*Title Page

Spatial and Temporal Variation of Papyrus Root Mat Thickness and Water Storage in a Tropical Wetland System

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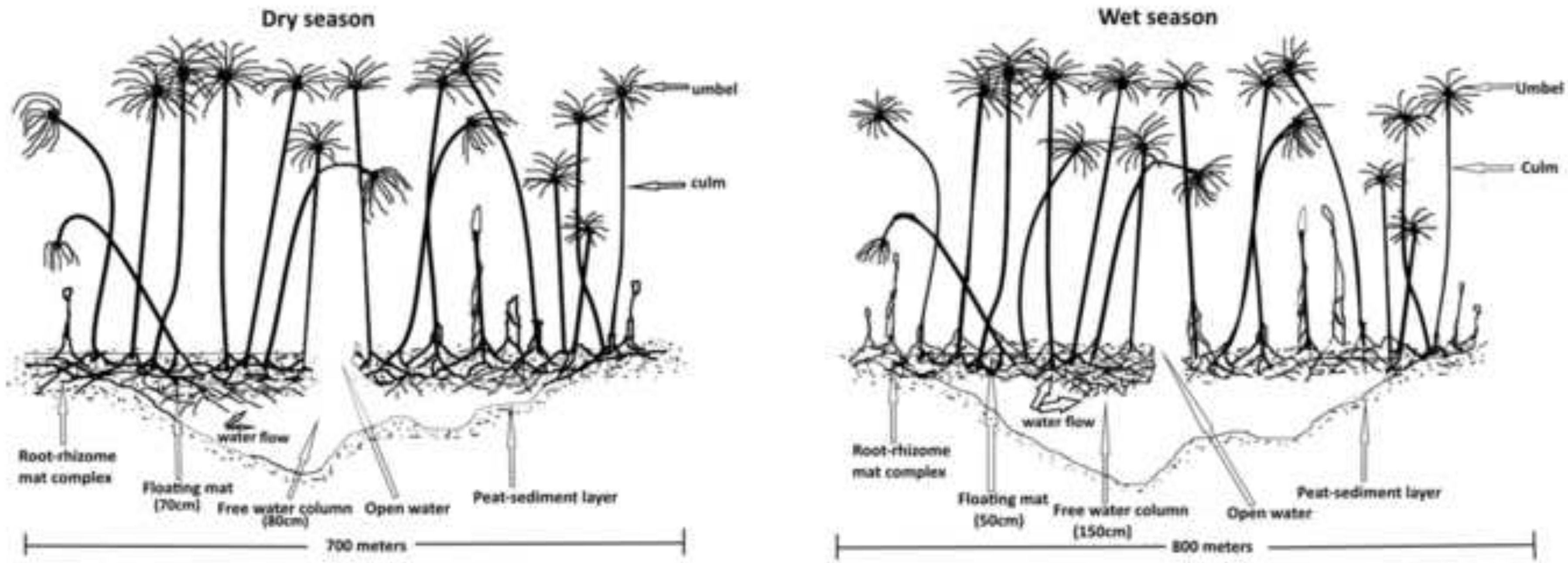
*Graphical Abstract



***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

- There was a negative correlation between changes in papyrus mat thickness and free water column between two seasons (r= -0.85, p= 000); indicating that the mat contracts in response to increase in free water column
- The mat contraction is spatially variable and is influenced by the rate of increase of free water column and wetland bathymetry. For example; 83% and 67% mat contraction at shallow and deep parts of the wetland respectively
- The increase in free water column facilitates storage of extra water in the studied tropical wetland. For example; up to 50% increase in storage volume in wet seasons

Abstract

Papyrus wetlands are predominant in permanently inundated areas of tropical Sub Saharan Africa (SSA) and offer both provisioning and regulatory services. Although a wealth of literature exists on wetland functions, the seasonal behaviour of the papyrus mat and function in water storage has received less attention. The objective of this study was to assess the role of papyrus root mat in water storage in a tropical wetland system in Eastern Uganda. We delineated seven transects through the wetland system and mapped wetland bathymetry along these transects. We used three transects to measure spatial and temporal changes in mat thickness and free water column; and to monitor variations in total depth during two seasons. The free water column increased across all transects in the wet season. However, changes in the mat thickness varied spatially and were influenced by the rate of increase of the free water column as well as wetland bathymetry. The proportion of mat contraction was higher at the shallow end of the wetland (83%) compared to the deep end (67%). There was a significant negative correlation between changes in free water column and papyrus mat thickness ($r= -0.85$, $p= 000$) indicating that the mat contracts in response to increase in free water column. Water depth varied from 1.5m to 2.1m during the monitoring period, corresponding to a water storage of 61,597 m^3 and 123,355 m^3 respectively. Therefore, there was a 50% change in water volume for the studied wetland section. The mat's ability to contract enables papyrus wetlands to store excess water entering the wetland as direct precipitation, storm water and channel inflows. 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.

Key words: Papyrus Wetland, Papyrus Mat, Water Storage, Tropical Wetland

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* which is a large herbaceous sedge whose culm grows up to five meters (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^{-2} y^{-1} (Jones & 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^{-2} y^{-1} and 76.7 g N m^{-2} y^{-1} (Kansiime & Nalubega, 1999; Okurut, 2000; van Dam *et al.*, 2007).

Although the functioning of papyrus wetlands has been widely studied, their regulatory functions especially water storage and flood mitigation has 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 but some stands can be detached during inundation by fast flowing water forming floating mats (Saunders *et al.*, 2012; van Dam *et al.*, 2007). The roots and rhizomes of papyrus intertwine to form a complex root-rhizome mat system that can support a body mass. 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 (Kansiime & Nalubega, 1999; Kipkemboi *et al.*, 2002). We illustrate the papyrus mat system in figure 1.

