



Norwegian University of Life Sciences  
Faculty of Environmental Sciences  
and Natural Resource Management (MINA)

Philosophiae Doctor (PhD)  
Thesis 2018:69

# **Water storage dynamics of papyrus wetlands and land use change in the Lake Kyoga basin, Uganda**

Vannlagringsdynamikk i papyrusvåtmarker  
og arealbruksendringer i Lake Kyogas  
nedbørfelt, Uganda

Ellen Jessica Kayendeke

# Water storage dynamics of papyrus wetlands and land use change in the Lake Kyoga basin, Uganda

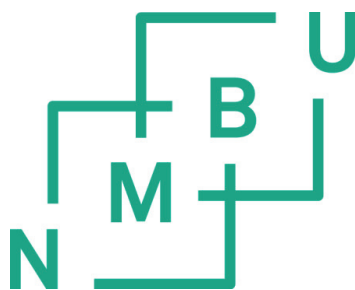
Vannlagringsdynamikk i papyrusvåtmarker og arealbruksendringer i Lake Kyogas nedbørfelt, Uganda

Philosophiae Doctor (PhD) Thesis

Ellen Jessica Kayendeke

Norwegian University of Life Sciences  
Faculty of Environmental Sciences and Natural Resource Management (MINA)

Ås (2018)



Thesis number 2018:69  
ISSN 1894-6402  
ISBN 978-82-575-1537-9

## PhD supervisors

### **Associate Professor, Helen Kristine French**

Faculty of Environmental Sciences and Natural Resource Management, NMBU

Address: P.O. Box 5003 NMBU, 1432 Ås, Norway

Phone: +47 9916 9947

E-mail: [helen.french@nmbu.no](mailto:helen.french@nmbu.no)

### **Professor Frank Kansiime**

Department of Environmental Management, Makerere University

Address: P.O. Box 7062 Kampala, Uganda

Phone: +256 772 506520

E-mail: [fkansiime@caes.mak.ac.ug](mailto:fkansiime@caes.mak.ac.ug)

### **Associate Professor Yazidhi Bamutaze**

Department of Geography, Geo-informatics, and Climatic Sciences, Makerere University

Address: P.O. Box 7062 Kampala, Uganda

Phone: +256 772 696751

E-mail: [bamutaze@caes.mak.ac.ug](mailto:bamutaze@caes.mak.ac.ug)

### **Professor Bal Ram Singh**

Faculty of Environmental Sciences and Natural Resource Management, NMBU

Address: P.O. Box 5003 NMBU, 1432 Ås, Norway

Phone: +47 6723 1859

E-mail: [balram.singh@nmbu.no](mailto:balram.singh@nmbu.no)

### **Professor Øystein Bjarne Dick**

Faculty of Science and Technology, NMBU

Address: P.O. Box 5003 NMBU, 1432 Ås, Norway

Phone: +47 4047 7975

E-mail: [oystein.dick@nmbu.no](mailto:oystein.dick@nmbu.no)

## Thesis Evaluation committee

### **Professor, PhD, Kenneth Irvine**

UNESCO-IHE Institute for Water Education

PO Box 3015 AX Delft, The Netherlands

Telephone: +31 (0)15 215 1873

E-mail: [k.irvine@unesco-ihe.org](mailto:k.irvine@unesco-ihe.org)

### **Senior research Scientist, PhD, Csilla Farkas**

Norwegian Institute of Bioeconomy Research, NIBIO

PO Box 115, 1431 Ås, Norway

Telephone: 94814727

E-mail: [csilla.farkas@nibio.no](mailto:csilla.farkas@nibio.no)

### **Associate Professor, Mona Henriksen**

Faculty of Environmental Sciences and Natural Resource Management, NMBU

Address: P.O. Box 5003 NMBU, 1432 Ås, Norway

Phone: +47 6723 1817

E-mail: [mona.henriksen@nmbu.no](mailto:mona.henriksen@nmbu.no)

## **Dedication**

This work is dedicated to my Parents: Dr. Rose Nabirye Chalo and Mr. Chalo Mugogoto Samuel and to my siblings: Doreen, Pauline, Solomon, and Derrick. Thank you for your love and encouragement; for creating countless moments of cheer and laughter when I was drowning in the work; and for standing in the gap for me. Thank you for being my number one cheer leaders!



## Acknowledgements

I am most grateful to the *Norwegian Agency for Development Cooperation* (NORAD), which provided funding for this PhD study through the *Norwegian Programme for Capacity Development in Higher Education and Research for Development* (NORHED). I am equally grateful to the *Regional Capacity Building for Sustainable Natural Resource Management & Agricultural Improvement under Climate Change* (CAPSNAC) project at Makerere University, through which my PhD study was approved for funding. In particular, I convey my thanks to the principle Investigator; Prof. Samuel Kyamanywa, and the entire CAPSNAC team for believing in me and supporting me throughout the study period. I appreciate the day to day support of Ms. Ruthie Mutyaba who organised all the travels between Uganda and Norway and followed up the various financial requests.

To my supervisors: Associate Professor. Helen French; Professor. Frank Kansiime; Associate Professor. Yazidhi Bamutaze; Professor. Bal Ram Singh; and Professor. Øystein Dick. I am eternally grateful to you all. Thank you for the time invested, intellectual guidance, encouragement, and patience. Special thanks to Professors; Helen French, Frank Kansiime, and Yazidhi Bamutaze who worked tirelessly with me even through weekends and holidays.

I am grateful to the staff at the Department of Environmental Sciences, Geology Group (NMBU) for your encouragement and support. Professor. Sylvi Haldorsen; for welcoming me into your family, and for sharing relevant literature and experiences during my study period in Norway, I can never thank you enough. Professor. Mona Henriksen, Mirian Wangen, Anne Greta, Vilma Bischof, and Håkon Strøm; thank you for the administrative support. I could never have made it without the help of each one of you.

Special thanks to Dr. Philip Nyenje, Dr. Opio Alfonse, Dr. Owor Michael, and Mr. David Kirya for advice during field instrumentation and assistance with data collection. Similarly, special thanks to Mr. Bright Twesigye and Mr. Kukutu Solomon Collin for spearheading the data collection exercise in Uganda. Thank you Solomon for the time you invested in designing the locally made equipment and familiarising yourself with the different automatic gadgets! Thank you for bearing with me and taking care of the monitoring site while I was in Norway. For all the times I asked you to travel to the study site at short notice, the hours we spent deliberating over fabricated and automatic equipment, as well as instrumentation plans. Thanks to all the field assistants led by Mr. Tebenkana, and the people of Nawangisa village for welcoming me into your community and supporting my field work through providing security and maintenance for

all field work equipment. I also thank Mr. Charles Gusongoirye and Mr. Edward Gabula for your help. You hosted us, pitched in during field work and stepped in when I needed financial support.

Mr. Leo Mwebembezi, Mr. Kigozi Frank, Ms. Carol Kagaba, Mr. Francis Kisitu, and Mr. Charles Kiwalabye; many thanks for the data you shared with me. My friends and colleagues: Geraldine Paula Babirye, Sarah Tumuhairwe, and Henry Makumbi; I extend very special thanks for assistance in surveying, availing GIS data and reading materials, as well as emotional support and encouragement.

The support I received from the Chair and all my colleagues in the Department of Environmental Management at Makerere University is phenomenal. For carrying my work load as I studied and for the continued encouragement during the PhD study period, I am so thankful always. My thanks especially to Professor James Okot Okumu, Dr. David Mfitumikiza, Dr. Eliezer Kateyo, Professor Vincent Muwanika, Professor John R.S. Tabuti, Prof. Majaliwa Mwanjololo, Mr. Erima Godwin, Mr. Japhes Kissa, Dr. Anthony Egeru, Mr. Natumanya Ezraah, Dr. Barasa Bernard, and Mr. Katongole Juma. I would also like to thank Professor Bernard Bashaasha and Professor Mnason Tweheyo for your support, especially endorsing my request for study leave.

The Ugandan community in Ås including: Doreen, Fredrick and Erick made my stay in Norway memorable and helped me deal with the stresses of PhD life. I thank you so much. My dear friends in the Geology group at NMBU and those from UiO - Arturs Putnins, Mari Haugene, Perrine Fernandez, Sverre Anmarkrud, Tove Robertsen, Bart Immerzeel, and Joris Stuurup; I thank you so much for your companionship and helping me laugh through the trials. Thank you for the countless times you showed me that I was not alone in the struggle!

The members of International Believers Fellowship (IBF) in Ås, I learnt a lot from you. Thank you for helping me grow as a Christian, for the prayers, encouragement and love, for the time we shared together, and for helping me discover some gifts I didn't know I had. Thank you dear friends Beatrice, Dorcas, Lazarus, Mekdes, Taiwo and Trust; may the Almighty God bless you all.

Last and importantly, I thank the Almighty God, for being my rock during the study period and for bringing me thus far.

***2 Corinthians 12:9: "my grace is sufficient for you, for my power is made perfect in weakness"***

## List of Acronyms

ADCP	Acoustic Doppler Current Profiler
ANOVA	Analysis of Variance
AVHRR	Advanced Very High Resolution Radiometer
BFAST	Breaks for Additive Season and Trend
CAPSNAC	Regional Capacity Building for Sustainable Natural Resource Management and Agricultural Improvement under Climate Change
CHC	CHC Navigation (company name)
CIAT	International Centre for Tropical Agriculture
DEM	Digital Elevation Model
DPSIR	Drivers, Pressures, State, Impact, and Response model for describing interactions between human actions and the environment
DWRM	Directorate of Water Resources Management
EC	Electrical conductivity
FAO	Food and Agricultural Organisation
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
HDF	Hierarchical Data Format
HYDATA	Hydrological Database and Analysis System
IMG	image file format
ISODATA	Iterative Self-Organising Data Analysis
Landsat	A sequence of Earth-observing satellite missions
MNDWI	Modified Normalised Difference Water Index
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSUM	Moving Sum
NARO	National Agricultural and Research Organisation
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
NFA	National Forest Authority
NGOs	Non-Governmental Organisations



NORAD	Norwegian Agency for Development Cooperation
NORHED	Norwegian Programme for Capacity Development in Higher Education and Research for Development
OLS	Ordinary Least Squares
OTT	OTT Hydromet (company name)
RTK	Real Time Navigation
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VIs	Vegetation Indices
WMD	Wetlands Management Department

## Table of contents

Dedication .....	i
Acknowledgements .....	iii
List of Acronyms .....	v
Abstract .....	ix
Sammendrag .....	xi
List of papers .....	xiii
1. Introduction .....	1
1.1. Definition and classification of wetlands .....	1
1.2. Papyrus wetlands .....	2
1.3. Wetlands of Uganda .....	5
1.4. Development of wetland agriculture in the Lake Kyoga Basin .....	6
1.5 Status of wetland mapping in Uganda .....	7
1.5. Problem statement .....	8
1.6. Objectives .....	9
2. Materials and methods .....	10
2.1. Study area .....	10
2.1.1. Mpologoma River catchment .....	10
2.1.2. The Naigombwa wetland site .....	12
2.2. Data collection .....	13
3. Overview of papers .....	16
3.1. Trend of vegetation productivity and moisture (paper I) .....	16
3.2. Wetland water storage and papyrus mat dynamics (paper II) .....	18
3.3. Wetland water balance (paper III) .....	18
4. Discussion .....	20
5. Conclusions, implications for wetland management and future research .....	22
References .....	25



## **Abstract**

Papyrus wetlands of the upper Nile basin in Eastern Africa provide water and fertile soils that are essential to sustain agricultural production. Due to the need to improve food security, there is increased pressure to convert wetlands into agricultural land. This results in removal of natural wetland vegetation and river diversions and yet the impacts of these changes on wetland functioning and basin wide hydrology are not fully understood.

The thesis objectives were to quantify changes in vegetation productivity and moisture, to assess the water storage dynamics of papyrus wetlands in different seasons, and to identify the key processes of the wetland's hydrological regime for papyrus wetlands in the Lake Kyoga basin, Uganda.

Time series of MODIS NDVI were classified to create a map of land cover complexes for the study area, and the NDVI trend of each cover complex was analysed using 'Breaks for Additive Season and Trend' (BFAST). Vegetation moisture was monitored by calculating Normalised Difference Water Index (NDWI) from Landsat data at 15 year intervals. The bathymetry of a section of the wetland was mapped to estimate the depth-volume relationship, from which water volume was calculated. A profiler rod was used to measure papyrus root mat thickness and depth of the free water column in the dry and wet seasons. Water balance components were calculated using climate, groundwater, wetland stage, and discharge data that were recorded at a selected wetland section.

The results showed that vegetation moisture and productivity have declined and are still declining as a result of land cover changes that occurred more than 15 years ago, since there were no significant land cover changes in the last 15 years. The study also showed that papyrus plants are physically adapted to increasing water levels in the wetlands because their root mat can compress with the pressure of the rising water, which increases the depth of the free water column beneath the plant. These dynamics facilitate an additional storage capacity of 50% in the wet season. Flow in the main wetland channel is the key component (99%) of the papyrus wetland's hydrological regime implying that the wetland is vulnerable to continued land use changes in the upstream catchment.

Converting wetlands into agricultural land, changes wetland hydrology, leading to reduced moisture availability and productivity in adjacent areas. Because wetlands serve as a boundary for groundwater, their drainage could lead to gradual reduction of the groundwater table over a larger area. Therefore, utilising stored wetland water for irrigation of small-scale farms could be a more sustainable option for improving agricultural productivity. However, further research is needed to understand the impacts of water withdrawal on wetland hydrology.

## Sammendrag

Papyrus-våtmarker i de øvre delene av Nilens nedbørfelt i Øst-Afrika sikrer vann og fruktbar jord, og er av stor betydning for å opprettholde landbruksproduksjon. På grunn av behovet for å forbedre matvaresikkerheten, er det økt press for å gjøre om våtmarker til jordbruksarealer. Dette fører til endringer av elveløpet og fjerning av naturlig våtmarksvegetasjon, til tross for at virkningene på våtmarkenes funksjon og nedbørfeltets hydrologi ikke er kjent.

Målene med dette doktorgradsarbeidet er å kvantifisere endringer i vegetasjonens produktivitet og vanninnhold, å kunne analysere papyrusvåtmarkenes sesongmessige vannlagingsdynamikk og å identifisere nøkkelprosesser i papyrusvåtmarkenes hydrologiske regime i Lake Kyogas nedbørfelt, Uganda.

Tidsseriene MODIS NDVI ble klassifisert for å lage et kart over arealbrukskomplekser for studieområdet, og NDVI-trenden i hvert kompleks ble analysert ved hjelp av 'Breaks for Additive Season and Trend' (BFAST). Vegetasjonens vanninnhold ble overvåket ved å beregne 'Normalized Difference Water Index' (NDWI) fra Landsat-data med 15 års mellomrom. Fra en undersøkelse av våtmarkens batymetri kunne dybde-volum forholdet bestemmes, for videre beregning av vannvolumet. En rotmattestang ble brukt til å måle rotmattetykkelsen og fri vannhøyde under rotmatta i både tørke- og regntiden. Vannbalansen ble beregnet fra klimadata, logging av våtmarks- og grunnvannsnivå og vannføringsdata for et utvalgt område av våtmarken.

Resultatene viser at vegetasjonens vanninnhold og produktivitet har avtatt og fortsetter å avta som et resultat av arealbruksendringer som fant sted for mer enn 15 år siden, ettersom det ikke har vært signifikante endringer i arealbruk de siste 15 årene. Studien viste også at papyrusplanter er fysisk tilpasset økt vannstand ved at rotmatten komprimeres med økt vannføring, noe som øker vanndybden under plantemassen. Denne dynamikken fører til at vannlagingskapasiteten øker med 50 % i regntiden. Vannføringen i hovedløpet dominerer den lokale vannbalansen og det hydrologiske regimet (utgjør 99%), noe som innebærer at papyrusvåtmarker er sårbare for fortsatt økning av landbruksområdene oppstrøms i nedbørfeltet.

Omgjøring av våtmarker til landbruksproduksjon endrer hydrologien i våtmarkene, og fører til redusert vanntilgjengelighet og produktivitet i omliggende jordbruksarealer. I tillegg vil avrenningen fra våtmarkene, pga. sin nære tilknytning til grunnvannet, føre til gradvis reduksjon i grunnvannsnivået over større områder. Det vil derfor være mere bærekraftig hvis vannlagringskapasiteten i våtmarkene ble benyttet til vanning av småskala gårdsbruk for å forbedre jordbruksproduktiviteten. Men mer forskning er nødvendig for å forstå virkningene av slikt vannuttak på våtmarkshydrologien.

## List of papers

1. Kayendeke, E.J., French, H.K., Bamutaze, Y., and Kansiime, F., 2018. Land Use Change and Vegetation Moisture Variations of a Tropical Wetland Catchment in the Lake Kyoga Basin, Uganda. Submitted to *Land degradation and Development*, under review
2. Kayendeke, E.J., Kansiime, F., French, H.K., and Bamutaze, Y., 2018. Spatial and temporal variation of papyrus root mat thickness and water storage in a tropical wetland system. Published online in *Science of The Total Environment*, 642, pp.925-936. <https://doi.org/10.1016/j.scitotenv.2018.06.087>. Printed with permission from Elsevier
3. Kayendeke, E.J., and French, H.K., 2018. Characterising the hydrological regime of a tropical papyrus wetland in the Lake Kyoga Basin, Uganda. Submitted to Springer book project: *"Agriculture and Ecosystem Resilience in Sub Saharan Africa"*, under review





# 1. Introduction

## 1.1. Definition and classification of wetlands

Wetlands are defined as transitional zones between permanently flooded areas and dry land, in which the water table is at or near the ground surface all year round or for part of the year (Rasmussen *et al.*, 2018). They provide goods and services that include food, fuel wood, raw materials, water storage, regulatory and supporting functions like flood mitigation, water purification, nutrient cycling, as well as numerous cultural services (de Groot *et al.*, 2018; Whigham, 2018).

A broader definition of wetlands was given by the RAMSAR convention as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres”. This definition therefore includes a wide range of wetland types including lakes, rivers, swamps, marshes, and peatlands among others (Gerbeaux *et al.*, 2018; Grobicki *et al.*, 2016).

The RAMSAR definition of wetlands is based on biological characteristics like type of vegetation, therefore similar wetland types are categorised under different names or individual wetland types are duplicated across categories. For example: forested swamps (Europe); marshes (Southern Hemisphere); and meadows (United States) all occur in seasonally flooded basins but are classified as different wetlands because of differences in climatic conditions and vegetation type (Semeniuk & Semeniuk, 1997).

Thus Semeniuk and Semeniuk (1995; 1997) proposed a classification system based on land form type and hydrological regime to aid with global comparison among wetlands. They suggested landform types such as basins, channels, flatlands, slopes, and hills while hydrological types include permanently flooded, seasonally flooded, permanently waterlogged and seasonally water logged regimes among others. They recommended that anyone of the landforms can be combined with any of the hydrological regimes to classify a given wetland independently of climatic setting or vegetation type. For example, a permanently flooded channel would be classified as a river regardless of vegetation type or lack thereof and climatic setting.

However, Brinson (2011) argued that there is no single correct way to classify wetlands but suggested three categories of classification based on wetland functions, structure, and utility. Structural classification is based on vegetation types while utility classification stresses how wetlands can be managed to enhance their ecosystem services (Brinson, 2011). Functional classification emphasizes hydrological characteristics like source of water and duration of flooding and is also referred to as hydrogeomorphic classification.

The hydrogeomorphic classification highlights the functioning and ecological importance of different wetlands (Semeniuk & Semeniuk, 2018). Indeed, although wetlands are known to provide various goods and services, the range of services differs among wetlands depending on water sources and their location within the landscape (Semeniuk & Semeniuk, 2018). For example, Acreman and Holden (2013) pointed out that upland and flood plain wetlands do not have the same flood mitigation capacity because of their location in the landscape.

Because of the different ways of defining wetlands, there is a broad range of wetlands including estuaries, peatlands, mangroves, tidal freshwater wetlands, and tropical freshwater wetlands (Milton *et al.*, 2018). This has made it difficult to have a comprehensive estimate of the global coverage of wetlands (Finlayson *et al.*, 2018), with documented estimates varying between 3.7 to 12.8 million km<sup>2</sup> (Finlayson *et al.*, 1999; Finlayson *et al.*, 2018; Lehner & Döll, 2004; Milton *et al.*, 2018).

## **1.2. Papyrus wetlands**

Papyrus wetlands are tropical swamps that are largely classified based on the dominant vegetation (*Cyperus papyrus* L.), since they occur in both riverine and lacustrine landscapes. They are predominant in central and eastern Africa, but have been observed in the Okavango delta in southern Africa as well as in the Middle East and southern Europe (Kipkemboi & van Dam, 2018). Although they are commonly referred to as swamps, they are actually marshes because they contain herbaceous rather than forested vegetation (Kipkemboi & van Dam, 2018).

Papyrus exists either in rooted or floating form, and spreads through germination of seeds exposed on wet soils or by rhizome propagation over open water bodies

(Gaudet, 1977; Terer *et al.*, 2014). Rooted papyrus have roots anchored in the sediment but can spread over open water to form continuous floating mats (Figure 1). The floating mats are formed by the entanglement of roots, rhizomes, and organic matter (Saunders *et al.*, 2012; van Dam *et al.*, 2007).



Figure 1: Floating papyrus wetland in Eastern Uganda, with open water at the inlet culvert. The depth of the water column beneath the papyrus mat varies between 1 to 2 meters

Both the above ground and below ground parts of papyrus plants contain large amounts of spongy air filled tissue (aerenchyma). The plants are thus adapted to growing in permanently inundated areas. They thrive in low energy environments that have moderate water level fluctuations and wind velocity (Mburu *et al.*, 2015). Rooted and floating papyrus plants survive on nutrients present in the soil and water, respectively (Kansiime & Nalubega, 1999). Floating plants access nutrients through exchanges of water between the water column beneath the plant and its root system. These exchanges are possible due to the loose structure of the floating mat (Azza *et al.*, 2000).

The plants are made up of roots and rhizomes from which culms grow (Chale, 1987). The plant's morphology is illustrated in Figure 2. Culms have a low photosynthetic ability (Mburu *et al.*, 2015), but are capped by umbels which are the main photosynthetic part of the plant (Mburu *et al.*, 2015; Saunders *et al.*, 2012; Terer *et al.*, 2014). The plant

grows to maturity in about 6 to 9 months (Mburu *et al.*, 2015), and can grow up to 6 m tall in suitable environments (Kipkemboi & van Dam, 2018). The growth stages of papyrus include: culms with closed umbels; culms with opening umbels; culms with fully open umbels; senescent culms; and dead culms. The different growth stages occur continuously, and decomposing plant material forms detritus that accumulates within the root-mat layer or falls through to the sediment layer (Jones & Muthuri, 1997; Muthuri *et al.*, 1989; Opio *et al.*, 2014).

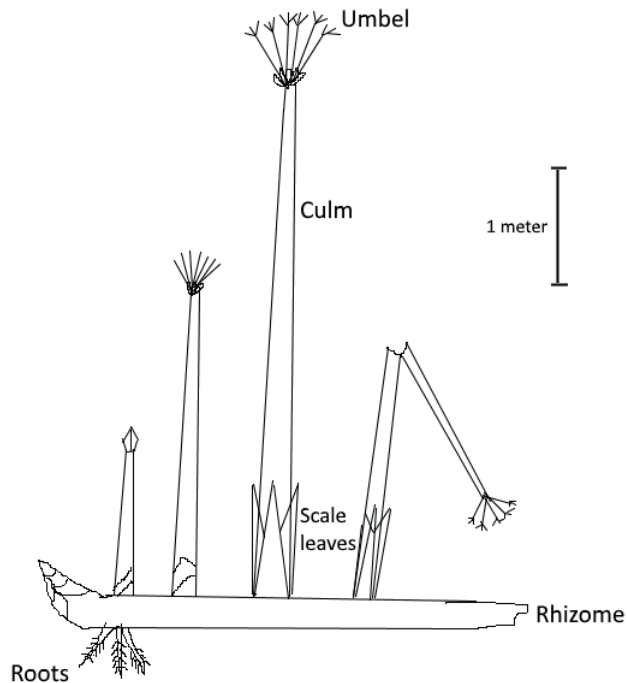


Figure 2: Illustration of papyrus morphology at different growth stages, adapted from Gaudet (1975)

Papyrus wetlands provide several goods and services including fuel wood, medicinal herbs, fish, raw materials for crafts and building materials as well as land for wetland edge agriculture (Donaldson *et al.*, 2016; Terer *et al.*, 2014). In addition, regulatory functions include water purification (van Dam *et al.*, 2007), flood mitigation and water storage (Saunders *et al.*, 2013). Thus they are important in supporting community livelihoods, but face pressures of excessive plant harvesting and encroachment for agricultural and industrial expansion (van Dam *et al.*, 2014).

### 1.3. Wetlands of Uganda

Wetlands cover about 11% of Uganda's land surface of which 66% are seasonal, 34 % are permanent, while swamp forests cover less than 1% of the total wetland area (GOU, 2016). Papyrus is the dominant vegetation in most of Uganda's permanent wetlands. For example: it occurs along shorelines of Lakes Victoria and Albert; in valley swamps and rivers of central and western Uganda; as well as in rivers of the Lake Kyoga basin in Eastern Uganda (Kipkemboi & van Dam, 2018).

Uganda was the first African country to pass a National wetlands policy in 1995 (GOU, 2016; Mafabi, 2018). The policy has five goals, three of which include: ending practices which diminish wetland productivity; maintaining wetland biological diversity; and integrating wetland concerns into other sectoral plans (Mafabi, 2018). The policy was strengthened by incorporating wetland matters into the 1995 Constitution, the National Environment Act of 1995, and the 1998 Land Act (Mafabi, 2018).

Great strides have been made in wetland conservation and management with an increased awareness of their functioning among local communities and politicians alike. In addition, a mapping exercise of the country's wetlands was recently completed (Mafabi, 2018). However, there are still challenges because of complicated land tenure systems, and weak enforcement of the law where people encroach on wetlands with impunity. In addition, there are existing knowledge gaps about the connections among climate, land use, surface and subsurface water. This is complicated by impacts of climactic variation and high population growth rate which is estimated at 3.2% per year (GOU, 2016; Mafabi, 2018).

Wetland encroachment has thus continued despite the efforts put in place to halt their degradation. The degradation is mainly due to expansion of residential and industrial areas, and conversion of wetlands for agricultural expansion in urban and rural areas, respectively (GOU, 2016). As a result, there was a 30% national decline in wetland coverage between 1994 and 2008, with only a 0.03% increase between 2008 and 2014 (GOU, 2016). The highest declines of 54% and 27% were recorded in the Lake Victoria and Lake Kyoga basins, respectively (NEMA, 2008b; Nsubuga *et al.*, 2014).

The main driver of wetland degradation is high population growth rate. For example, Uganda's population increased by 169% between 1986 and 2014. This has led to widespread conversion of wetlands for agricultural production (GOU, 2016; Turyahabwe *et al.*, 2013). Although agricultural activities have expanded into wetlands, crop yields have remained low mainly because of poor land management with only 30% of cultivated land managed sustainably, and climatic variability characterised by prolonged dry spells (GOU, 2017). Because of the low yields, only 10% of communities adjacent to wetlands are food secure, and this is likely to drive further wetland degradation as people strive to improve food security (Yikii *et al.*, 2017).

#### **1.4. Development of wetland agriculture in the Lake Kyoga Basin**

The Lake Kyoga basin is located in Eastern and North-eastern Uganda, it covers an area of 57,000 km<sup>2</sup> and drains 41 districts. Rice production started in 1942 with the establishment of the Doho rice scheme along River Manafwa (Figure 3a). The scheme covers about 32 km<sup>2</sup> and has a network of channels to irrigate the rice fields as well as a dam for water storage (GOU, 2016). The scheme collapsed after 1945 and rice production reduced greatly until the government rehabilitated it between 1976 and 1989 (Nakano & Otsuka, 2011; Sserunkuuma *et al.*, 2004).

Local farmers formed the "Doho Rice Scheme Farmers' Association" in 1994, and government devolved management of the scheme to the association (Nakano & Otsuka, 2011). Currently, the government does not offer financial support for running the scheme apart from maintaining an irrigation management office whose staff offer extension services to the farmers. Small scale farmers (out growers) took advantage of water draining from the scheme and established rice fields downstream of the main scheme (Nakano & Otsuka, 2011). The neighbouring Namatala wetland (Figure 3a) has also been encroached upon with up to 90% of the wetland converted for rice growing (GOU, 2016).

The basin has another large scale rice scheme adjacent to River Malaba (Figure 3a). The scheme is called "Kibimba rice scheme" and covers approximately 6 km<sup>2</sup>. This scheme was established in 1973 with the help of the Chinese government, in a bid to increase food production for the country. This scheme was sold to Tilda Rice (Uganda)

in 1996 (Pisters, 2014). Another wetland of interest is the Naigombwa wetland (Figure 3a), which is currently utilised for rice growing by small scale farmers. Part of this wetland was sold to a private company in 2009 for large scale rice production although production is yet to start (Pisters, 2014).

Despite expansion of rice fields in the Lake Kyoga basin, food security declined by 13% between 2010 and 2016 (GOU, 2017). The rice expansion is mainly due to the increasing market for rice, which encourages farmers to invest in rice production rather than increasing subsistence food production. They often sell up to 55% of the rice produced leaving them with insufficient food for consumption, and then use proceeds from the sales to buy additional food for their families (GOU, 2017; NEMA, 2008a; Uganda Bureau of Statistics, 2017).

Agriculture in upland areas is mainly rain-fed and crop production is low because no external inputs are used to improve soil fertility. Although there are a number of farmer field schools run by Makerere University, National Agricultural Research Organisation (NARO), and International Centre for Tropical Agriculture (CIAT) to help farmers improve soil fertility, the farmers are reluctant to leave the wetlands because of increasing rainfall variability in the basin (NEMA, 2008a).

## **1.5 Status of wetland mapping in Uganda**

The Wetland Inspection Division (currently, the Wetlands Management Department) built inventories for wetlands in approximately 30 districts of Uganda between 1995 and 2005, and created the National Wetlands Information System (Wetlands Management Department *et al.*, 2009). The information system tracks changes in wetland uses and classifies them according to level of impact. However, there are no accurate statistics on changes in wetland coverage since generated maps give information for a single point in time (Wetlands Management Department *et al.*, 2009). Further, the large expanse of the wetlands make detailed mapping difficult. For example, the most recent wetland map (2010) classified some degraded wetland areas as papyrus areas, which indicates that the mapping exercises cannot keep pace with the rapid land use changes.



In the absence of land use change records, as well as information about their impacts on land productivity and hydrology for ungauged catchments; time series of remote sensing data can be used to make rapid assessments of historical land use/cover changes and to monitor land degradation. For example, Ali *et al.* (2013) used hyper temporal Normalised Difference Vegetation Index (NDVI) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to monitor land cover gradients in Greece. Furthermore, vegetation productivity and moisture can be monitored using time series of NDVI and Normalised Difference Water Index (NDWI). This is possible because NDVI and NDWI indices are highly correlated to vegetation primary productivity and open water surfaces, respectively (Dobriyal *et al.*, 2012; Schyns *et al.*, 2015; Verbesselt *et al.*, 2010). Both indices range from -1 to 1; where high values indicate high vegetation biomass and presence of open water for NDVI and NDWI, respectively. The formulas for NDVI and NDWI are given in equations 1 and 2 (Gao, 1996; Kastens *et al.*, 2005);

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad (2)$$

where NDVI = Normalised Difference Vegetation Index, NDWI = Normalised Difference Water Index, and NIR/RED/SWIR = spectral reflectance in the near infrared, red, and shortwave infrared portions of the electromagnetic spectrum

This thesis contributes to a better understanding of land use changes within wetlands in the Lake Kyoga basin by exploring low cost means for mapping land use history. In addition, new information on papyrus wetland dynamics as a function of hydrological conditions was generated by monitoring papyrus mat responses to water level fluctuations, and quantifying water storage in the dry and wet seasons.

