 0.07 ± 0.02 in the unplanted VF and 0.08 ± 0.02 determined in the planted VF mesocosms. It was also observed that variability of N_2O flux was more pronounced in HF compared to VF mesocosms.

Figure 5 shows the time-series analysis to elucidate temporal variability of gaseous fluxes from April to June 2014. On a temporal scale, generally higher fluxes for CH_4 and N_2O were found in rainy periods of April and May before a gradual decrease in June. On the contrary, CO_2 fluxes generally increased in all mesocosms from April to the dry season in June. However, it was also observed that despite these general trends variation in N_2O was quite stochastic with high variability compared to CH_4 and CO_2.



4a **4b** **4c**

Figure 4: A comparison of gaseous fluxes (A) CH_4 (B) CO_2 and (C) N_2O in the planted and unplanted HF and VF mesocosms for a three months monitoring campaign from April to June 2014, (n=12). Box lines indicate upper and lower quartiles. Whiskers extend to the 95th and 5th percentiles. Letters indicate significance level; similar letters, if P > 0.05 and different letters, if P < 0.05 between treatments



5a **5b** **5c**

Figure 5: Temporal variation in gaseous fluxes, (A) CH_4 (B) CO_2 and (C) N_2O in the planted and unplanted HF and VF mesocosms during weekly monitoring from April to June 2014.

4.0 Discussion

Precipitation is the main driver for seasonal variability and ultimately the hydrological dynamics of wetland environments in the tropics (Mitsch et al., 2010; Neue et al., 1997) as demonstrated by the rainfall pattern (Fig. 2) in this study. On the contrary, both temperature and pH did not vary significantly ($P > 0.05$), but where in the range providing favorable conditions for microbial activity and processes (Table 1), which influence gaseous emission of CH_4, CO_2 and N_2O (Bitton 2010; Faulwetter et al., 2009; Saeed and Sun 2012; Samsó and García 2013). Consequently, on a temporal scale precipitation was the main factor that could be used to explain the observed variation in gaseous fluxes from April to June 2014 (Fig. 5). Whereas CH_4 and N_2O fluxes were generally high in April and May compared to June, CO_2 exhibited an opposite trend with lower fluxes in April compared to June in all mesocosms. It could therefore be hypothesized that precipitation events induced anaerobic conditions due to treatment bed hydraulic saturation hence reducing DO concentrations and ultimately leading to lower redox potential (Gutknecht et al., 2006; Kadlec and Wallace 2009; Neue et al., 1997; Weerakoon et al., 2013). The phenomenon of seasonal variation could be linked to the high CV variability of effluent DO (Table 1) from all mesocosms, which was more pronounced in HF mesocosms with constrained hydraulic drainage compared to VF configurations. Consequently, anaerobic microbial activity and processes could have been more predominant especially in the HF mesocosms during the wet season hence enhancing methanogenesis (higher CH_4 flux) and denitrification (relatively higher N_2O flux (Bitton 2010; Faulwetter et al., 2009; Saeed and Sun 2012; Samsó and García 2013). These findings could however be elucidated with a longer period and more dense gaseous emission monitoring to ascertain the significance of seasonal variation.

Besides potential seasonal influence on DO dynamics due to precipitation, it was demonstrated in this study, based on effluent DO concentrations (Table 1) that plants and specifically *C. papyrus* had a significant ($P < 0.05$) impact on enhancing aerobic conditions in treatment beds and ultimately GHGs emissions (Fig. 4). These findings are also consistent with other studies, in which plants have been found to enhance aerobic conditions which promote aerobic heterotrophic OM degradation coupled with higher CO_2 flux, compared to anaerobic heterotrophic degradation which enhances significant CH_4 flux (Maltais-Landry et al., 2009b; Maltais-Landry et al., 2009c; Mander et al., 2008; Saeed and Sun 2012). Moreover, anaerobic conditions also promote denitrification which increases N_2O flux (Bitton 2010; Samsó and García 2013), which was also found to be remarkably low in this study. However, the efficiency of oxygen transfer into the rhizosphere has been found to differ based on the plant type or species used (Maltais-Landry et al., 2009a). Generally, in this study, *C. Papyrus* in VF and HF beds was found to be effective in inhibition of CH_4 flux, but enhanced significant CO_2 flux. On the contrary, and consistent with other studies, N_2O fluxes were not clearly influenced by either presence of plants or structural configuration in terms of VF or HF design (Maltais-Landry et al., 2009a; Mander et al., 2008; Picek et al., 2007).

Besides providing a source of carbon for microbial biomass accumulation and nitrogen transformation processes (Saeed and Sun 2012; von Sperling and Augusto de Lemos Chernicharo 2005), OM degradation processes can influence gaseous carbon flux depending on oxygen availability (Bitton 2010; Saeed and Sun 2012). High organic loading rate (as was the case in this study) compared to oxygen supply, can rapidly induce anaerobic environments (Bitton 2010; Kadlec and Wallace 2009) which result into release of CH_4 under favorable temperature and pH conditions (Faulwetter et al., 2009). However, it was established from the findings of this study, that a coupled role of batch hydraulic loading and use of plants enhanced significant ($P > 0.05$) aerobic degradation of OM leading to high CO_2 fluxes, with higher efficiency ($P > 0.001$) in VF mesocosms (Fig. 3 and Fig. 4B). Specifically, planted VF mesocosms significantly ($P > 0.05$) removed BOD_5, COD and biodegradable OM (Table 2 and Fig. 3) which could be attributed to significantly higher DO concentration, (Table 1).

Although significantly lower than the planted VF mesocosms, planted HF mesocosms also exhibited higher aerobic OM degradation hence higher CO_2 relative to CH_4 fluxes, in comparison with the unplanted HF beds. These observations are consistent with other findings in which the use of plants and batch hydraulic loading induce oxygen influx in the treatment beds which enhance (i) increased aerobic microbial degradation of OM hence higher fluxes of CO_2 (Maltais-Landry et al., 2009b; Picek et al., 2007; Teiter and Mander 2005), (ii) inhibition of methanogenesis which reduce CH_4 fluxes (Faulwetter et al., 2009; Saeed and Sun 2012), and (iii) oxidation of traces of CH_4 that may be produced from isolated anaerobic pockets of the substrate to form CO_2 (Mander et al., 2008; Saeed and Sun 2012).

Adequate DO concentration and availability of readily biodegradable OM enhanced efficient oxidation of NH_4-N to NO_3-N in planted VF compared to the unplanted VF and HF mesocosms. On the contrary, although insignificant, there was some reduction of NO_3-N in the unplanted HF mesocosms pointing to potential denitrification processes (Sirivedhin and Gray 2006; Teiter and Mander 2005) due to low DO concentrations. These observations are consistent with other findings in which VF treatment beds predominantly enhance nitrification compared to HF CWs due to prevalence of aerobic environments (Canga et al., 2011; Langergraber et al., 2008; Vymazal 2007). In this study, the planted HF mesocosms also exhibited remarkably high nitrification efficiency (by NH_4-N oxidation), probably due to a combination of batch hydraulic loading and the use of plants. Moreover, the shallow beds could also enhance atmospheric oxygen diffusion (Albuquerque et al., 2009).

Generally, specific literature on CH_4, CO_2 and N_2O emissions from SSF CWs in the East African region could not be found from major international publication sources. Consequently, an attempt was made to compare gaseous fluxes established in this study with findings from selected studies in Europe and North America. Regarding CH_4 fluxes (Fig. 4A); the higher performance in inhibition of CH_4 flux in planted SSF CWs is consistent with findings from other studies (Maltais-Landry et al., 2009a; Maltais-Landry et al., 2009b; Mander et al., 2014a). The highest mean CH_4 flux of 38.3 ± 3.3 mg CH_4-C m^{-2} h^{-1} was found in unplanted HF mesocosms compared to the lowest (3.3 ± 0.4 mg CH_4-C m^{-2} h^{-1}) established in planted VF. The low CH_4 fluxes in planted VF mesocosms of this study, was also consistent with reviewed data in various VF CWs (Maltais-Landry et al., 2009b; Mander et al., 2014a) , in the range of 0.3 - 5.9 mg CH_4-C m^{-2} h^{-1}. In addition, the efficiency of planted VF mesocosms in CH_4 emission inhibition, was demonstrated with comparison to the results of artificially aerated and planted HF mesocosms in Canada which achieved a maximum flux of 4.6 mg CH_4-C m^{-2} h^{-1} (Maltais-Landry et al., 2009a) under a greenhouse controlled environment. On the contrary, the high mean CH_4 flux in HF mesocosms was remarkably greater than most results reviewed from other studies (Maltais-Landry et al., 2009b; Mander et al., 2008; Mander et al., 2014b; Teiter and Mander 2005), except the HF CW in Czech Republic (Picek et al., 2007) which achieved CH_4 fluxes of up to 93 mg CH_4-C m^{-2} h^{-1}.

The CO_2 fluxes (mg CO_2-C m^{-2} h^{-1}) established in planted VF (2272.8 ± 191.0) and planted HF (2213.5 ± 122.4) mesocosms for this study were higher than what was found in references from the temperate region (Mander et al., 2014a; Mander et al., 2008; Picek et al., 2007). For example; the HF CW in Czech Republic (Picek et al., 2007) with some of the highest CO_2 fluxes achieved a maximum of 309 mg CO_2-C m^{-2} h^{-1} which is about 7 times lower than what was measured in the planted VF and HF mesocosms. However, despite the fact that the organic hydraulic loading rate could not be readily verified for comparison, the HF CW in Czech Republic had a mean influent COD concentration of about 123 ± 62 mg l^{-1} compared to 298±16 mg l^{-1} for this study. It could therefore be concluded that one of the contributing factors for high CO_2 flux was high organic loading rate applied, coupled with higher temperatures (Caselles-Osorio et al., 2007; Faulwetter et al., 2009; Saeed and Sun 2012; von Sperling and Augusto de Lemos Chernicharo 2005) in East Africa, and the use of a highly productive plant, *C. Papyrus*, with significant CO_2 flux rates under constant water supply and high nutrient conditions (Saunders et al., 2007).

The N_2O flux was generally found to be low with insignificant variation between treatments as reported in other studies (Maltais-Landry et al., 2009a; Maltais-Landry et al., 2009b; Maltais-Landry et al., 2009c; Mander et al., 2014a; Mander et al., 2008; Picek et al., 2007; Teiter and Mander 2005). The N_2O flux dynamics highlighted the potential of coupled nitrification and denitrification processes (Maltais-Landry et al., 2009a) in both VF and HF mesocosms. This is due to the micro-heterogeneity of aerobic and anaerobic zones in substrate beds with multiple opportunities for tightly coupled microbial processes such as; nitrification and denitrification as well as fermentation and methanogenesis (Bitton 2010; Faulwetter et al., 2009; Ramond et al., 2012; Samsó and García 2013; Sirivedhin and Gray 2006; von Sperling and Augusto de Lemos Chernicharo 2005).

In general, the findings of this study indicate that use of C. Papyrus under batch hydraulic loading conditions can significantly enhance aerobic conditions with beneficial impacts of low GHGs emissions through inhibition of CH_4 and N_2O gaseous flux. This approach also provides an alternative for artificial aeration which can impose additional sustainability challenges in terms of costs for external energy inputs, and increase in the carbon foot print of CWs. Additionally, apart from the low GHGs emissions, satisfactory removal of organic matter and NH4-N oxidation was achieved, hence providing high potential for organic pollution control and coupled total N elimination with the receiving natural environment.