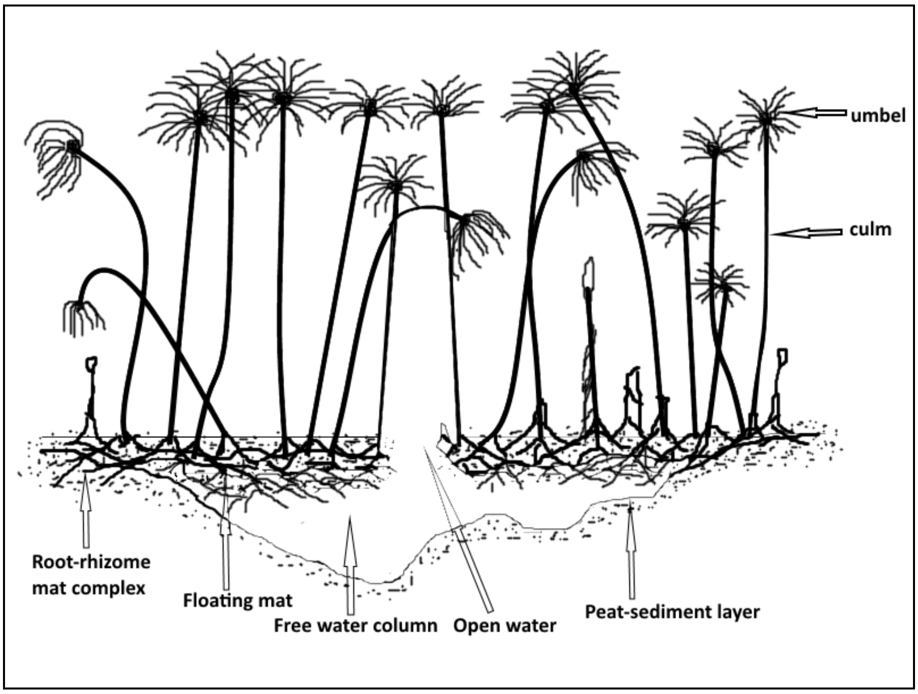


Figure 1. Vertical section through the Papyrus mat system perpendicular to the direction of flow; with rooted and floating papyrus, and the free water column

However, increasing pressure for agricultural expansion has led many papyrus wetlands to be converted for agriculture especially rice growing (Kipkemboi & van Dam, 2016). As a result, agricultural crops replace natural papyrus vegetation in the degraded wetlands (Kansiime *et al.*, 2005). Yet the role of the papyrus mat in wetland functioning is not fully understood. Analysing the spatial and temporal dynamics of the papyrus mat system is crucial for understanding 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 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 role of an intact papyrus wetland in water storage, and the dynamics of the root mat in relation to high and low flow conditions. 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 the papyrus mat contracts when water levels increase to accommodate the excess water.

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 (Figure 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^2 and drains an area of 734 km^2. 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 high way 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 (Figure 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 21^0C respectively (Kigobe *et al.*, 2014). The basin's monitoring network is inadequate due to sparse coverage and incomplete records due to 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 meters above sea level, and the soils are mainly ferralitic with reddish brown sandy loams.

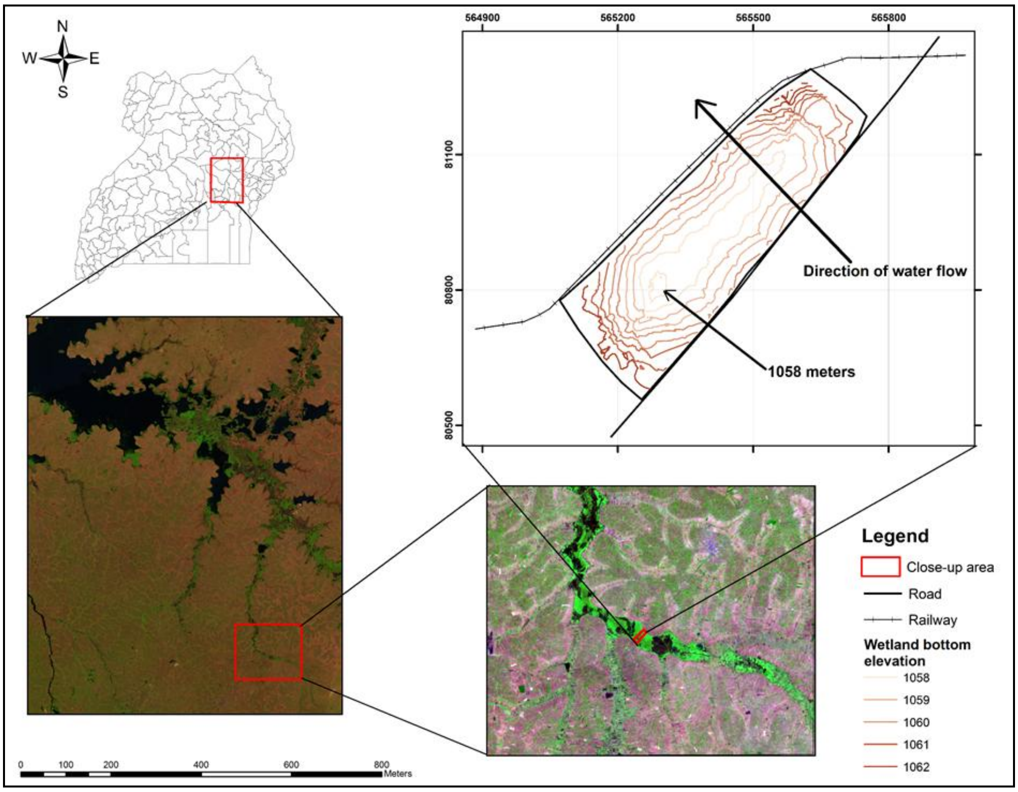


Figure 2: Location of study site in Eastern Uganda, the contours illustrate the wetland's bottom elevation/bathymetry with elevation range of 1058-1062 meters

2.2. Layout and sampling design

The layout and sampling design is illustrated in figure 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. This boundary shifts outwards by about 30 meters during periods of high flows, and the transitional area 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 100m 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 270m (Transect1) and transect 7 is the shortest at 170m.