## 1.5. Problem statement

As many countries, Uganda inclusive, seek to improve food security for rural populations, there is an increased backing by African governments and Non-Governmental Organisations (NGOs) for increased wetland agriculture to improve food

production (Leemhuis *et al.*, 2016). Therefore, there is widespread conversion of wetlands for agricultural expansion especially for rice paddies, and river channelization for irrigation.

Since wetlands provide a wealth of other goods and services aside from food production, it is important to balance the need to use wetlands for improved agricultural productivity and protecting their functioning (Burghof *et al.*, 2017; Leemhuis *et al.*, 2016), especially since the long term maintenance of agriculture depends on these very ecosystem services like water availability and fertile soils (Vlek *et al.*, 2017). Despite wetlands' importance, there are currently no records on the impacts of land cover changes on vegetation productivity and moisture availability within data scarce basins of Sub-Saharan Africa. Further, although the regulatory and provisioning services of papyrus wetlands like water storage are well known, they are not quantified which makes it difficult to make sustainable compromises between food production and wise use of the wetlands (van Dam *et al.*, 2014).

## **1.6. Objectives**

The overall objective of this study was to assess the water storage capacity of papyrus wetlands under changing land uses in the Lake Kyoga Basin. The objectives for the individual papers are:

Paper I: To assess the impacts of land use changes on vegetation moisture and productivity in the Lake Kyoga Basin. The specific objectives were: (i) to map the spatial coverage of intact wetlands and other land uses using MODIS NDVI time series; (ii) to use NDVI as a proxy to monitor the trend of vegetation productivity; and (iii) to monitor changes in vegetation moisture using Landsat derived NDWI

Paper II: To assess the water storage dynamics of a papyrus wetland section. Specifically the study sought to: (i) to assess the response of the papyrus root mat to changing water levels; and (ii) to quantify the water storage capacity in the dry and wet seasons

Paper III: To quantify the water balance for a papyrus wetland section, with specific objectives to: (i) to identify the main components of the wetland's water balance; and (ii) to estimate the wetland's retention time in the dry and wet seasons.

## **2. Materials and methods**

### **2.1. Study area**

The study was carried out at two scales: at the landscape scale (paper I) where the impacts of land cover changes on vegetation moisture and productivity were quantified within the Mpologoma River catchment (Figure 3a); and at the local scale where the water storage capacity, and papyrus root mat dynamics were assessed (paper II) for a section of the Naigombwa wetland (Figure 3b). In addition, the wetland water balance was calculated for the Naigombwa wetland section (paper III).

#### **2.1.1. Mpologoma River catchment**

The Mpologoma River catchment is a sub catchment of the Lake Kyoga basin and covers approximately 8,900 km<sup>2</sup>. It drains 11 districts, and its elevation ranges from 1020 to 4310 m.a.s.l. The Mpologoma River has four tributaries: Namatala, Manafwa, Malaba, and Naigombwa (Figure 3a). It contributes about 600 million m<sup>3</sup> of water to Lake Kyoga (Hughes & Hughes, 1992). These rivers are referred to as wetlands from here on, following the hydrogeomorphic classification scheme for wetlands of Semeniuk and Semeniuk (1995; 1997). The dominant vegetation in undisturbed portions of the wetlands is papyrus, which exists as floating mats in permanently flooded areas but is rooted at river edges.

The geology of the Mpologoma catchment is made of up of Precambrian crystalline basement rocks. The rocks are covered by a layer of weathered material referred to as regolith whose average thickness is 30m (Howard & Griffith, 2009; Howard *et al.*, 1992; Smedley, 2001). High altitude areas are dominated by clayey soils while mid latitudes and low lands have clay loams and sandy loams, respectively (Mbogga, 2012). The area has a bimodal rainfall pattern with average annual rainfall of 1300 mm (Kigobe *et al.*, 2014). Rainfall seasons are typically from March to May, and September to November but rainfall patterns have become erratic in recent years. For example the first rain season is more unpredictable with late onset and early cessation of rains, while the second season has a higher frequency of high intensity rainfall events (Kansiime *et al.*, 2013).

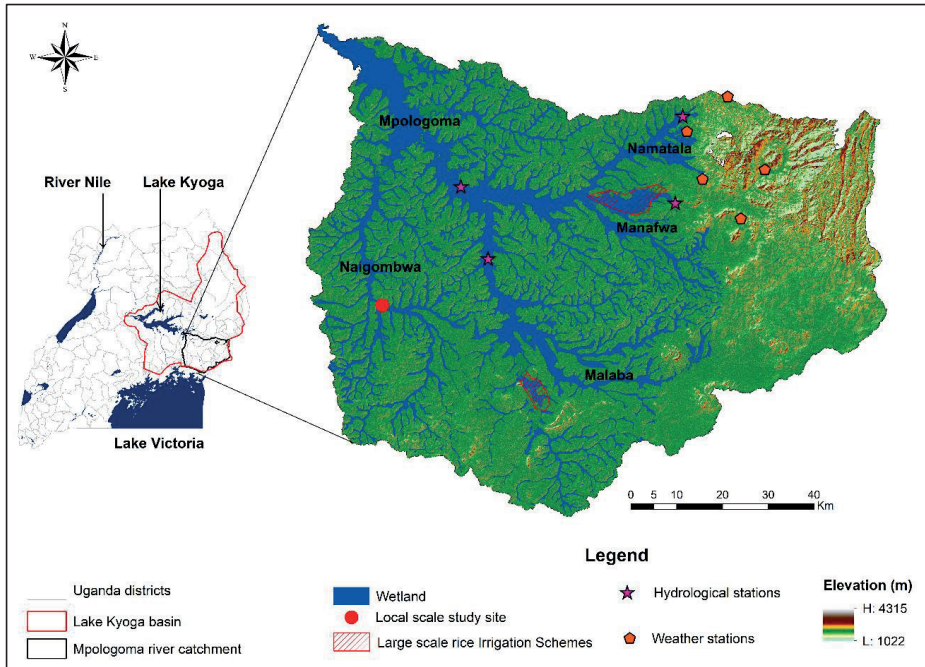


Figure 3a: The Mpologoma river catchment within Lake Kyoga basin, showing the location of the local scale monitoring site along Naigombwa River, and large scale rice irrigation schemes

The main land use is subsistence agriculture, the low lands have both small scale and commercial rice farms and other food crops like maize, beans, and cassava, while highlands have coffee banana systems, with commercial production of coffee and vegetables (NEMA, 2008a). In the highlands, cultivation is carried out up to the banks of river Manafwa, which has increased siltation and affected quality of the water for domestic use. In the low lands, the river is increasingly channelized to provide irrigation water for rice paddies which has reduced the volume of flow. The reduced volume makes it easier for further channelization of the river (NEMA, 2008a; Sserunkuuma *et al.*, 2004).

The Mpologoma River catchment has four weather stations and four hydrological monitoring stations. Two of the weather stations are now defunct while the other two record only rainfall data since 2010. None of the weather stations have complete data records (Mbogga, 2012), and they are unevenly distributed through the catchment (Figure 3a).

## 2.1.2. The Naigombwa wetland site

The Naigombwa River drains northwards into the Mpologoma River. Its catchment area is relatively flat with elevation varying from 1056 to 1348 m.a.s.l., the soils are mainly ferralitic with reddish brown sandy loams (NEMA, 2008b). Part of the Naigombwa wetland that is located upstream of the instrumentation site (Figure 3a) is used for small scale rice farming, with the rice planted directly in the stream. Although the stream was initially perennial, the upstream section now dries out in periods of delayed onset of rains which exacerbates droughts in the area (Iganga District Environmental Officer, personal communication, 27th May 2014).

The monitoring site is located at a section of the Naigombwa wetland that is demarcated by a highway and railway line in the South east and North west, respectively (Figure 3b). The wetland section is 0.18 km<sup>2</sup> in size and drains an area of 734 km<sup>2</sup>. The ground water divide for this wetland section is approximately at 250 m and 170 m for the western and eastern edges of the wetland, therefore the ground water contributing area is less than 0.1 km<sup>2</sup> on both sides of the wetland. Main activities in and around the wetland include papyrus harvesting, fishing, livestock grazing, and subsistence agriculture at wetland edges. The wetland water is used for washing, building, and livestock watering.



Figure 3b: The instrumentation site along Naigombwa River, bright red points represent locations of automatic water divers

## 2.2. Data collection

For paper I: precipitation data was downloaded from the website (<https://globalweather.tamu.edu/>) of National Centers for Environmental Prediction (NCEP). The data is provided on a 35 by 35 meter grid and ranges from January 1979 to July 2014. MODIS NDVI time series (2001-2016) and Landsat data (1986, 2001, 2017) were downloaded from the National Aeronautics and Space Administration (NASA) archive (<https://reverb.echo.nasa.gov/reverb/>) and from the United States Geological Survey (USGS) data archive (<https://earthexplorer.usgs.gov/>), respectively.

For paper II: access transects were cut through the wetland, and the wetland's bathymetry was mapped at points along the transects and around wetland edges (Figure 4) using a CHC GNSS receiver (Model: X900; operation mode: RTK). Automatic water divers were used to record daily values of wetland water depth at three points in the wetland centre (Figure 3b). A profiler rod was used to measure papyrus root mat thickness and depth of the water column beneath the plant in the dry and wet seasons (Figure 4).

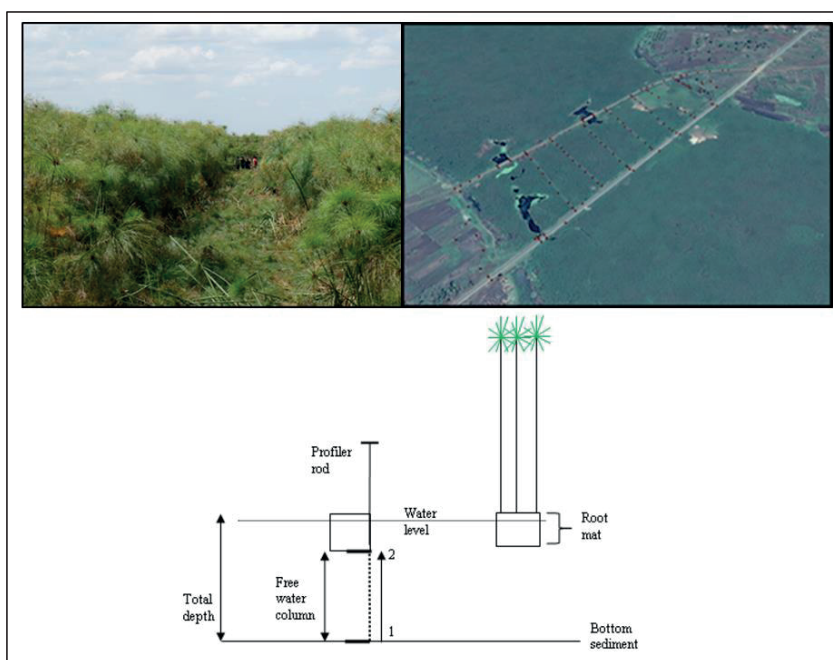


Figure 4: Clockwise from top left: cutting access transects through the wetland; location of points at which wetland bathymetry was mapped; and illustration of method used to measure papyrus mat thickness and depth of free water column

For paper III: data on groundwater, wetland stage, and climatic data (rainfall, temperature, humidity, wind speed) were recorded daily using shallow ground water wells, staff gages, and an automatic weather station (model: Davis Vantage Vue 6250), respectively. In addition, discharge measurements were carried out at all inlet and outlet culverts on five separate occasions using an OTT current meter (Figure 5).



Figure 5: Clockwise from top left: borehole monitoring, setting up weather station, installation of water gauges at wetland in lets and outlets, discharge measurements

The monitoring duration of the different datasets is shown in Table 1. Wetland stage had the longest monitoring record of 20 months, while climate and groundwater monitoring was for 18 and 19 months, respectively. Discharge measurements were done in each successive dry and wet season over a 10 month period. A survey of the wetland's bathymetry was done once in January 2016, while the wetlands water depth was monitored for 12 months.

Table 1: Duration of monitoring datasets at the local wetland site

<i>Data sets</i>	<b>Time period</b>																			
	<b>2015</b>										<b>2016</b>									
	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
<i>Climate</i>			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Wetland stage</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Groundwater level</i>		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Discharge*</i>	x		x		x			x		x										
<i>Survey of wetland baythmetry</i>									x											
<i>Wetland water depth</i>									x	x	x	x	x	x	x	x	x	x	x	x

\*No discharge measurements done after February 2016 because of construction works on culverts



### 3. Overview of papers

#### 3.1. Trend of vegetation productivity and moisture (paper I)

The aim of the first paper was to understand the historical land use patterns within the Mpologoma River catchment, and their impacts on vegetation moisture and productivity. This paper's novelty is that it utilised hyper-temporal image analysis to link the catchment's hydrological history to spatial differences in vegetation productivity for an ungauged catchment in the Lake Kyoga basin. The Drivers, Pressures, State, Impact, and Response (DPSIR) framework was used to appreciate the ecosystem goods and services provided by natural resources within the catchment (Figure 6). Ecosystem goods include portable water, food from crops and fish, fuel wood, craft materials, while services comprise climate regulation, flood mitigation, and water storage (Kansiime *et al.*, 2007). The framework identified land cover changes and river modification as the main pressures on the natural resources.

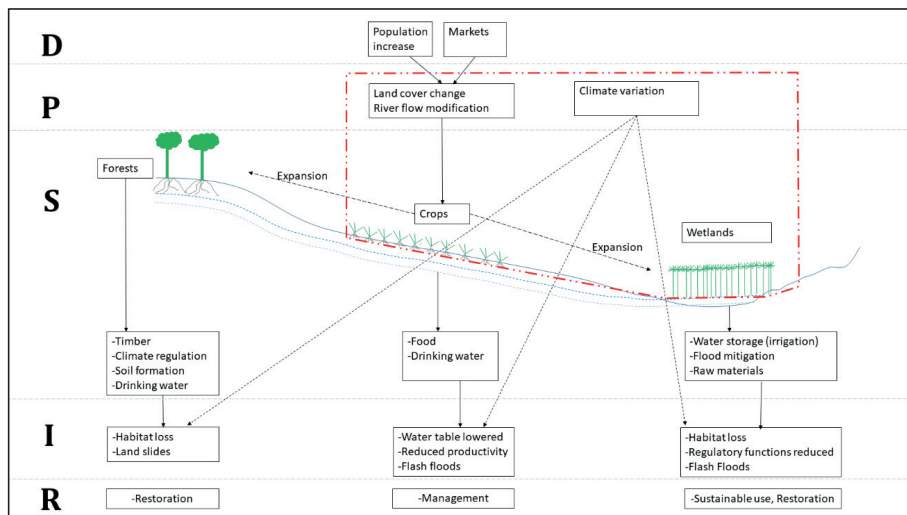


Figure 6: Illustration of impacts of land use changes on ecosystem services using the DPSIR framework

The paper's objectives were to quantify the impacts of land cover changes and flow modification on vegetation moisture and productivity. Changes in vegetation moisture were assessed using the Normalised Difference Water Index (NDWI). NDWI was calculated from three Landsat images (1986, 2001, 2017) taken at 15 year intervals over

a 30 year period. The trend of vegetation productivity was calculated from a time series of MODIS NDVI images (2001 to 2016). These images were also used to create a land cover map for the study catchment (Figure 7).

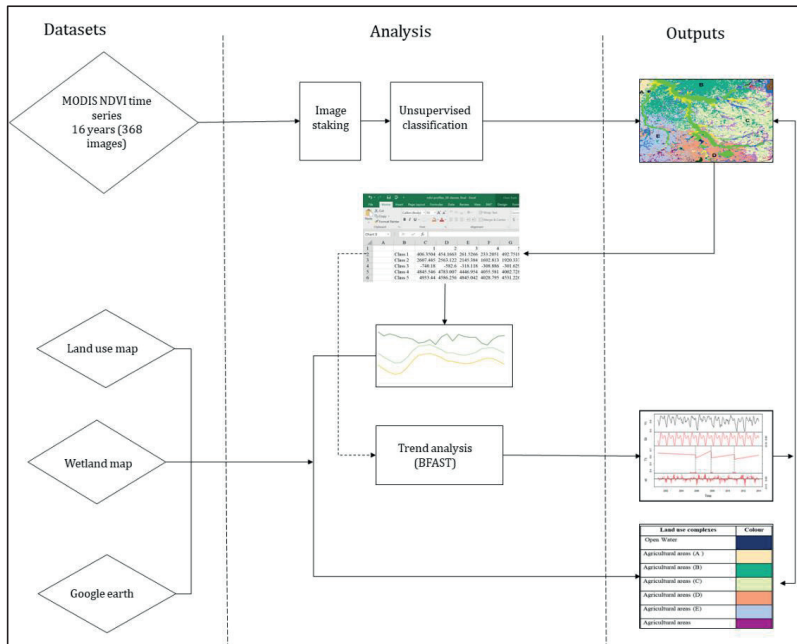


Figure 7: methodological flow chart for MODIS NDVI image processing and trend analysis

Results showed a reducing trend for both vegetation moisture and vegetation productivity despite an increasing trend in precipitation. This was attributed to agricultural encroachment on wetland systems that occurred prior to 2001. The research therefore illustrated that wetland degradation can have lasting impacts on wetland hydrology, and productivity of adjacent agricultural land.

This paper contributed to a better understanding of the current state of the environment in the catchment by quantifying the spatial extent of intact and degraded wetlands. It also brought into perspective the pressure on papyrus wetlands, and associated impacts on ecosystem services. Since the water storage capacity of these wetlands has not been quantified before, the subsequent papers sought to give a better understanding of the functioning of papyrus wetlands by carrying out experiments at a small wetland section within the catchment.

### **3.2. Wetland water storage and papyrus mat dynamics (paper II)**

Paper II had two objectives which were: (i) to assess papyrus root mat dynamics at changing water levels; and (ii) to quantify the water storage capacity of a papyrus wetland section in the dry and wet seasons. The paper's novelty is that it quantified the water storage capacity of papyrus wetlands and papyrus root mat dynamics which had not been done before.

For the first objective, measurements of papyrus mat thickness and depth of the free water column were made along three transects in the wetland in the dry and wet seasons. The data was examined using both Analysis of Variance (ANOVA) and correlation analysis. For the second objective, a survey of the wetland's bottom elevation was carried out to generate data on the wetland's bathymetry, from which the depth-volume relationship was estimated. Monitored depth data was then used to calculate wetland volume in the dry and wet seasons.

Results showed that the depth of the free water column increased across all transects in the wet season. Changes in mat thickness were influenced by the rate of rise of the free water column, and spatial location within the wetland. There was a significant negative correlation between changes in free water column and papyrus mat thickness ( $n=32$ ,  $r=-0.85$ ,  $p=0.000$ ) between the two seasons. This indicated that the papyrus mat compresses in response to increases in free water column. The observed increase in water column facilitates storage of excess water during rainy seasons. Indeed, there was a 50% increase in water storage capacity for the wetland section in the wet season.

The paper alluded to the opportunity that this storage function could provide for sustainable agricultural improvement, but stressed the importance of additional research to understand the water level threshold required for maintaining the wetland's hydrology.

### **3.3. Wetland water balance (paper III)**

Paper III aimed to identify the main components of the water balance, and to estimate retention time in the dry and wet seasons. Monitoring stations were set up to collect data on water flows into and out of the wetland. These flows were described using a conceptual model (Figure 8). Each component in the conceptual model was calculated

using the monitoring data at the study site, and aggregated to monthly time steps. A monthly water balance was then estimated by subtracting all water outputs from the inflows according to equation 1.

$$ds/dt = Q_{in} + P + Q_{g_{in}} + Q_f - Q_{out} - ET - e \text{ (all terms in m}^3\text{/day)} \quad (1)$$

where  $ds/dt$  = change in storage,  $Q_{in}$  = channel inflow,  $P$  = precipitation,  $Q_{g_{in}}$  = groundwater discharge,  $Q_f$  = overland flow from edges of wetland section,  $Q_{out}$  = channel outflow,  $ET$  = evapotranspiration,  $e$  = residual error

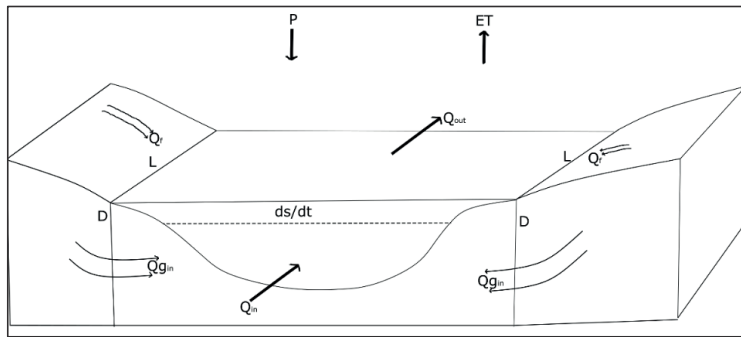


Figure 8: Conceptual model of the water balance for the wetland section.

Water retention was estimated using two methods: by calculating the volume-discharge ratio; and use of salt as a tracer to estimate water velocity and the travel time from the inlet to outlet culverts. The water balance of the studied wetland section is dominated by channel flow contributing approximately 99.7% of the total inputs, while precipitation and ground water discharge contributed 0.2% and 0.1%, respectively. Estimated retention time varied between 2 hours and 7 days during periods of high and low flows, respectively. The groundwater gradient showed groundwater flow towards the wetland throughout the monitoring period, with average gradients of 0.0074 and 0.0043 on the western and eastern sides of the wetland edge, respectively. It was noted that the wetland's hydrology is vulnerable to continued land cover changes in the upstream catchment. Further, because the wetland serves as a boundary for the local groundwater, wetland drainage could impact groundwater levels. The study proposed further research using catchment models to assess impacts of land use changes on channel flows.

## 4. Discussion

The main pressure causing wetland degradation in the Lake Kyoga basin is the need for land for agricultural expansion. This is driven by increasing population and market changes, including increased demand for rice (Turyahabwe *et al.*, 2013). Results showed that agricultural expansion into wetlands and associated river diversions reduce vegetation productivity in the long run due to reduction in plant available moisture for evapotranspiration. The reduction in plant available moisture (Paper I) is likely caused by changes in wetland hydrology, which have long term impacts on ground water level and soil moisture availability (Falkenmark, 2001; Gordon *et al.*, 2010).

It is therefore important to maintain a balance between agricultural productivity and wise use of the wetlands, especially since increasing the agricultural land does not necessarily increase food security for small scale farmers (GOU, 2017). However, there is still insufficient knowledge on the best agricultural management practices for the different types of wetlands (permanent and seasonal). This makes it difficult to plan what proportions of wetlands should be utilised for agriculture, and how the farming should be carried out (McCartney *et al.*, 2010; McCartney & Houghton-Carr, 2009). In addition, the impacts of land use changes on wetland functioning are not well understood. This is partly because of limited monitoring data within Ugandan wetlands (Langan *et al.*, 2018). Despite the data scarcity, this research demonstrated through trend analysis of NDVI time series that wetland degradation leads to reduced productivity, and increased flood incidents in downstream areas (Paper I).

In spite of the wide spread encroachment on wetlands, the expansion of commercial rice farms does not translate into improved food security mainly because the produced rice is sold to affluent urban dwellers or exported, while local farmers remain dependent on low yields from subsistence farming. Even in cases where rice out growers benefit from water discharged from irrigation schemes, the benefits accrued are at the expense of downstream communities due to reduction in quality and quantity of river discharge (NEMA, 2008a). It is important therefore to invest in measures that improve productivity of small scale farms in a sustainable manner.

It is this need that motivated the second study (Paper II); which quantified the water storage capacity and demonstrated that even a small wetland section is capable of storing a large volume of water. This stored water is currently used by local

communities for washing as well as construction, but there is a potential to utilise this water to improve the adaptive capacity of small scale farmers to climatic stresses. However, the farmers need financial backing to come up with cost effective methods for water harvesting as well as capacity building on irrigation best practices, especially regarding water use efficiency (Falkenmark, 2001; Gordon *et al.*, 2010).

It is important to note that the water storage capacity of the wetland depends on channel depth (Kayendeke *et al.*, 2018). This means that upstream land uses which increase erosion gradually lead to changes in channel morphology as sediments settle at the bottom. Therefore, the storage capacity of a seemingly intact wetland can still be reduced by upstream land uses like farming along river banks, as has been observed for upstream areas of River Manafwa (NEMA, 2008a).

Paper II also looked at papyrus root mat dynamics, and showed that the papyrus plant is physically adapted to the changing water levels in the wetlands. The paper described for the first time the relationship between papyrus mat thickness and the free water column beneath the plant, and alludes to the flood mitigation potential of these wetlands due to friction drag by the plant mat system. The paper provides new insight into the plant's role in wetland functioning and gives more reason to advocate for the protection of natural wetland vegetation.

Paper III looked at the key processes of the wetland's hydrological regime, since understanding a wetland's hydrology is critical to its sustainable management (Falkenmark, 2001). The research showed that flow in the main wetland channel is the key component of the hydrological regime of the studied wetland section. Therefore maintenance of the wetland's functioning should concentrate on holistic management in the entire catchment because unrestricted upstream drainage will eventually cause a shift in the hydrological regime of downstream wetlands and negatively affect associated agricultural activities (Falkenmark, 2001; Gordon *et al.*, 2010). There is also a need to devise appropriate means of measuring discharge and flow dynamics within wetlands for their hydrology to be better understood, since current discharge methods were developed for open water channels.

However, implementation of these management changes requires institutional support, which can be obtained through continued dialogue with politicians and policy makers (Allan *et al.*, 2013). Further, stakeholder participation especially of the local

community is the key to coming up with sustainable and feasible management alternatives. This is because new scientific knowledge does not automatically translate into positive changes in land management due to entrenched cultural and institutional perceptions and attitudes (Schoeman *et al.*, 2014; Wanyama *et al.*, 2017).

It is important to note though that halting wetland degradation requires that the underlying pressures of degradation like poverty and high population growth rate be addressed (Galatowitsch, 2018), since it is difficult to maintain wise use of wetlands without alternative livelihood options for local communities (Mafabi, 2018). Furthermore, it is vital to recognise that there is no single correct approach for sustainable wetland management but it is important to collaborate with researchers and other stakeholders from different fields, promote data sharing, as well as being open to learning from indigenous knowledge (Allan *et al.*, 2013; Mafabi, 2018; Schoeman *et al.*, 2014; Varady *et al.*, 2016; Wang *et al.*, 2016; Zeitoun *et al.*, 2016).

## **5. Conclusions, implications for wetland management and future research**

Wetland degradation has undesirable impacts on catchment hydrology like reduction in river discharge and soil moisture availability. This study demonstrated reducing soil moisture condition within the Mpologoma River basin (paper I). These observed changes could be an indicator for the less visible changes in the groundwater table (Chen & Hu, 2004; Cooper *et al.*, 2006; Soylu *et al.*, 2014). This should be a cause for concern since such creeping changes may go unnoticed until they have reached an irreversible stage, in which case corrective measures would not readily return the system back to its natural state (Falkenmark, 2001; Varady *et al.*, 2016). Indeed, Howard and Griffith (2009) demonstrated through modelling of the Aroca catchment (located north of Lake Kyoga), that it can take up to 100 years for a declining water table to stabilize.

Therefore wetland management should not be biased towards increasing food production alone, but should seek to strike a balance among the various ecosystem services provided by these systems. As this PhD work has demonstrated, the reduction in wetland area has resulted in declining productivity within the wetland and in agricultural areas (paper I). Thus, the long term maintenance of food production

requires sustainable wetland management. This implies integrating both water supply and demand based strategies, where existing supply is exploited while implementing reforms that promote efficient use of available water sources (Wang *et al.*, 2016).

This study has demonstrated that papyrus wetlands have a large water storage capacity (paper II), which if exploited have potential to contribute to increased food security for small scale farmers. In addition, the papyrus mat dynamics described in this thesis (paper II) demonstrate the role of natural vegetation in wetland functioning. Wetland functioning is thus impacted just as much by onsite removal of natural vegetation as it is by upstream land cover changes. Sustainable use of these wetlands will require further research to understand the water level threshold that would sustain the existing hydrological cycle. Therefore, continued monitoring of the wetland hydrology at different spatial and temporal scales is key, since such information is essential to come up with appropriate plans for upstream and downstream water needs (Gordon *et al.*, 2010).

The water balance estimation showed that flow in the main wetland channel dominates the hydrological regime, and that there is a ground water gradient towards the studied wetland section (paper III). Since the wetland water levels serve as a boundary for groundwater, it is important to invest in groundwater monitoring networks so that impacts of wetland changes on groundwater can be more readily assessed. Further, research using catchment based models will go a long way in illustrating the linkages among wetland systems, groundwater levels, land use changes, water availability and agricultural productivity (Falkenmark, 2001).

This research contributes to a better system understanding of papyrus wetlands, which is a prerequisite for effective wetland management. However, attaining sustainable wetland management will require incorporating adaptive management into existing management plans. This is because there are always inherent uncertainties in natural resource management that arise from incomplete knowledge, and changes in climate, culture, water demand, economic and political situations. This kind of management allows resource managers to learn from previous actions through continuous monitoring of feedback mechanisms; this requires collaboration across research fields, community participation in decision making, and strengthening of



dialogue with policy makers (Allan *et al.*, 2013; Schoeman *et al.*, 2014; Varady *et al.*, 2016; Wang *et al.*, 2016; Zeitoun *et al.*, 2016).