5.0 Conclusions

The experimental conditions of the HF and VF mesocosms under warm equatorial climatic conditions in East Africa were favorable for enhancing aerobic OM degradation with higher CO_2 fluxes compared to the temperate climate. The demonstrated inhibition of CH_4 emission is also essential in addressing the impacts of climate change since it is more harmful to the ozone layer compared to CO_2.

Precipitation was found to be a major driver for seasonal carbon and nitrogen gaseous fluxes due to its potential influence on SSF CWs hydraulic saturation and hence oxygen fluctuation in treatment beds. This however requires more investigation to ascertain the significance of seasonal variation on gaseous fluxes in SSF CWs in East Africa.

Papyrus plants coupled with batch hydraulic loading conditions enhanced aerobic conditions in HF and VF treatment beds. This resulted into high rates of aerobic OM degradation which enhanced higher CO_2 fluxes and significantly lower CH_4 flux in both planted HF and VF mesocosms.

The N_2O fluxes were relatively low and did not vary significantly among treatments. It could be noted however that although nitrification was predominant, coupled nitrification and denitrification was potentially present. This could provide an opportunity for total N removal hence control of eutrophication in receiving aquatic environments.

Acknowledgements

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PART V

5.0 General Discussion, Conclusions and Recommendations

5.1 WWTP performance against wastewater discharge standards

Masaka municipal WWTP performance regarding high effluent pollution fluxes and non-compliance to discharge standards demonstrated typical challenges of wastewater management not only in Uganda, but also other urban areas in sub-Saharan Africa (Kivaisi 2001; Nyenje et al., 2012; Polprasert 2006). Although the WWTP was designed as a centralized conventional mechanically aerated bioreactor system, to provide primary and secondary treatment to municipal wastewater prior to discharge, the effluent concentrations were found to be in the range of raw or pre-settled sewage with minimum treatment (Crites et al., 2006a; Jorgensen 2000; Lester et al., 2009; Metcalf and Eddy 2004) for the entire five year assessment period. This trend has been demonstrated in many developing countries compared to developed countries (Figure 5) where political commitment and financial resources have been invested in wastewater treatment and compliance to stringent effluent discharge standards to safeguard environmental pollution and public health risks (von Sperling and Augusto de Lemos Chernicharo 2002).

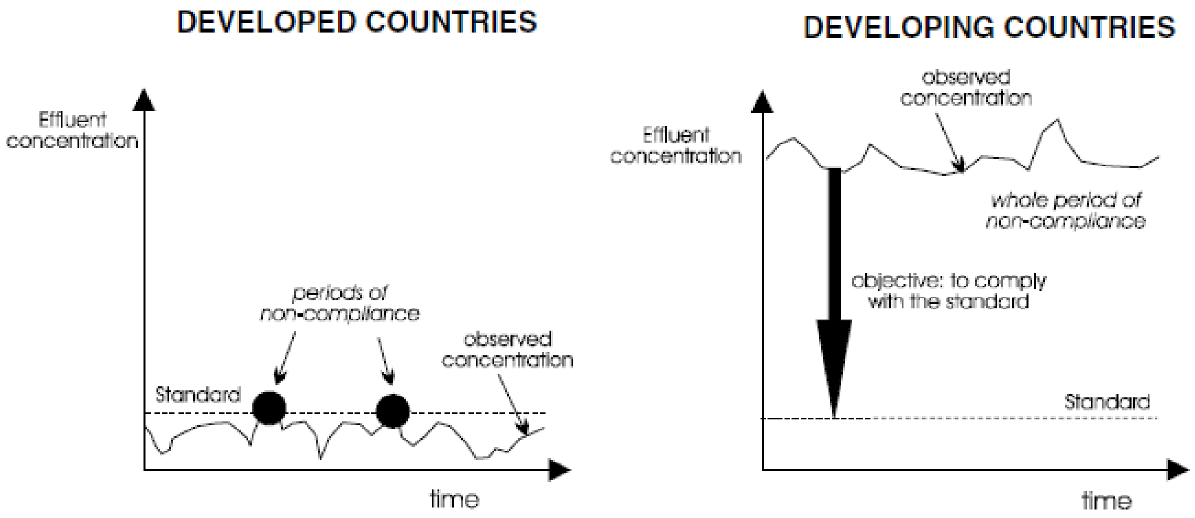

Figure 1: A comparison of developed and developing countries regarding compliance to discharge standards; Adopted (von Sperling and Augusto de Lemos Chernicharo 2002).

Therefore, the low sustainability of centralised mechanical wastewater treatment technologies in developing countries (Kivaisi 2001; Muga and Mihelcic 2008; Polprasert 2006; Zurita et al., 2012) is critically highlighted from this study. In addition, the poor performance regarding effluent quality pinpoints a major capacity gap not only in terms of technology and environmental sustainability, but also emphasises the challenge of inadequate financing for operation and maintenance of centralised mechanical WWTPs especially in sub-Saharan Africa. Moreover consistent non-compliance of the WWTP to the national effluent quality standards indicates inadequate implementation of the monitoring and corrective enforcement mechanisms of the existing legal regime by the municipality and other relevant regulatory agencies.

5.2 Role of urban wetlands in attenuation of municipal wastewater pollution

Despite the deficiency in the performance of Masaka WWTP, Nakayiba wetland provided an effective buffer for attenuation of downstream environmental pollution. Overall, the wetland pollution removal for: suspended solids, pathogens, organic matter and nutrients were found to be over 65% reduction compared to the inflow load. Many other studies have demonstrated that wetland ecosystems in the Lake Victoria region play a major role in pollution abatement and water quality regulation (Co´zar et al., 2007; Kansiime et al., 2007a; Kansiime et al., 2007b; Kelderman et al., 2007; Machiwa 2003; van Dam et al., 2007) as exhibited in Nakayiba wetland. The natural wetland wastewater treatment processes including the physical, hydrological and biogeochemical dynamics are also well documented (Kadlec and Wallace 2009; Mitsch and Gosselink 2000). The heterogeneous vegetation structure, soil and stream-wetland hydrological exchange processes coupled with various hydraulic retention opportunities (Fisher and Acreman 2004a; Kadlec and Wallace 2009; McJannet et al., 2012; Mitsch and Gosselink 2000) are vital pathways for effective mass removal of pollutants in urban wetland ecosystems.

It was also observed that the first 750m section of the wetland (35% of the total length of the study area) was found to be more efficient in pollution removal. This is in agreement with the non-linear behavior of riparian buffer zones, which generally show a higher removal efficiency of materials in the first sections compared to the remote parts (Mander et al., 2005). In addition, the downstream residual concentration was generally higher compared to the upstream reference sampling site for nutrients and organic matter. It could therefore be hypothesised based on the findings of this study, that although urban wetlands are critical sinks for multiple municipal pollutants, their resilience to heavy loading rates on a temporal scale cannot be guaranteed. Moreover the urban wetlands buffering capacity is susceptible to intense degradation due to multiple urban development pressure especially due to industrialisation and growth of informal settlements in East African cities.

5.3 Performance of subsurface flow constructed wetland buffer strips

5.3.1 Physical chemical environment

The physical-chemical environment of the mesocosms regarding pH and temperature did not vary significantly, and was within the optimum range for most microbial mediated biogeochemical processes for wastewater treatment (Faulwetter et al., 2009; Metcalf and Eddy 2004; Saeed and Sun 2012). Influent and effluent pH was in the range of 6.5-8.5, whereas temperature varied from a minimum of 20 ºC to a maximum of about 27 ºC. Under these environmental conditions, essential microbial driven biogeochemical processes such as ammonification, nitrification, and denitrification have been found to be efficient (Faulwetter et al., 2009; Metcalf and Eddy 2004; Philippe et al., 2010; Saeed and Sun 2012; Sirivedhin and Gray 2006; Vymazal 2007) provided other performance factors are favourable.

The batch loading method provided a drying and rewetting regime (Venterink et al., 2002) in all mesocosms hence periodic influx of atmospheric oxygen (Langergraber et al., 2011; Meng et al., 2014; Polprasert 2006; Wu et al., 2014). Consequently, all mesocosms showed effluent DO concentrations ≥ 1.3 mg l^{-1}, with the highest mean DO of 4.25 ± 0.25 mg l^{-1} attained in planted VF mesocosms. Although effluent DO does not necessarily fully explain the coupled heterogeneous substrate aerobic-anaerobic zones (Saeed and Sun 2012; Vymazal 2007), the observed significantly higher effluent DO concentration in planted mesocosms could be attributed to efficient transfer of oxygen into the rhizosphere by *C. papyrus* (Kansiime et al., 2007b; Kyambadde et al., 2004). Moreover, even predominantly anaerobic HF systems (Kadlec and Wallace 2009; Vymazal 2007; Vymazal 2013) exhibited high aerobic effluent in the planted mesocosms. It could therefore be concluded that the observed high DO effluent concentration for this study was a coupled role of papyrus plants, batch feeding mode and a shallow substrate bed in HF mesocosms.

5.3.2 Removal of suspended solids and organic matter

Although, WWTP effluent was used as the influent for the mesocosms in this study, its quality regarding TSS, BOD_5 and COD were found to be within the range of raw or pre-settled sewage. However, effluent analysis from all the mesocosms indicated that both VF and HF treatment units significantly reduced the inflow mass loads for TSS, BOD_5 and COD by over 50%, with TSS effluent concentrations achieving the WDS ($\leq$100mgl^{-1}) for Uganda. Influent biodegradable organic matter (BOD_5 , 218 ±56 mgl^{-1}; COD, 303 ±16 mgl^{-1}; BOD5/COD ≥ 0.5) was high and provided organic carbon (Crites et al., 2006a; Metcalf and Eddy 2004; von Sperling and Augusto de Lemos Chernicharo 2005) that was degraded aerobically at high rates (Faulwetter et al., 2009; Saeed and Sun 2012). This could therefore explain the high elimination rates for organic matter especially in VF mesocosms.

Removal of organic matter through the SSF CW mesocosms in this particular study was essential in addressing challenges of organic pollution (Meng et al., 2014; von Sperling and Augusto de Lemos Chernicharo 2005) from municipal wastewater in receiving environments which may result into (i) depletion of DO in surface waters, (ii) accumulation of organic suspended solids and associated public nuisances such as odour, and (iii) public health risks due to proliferation of pathogens in surface and ground water (Langergraber 2013; Metcalf and Eddy 2004; Ujang and Henze 2006).

5.3.3 Nutrients removal efficiency and elimination rates

The removal of nutrients was generally high considering the fact that; (i) the influent concentrations and load especially for NH_4^+, TN and TP were high (ii) the mesocosms were designed as single stage VF and HF systems, which have been found to be limited regarding nutrient removal (Vymazal 2007) especially for N elimination (Canga et al., 2011; Vymazal 2013; Wu et al., 2014). However, based on the primary goal of enhancing the aerobic mediated processes especially nitrification, the mesocosms performance was satisfactory in the planted VF and HF experimental units.

All VF and planted HF mesocosms exhibited significant ($P<0.05$) reduction in NH_4^+ and increased NO_3^- concentrations in the effluent. Moreover these changes were also concomitant with the elevated DO effluent concentration in the same mesocosms compared to the unplanted HF control experimental units. Therefore, it was evident from these findings that VF mesocosms effectively enhanced nitrification, which is well documented from other studies (Abou-Elela et al., 2013; Langergraber et al., 2011; Zurita et al., 2009) and performance reviews of CWs (Canga et al., 2011; Vymazal 2007; Wu et al., 2014). However, the enhanced nitrification process in planted HF mesocosms could be explained by multiple oxygen influx options introduced in the experimental setting for this study.