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 meters from the edge (Figure 3). Automatic divers were installed at the centres of transects 1, 3 and 5 for continuous monitoring of water depth. We obtained local precipitation data from a weather station 1km from the wetland study site.

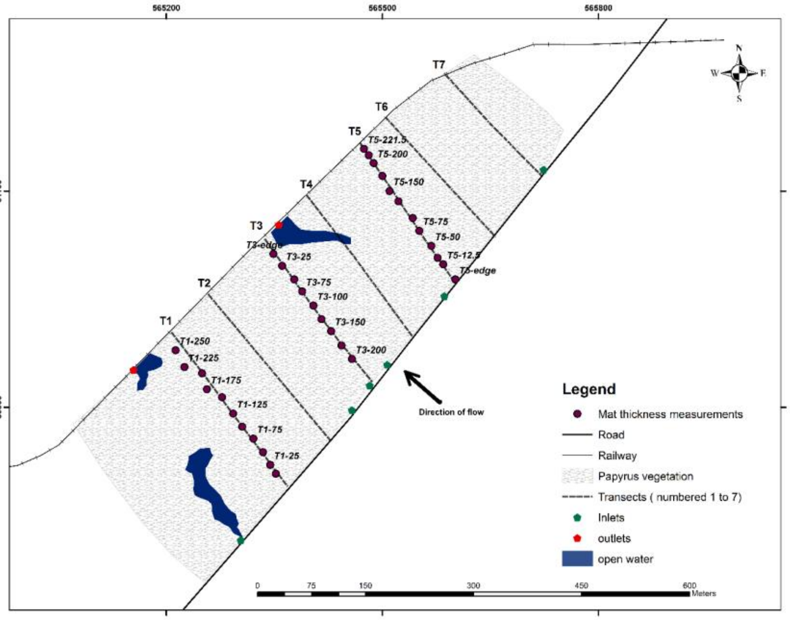


Figure 3: Layout and sampling design of the selected wetland section

2.3. Deriving wetland bathymetry

Wetland bottom elevation was mapped by surveying 137 points along the seven access transects, and around the wetland edges (Figure 4). We used an auto level 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.

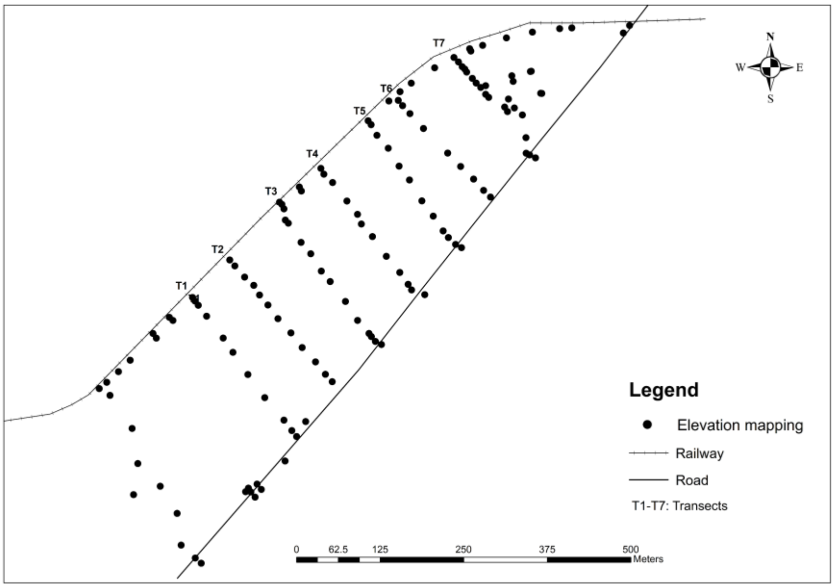


Figure 4: Survey points used for mapping wetland bottom elevation

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 & 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. Water volume was calculated for a range of water depths from 0 to 3.5m at 0.5 increments. A scatter plot of volume against water depth revealed a polynomial relationship. We therefore fit a third order polynomial model (equation 1) to the data with an adjusted R square value of 0.99;

$$WV = 2382.4 - 24987.6WD + 47793.2WD^2 - 4030WD^3 \qquad (1)$$

Where; WV = wetland water volume, WD = water depth

2.4. Monitoring Water depth

Automatic divers (Micro-Diver: DI6) were installed along transects 1, 3, and 5 in January 2016 to monitor water pressure changes in different seasons. The divers recorded water pressure every 30 minutes over a period of five months. Barometric pressure was recorded using a barometric diver (Baro-Diver: DI500), which was installed in a borehole 50 meters from the wetland edge. The pressure recordings were used to calculate water depth variations in the wetland using equation 2 (Schlumberger Water Services, 2014);

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

Where; WD=Water depth, TOC=Top of casing, CL=Cable length, P_{Diver} =Water pressure diver, P_{Baro} =Barometric pressure diver, ρ=Water density (1,000 kg/m^3), g=Acceleration due to gravity (9.81 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.

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 meters up to the opposite edge of the wetland. A profiling rod was used to measure the mat thickness and water depth as illustrated in Figure 5. 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.