## References

- Acreman, M., Holden, J. 2013. How Wetlands Affect Floods. *Wetlands* **33**: 773-786. doi:10.1007/s13157-013-0473-2
- Ali, A., De Bie, C., Skidmore, A.K., Scarrott, R., Hamad, A., Venus, V., Lymberakis, P. 2013. Mapping Land Cover Gradients through Analysis of Hyper-Temporal NDVI Imagery. *International Journal of Applied Earth Observation and Geoinformation* **23**: 301-312. doi:10.1016/j.jag.2012.10.001
- Allan, C., Xia, J., Pahl-Wostl, C. 2013. Climate Change and Water Security: Challenges for Adaptive Water Management. *Current Opinion in Environmental Sustainability* **5**: 625-632. doi:10.1016/j.cosust.2013.09.004
- Azza, N.G.T., Kansime, F., Nalubega, M., Denny, P. 2000. Differential Permeability of Papyrus and Miscanthidium Root Mats in Nakivubo Swamp, Uganda. *Aquatic Botany* **67**: 169-178. doi:10.1016/S0304-3770(00)00093-0
- Brinson, M.M. 2011. Classification of Wetlands. In: BA LePage (Ed.), *Wetlands: Integrating Multidisciplinary Concepts* (pp. 95-113). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-0551-7\_5
- Burghof, S., Gabiri, G., Stumpp, C., Chesnaux, R. 2017. Development of a Hydrogeological Conceptual Wetland Model in the Data-Scarce North-Eastern Region of Kilombero Valley, Tanzania. *Hydrogeology Journal* **26**: 267-284. doi:10.1007/s10040-017-1649-2
- Chale, F.M.M. 1987. Plant Biomass and Nutrient Levels of a Tropical Macrophyte (*Cyperus papyrus*) Receiving Domestic Waste Water. *Hydrobiological Bulletin* **21**: 167-170. doi:10.1007/BF02255442
- Chen, X., Hu, Q. 2004. Groundwater Influences on Soil Moisture and Surface Evaporation. *Journal of Hydrology* **297**: 285-300. doi:10.1016/j.jhydrol.2004.04.019
- Cooper, D.J., Sanderson, J.S., Stannard, D.I., Groeneveld, D.P. 2006. Effects of Long-Term Water Table Drawdown on Evapotranspiration and Vegetation in an Arid Region Phreatophyte Community. *Journal of Hydrology* **325**: 21-34. doi:10.1016/j.jhydrol.2005.09.035
- de Groot, D., Brander, L., Finlayson, C.M. 2018. Wetland Ecosystem Services. In: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and*

- Methods* (pp. 323-333). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_66
- Dobriyal, P., Qureshi, A., Badola, R., Hussain, S.A. 2012. A Review of the Methods Available for Estimating Soil Moisture and its Implications for Water Resource Management. *Journal of Hydrology* **458-459**: 110-117. doi:10.1016/j.jhydrol.2012.06.021
- Donaldson, L., Woodhead, A.J., Wilson, R.J., Maclean, I.M. 2016. Subsistence Use of Papyrus is Compatible with Wetland Bird Conservation. *Biological Conservation* **201**: 414-422. doi:10.1016/j.biocon.2016.07.036
- Falkenmark, M. 2001. The Greatest Water Problem: The Inability to Link Environmental Security, Water Security and Food Security. *International Journal of Water resources development* **17**: 539-554. doi:10.1080/07900620120094073
- Finlayson, C.M., Davidson, N.C., Spiers, A.G., Stevenson, N.J. 1999. Global Wetland Inventory - Current Status and Future Priorities. *Marine and Freshwater Research* **50**: 717-727. doi:10.1071/MF99098
- Finlayson, C.M., Milton, G.R., Prentice, R.C. 2018. Wetland Types and Distribution. In: CM Finlayson, GR Milton, RC Prentice, NC Davidson (Eds.), *The Wetland Book: II: Distribution, Description, and Conservation* (pp. 19-35). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4001-3\_186
- Galatowitsch, S.M. 2018. Natural and Anthropogenic Drivers of Wetland Change. In: CM Finlayson, GR Milton, RC Prentice, NC Davidson (Eds.), *The Wetland Book: II: Distribution, Description, and Conservation* (pp. 359-367). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4001-3\_217
- Gao, B.C. 1996. NDWI—a Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space. *Remote Sensing of Environment* **58**: 257-266. doi:10.1016/S0034-4257(96)00067-3
- Gaudet, J.J. 1975. Mineral Concentrations in Papyrus in Various African Swamps. *Journal of Ecology* **63**: 483-491. doi:10.2307/2258731
- Gaudet, J.J. 1977. Natural Drawdown on Lake Naivasha, Kenya and the Formation of Papyrus Swamps *Aquatic Botany* **3**: 1-47. doi:10.1016/0304-3770(77)90002-X
- Gerbeaux, P., Finlayson, C.M., van Dam, A.A. 2018. Wetland Classification: Overview. In: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and*

- Methods* (pp. 1461-1468). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_329
- Gordon, L.J., Finlayson, C.M., Falkenmark, M. 2010. Managing Water in Agriculture for Food Production and Other Ecosystem Services. *Agricultural Water Management* **97**: 512-519. doi:10.1016/j.agwat.2009.03.017
- GOU. 2016. Uganda Wetlands Atlas: Volume Two. Kampala, Uganda.
- GOU. 2017. Towards Zero Hunger. A Strategic Review of Sustainable Development Goal 2 in Uganda. Kampala, Uganda.
- Grobicki, A., Chalmers, C., Jennings, E., Jones, T., Peck, D. 2016. An Introduction to the Convention on Wetlands (Previously the Ramsar Convention Manual). Ramsar Convention Secretariat, Gland, Switzerland.
- Howard, K.E.N., Griffith, A. 2009. Can the Impacts of Climate Change on Groundwater Resources Be Studied without the Use of Transient Models? *Hydrological Sciences Journal* **54**: 754-764. doi:10.1623/hysj.54.4.754
- Howard, K.W.F., Hughes, M., Charlesworth, D.L., Ngobi, G. 1992. Hydrogeologic Evaluation of Fracture Permeability in Crystalline Basement Aquifers of Uganda. *Applied Hydrogeology* **1**: 55-65. doi:10.1007/s100400050029
- Hughes, R.H., Hughes, J.S. 1992. A Directory of African Wetlands. IUCN, Gland, Switzerland and Cambridge, UK.
- Jones, M.B., Muthuri, F.M. 1997. Standing Biomass and Carbon Distribution in a Papyrus (*Cyperus papyrus* L.) Swamp on Lake Naivasha, Kenya. *Journal of Tropical Ecology* **13**: 347-356.
- Kansiime, F., Nalubega, M. 1999. *Wastewater Treatment by a Natural Wetland: The Nakivubo Swamp, Uganda. Processes and Implications*. (PhD Thesis), Wageningen Agricultural University, Netherlands.
- Kansiime, F., Sanders, M.J., Loisella, S.A. 2007. Functioning and Dynamics of Wetland Vegetation of Lake Victoria: An Overview. *Wetlands Ecology and Management* **15**: 443-451. doi:10.1007/s11273-007-9043-9
- Kansiime, M.K., Wambugu, S.K., Shisanya, C.A. 2013. Perceived and Actual Rainfall Trends and Variability in Eastern Uganda: Implications for Community Preparedness and Response. *Journal of Natural Sciences Research* **3**: 179-194.
- Kastens, J.H., Kastens, T.L., Kastens, D.L.A., Price, K.P., Martinko, E.A., Lee, R.-Y. 2005. Image Masking for Crop Yield Forecasting Using AVHRR NDVI Time Series

- Imagery. *Remote Sensing of Environment* **99**: 341-356.  
doi:10.1016/j.rse.2005.09.010
- Kayendeke, E.J., Kansime, F., French, H.K., Bamutaze, Y. 2018. Spatial and Temporal Variation of Papyrus Root Mat Thickness and Water Storage in a Tropical Wetland System. *Science of The Total Environment* **642**: 925-936.  
doi:10.1016/j.scitotenv.2018.06.087
- Kigobe, M., Wheeler, H., McIntyre, N. 2014. Statistical Downscaling of Precipitation in the Upper Nile: Use of Generalized Linear Models (Glm) for the Kyoga Basin. In: AM Melesse, W Abtew, SG Setegn (Eds.), *Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics* (pp. 421-449). Cham: Springer International Publishing. doi:10.1007/978-3-319-02720-3\_22
- Kipkemboi, J., van Dam, A.A. 2018. Papyrus Wetlands. In: CM Finlayson, GR Milton, RC Prentice, NC Davidson (Eds.), *The Wetland Book: II: Distribution, Description, and Conservation* (pp. 183-197). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4001-3\_218
- Langan, C., Farmer, J., Rivington, M., Smith, J.U. 2018. Tropical Wetland Ecosystem Service Assessments in East Africa; a Review of Approaches and Challenges. *Environmental Modelling & Software* **102**: 260-273.  
doi:10.1016/j.envsoft.2018.01.022
- Leemhuis, C., Amler, E., Diekkrüger, B., Gabiri, G., Näschen, K. 2016. East African Wetland-Catchment Data Base for Sustainable Wetland Management. *Proceedings of the International Association of Hydrological Sciences* **374**: 123.  
doi:10.5194/piahs-374-123-2016
- Lehner, B., Döll, P. 2004. Development and Validation of a Global Database of Lakes, Reservoirs and Wetlands. *Journal of Hydrology* **296**: 1-22.  
doi:10.1016/j.jhydrol.2004.03.028
- Mafabi, P. 2018. National Wetland Policy: Uganda. In: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and Methods* (pp. 807-812). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_154
- Mbogga, M. 2012. Climate Profiles and Climate Change Vulnerability Assessment for the Mbale Region of Uganda. *UNDP Consultancy report. Kampala, Uganda.*

- Mburu, N., Rousseau, D.P.L., van Bruggen, J.J.A., Lens, P.N.L. 2015. Use of the Macrophyte *Cyperus papyrus* in Wastewater Treatment. In: J Vymazal (Ed.), *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape* (pp. 293-314). Cham: Springer International Publishing. doi:10.1007/978-3-319-08177-9\_20
- McCartney, M., Rebelo, L., Senaratna, S., De Silva, S. 2010. Wetlands, Agriculture and Poverty Reduction. Colombo, Sri Lanka: International Water Management Institute.
- McCartney, M.P., Houghton-Carr, H.A. 2009. Working Wetland Potential: An Index to Guide the Sustainable Development of African Wetlands. *Natural Resources Forum* **33**: 99-110. doi:10.1111/j.1477-8947.2009.01214.x
- Milton, G.R., Prentice, R.C., Finlayson, C.M. 2018. Wetlands of the World. In: CM Finlayson, GR Milton, RC Prentice, NC Davidson (Eds.), *The Wetland Book: II: Distribution, Description, and Conservation* (pp. 3-16). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4001-3\_182
- Muthuri, F.M., Jones, M.B., Imbamba, S.K. 1989. Primary Productivity of Papyrus (*Cyperus papyrus*) in a Tropical Swamp; Lake Naivasha, Kenya. *Biomass* **18**: 1-14. doi:10.1016/0144-4565(89)90077-2
- Nakano, Y., Otsuka, K. 2011. Determinants of Household Contributions to Collective Irrigation Management: The Case of the Doho Rice Scheme in Uganda. *Environment and Development Economics* **16**: 527-551. doi:10.1017/S1355770X11000167
- NEMA. 2008a. Pilot Integrated Environment Assessment of the Lake Kyoga Catchment Area. National Environment Management Authority (NEMA), Kampala.
- NEMA. 2008b. State of Environment Report for Uganda (2008). National Environment Management Authority (NEMA), Kampala Uganda.
- Nsubuga, F., Namutebi, E.N., Nsubuga-Ssenfuma, M. 2014. Water Resources of Uganda: An Assessment and Review. *Journal of Water Resource and Protection* **6**: 1297-1315. doi:10.4236/jwarp.2014.614120
- Opio, A., Jones, M., Kansime, F., Otiti, T. 2014. Growth and Development of *Cyperus papyrus* in a Tropical Wetland. *Open Journal of Ecology* **4**: 113-123. doi:10.4236/oje.2014.43013

- Pisters, S. 2014. Privatization of Wetlands; Redefining Rural Livelihoods and Food: Privatization and Land Acquisitions in the Wetlands of Eastern Uganda. (Master thesis), Wageningen University, Netherlands.
- Rasmussen, T.C., Deemy, J.B., Long, S.L. 2018. Wetland Hydrology. *In*: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and Methods* (pp. 201-216). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_71
- Saunders, M.J., Kansime, F., Jones, M.B. 2012. Agricultural Encroachment: Implications for Carbon Sequestration in Tropical African Wetlands. *Global Change Biology*. doi:10.1111/j.1365-2486.2011.02633.x
- Saunders, M.J., Kansime, F., Jones, M.B. 2013. Reviewing the Carbon Cycle Dynamics and Carbon Sequestration Potential of *Cyperus papyrus* L. Wetlands in Tropical Africa. *Wetlands Ecology and Management* **21**. doi:10.1007/s11273-013-9314-6
- Schoeman, J., Allan, C., Finlayson, C.M. 2014. A New Paradigm for Water? A Comparative Review of Integrated, Adaptive and Ecosystem-Based Water Management in the Anthropocene. *International Journal of Water resources development* **30**: 377-390.
- Schyns, J.F., Hoekstra, A.Y., Booij, M.J. 2015. Review and Classification of Indicators of Green Water Availability and Scarcity. *Hydrol. Earth Syst. Sci.* **19**: 4581-4608. doi:10.5194/hess-19-4581-2015
- Semeniuk, C.A., Semeniuk, V. 1995. A Geomorphic Approach to Global Classification for Inland Wetlands. *Vegetatio* **118**: 103-124. doi:10.1007/bf00045193
- Semeniuk, C.A., Semeniuk, V. 2018. Wetland Classification: Hydrogeomorphic System. *In*: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and Methods* (pp. 1483-1489). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_331
- Semeniuk, V., Semeniuk, C.A. 1997. A Geomorphic Approach to Global Classification for Natural Inland Wetlands and Rationalization of the System Used by the Ramsar Convention – a Discussion. *Wetlands Ecology and Management* **5**: 145-158. doi:10.1023/a:1008207726826
- Smedley, P. 2001. Groundwater Quality: Uganda. British Geological Survey.

- Soylu, M.E., Kucharik, C.J., Loheide, S.P. 2014. Influence of Groundwater on Plant Water Use and Productivity: Development of an Integrated Ecosystem – Variably Saturated Soil Water Flow Model. *Agricultural and Forest Meteorology* **189-190**: 198-210. doi:10.1016/j.agrformet.2014.01.019
- Sserunkuuma, D., Ochom, N., Ainembabazi, H. 2004. Collective Action in Canal Irrigation Systems Management: The Case of Doho Rice Scheme in Uganda. IFPRI Eastern Africa Food Policy Network, Network Funded Report.
- Terer, T., Muasya, A.M., Higgins, S., Gaudet, J.J., Triest, L. 2014. Importance of Seedling Recruitment for Regeneration and Maintaining Genetic Diversity of *Cyperus papyrus* During Drawdown in Lake Naivasha, Kenya. *Aquatic Botany* **116**: 93–102. doi:10.1016/j.aquabot.2014.02.008
- Turyahabwe, N., Tumusiime, D.M., Kakuru, W., Barasa, B. 2013. Wetland Use/Cover Changes and Local Perceptions in Uganda. *Sustainable Agriculture Research* **2**: 95. doi:10.5539/sar.v2n4p95
- Uganda Bureau of Statistics. 2017. Statistical Abstract. Kampala, Uganda.
- van Dam, A.A., Dardona, A., Kelderman, P., Kansime, F. 2007. A Simulation Model for Nitrogen Retention in a Papyrus Wetland near Lake Victoria, Uganda (East Africa). *Wetlands Ecology and Management* **15**: 469–480. doi:10.1007/s11273-007-9047-5
- van Dam, A.A., Kipkemboi, J., Mazvimavi, D., Irvine, K. 2014. A Synthesis of Past, Current and Future Research for Protection and Management of Papyrus (*Cyperus papyrus* L.) Wetlands in Africa. *Wetlands Ecology and Management* **22**: 99-114. doi:10.1007/s11273-013-9335-1
- Varady, R.G., Zuniga-Teran, A.A., Garfin, G.M., Martín, F., Vicuña, S. 2016. Adaptive Management and Water Security in a Global Context: Definitions, Concepts, and Examples. *Current Opinion in Environmental Sustainability* **21**: 70-77. doi:10.1016/j.cosust.2016.11.001
- Verbesselt, J., Hyndman, R., Newnham, G., Culvenor, D. 2010. Detecting Trend and Seasonal Changes in Satellite Image Time Series. *Remote Sensing of Environment* **114**: 106-115. doi:10.1016/j.rse.2009.08.014
- Vlek, P.L., Khamzina, A., Tamene, L. 2017. Land Degradation and the Sustainable Development Goals: Threats and Potential Remedies. The International Center for Tropical Agriculture (CIAT), Nairobi, Kenya.



- Wang, X.-j., Zhang, J.-y., Shahid, S., Guan, E.-h., Wu, Y.-x., Gao, J., He, R.-m. 2016. Adaptation to Climate Change Impacts on Water Demand. *Mitigation and Adaptation Strategies for Global Change* **21**: 81-99. doi:10.1007/s11027-014-9571-6
- Wanyama, J., Ssegane, H., Kisekka, I., Komakech Allan, J., Banadda, N., Zziwa, A., Ebong Tobias, O., Mutumba, C., Kiggundu, N., Kayizi Ronald, K., Mucunguzi Dominic, B., Kiyimba Florence, L. 2017. Irrigation Development in Uganda: Constraints, Lessons Learned, and Future Perspectives. *Journal of Irrigation and Drainage Engineering* **143**: 04017003. doi:10.1061/(ASCE)IR.1943-4774.0001159
- Wetlands Management Department, Ministry of Water and Environment, Uganda Bureau of Statistics, International Livestock Research Institute, World Resources Institute. 2009. Mapping a Better Future: How Spatial Analysis Can Benefit Wetlands and Reduce Poverty in Uganda. Kampala, Uganda.
- Whigham, D. 2018. Ecosystem Processes. In: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and Methods* (pp. 285-296). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_68
- Yikii, F., Turyahabwe, N., Bashaasha, B. 2017. Prevalence of Household Food Insecurity in Wetland Adjacent Areas of Uganda. *Agriculture & Food Security* **6**: 63. doi:10.1186/s40066-017-0147-z
- Zeitoun, M., Lankford, B., Krueger, T., Forsyth, T., Carter, R., Hoekstra, A.Y., Taylor, R., Varis, O., Cleaver, F., Boelens, R. 2016. Reductionist and Integrative Research Approaches to Complex Water Security Policy Challenges. *Global Environmental Change* **39**: 143-154. doi:10.1016/j.gloenvcha.2016.04.010

# PAPER I



# Land use change and vegetation moisture variations of a papyrus wetland catchment in the Lake Kyoga basin, Uganda

Ellen Jessica Kayendeke<sup>1,3</sup>, Helen K. French<sup>1</sup>, Yazidhi Bamutaze<sup>2</sup>, Frank Kansiime<sup>3</sup>

- <sup>1.</sup> Department of Environmental Sciences, Norwegian University of Life Sciences, 1432 Ås, Norway
- <sup>2.</sup> Department of Geography, Geo-informatics, and Climatic Sciences, Makerere University, P.O. Box 7062, Kampala Uganda
- <sup>3.</sup> Department of Environmental Management, Makerere University, P.O. Box 7062, Kampala Uganda

## **Abstract**

Papyrus wetlands are an important source of livelihoods for rural communities. These ecosystems however, face pressures of conversion into agricultural land, yet the impacts on vegetation productivity and moisture availability are not known. This paper utilised hyper-temporal image analysis in a novel way, to link the catchment's hydrological history to spatial differences in vegetation productivity in an ungauged catchment of the Lake Kyoga basin, Uganda. The study objective was to reconstruct land cover change impacts using hyper-temporal image analysis. A MODIS NDVI time series was classified into land use complexes, and the trend of the land uses was calculated using Breaks for Additive Season and Trend (BFAST). The last 15 year period was characterised by a declining trend in vegetation productivity (-0.01 to -0.05), that is explained by previous land conversions. Areas with low vegetation moisture increased by 110% between 1986 and 2017, while those with high and moderate vegetation moisture reduced by 15% and 22%, respectively. The method was able to segregate areas with unique hydrological histories i.e. flooding versus drying trends; and therefore has a potential to help plan targeted restoration measures, and to monitor outcomes of implemented actions. This work demonstrates hyper-temporal image analysis as a promising tool for catchment based management of ungauged basins.

**Key words: Papyrus wetland, Land use change, NDVI, MNDWI, Vegetation moisture, hyper-temporal**

# 1. Introduction

Papyrus wetlands cover extensive areas in Sub-Saharan Africa and are dominant in floodplain wetlands within the Nile basin. The areal coverage of the papyrus wetlands is not known. For example, estimates for the Sudd wetland alone in South Sudan vary between 2,800 to 40,000 km<sup>2</sup> (Kipkemboi & van Dam, 2018). The wetlands provide regulatory and provisioning services like water purification, flood mitigation, and water storage. They are an important livelihood source for rural communities through land uses like papyrus and water harvesting, livestock watering, fishing and hunting (Kipkemboi & van Dam, 2018; Millennium Ecosystem Assessment, 2005). However, the wetlands are under threat from agricultural encroachment that alters natural vegetation and water levels.

Wetland encroachment can be in form of replacing natural vegetation with crops like sugar cane and rice at river edges or through hydrological changes like diverting water to irrigate rice paddies (NEMA, 2008a). This accelerates the rate of wetland drainage, which in turn affects their ability to provide ecosystem services (NEMA, 2016). In Uganda, there was an 11% decline in wetland coverage between 1994 and 2008, with the greatest decline occurring in the Lake Victoria (54%) and Lake Kyoga (27%) basins (NEMA, 2008b; Nsubuga *et al.*, 2014).

The Lake Kyoga basin is located in Eastern Uganda, and its wetlands have been extensively encroached upon for agricultural expansion (NEMA, 2008a). Namaalwa *et al.* (2013) established for a small Kyoga sub-basin that conversion from natural wetland vegetation to agricultural areas started in the upstream areas and gradually expanded downstream.

However, a more comprehensive understanding of land cover dynamics at a larger scale is essential since the impacts of land cover change often extend beyond the scale of the change (Millennium Ecosystem Assessment, 2003). Despite the pressures on the wetlands, there is currently no up to date assessments of land cover change impacts on vegetation productivity and moisture availability for the Lake Kyoga basin.

However, such data can be obtained in a cost effective way by using freely available remote sensing data. Remote sensing provides indirect information about the ground surface by recording information about electromagnetic properties of the earth. For example, data from various sensors like Advanced Very-High-Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), Satellite Pour l'Observation de la Terre (SPOT), and Landsat have been successfully utilised in the past for land cover mapping and monitoring (Coppin *et al.*, 2004).

Land cover monitoring involves characterising differences in the state of land cover by observing it at different times. Remote sensing data has a high temporal coverage and resolution which helps with comparison among dates (Kerle *et al.*, 2004). There are different change detection techniques but a suitable method for any given study depends on the characteristics of the study area, and cost of image data (Lu *et al.*, 2004). Although sensors like Thematic mapper (TM), and SPOT have a high spatial resolution, coarser resolution data like MODIS and AVHRR are sometimes more applicable because of low cost and larger spatial coverage (Lu *et al.*, 2004).

In addition to land cover mapping, remote sensing data is used for monitoring land degradation (Higginbottom & Symeonakis, 2014). Land degradation studies quantify changes in hydrological condition and/or vegetation vigour, which can be done using water and vegetation indices (VIs) especially for areas with limited reference data (Young *et al.*, 2017). For instance, the Normalised Difference Water Index (NDWI) is useful for monitoring vegetation moisture (Gu *et al.*, 2007). Vegetation moisture is water temporarily stored in plant canopies which is available for evapotranspiration (Schyns *et al.*, 2015). Since vegetation stress can be caused by a prolonged soil moisture deficit, vegetation moisture estimates can be used to make inferences about soil moisture (Dobriyal *et al.*, 2012). Vegetation moisture estimation is especially useful in highly vegetated areas, where the relationship between soil moisture and remote sensing indices is weak (Petropoulos *et al.*, 2015; Zhang & Zhou, 2016).

On the other hand, the Normalised Difference Vegetation Index (NDVI) is used for monitoring vegetation primary productivity because it is correlated to vegetation photosynthetic activity (Pettorelli *et al.*, 2005; Verbesselt *et al.*, 2010). Various studies have used the MODIS NDVI time series to monitor changes in trend and vegetation phenology (Grogan *et al.*, 2016; Gu *et al.*, 2007; Verbesselt *et al.*, 2010). The MODIS dataset has a moderate spatial resolution of 250 m compared with the coarse 1 km resolution of AVHRR data. In addition, its higher temporal resolution compared to Landsat data makes it better suited for studies in tropical regions where cloud cover is recurrent (Grogan *et al.*, 2016).



The Lake Kyoga basin has heterogeneous land uses and a high frequency of cloud cover (Turyahabwe *et al.*, 2013), which makes it difficult to distinguish wetlands from agricultural areas using conventional mapping techniques. In addition, the presence of vegetation makes direct monitoring of soil moisture difficult. For these reasons, we choose the vegetation (NDVI) and water (NDWI) indices to monitor vegetation productivity and vegetation moisture changes respectively.

This research demonstrated the feasibility of using hyper-temporal image analysis for monitoring the impacts of wetland degradation in ungauged basins. The objective was to map land cover changes, and quantify their impacts on vegetation productivity and moisture using remote sensing data. The specific objectives were: (i) to map the spatial coverage of intact wetlands and other land uses using MODIS NDVI time series; (ii) to use NDVI as a proxy to monitor the trend of vegetation productivity; and (iii) to monitor changes in vegetation moisture using Landsat derived NDWI.

We hypothesised that wetland degradation reduces soil moisture in and around the wetlands, which in turn reduces plant available moisture. Therefore, expansion into wetlands may improve productivity in the short term but leads to reduced vegetation productivity in the long run.

## 1.1. Conceptual framework

The impacts of wetland encroachment on ecosystem services within the Lake Kyoga catchment is illustrated using the Drivers, Pressures, State, Impact, and Response (DPSIR) framework in Figure 1. The driving forces of change in the catchment are increasing population, and increasing market for rice. The pressures include land use changes and modification of river flow, as well as climatic variation (Turyahabwe *et al.*, 2013). Changes in land use are endogenous because they are directly impacted by stakeholder decisions while climatic variations are exogenous (Millennium Ecosystem Assessment, 2003). These pressures cause expansion of agricultural activities into wetlands in the low lands; this lowers water levels leading to reduced water table in adjacent areas (NEMA, 2008a). The lowered water table affects moisture availability for food production, and sustainability of shallow wells. The impacts of land use changes are worsened by increasing climatic variability in the catchment. This is characterised by late onset of rains and disproportionate distribution of rainfall; with heavy rains reported in the highlands and a higher frequency of droughts in low lands (Hisali *et al.*, 2011; Kansiime *et al.*, 2013). Our research focuses on mapping endogenous pressures, and quantifying their impacts on vegetation moisture and productivity.

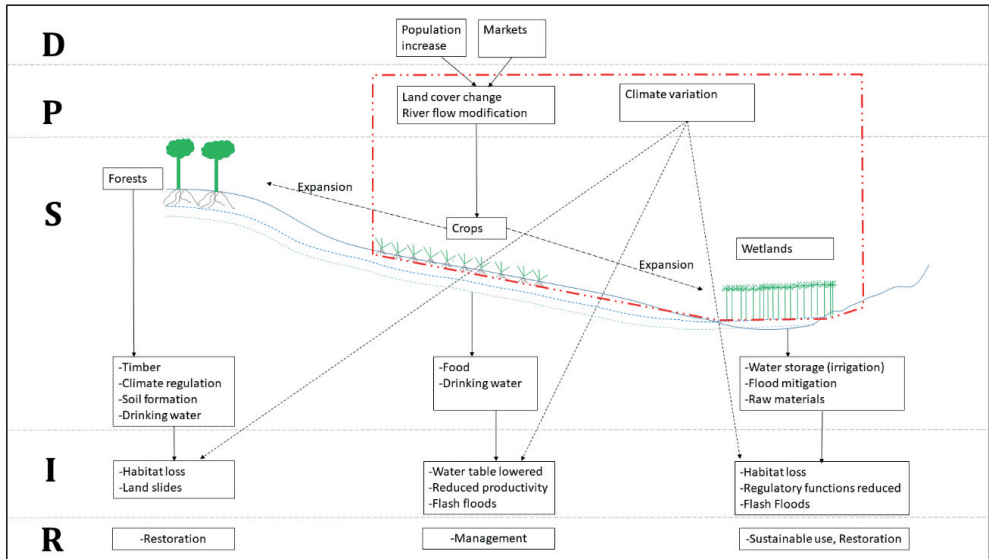


Figure 1: Illustration of impacts of agricultural expansion on ecosystem functioning using the DPSIR framework. Red polygon indicates the focus of the study on agricultural expansion into wetlands

## 2. Materials and methods

### 2.1. Study Area

The study was conducted in the Mpologoma River catchment, within the Lake Kyoga basin in eastern Uganda (Figure 2). The catchment size is 8,960 km<sup>2</sup> with elevation ranging from 1020 to 4310 meters above sea level and it drains 11 districts of Uganda (Nsubuga *et al.*, 2017). The average annual rainfall is 1,300 mm distributed between two rain seasons: March to May, and September to November. Commercial and small scale rice fields are predominant in the low lands. Other crops include maize, beans, cassava, groundnuts, coffee, and bananas. (NEMA, 2008a). The Mpologoma wetland's main inflow is the Mpologoma River, whose tributaries include Namatala, Manafwa, Malaba, and Naigombwa rivers (Figure 2).

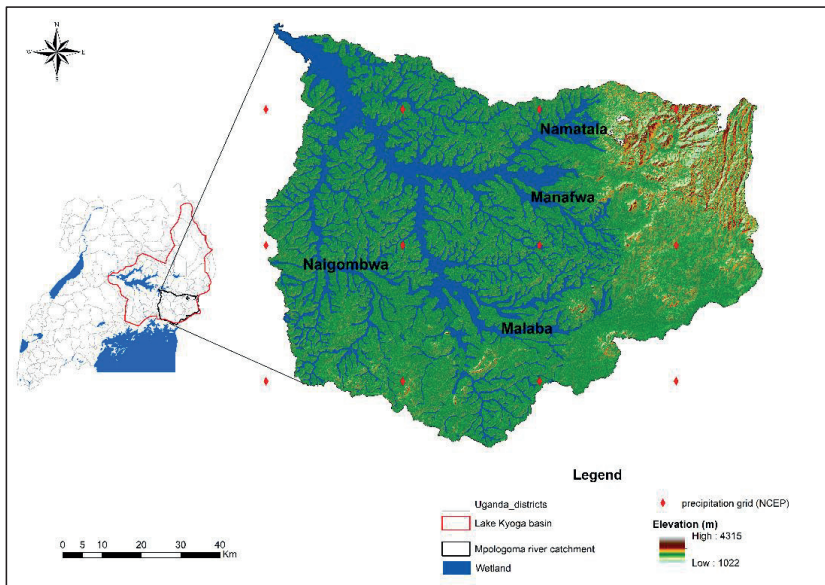


Figure 2: The Mpologoma river catchment with elevation data derived from a 30-meter digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM)

## 2.2. Datasets

The datasets used in this study are given in Table 1. Remote sensing data from MODIS and Landsat sensors was used to analyse land cover and vegetation moisture changes, respectively. Time series of meteorological data for the study area was obtained from the National Centers for Environmental Prediction (NCEP) for the period 2001 to 2014. This dataset was used for climatological trend analysis since weather stations in the catchment are currently not operational (United Nations Development Programme, 2013). The meteorological dataset is on a 35 by 35 meter grid (Figure 2). We estimated spatial precipitation using Thiessen Polygons, following the equation proposed by Kopec (1963);

$$P = \frac{A_1P_1 + A_2P_2 + \dots + A_nP_n}{A} \quad (1)$$

where P = average catchment precipitation, A = area of catchment,  $A_1, A_2 \dots A_n$  = area of individual Thiessen polygons,  $P_1, P_2 \dots P_n$  = precipitation at gauges within the polygons

We obtained shape files of land use and wetland coverage from National Forest Authority (NFA) and Wetland Management Department (WMD), respectively. We used the maps in combination with records from the Dartmouth Flood Observatory and Google Earth images, to validate results from hyper-temporal and trend analysis. A digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM), was used to display elevation variations in the study area.

Table 1: Datasets used for analysis of land use and vegetation moisture changes in Mpologoma river catchment

No	Data	Source; year(s)	Resolution
1	MODIS NDVI (MOD13Q1, Version 05)	<a href="https://reverb.echo.nasa.gov/reverb/">https://reverb.echo.nasa.gov/reverb/</a> ; 2001 - 2016	250m, 16 days
2	Landsat surface reflectance (Landsat 7 & 8)	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> ; 1986, 2001, & 2017	30m, 16 days
3	Precipitation	The National Centers for Environmental Prediction: <a href="https://globalweather.tamu.edu/">https://globalweather.tamu.edu/</a> ; 2001-2014	35*35m, daily
4	Wetland map	Wetland Management Department (WMD); 2010	N/A
5	Land use map	National Forest Authority (NFA); 2005	N/A
6	STRM DEM	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> ; 2000	30m
7	Global Active Archive of Large Flood Events	Dartmouth Flood Observatory  <a href="http://floodobservatory.colorado.edu/Archives/index.html">http://floodobservatory.colorado.edu/Archives/index.html</a> ); 1985-present	N/A
8	Google Earth images	Google Earth Pro, version 7.3.1	N/A

### **2.3. MODIS NDVI classification for characterisation of current land cover state**

We downloaded MODIS NDVI images (MOD13Q1, Version 05) from the National Aeronautics and Space Administration (NASA) archive (<https://reverb.echo.nasa.gov/reverb/>). The dataset has an NDVI image for each 16-day period, making 23 images for each year. Images from January 2001 to December 2016 were downloaded, amounting to 368 images for the 16-year period. The downloaded images were imported from Hierarchical Data Format (HDF) to Image file format (IMG) using Erdas Imagine 2016 software.

We used the Erdas Imagine “stack” tool to combine the images into a single image with 368 bands. The extent of the stacked image was reduced to the Kyoga sub-basin using the “subset” tool. The subset image was then re-projected from sinusoidal to Universal Transverse Mercator (UTM) coordinate system using nearest neighbour resampling method. We carried out unsupervised classification on the image using the Iterative Self-Organizing Data Analysis (ISODATA) clustering algorithm of Erdas Imagine software. The classification was done several times with a different number of classes (5 to 100) for each run, following the method of De Bie *et al.* (2008). We selected the most representative number of classes for our study area by calculating divergence statistics for the classified images. Divergence statistics give the minimum distance between pairs of image clusters, as well as the average distance among all clusters (Davis *et al.*, 1978). The image with the highest minimum and average divergence is usually judged as most representative for a

given study area (De Bie *et al.*, 2011). We selected an image with 38 classes because it had the highest minimum and average divergence.