Although nitrification does not lead to total nitrogen removal (Vymazal 2007), the planted mesocosms especially VF experimental units registered remarkable TN (≥ 60%) mass removal efficiency which could be attributed to processes applicable for the experimental set up, such as; biomass assimilation reported in VF CWs (Saeed and Sun 2012) and plant uptake by C. papyrus (Kansiime et al., 2007b; Kivaisi 2001; Kyambadde et al., 2004). Other processes that could potentially have a minor role but reported in similar systems include; completely autotrophic nitrite removal over nitrate (Saeed and Sun 2012), ammonia volatilization (Vymazal 2007) and denitrification which is reported to occur in some substrate patches even when aerobic conditions dominate (Faulwetter et al., 2009; Gutknecht et al., 2006; Saeed and Sun 2012).

Removal processes of P are more stochastic than N due to influence of multiple dynamic physical and chemical processes including but not limited to temperature, pH, redox potential, DO, COD (Metcalf and Eddy 2004; von Sperling and Augusto de Lemos Chernicharo 2005) and many others. However, based on the mesocosms design, physical and chemical characteristics in comparison to other studies regarding P removal processes from treatment wetlands (Abou-Elela et al., 2013; Despland et al., 2014; Faulwetter et al., 2009; Kadlec and Wallace 2009; Kansiime et al., 2007a; Kelderman et al., 2007; Kyambadde et al., 2005; Kyambadde et al., 2004; Mburu et al., 2013; Saeed and Sun 2012; Vymazal 2007), the significant overall P elimination rate especially in planted VF mesocosms could be attributed to (i) plant uptake and accumulation of regularly harvested above ground biomass including significant storage by below ground biomass (Kansiime et al., 2007a; Kyambadde et al., 2005; Kyambadde et al., 2004; Odong et al., 2013), which was not assessed in this study; (ii) high rate of aerobic microbial assimilation (Faulwetter et al., 2009; Metcalf and Eddy 2004; Saeed and Sun 2012; von Sperling and Augusto de Lemos Chernicharo 2005), which could be significantly enhanced in planted VF mesocosms; (iii) particulate bound P removal through TSS (sediment) retention, which was efficiently exhibited in planted mesocosms (Kadlec and Wallace 2009; Kansiime et al., 2007b; Kelderman et al., 2007; Kyambadde et al., 2004) and (iv) potential precipitation under aerobic conditions in the rhizosphere which has been reported in papyrus treatment systems (Kyambadde et al., 2005; Kyambadde et al., 2004).

Generally, the mean N and P elimination rates (g m^{-2} d^{-1}) were 9.16 N and 5.41 P in planted VF, and 1.97 N and 1.02 P in planted HF mesocosms, respectively. The lowest mean nutrient elimination rate (g m^{-2} d^{-1}) was 1.10 N and 0.62 P found in unplanted HF controls. Nutrient accumulation in plants and sediment retention were also found to be essential processes.

5.3.4 Carbon and nitrogen gaseous fluxes

It was demonstrated in this study that *C. papyrus* had a significant ($P < 0.05$) impact on enhancing aerobic conditions in treatment beds and ultimately GHGs emissions. These findings are also consistent with other studies, in which plants have been found to enhance aerobic conditions which promote aerobic heterotrophic OM degradation coupled with higher CO_2 flux, compared to anaerobic heterotrophic degradation which enhances significant CH_4 flux (Maltais-Landry et al., 2009b; Maltais-Landry et al., 2009c; Mander et al., 2008; Saeed and Sun 2012). Moreover, anaerobic conditions also promote denitrification which increases N_2O flux (Bitton 2010; Samsó and García 2013), which was also found to be remarkably low in this study. However, the efficiency of oxygen transfer into the rhizosphere has been found to differ based on the plant type or species used (Maltais-Landry et al., 2009a). Generally, in this study, *C. Papyrus* in VF and HF beds was found to be effective in inhibition of CH_4 flux, but enhanced significant CO_2 flux. On the contrary, and consistent with other studies, N_2O fluxes were not clearly influenced by either presence of plants or structural configuration in terms of VF or HF design (Maltais-Landry et al., 2009a; Mander et al., 2008; Picek et al., 2007).

Generally, the highest mean CH_4 flux (mg CH_4-C m^{-2} h^{-1}) was 38.3 ± 3.3 in unplanted HF compared to the lowest (3.3 ± 0.4) established in planted VF mesocosms. CO_2 fluxes (mg CO_2-C m^{-2} h^{-1}) were significantly higher ($P < 0.05$) in planted mesocosms, with no significant difference ($P > 0.05$) between the planted HF (2213.5 ± 122.4) and VF (2272.8 ± 191.0) mesocosms. The high CO_2 flux was attributed to sufficient dissolved oxygen concentration which suggested high rates of aerobic OM degradation in planted mesocosms. On the contrary, N_2O fluxes were relatively low and did not vary significantly ($P > 0.05$) in all treatments. This could be attributed to the inhibition of denitrification under aerobic conditions, which however enhanced significant nitrification, especially in the planted mesocosms. Generally, in this study CO_2 gaseous flux, compared to CH_4 and N_2O fluxes, was the most significant under induced aerobic conditions enhanced by use of papyrus plants and an intermittent loading regime.

5.4 General conclusions and recommendations

The deficiency in performance of Masaka WWTP showed a great challenge of wastewater management in sub-Saharan Africa in terms of environmental pollution. Whereas remnants of such centralized wastewater systems and technologies in municipalities and cities of East Africa still exist and are wide spread, they are overloaded, dilapidated and with significant operation and maintenance deficits. This indicates lack of sustainability in terms of investment and/or capacity to operate and maintain such technologies. Although a natural wetland buffer offered a robust opportunity for wastewater treatment and downstream pollution control (for pathogens, organic matter, suspended solids and nutrients) to Masaka Municipality, the long term response of the system to high pollution loads is not certain and provides future environmental and public health risks to the urban ecosystem. The aforementioned uncertainty and risks notwithstanding, the role of Nakayiba wetland in pollution attenuation underpinned the need for integrating wetland ecosystems in the urban physical development plans of the region to safeguard their landscape functions especially in terms of enhancing wastewater treatment and sanitation management.

It is imperative that a paradigm shift in approach to proven and tested sanitation and wastewater management approaches be applied in East African cities and municipalities. For example use of CWs as technical on-site or decentralized systems have been found to be robust and sustainable (Langergraber 2013) not only for municipal wastewater treatment (Zhang et al., 2014; Zurita et al., 2012), but are also efficient in treating industrial, pharmaceutical, leachate and other emerging pollutants (Verlicchi and Zambello 2014; Vymazal 2009). Moreover, CWs can also be used in combination with existing mechanical WWTPs for tertiary treatment or as buffer systems for reducing effluent pollution due to performance deficits as demonstrated by Masaka municipal WWTP.

Generally, this study specifically demonstrated the feasibility of using CWs as buffer systems for remediation of high organic and nutrient (N and P) pollution loads from deficient municipal wastewater treatment systems. VF mesocosms planted with papyrus were found to be more efficient regarding removal of suspended solids, organic matter and nutrients. On the contrary, HF systems were limited in efficiency regarding treating wastewater with high organic loading rates. Use of *C. papyrus* with batch hydraulic loading mode in both HF and VF mesocosms enhanced; (a) oxygen transfer in the treatment beds hence creating aerobic conditions suitable for efficient microbial processes with high metabolic rates, (b) aerobic organic matter degradation hence significant reduction of COD and BOD_5 loads to the natural environment, (c) NH_4^+ removal through nitrification which provides a great opportunity for facilitating coupled denitrification with the receiving natural wetland, and (d) high TN and TP elimination rates through plant uptake and sediment retention. It could therefore be concluded that use of CWs as wastewater treatment buffer systems can be easily adopted as flexible and a technologically less intensive option in East Africa to provide a natural continuum for nutrient removal processes from effluents of deficient WWTPs. This can on a long term scale increase the resilience and overall pollution buffering capacity of the receiving environment hence water quality regulation and reduction of public health risks.

The experimental conditions including use of papyrus plants coupled with batch hydraulic loading enhanced aerobic conditions in planted HF and VF treatment beds which influenced carbon and nitrogen gaseous fluxes in the mesocosms. Higher rates of aerobic OM degradation enhanced higher CO_2 fluxes and significantly lower CH_4 flux due to inhibition of methanogenesis in planted HF and VF mesocosms. In addition, although coupled nitrification-denitrification processes were established, nitrification was found to be predominant over denitrification hence lower N_2O fluxes especially in planted mesocosms. It could therefore be concluded that the use of SSF CWs can be an essential technological intervention for addressing climate change mitigation, and in line with the global agenda for low carbon development.

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Appendices

Appendix 1: Physical-chemical characterisation of HF and VF CWs used for municipal wastewater treatment at mesocosms scale

HF-Horizontal sub-surface flow; **VF**-Horizontal sub-surface flow

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
Influent	NA	22/03/2013	8.1	24.0	1885.5	0.5	149.0	169.5	264.5
H1	no	22/03/2013	7.4	23.0	1005.0	0.7	24.0	109.0	119.0
H2	no	22/03/2013	7.6	26.5	830.0	0.4	47.0	104.0	123.0
H3	yes	22/03/2013	7.8	23.0	935.0	2.3	18.0	79.0	169.0
H4	yes	22/03/2013	7.9	25.0	940.0	1.2	32.0	95.0	195.0
V1	no	22/03/2013	8.3	24.0	700.0	0.4	12.0	86.0	112.0
V2	no	22/03/2013	7.5	23.0	625.0	2.8	10.0	107.0	107.0
V3	yes	22/03/2013	7.4	22.0	567.0	2.0	26.0	71.0	71.0
V4	yes	22/03/2013	7.1	25.0	813.0	4.2	11.0	82.0	86.0
Influent	NA	12/04/2013	6.9	22.5	1540.5	0.0	153.0	117.5	247.5
H1	no	12/04/2013	7.7	22.0	673.0	0.5	66.5	50.5	101.5
H2	no	12/04/2013	7.9	23.0	839.0	1.4	51.8	42.6	79.3
H3	yes	12/04/2013	7.8	24.0	781.0	1.8	47.2	48.2	83.6
H4	yes	12/04/2013	7.8	23.0	908.5	3.4	63.0	42.7	92.4
V1	no	12/04/2013	7.7	22.0	748.0	1.3	57.3	39.5	98.4
V2	no	12/04/2013	7.5	23.0	855.0	2.8	41.4	41.0	72.3
V3	yes	12/04/2013	7.6	24.0	927.0	3.7	15.8	28.4	68.4
V4	yes	12/04/2013	7.9	23.0	768.5	3.5	41.3	15.8	72.3
Influent	NA	26/04/2013	8.7	25.0	1681.0	1.1	178.0	141.0	291.4
H1	no	26/04/2013	7.7	23.0	802.0	1.3	65.0	39.3	128.0
H2	no	26/04/2013	6.9	23.0	753.0	2.2	61.0	52.8	112.0

