Vol. 37(1), pp. 1-18, June 2018
ISSN 1821-536X (print)
ISSN 2619-8789 (electronic)

Tanzania Journal of Engineering and Technology

Full Length Research Paper

Hydrology and Hydraulics of the Lubigi Wetland in Uganda

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ABSTRACT

The Lubigi wetland, which is located in the north-western part of Kampala, receives polluted water from Kampala city and discharges it into Mayanja River. However, there is lack of information and knowledge on the hydrology and hydraulics of the Lubigi wetland, which are important for protection of wetland ecosystems and fulfill the Uganda national policy for the conservation and management of wetland resources. The national policy aims at promoting the conservation of Uganda's wetlands, in order to sustain their ecological and socio-economic functions for the present and future well-being of all the people of Uganda. Pertinent data collection, field tests and surveys were carried out to gather data necessary for establishing the current status of the hydraulics and hydrology of Lubigi wetland. The results revealed that the Lubigi wetland demonstrates considerable impounding reservoir and flood buffering capacity. This is an important service provided by the wetland, to alleviate possible negative impacts of storms and floods events. The Lubigi wetland total influents and effluents discharges, have mean values of 222,377.60±132,365 m^3/day and 221,356.80±122,256 m^3/d, respectively. The wetland water balance is dominated by the influent discharges which account for 93.21% of the total water influx, and the effluent discharges which account for 97.7% of the total water outflow. The wetland main study area hydraulic residence times, varies between 6.0 hours and 10 days. Hence, the wetland is endowed with abundant water fluxes, water impounding capacity and adequate hydraulic retention times. The volumetric efficiency of the wetland main study area is 63% and 38% during wet season and dry season, respectively. This indicates that on average only about 50% of the volume of the Lubigi wetland main study area is lost through short-circuiting. The dispersion number of the wetland was about 0.01 to 0.03, which indicates that the flow regime through wetland is close to plug flow.

Key words: Lubigi wetland, Hydraulics, Hydrology.

INTRODUCTION

Natural wetlands occur in areas where soils are naturally or artificially inundated or saturated with water, due to high ground water or surface water levels during some periods or all year round (Neue *et al.*, 1997). Consequently, the main environmental forcing factor in natural wetlands is hydrology (Junk, 2005).

Hydrological factors such as precipitation, ground water characteristics, surface water flow and evapotranspiration (which control the amount, frequency and flow rate/dynamics of water) in natural wetlands are known to affect other environmental factors such as salinity, soil anaerobicity and nutrient availability. These in turn, determine the flora and fauna that develop in a natural wetland (Kansiime and Nalubega, 1999; Muraza, 2013; Mayo *et al.*, 2014). In addition, hydrology also affects and influences nutrient flows, vegetation and microbial ecology and hence wetland water quality development (Kansiime and Nalubega, 1999; Mayo *et al.*, 2018). At the same time, the biotic factors in turn affect the wetland's hydrology and biochemistry (Mitsch and Gosselink, 2007).

Hydrology thus affects nutrient flows, vegetation ecology and microbial ecology. These in turn, influence the capacity of the wetland to remove pollutants from wastewater (Mburu *et al.,* 2013). This capacity in particular depends on the quantity of wastewater flowing into the wetland, the wetland basin geometry, morphological features and characteristics which affect the hydraulic residence time and wastewater distribution and the the interactive processes between the water, wetland sediments, suspended solids, flora and microbial populations.

In natural wetlands, hydrology is also known to directly influence temporal changes in depth i.e the hydroperiod, and the morphology of the wetland bottom (Kadlec and Wallace, 2009). In the tropics, most surface water fed i.e rheotrophic natural wetlands are subjected to considerable water-level fluctuations depending on the dry and rainy seasons, and hence the wetlands assume floodplain characteristics (Junk, 2005; Mitsch, 2009). Consequently, flora and fauna living in these wetlands not only tolerate, but also require these water-level fluctuations for the long-term survival of their populations (Junk, 2005). In addition, natural wetlands are characterised by horizontal and lateral flows with areas of water pools (stagnant water) influencing spatial water distribution and storage capacity or the hydraulic retention of the system. However, predominantly channelized horizontal flow, causes short retention and contact times between the allochthonous water and the bulk of the autochthonous water in the wetland system. This leads to low nutrient exchanges and a reduction in the purification capacity of the wetland system (Kansiime and Nalubega, 1999).