In order to create a legend for the classified image, we extracted image statistics and exported the data to Excel software. We calculated average annual NDVI values for each image class, and created NDVI profiles for the averaged data. After visual inspection of the NDVI profiles, classes with similar NDVI profiles were merged (De Bie *et al.*, 2011). We used the seasonal characteristics of NDVI profiles, and our knowledge of the study area to differentiate among land cover types. The classified image was validated using land use and wetland maps obtained from government agencies.

### **2.3.1. Analysis of trends in NDVI classes to identify areas where change occurred, and areas impacted by land cover changes**

Time series data (2001-2016) of the image classes was imported into R software for analysis of trends. We also analysed trend of the precipitation dataset, and compared the trend in precipitation to that within the NDVI classes.

The time series were decomposed into seasonal, trend, and remainder components using the Breaks for Additive Season and Trend (BFAST) method. The BFAST method fits piecewise linear trend and seasonal models to the time series using a model of the form (Grogan *et al.*, 2016; Verbesselt *et al.*, 2010);

$$Y_t = T_t + S_t + e_t \quad (2)$$

where  $Y_t$  = the observed time series,  $T_t$  = the trend component,  $S_t$  = the seasonal component, and  $e_t$  = the remainder component.



The method which is implemented in R software, uses Ordinary Least Squares (OLS) and residuals-based Moving Sum (MOSUM) to check for occurrence and significance of break points ( $P < 0.05$ ). The breaks represent sudden changes in the time series. For significant changes: the magnitude and direction of the change; and the slopes of gradual changes before and after breaks are calculated (Verbesselt *et al.*, 2010).

#### **2.4. Monitoring vegetation moisture using Landsat derived NDWI**

We monitored vegetation moisture using three Landsat images (1986, 2001, 2017) taken at 15 year intervals over a 30 year period. The Landsat dataset affords an opportunity to establish the vegetation moisture state prior to 2001, but also serves as a validation of the results of vegetation productivity from the MODIS NDVI dataset (2001-2016).

We downloaded Landsat surface reflectance data from United States Geological Survey (USGS) data archive, using the earth explorer platform (<https://earthexplorer.usgs.gov/>). The data is atmospherically corrected and processed to Level-1 Precision Terrain quality. More information about surface reflectance pre-processing can be found in the Landsat product guide (Masek *et al.*, 2006; U.S. Geological Survey, 2018). Subsequent image analysis was done using ArcGIS software (10.4).

The study area extent is covered by four Landsat scenes with path/row numbers: 170/59; 170/60; 171/59; and 171/60. Therefore, we downloaded four Landsat scenes for each year, and the images for individual years were merged using the ArcGIS 'mosaic' tool. There was

a 7 to 9 day difference between images from paths 170 and those from path 171. We downloaded images acquired in the dry season (January to February) to minimise occurrence of cloud cover.

We used Landsat pixel quality information to create a cloud mask for the 1986 image since it had the highest percentage of cloud cover. Areas covered by the cloud mask were converted into no-data values to remove influence of clouds on further analysis. Similarly, the corresponding spatial areas in the 2001 and 2017 images were converted into no-data values, so that there was a common dataset for comparison. Some information was lost from the later images since cloud free pixels were also removed. We calculated Modified Normalised Difference Water Index (MNDWI) rather than NDWI because it suppresses noise from built-up areas, which are sometimes classified as open water areas (Xu, 2006). The index was calculated with map algebra tools in ArcGIS following equation 3;

$$MNDWI = GREEN - SWIR / GREEN + SWIR \quad (3)$$

where; GREEN and SWIR are Landsat spectral bands representing the green, and short wave infrared portions of the electromagnetic spectrum.

### 3. Results

#### 3.1. Current state of land cover in the Mpologoma River basin

The NDVI derived map was used to illustrate the current land cover complexes in the catchment (Figure 3). Small scale agriculture covers 73% of the total area while wetlands, open water, woodlands, forests, and grasslands cover 15%, 5%, 3.4%, 2.6%, and 0.8%, respectively. Of the total wetland area; 7% are seasonal wetlands which are utilised for agriculture, while 2% of the permanent wetland has also been converted for agriculture.

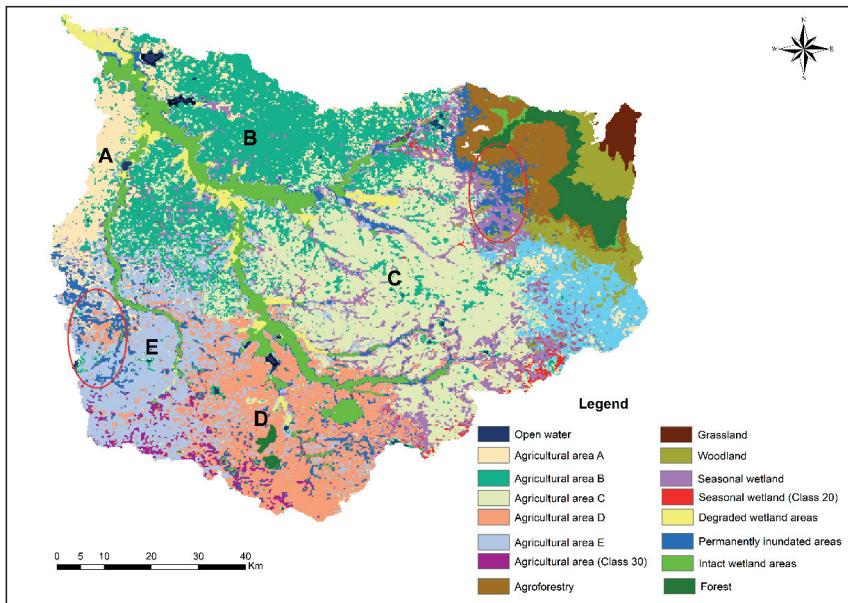


Figure 3: NDVI classes representing different land cover/use complexes in Mpologoma catchment. Red circles highlight differences between the NDVI derived map and the land use/wetland maps

The spatial location of cover types in the NDVI map closely matched those in the land use map from National Forest Authority (NFA); but the NDVI derived map shows that endogenous pressure on the permanent wetland (yellow polygons in Figure 3), is more

wide spread than the extent of commercial agriculture shown in the land use map (Figure 4). This pressure is not represented on the land use map because the map gives information of a single point in time; and yet land cover changes initially start at a small scale, and gradually build up.

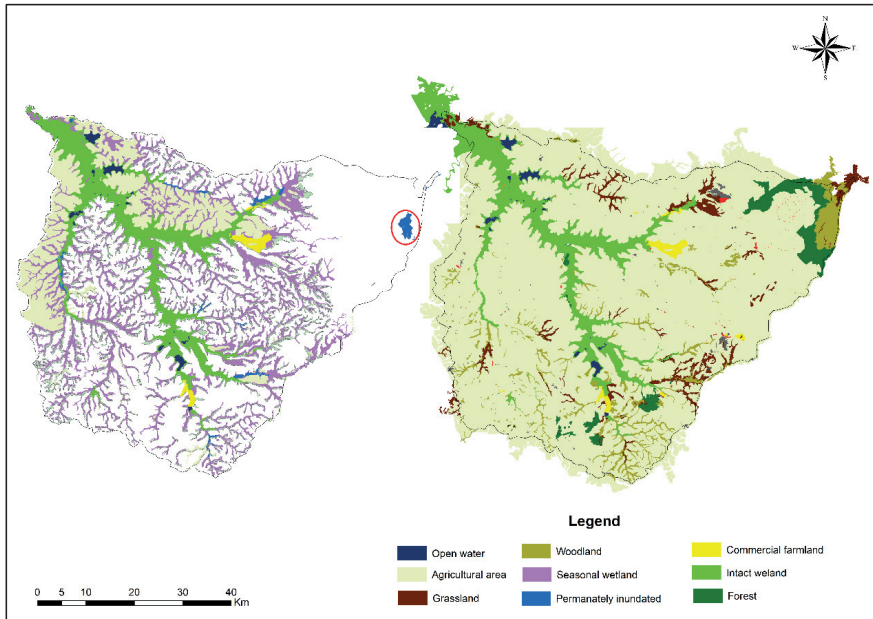


Figure 4: Wetland (left) and land use/cover (right) maps of Uganda that were used to validate the NDVI map. Note that the maps do not cover the far eastern side of the Mpologoma catchment because it falls on the Kenyan side

Seasonal wetlands on the western side of the catchment (red circle on left side of Figure 3) were misclassified as permanently inundated areas in the NDVI map, most likely due to the practice of maintaining rice paddies in both growing seasons. On the other hand, water falls on the slopes of mountain Elgon (red circle on right side of Figure 3) were correctly detected as permanently inundated areas in the NDVI map.

### **3.2 Characterising land cover changes and their impacts within the catchment**

The results from BFAST analysis show that there was only one significant change in NDVI phenology within the mapped cover complexes during the analysis period (2001-2016). This change in cover type, occurred in NDVI class 20 (Figure 3) in year 2011. We established through Google images that these areas have been converted from agriculture to small plantation forests. Aside from this conversion, the state of land cover in the rest of the catchment was stable during the analysis period. This means that disturbances mapped as degraded wetland areas in Figure 3 occurred prior to 2001.

Results also showed that there was a declining NDVI trend for all the cover complexes except grasslands, woodlands, and forests (Table 2). The slope of the decline varied among land cover complexes, with the lowest and highest slopes observed for intact wetlands (-0.003) and agricultural areas A and D (-0.05), respectively. Most agricultural areas had a slight improvement in vegetation productivity after 2010 but wetland trend declined throughout the monitoring period (Table 2).

Table 2: Description of land cover/use complexes for different NDVI class groups; with information on slope and direction of NDVI trend; where (+) and (-) represent positive and negative trend respectively

Land use complexes	Colour	NDVI Groups	Slope of trend
Open Water		3,4	N/A
Agricultural area (A)		6, 7, 9,16	-0.01, -0.05, 0.01
Agricultural area (B)		8, 12, 15	-0.02, -0.03, 0.06, 0.02
Agricultural area (C)		14, 18	-0.01, -0.02, -0.01
Agricultural area (D)		19, 26, 28	-0.01, -0.05, 0.003
Agricultural area (E)		21, 27	-0.01, -0.03, 0.04, 0.02
Agricultural area		30	-0.02, -0.04, -0.01
Agricultural area		13	-0.01, -0.03, -0.01
Agroforestry		29	-0.01, -0.04, -0.01, 0.04
Grassland		11, 22	N/A
Woodland		17, 33, 36	N/A
Seasonal wetland†		20	-0.04, -0.02
Seasonal wetland		23	-0.01, -0.04, -0.004
Degraded wetland		24	-0.01, -0.01, -0.002
Permanently wet areas		25	-0.01, 0.05, 0.01, 0.02
Intact Papyrus areas		31, 32	-0.003
Forest		34, 35, 38	N/A

†Class 20 had a change in phenology in 2011, which represents change in land cover type.

The land cover changed from agriculture to plantation forest

In addition, we observed flood disturbances characterised by sudden increases in NDVI for agricultural area C in 2006 and 2010, but intact wetlands had no such disturbances (Figure 5).

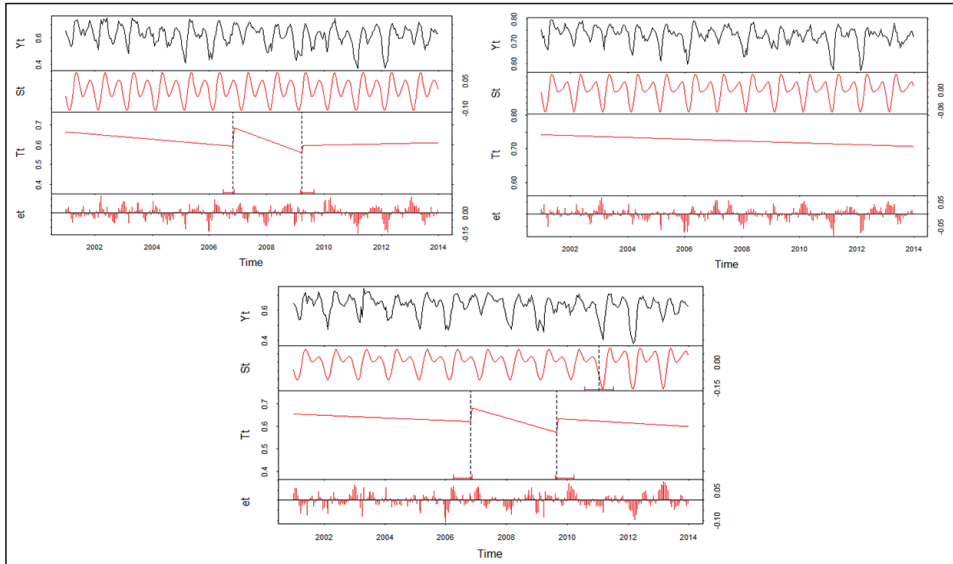


Figure 5: Illustration of NDVI trend for different land cover complexes. Clockwise from top left; Agricultural areas with flooding disturbances marked by sudden rise in NDVI (Agricultural area C), intact papyrus wetland with no disturbances, and seasonal wetland with change in both trend and phenology (Seasonal wetland, class 20). Where  $Y_t$ ,  $S_t$ ,  $T_t$ , and  $e_t$  on the Y-axis represent the NDVI time series, the seasonal component, the trend component and the residual component respectively

The observed decline in vegetation productivity does not correlate to precipitation patterns, which showed an increasing trend with a slope of 10 (Figure 6). This means that the observed trend in vegetation productivity is driven by endogenous pressures.

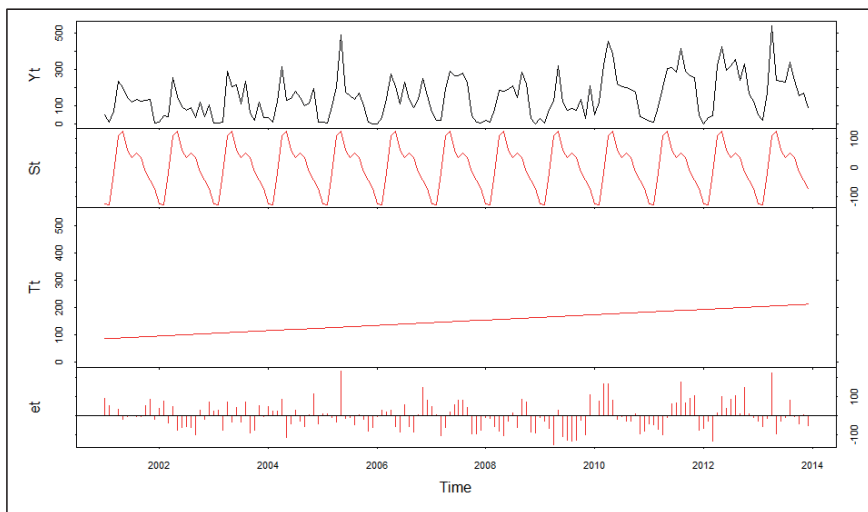


Figure 6: The trend in catchment precipitation increased with a slope of 10 during the monitoring period. Where  $Y_t$ ,  $S_t$ ,  $T_t$ , and  $e_t$  on the Y-axis represent the precipitation time series (mm), the seasonal component, the trend component and the residual component respectively

### 3.3. Changes in vegetation moisture

The highest vegetation moisture was observed in the intact Mpologoma wetland on all the image dates (Figure 7). This is because the wetland is permanently flooded, which increases plant available moisture in these areas. Areas of low vegetation moisture increased by 110% between 1986 and 2017 while medium and high vegetation moisture decreased by 22% and 15% respectively (Table 3). Areas of low vegetation moisture were localised in upstream areas in 1986 but these spread to lowlands in 2001 and 2017 (Figure 7). In addition, the distribution of vegetation moisture within the wetland became patchier in the later years.



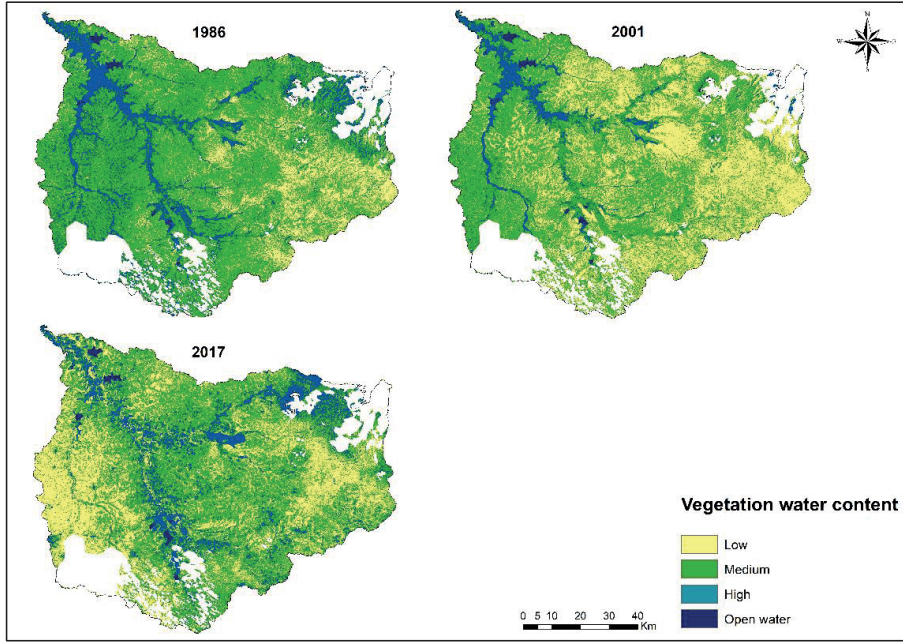


Figure 7: Modified Normalised Difference Water Index for 1986, 2001 and 2017; showing variation of vegetation moisture. Visible mosaic line because images from two Landsat paths and dates were combined

Table 3: Vegetation moisture variation in Mpologoma catchment between 1986 and 2017

Vegetation moisture Class	Class range	Area of class (km <sup>2</sup> )		
		1986	2001	2017
High	0 → -0.4	1,260	520	1,070
Moderate	-0.4 → -0.5	5,430	4,350	4,250
Low	-0.5 → -1	1,230	3,050	2,600
<b>Total area</b>		<b>7920</b>	<b>7920</b>	<b>7920</b>

## **4. Discussion**

### **4.1. State of land cover in the Mpologoma River basin**

Our research showed that there are encroachments along the edges of the Mpologoma wetland. This observation is supported by results from Ssanyu *et al.* (2014)'s field survey along the Mpologoma River system (e.g Figure.1 in Ssanyu et al., 2014). This degradation is driven by farmers' perceptions of improved crop yields at wetland edges (Kakuru *et al.*, 2013). However, the removal of natural wetland vegetation, and river diversions lead to a further reduction in river discharge (NEMA, 2008a). It is important therefore, to train farmers on sustainable use of available wetland water, as opposed to draining the wetlands.

### **4.2. Land cover changes and their impacts**

The driving forces of wetland degradation in the catchment (DPSIR framework, Figure 1) are increasing (GOU, 2017; Uganda Bureau of Statistics, 2017). However, only the change from small scale agriculture to plantation forest occurring in NDVI class 20 (Table 2 and Figure 3) was identified using BFAST time series analysis. This could give an impression that there were no endogenous pressures in the catchment during the analysis period (2001-2016). This is not necessarily true because changes from natural wetland vegetation to rice paddies though present, may not create a significant change in NDVI phenology to be detected by the BFAST method. Nevertheless, the rate of wetland degradation reduced in the last 15 years compared to the preceding period (Turyahabwe *et al.*, 2013). Therefore, the observed decline in vegetation productivity, and increase in flooding frequency for some areas, are most likely long term impacts of previous land cover changes.

The NDVI map is useful for categorising areas impacted by endogenous pressures because such areas give a unique signature compared with other land complexes. This is illustrated by information given by the Iganga District Environmental Officer (personal communication, 27th May 2014). The officer explained that upstream sections of the Naigombwa River (Figure 2); classified as a distinct agricultural class (NDVI Class 30; Table 2 and Figure 3), were formerly perennial streams which now frequently dry out during drought periods. This shows that the created map has a lot of information about land management and hydrological characteristics of the catchment. However, it can only be understood by linking the map to local knowledge of historical changes. Therefore, this research would have benefited from a survey about observed changes in the timing and duration of inundation/water logging in wetlands and adjacent agricultural lands. Such a survey was not financially feasible for the current study but can be incorporated into future research.

### **4.3. Flooding dynamics and vegetation moisture variations**

Additional information about the hydrological characteristics of the agricultural complexes became apparent after statistics from the map were examined using trend analysis. For example, Figure 5 shows more than just the NDVI trend for the selected land cover complexes. The figure also gives insight about when floods occurred, as indicated by a sudden rise in NDVI (Powell *et al.*, 2014; Sims & Colloff, 2012).

The floods were validated using records from the Dartmouth Flood Observatory (Brakenridge, 2010). The records show that flooding incidents were reported for the Kyoga basin in August 2006, August 2007 and September 2010. It is interesting to note that the sub counties recorded as flood prone in the Dartmouth records, are those surrounding the largest commercial farmland in Figure 4. On the other hand, other parts of the catchment (Naigombwa wetland), are experiencing drying trends as shown by NDVI class 30. This information is complemented by results from NDWI analysis which show that although the vegetation moisture condition is deteriorating; there was some improvement for agricultural area C between 2001 and 2017, while agricultural area E continued to deteriorate.

The two main disadvantages of the Landsat data were: the time gap between image scenes, which could have amplified any differences in climatic conditions (wet or dry); and the high frequency of cloud cover, which made it difficult to monitor at shorter time intervals. This dataset is therefore better suited for giving a general overview of changes in the catchment rather than for detailed change detection at smaller scales.

However, when the two methods (image and trend analysis) are combined, they can help to identify areas that need restoration measures; which is currently difficult with the sparse gauging in the catchment. If alternative monitoring tools, such as those demonstrated by this study are not capitalized on, impacts of endogenous pressures on discharge and the water table may go unnoticed and eventually cause irreversible changes in the catchment's hydrology (Falkenmark, 2001; Finlayson, 2018). This is illustrated by the fact that

vegetation productivity and moisture are on a declining trend despite the reduced rate of land conversions in more recent years.

With improved documentation of land conversions and their impacts on catchment hydrology, response measures like restoration of degraded wetlands can be targeted at specific locations while promoting wise use of intact wetlands at the larger scale. The time series dataset can also be updated on a yearly basis to monitor feedback mechanisms if any, of implemented actions.

#### **4.4. Conclusion**

In this study, we utilised a combination of hyperspectral image analysis and trend analysis to map vegetation moisture and productivity; and to categorise areas impacted by wetland degradation in the Mpologoma River basin. Results showed that vegetation moisture and productivity are decreasing, despite a reduction in the rate of wetland degradation in the past 15 years. This implies that previous land cover conversions still have long lasting impacts on the catchment's hydrology. The combination of image and trend analysis provides a monitoring tool for poorly gauged catchments; which can be used to isolate areas for targeted action, and provide an opportunity for monitoring the outcomes of implemented actions.

## **Acknowledgement**

This work was funded by the 'Norwegian Programme for Capacity Development in Higher Education and Research for Development (NORHED)'; Grant number: 3303010034. The funding is through the 'Regional Capacity Building for Sustainable Natural Resource Management and Agricultural Improvement under Climate Change (CAPSNAC)' Project housed at Makerere University, Uganda.

## References

- Brakenridge GR. 2010. Global Active Archive of Large Flood Events. Retrieved 20/04/2015 <http://floodobservatory.colorado.edu/Archives/index.html>
- Coppin P, Jonckheere I, Nackaerts K, Muys B, Lambin E. 2004. Review Article Digital Change Detection Methods in Ecosystem Monitoring: A Review. *International Journal of Remote Sensing* **25**: 1565-1596. doi:10.1080/0143116031000101675
- Davis SM, Landgrebe DA, Phillips TL, Swain PH, Hoffer RM, Lindenlaub JC, Silva LF. 1978. Remote Sensing: The Quantitative Approach. United States of America: McGraw-Hill, Inc.
- De Bie CAJM, Khan MR, Smakhtin VU, Venus V, Weir MJC, Smaling EMA. 2011. Analysis of Multi-Temporal SPOT NDVI Images for Small-Scale Land-Use Mapping. *International Journal of Remote Sensing* **32**: 6673-6693. doi:10.1080/01431161.2010.512939
- De Bie CAJM, Khan MR, Toxopeus AG, Venus V, Skidmore AK. 2008. Hypertemporal Image Analysis for Crop Mapping and Change Detection. Paper presented at the ISPRS 2008. Proceedings of the XXI congress: Silk road for information from imagery: the International Society for Photogrammetry and Remote Sensing, Beijing, China.
- Dobriyal P, Qureshi A, Badola R, Hussain SA. 2012. A Review of the Methods Available for Estimating Soil Moisture and its Implications for Water Resource Management. *Journal of Hydrology* **458-459**: 110-117. doi:10.1016/j.jhydrol.2012.06.021
- Falkenmark M. 2001. The Greatest Water Problem: The Inability to Link Environmental Security, Water Security and Food Security. *International Journal of Water resources development* **17**: 539-554. doi:10.1080/07900620120094073
- Finlayson CM. 2018. Millennium Ecosystem Assessment. In: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and Methods* (pp. 355-359). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_81
- GOU. 2017. Towards Zero Hunger. A Strategic Review of Sustainable Development Goal 2 in Uganda. Kampala, Uganda.

- Grogan K, Pflugmacher D, Hostert P, Verbesselt J, Fensholt R. 2016. Mapping Clearances in Tropical Dry Forests Using Breakpoints, Trend, and Seasonal Components from Modis Time Series: Does Forest Type Matter? *Remote Sensing* **8**: 657. doi:10.3390/rs8080657
- Gu Y, Brown JF, Verdin JP, Wardlow B. 2007. A Five-Year Analysis of Modis NDVI and NDWI for Grassland Drought Assessment over the Central Great Plains of the United States. *Geophysical Research Letters* **34**. doi:10.1029/2006GL029127
- Higginbottom TP, Symeonakis E. 2014. Assessing Land Degradation and Desertification Using Vegetation Index Data: Current Frameworks and Future Directions. *Remote Sensing* **6**: 9552-9575. doi:10.3390/rs6109552
- Hisali E, Birungi P, Buyinza F. 2011. Adaptation to Climate Change in Uganda: Evidence from Micro Level Data. *Global Environmental Change* **21**: 1245-1261. doi:10.1016/j.gloenvcha.2011.07.005
- Kakuru W, Turyahabwe N, Mugisha J. 2013. Total Economic Value of Wetlands Products and Services in Uganda. *The Scientific World Journal* **2013**: 13. doi:10.1155/2013/192656
- Kansiime MK, Wambugu SK, Shisanya CA. 2013. Perceived and Actual Rainfall Trends and Variability in Eastern Uganda: Implications for Community Preparedness and Response. *Journal of Natural Sciences Research* **3**: 179-194.
- Kerle N, Janssen LL, Huurneman GC. 2004. Principles of Remote Sensing. *ITC, Educational textbook series* **2**: 250.
- Kipkemboi J, van Dam AA. 2018. Papyrus Wetlands. In: CM Finlayson, GR Milton, RC Prentice, NC Davidson (Eds.), *The Wetland Book: II: Distribution, Description, and Conservation* (pp. 183-197). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4001-3\_218
- Kopec RJ. 1963. An Alternative Method for the Construction of Thiessen Polygons. *The Professional Geographer* **15**: 24-26. doi:10.1111/j.0033-0124.1963.024\_r.x
- Lu D, Mausel P, Brondízio E, Moran E. 2004. Change Detection Techniques. *International Journal of Remote Sensing* **25**: 2365-2401. doi:10.1080/0143116031000139863



- Masek JG, Vermote EF, N.E. S, Wolfe R, Hall FG, Huemmrich KF, Gao F, Kutler J, Lim T-K. 2006. A Landsat Surface Reflectance Dataset for North America, 1990–2000. *IEEE Geoscience and Remote Sensing Letters* **3**: 68-72. doi:10.1109/LGRS.2005.857030
- Millennium Ecosystem Assessment. 2003. Ecosystems and Human Well-Being: A Framework for Assessment: Island Press, Washington, DC, USA.
- Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.
- Namaalwa S, Van dam AA, Funk A, Ajie GS, Kaggwa RC. 2013. A Characterization of the Drivers, Pressures, Ecosystem Functions and Services of Namatala Wetland, Uganda. *Environmental Science & Policy* **34**: 44-57. doi:10.1016/j.envsci.2013.01.002
- NEMA. 2008a. Pilot Integrated Environment Assessment of the Lake Kyoga Catchment Area. National Environment Management Authority (NEMA), Kampala.
- NEMA. 2008b. State of Environment Report for Uganda (2008). National Environment Management Authority (NEMA), Kampala Uganda.
- NEMA. 2016. State of the Environment Report for Uganda 2014 National Environment Management Authority (NEMA), Kampala Uganda.
- Nsubuga F, Botai JO, Olwoch JM, Rautenbach CJd, Kalumba AM, Tsela P, Adeola AM, Sentongo AA, Mearns KF. 2017. Detecting Changes in Surface Water Area of Lake Kyoga Sub-Basin Using Remotely Sensed Imagery in a Changing Climate. *Theoretical and Applied Climatology* **127**: 327-337. doi:10.1007/s00704-015-1637-1
- Nsubuga F, Namutebi EN, Nsubuga-Ssenfuma M. 2014. Water Resources of Uganda: An Assessment and Review. *Journal of Water Resource and Protection* **6**: 1297-1315. doi:10.4236/jwarp.2014.614120
- Petropoulos GP, Ireland G, Barrett B. 2015. Surface Soil Moisture Retrievals from Remote Sensing: Current Status, Products & Future Trends. *Physics and Chemistry of the Earth, Parts A/B/C* **83**: 36-56. doi:10.1016/j.pce.2015.02.009
- Pettorelli N, Vik JO, Mysterud A, Gaillard J-M, Tucker CJ, Stenseth NC. 2005. Using the Satellite-Derived NDVI to Assess Ecological Responses to Environmental Change. *Trends in Ecology & Evolution* **20**: 503-510. doi:10.1016/j.tree.2005.05.011

- Powell S, Jakeman A, Croke B. 2014. Can NDVI Response Indicate the Effective Flood Extent in Macrophyte Dominated Floodplain Wetlands? *Ecological Indicators* **45**: 486-493. doi:10.1016/j.ecolind.2014.05.009
- Schyns JF, Hoekstra AY, Booij MJ. 2015. Review and Classification of Indicators of Green Water Availability and Scarcity. *Hydrol. Earth Syst. Sci.* **19**: 4581-4608. doi:10.5194/hess-19-4581-2015
- Sims NC, Colloff MJ. 2012. Remote Sensing of Vegetation Responses to Flooding of a Semi-Arid Floodplain: Implications for Monitoring Ecological Effects of Environmental Flows. *Ecological Indicators* **18**: 387-391. doi:10.1016/j.ecolind.2011.12.007
- Ssanyu GA, Kipkemboi J, Mathooko JM, Balirwa J. 2014. Land-Use Impacts on Small-Scale Mpologoma Wetland Fishery, Eastern Uganda: A Socio-Economic Perspective. *Lakes & Reservoirs: Research & Management* **19**: 280-292. doi:doi.org/10.1111/lre.12073
- Turyahabwe N, Tumusiime DM, Kakuru W, Barasa B. 2013. Wetland Use/Cover Changes and Local Perceptions in Uganda. *Sustainable Agriculture Research* **2**: 95. doi:10.5539/sar.v2n4p95
- U.S. Geological Survey. 2018. Product Guide: Landsat 4-7 Surface Reflectance (Ledaps) Product.
- Uganda Bureau of Statistics. 2017. Statistical Abstract. Kampala, Uganda.
- United Nations Development Programme. 2013. Climate Profiles and Climate Change Vulnerability Assessment for the Mbale Region of Uganda. Uganda.
- Verbesselt J, Hyndman R, Newnham G, Culvenor D. 2010. Detecting Trend and Seasonal Changes in Satellite Image Time Series. *Remote Sensing of Environment* **114**: 106-115. doi:10.1016/j.rse.2009.08.014
- Xu H. 2006. Modification of Normalised Difference Water Index (NDWI) to Enhance Open Water Features in Remotely Sensed Imagery. *International Journal of Remote Sensing* **27**: 3025-3033. doi:10.1080/01431160600589179
- Young NE, Anderson RS, Chignell SM, Vorster AG, Lawrence R, Evangelista PH. 2017. A Survival Guide to Landsat Preprocessing. *Ecology* **98**: 920-932. doi:10.1002/ecy.1730
- Zhang D, Zhou G. 2016. Estimation of Soil Moisture from Optical and Thermal Remote Sensing: A Review. *Sensors* **16**: 1308. doi:10.3390/s16081308



# PAPER II





section. This water regulatory function mitigates severity of floods downstream, but the stored water is also useful to the surrounding communities for wetland-edge farm irrigation during dry seasons.