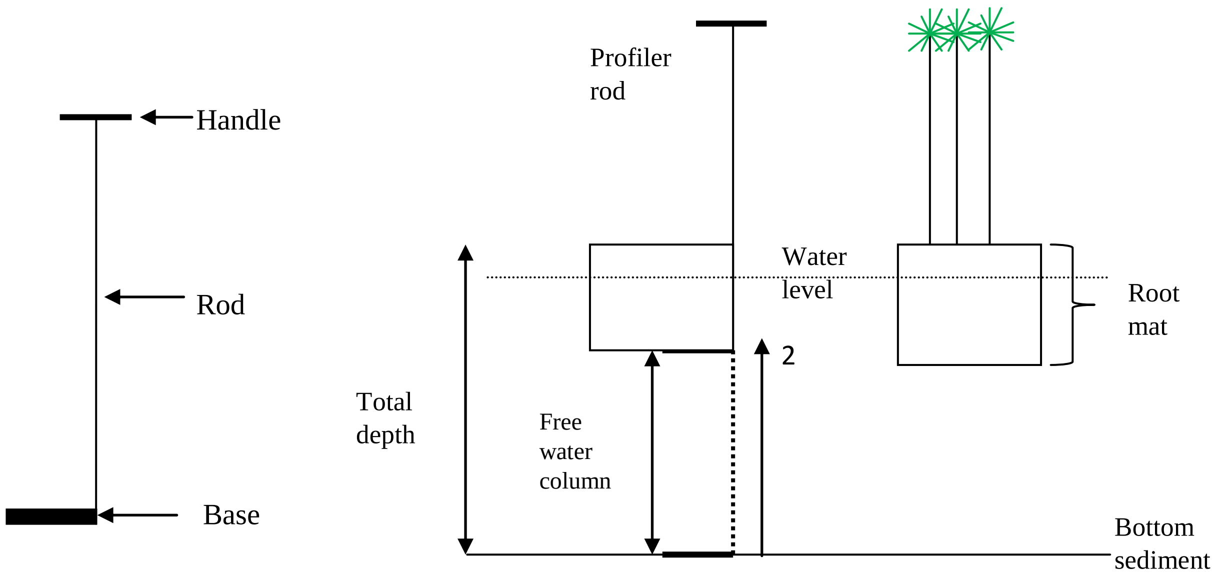


Figure 5: Illustration of profiler rod (left), and measurement technique for water depth and mat thickness (right). Where 1: total depth measurement, and 2: mat thickness measurement

2.5.1. Delineation of zones along transects

Transects 1, 3 and 5 were divided into three zones according to differences in water depth along the transects. Zone I was at a distance of 0-100m from the highway edge while zones II and III were at distances of 100-175m and 175-250m respectively (Figure 6). We created these zones because we anticipated that water depth is influenced by wetland bathymetry; and differs between the centre and fringes of the wetland.

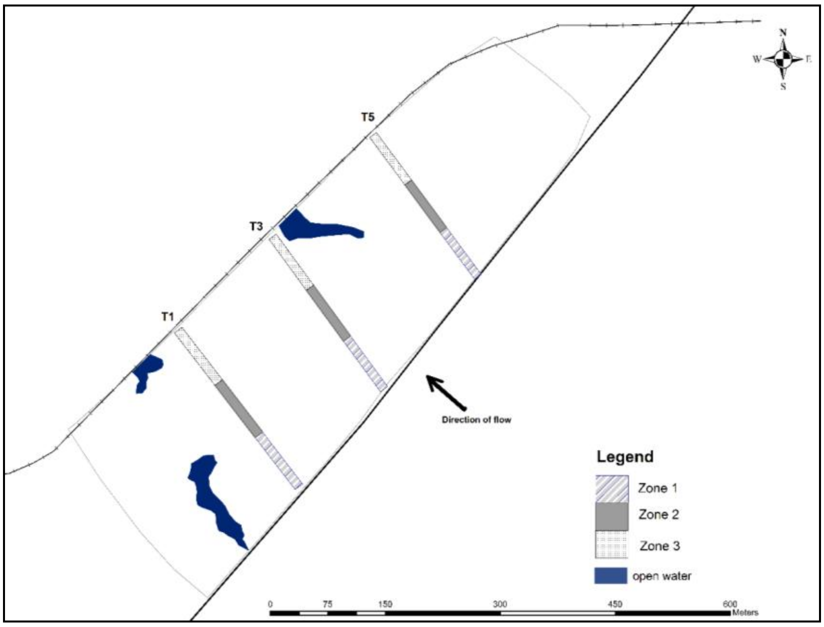


Figure 6: Location of zones along transects 1, 3 and 5. Zones were selected based on distance from the highway

2.6. Statistical analysis

The Kruskal-Wallis ANOVA test was used to analyse differences in mat thickness and free water column among zones of each transect. 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.

3. Results and discussion

3.1. Wetland bathymetry

The spatial variation in wetland bottom elevation is illustrated in Figure 7. Wetland bottom elevation ranges between 1058 and 1062 meters 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 (Figure 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).