Superimposed on natural processes, anthropogenic activities such as drainage and agriculture may affect the wetland water balance and the timing of water flows, through interventions such as urban development and the removal of vegetation cover, as observed in the Nabajjuzi natural wetland catchment in Uganda (Kashaigili, 2008). Such human-induced disturbances, increase the storm water run-off flow component, and reduce the base flow regimes during the dry seasons (Ellery *et al.*, 2003; Kashaigili, 2008). In considering the discharge of wastewaters into natural wetlands, the relationship between hydrology and the wetland ecosystem characteristics needs to be recognized. Factors such as the sources of the wastewater, flow rates, flow velocities, flow depths, hydraulic retention times, renewal rates and durations and frequencies of inundation have a major bearing on the chemical and physical properties of the wetland substrate. These properties in turn influence the character and health of the ecosystem, as reflected by the species composition and richness, primary productivity, organic deposition and flux, and nutrient cycling (U.S. Environmental Protection Agency, 2000).

The importance of hydrology in maintaining the structure and functioning of a natural wetland has been emphasized by Asp (2009), who reported that hydrology is the single most important determinant for the establishment and maintenance of specific types of natural wetlands and wetland species. Howell *et al.* (1988) specified water depth, its seasonality and nutrient status as the controlling factors for the distribution of natural wetland types. Natural wetlands typically tend to be characterized by channelised flows, short-circuiting, areas with pools of stagnant water, dead zones and obstructive sediments banks, all of which tend to have impacts on major flow paths and patterns and hydraulic retention times and their distributions, which in turn affect the levels of nutrient exchange and pollutants removal (Kipkemboi *et al.*, 2007; Mayo *et al.*, 2014).

The main method used to study internal hydraulic processes, is to release an inert substance like lithium, bromide or chloride as a tracer, and then subsequently to measure the concentration changes over time at fixed positions along the water and tracer flow path (Persson and Wittgren, 2003; Headley and Kadlec, 2007; Kadlec and Wallace, 2009). One result of such a tracer study, is the determination of the actual hydraulic residence time of the wetland at the time of carrying out of the study, which is defined as the centroid of the tracer concentration versus time response curve, plotted from the tracer study data (U.S. Environmental Protection Agency, 2000). The tracer concentration versus time response curve can further be analysed to determine the natural wetland dispersion number. According to Kadlec and Wallace (2009), riverine ecosystems are often conceptualised as being "plug flow" with some dispersion.

Other tracer studies performed in constructed wetlands systems, have also reported observing "plug flow" with significant amounts of dispersion (Sanford *et al.*, 1995; Bhattarai and Griffin, 1998; Liehr, 2000; George, 2000). Results from other tracer studies, have shown that the hydraulic characteristics of wetlands can be approximated by a series of 4 to 6 equally-sized "completely mixed flow" reactors (Crites and Tchobanoglous, 1998; Kadlec and Wallace, 2009).

However, the use of artificial tracers to study flow dynamics in natural wetlands is difficult and laborious, and the dispersivity of these tracers was found to remain quite unpredictable due to the heterogeneity and spatial and temporal variability in these systems (Abira, 2007). On the other hand, natural tracers such as Electrical Conductivity are reported to be simple tools which can provide a semi-quantitative description of the wetland transport processes (Gaudet, 1979; Mitsch and Reeder, 1991). Heut (1991) for example, found that in Lake Tjeuke in the Netherlands, Electrical Conductivity was strongly correlated to the conservative and inert chloride ion Cl^-, which is a suitable tracer. In a natural wetland receiving wastewater flows, the Electrical conductivity is usually still higher than the background values, thus making Electrical conductivity a potential natural tracers (Kansiime and Nalubega, 1999). The main aim of the study was therefore to determine hydraulic characteristics and water balance of the wetlands as the important parameters for vegetation and microbial ecology. The output obtained from this work may be used for mathematical modelling of pollutants discharged into the wetland.

MATERIALS AND METHODS

The Lubigi wetland main study area

The main study area investigated in this research study, is as shown in Figure 1. The area comprises of the Upper Lubigi wetland, which is delineated in the north-east of Kampala city by the Hoima Road, with the main wastewater inlet located at latitude 00°20'48" N and longitude

32°32’28” E; and in the south-west by the Sentema Road with the main effluent outlets located at latitude 00°19’56” N and longitude 32°31’34” E (Figure 1). This section of the wetland covers an area of approximately 1.1 km^2, at an altitude of approximately 1,158 m above mean sea level, with a total drainage catchment area of approximately 40.0 km^2. This is the section of the wetland, which receives the initial and direct impacts of the visually heavily polluted wastewater from the upstream Nsooba-Lubigi storm water drainage channel and the Lubigi Sewage Treatment Plant.