© 2018 Elsevier B.V. All rights reserved.

## 1. Introduction

Papyrus wetlands are predominant in permanently inundated areas of Sub Saharan Africa (Mburu et al., 2015; Morrison et al., 2013). They are dominated by monocultures of *Cyperus papyrus* L., which is a large herbaceous sedge whose culm grows up to five metres (Terer et al., 2012). Sometimes they grow in combination with other species like *Miscanthidium violaceum*, *Phragmites mauritianus* and *Typha domingensis* (van Dam et al., 2007). The wetlands are a source of fuel, medicinal herbs, fishing grounds, raw materials for crafts, building materials, and inundated wetland edges are utilised for agricultural activities (Donaldson et al., 2016; Terer et al., 2014).

Papyrus wetlands also provide services of water purification, flood mitigation, water storage, and are important carbon sinks (Mburu et al., 2015; Saunders et al., 2007; Saunders et al., 2013; van Dam et al., 2007). For example, papyrus wetlands can store up to 1.6 kg C m<sup>-2</sup> y<sup>-1</sup> (Jones and Humphries, 2002) and contribute to improved water quality through uptake of faecal coliforms, phosphorus, as well as nitrogen uptake varying between 17.2 g N m<sup>-2</sup> y<sup>-1</sup> and 76.7 g N m<sup>-2</sup> y<sup>-1</sup> (Kansiime and Nalubega, 1999; Okurut, 2000; van Dam et al., 2007).

Although the water purification function of papyrus wetlands has been widely studied, their provisioning and regulatory functions especially water storage and flood mitigation have received less attention (van Dam et al., 2014). A few studies highlight the importance of the papyrus mat system in water storage (Kansiime et al., 2007; Kipkemboi et al., 2002); but to the best of our knowledge, there is no literature describing the spatial and temporal variation of the papyrus mat structure in different seasons and how this phenomenon affects water storage.

Papyrus plants exist either in rooted or floating form, rooted papyrus are anchored in the sediment at shallow ends of the wetlands. Some stands can be detached during inundation by fast flowing water, forming floating mats. The mats are made up of loosely intertwined roots and rhizomes, and can spread by rhizome propagation over open water to form a continuous root-rhizome-mat system (Boar, 2006; Saunders et al., 2012; van Dam et al., 2007). The mat system can support the weight of an adult male of approximately 80 kg. The loose structure of the floating mat allows exchanges of water between the free water column beneath the plant and its root system (Azza et al., 2000), which enables the plants to access nutrients in the water.

The configuration or morphology of the rhizome-root-mat complex is believed to influence the functioning of papyrus wetlands. For example, Kipkemboi et al. (2002) observed that the floating papyrus mat in Namiiri and Lubigi wetlands moved upwards with rising water levels during periods of flooding. In addition, the mat system reduces water velocity which increases water retention time (Kansiime and Nalubega, 1999). Indeed, Ryken et al. (2015) demonstrated the buffering capacity of papyrus wetlands when they showed that the timing and amount of peak discharge was delayed and lowered for catchments with intact wetlands compared to those with degraded wetlands.

We illustrate a typical papyrus wetland cross-section in Fig. 1. The wetland has a peat-sediment layer overlaying a solid bottom of varying topography. The dominant vegetation is papyrus, which is rooted at the edges but floats over the water in the wetland centre. We define the wetland edge as the dry season water boundary, while the transition zone is the area that is seasonally flooded in the wet season. The term 'free water column' is used to define the column of water beneath the floating vegetation and we use this term from here on. The wetland has open water areas at inlets and outlets, although small patches of

open water occur in the central parts too. The density of plants in the figure is simplified but actual culm density varies between 16 and 36 culms m<sup>-2</sup> (Opio et al., 2014).

Fig. 1 also illustrates the response of the papyrus mat to seasonal changes in the hydro period. The friction of the floating mat as well as return flow within the free water column reduce water velocity. These processes are described by Liu et al. (2017) and Zhang and Nepf (2011) who demonstrated using tank experiments, that velocity is reduced both within the root layer as well as in the free water column. This increases the retention time, which in turn mitigates impact of floods downstream and enhances aquifer recharge and bank storage through infiltration.

In wet seasons, water levels increase because of higher flows. The papyrus plant rises with the water because it is buoyant. In this way, the water storage of the wetland increases. When the water level exceeds the maximum wetland depth, water seeps through the rooted papyrus mat and floods the transition zone (Fig. 1). The wetland releases stored water slowly in the dry season, which makes it available for domestic and irrigation use.

Despite the services of papyrus wetlands, increasing pressure for agricultural expansion has led many wetlands to be converted for agriculture especially rice growing (Kipkemboi and van Dam, 2016). As a result, agricultural crops replace natural vegetation in the wetlands (Kansiime et al., 2005). The conversion starts at the wetland edges during periods of low flow when farmers slash the above ground biomass (culms) of rooted papyrus. They then dig out the roots and rhizomes from the ground and burn them to prevent regeneration of the plant in the wet season.

Gradually this procedure extends into the wetland. In the deeper parts of the wetlands, farmers create artificial channels to drain water from slightly raised rice plots established in the wetland. As a result, draining reduces the water level in these parts of the wetland to a level near the ground surface. There are two ways of wetland conversion, the first involves creating artificial drainage channels and the second involves filling the wetland with soil especially for very deep channels. Small-scale farmers rarely attempt the latter process because it is costly, but it is easier to undertake for commercial rice expansion.

Due to the mounting pressure on wetlands, it is crucial to understand the regulatory (flood control) and provisioning (water provision) services of papyrus wetlands. Improved understanding of the dynamics of this system could enhance sustainable management and utilisation of wetlands to increase agricultural productivity under a changing climate. For example, rather than draining wetlands to grow crops (van Dam et al., 2014), local communities could utilize stored wetland water to irrigate crops grown at wetland edges especially during the dry season.

This study was carried out to assess the response of the papyrus root mat to changing water levels. The wetland of interest has rooted papyrus at the edges and floating papyrus in the centre of the wetland. The changes in the root mat are important to know, since they influence flow paths as well as the amount of interaction between water and the root-rhizome mat complex. We measured detailed wetland bathymetry, and the spatial distribution of mat thickness at different water depths.

The hypothesis is that during periods of high water flow, the depth of the free water column beneath the papyrus mat increases. This increase exerts a force on the papyrus mat, which causes it to rise. However, as the water level increases further, the papyrus mat begins to compress. In this way, the wetland accommodates more water, which increases its storage in the wet season.

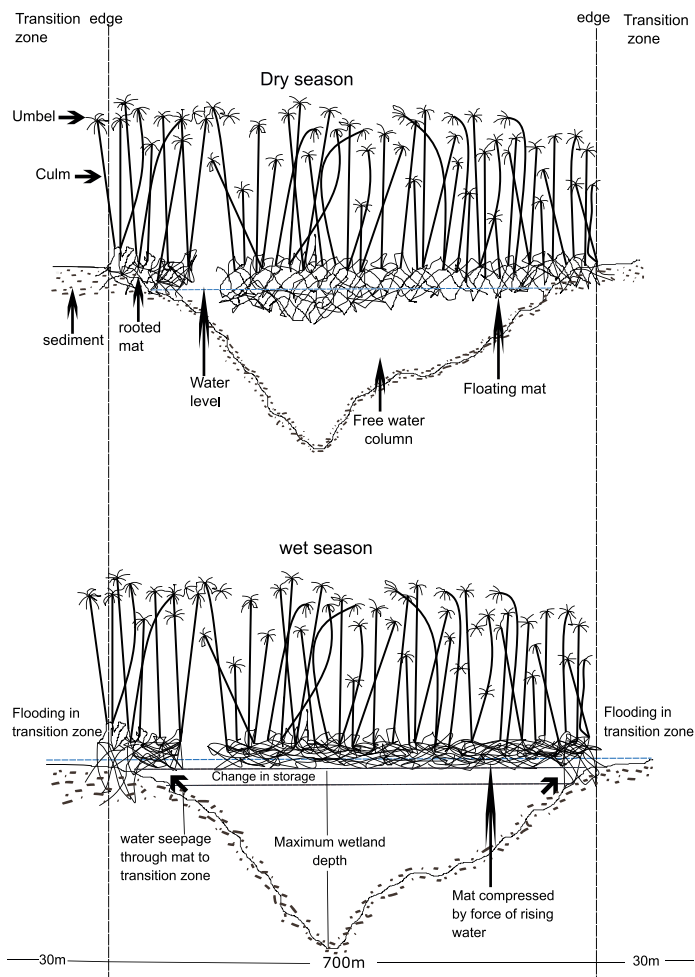


Fig. 1. Wetland cross section showing the dynamics of rooted and floating papyrus mat, and the free water column in the dry and wet season.

## 2. Materials and methods

### 2.1. Study area

This study was carried out in the Naigombwa wetland, Iganga district in the Lake Kyoga Basin of Eastern Uganda (Fig. 2). Iganga district has three main wetland systems; Lumbuye, Naigombwa, and Mpologoma which all drain northwards into Lake Kyoga, and finally into the river Nile. The wetland channels are slightly meandering, with low gradient and high width to depth ratios. A small section of the Naigombwa wetland demarcated by a highway and railway line was selected for this study. It has an area of 0.18 km<sup>2</sup> and drains an area of 734 km<sup>2</sup>. Parts of the wetland upstream of the study section were extensively drained for rice growing whereas the downstream part still has intact papyrus vegetation.

The section was chosen because major inflows and outflows in culverts of the highway and railway line can be quantified more easily. In addition, the road improves accessibility to this wetland section compared to other parts of the wetland. It has one large culvert and six small ones along the highway in the southeast, which are the main

flows into the wetland. A railway line crosses the downstream end in the North West and has two large culverts for outflows (Fig. 3).

The mean annual rainfall and temperature from historical records (1961–1990) of stations in the Kyoga basin is 1300 mm distributed between two rainy seasons, and 21 °C respectively (Kigobe et al., 2014). The basin's monitoring network is inadequate due to sparse coverage and incomplete records from break down of some stations (COWI, 2010; Kigobe et al., 2011). Consequently, the Naigombwa sub-catchment lacks a long-term meteorological record. The sub-catchment is relatively flat with elevations varying from 1056 to 1348 m above sea level, and the soils are mainly ferralitic with reddish brown sandy loams.

### 2.2. Layout and sampling design

The layout and sampling design is illustrated in Fig. 3. A highway in the south east, and a railway on the north western side define the man-made wetland boundary. The natural edges of the wetland are shown by the periphery of the papyrus vegetation. The wetland's water boundary shifts outwards by about 30 m and floods the transition zone during



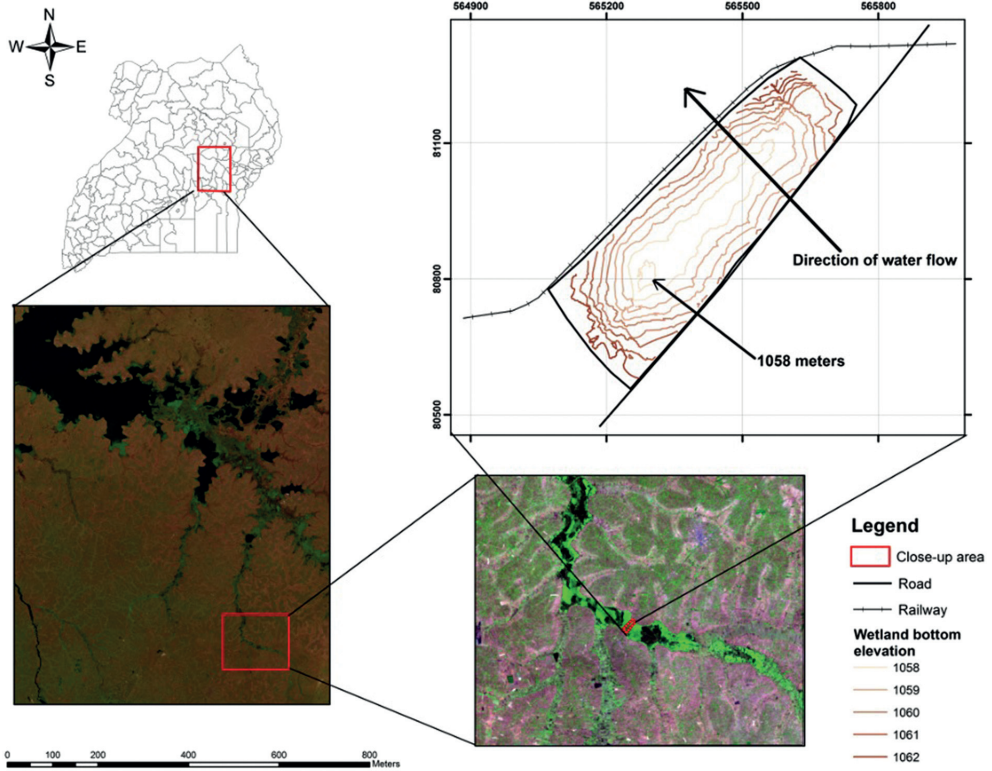


Fig. 2. Location of the study site in Eastern Uganda, the contours illustrate the wetland's bottom elevation/bathymetry.

periods of high flows. The transition zone is used for rice paddies in the rainy seasons.

We digitized outlines of the highway and railway line from a google earth image of the wetland. Seven access transects numbered 1 to 7 were cut through the wetland parallel to the water flow. The transects were set approximately 100 m apart at the highway, however they are not completely parallel to each other since it was difficult to keep a perfect line of sight beyond the papyrus canopy while cutting through the papyrus bush. The longest transect is 270 m (Transect1) and transect 7 is the shortest at 170 m.

All the seven transects were used for mapping the wetland's bottom elevation, while transects 1, 3 and 5 were used for measuring papyrus mat thickness and depth of the free water column. Labels along the three transects indicate transect number and distance from wetland edge. For example, T1-25 represents a measurement taken along transect 1 at 25 m from the edge (Fig. 3). Automatic divers were installed at the centres of transects 1, 3 and 5 for continuous monitoring of water depth. We monitored local precipitation patterns using an automatic weather station (model: Davis Vantage Vue 6250) located 1 km from the wetland. We installed water level gauges at the largest inlet culvert and at the two outlets, where we monitored wetland stage during the study period.

2.3. Deriving wetland bathymetry

Bathymetry is defined as the elevation and shape of land that is underneath a waterbody (Huertos and Smith, 2013). We mapped the wetland's bottom elevation by surveying 137 points along the seven

access transects, and around the wetland edges on 13th January 2016. We used a CHC GNSS receiver (Model: X900; operation mode: RTK) to record position (X, Y coordinates) and wetland bottom elevation of the 137 points. The elevation data was imported into a GIS environment (ArcMap 10.5). We then created a digital elevation model for the wetland by interpolating the elevation data using the natural neighbour interpolation method.

2.3.1. Deriving relationship between water level and wetland volume

We used ArcMap 3D analyst tools (surface volume tool) to calculate wetland water volume for a range of predetermined water depths/elevations for the derived bathymetry map following procedures by Huertos and Smith (2013). The tool takes into account the shape of the wetland, and it calculates the volume of water that would fill the wetland as the water depth at the deepest point of the wetland increases from zero to the maximum water elevation (Fig. 1). Water volume was calculated for a range of water depths from 0 to 3.5 m at 0.5 increments. A scatter plot of volume against water depth revealed a polynomial relationship. We therefore fit a third order polynomial model (Eq. (1)) to the data with an adjusted R square value of 0.99;

$$WV = 2382.4 - 24987.6WD + 47793.2WD^2 - 4030WD^3 \tag{1}$$

where WV = wetland water volume, WD = water depth.

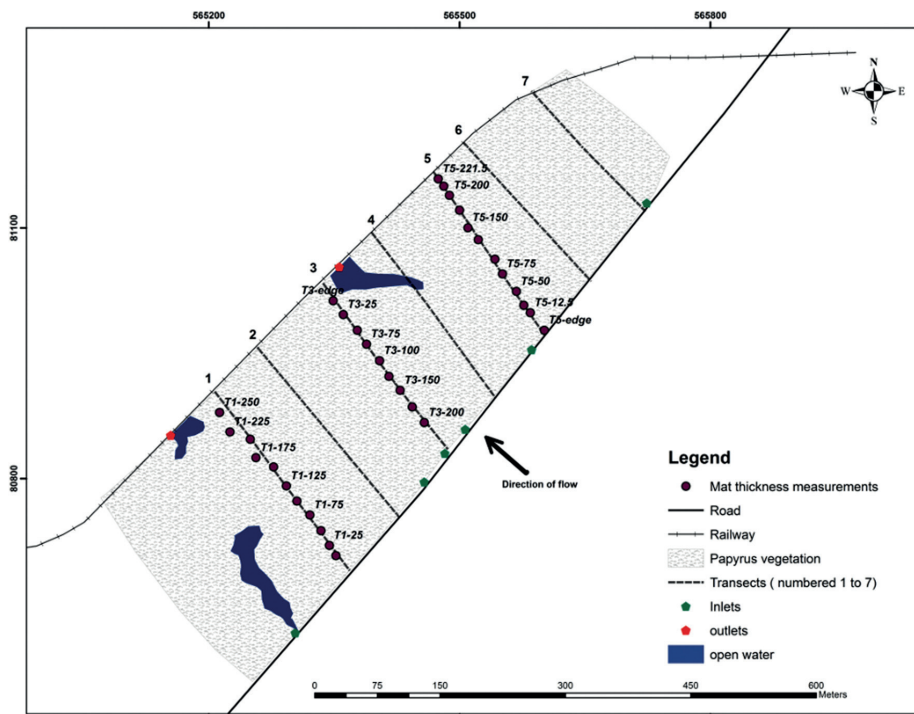


Fig. 3. Layout and sampling design of the selected wetland section.

#### 2.4. Monitoring water depth

We installed three automatic divers, one each at the centres of transects 1, 3 and 5 (supplier: Geonor AS, model: Micro-Diver DI6) on 13th January 2016 to monitor water pressure changes in different seasons.

The divers recorded water pressure every 30 min over a period of five months. Barometric pressure was recorded using a barometric diver (model: Baro-Diver DI500), which was installed in a borehole 50 m from the wetland edge. The pressure recordings were used to calculate water depth variations in the wetland using Eq. (2) (Schlumberger

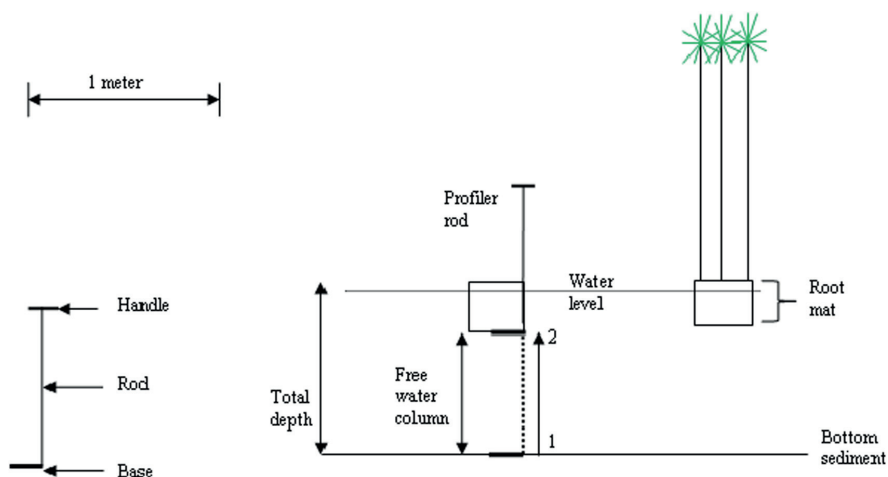


Fig. 4. Illustration of profiler rod (left), and the measurement technique for mat thickness and free water column (right), where 1 is the total depth measurement and 2 is the mat thickness measurement.

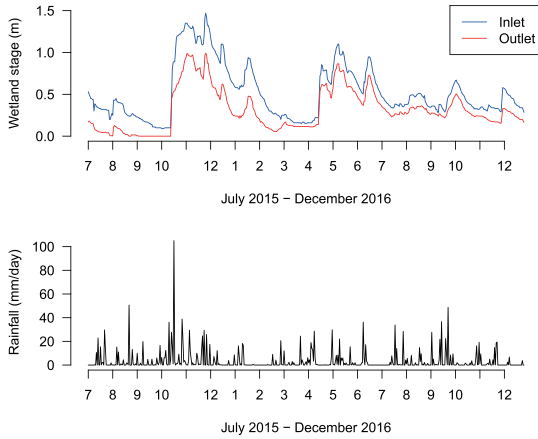


Fig. 5. Wetland stage and precipitation during the monitoring period.

Water Services, 2014);

$$WD = TOC - CL + 9806.65 \frac{P_{Diver} - P_{Baro}}{\rho g} \quad (2)$$

where WD = Water depth, TOC = Top of casing, CL = Cable length,  $P_{Diver}$  = Water pressure diver,  $P_{Baro}$  = Barometric pressure diver,  $\rho$  = Water density ( $1000 \text{ kg/m}^3$ ),  $g$  = Acceleration due to gravity ( $9.81 \text{ m/s}^2$ ).

After calculating the water depth changes, we computed the variation in wetland water volume in the dry and wet season using the volume-water depth relationship derived from the bathymetry data in Section 2.3.1.

### 2.5. Measurement of mat thickness and free water column

Mat thickness and depth of the free water column beneath the papyrus mat, were measured along transects 1, 3, and 5 in the dry season and beginning of the second wet season on 17/03/2016 and 27/05/2016 respectively. We chose the beginning rather than middle of the wet season since it would be unsafe to walk on the floating mat during periods of very high flows. For each transect; mat thickness, total depth, and X, Y coordinates were recorded starting from the man-made boundary at the highway, and thereafter every 25 m up to the opposite edge of the wetland. A profiling rod was used to measure the mat thickness and water depth as illustrated in Fig. 4. The rod was pushed through the mat until its base touched the peat-sediment layer and this gave the total depth of both the papyrus mat and free water column. The rod was then lifted until its base touched the bottom of the mat to measure the mat thickness. The difference between the total depth and mat thickness was used to calculate depth of the free water column. At each location, measurements were taken 3 to 5 times on either side of the transect, and an average value was computed. Locations of the measurements were taken using a Global positioning system.

### 2.6. Statistical analysis

The data for each transect was divided into three zones according to differences in water depth along the respective transects. The zones were termed 'highway edge (zone I)', 'central zone (zone II)', and 'railway edge (zone III)', and were at distances of 0–100, 100–175, and 175–250 m from the highway respectively. We used the Kruskal-Wallis ANOVA test to analyse differences in mat thickness and free water column among the created zones. Differences in mat thickness and free water column between the three transects were also analysed using ANOVA. The relationship between mat thickness and free water column was tested with the Spearman rank correlation coefficient. We calculated the percentage changes in mat thickness and free water column from the dry to wet season, and used ArcMap software to illustrate the spatial distribution of the changes.

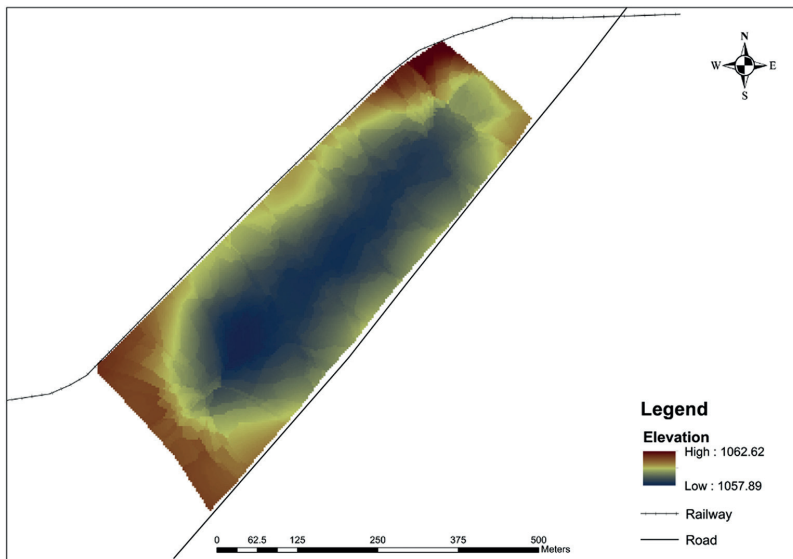


Fig. 6. Elevation of wetland bottom.

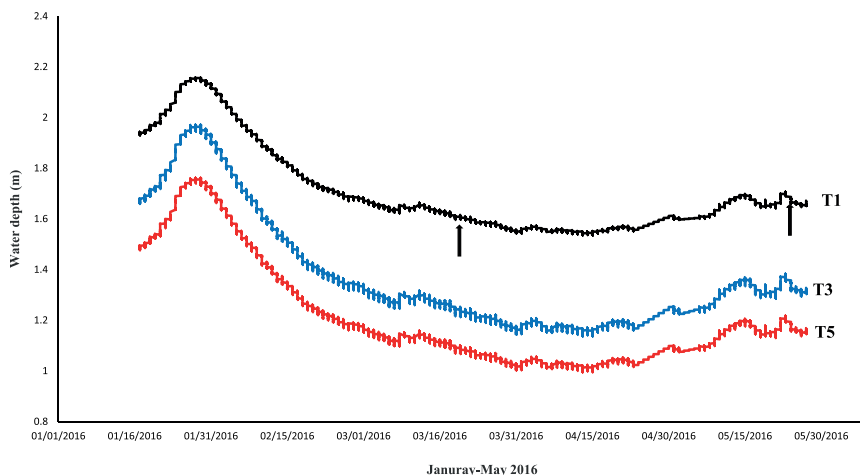


Fig. 7. Variation in total water depth along the three transects, black arrows indicate the dates at which mat measurements were taken. T1, T3, T5 represent transects 1, 3 and 5.

### 3. Results and discussion

#### 3.1. Precipitation and wetland stage patterns

The rainfall dataset begins just before the beginning of the second rain season (October to December) of 2015. This rain season was characterised by a high rainfall amount adding up to 555 mm. In contrast, 2016 had less rainfall with the first (March to May) and second (August to October) rainy seasons having a cumulative rainfall of 297 mm and 290 mm respectively (Fig. 5). There was no significant correlation between local rainfall and the wetland stage at the inlet ( $r = 0.05$ ) and outlet ( $r = 0.06$ ). The cross correlation between rainfall and wetland stage was 0.2 at a lag of two weeks.

#### 3.2. Wetland bathymetry

The spatial variation in wetland bottom elevation is illustrated in Fig. 6. Wetland bottom elevation ranges between 1058 and 1062 m above sea level, with lower elevation in the wetland centre and higher elevation on its fringes. The wetland depth is highest along transect 1, which could be because the transect is located immediately

downstream of a concave bend where higher water velocity and erosion increase depth compared to other areas of the wetland section (Fig. 2). The underlying channel processes are however not the focus of this study. The differences in wetland depth influence the spatial variation in mat thickness within the wetland section such that mat thickness is larger in deeper areas (transect 1) and smaller in shallow areas (transect 5).

#### 3.3. Spatial and seasonal variations in water depth

Results of seasonal trends in the total water depth along three transects are shown in Fig. 7. The largest water depth was recorded in January, which is the end of the first rainy season. The water depth gradually reduced throughout the dry season, and began rising again after the beginning of the second rainy season. Transect 1 had a higher water depth throughout the monitoring period while lowest depth was observed along transect 5. There was an increase in water depth for all transects on the second date of mat measurements compared to the first date of mat measurements. The observed increments were 0.04 m, 0.05 m, and 0.05 m for transects 1, 3 and 5 respectively.

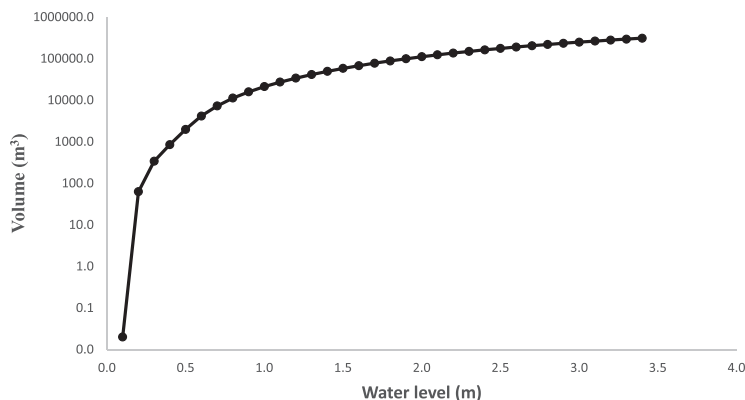


Fig. 8. Estimated wetland volume as a function of total water depth for the study section.

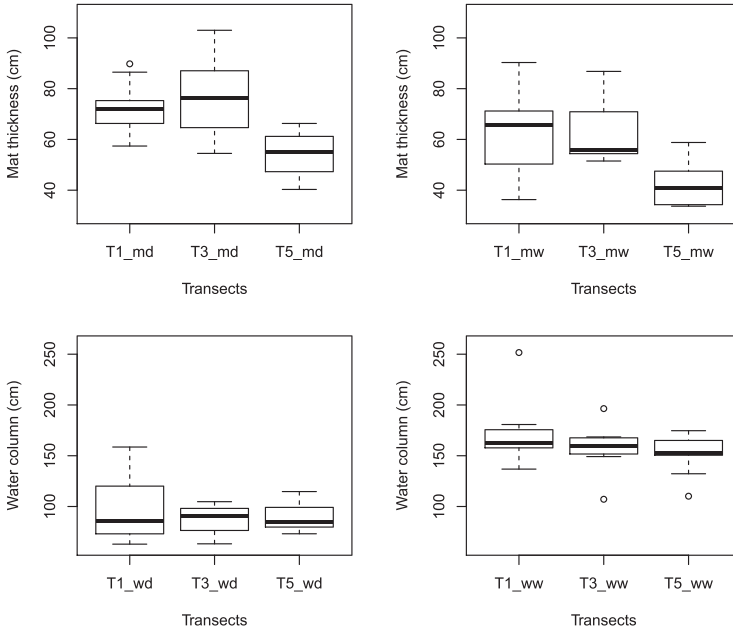


Fig. 9. Variation in mat thickness and free water column among transects in the dry and wet seasons. Where md, mw, wd, ww represent mat thickness in dry season, mat thickness in wet season, water column in dry season and water column in wet season respectively.