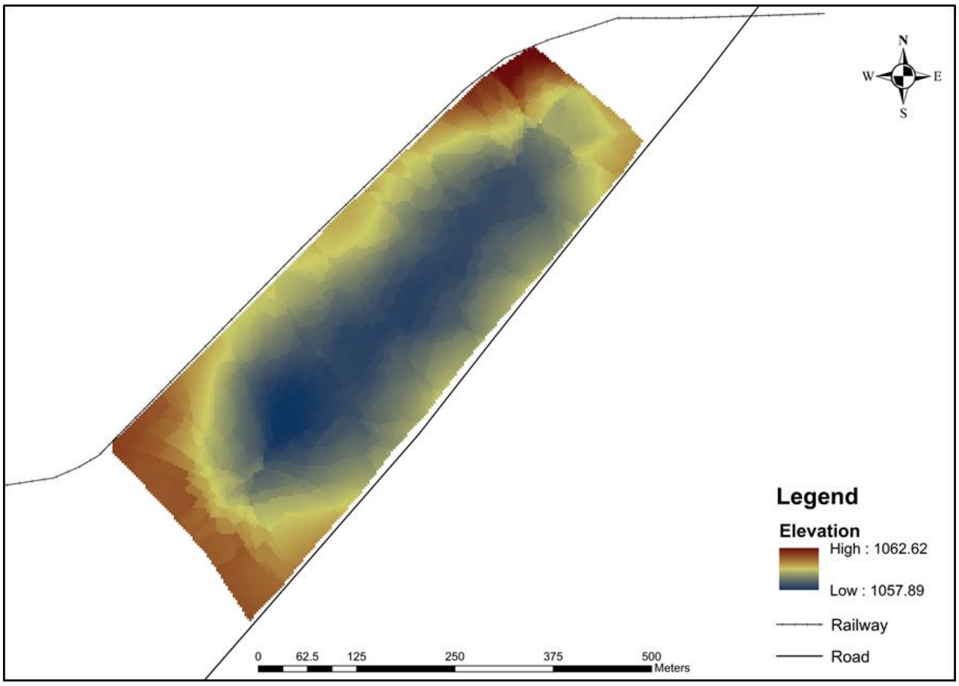


Figure 7: Elevation of the wetland bottom

3.2. Spatial and seasonal variations in water depth

Results of seasonal trends in the water depth along three transects are shown in Figure 8. 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 begun 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 at the beginning of the second wet season compared to water depth in the dry season. The observed increments were 0.04m, 0.05m, and 0.05m for transects 1, 3 and 5 respectively.

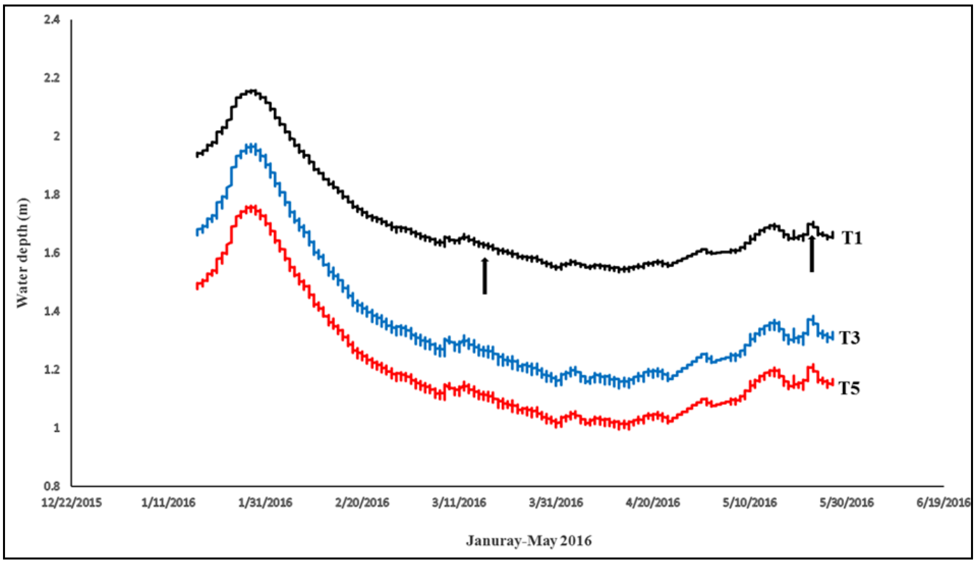


Figure 8: Variation in water depth along the three transects; black arrows indicate dates at which mat measurements were taken. Where T1, T3, T5 represent transects 1, 3 and 5

Water depth at the deepest point (transect 1) varied between 1.53 m and 2.1. From the water volume-depth relationship (equation 1); this corresponds to a water volume of 61,597 m^3 and 123,355 m^3 respectively, and reveals a 50% change in water volume during the monitoring period. The water volume-depth relationship is illustrated in figure 9. A log scale is used for displaying water volume to show the range of volumes that would be expected for a drained wetland section. The large storage capacity of a 0.18 km^2 wetland section indicates an enormous storage potential of the entire wetland system (84 km^2). 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 & Holden, 2013). In addition, the stored water is available for domestic and irrigation use especially during dry periods.

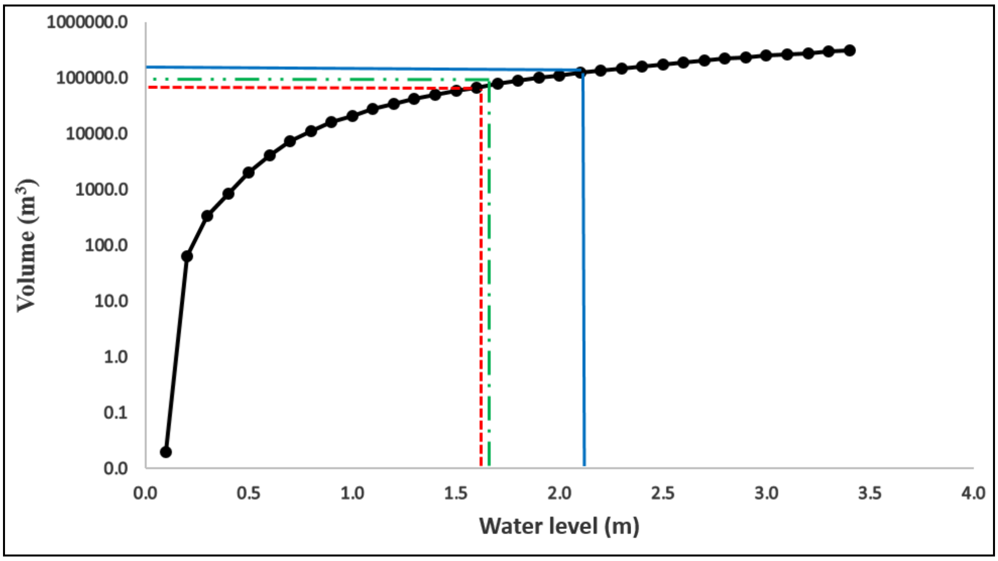


Figure 9: Estimated wetland volume as a function of water depth for the study section; blue line shows the volume corresponding to highest water level recorded (January), green line represents volume at the second date of mat measurements (May) and red line represents volume on the first date of mat measurements (March).