Sampling unit	Papyrus Plants	Date	pH	Temp ⁰C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	26/04/2013	7.8	24.0	984.0	3.2	65.0	43.2	98.5
H4	yes	26/04/2013	7.8	21.5	1002.0	3.6	53.2	26.5	108.0
V1	no	26/04/2013	7.7	25.0	853.0	2.0	31.0	47.0	85.5
V2	no	26/04/2013	7.5	23.5	974.0	3.8	46.0	44.5	111.0
V3	yes	26/04/2013	7.6	24.0	791.0	4.7	22.6	34.5	77.5
V4	yes	26/04/2013	7.9	22.0	951.0	4.4	17.4	18.3	69.5
Influent	NA	10/05/2013	7.9	23.0	2642.0	1.5	165.5	138.0	552.0
H1	no	10/05/2013	7.2	21.0	2005.0	1.7	73.8	41.6	108.0
H2	no	10/05/2013	7.3	22.0	1697.0	0.9	61.4	37.2	94.0
H3	yes	10/05/2013	7.3	23.0	1708.0	2.1	45.6	27.3	63.9
H4	yes	10/05/2013	6.7	21.5	1792.0	3.2	51.3	36.0	88.2
V1	no	10/05/2013	7.8	24.0	1930.0	1.4	41.3	25.4	78.0
V2	no	10/05/2013	7.4	23.0	1888.0	3.8	53.7	32.9	84.0
V3	yes	10/05/2013	6.8	20.5	1893.0	6.0	17.4	19.6	63.0
V4	yes	10/05/2013	7.1	23.0	1680.0	4.2	24.7	22.1	52.0
Influent	NA	24/05/2013	7.8	23.5	2642.0	0.1	141.7	138.0	452.0
H1	no	24/05/2013	7.7	24.0	2005.0	0.0	52.8	31.6	88.2
H2	no	24/05/2013	7.9	23.0	1697.0	0.0	54.8	52.0	140.0
H3	yes	24/05/2013	7.8	21.5	1708.0	0.3	33.8	27.3	83.5
H4	yes	24/05/2013	7.8	25.0	1792.0	0.2	48.4	43.0	78.6
V1	no	24/05/2013	7.7	23.0	1930.0	0.4	41.8	35.4	83.7
V2	no	24/05/2013	7.5	22.0	1888.0	0.8	36.4	42.4	106.0
V3	yes	24/05/2013	7.6	23.0	1893.0	2.0	25.3	23.8	57.1
V4	yes	24/05/2013	7.9	24.5	1680.0	2.2	14.7	19.1	71.0
Influent	NA	14/06/2013	7.8	26.0	2843.0	0.0	229.6	244.0	491.0
H1	no	14/06/2013	7.7	24.0	1003.0	0.6	68.2	73.0	156.0
H2	no	14/06/2013	7.9	26.5	984.0	0.2	61.0	69.2	201.0

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	14/06/2013	7.8	23.0	1200.0	1.5	65.0	47.0	143.0
H4	yes	14/06/2013	7.8	24.0	1342.0	1.7	71.0	52.0	150.0
V1	no	14/06/2013	7.7	22.0	1006.0	0.9	49.0	42.8	198.0
V2	no	14/06/2013	7.5	25.0	845.0	1.8	56.0	53.0	131.0
V3	yes	14/06/2013	7.6	24.0	1501.0	5.7	35.0	38.0	105.0
V4	yes	14/06/2013	7.9	26.0	1513.0	5.2	44.0	31.0	81.0
Influent	NA	28/06/2013	7.5	25.0	1938.0	1.0	331.0	175.0	387.5
H1	no	28/06/2013	7.1	24.0	972.0	1.2	54.0	56.0	181.0
H2	no	28/06/2013	7.0	23.0	891.0	0.9	81.0	87.0	122.0
H3	yes	28/06/2013	6.9	22.0	1004.0	2.8	47.3	39.0	92.0
H4	yes	28/06/2013	7.0	25.0	998.0	1.7	63.4	48.0	109.0
V1	no	28/06/2013	7.5	24.0	894.0	0.9	54.0	43.0	110.0
V2	no	28/06/2013	7.3	25.0	762.0	3.3	63.2	62.0	107.0
V3	yes	28/06/2013	6.8	23.0	902.0	2.5	55.0	17.0	69.5
V4	yes	28/06/2013	6.7	24.0	1017.0	4.7	45.0	51.0	71.0
Influent	NA	12/07/2013	6.1	26.0	1894.0	0.4	308.5	189.5	320.0
H1	no	12/07/2013	6.0	22.0	1002.0	1.0	121.0	73.9	128.3
H2	no	12/07/2013	6.0	23.0	907.0	1.9	103.0	89.4	207.3
H3	yes	12/07/2013	6.0	25.0	1281.0	2.3	78.0	50.3	123.1
H4	yes	12/07/2013	6.0	24.0	1539.0	3.9	93.0	78.0	147.5
V1	no	12/07/2013	6.0	22.0	900.0	1.8	41.0	82.0	172.4
V2	no	12/07/2013	6.0	21.5	894.0	3.3	56.0	72.0	194.0
V3	yes	12/07/2013	6.0	25.0	1502.0	4.2	41.0	32.8	98.4
V4	yes	12/07/2013	6.0	26.0	1039.0	4.0	52.0	50.2	93.6
Influent	NA	26/07/2013	8.1	25.5	2531.0	1.6	345.0	295.0	362.7
H1	no	26/07/2013	7.4	23.0	900.0	1.8	53.0	97.7	154.6
H2	no	26/07/2013	7.6	22.0	1004.0	2.7	79.0	84.1	213.4

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	26/07/2013	7.8	25.5	1500.0	3.7	53.0	46.0	102.0
H4	yes	26/07/2013	7.9	24.0	1603.0	4.1	68.0	52.0	117.0
V1	no	26/07/2013	8.3	21.5	879.0	2.5	37.0	89.3	181.0
V2	no	26/07/2013	7.5	22.5	700.0	4.3	59.0	57.3	172.4
V3	yes	26/07/2013	7.4	23.0	1505.0	5.2	46.0	31.8	102.2
V4	yes	26/07/2013	7.6	23.5	1784.0	4.9	23.0	45.2	89.1
Influent	NA	09/08/2013	6.8	26.5	188.5	2.0	142.0	180.0	284.7
H1	no	09/08/2013	7.5	22.0	1001.0	2.2	74.0	104.0	132.5
H2	no	09/08/2013	7.9	23.0	1002.0	1.4	69.0	69.5	104.0
H3	yes	09/08/2013	7.8	24.0	1400.0	2.6	72.0	50.5	98.6
H4	yes	09/08/2013	7.8	23.5	1250.0	3.7	61.0	65.8	102.0
V1	no	09/08/2013	7.7	21.5	1038.0	1.9	38.6	89.0	108.3
V2	no	09/08/2013	7.5	22.0	985.7	4.3	42.7	101.0	128.0
V3	yes	09/08/2013	7.6	25.0	1390.0	6.5	28.1	38.0	57.9
V4	yes	09/08/2013	8.1	22.0	1600.0	4.7	37.5	42.0	92.0
Influent	NA	30/08/2013	7.5	25.0	1539.0	0.6	152.8	201.5	307.0
H1	no	30/08/2013	7.1	24.0	1520.0	0.2	79.0	104.0	152.0
H2	no	30/08/2013	7.0	23.0	1500.0	0.2	102.0	92.4	127.0
H3	yes	30/08/2013	6.9	25.0	1382.0	0.8	92.0	81.4	73.1
H4	yes	30/08/2013	7.0	22.0	1703.0	0.7	68.4	72.5	105.0
V1	no	30/08/2013	7.5	21.5	1472.0	0.9	53.2	96.2	107.5
V2	no	30/08/2013	7.3	22.0	988.4	1.3	39.6	84.0	152.4
V3	yes	30/08/2013	6.8	22.0	1738.5	2.5	18.6	50.0	74.8
V4	yes	30/08/2013	6.7	23.0	1500.0	2.7	23.0	49.5	92.7
Influent	NA	06/09/2013	6.1	23.0	1875.0	0.5	192.0	231.0	338.6
H1	no	06/09/2013	6.0	22.0	1500.0	1.1	121.0	66.2	102.0
H2	no	06/09/2013	6.0	21.5	1338.0	0.7	102.0	97.2	157.0

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	06/09/2013	8.2	24.0	1639.0	2.0	82.0	48.4	88.0
H4	yes	06/09/2013	6.0	23.0	1598.0	2.2	79.0	83.0	92.6
V1	no	06/09/2013	6.0	24.0	1200.0	1.4	73.0	85.7	127.0
V2	no	06/09/2013	8.0	24.0	1546.0	2.3	58.0	80.3	99.3
V3	yes	06/09/2013	6.0	23.0	1712.0	6.2	37.4	44.0	61.8
V4	yes	06/09/2013	7.4	25.0	1435.0	5.7	54.0	52.0	72.0
Influent	NA	20/09/2013	7.8	25.0	2003.5	1.1	178.0	195.2	291.4
H1	no	20/09/2013	8.0	24.0	1206.0	1.3	117.0	84.9	121.0
H2	no	20/09/2013	6.6	23.0	1001.0	1.0	99.2	71.6	109.0
H3	yes	20/09/2013	8.1	22.0	1612.0	2.9	59.5	47.4	101.0
H4	yes	20/09/2013	7.8	25.0	1429.0	1.8	102.0	56.0	72.9
V1	no	20/09/2013	6.8	22.0	981.0	1.0	88.0	63.0	132.0
V2	no	20/09/2013	7.5	23.0	1002.0	3.4	59.2	67.0	104.0
V3	yes	20/09/2013	7.6	25.0	1582.0	2.6	24.7	28.6	63.4
V4	yes	20/09/2013	8.1	23.0	1924.0	4.8	61.0	59.0	81.0
Influent	NA	18/10/2013	7.8	22.0	1756.0	0.6	167.9	144.5	267.0
H1	no	18/10/2013	7.3	21.5	902.0	1.1	121.0	81.0	131.0
H2	no	18/10/2013	6.0	22.0	1507.0	2.0	116.0	78.0	123.0
H3	yes	18/10/2013	6.5	23.0	1400.0	2.4	92.4	36.0	79.0
H4	yes	18/10/2013	6.0	23.0	1002.0	4.0	87.3	46.0	107.0
V1	no	18/10/2013	8.1	22.0	1007.0	1.9	72.0	42.8	136.0
V2	no	18/10/2013	6.0	20.5	906.0	3.4	73.5	56.0	127.0
V3	yes	18/10/2013	7.8	22.0	1221.0	4.3	72.0	41.7	82.4
V4	yes	18/10/2013	8.5	23.0	1439.0	4.1	67.0	32.0	101.7
Influent	NA	25/10/2013	7.4	23.0	1616.0	1.7	201.7	129.7	198.5
H1	no	25/10/2013	8.2	23.0	803.0	1.9	98.4	53.0	111.0
H2	no	25/10/2013	6.8	22.0	798.2	2.8	87.5	82.0	92.4