Water depth at the deepest point (transect 1) varied between 1.53 m and 2.1. From the water volume–depth relationship (Eq. (1)), this corresponds to a water volume of 61,597 m<sup>3</sup> and 123,355 m<sup>3</sup> respectively

and reveals a 50% change in water volume during the monitoring period. The water volume–depth relationship is illustrated in Fig. 8. A log scale is used for displaying water volume to show the range of volumes

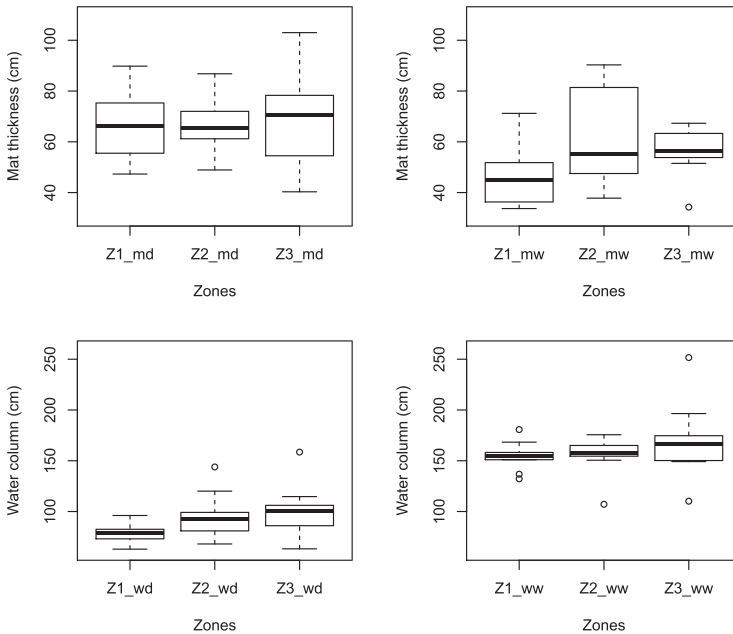


Fig. 10. Variation in mat thickness and free water column among zones in the dry and wet seasons. Where md, mw, wd, ww represent mat thickness in dry season, mat thickness in wet season, water column in dry season and water column in wet season respectively.

**Table 1**  
Means of mat thickness and free water column by zone.

Zones	Mean mat thickness (cm)			Mean water column (cm)		
	Dry	Wet	% change	Dry	Wet	% change
I	66.9	48.1	-28.1	77.8	154.5	98.6
II	66.1	62.4	-5.6	96.4	155.8	61.6
II	68.5	56.3	-17.8	101.0	170.0	68.3

that correspond to different water depths. The volume–depth relationship gives an impression about how different wetland management options which modify water depth, could impact the storage capacity.

The large storage capacity of a 0.18 km<sup>2</sup> wetland section indicates an enormous storage potential of the entire wetland system (84 km<sup>2</sup>). The excess water stored during the wet season reduces the impact of flooding downstream of the wetland since the stored water is released slowly compared to a degraded wetland system, thereby delaying the flood peak and its volume (Acreman and Holden, 2013). In addition, the stored water is available for domestic and irrigation use especially during dry periods.

Liu et al. (2017) and Zhang and Nepf (2011) demonstrated through experiments that the roots of floating vegetation reduce velocity of water flowing through the root system. They also illustrated how the cooling effect of the floating vegetation causes a density gradient between the shaded water column and open water. Their experiments show that as warmer water flows towards a shaded region, it floats on top of the cooler water because it is less dense. The cooler water sinks to the bottom, but because it has a lower velocity it retards the flow of incoming warm water at the bottom of the channel (e.g. Fig. 4 in Zhang and Nepf, 2011). Although the described processes were based on tank experiments, they can be related to our study site because there is both open water at inlet culverts and shaded water under the floating papyrus. We propose therefore that the presence of floating vegetation reduces the rate of water release from intact wetlands via both vegetation drag (friction) and temperature induced gradients, while the water would quickly flow through a degraded system in many cases destroying the crops therein.

### 3.4. Spatial and seasonal variation of mat thickness and free water column

#### 3.4.1. Mat thickness

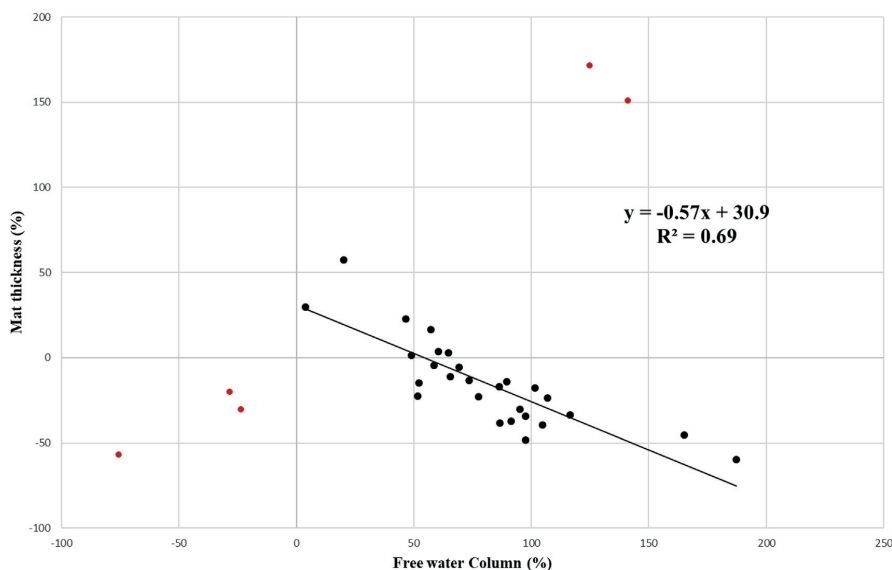
The lowest and highest variations in mat thickness in the dry season were observed along transect 5 and transect 3 respectively (Fig. 9). The observed differences in mat thickness between transects were statistically significant ( $p = 0.002$ ). Dunn's post hoc test revealed that mat thickness along transect 5 was significantly smaller than that of transect 1, which in turn was not significantly different from transect 3. However, differences in mat thickness among zones (Fig. 10) were not statistically significant ( $p = 0.98$ ).

In the wet season, the smallest mat thickness ( $41.2 \pm 7.6$ ) was recorded along transect 5 (Fig. 9), and the differences in mat thickness among transects were significant ( $p = 0.003$ ). Transect 5 had a significantly smaller mat thickness compared to transects 1 and 3, but there was no significant difference in mat thickness between transects 1 and 3. There were no significant differences in mat thickness between zones ( $p = 0.18$ ). Although the mean mat thickness (cm) reduced in all zones, the variation of mat thickness in the central zone (II) increased (Fig. 10).

The increased variability in the central zone is mostly likely explained by larger differences in topography compared to the other two zones. Headley and Tanner (2006) proposed that variability in mat thickness can be influenced by the productivity of the plants. This is a likely driver of mat thickness variation for our system. For instance, we observed that transect 1 which is the closest to the largest inlet culvert, had a larger mat thickness compared to transects 3 and 5 in both seasons. This could be because plant roots along transects 1 have more frequent interaction with inflowing water compared to those along transects 3 and 5.

#### 3.4.2. Patterns of free water column in the wetland system

The largest variation in free water column in the dry season was along transect 1 ( $98.2 \pm 34.5$ ), and the lowest value of free water column (67.9) was also along transect 1 (Fig. 9). There was no significant difference in the means of free water column between transects ( $p = 1$ ) in the dry season. However, the free water column was significantly different among zones with  $p = 0.003$  (Fig. 10). Dunn's post hoc test



**Fig. 11.** Relationship between changes in mat thickness and changes in free water column between the two seasons; red points are outliers at transect edges.

revealed that zone 1 had a significantly lower water column compared to zones 2 and 3.

In the wet season, there were no significant differences in free water column between the transects ( $p = 0.32$ ) nor were there significant differences in water column between zones ( $p = 0.53$ ). Over all, free water column increased from the dry to wet season along all transects and in all zones. The highest increment in free water column occurred in zone 1 which initially had low free water column compared to zones 2 and 3 (Table 1).

The mechanism for the mat compression is driven by the force of the rising water against the weight of the plant system. This adaptation to water level rise could be unique to papyrus compared to other tropical wetland species. For example, papyrus is more buoyant and compressible because it has a loosely intertwined mat compared to the thick and tightly intertwined mat of *Miscanthidium* (Azza et al., 2000). The buoyancy of the papyrus mat, similar to that observed in fen mats (Stofberg et al., 2016) is because the rhizomes and spaces within the mat are filled with air (Kipkemboi et al., 2002).

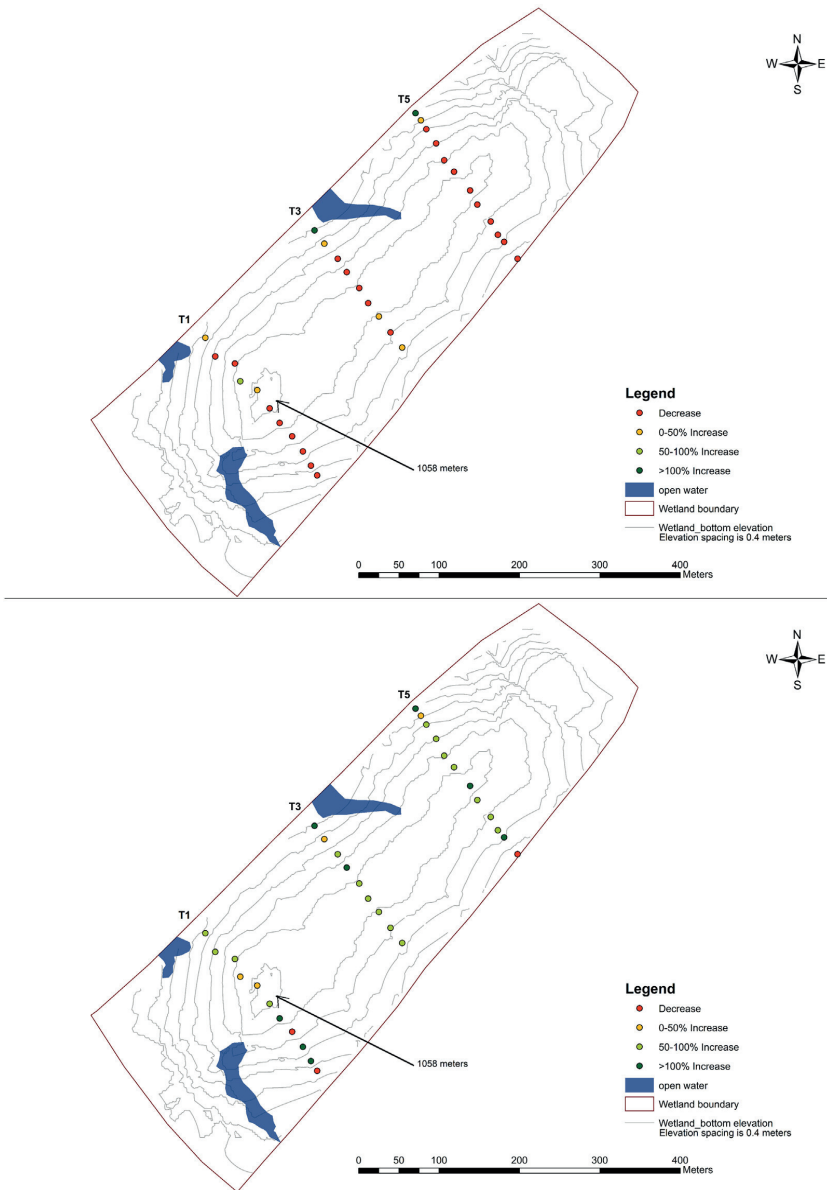


Fig. 12. Percentage change in mat thickness (top), and free water column (bottom) from the dry to the wet season.

However, the mat compression implies less water flowing through the mat, which could also have implications on the wetland's purification function. This is because nitrogen and faecal coliform uptake by papyrus is enhanced by the interaction of water with the papyrus root mat (Kansiime and Nalubega, 1999), which could be reduced if the mat is highly compressed.

### 3.5. Correlation between mat thickness and free water column

There was a weak but significant correlation between mat thickness and free water column in the dry season ( $r = -0.46, p = 0.016$ ) but no significant relationship was found between the two variables in the wet season ( $r = -0.14, p = 0.47$ ). We found a strong negative correlation between percentage changes in mat thickness and free water column between the two seasons ( $r = -0.85, p = 0.00$ ), with a coefficient of determination of 69% (Fig. 11).

The outliers in Fig. 11 are values recorded at the railway edge of transects 3 and 5 (upper right corner), and on the highway edge of transects 1 and 5 (lower left corner). Emergent vegetation was observed in these areas, which indicates that the response of the papyrus mat to changes in the water column is affected by edge effects (Turner et al., 2001) and differs among rooted and floating papyrus.

For instance, the mat on the highway edge sinks in the wet season, probably due to the increased water velocity and sediment trapped by the mat at the inlet. In contrast, the papyrus mat at the railway edge responds to increasing water column by expanding as opposed to compressing. This could be because more water flows through the loose mat at the railway edge in the wet season, causing it to expand.

Although there was a high coefficient of determination (69%) explaining the correlation between changes in mat thickness and free water column, there are other factors that could influence mat thickness at different places within the wetland such as flow direction and velocity, fishing, papyrus harvesting, as well as age of the plant among others.

### 3.6. Spatial variation in mat thickness and free water column changes between seasons

Fig. 12 illustrates the spatial variation in percentage changes of mat thickness and water column changes from dry to wet season. There was an increase in water column in the wet season for all transects except for the outliers identified in Section 3.5. Increases in water column that were less than 50% had a corresponding increase in mat thickness whereas increases in water column higher than 50% caused a reduction in mat thickness (Fig. 12). We hypothesized that increase in depth of the free water column in the wet season causes the papyrus root mat to compress. However, our results show that the response of the papyrus mat to increasing depth of the free water column is variable. The mat thickness can increase or decrease depending on the rate of increase of the free water column.

This result indicates that water flows through the mat at initial stages of water level rise. The increase in mat thickness is most likely due to water pushing its way through the mat's interstitial spaces. It is only after the increase in water column exceeds 50% of its initial depth that the mat begins to compress.

Transect 5 had a higher percentage of points with reduced mat thickness (83%) compared to transect 1 (67%) and 3 (56%). For transect 1, the mat thickness was reduced at all points except in the deepest part of the wetland. This could be related to the wetland's bathymetry and the resulting flow pattern during the wet season that may exert less pressure on the overlying papyrus mat in the deep parts (Transect 1) than the shallow areas (Transect 5). This reflects differences in the available space for water storage in different parts of the wetland.

Our research reveals that in addition to the vertical movement of the papyrus mat with increasing water levels (Headley and Tanner, 2006; Kansiime et al., 2007; Kipkemboi et al., 2002) the mat has the ability to compress to create room for excess water. This has contributed to

an initial understanding of the papyrus mat behaviour at varying water levels. However, continued monitoring at different locations, and also during peak flow is required to understand the mat dynamics. In addition, it is important to quantify the friction effects of floating vegetation on the water velocity. This is important for estimating the storage capacity and flood mitigation potential of larger wetland systems.

## 4. Conclusion

In this paper, we demonstrated for the first time how the papyrus mat thickness is affected by changes in wetland water levels. The mat rises vertically with increasing water level and has the ability to compress by more than 50% of its initial size, which creates more space for the excess water. The observed change in water depth was 0.57 m but the corresponding change in water volume of 61,758 m<sup>3</sup> is substantial.

This is a significant wetland function since many communities in eastern Uganda as well as other countries of sub-Saharan Africa have been grappling with recurrent droughts and flooding in recent years. This coupled with rampant degradation in upstream areas has reduced food security in the region. Therefore, the storage and flood mitigation functions of papyrus wetlands provide an opportunity for adaptation to erratic and high intensity rainfall events.

It is important therefore, to recognise the opportunity that these wetlands provide for sustainable agricultural improvement as opposed to being obstacles to increasing productivity. This research contributes with knowledge on the response of the papyrus mat to water level changes, and by quantifying the wetland's storage potential in different seasons. However, we recommend additional research to understand the water level threshold for maintaining the wetland's natural hydrology because this would inform sustainable wetland use.

## Acknowledgement

This work was funded by the 'Norwegian Programme for Capacity Development in Higher Education and Research for Development (NORHED)'; Grant number: 3303010034. The funding is through the 'Regional Capacity Building for Sustainable Natural Resource Management and Agricultural Improvement under Climate Change (CAPSNAC)' Project housed at Makerere University, Uganda.

We appreciate Dr. Opio Alfonse, Mr. Bright Twesigye and Mr. Kukutu Solomon for their assistance in the data collection exercise in the Naigombwa wetland.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.06.087>.

## References

- Acreman, M., Holden, J., 2013. How wetlands affect floods. *Wetlands* 33:773–786. <https://doi.org/10.1007/s13157-013-0473-2>.
- Azza, N.G.T., Kansiime, F., Nalubega, M., Denny, P., 2000. Differential permeability of papyrus and Miscanthidium root mats in Nakivubo Swamp, Uganda. *Aquat. Bot.* 67: 169–178. [https://doi.org/10.1016/S0304-3770\(00\)00093-0](https://doi.org/10.1016/S0304-3770(00)00093-0).
- Boar, R.R., 2006. Responses of a fringing *Cyperus papyrus* L. swamp to changes in water level. *Aquat. Bot.* 84:85–92. <https://doi.org/10.1016/j.aquabot.2005.07.008>.
- COWI, 2010. Operationalisation of Catchment-Based Water Resources Management Kampala.
- van Dam, A.A., Dardona, A., Kelderman, P., Kansiime, F., 2007. A simulation model for nitrogen retention in a papyrus wetland near Lake Victoria, Uganda (East Africa). *Wetl. Ecol. Manag.* 15:469–480. <https://doi.org/10.1007/s11273-007-9047-5>.
- van Dam, A.A., Kipkemboi, J., Mazvimavi, D., Irvine, K., 2014. A synthesis of past, current and future research for protection and management of papyrus (*Cyperus papyrus* L.) wetlands in Africa. *Wetl. Ecol. Manag.*:99–114 <https://doi.org/10.1007/s11273-013-9335-1>.
- Donaldson, L., Woodhead, A.J., Wilson, R.J., Maclean, I.M., 2016. Subsistence use of papyrus is compatible with wetland bird conservation. *Biol. Conserv.* 201:414–422. <https://doi.org/10.1016/j.biocon.2016.07.036>.
- Headley, T.R., Tanner, C.C., 2006. Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review (New Zealand).



- Huertos, M.L., Smith, D., 2013. Wetland bathymetry and mapping. In: Anderson, J., Davis, C. (Eds.), *Wetland Techniques*. Springer:pp. 49–86 [https://doi.org/10.1007/978-94-007-6860-4\\_2](https://doi.org/10.1007/978-94-007-6860-4_2).
- Jones, M., Humphries, S., 2002. Impacts of the C4 sedge *Cyperus papyrus* L. on carbon and water fluxes in an African wetland. *Hydrobiologia* 488:107–113. [https://doi.org/10.1007/978-94-017-2031-1\\_10](https://doi.org/10.1007/978-94-017-2031-1_10).
- Kansiime, F., Nalubega, M., 1999. *Wastewater Treatment by a Natural Wetland: The Nakivubo Swamp, Uganda. Processes and Implications*. (PhD Thesis), Wageningen Agricultural University, Netherlands.
- Kansiime, F., Oryem-Origa, H., Rukwago, S., 2005. Comparative assessment of the value of papyrus and Cocoyams for the restoration of the Nakivubo wetland in Kampala, Uganda. *Phys. Chem. Earth Parts A/B/C* 30:698–705. <https://doi.org/10.1016/j.pce.2005.08.010>.
- Kansiime, F., Sanders, M.J., Loisella, S.A., 2007. Functioning and dynamics of wetland vegetation of Lake Victoria: an overview. *Wetl. Ecol. Manag.* 15:443–451. <https://doi.org/10.1007/s11273-007-9043-9>.
- Kigobe, M., McIntyre, N., Wheeler, H., Chandler, R., 2011. Multi-site stochastic modelling of daily rainfall in Uganda. *Hydrol. Sci. J.* 56:17–33. <https://doi.org/10.1080/02626667.2010.536548>.
- Kigobe, M., Wheeler, H., McIntyre, N., 2014. Statistical downscaling of precipitation in the upper Nile: use of generalized linear models (GLMs) for the Kyoga Basin. In: Melesse, A.M., Abtew, W., Setegn, S.G. (Eds.), *Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics*. Springer International Publishing, Cham: pp. 421–449. [https://doi.org/10.1007/978-3-319-02720-3\\_22](https://doi.org/10.1007/978-3-319-02720-3_22).
- Kipkemboi, J., van Dam, A.A., 2016. Papyrus wetlands. In: Finlayson, C.M., Milton, G.R., Prentice, R.C., Davidson, N.C. (Eds.), *The Wetland Book: II: Distribution, Description and Conservation*. Springer Netherlands, Dordrecht:pp. 1–15. [https://doi.org/10.1007/978-94-007-6173-5\\_218-1](https://doi.org/10.1007/978-94-007-6173-5_218-1).
- Kipkemboi, J., Kansiime, F., Denny, P., 2002. The response of *Cyperus papyrus* (L.) and *Miscanthidium violaceum* (K. Schum.) Robyns to eutrophication in natural wetlands of Lake Victoria, Uganda. *Afr. J. Aquat. Sci.* 27:11–20. <https://doi.org/10.2989/16085914.2002.9626570>.
- Liu, Z., Chen, Y., Wu, Y., Wang, W., Li, L., 2017. Simulation of exchange flow between open water and floating vegetation using a modified Rng K-E turbulence model. *Environ. Fluid Mech.* 17:355–372. <https://doi.org/10.1007/s10652-016-9489-5>.
- Mburu, N., Rousseau, D.P.L., van Bruggen, J.J.A., Lens, P.N.L., 2015. Use of the macrophyte *Cyperus papyrus* in wastewater treatment. In: Vymazal, J. (Ed.), *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape*. Springer International Publishing, Cham:pp. 293–314. [https://doi.org/10.1007/978-3-319-08177-9\\_20](https://doi.org/10.1007/978-3-319-08177-9_20).
- Morrison, E.H., Upton, C., Pacini, N., Odhiambo-K'oyoo, K., Harper, D.M., 2013. Public perceptions of papyrus: community appraisal of wetland ecosystem services at Lake Naivasha, Kenya. *Ecohydrol. Hydrobiol.* 13:135–147. <https://doi.org/10.1016/j.ecohyd.2013.03.008>.
- Okurut, T.O., 2000. *A Pilot Study on Municipal Wastewater Treatment Using a Constructed Wetland in Uganda*. (PhD Thesis), Wageningen University, Netherlands.
- Opio, A., Jones, M., Kansiime, F., Otiiti, T., 2014. Growth and development of *Cyperus papyrus* in a tropical wetland. *Open J. Ecol.* 4:113–123. <https://doi.org/10.4236/oje.2014.43013>.
- Ryken, N., Vanmaercke, M., Wanyama, J., Isabiry, M., Vanonckelen, S., Deckers, J., Poesen, J., 2015. Impact of papyrus wetland encroachment on spatial and temporal variabilities of stream flow and sediment export from wet tropical catchments. *Sci. Total Environ.* 511:756–766. <https://doi.org/10.1016/j.scitotenv.2014.12.048>.
- Saunders, M.J., Jones, M.B., Kansiime, F., 2007. Carbon and water cycles in tropical papyrus wetlands. *Wetl. Ecol. Manag.* 15:489–498. <https://doi.org/10.1007/s11273-007-9051-9>.
- Saunders, M.J., Kansiime, F., Jones, M.B., 2012. Agricultural encroachment: implications for carbon sequestration in tropical African wetlands. *Glob. Chang. Biol.* <https://doi.org/10.1111/j.1365-2486.2011.02633.x>.
- Saunders, M.J., Kansiime, F., Jones, M.B., 2013. Reviewing the carbon cycle dynamics and carbon sequestration potential of *Cyperus papyrus* L. wetlands in tropical Africa. *Wetl. Ecol. Manag.* 21. <https://doi.org/10.1007/s11273-013-9314-6>.
- Schlumberger Water Services, 2014. *Diver Manual*.
- Stofberg, S.F., van Engelen, J., Witte, J.-P.M., van der Zee, S.E., 2016. Effects of root mat buoyancy and heterogeneity on floating fen hydrology. *Ecohydrology* 9:1222–1234. <https://doi.org/10.1002/eco.1720>.
- Terer, T., Triest, L., Muasya, A.M., 2012. Effects of harvesting *Cyperus papyrus* in undisturbed wetland, Lake Naivasha, Kenya. *Hydrobiologia* 680:135–148. <https://doi.org/10.1007/s10750-011-0910-2>.
- Terer, T., Muasya, A.M., Higgins, S., Gaudet, J.J., Triest, L., 2014. Importance of seedling recruitment for regeneration and maintaining genetic diversity of *Cyperus papyrus* during drawdown in Lake Naivasha, Kenya. *Aquat. Bot.* 116:93–102. <https://doi.org/10.1016/j.aquabot.2014.02.008>.
- Turner, M.G., Gardner, R.H., O'Neill, R.V., 2001. *Landscape Ecology in Theory and Practice: Pattern and Process*. Springer science + Business media.
- Zhang, X., Neph, H.M., 2011. Exchange flow between open water and floating vegetation. *Environ. Fluid Mech.* 11:531. <https://doi.org/10.1007/s10652-011-9213-4>.

# PAPER III



# Characterising the hydrological regime of a tropical papyrus wetland in the Lake Kyoga Basin, Uganda

Ellen Jessica Kayendeke<sup>1,2</sup> and Helen K French<sup>1</sup>

1. Faculty of Environmental Sciences and Natural Resource Management ,  
Norwegian University of Life Sciences, Box 5003, 1430 Aas, Norway

2. Department of Environmental Management, Makerere University, Box 7062,  
Kampala Uganda

## **Abstract**

Papyrus wetlands are predominant in permanently flooded areas of Sub-Saharan Africa, covering approximately 40,000 km<sup>2</sup> in East and Central Africa. Previous studies have quantified and valued ecosystem services of these wetlands but there is still a need to understand the key processes of the wetlands' hydrology. The study objective was to quantify the seasonal variations in water balance and retention time of a papyrus wetland section. Discharge measurements were carried out to quantify channel flow in upstream and downstream parts of the wetland section. Groundwater fluxes were estimated using borehole triangulation of groundwater levels, while precipitation and other climatic variables for estimating evapotranspiration were monitored using an automatic weather station located 1 km from the study site. The retention time of the wetland section was estimated from tracer experiments, and by calculating the volume-discharge ratio. Results show that the water balance of the section is dominated by wetland channel flow, contributing approximately 99.7% of the total inputs while precipitation and groundwater discharge contribute approximately 0.2% and <0.1% respectively. Estimated retention time varied between 2 hours and 7 days during periods of high and low flows, respectively. The groundwater gradient showed flow towards the wetland throughout the monitoring period, with average gradients of 0.0074 and 0.0043 on the western and eastern edges of the wetland, respectively. Since wetland channel flow is dominant, the wetland's hydrology is vulnerable to land cover changes and resultant changes in surface runoff from the upstream catchment. Further research on impacts of land use changes within the upstream catchment on wetland channel flow is recommended.

Key words: Papyrus wetland, water balance, retention time

## 1. Introduction

Papyrus wetlands are predominant in permanently flooded areas of East and Central Africa. Their extent is not known but estimates range from 20,000 to 85,000 km<sup>2</sup>. They are dominated by papyrus (*Cyperus papyrus* L.), which is a herbaceous sedge that can grow up to five meters (Kipkemboi & van Dam, 2018). Papyrus can grow firmly rooted at water edges or in water logged areas but is physically adapted to flooded areas because its culms and rhizomes have large quantities of air filled plant tissue (Kipkemboi & van Dam, 2018; Mburu *et al.*, 2015), which enables it to form floating mats in permanently inundated areas (Figure 1). This ability gives papyrus a competitive advantage over other aquatic plants that are less adapted to permanent flooding (Kipkemboi & van Dam, 2018). The floating mats are made up of interconnected roots, rhizomes and organic matter (Azza *et al.*, 2000). The plants spread through both rhizome propagation and seed germination (Gaudet, 1977; Terer *et al.*, 2014), and thrive in low energy environments where wind velocity and water level fluctuations are moderate (Mburu *et al.*, 2015; Morrison *et al.*, 2013; Terer *et al.*, 2012).



Figure 1: Floating papyrus wetland in Eastern Uganda, with open water at inlet culvert. The depth of the water column beneath the papyrus mat varies between 1 to 2 meters

Papyrus wetlands provide several goods and services like food (fish and crops at wetland edges), fuel wood, raw materials for crafts and building, and water for domestic and irrigation use. In addition, they have various regulatory functions including carbon storage, flood mitigation and water purification (Donaldson *et al.*, 2016; Mburu *et al.*, 2015; Saunders *et al.*, 2013; Terer *et al.*, 2014; van Dam *et al.*, 2007). The potential of papyrus wetlands in removal of faecal coliforms and nutrients from water has been documented (Kansiime & Nalubega, 1999; Kyambadde *et al.*, 2004; Mburu *et al.*, 2015; Okurut, 2000). For example, measured values of nitrogen uptake for papyrus wetlands fringing Lake Victoria vary between  $0.047 \text{ g N m}^{-2} \text{ d}^{-1}$  and  $0.21 \text{ g N m}^{-2} \text{ d}^{-1}$  (Gaudet, 1977; Kansiime & Nalubega, 1999; van Dam *et al.*, 2007) while estimated carbon uptake varies between  $0.48 \text{ kg C m}^{-2} \text{ y}^{-1}$  and  $1.6 \text{ kg C m}^{-2} \text{ y}^{-1}$  (Jones & Humphries, 2002; Saunders *et al.*, 2007). The nutrients and carbon are removed permanently from the wetland system when the papyrus plant is harvested (Kansiime *et al.*, 2007).

Despite their provisioning and regulatory functions, papyrus wetlands in East Africa are not protected due to poor implementation of existing laws, and are managed by neighbouring communities according to their livelihood needs. Activities in the wetlands are often unregulated, which has led to over exploitation and permanent conversion of the wetlands for agricultural activities. Estimates of papyrus loss within the East African region range from 0.5 to 5% per annum (Kipkemboi & van Dam, 2018; van Dam *et al.*, 2014), whereas Uganda had a 30% loss in total wetland area between 1994 and 2009 (Turyahabwe *et al.*, 2013; WMD, 2009).

Research on papyrus wetlands until now has mainly dealt with: water purification potential; economic value of ecosystem services; papyrus biomass and reproduction; carbon storage; and fish production among others (Emerton *et al.*, 1999; Gaudet, 1977; Jones & Humphries, 2002; Kansiime & Nalubega, 1999; Opio *et al.*, 2014; Saunders *et al.*, 2013; Ssanyu *et al.*, 2014; Terer *et al.*, 2014). Nonetheless there is still a need to identify the key processes of the wetlands' hydrology since this would aid with designing suitable management options (Rasmussen *et al.*, 2018; van Dam *et al.*, 2014).

The overall study objective was to quantify the seasonal variations in the water balance of a papyrus wetland section and the specific objectives were: (i) to identify the main components of the wetland's water budget; and (ii) to estimate the wetland's retention time in the dry and wet seasons. The hypothesis was that the hydrological regime including retention time is driven by flow in the main channel; with discharge fluctuations mirroring seasonal rainfall variations, and highest retention time occurring in periods of low flows.



## 2. Materials and methods

### 2.1. Description of the study site

This study was carried out in a section of the Naigombwa wetland, located within the Mpologoma River basin in Eastern Uganda (Figure 2a). The Mpologoma basin is approximately 8,900 km<sup>2</sup> and is part of the Nile basin. Mpologoma River has four tributaries including Namatala, Manafwa, Malaba and Naigombwa rivers. The rivers have vast expanses of papyrus vegetation, which forms floating mats in permanently flooded areas but is rooted at river edges. These rivers are referred to as wetlands from here on, following the hydrogeomorphic classification scheme for wetlands (Semeniuk & Semeniuk, 1995; Semeniuk & Semeniuk, 1997). The upstream areas of these wetlands have been extensively drained for agricultural expansion, and the natural wetland vegetation has been replaced with rice farms (Namaalwa *et al.*, 2013). In addition, the rivers are diverted through channels that provide irrigation water for rice paddies (NEMA, 2008).

The mean annual rainfall and temperature from historical records (1961–1990) of stations in the Mpologoma basin is 1300 mm distributed between two rainy seasons (March to May and September to November) and 21°C, respectively (Kigobe *et al.*, 2014). We define the onset of the rainy season as the first of two or more consecutive days of at least 1 mm of rainfall each, whose total is greater than 20 mm and less than 5 consecutive dry days in subsequent days (MacLeod, 2018).

The main land use in the catchment is subsistence agriculture, with crops like maize, beans and cassava. The Manafwa and Malaba wetlands have large scale rice irrigation schemes, but small scale rice farms were also started immediately downstream of the irrigation schemes. Upstream areas of Namatala and Naigombwa wetlands have also been converted for small scale rice farming.