3.2.1 Relationship between precipitation and water depth

The frequency and quantity of the local precipitation was low at the beginning of the dry season in January 2016; with a cumulative rainfall of 73 mm. This was followed by a dry spell in February and March. The second rainy season started at the beginning of April with cumulative precipitation of 134mm and 99mm for April and May respectively (Figure 10).

There was no significant correlation between local precipitation and the water depth variations at the three transects; transect 1 (r= -0.08), transect 3 (r= -0.1), and transect 5 (r= -0.04); and the cross correlations between precipitation and water depth were not significant. This was expected because the water regime of the wetland section is influenced by the large upstream catchment. The nearest weather station in the wider catchment with available precipitation records during the monitoring period is approximately 100km away from the study site. The rainfall trends at the second station are similar to those observed at the study site although the amount and frequency of precipitation is lower at the study site (Figure 10). The strongest correlation between precipitation data from the second station and water depth (r=0.2) was observed at a lag of two weeks which indicates a long time of concentration for the basin. However, there is need for a better monitoring network to improve understanding of the basin hydrology, which would be the basis for sustainable management of wetland systems within the basin.

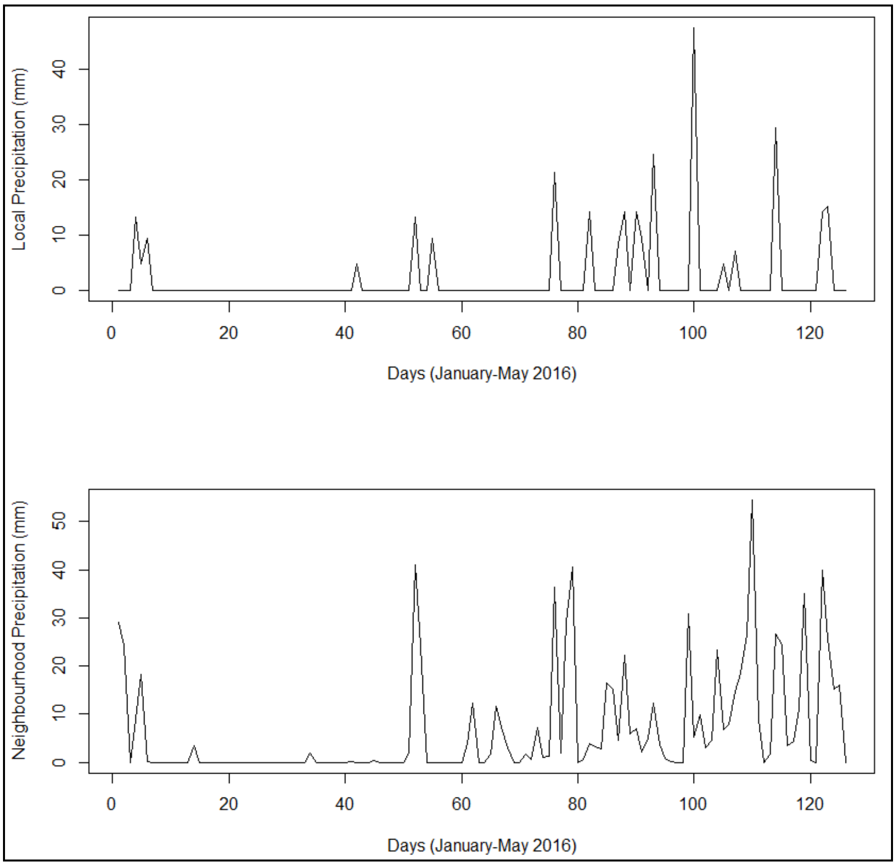


Figure 10: Local (top) and neighbouring (bottom) precipitation patterns during the 5 months monitoring period

3.3. Spatial and seasonal Variation of mat thickness and free water column

3.3.1 Mat thickness

The lowest and highest variations in mat thickness in the dry season were observed along transect 5 and transect 3 respectively (Figure 11). 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 (Figure 12) were not statistically significant (p=0.98).

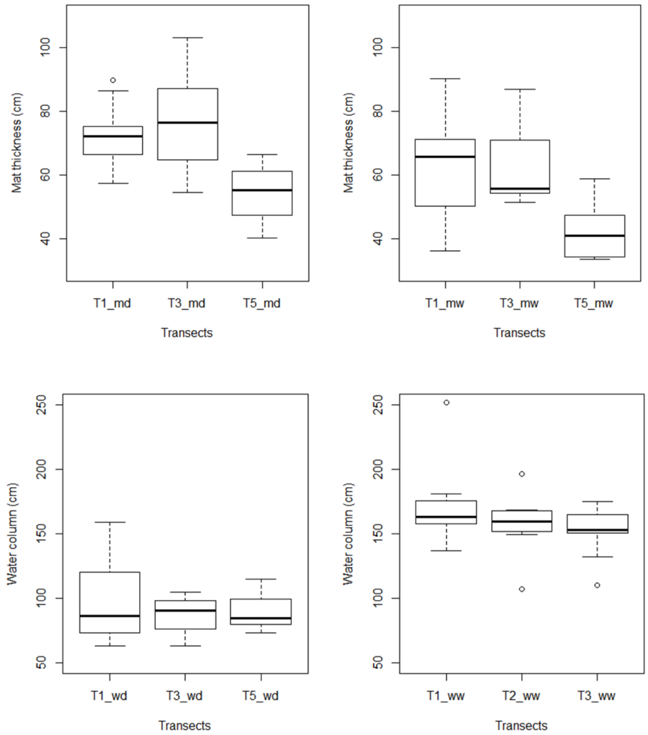


Figure 11: Variation in mat thickness (top) and free water column (bottom) in the dry and wet seasons. Where; md, mw, wd, ww represent mat thickness in dry season, mat thickness in wet season, water column in dry season and water column in wet season respectively

In the wet season, the smallest mat thickness (41.2 ± 7.6) was recorded along transect 5 (Figure 11); 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 ($p=0.18$). Overall, there was a reduction in mean mat thickness from the dry to wet season for transects and zones (Figure 11 &12), implying that the mat contracts with increasing water levels. Although the mean mat thickness reduced in all zones, the variation of mat thickness in zone two increased; which indicates that there was larger variability in mat thickness in the central part of the wetland compared to edges during the wet season (Figure 12).