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	25/10/2013	7.4	24.0	1002.0	3.8	53.1	38.9	79.3
H4	yes	25/10/2013	8.2	23.0	998.4	4.2	77.6	48.0	58.4
V1	no	25/10/2013	8.4	21.5	737.5	2.6	63.2	71.8	96.3
V2	no	25/10/2013	6.9	21.0	900.5	4.4	56.9	55.0	117.0
V3	yes	25/10/2013	8.1	23.0	891.4	5.3	38.8	37.8	78.0
V4	yes	25/10/2013	7.6	22.0	1172.0	5.0	42.7	29.6	62.0
Influent	NA	12/02/2014	6.6	24.0	1634.0	2.1	262.0	127.0	390.0
H1	no	12/02/2014	7.4	24.5	803.0	2.3	98.4	53.0	111.0
H2	no	12/02/2014	6.5	23.0	798.2	1.5	87.5	82.0	92.4
H3	yes	12/02/2014	6.7	23.0	1563.0	2.7	78.0	40.8	149.0
H4	yes	12/02/2014	6.7	25.0	1578.0	3.8	44.0	59.0	171.0
V1	no	12/02/2014	6.7	24.0	1568.0	2.0	29.0	40.9	118.0
V2	no	12/02/2014	6.6	23.0	1255.0	4.4	16.0	62.5	193.0
V3	yes	12/02/2014	6.7	22.0	1722.0	6.6	12.0	46.4	147.0
V4	yes	12/02/2014	6.8	25.0	1674.0	4.8	41.0	50.2	139.0
Influent	NA	12/02/2014	6.1	22.5	1497.0	0.7	270.0	154.2	272.0
H1	no	19/02/2014	6.0	22.0	1516.0	0.6	57.0	55.0	154.0
H2	no	19/02/2014	6.0	23.0	1420.0	0.6	59.0	44.7	141.0
H3	yes	19/02/2014	6.0	24.0	1604.0	0.9	61.0	54.3	162.0
H4	yes	19/02/2014	6.0	23.0	1458.0	0.8	46.0	49.7	145.0
V1	no	19/02/2014	6.0	22.0	1553.0	1.0	35.0	39.3	150.0
V2	no	19/02/2014	6.0	23.0	1545.0	1.4	40.0	37.8	150.0
V3	yes	19/02/2014	6.0	24.0	1629.0	2.6	27.0	57.8	140.0
V4	yes	19/02/2014	6.0	23.0	1597.0	2.8	33.0	33.0	139.0
Influent	NA	27/02/2014	7.6	25.0	1560.0	0.6	136.0	136.0	267.0
H1	no	27/02/2014	7.6	23.0	1543.0	1.2	55.0	69.0	197.0
H2	no	27/02/2014	7.2	23.0	1500.0	0.8	67.0	33.0	139.0

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	27/02/2014	7.0	24.0	1329.0	2.1	33.0	29.0	167.0
H4	yes	27/02/2014	6.8	21.5	1297.0	2.3	45.0	36.5	122.0
V1	no	27/02/2014	7.1	25.0	1494.0	1.5	23.0	42.0	103.0
V2	no	27/02/2014	7.2	23.5	1520.0	2.4	21.0	30.1	103.0
V3	yes	27/02/2014	7.1	24.0	1420.0	6.3	23.0	50.0	87.0
V4	yes	27/02/2014	7.0	22.0	1491.0	5.8	41.0	21.2	69.0
Influent	NA	28/02/2014	7.5	23.0	1469.0	1.6	147.0	111.3	349.0
H1	no	28/02/2014	7.5	21.0	1585.0	1.8	55.0	41.0	138.0
H2	no	28/02/2014	7.3	22.0	1478.0	1.5	67.0	48.7	154.0
H3	yes	28/02/2014	6.8	23.0	1241.0	3.4	33.0	18.7	44.0
H4	yes	28/02/2014	6.7	21.5	1194.0	2.3	45.0	29.7	68.0
V1	no	28/02/2014	7.1	24.0	1541.0	1.5	11.0	10.1	86.0
V2	no	28/02/2014	7.0	23.0	1567.0	3.9	14.0	9.7	96.0
V3	yes	28/02/2014	6.9	20.5	1491.0	3.1	17.0	37.1	64.0
V4	yes	28/02/2014	7.0	23.0	1605.0	5.3	17.0	17.9	58.0
Influent	NA	04/03/2014	7.9	23.5	1543.0	1.0	158.0	155.1	178.0
H1	no	04/03/2014	7.7	24.0	1332.0	1.6	48.0	32.1	105.0
H2	no	04/03/2014	7.5	23.0	1329.0	2.5	28.0	38.1	92.0
H3	yes	04/03/2014	6.8	21.5	1232.0	2.9	49.0	34.7	73.0
H4	yes	04/03/2014	6.8	25.0	1603.0	4.5	21.0	30.3	109.0
V1	no	04/03/2014	7.4	23.0	1367.0	2.4	19.0	20.4	54.0
V2	no	04/03/2014	7.2	22.0	1357.0	3.9	17.0	21.4	81.0
V3	yes	04/03/2014	7.0	23.0	1381.0	4.8	18.0	22.5	60.0
V4	yes	04/03/2014	7.1	24.5	1481.0	4.6	27.0	23.1	73.0
Influent	NA	11/03/2014	7.9	25.0	1143.0	2.2	124.0	151.0	187.0
H1	no	11/03/2014	7.8	24.0	1316.0	2.4	58.0	55.6	161.0
H2	no	11/03/2014	7.4	23.0	1317.0	3.3	48.0	47.1	131.0

Sampling unit	Papyrus Plants	Date	pH	Temp ⁰C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	11/03/2014	6.8	25.0	1217.0	4.3	30.0	61.0	150.0
H4	yes	11/03/2014	7.1	22.0	1320.0	4.7	20.0	62.0	118.0
V1	no	11/03/2014	7.2	21.5	1309.0	3.1	28.0	20.0	105.0
V2	no	11/03/2014	7.3	22.0	1365.0	4.9	29.0	28.0	104.0
V3	yes	11/03/2014	7.3	22.0	1354.0	5.8	79.0	12.0	55.0
V4	yes	11/03/2014	6.7	23.0	1408.0	5.5	87.0	31.0	64.0
Influent	NA	18/03/2014	7.7	23.0	934.0	2.6	124.0	171.0	287.0
H1	no	18/03/2014	7.3	22.0	849.0	2.8	58.0	75.6	126.0
H2	no	18/03/2014	6.9	21.5	887.0	2.0	48.0	67.1	142.0
H3	yes	18/03/2014	6.1	24.0	414.0	3.2	30.0	81.0	95.0
H4	yes	18/03/2014	6.3	23.0	661.0	4.3	20.0	82.0	106.0
V1	no	18/03/2014	6.5	24.0	867.0	2.5	28.0	40.0	95.0
V2	no	18/03/2014	6.8	24.0	896.0	4.9	29.0	48.0	113.0
V3	yes	18/03/2014	6.6	23.0	914.0	7.1	19.0	32.0	68.0
V4	yes	18/03/2014	6.7	25.0	1030.0	5.3	27.0	51.0	74.0
Influent	NA	25/03/2014	7.8	25.0	1755.0	1.2	145.0	158.0	325.0
H1	no	25/03/2014	6.7	24.0	1283.0	0.8	67.0	62.6	199.0
H2	no	25/03/2014	6.8	23.0	1367.0	0.8	79.0	54.1	169.0
H3	yes	25/03/2014	6.7	22.0	1301.0	1.4	51.0	68.0	188.0
H4	yes	25/03/2014	6.9	25.0	1505.0	1.3	50.0	69.0	206.0
V1	no	25/03/2014	7.5	22.0	1504.0	1.5	38.0	27.0	143.0
V2	no	25/03/2014	7.0	23.0	1375.0	1.9	43.0	35.0	152.0
V3	yes	25/03/2014	7.1	25.0	1362.0	3.1	24.0	19.0	123.0
V4	yes	25/03/2014	6.7	23.0	1318.0	3.3	48.0	38.0	132.0
Influent	NA	01/04/2014	7.2	22.5	1291.0	1.1	143.0	166.0	287.0
H1	no	01/04/2014	7.8	22.0	853.0	1.7	77.0	70.6	161.0
H2	no	01/04/2014	6.9	23.0	1089.0	1.3	67.0	62.1	131.0

Sampling unit	Papyrus Plants	Date	pH	Temp °C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	01/04/2014	6.3	24.0	873.0	2.6	49.0	76.0	150.0
H4	yes	01/04/2014	6.4	23.0	1074.0	2.8	39.0	77.0	168.0
V1	no	01/04/2014	6.8	22.0	1165.0	2.0	47.0	35.0	105.0
V2	no	01/04/2014	6.7	23.0	1168.0	2.9	48.0	43.0	114.0
V3	yes	01/04/2014	6.5	24.0	1138.0	6.8	38.0	27.0	85.0
V4	yes	01/04/2014	6.6	23.0	1455.0	6.3	20.0	46.0	94.0
Influent	NA	08/04/2014	7.2	25.0	1483.0	0.5	116.0	135.0	187.0
H1	no	08/04/2014	7.0	23.0	852.0	0.1	40.0	39.6	161.0
H2	no	08/04/2014	6.9	23.0	826.0	0.1	36.0	31.1	131.0
H3	yes	08/04/2014	5.8	24.0	1400.0	0.7	52.0	45.0	150.0
H4	yes	08/04/2014	5.8	21.5	1817.0	0.6	60.0	46.0	158.0
V1	no	08/04/2014	6.6	25.0	679.0	0.8	20.0	24.0	145.0
V2	no	08/04/2014	6.5	23.5	743.0	1.2	22.0	32.0	114.0
V3	yes	08/04/2014	6.4	24.0	602.0	2.4	30.0	15.0	75.0
V4	yes	08/04/2014	6.8	22.0	857.0	2.6	44.0	21.0	84.0
Influent	NA	15/04/2014	7.8	22.5	1143.0	0.4	162.0	151.0	387.0
H1	no	15/04/2014	7.4	22.0	1316.0	1.0	68.0	55.6	161.0
H2	no	15/04/2014	6.8	23.0	1317.0	0.6	72.0	47.1	126.0
H3	yes	15/04/2014	7.1	24.0	1217.0	1.9	45.0	61.0	162.0
H4	yes	15/04/2014	7.2	23.0	1320.0	2.1	52.0	62.0	138.0
V1	no	15/04/2014	7.3	22.0	1309.0	1.3	39.0	20.0	145.0
V2	no	15/04/2014	7.3	23.0	1365.0	2.2	41.0	28.0	114.0
V3	yes	15/04/2014	6.7	24.0	1354.0	6.1	31.0	12.0	115.0
V4	yes	15/04/2014	7.5	23.0	1408.0	5.6	28.0	31.0	106.0
Influent	NA	07/05/2014	8.3	26.5	1288.0	1.4	137.0	163.5	200.0
H1	no	07/05/2014	8.2	25.5	1461.0	1.6	71.0	68.1	174.0
H2	no	07/05/2014	7.8	24.5	1462.0	1.3	61.0	59.6	144.0