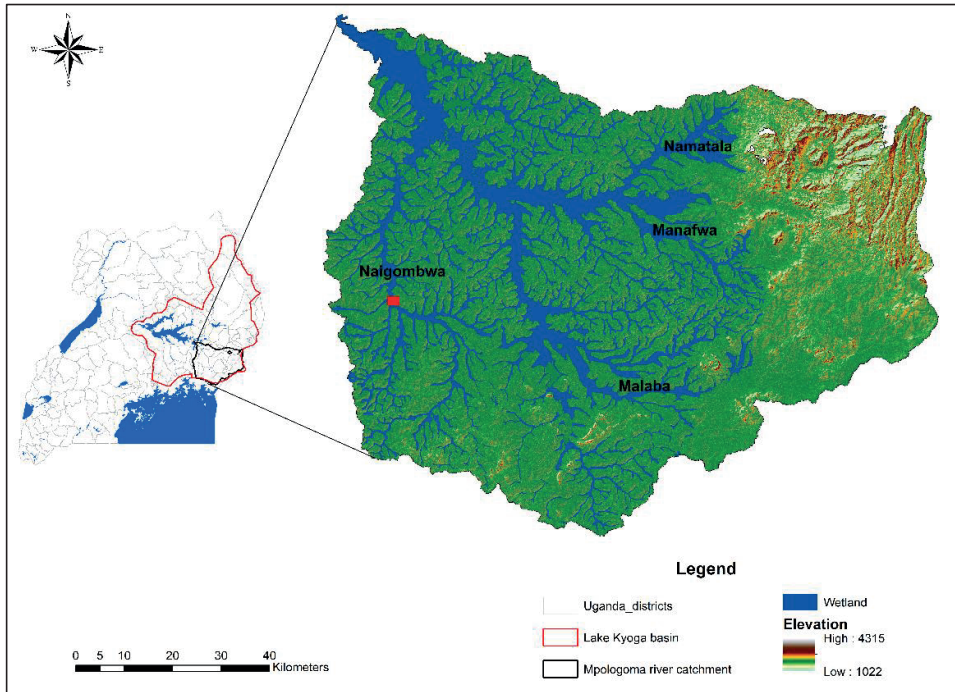


Figure 2a: The Mpologoma river basin of Eastern Uganda. The red square shows location of the study site along the Naigombwa wetland

The Naigombwa wetland is located in Iganga District, and drains northwards into the Mpologoma River (Figure 2a). The Naigombwa sub-catchment is relatively flat with elevation varying from 1056 to 1348 meters above sea level, and the soils are mainly ferralitic with reddish brown sandy loams. The main land use is subsistence agriculture and common crops include maize, beans, cassava, and sweet potatoes among others.

Our study section was chosen because it is demarcated by a highway and railway line which improves accessibility to the wetland (Figure 2b). In addition, major inflows and outflows in culverts of the two causeways can be quantified more easily. The wetland section has an area of 0.18 km<sup>2</sup> and drains an area of 734 km<sup>2</sup>. The groundwater divide for this wetland section is assumed to coincide with the topography, and is at approximately 250 m and 170 m from the western and eastern edges of the wetland, respectively. Therefore, the groundwater contributing area is less than 0.1 km<sup>2</sup> on both sides of the wetland (<0.02% of total catchment area). The section has one large culvert

and six small ones along the highway in the southeast, which are the main flows into the wetland. A railway line crosses the downstream end in the North West and has two large culverts for outflows. The dominant vegetation in the wetland section is papyrus although palm trees, and a variety of grasses are present at the edges of the wetland. Less than 1% of the total wetland section is open water, which occurs near inlets and outlets (Figure 2b).



Figure 2b: The instrumented section of the wetland along Naigombwa River; bright red stars represent locations of automatic water divers

## 2.2. Description of instrumentation at wetland site

We installed six shallow groundwater monitoring wells, three on either side of the wetland section (Figure 2b) to monitor groundwater responses to rainfall and wetland level changes. The wells were also used to calculate the direction of groundwater flow and its gradient relative to the wetland water level. Soil characteristics at the borehole locations are illustrated in Figure 3.

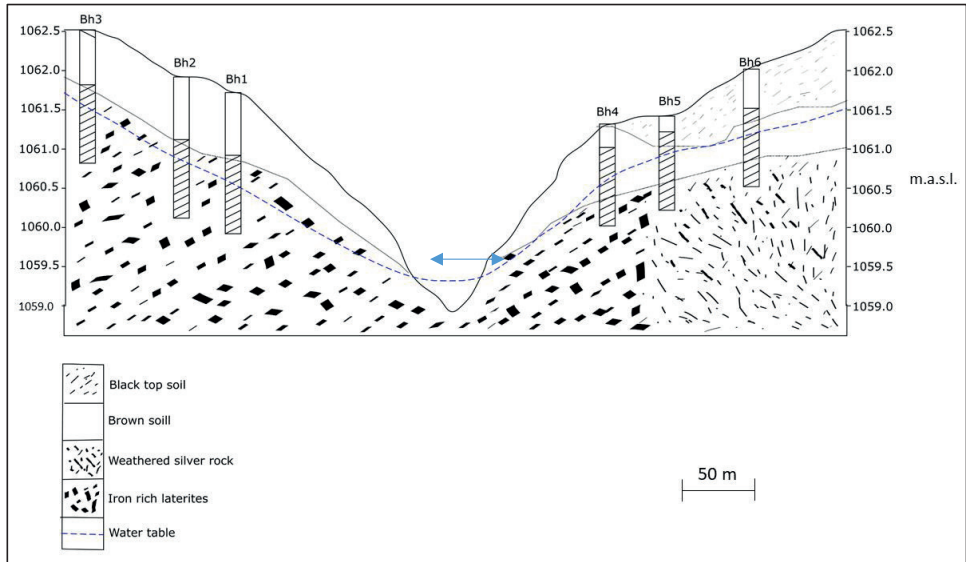


Figure 3: Vertical section through the wetland and its edges, showing soil characteristics at wetland edges where boreholes were installed. Note that the wetland channel (blue double arrow) is simplified in the illustration but actual width is about 700m

The borehole depths ranged from 1.21 to 1.81 meters below ground level (Table 1). The screen length and diameter for all boreholes were 1 m and 0.051 m respectively. We estimated hydraulic conductivity by conducting both falling head (July 2015) and rising head (January 2016) slug tests. We used the Bouwer and Rice (1976) equation to calculate saturated hydraulic conductivity;

$$K_s = \frac{r_c^2 \ln(R_e/r_w)}{2L} \frac{1}{t} \ln \frac{y_0}{y_t} \quad (1)$$

where  $K_s$ =saturated hydraulic conductivity,  $r_c$ =radius of the casing,  $R_e$ =effective radius,  $r_w$ =horizontal distance from well centre to undisturbed aquifer (the width of the backfill material was measured using a tape measure),  $L$ =height of well screen,  $t$ =time,  $y_0$ =water level at initial time,  $y_t$ =water level at time  $t$

The units of the calculated hydraulic conductivity were converted to meters per day ( $\text{md}^{-1}$ ) to correspond to units of other water balance components. The calculated conductivities are lower than estimates by Owor *et al.* (2011) for boreholes at the

southern shores of Lake Kyoga ( $0.4 - 15 \text{ md}^{-1}$ ). However, the low values can be attributed to the presence of material that was deposited during construction of railway line. Similar values ( $< 0.02 \text{ md}^{-1}$ ) were estimated for a site that is close to a railway pier on the northern shore of Lake Victoria (Owor *et al.*, 2011).

Table 1: Borehole logs and saturated hydraulic conductivity ( $K_s$ )

Location	Site	Elevation (masl <sup>1</sup> )	Depth (mbgl <sup>2</sup> )	Geologic unit	K (m/s)	K (m/d)
<b>Western side of wetland edge</b>	Bh1	1061.7	1.81	Clay loam, laterite	3.4E-7	2.9E-2
	Bh2	1061.9	1.69	Clay loam, laterite	5.0E-8	4.0E-3
	Bh3	1062.5	1.73	Clay loam, laterite	1.3E-7	1.1E-2
<b>Eastern side of wetland edge</b>	Bh4	1061.3	1.29	Clay loam, laterite	1.2E-7	1.0E-2
	Bh5	1061.4	1.21	Black top soil, clay loam, weathered silver rock	3.2E-6	2.8E-1
	Bh6	1062	1.53	Black top soil, clay loam, weathered silver rock	2.3E-7	2.0E-2

<sup>1</sup>Ground surface elevation, meters above sea level

<sup>2</sup>meters below ground level

Staff gauges were installed near the main inlet culvert of the highway and outlet culverts at the railway to monitor wetland levels during the study period (Figure 2b). Water velocity measurements were carried out by staff of the Directorate of Water Resources Management (DWRM) five times over a 10 month period, spread out during periods of low and high flows. Since this method requires open water surface, measurements were done at all inlet and outlet culverts where there is a free water surface (Figure 2b).

The measurements were done using an OTT current meter except the measurements on July 2015, which were done using an acoustic Doppler current profiler (ADCP). The wetland stage was recorded on all measurement dates. In addition the width and depth of water in the culverts were measured to calculate the effective cross-sectional area. The rating equation, which provides a relationship between wetland stage and discharge for this particular section of the wetland was derived by DWRM staff using

Hydata software (Institute of Hydrology, 1992), based on discharge measurements and corresponding gauge readings.

We obtained data on precipitation, air temperature, wind speed, relative humidity, and dew point temperature from a weather station (model: Davis Vantage Vue 6250) located approximately 1 km from the wetland section. The climate data was logged at 30 minute intervals. We also monitored variations in water depth at the wetland centre (Figure 2b) at 30 minute intervals using automatic divers (supplier: Geonor AS, model: Micro-Diver DI6). The elevation and shape of the wetland bottom was surveyed in January 2016. Table 2 shows the duration of monitoring for the different datasets.

Table 2: Monitoring datasets at the wetland site

<i>Data sets</i>	<b>Time period</b>																			
	<b>2015</b>										<b>2016</b>									
	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
<i>Climate</i>			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Wetland stage</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Groundwater l.</i>		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>Discharge<sup>1</sup></i>	x		x		x			x		x										
<i>Survey of wetland bathymetry</i>									x											
<i>Water depth</i>									x	x	x	x	x	x	x	x	x	x	x	x

<sup>1</sup>No discharge measurements done after February 2016 because of construction works on culverts

## 2.3. Estimation of water balance components

### 2.3.1. Conceptual model of water balance for the wetland section

We calculated a monthly water balance for the wetland section (0.18 km<sup>2</sup>) by considering major flows in and out of the section (equation 2). The conceptual water balance for the wetland section is illustrated in Figure 4.

$$ds/dt = Q_{in} + P + Q_{g_{in}} + Q_f - Q_{out} - ET - e \text{ (all terms in m}^3\text{/day)} \quad (2)$$

where  $ds/dt$  = change in storage,  $Q_{in}$  = channel inflow,  $P$  = precipitation,  $Q_{g_{in}}$  = Groundwater discharge,  $Q_f$  = overland flow from edges of wetland section,  $Q_{out}$  = channel outflow,  $ET$  = evapotranspiration,  $e$  = residual error

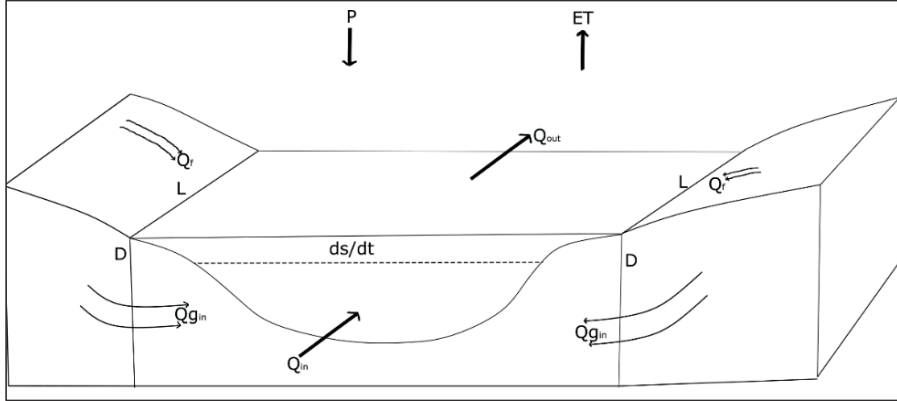


Figure 4: Vertical section through the wetland section perpendicular to the main flow direction, illustrating the water balance components of the wetland section

Daily precipitation was recorded at the weather station. We assumed that overland flow from edges of wetland section ( $Q_f$ ) was negligible due to the small size of the wetland section, therefore it was excluded from the calculations. Surface flows from the upstream catchment area are included in channel inflow calculations ( $Q_{in}$ ). The water balance was calculated for a period of 8 months, from July 2015 to February 2016 because there were no discharge measurements beyond February 2016 (Table 2).

### 2.3.2. Groundwater gradient and direction

Groundwater discharge  $Q_{g_{in}}$  [ $m^3d^{-1}$ ] from the wetland edges was calculated using Darcy's law as shown in equation 3;

$$Q_{g_{in}} = -K_s A \frac{dh}{dl} \quad (3)$$

where  $Q_{g_{in}}$  = Groundwater discharge [ $m^3d^{-1}$ ],  $K_s$  = saturated hydraulic conductivity [ $md^{-1}$ ],  $A$ =cross sectional area [ $m^2$ ],  $dh/dl$ =hydraulic gradient

The saturated hydraulic conductivities ( $K_s$ ) for individual boreholes (Table 1) were averaged on each side of the wetland, which gave an average value of  $0.015\text{md}^{-1}$  and  $0.104\text{md}^{-1}$  for the west and east side of the wetland respectively. The cross sectional area ( $A$  [ $\text{m}^2$ ]) perpendicular to the direction of flow was calculated by multiplying the length of wetland edge ( $L= 258\text{m}$  and  $174\text{m}$  on the west and east sides, respectively) with an estimated depth ( $D=9\text{m}$ ) of the unconfined aquifer (Figure 4). The depth of the unconfined aquifer was estimated from local borehole logs, which show that the average depth to bedrock is 9 m below the ground surface. We calculated daily values of the magnitude and direction of hydraulic gradient [ $dh/dl$ ] from the groundwater time series data using the 3 point estimation tool (3PE) as described by Beljin *et al.* (2014).

### 2.3.3. Estimation of flow in the main channel

Wetland channel inflow ( $Q_{\text{in}}$ ) and outflow ( $Q_{\text{out}}$ ) through the culverts were estimated using the rating equations derived from discharge measurements and corresponding gauge measurements (equations 4 and 5 respectively).

$$Q_{\text{in}} = 6.03 (H_1 + 0.096)^{2.8} \quad (4)$$

$$Q_{\text{out}} = 8.75 (H_2 - 0.648)^{2.8} \quad (5)$$

where  $Q_{\text{in}}$  = channel inflow ( $\text{m}^3/\text{d}$ ),  $Q_{\text{out}}$  = channel outflow ( $\text{m}^3/\text{d}$ ),  $H_1$  = stage at inlet (m),  $H_2$  = stage at outlet (m) (average of two outlets)

We estimated flow in the causeways (highway and railway) by using Darcy's law and assuming saturated hydraulic conductivity and hydraulic gradients in the same order of magnitude as those observed at wetland edges. The contributing area was calculated from the length of the causeway multiplied by the height of the water level near the causeways. Based on these assumptions, this flow was much smaller than groundwater flow from the wetland edges ( $<0.1\%$ ). We therefore assumed for the water balance calculations, that all channel flow into and out of the wetland section was directed through the culverts.



### 2.3.4. Estimation of evapotranspiration

Evapotranspiration was estimated using a modification of the FAO 56 Penman-Monteith equation, which calculates a reference evapotranspiration for alfalfa (Zotarelli *et al.*, 2010);

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (6)$$

where  $ET_{sz}$  = reference evapotranspiration rate ( $\text{mm d}^{-1}$ ),  $\Delta$ =slope of the saturated vapour pressure curve [ $\delta e_s / \delta T$ , where  $e_s$  = saturated vapor pressure (kPa) and  $T_{\text{mean}}$  = daily mean temperature ( $^{\circ}\text{C}$ )],  $R_n$  = net radiation flux ( $\text{MJ m}^{-2} \text{d}^{-1}$ ),  $G$ = sensible heat flux into the soil ( $\text{MJ m}^{-2} \text{d}^{-1}$ ),  $\gamma$ = psychrometric constant ( $\text{kPa } ^{\circ}\text{C}^{-1}$ ),  $C_n$ = the numerator constant for the reference crop type (alfalfa) at 24 hour time step (1600),  $C_d$ =denominator constant for the reference crop type (alfalfa) at 24 hour time step (0.38),  $T$  = mean daily air temperature ( $^{\circ}\text{C}$ ),  $u_2$  = wind speed ( $\text{m s}^{-1}$ ),  $e_s$  = saturation vapour pressure (kPa),  $e_a$  = actual vapour pressure (kPa), the constant 0.4808 is a conversion factor for net radiation to mm/day

The soil heat flux ( $G$ ) is considered negligible in some heat balance studies because it is the smallest component of all the terms and also because most incoming energy into the soil is eventually lost to the atmosphere in the night as long wave radiation (Anadranistakis *et al.*, 1997; Sauer & Horton, 2005). In our study section, water is above ground level at all times and its depth varies between 1 and 2 meters, therefore we used a value of zero for the soil heat flux because we assumed soil heating mechanisms to have minimal influence on the evapotranspiration rate.

### 2.3.5. Independent estimates of wetland storage

We surveyed the wetland's bathymetry to obtain a digital elevation model (DEM), and used the acquired DEM to obtain a depth-volume relationship using ArcMap 3D analyst tools. The details of the methods used are described in Kayendeke *et al.* (2018). The goal of obtaining the depth-volume relationship was that wetland water volume could be estimated from the wetland depth data recorded at the wetland site. However, we did not have depth data from July to December 2015 since depth monitoring did not start

until January 2016 (Table 2). But since wetland stage data spans the entire monitoring period, we estimated water depth for July-December 2015 using the relationship between water depth and wetland stage. We then calculated daily nominal residence times for the wetland using a ratio of volume to channel discharge (Kadlec & Knight, 1996; Zahraeifard & Deng, 2011), to evaluate the magnitude and variation of retention time over the 8 months period.

## **2.4. Wetland flow direction and velocity**

We conducted salt tracer experiments to get information on micro scale flow dynamics within the study section using a portable Electrical Conductivity (EC) meter (Orion Star A329). The experiments were done in the dry season on the 17<sup>th</sup> and 18<sup>th</sup> of January 2017 at the main inlet culvert and in an undisturbed papyrus area (Figure 2b), respectively. At the inlet culvert, we recorded baseline electrical conductivity (EC) on both sides of the highway. The tracer was prepared by adding 500g of salt (NaCl) to 20 litres of water taken from the same wetland, and stirred until all the salt was completely dissolved. It was then released on the upstream end of the highway culvert. The EC measurements were recorded at the point of release as well as at the downstream side of the highway culvert at one minute intervals (Figure 5).

For the papyrus plot, we made 12 holes through the papyrus root mat. The holes were 0.75 m apart except the diagonals which were 1.5 m apart (Figure 5). We choose to have minimal distance between the holes since we had observed very low velocity at the inlet culvert the previous day. We went ahead with the tracer experiment despite the low flows because we wanted to understand vertical flow dynamics between the papyrus root mat and the water column beneath it. In addition, we were interested in velocity differences between the mat and water column. We recorded the baseline EC values at all points. We then prepared the tracer by adding 100 g of salt to 10 litres of water, and released it at the centre point (0) where the released tracer solution entered into the root mat as well as the free water column beneath it. We proceeded to measure EC values at all points in a clockwise spiral shape (from 0 to 12) until EC values returned to

the recorded baseline values. Individual EC measurements were taken both in the water column beneath the papyrus root mat, and within the root mat.

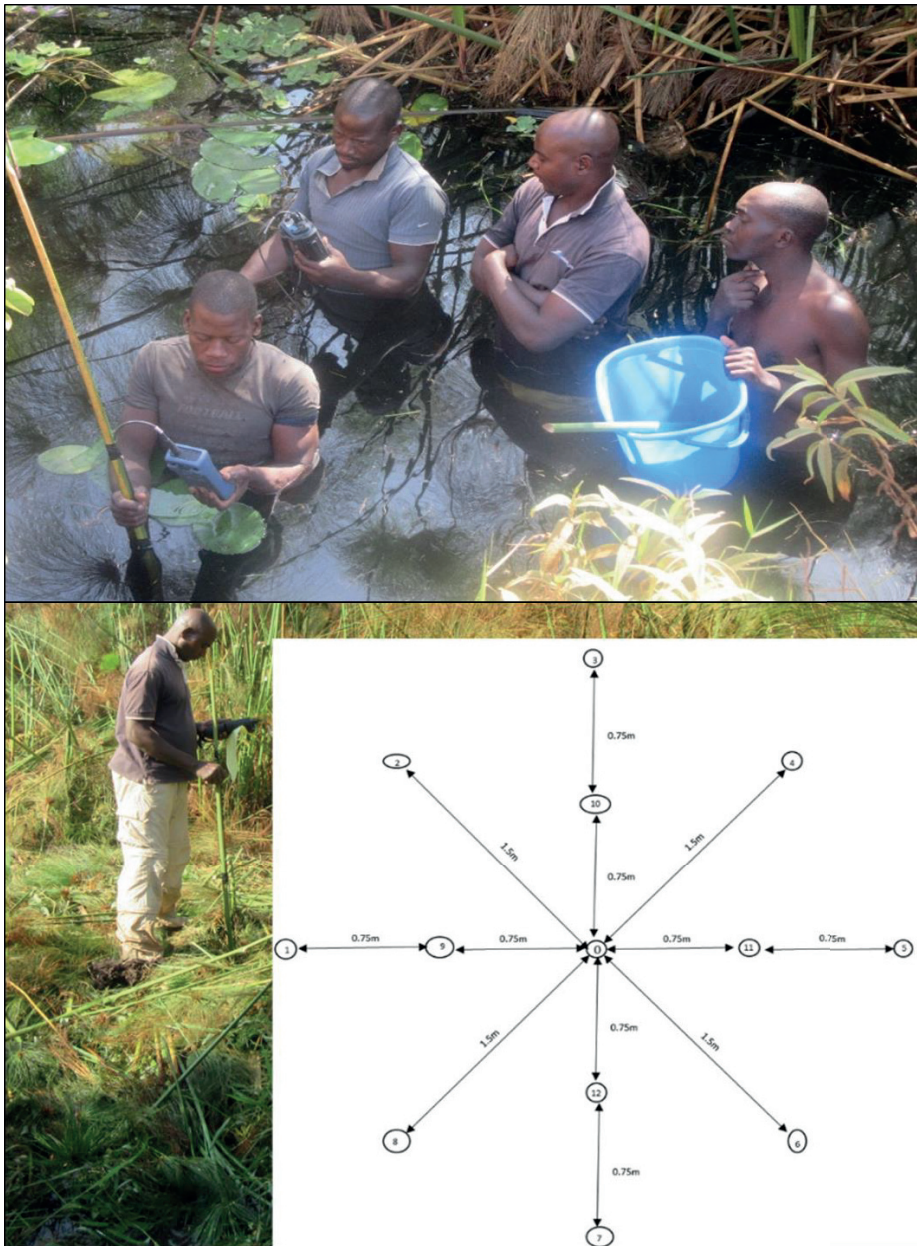


Figure 5: Top: EC measurements at the inlet culvert. Bottom: set up of experimental plot in the papyrus zone

### 3. Results and discussion

#### 3.1. Precipitation patterns

The rainfall dataset begins just before the beginning of the second rain season (September to December) of 2015. The frequency of successive rain days increased in mid-August through to the end of December, and the total rainfall amount for that season was 555 mm (Figure 6). The rainfall seasons in 2016 had lower frequency and quantity of rainfall, with the first (March to June) and second (August to October) seasons having a cumulative rainfall of 297 mm and 290 mm, respectively.

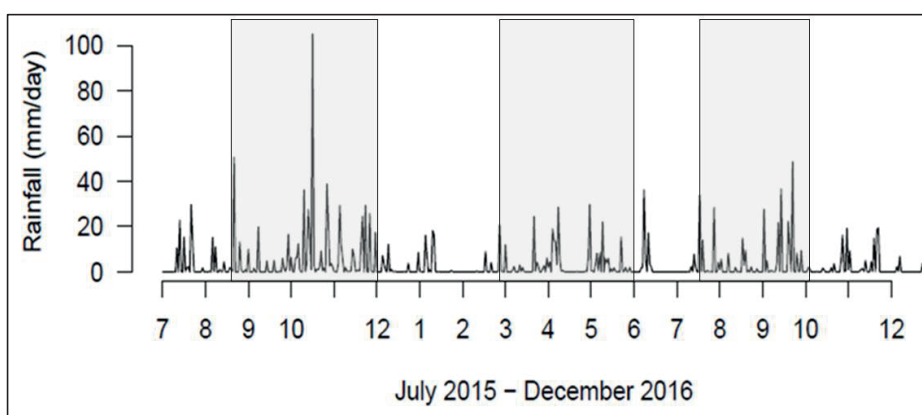


Figure 6: Observed precipitation during the monitoring period (18 months) with rain seasons in grey

#### 3.2. Groundwater gradient and direction

We observed a negative groundwater gradient towards the wetland on either side of the wetland edge throughout the monitoring period, indicating groundwater discharge into the wetland. The average hydraulic gradients were -0.0074 and -0.0043 on the western and eastern sides of the wetland, respectively (Figure 7). The gradient on the western side of the wetland was in south-eastern direction towards borehole 1, whereas on the eastern side, the gradient was in the south-western direction toward borehole 5. Despite the angular direction of flow of groundwater towards the wetland, the discharge is calculated assuming a groundwater flow perpendicular to both the wetland edge and to the flow direction in the main wetland channel. The groundwater discharge pattern towards the wetland is most likely controlled by heterogeneities in the hydrogeological

properties of the surrounding slopes, but it was neither the scope nor the resources of this study to map this spatial variability in groundwater flow pattern. It is however interesting to note that the direction is fairly constant in time on both sides of the wetland.

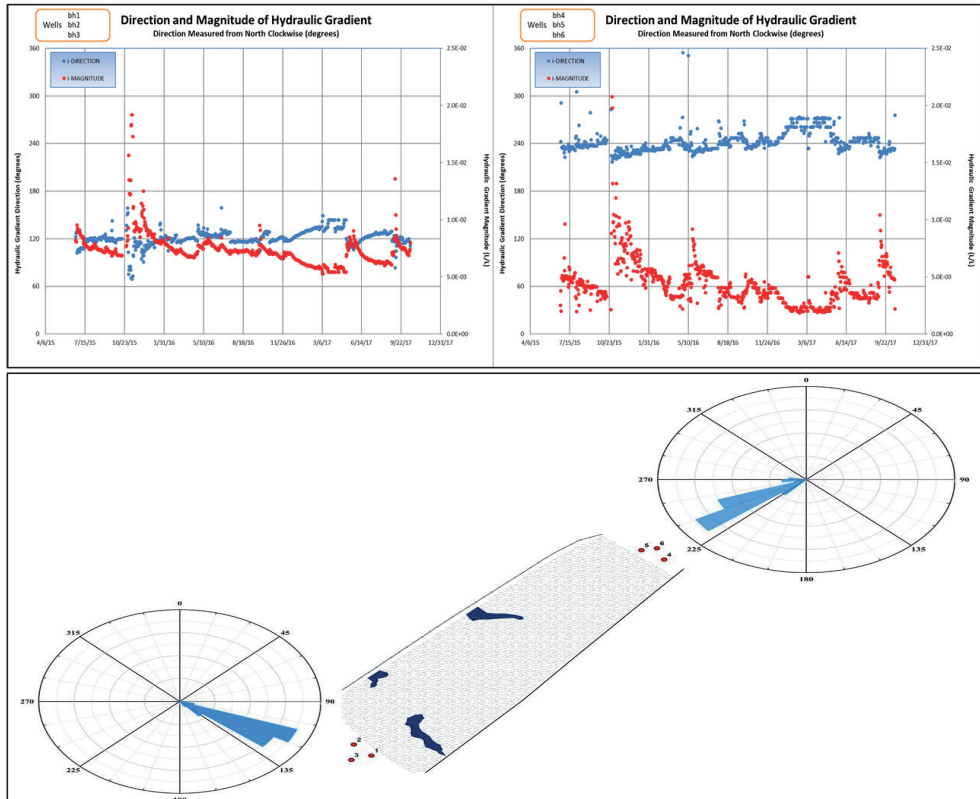


Figure 7: Variation in direction and magnitude of hydraulic gradient on the west and eastern side of wetland edge (top), Dominant direction of hydraulic gradient during the monitoring period (bottom)

The groundwater gradient had a significant correlation with both local rainfall and wetland stage although there was a higher correlation to wetland stage (0.67,  $p=000$ ) than to local rainfall (0.22,  $p=000$ ) (Figure 8). High rainfall amounts led to an immediate response in the hydraulic gradient. In addition, the gradient increased in periods of cumulative rainfall but declined in periods with longer dry spells (Figure 8). On the other

hand, variations in hydraulic gradient mirrored changes in wetland water level (Figure 8).

The methods used give an idea of the groundwater gradient at the wetland site. However, because of the small number of boreholes used, the groundwater flow patterns at a larger scale are still undefined. Since surface and groundwater interaction are complex, further insight into the dynamics of the system requires an extensive monitoring network (Krasnostein & Oldham, 2004; Trask *et al.*, 2017). Additional monitoring networks (e.g. piezometer nests) within the study area should give a better understanding of vertical groundwater gradients at the wetland edge as well as subsurface hydrogeological properties.

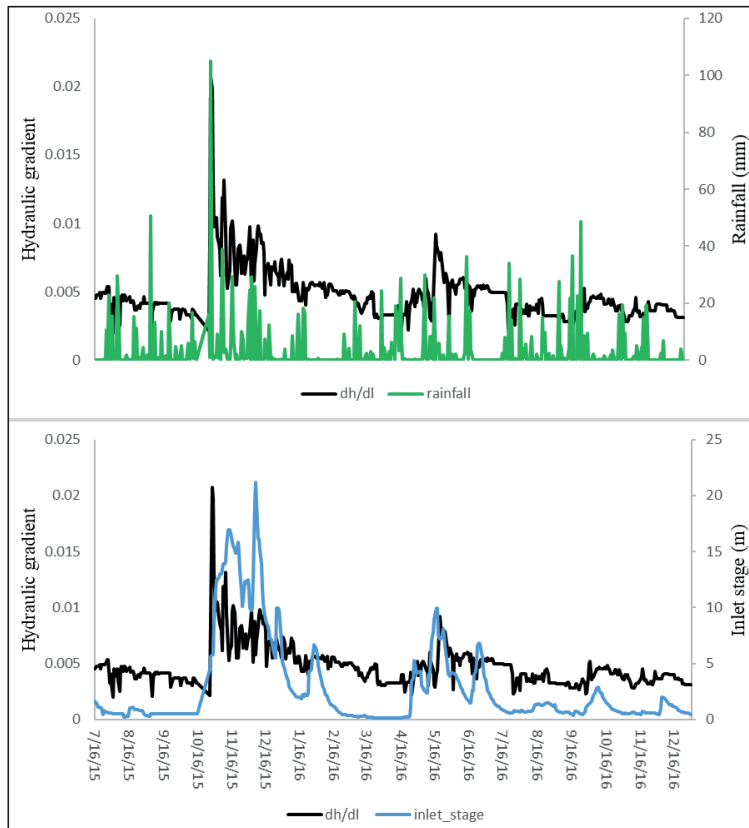


Figure 8: Hydraulic gradient (black lines) on eastern edge of wetland, plotted together with rainfall (top) and wetland stage (bottom)

### 3.3. Wetland water balance

The calculated water balance (Table 3) shows that the wetland is dominated by wetland channel flow contributing approximately 99.7% of the total inputs into the wetland while direct precipitation and groundwater discharge contributed approximately 0.2% and <0.1%, respectively. Estimates of total evapotranspiration were 30% higher than total precipitation during the study period. Between July and November 2015, outflows exceeded inflows and there was a net loss in storage during this time. The months of December 2015 and January 2016 had higher inflows than outflows with a net increase in storage, but the flow reversed again in February 2016. The water balance averaged over the 8 months period, shows that there was a net increase of storage of approximately 2,700 m<sup>3</sup>.