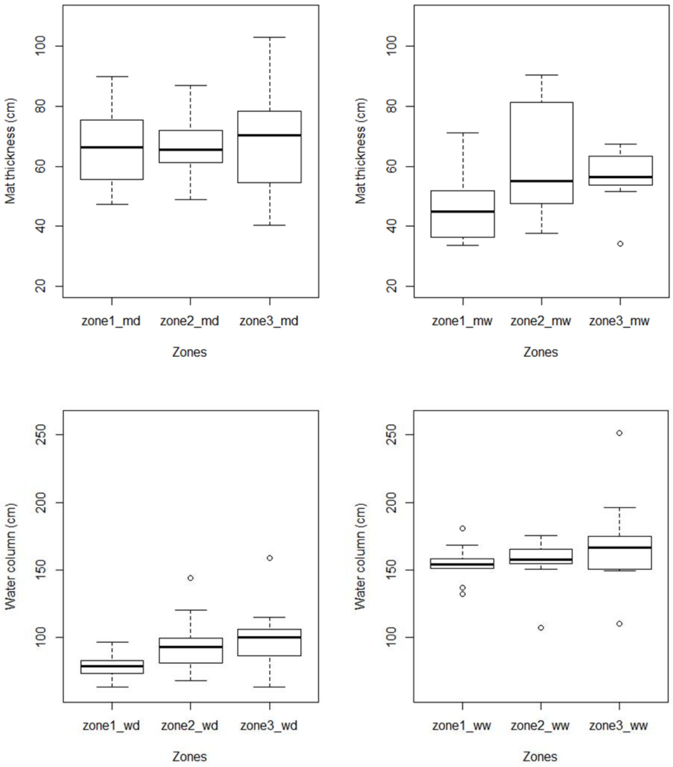


Figure 12: Variation in mat thickness and free water column by zones. Where; md, mw, wd, ww represent mat thickness in dry season, mat thickness in wet season, water column in dry season and water column in wet season respectively

3.3.2. Patterns of Free water column in the wetland system

The largest variation in free water column in the dry season was along transect 1 (111.8 ± 40.6), and the lowest value of free water column (67.9±5.1) was also along transect 1 (Figure 11). There was no significant difference in 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 (Figure 12); Dunn's post hoc test 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 (Figure 12). The highest increment in free water column occurred in zone 1 which initially had low free water column compared to zones 2 and 3 (Figure 11 & 12).

In general, during high water flow the excess water exerts pressure on the papyrus mat. This causes it to move vertically upwards, which creates more space for the water in the free water column. This explains the increase in depth of the free water column across all transects and zones in the wet season. However, as the water flow increases so does the pressure against the mat, which causes the mat to contract as it moves upwards. The buoyancy of the papyrus mat, similar to that observed in fern mats (Stofberg *et al.*, 2016); as well its ability to contract therefore influences the wetland's water regulatory and provisioning services. The mat compaction 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 & Nalubega, 1999); which could be reduced if the mat is highly compacted.

The observed temporal and spatial changes in the mat could be unique to the papyrus plant since other tropical wetland species have varying levels of buoyance, and tolerance to high water levels. For example, Miscanthidium which grows in combination with papyrus has a denser and compact mat system (Azza et al., 2000). Its bulkiness coupled with a reduced capacity to contract with increasing water levels, could result in less overall storage within the free water column during wet seasons.

On the other hand, draining and replacement of natural papyrus vegetation with agricultural crops, completely changes the wetland's hydrology. For example, replacement of papyrus with cocoyam in the Nakivubo wetland resulted in water channelization in the wetland (Kansiime *et al.*, 2005). Therefore, both the replacement of papyrus vegetation with other aquatic species or with agricultural crops could negatively affect the wetland's regulatory functions.

3.4. 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 ($r= -0.85$, $p=000$), with a coefficient of determination of 69% (Figure 13). This implies that in general, the mat thickness reduced with increases in free water column.

The outliers in red 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 differs among rooted and floating papyrus.

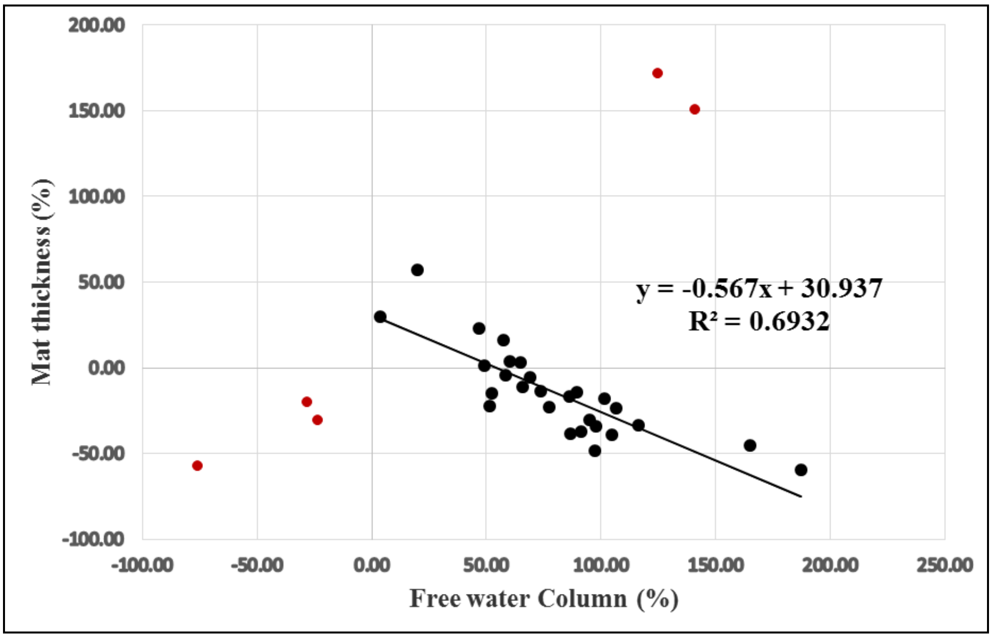


Figure 13: Relationship between changes in mat thickness and changes in free water column between the two seasons; red points are outliers at transect edges

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.