Sampling unit	Papyrus Plants	Date	pH	Temp ^0C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	07/05/2014	7.2	26.5	1362.0	3.2	43.0	73.5	163.0
H4	yes	07/05/2014	7.5	23.5	1465.0	2.1	33.0	74.5	131.0
V1	no	07/05/2014	7.6	23.0	1454.0	1.3	41.0	32.5	118.0
V2	no	07/05/2014	7.7	23.5	1510.0	3.7	42.0	40.5	117.0
V3	yes	07/05/2014	7.7	23.5	1499.0	2.9	32.0	24.5	68.0
V4	yes	07/05/2014	7.1	24.5	1553.0	5.1	30.0	43.5	77.0
Influent	NA	21/05/2014	8.1	24.5	1079.0	0.8	170.0	196.5	300.0
H1	no	21/05/2014	7.7	23.5	994.0	1.4	104.0	101.1	139.0
H2	no	21/05/2014	7.3	23.0	1032.0	2.3	94.0	92.6	155.0
H3	yes	21/05/2014	6.5	25.5	559.0	2.7	76.0	106.5	108.0
H4	yes	21/05/2014	6.7	24.5	806.0	4.3	66.0	107.5	119.0
V1	no	21/05/2014	6.9	25.5	1012.0	2.2	74.0	65.5	118.0
V2	no	21/05/2014	7.2	25.5	1041.0	3.7	75.0	73.5	126.0
V3	yes	21/05/2014	7.0	24.5	1059.0	4.6	55.0	57.5	81.0
V4	yes	21/05/2014	7.1	26.5	1175.0	4.4	40.0	43.5	87.0
Influent	NA	28/05/2014	8.2	26.5	1900.0	2.0	158.0	1800.0	226.0
H1	no	28/05/2014	7.1	25.5	1428.0	2.2	80.0	104.6	180.0
H2	no	28/05/2014	7.2	24.5	1512.0	3.1	92.0	96.1	170.0
H3	yes	28/05/2014	7.1	23.5	1446.0	4.1	64.0	110.0	169.0
H4	yes	28/05/2014	7.3	26.5	1650.0	4.5	63.0	111.0	207.0
V1	no	28/05/2014	7.9	23.5	1649.0	2.9	51.0	69.0	134.0
V2	no	28/05/2014	7.4	24.5	1520.0	4.7	56.0	77.0	123.0
V3	yes	28/05/2014	7.5	26.5	1507.0	5.6	37.0	61.0	104.0
V4	yes	28/05/2014	7.1	24.5	1463.0	5.3	61.0	53.5	93.0
Influent	NA	04/06/2014	7.6	24.0	1436.0	2.4	137.0	163.5	191.0
H1	no	04/06/2014	8.2	23.5	998.0	2.6	71.0	68.1	145.0
H2	no	04/06/2014	7.3	24.5	1234.0	1.8	61.0	59.6	135.0

Sampling unit	Papyrus Plants	Date	pH	Temp ^{0}C	EC ųs/cm	DO mg/l	TSS mg/l	BOD mg/l	COD mg/l
H3	yes	04/06/2014	6.7	25.5	1018.0	3.0	43.0	73.5	134.0
H4	yes	04/06/2014	6.8	24.5	1219.0	4.1	33.0	74.5	172.0
V1	no	04/06/2014	7.2	23.5	1310.0	2.3	41.0	32.5	99.0
V2	no	04/06/2014	7.1	24.5	1313.0	4.7	42.0	40.5	88.0
V3	yes	04/06/2014	6.9	25.5	1283.0	6.9	32.0	24.5	69.0
V4	yes	04/06/2014	7.0	24.5	1600.0	5.1	33.0	43.5	58.0
Influent	NA	12/06/2014	7.6	26.5	1628.0	1.0	129.0	175.5	212.0
H1	no	12/06/2014	7.4	24.5	997.0	0.6	53.0	80.1	166.0
H2	no	12/06/2014	7.3	24.5	971.0	0.6	49.0	71.6	156.0
H3	yes	12/06/2014	6.2	25.5	1545.0	1.2	65.0	85.5	155.0
H4	yes	12/06/2014	6.2	23.0	1962.0	1.1	73.0	86.5	193.0
V1	no	12/06/2014	7.0	26.5	824.0	1.3	33.0	44.5	120.0
V2	no	12/06/2014	6.9	25.0	888.0	1.7	35.0	52.5	109.0
V3	yes	12/06/2014	6.8	25.5	747.0	2.9	43.0	36.5	90.0
V4	yes	12/06/2014	7.2	23.5	1002.0	3.1	57.0	55.5	79.0
Influent	NA	28/06/2014	8.2	24.0	1288.0	0.9	175.0	168.5	400.0
H1	no	28/06/2014	7.8	23.5	1461.0	1.5	81.0	73.1	174.0
H2	no	28/06/2014	7.2	24.5	1462.0	1.1	85.0	64.6	139.0
H3	yes	28/06/2014	7.5	25.5	1362.0	2.4	58.0	78.5	155.0
H4	yes	28/06/2014	7.6	24.5	1465.0	2.6	65.0	79.5	151.0
V1	no	28/06/2014	7.7	23.5	1454.0	1.8	52.0	37.5	148.0
V2	no	28/06/2014	7.7	24.5	1510.0	2.7	54.0	45.5	127.0
V3	yes	28/06/2014	7.1	25.5	1499.0	6.6	44.0	29.5	108.0
V4	yes	28/06/2014	7.9	24.5	1553.0	6.1	41.0	48.5	89.0

Appendix 2: Nutrient performance analysis for HF and VF CWs used for municipal wastewater treatment at mesocosm scale

HF-Horizontal sub-surface flow; **VF**-Horizontal sub-surface flow; H1, H2, V1 and V2 are **unplanted**; H3, H4, V3 and V4 are planted with ***C. papyrus***

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
Influent	22/03/2013	48.16	0.18	4.42	75.52	21.60	32.53
H1	22/03/2013	12.80	0.22	3.77	67.84	19.50	31.90
H2	22/03/2013	21.20	0.19	4.12	70.08	18.40	28.60
H3	22/03/2013	13.70	0.19	2.16	51.08	16.70	30.00
H4	22/03/2013	10.80	0.08	3.74	65.84	19.80	30.80
V1	22/03/2013	11.20	0.19	4.45	66.28	14.20	25.10
V2	22/03/2013	7.13	0.06	4.75	55.70	16.80	24.30
V3	22/03/2013	8.93	0.26	6.45	46.12	12.20	16.30
V4	22/03/2013	5.82	0.37	8.34	48.15	15.20	14.80
Influent	12/04/2013	38.25	0.02	2.87	68.43	15.63	21.83
H1	12/04/2013	13.20	0.01	1.80	61.16	12.40	15.54
H2	12/04/2013	8.49	0.02	2.20	45.29	13.93	17.93
H3	12/04/2013	7.24	0.01	1.30	52.84	7.92	11.45
H4	12/04/2013	9.50	0.03	2.20	47.43	10.43	17.93
V1	12/04/2013	9.48	0.02	4.80	35.63	10.93	11.28
V2	12/04/2013	7.16	0.01	3.10	52.74	5.72	9.63
V3	12/04/2013	6.92	0.02	6.30	29.35	1.52	2.08
V4	12/04/2013	2.84	0.04	5.10	33.51	1.86	3.13
Influent	10/05/2013	40.47	0.19	4.75	58.26	22.26	39.43
H1	10/05/2013	9.97	0.01	4.70	51.61	21.60	22.74
H2	10/05/2013	16.36	0.02	5.01	48.35	14.80	31.80

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	10/05/2013	10.91	0.03	4.60	40.32	13.40	19.20
H4	10/05/2013	11.37	0.01	3.80	32.34	20.05	23.80
V1	10/05/2013	10.53	0.03	3.40	46.12	12.60	15.60
V2	10/05/2013	9.35	0.02	4.90	41.53	15.20	26.70
V3	10/05/2013	5.16	0.03	9.40	31.14	11.30	13.50
V4	10/05/2013	8.48	0.04	6.20	22.46	9.70	19.30
Influent	14/06/2013	47.12	0.46	8.30	67.21	30.16	42.12
H1	14/06/2013	32.19	0.13	6.50	51.61	20.56	41.82
H2	14/06/2013	20.64	0.12	8.10	48.35	33.11	33.15
H3	14/06/2013	12.83	0.03	6.20	41.22	15.23	15.83
H4	14/06/2013	15.64	0.03	4.60	48.15	14.67	33.42
V1	14/06/2013	15.67	0.41	7.60	46.12	30.36	33.26
V2	14/06/2013	20.80	0.32	8.80	41.53	18.36	41.15
V3	14/06/2013	11.65	0.61	9.50	31.14	10.32	23.64
V4	14/06/2013	10.51	0.58	10.30	22.46	8.10	10.45
Influent	12/07/2013	23.92	0.08	3.30	48.37	15.36	31.23
H1	12/07/2013	12.38	0.02	2.90	39.56	13.11	28.43
H2	12/07/2013	13.64	0.01	3.20	40.11	12.06	21.38
H3	12/07/2013	9.75	0.01	2.20	25.71	9.24	11.43
H4	12/07/2013	10.32	0.03	1.90	33.62	8.56	22.32
V1	12/07/2013	11.85	0.02	3.60	35.60	13.63	30.19
V2	12/07/2013	8.24	0.03	5.80	16.82	6.05	10.25
V3	12/07/2013	5.84	0.04	4.50	12.37	5.84	8.85
V4	12/07/2013	15.37	0.02	3.10	24.73	10.67	29.34
Influent	09/08/2013	31.24	0.12	4.63	38.45	17.36	33.47
H1	09/08/2013	17.83	0.02	4.40	25.93	14.62	23.72
H2	09/08/2013	18.94	0.01	4.20	21.34	13.29	18.37

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	09/08/2013	14.76	0.07	2.90	17.75	10.45	9.18
H4	09/08/2013	15.23	0.09	3.70	19.83	9.61	15.23
V1	09/08/2013	16.82	0.08	3.60	20.57	10.55	18.58
V2	09/08/2013	12.65	0.07	5.40	31.34	14.68	20.95
V3	09/08/2013	5.48	0.08	8.80	11.52	7.25	8.56
V4	09/08/2013	8.83	0.13	6.20	12.37	6.11	7.33
Influent	06/09/2013	23.58	0.37	6.50	35.65	16.38	29.54
H1	06/09/2013	15.82	0.09	6.00	33.60	13.55	19.75
H2	06/09/2013	11.36	0.08	5.90	31.24	15.76	20.64
H3	06/09/2013	11.93	0.09	4.80	20.56	11.38	18.55
H4	06/09/2013	10.06	0.11	5.60	18.94	10.03	16.17
V1	06/09/2013	7.85	0.11	7.10	25.53	11.45	18.95
V2	06/09/2013	9.22	0.13	9.20	29.11	17.23	21.20
V3	06/09/2013	3.53	0.34	13.60	15.42	7.71	11.79
V4	06/09/2013	4.47	0.21	11.20	13.48	8.48	10.63
Influent	18/10/2013	23.58	0.37	3.50	35.65	16.38	29.54
H1	18/10/2013	15.82	0.09	3.21	33.60	13.55	19.75
H2	18/10/2013	11.36	0.08	2.90	31.24	15.76	20.64
H3	18/10/2013	11.93	0.09	3.80	20.56	11.38	18.55
H4	18/10/2013	10.06	0.11	5.00	18.94	10.03	16.17
V1	18/10/2013	7.85	0.11	8.10	25.53	11.45	18.95
V2	18/10/2013	9.22	0.13	10.30	29.11	17.23	21.20
V3	18/10/2013	3.53	0.34	14.80	15.42	7.71	11.79
V4	18/10/2013	4.47	0.21	12.60	13.48	8.48	10.63
Influent	12/02/2014	50.56	0.63	4.92	65.52	22.40	33.33
H1	12/02/2014	15.20	0.67	4.27	57.84	20.30	32.70
H2	12/02/2014	23.60	0.64	4.62	60.08	19.20	29.40