Table 3: Monthly water balance of Naigombwa wetland section (m<sup>3</sup>)

	<b>Q<sub>in</sub></b>	<b>R</b>	<b>Q<sub>G</sub></b>	<b>Q<sub>out</sub></b>	<b>ET</b>	<b>dS/dt</b>
<i>Jul-15</i>	169,529	554	1.0	170,674	781	-1,371
<i>Aug-15</i>	53,597	481	0.9	62,032	855	-8,808
<i>Sep-15</i>	39,960	635	0.9	42,364	893	-2,661
<i>Oct-15</i>	127,290	1,503	1.5	131,313	923	-3,442
<i>Nov-15</i>	1,195,913	950	1.5	1,240,389	886	-44,410
<i>Dec-15</i>	917,534	804	1.5	825,320	865	92,155
<i>Jan-16</i>	293,435	423	1.2	254,652	877	38,329
<i>Feb-16</i>	135,422	65	1.1	140,176	940	-5,627
<i>8month average</i>	372,824	689	1.2	364,360	883	2,766

We observed an increase in precipitation from September to December 2015. However, channel flows did not start increasing until October 2015, which implies a one month lag between rainfall and channel flows. The lag could be due to storage effects within the catchment, where infiltrated water is discharged into the river after rainfall has ceased (Tomasella *et al.*, 2008). We hypothesized that channel flows through the wetland mirror rainfall variations, this is partially true but results also show a one month lag between rainfall and channel flows.

Since channel flow is the main input to the wetland section, this illustrates that the hydrological regime is vulnerable to land use changes in the upstream catchment because these influence the magnitude and timing of flows into the wetland (Krasnostein & Oldham, 2004). Land use changes can play an important role because they influence infiltration rates, wetland water levels, and flow dynamics within the catchment. For example, the increasing extent of rice farms in the Mpologoma River catchment reduces infiltration rate especially during the growing season. This is because the fields are maintained with standing water and yet areas with saturated soils have little additional storage capacity (Acreman & Holden, 2013). Such areas are therefore expected to generate saturation excess overland flow more quickly compared to soils that are not saturated. Therefore, having a large expanse of rice paddies could increase the risk of flash floods in rainy seasons.

The water balance estimates give an indication of the key processes of the wetland's hydrological regime. Since the monitored water dynamics cover a short time period, continued monitoring is important to get further insight into annual variations in hydrology. Although water balance estimates were affected by the small number of discharge measurements, the stage discharge relationship can be updated as more data is collected. Another issue of concern is that the method we applied to estimate discharge was developed for use with open water channels (Gore & Banning, 2017), and could only be used at the inlet and outlet culverts. Therefore, the effect of water spreading into the remaining wetland area and the drag on water flow from the floating vegetation may not be correctly reflected in the calculations.

### **3.4. Independent estimates of wetland storage**

There was a low correlation ( $r=0.49$ ) between wetland stage measured at the culvert and water depth at the centre of the wetland. The poor relationship between the two variables (Figure 9), could be due to delay in water level rise between the culvert and the wetland centre that is dominated by floating papyrus. There is a better correlation between wetland stage and water depth in the dry season, which is illustrated by the



upper limb of data (Figure 9). However, this correlation reduces in the wet season as shown by the lower limb of the data. This is because water velocity at the inlet and outlet culverts increases in the wet season, which creates fast flow between the inlet and outlet culvert. On the other hand, velocity at the wetland centre is slowed down due to presence of floating vegetation, which reduces the correlation between wetland stage and water depth. Because of the low correlation between wetland stage and water depth in the wet season, the accuracy of corresponding volume estimates was very low. Consequently, change in storage for the water balance was estimated as part of the residual term as shown in Table 3.

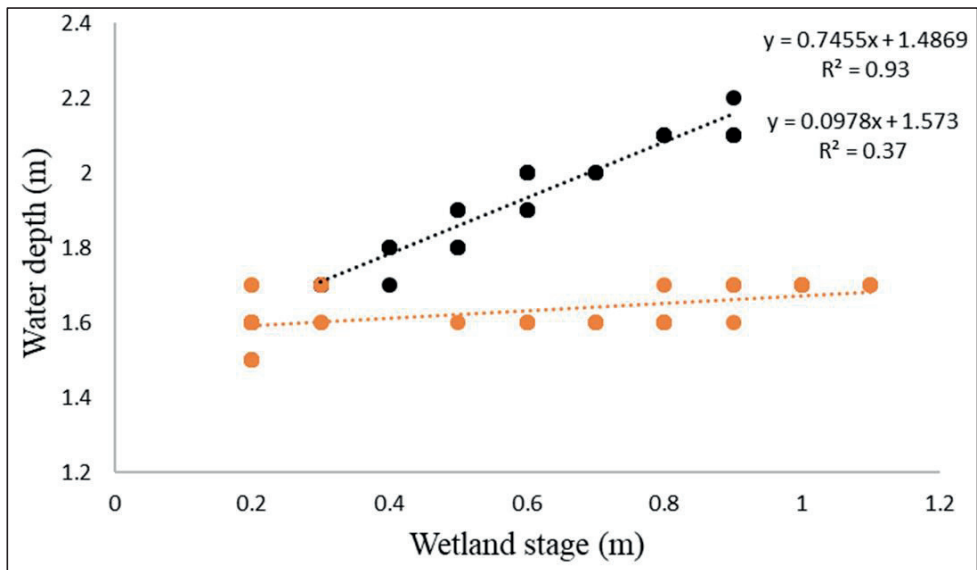


Figure 9: Relationship between wetland stage and water depth at the wetland centre. The upper and lower limbs of the data represent correlations in the dry and wet seasons, respectively

Despite the high uncertainty in the water depth estimates, we utilised them to get crude daily estimates of water volume and calculated retention time using the volume-discharge ratio. Based on these estimates, the shortest and longest retention times were 2 hours and 7 days, observed between November to December 2015, and February to April 2016, respectively.

Since the water balance estimates at monthly time steps may smooth out some of the hydrodynamic interactions between precipitation and discharge, we analysed the cumulative precipitation, discharge, and retention time on a daily basis (Figure 10), to explore their relationship in more detail. In Figure 10 we see that the peaks in discharge correspond to periods with a high accumulation of precipitation. During the same period, the retention time (the bottom part of Figure 10) is only a few hours, while it increases to around 1 week in periods of low flow. Retention time is highest between February and April 2016 during low flows.

The observed retention times indicate that the flow to volume ratio is very high, which is because of the small size of the wetland section relative to its catchment area. It's important to note the flows are modified by the position of the culverts. We propose therefore, that there is preferential flow and higher velocities from the inlet culvert at the highway to the downstream culverts at the railway, but other parts of the wetland with floating papyrus vegetation have lower velocities. The estimated retention time is therefore not representative of the wetland as a whole.

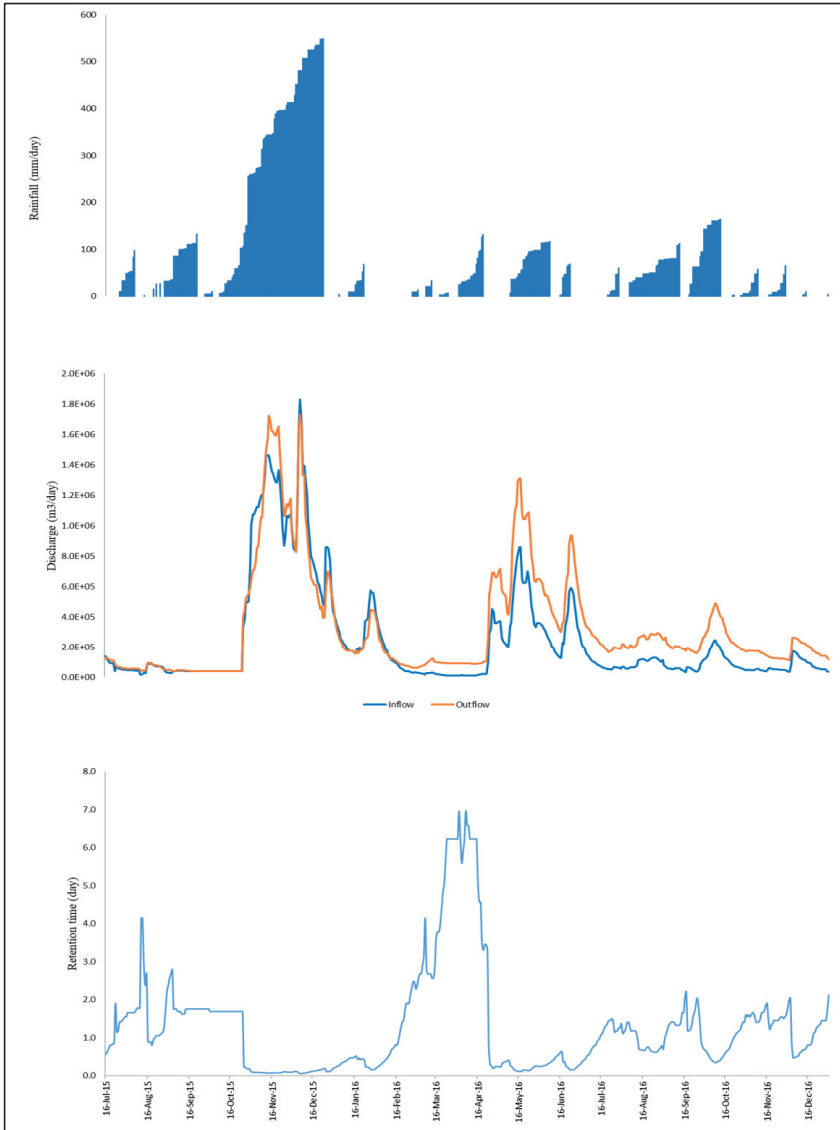


Figure 10: Top: Accumulated precipitation separated by dry spells (defined as days with less than 1mm/day and more than 5 successive days of no rain), middle: Discharge in and out of wetland section, bottom: estimated retention time for wetland section

### 3.5. Water flow patterns

There was a low velocity at the inlet culvert during the tracer experiment, therefore EC at the downstream side of the highway increased only slightly above baseline values (Figure 11). We used the time (6 hrs: 36 minutes) at which the highest EC value was recorded at the downstream end to estimate water velocity through the culvert underneath the highway. The width (travel distance) of the road is 13m; which gives a velocity of  $5.47 \times 10^{-4}$  m/s.

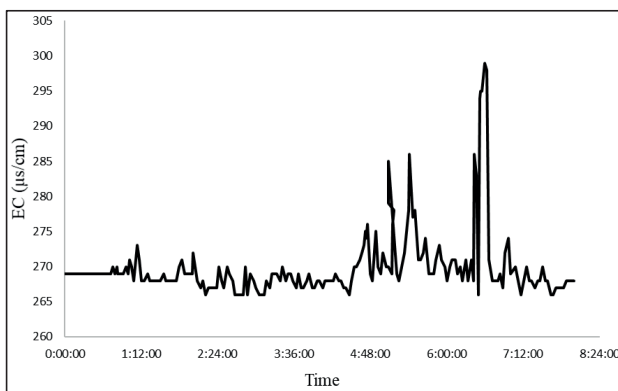


Figure 11: EC variation with time at outlet of highway culvert

If the same velocity is assumed throughout the wetland section; and a travel distance of 290 m between the inlet and outlet culvert, this gives an estimated retention time of 6 days. This estimate is comparable to the highest observed retention time of 7 days that was estimated using the volume-discharge ratio. However, as mentioned in the previous section, this retention time represents water flow between the inlet and outlet culvert and not the flow in other areas of the wetland. We therefore estimated flows in other wetland areas using tracer measurements in the papyrus plot.

For the papyrus plot, we used contour plots to visualise changes in EC around the centre point (where the tracer was released) at specific time intervals. The contour plots from top left in clockwise direction, represent time intervals at; 0-20minutes, 48-1:04hours, 1:36-2:02 hours, and 2:28-2:40 hours, respectively (Figure 12). There was some increase in EC at points 10 and 11 that are west and north of the centre point,

respectively. The increases were observed both within the root mat (Figure 12a) and in the water column beneath it (Figure 12b). However, EC did not increase much beyond these two points which indicates that there was little movement of water. Since EC was monitored manually by moving from one point to another on top of the floating papyrus mat, the effect of walking on the root mat might have caused the observed dispersion pattern of the tracer from the centre point. We propose that a larger water velocity would have showed a more skewed pattern of the tracer movement. We therefore conclude that there is low velocity in this part of the wetland.

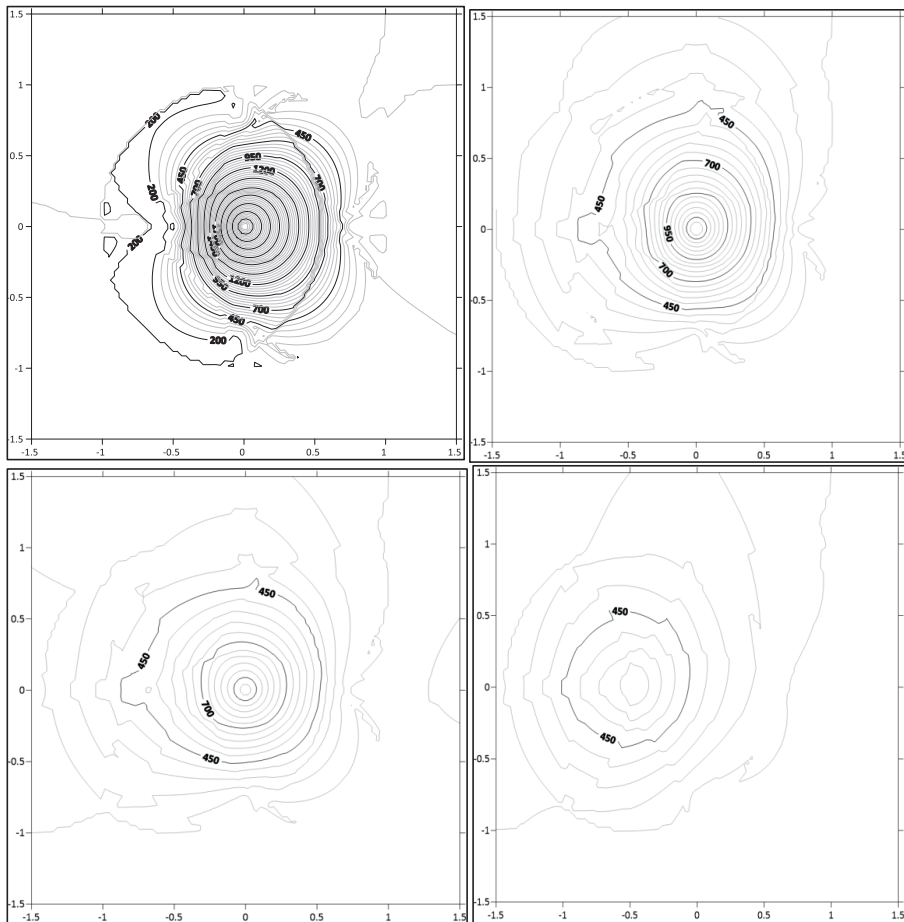


Figure 12a: EC ( $\mu\text{s}/\text{cm}$ ) distribution within the papyrus root mat

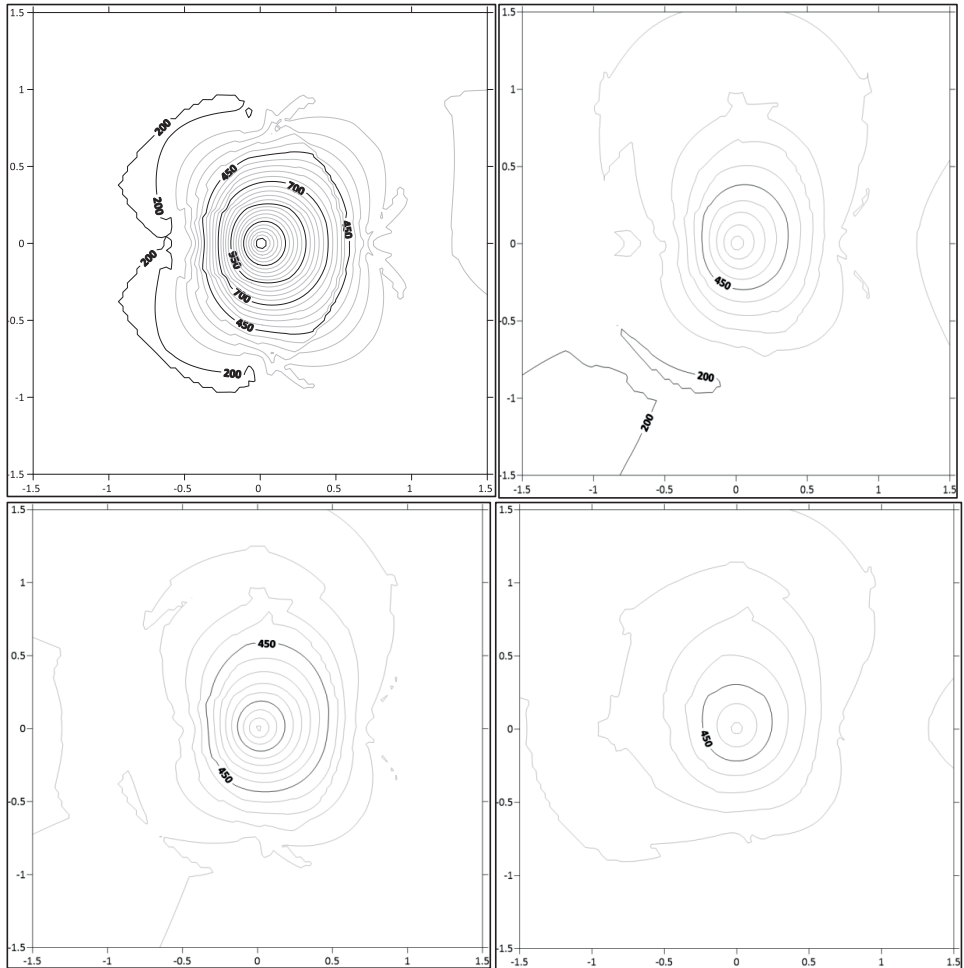


Figure 12b: EC ( $\mu\text{s}/\text{cm}$ ) distribution below the root mat.

#### 4. Conclusion

In this study, we characterised the water balance components of a section of a papyrus wetland, and identified flow in the main channel as the dominating factor, contributing 99.7% of total inputs. The wetland's retention time between the inlet and outlet culverts varied between 2 hours and 7 days during periods of high and low flows, respectively. Further, hydraulic gradients on either side of the wetland indicate groundwater flow towards the wetland throughout the monitoring period. The observed dynamics of the groundwater flow toward the wetland implies that the wetland plays a major role as a

boundary condition for the local groundwater system and that draining the wetland would impact groundwater levels in the areas along the wetland edges in the long run. Although the water balance approach has its limitations, it gives an initial understanding of the key processes in the hydrological regime of a small wetland section.

For future research, we propose that more comprehensive water flow measurements through areas of floating papyrus vegetation can be obtained by using automatic sensors to reduce impact of movement on the experimental results. In addition, investing in wider monitoring networks like piezometer nests will lead to an improved understanding of vertical ground water fluxes and subsurface hydrogeological properties. We also recommend further research using catchment based models to assess possible impacts of land use changes within the upstream catchment on channel flows.

## **Acknowledgements**

This work was funded by the 'Norwegian Programme for Capacity Development in Higher Education and Research for Development (NORHED)'; Grant number: 3303010034. The funding is through the 'Regional Capacity Building for Sustainable Natural Resource Management and Agricultural Improvement under Climate Change (CAPSNAC)' Project housed at Makerere University, Uganda.

We appreciate Dr. Michael Owor and Dr. Philip Njenje for advice and assistance in installation of monitoring boreholes. We also thank Mr. Bright Twesigye, Mr. Kukutu Solomon Collin for their assistance in the data collection exercise in and around the Naigombwa wetland. We thank Mr. Frank Kigozi for help with wetland gauge installation and for carrying out the discharge measurements. Finally, Mr. Kisitu Francis is greatly appreciated for providing information about drinking water wells in the areas surrounding the wetland section.

## References

- Acreman, M., Holden, J. 2013. How Wetlands Affect Floods. *Wetlands* **33**: 773-786. doi:10.1007/s13157-013-0473-2
- Anadranistakis, M., Liakatas, A., Alexandris, S., Aggelides, S., Kerkides, P., Rizos, S., Poulouvassilis, A. 1997. Soil Heat Flux in the Penman-Monteith Evapotranspiration Equation. Paper presented at the ISHS Acta Horticulturae: II International Symposium on Irrigation of Horticultural Crops, Chania, Crete, Greece
- Azza, N.G.T., Kansime, F., Nalubega, M., Denny, P. 2000. Differential Permeability of Papyrus and Miscanthidium Root Mats in Nakivubo Swamp, Uganda. *Aquatic Botany* **67**: 169-178. doi:10.1016/S0304-3770(00)00093-0
- Beljin, M., Ross, R.R., Acree, S.D. 2014. 3pe: A Tool for Estimating Groundwater Flow Vectors. (EPA/600/R-14/273, 2014). Washington, DC, : U.S. Environmental Protection Agency.
- Donaldson, L., Woodhead, A.J., Wilson, R.J., Maclean, I.M. 2016. Subsistence Use of Papyrus is Compatible with Wetland Bird Conservation. *Biological Conservation* **201**: 414-422. doi:10.1016/j.biocon.2016.07.036
- Emerton, L., Iyango, L., Luwum, P., Malinga, A. 1999. The Present Economic Value of Nakivubo Urban Wetland, Uganda. *Nairobi: IUCN*.
- Gaudet, J.J. 1977. Natural Drawdown on Lake Naivasha, Kenya and the Formation of Papyrus Swamps *Aquatic Botany* **3**: 1-47. doi:10.1016/0304-3770(77)90002-X
- Gore, J.A., Banning, J. 2017. Chapter 3 - Discharge Measurements and Streamflow Analysis. In: FR Hauer, GA Lamberti (Eds.), *Methods in Stream Ecology, Volume 1 (Third Edition)* (pp. 49-70). Boston: Academic Press. doi:10.1016/B978-0-12-416558-8.00003-2
- Institute of Hydrology. 1992. Hydata Operation Manual. Hydrological Data Processing System, Version 3.1. Wallingford, UK.
- Jones, M., Humphries, S. 2002. Impacts of the C4 Sedge *Cyperus papyrus* L. On Carbon and Water Fluxes in an African Wetland. *Hydrobiologia* **488**: 107-113. doi:10.1007/978-94-017-2031-1\_10
- Kadlec, R.H., Knight, R. 1996. Treatment Wetlands. Crc. *Baca Raton, FL*.



- Kansiime, F., Nalubega, M. 1999. *Wastewater Treatment by a Natural Wetland: The Nakivubo Swamp, Uganda. Processes and Implications*. (PhD Thesis), Wageningen Agricultural University, Netherlands.
- Kansiime, F., Sanders, M.J., Loisella, S.A. 2007. Functioning and Dynamics of Wetland Vegetation of Lake Victoria: An Overview. *Wetlands Ecology and Management* **15**: 443-451. doi:10.1007/s11273-007-9043-9
- Kayendeke, E.J., Kansiime, F., French, H.K., Bamutaze, Y. 2018. Spatial and Temporal Variation of Papyrus Root Mat Thickness and Water Storage in a Tropical Wetland System. *Science of The Total Environment* **642**: 925-936. doi:10.1016/j.scitotenv.2018.06.087
- Kigobe, M., Wheeler, H., McIntyre, N. 2014. Statistical Downscaling of Precipitation in the Upper Nile: Use of Generalized Linear Models (Glms) for the Kyoga Basin. In: AM Melesse, W Abtew, SG Setegn (Eds.), *Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics* (pp. 421-449). Cham: Springer International Publishing. doi:10.1007/978-3-319-02720-3\_22
- Kipkemboi, J., van Dam, A.A. 2018. Papyrus Wetlands. In: CM Finlayson, GR Milton, RC Prentice, NC Davidson (Eds.), *The Wetland Book: II: Distribution, Description, and Conservation* (pp. 183-197). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-4001-3\_218
- Krasnostein, A., Oldham, C. 2004. Predicting Wetland Water Storage. *Water Resources Research* **40**.
- Kyambadde, J., Kansiime, F., Gumaelius, L., Dalhammar, G. 2004. A Comparative Study of *Cyperus papyrus* and *Miscanthidium violaceum*-Based Constructed Wetlands for Wastewater Treatment in a Tropical Climate. *Water Research* **38**: 475-485. doi:10.1016/j.watres.2003.10.008
- MacLeod, D. 2018. Seasonal Predictability of Onset and Cessation of the East African Rains. *Weather and Climate Extremes*. doi:10.1016/j.wace.2018.05.003
- Mburu, N., Rousseau, D.P.L., van Bruggen, J.J.A., Lens, P.N.L. 2015. Use of the Macrophyte *Cyperus papyrus* in Wastewater Treatment. In: J Vymazal (Ed.), *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape* (pp. 293-314). Cham: Springer International Publishing. doi:10.1007/978-3-319-08177-9\_20

- Morrison, E.H., Upton, C., Pacini, N., Odhiambo-K'oyooh, K., Harper, D.M. 2013. Public Perceptions of Papyrus: Community Appraisal of Wetland Ecosystem Services at Lake Naivasha, Kenya. *Ecohydrology & Hydrobiology* **13**: 135-147. doi:10.1016/j.ecohyd.2013.03.008
- Namaalwa, S., Van dam, A.A., Funk, A., Ajie, G.S., Kaggwa, R.C. 2013. A Characterization of the Drivers, Pressures, Ecosystem Functions and Services of Namatala Wetland, Uganda. *Environmental Science & Policy* **34**: 44-57. doi:10.1016/j.envsci.2013.01.002
- NEMA. 2008. Pilot Integrated Environment Assessment of the Lake Kyoga Catchment Area. National Environment Management Authority (NEMA), Kampala.
- Okurut, T.O. 2000. *A Pilot Study on Municipal Wastewater Treatment Using a Constructed Wetland in Uganda* (PhD Thesis), Wageningen University Netherlands.
- Opio, A., Jones, M., Kansime, F., Otiti, T. 2014. Growth and Development of *Cyperus papyrus* in a Tropical Wetland. *Open Journal of Ecology* **4**: 113-123. doi:10.4236/oje.2014.43013
- Owor, M., Taylor, R., Mukwaya, C., Tindimugaya, C. 2011. Groundwater/Surface-Water Interactions on Deeply Weathered Surfaces of Low Relief: Evidence from Lakes Victoria and Kyoga, Uganda. *Hydrogeology Journal* **19**: 1403-1420. doi:10.1007/s10040-011-0779-1
- Rasmussen, T.C., Deemy, J.B., Long, S.L. 2018. Wetland Hydrology. In: CM Finlayson, M Everard, K Irvine, RJ McInnes, BA Middleton, AA van Dam, NC Davidson (Eds.), *The Wetland Book: I: Structure and Function, Management, and Methods* (pp. 201-216). Dordrecht: Springer Netherlands. doi:10.1007/978-90-481-9659-3\_71
- Sauer, T.J., Horton, R. 2005. Soil Heat Flux. In: JL Hatfield, JM Baker (Eds.), *Micrometeorology in Agricultural Systems. Asa Monograph* (Vol. **47**: pp. 131-154). Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. doi:10.2134/agronmonogr47.c7
- Saunders, M.J., Jones, M.B., Kansime, F. 2007. Carbon and Water Cycles in Tropical Papyrus Wetlands. *Wetlands Ecology and Management* **15** 489-498. doi:10.1007/s11273-007-9051-9
- Saunders, M.J., Kansime, F., Jones, M.B. 2013. Reviewing the Carbon Cycle Dynamics and Carbon Sequestration Potential of *Cyperus papyrus* L. Wetlands in Tropical Africa. *Wetlands Ecology and Management* **21**. doi:10.1007/s11273-013-9314-6

- Semeniuk, C.A., Semeniuk, V. 1995. A Geomorphic Approach to Global Classification for Inland Wetlands. *Vegetatio* **118**: 103-124. doi:10.1007/bf00045193
- Semeniuk, V., Semeniuk, C.A. 1997. A Geomorphic Approach to Global Classification for Natural Inland Wetlands and Rationalization of the System Used by the Ramsar Convention – a Discussion. *Wetlands Ecology and Management* **5**: 145-158. doi:10.1023/a:1008207726826
- Ssanyu, G.A., Kipkemboi, J., Mathooko, J.M., Balirwa, J. 2014. Land-Use Impacts on Small-Scale Mpologoma Wetland Fishery, Eastern Uganda: A Socio-Economic Perspective. *Lakes & Reservoirs: Research & Management* **19**: 280-292. doi:doi.org/10.1111/lre.12073
- Terer, T., Muasya, A.M., Higgins, S., Gaudet, J.J., Triest, L. 2014. Importance of Seedling Recruitment for Regeneration and Maintaining Genetic Diversity of *Cyperus papyrus* During Drawdown in Lake Naivasha, Kenya. *Aquatic Botany* **116**: 93–102. doi:10.1016/j.aquabot.2014.02.008
- Terer, T., Triest, L., Muasya, A.M. 2012. Effects of Harvesting *Cyperus papyrus* in Undisturbed Wetland, Lake Naivasha, Kenya. *Hydrobiologia* **680**: 135-148. doi:10.1007/s10750-011-0910-2
- Tomasella, J., Hodnett, M.G., Cuartas, L.A., Nobre, A.D., Waterloo, M.J., Oliveira, S.M. 2008. The Water Balance of an Amazonian Micro-Catchment: The Effect of Interannual Variability of Rainfall on Hydrological Behaviour. *Hydrological Processes* **22**: 2133-2147. doi:10.1002/hyp.6813
- Trask, J.C., Fogg, G.E., Puente, C.E. 2017. Resolving Hydrologic Water Balances through a Novel Error Analysis Approach, with Application to the Tahoe Basin. *Journal of Hydrology* **546**: 326-340. doi:10.1016/j.jhydrol.2016.12.029
- Turyahabwe, N., Tumusiime, D.M., Kakuru, W., Barasa, B. 2013. Wetland Use/Cover Changes and Local Perceptions in Uganda. *Sustainable Agriculture Research* **2**: 95. doi:10.5539/sar.v2n4p95
- van Dam, A.A., Dardona, A., Kelderman, P., Kansime, F. 2007. A Simulation Model for Nitrogen Retention in a Papyrus Wetland near Lake Victoria, Uganda (East Africa). *Wetlands Ecology and Management* **15**: 469–480. doi:10.1007/s11273-007-9047-5
- van Dam, A.A., Kipkemboi, J., Mazvimavi, D., Irvine, K. 2014. A Synthesis of Past, Current and Future Research for Protection and Management of Papyrus (*Cyperus*

- papyrus* L.) Wetlands in Africa. *Wetlands Ecology and Management* **22**: 99-114.  
doi:10.1007/s11273-013-9335-1
- WMD. 2009. Mapping a Better Future: How Spatial Analysis Can Benefit Wetlands and Reduce Poverty in Uganda. Wetlands Management Department, Ministry of Water and Environment.
- Zahraeifard, V., Deng, Z. 2011. Hydraulic Residence Time Computation for Constructed Wetland Design. *Ecological engineering* **37**: 2087-2091.  
doi:10.1016/j.ecoleng.2011.08.011
- Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W., Morgan, K.T. 2010. Step by Step Calculation of the Penman-Monteith Evapotranspiration (Fao-56 Method). *Institute of Food and Agricultural Sciences. University of Florida.*







ISBN: 978-82-575-1537-9

ISSN: 1894-6402



Norwegian University  
of Life Sciences

Postboks 5003  
NO-1432 Ås, Norway  
+47 67 23 00 00  
[www.nmbu.no](http://www.nmbu.no)