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

Figure 14 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 expect for the outliers identified in section 3.4. 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 (Figure 14).

Exceptions to the above observations were noted along man-made boundaries. For instance, at the railway edge of transects 1, 3, and 5; a more than 50% increase in free water column caused an expansion rather than contraction of the mat (Figure 14). These outliers are due to edge influences (Turner *et al.*, 2001). Since the plants along the edges are rooted, increased water levels cause the root mat to expand like a sponge. In some cases, the water pressure causes the mat to rise slightly; which enables water to seep through and temporally inundate the wetland's edges/transition zone.

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.

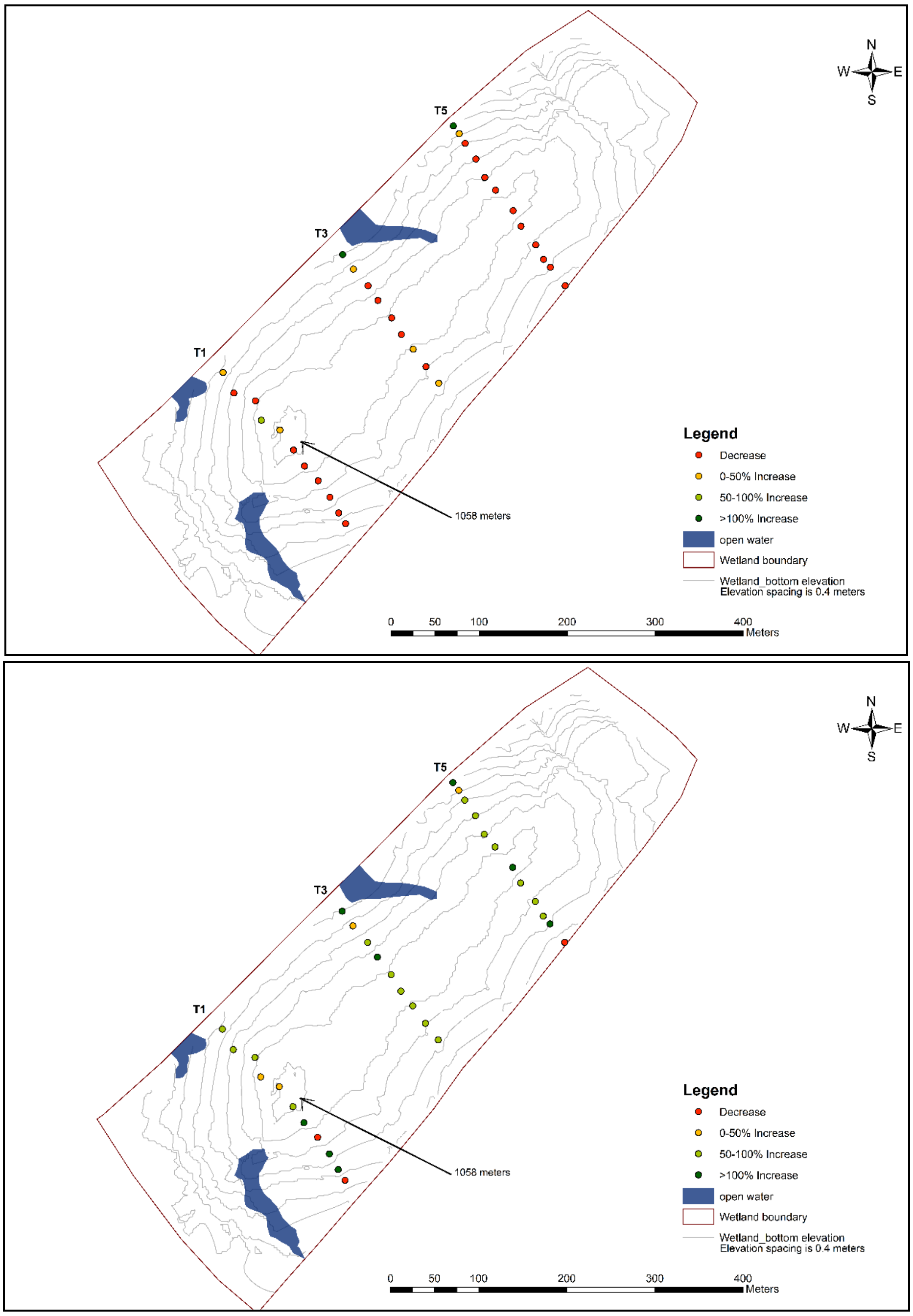


Figure 14: Percentage change in mat thickness (top), and free water column (bottom) from the dry to the wet season

Our research reveals that in addition to the vertical movement of the papyrus mat with increasing water levels (Headley & Tanner, 2006; Kansiime *et al.*, 2007; Kipkemboi *et al.*, 2002) the mat has the ability to contract 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 contract by more than 50% of its initial size, which creates more space for the excess water. The free water column beneath the papyrus mat increases across all transects in the wet season implying an overall increase in wetland water volume. We estimated the volumes associated with the water depth variations of the wetland section; which ranged from 61,597 m^3 to 123,355 m^3 showing a 50% change in storage potential during the monitoring period. This illustrates how the papyrus mat dynamics influence water storage in papyrus wetlands, and enhances understanding of the wetland's regulatory and provisioning functions.

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