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	12/02/2014	16.10	0.64	2.66	41.08	17.50	30.80
H4	12/02/2014	13.20	0.53	4.24	55.84	20.60	31.60
V1	12/02/2014	13.60	0.64	4.95	56.28	15.00	25.90
V2	12/02/2014	9.53	0.51	5.25	45.70	17.60	25.10
V3	12/02/2014	11.33	0.71	6.95	36.12	13.00	17.10
V4	12/02/2014	8.22	0.82	8.84	38.15	16.00	15.60
Influent	12/02/2014	40.65	0.47	3.37	58.43	16.43	22.63
H1	19/02/2014	15.60	0.46	2.30	51.16	13.20	16.34
H2	19/02/2014	10.89	0.47	2.70	35.29	14.73	18.73
H3	19/02/2014	9.64	0.46	1.80	42.84	8.72	12.25
H4	19/02/2014	11.90	0.48	2.70	37.43	11.23	18.73
V1	19/02/2014	11.88	0.47	5.30	25.63	11.73	12.08
V2	19/02/2014	9.56	0.46	3.60	42.74	6.52	10.43
V3	19/02/2014	9.32	0.47	6.80	19.35	2.32	2.88
V4	19/02/2014	5.24	0.49	5.60	23.51	2.66	3.93
Influent	27/02/2014	42.87	0.64	5.25	48.26	23.06	40.23
H1	27/02/2014	12.37	0.46	5.20	41.61	22.40	23.54
H2	27/02/2014	18.76	0.47	5.51	38.35	15.60	32.60
H3	27/02/2014	13.31	0.48	5.10	30.32	14.20	20.00
H4	27/02/2014	13.77	0.46	4.30	22.34	20.85	24.60
V1	27/02/2014	12.93	0.48	3.90	36.12	13.40	16.40
V2	27/02/2014	11.75	0.47	5.40	31.53	16.00	27.50
V3	27/02/2014	7.56	0.48	9.90	21.14	12.10	14.30
V4	27/02/2014	10.88	0.49	6.70	12.46	10.50	20.10
Influent	28/02/2014	49.52	0.91	8.80	57.21	30.96	42.92
H1	28/02/2014	34.59	0.58	7.00	41.61	21.36	42.62
H2	28/02/2014	23.04	0.57	8.60	38.35	33.91	33.95

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	28/02/2014	15.23	0.48	6.70	31.22	16.03	16.63
H4	28/02/2014	18.04	0.48	5.10	38.15	15.47	34.22
V1	28/02/2014	18.07	0.86	8.10	36.12	31.16	34.06
V2	28/02/2014	23.20	0.77	9.30	31.53	19.16	41.95
V3	28/02/2014	14.05	1.06	10.00	21.14	11.12	24.44
V4	28/02/2014	12.91	1.03	10.80	12.46	8.90	11.25
Influent	04/03/2014	26.32	0.53	3.80	38.37	16.16	32.03
H1	04/03/2014	14.78	0.47	3.40	29.56	13.91	29.23
H2	04/03/2014	16.04	0.46	3.70	30.11	12.86	22.18
H3	04/03/2014	12.15	0.46	2.70	15.71	10.04	12.23
H4	04/03/2014	12.72	0.48	2.40	23.62	9.36	23.12
V1	04/03/2014	14.25	0.47	4.10	25.60	14.43	30.99
V2	04/03/2014	10.64	0.48	6.30	6.82	6.85	11.05
V3	04/03/2014	8.24	0.49	5.00	2.37	6.64	9.65
V4	04/03/2014	17.77	0.47	3.60	14.73	11.47	30.14
Influent	11/03/2014	33.64	0.57	5.13	28.45	18.16	34.27
H1	11/03/2014	20.23	0.47	4.90	15.93	15.42	24.52
H2	11/03/2014	21.34	0.46	4.70	11.34	14.09	19.17
H3	11/03/2014	17.16	0.52	3.40	7.75	11.25	9.98
H4	11/03/2014	17.63	0.54	4.20	9.83	10.41	16.03
V1	11/03/2014	19.22	0.53	4.10	10.57	11.35	19.38
V2	11/03/2014	15.05	0.52	5.90	21.34	15.48	21.75
V3	11/03/2014	7.88	0.53	9.30	1.52	8.05	9.36
V4	11/03/2014	11.23	0.58	6.70	2.37	6.91	8.13
Influent	18/03/2014	61.50	0.19	0.75	68.90	22.26	39.43
H1	18/03/2014	52.45	0.01	1.25	61.40	21.60	22.74
H2	18/03/2014	54.50	0.02	2.20	58.70	14.80	31.80

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	18/03/2014	35.85	0.03	4.60	40.32	13.40	19.20
H4	18/03/2014	20.40	0.01	5.82	42.30	20.05	23.80
V1	18/03/2014	25.90	0.03	5.00	36.00	12.60	15.60
V2	18/03/2014	33.70	0.02	10.35	41.53	15.20	26.70
V3	18/03/2014	16.25	0.03	11.87	21.80	11.30	13.50
V4	18/03/2014	20.60	0.04	8.46	31.46	9.70	19.30
Influent	25/03/2014	133.00	0.02	0.95	153.00	52.12	40.16
H1	25/03/2014	87.30	0.13	0.83	103.00	51.82	30.56
H2	25/03/2014	76.80	0.13	1.83	92.60	43.15	43.11
H3	25/03/2014	42.30	0.03	2.27	68.40	25.83	25.23
H4	25/03/2014	47.70	0.24	6.71	70.20	43.42	24.67
V1	25/03/2014	51.20	0.41	4.26	60.50	43.26	40.36
V2	25/03/2014	44.50	0.51	8.80	55.70	51.15	28.36
V3	25/03/2014	33.20	0.34	9.50	42.85	33.64	20.32
V4	25/03/2014	35.80	0.56	11.80	43.60	20.45	18.10
Influent	01/04/2014	87.00	0.08	1.80	95.52	20.36	36.23
H1	01/04/2014	42.75	0.01	0.90	52.84	18.11	33.43
H2	01/04/2014	43.75	0.51	2.20	55.08	17.06	26.38
H3	01/04/2014	26.00	0.36	3.20	36.08	14.24	16.43
H4	01/04/2014	39.50	0.21	2.90	50.84	13.56	27.32
V1	01/04/2014	35.50	0.52	4.60	51.28	18.63	35.19
V2	01/04/2014	30.50	0.81	6.80	40.70	11.05	15.25
V3	01/04/2014	26.00	0.78	10.50	31.12	10.84	13.85
V4	01/04/2014	27.00	0.65	8.10	33.15	15.67	34.34
Influent	08/04/2014	56.00	0.04	3.84	83.22	28.60	39.63
H1	08/04/2014	38.25	0.03	2.69	64.84	20.00	26.75
H2	08/04/2014	43.50	0.04	3.24	62.08	16.00	33.50

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	08/04/2014	29.75	0.03	5.04	57.08	11.70	27.60
H4	08/04/2014	35.50	0.05	4.23	52.84	15.40	25.40
V1	08/04/2014	29.75	0.04	5.75	43.28	17.70	27.50
V2	08/04/2014	26.25	0.03	7.84	47.70	27.40	16.30
V3	08/04/2014	15.50	0.04	10.83	45.12	7.50	17.50
V4	08/04/2014	24.00	0.06	9.67	48.15	10.90	12.30
Influent	15/04/2014	53.25	0.07	3.37	73.43	20.63	26.83
H1	15/04/2014	28.20	0.06	2.30	66.16	17.40	20.54
H2	15/04/2014	23.49	0.07	2.70	50.29	18.93	22.93
H3	15/04/2014	19.24	0.06	1.80	57.84	12.92	16.45
H4	15/04/2014	14.50	0.08	2.70	52.43	15.43	22.93
V1	15/04/2014	14.48	0.07	5.30	40.63	15.93	16.28
V2	15/04/2014	12.16	0.06	3.60	57.74	10.72	14.63
V3	15/04/2014	11.92	0.07	6.80	34.35	6.52	7.08
V4	15/04/2014	10.84	0.09	5.60	38.51	6.86	8.13
Influent	07/05/2014	60.85	0.24	4.67	78.37	33.45	44.48
H1	07/05/2014	43.10	0.28	3.52	59.99	24.85	31.60
H2	07/05/2014	48.35	0.25	4.07	57.23	20.85	38.35
H3	07/05/2014	34.60	0.25	5.87	52.23	16.55	32.45
H4	07/05/2014	40.35	0.14	5.06	47.99	20.25	30.25
V1	07/05/2014	34.60	0.25	6.58	38.43	22.55	32.35
V2	07/05/2014	31.10	0.12	8.67	42.85	32.25	21.15
V3	07/05/2014	20.35	0.32	11.66	40.27	12.35	22.35
V4	07/05/2014	28.85	0.43	10.50	43.30	15.75	17.15
Influent	21/05/2014	63.35	0.25	1.60	61.05	24.11	41.28
H1	21/05/2014	54.30	0.07	2.10	53.55	23.45	24.59
H2	21/05/2014	56.35	0.08	3.05	50.85	16.65	33.65

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	21/05/2014	37.70	0.09	5.45	32.47	15.25	21.05
H4	21/05/2014	22.25	0.07	6.67	34.45	21.90	25.65
V1	21/05/2014	27.75	0.09	5.85	28.15	14.45	17.45
V2	21/05/2014	35.55	0.08	11.20	33.68	17.05	28.55
V3	21/05/2014	18.10	0.09	12.72	13.95	13.15	15.35
V4	21/05/2014	22.45	0.10	9.31	23.61	11.55	21.15
Influent	28/05/2014	134.85	0.08	1.80	145.15	53.97	42.01
H1	28/05/2014	89.15	0.19	1.68	95.15	53.67	32.41
H2	28/05/2014	78.65	0.19	2.68	84.75	45.00	44.96
H3	28/05/2014	44.15	0.09	3.12	60.55	27.68	27.08
H4	28/05/2014	49.55	0.30	7.56	62.35	45.27	26.52
V1	28/05/2014	53.05	0.47	5.11	52.65	45.11	42.21
V2	28/05/2014	46.35	0.57	9.65	47.85	53.00	30.21
V3	28/05/2014	35.05	0.40	10.35	35.00	35.49	22.17
V4	28/05/2014	37.65	0.62	12.65	35.75	22.30	19.95
Influent	04/06/2014	88.85	0.14	2.65	87.67	22.21	38.08
H1	04/06/2014	44.60	0.07	1.75	44.99	19.96	35.28
H2	04/06/2014	45.60	0.57	3.05	47.23	18.91	28.23
H3	04/06/2014	27.85	0.42	4.05	28.23	16.09	18.28
H4	04/06/2014	41.35	0.27	3.75	42.99	15.41	29.17
V1	04/06/2014	37.35	0.58	5.45	43.43	20.48	37.04
V2	04/06/2014	32.35	0.87	7.65	32.85	12.90	17.10
V3	04/06/2014	27.85	0.84	11.35	23.27	12.69	15.70
V4	04/06/2014	28.85	0.71	8.95	25.30	17.52	36.19
Influent	12/06/2014	57.85	0.10	4.69	75.37	30.45	41.48
H1	12/06/2014	40.10	0.09	3.54	56.99	21.85	28.60
H2	12/06/2014	45.35	0.10	4.09	54.23	17.85	35.35

Sampling unit	Date	NH_4^+ N mg/l	NO_2^- N mg/l	NO_3^- N mg/l	TN mg/l	PO_4^{3-} P mg/l	TP mg/l
H3	12/06/2014	31.60	0.09	5.89	49.23	13.55	29.45
H4	12/06/2014	37.35	0.11	5.08	44.99	17.25	27.25
V1	12/06/2014	31.60	0.10	6.60	35.43	19.55	29.35
V2	12/06/2014	28.10	0.09	8.69	39.85	29.25	18.15
V3	12/06/2014	17.35	0.10	11.68	37.27	9.35	19.35
V4	12/06/2014	25.85	0.12	10.52	40.30	12.75	14.15
Influent	28/06/2014	55.10	0.13	4.22	65.58	22.48	28.68
H1	28/06/2014	30.05	0.12	3.15	58.31	19.25	22.39
H2	28/06/2014	25.34	0.13	3.55	42.44	20.78	24.78
H3	28/06/2014	21.09	0.12	2.65	49.99	14.77	18.30
H4	28/06/2014	16.35	0.14	3.55	44.58	17.28	24.78
V1	28/06/2014	16.33	0.13	6.15	32.78	17.78	18.13
V2	28/06/2014	14.01	0.12	4.45	49.89	12.57	16.48
V3	28/06/2014	13.77	0.13	7.65	26.50	8.37	8.93
V4	28/06/2014	12.69	0.15	6.45	30.66	8.71	9.98

Appendix 3: Curriculum Vitae

Najib Bateganya Lukooya

General Background

Najib Bateganya Lukooya is a Male Ugandan, Born in Njeru Municipality, Buikwe District Uganda. He is married and a permanent resident of Seeta, Mukono (Uganda). He is currently an Environmental Management Specialist, Directorate of Public Health and Environment, Kampala Capital City Authority, Uganda.

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Skype: Najib2k

Academic Profile

2012-2015: **PhD** Environmental Engineering and Water Management, University for Natural Resources and Life Sciences, BOKU, Vienna, Austria
2008-2010: **MSc** Environmental Sciences (Limnology and Wetlands Ecosystems Specialisation), UNESCO-IHE Institute for Water Education, Delft, The Netherlands and International Post Graduate Training in Limnology (IPGL), Austrian Academy of Sciences
1998-2002: **BSc** Chemistry, Biology/Education (Hons), Makerere University, Kampala, Uganda

Additional Specialised Competencies/Trainings:

1. **Economics of Climate-Resilient Development** (1st - 22nd, April 2015) – organised and conducted by the World Bank Group
2. **Safe and Resilient Cities** spring 2015, Organised and conducted by the World Bank Group
3. **GHG National Inventory Training** (IPCC inventory software and sector specific guidelines) (13th – 15th August 2014, Entebbe Uganda) organised and conducted by UNDP in collaboration with Climate Change Department, Ministry of Water and Environment under the Low Emission Capacity Building Project
4. **National Appropriate Mitigation Actions** (NAMAs) development; workshop (25th November 2014, Entebbe Uganda) organised and conducted by UNDP in collaboration with Climate Change Department, Ministry of Water and Environment under the Low Emission Capacity Building project
5. **Management of Land Acquisition, Resettlement and Rehabilitation** (5th – 9th August 2013, Kampala, Uganda) – Organised and conducted by the World Bank and the Social Economic Empowerment Consortium
6. **Water Quality: Water Treatment and Sanitation around Lake Victoria** (28th – 29th May 2013, Kisumu, Kenya) organised by French Development Agency and Lake Victoria Commission

7. **Environmental Protection and Management** (14th -25th January 2013) – Conducted by Singapore Environment Institute; Under the Singapore Corporation Programme award, and sponsored by Ministry of Foreign Affairs, Singapore.
8. **Strengthening Public Participation in Environmental Decision-Making**: Building connections for Africa and Middle East Workshop – Rabat-Morocco (7th-9th January 2013)-Organised and conducted by the United States-Environmental Protection Agency and hosted by Ministry of Foreign Affairs, Morocco.
9. **Project Management**-An Introduction Workshop (2nd June 2012): Organised and conducted by the Austrian Agency for International Corporation in Education and Research (OeAD)
10. **Leadership and Change Management** (13th -15th December, 2011) summit organised by National Water and Sewerage Corporation, International resource and Education Centre, Bugolobi, Kampala Uganda. Key themes discussed included; Climate Change, sustainable water systems, integrated water resource management, Governance, finance and management and Knowledge and capacity building.
11. **Modelling pollution sources, flow dynamics and risk assessment in urban catchments using GIS and remote sensing** (September, 2010): Training workshop Organized under the EU FP7 WETwin Project in collaboration with National Water and Sewerage Cooperation, Kampala Uganda
12. UNESCO-IHE Delft, the Netherlands: Water colloquium training seminar series (2008-2010).
    - **Integrating river water quality processes in catchment modelling for ecological risk assessment**: conducted by Dr. Ann van Griensven, January 2009.
    - **Biofilm complexity to mathematical models**: conducted by Prof. Eberhard Morgenroth from Illinois, state University (USA), January, 2009.
    - **Reinventing Hygiene for the 21st Century**: conducted by Prof. Charles Gerba from University of Arizona, December, 2008.
    - **Disinfection By-products (DBPs) and the safety of Drinking water**: conducted by Prof. Sadahiko Itoh from Kyoto University, December, 2008.
13. **International post-graduate training in Tropical Limnology** (October 2007) Egerton University, Nakuru, Kenya in collaboration with Austrian Academy of Sciences: Focused on research and management approaches for water resources management and wetland ecosystems in tropical environments of East Africa
14. **Professional Presentation skills Course** (2004) Organised and conducted by Uganda Management Institute (UMI) Kampala, Uganda.

Professional Experience and Profile

Current:

- **Environment Management Specialist**; Directorate of Public Health and Environment, Kampala Capital City Authority (KCCA), Uganda
- **Research Scientist-Bioframes Working Group**: Inter-University Water Research Institute, (WasserCluster Lunz am see), Austria. Our team investigates nutrient cycling and carbon dynamics in surface water dominated wetlands, their role in riverine landscapes and their importance in providing ecosystem services.

Key Professional/technical Roles undertaken (2005-2015)

1. **Team Leader**, Faecal Sludge (FS) Resource Reuse and Recovery (RRR) Project-Phase 2, Implemented in Kampala City by KCCA in partnership with GIZ-RUWASS and co-financed by the Swiss Development Cooperation (SDC)
2. **Team leader**, Water, Waste and Energy Component; Low Carbon Emission Development Strategy for Kampala City financed by the French Development Agency (2014 to date)
3. **Technical manager**, Green Urban Development study in Kampala City with financial and technical support from World Bank
4. **Environment Specialist**, Lake Victoria Environment Management Project (LVEMP II)- Pollution control component implemented by KCCA in partnership with Ministry of Water and Environment with funding from the World Bank
5. **Project Manager**, Kampala Industrial Pollution control Project funded by GIZ-RUWASS in Kampala City
6. **National technical task team member**; Review of the Uganda National Environment Management Policy, National Environment Management Act and Environmental Regulations
7. **Technical Board member**; The National Low Emission Capacity Building Project, Ministry of Water and Environment with support from UNDP
8. **Technical task team member**; SCUSA (Sanitation Crisis in Unsewered Slum Areas) Grey Water Project, financed through, and implemented by UNESCO-IHE, Institute for Water Education, Delft, the Netherlands and Makerere University, Kampala, in partnership with KCCA, Kampala, Uganda.
9. **Task team Coordinator**; Improving Faecal Sludge (FS) Management in Kampala City, Uganda, Funded by Bill and Melinda Gates Foundation and DFID-UK
10. **Team Leader, Environment and Social safeguards**: Kampala Infrastructure and Institutional Development Project (KIIDP II), implemented by Kampala Capital City Authority (KCCA), Uganda and funded by World Bank
11. **Research Associate -Wetland Hydrology and Water Quality**: WETwin project- under the European Union Seventh Research Framework (EU-FP7).
12. **Associate Researcher/Lecturer (Part-time)**: Makerere University (MAK) and Islamic University in Uganda (IUIU).

<u>Selected Publications and Conference Papers</u>

1. A.Y. Katukiza, K. Musabe, S. Nsubuga, J.T. Tukahirwa, J. Byansi, **N.L. Bateganya**., 2015. A Business model approach for sustainable faecal sludge management in a typical Sub-Saharan Africa city: the Case of Kampala in Uganda. (Manuscript under peer review)

2. **Bateganya, L. N**; Tukahirwa, T.J; Busulwa, H; Hein, T.; 2013. Integrating wetland ecosystem services into the planning of urban landscapes in developing cities of East Africa: Lessons from European riverine wetlands and floodplains. In Urbanisation and Global Environment Change – Emerging scholars Edition, No. 9 July 2013. https://ugec.org/docs/ugec/viewpoints/Viewpoints9-July2013.pdf

3. **Bateganya, N.L**.; Kazibwe, A.; Langergraber, G.; Okot-Okumu, J.; Hein, T., 2015. Performance of subsurface flow constructed wetland mesocoms in enhancing nutrient removal from municipal wastewater in warm tropical environments. Environmental Technology

4. **Bateganya, N.L**.; Mentler, A.; Busulwa, H.; Langergraber, G.; Hein, T., 2015. Carbon and nitrogen gaseous fluxes from subsurface flow wetland buffer strips at mesocosm scale in East Africa. Ecological Engineering (Submitted manuscript under peer review)

5. **Bateganya, N.L**.; Nakalanzi, D.; Babu, M.; Hein, T., 2015. Buffering municipal wastewater pollution using urban wetlands in sub-Saharan Africa: A case of Masaka Municipality, Uganda. Environmental Technology:1-35

6. **Bateganya, L.N** 2010. Hydrological and Water Quality Characterisation of a tropical riverine Wetland: Nabajjuzi, Masaka, Uganda. MSc Thesis, UNESCO-IHE, Delft, the Netherlands and WETwin (EU-FP7) project

7. **Najib Lukooya Bateganya** and Anna Kristina Kanathigoda 2015. Strengthening pit emptying through private sector led service delivery in Kampala City, Uganda. Conference paper; proceedings of the 3rd International Faecal Sludge Management Conference, Hanoi, Vietnam, January 2015.
8. http://www.susana.org/en/resources/conference-materials-2/2015/259-fsm3

9. **Najib Lukooya Bateganya**, 2014. The Kampala city transformation process: Some experiences and challenges in improving sanitation. Conference paper; proceedings of the Unclogging of Blockages in Sanitation Conference; Kampala, Uganda; February 18-20 2014. http://forum.susana.org/forum/categories/142-upscaling-sanitation-governance-institutional-aspects-sanitation-policies/6467-unclogging-the-blockages-in-sanitation-meeting-uganda-february-17-20-2014- feedback-about-the-event

10. **Najib Lukooya Bateganya**, Diana Nakalanzi, Mohammed Babu, Thomas Hein., 2013.Wastewater pollution attenuation in a tropical urban wetland system: Nakayiba, Masaka, Uganda. Conference paper (O.132); proceedings of the 5th International Symposium on Wetland Pollutant Dynamics and Control, WETPOL 2013, co-organized by the Ecole des Mines de Nantes and GEPEA, Nantes, France, October 13-17, 2013. http://www.emn.fr/z-ener/wetpol2013/

11. Tukahirwa T.J and **Bateganya L.N**., 2015. The Role of Policy and Institutional Reform in Enhancing the Technical Efficiency of Urban Authorities: Reference to Solid Waste Management in Kampala City, Uganda. In Future Directions of Municipal Solid Waste Management in Africa. African Institute of South Africa, Pretoria, South Africa. http://www.africanbookscollective.com/books/future-directions-of-municipal-solid-waste-management-in-africa