Lubigi wetland has a variety of plant species, but nine plant species are dominant including *Echinochloa pyramidalis, Cyperus papyrus, Thelypteris acuminata* and *Paspalum crobiculatum. Echinochloa pyramidalis* was particularly dorminant near the wetland main water inlet zone, and also along the wetland main central drainage channel. Other plant species include *Typha capensis, Persicaria cordata, Rottboellia cochinchinensis, Oldenlandia lansifolia* and *Ipomoea rubens*.

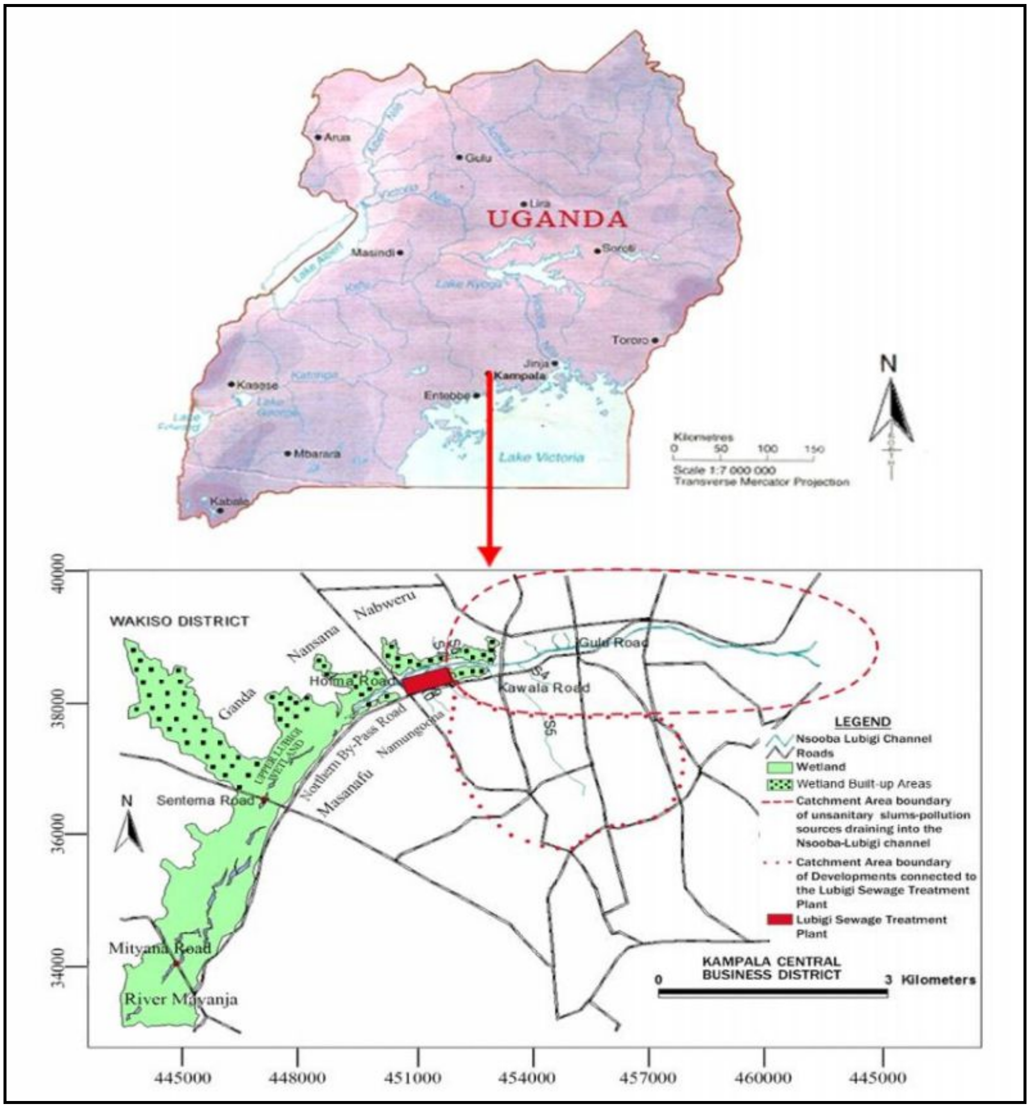

Figure 1: Map of the Lubigi Wetland Main Study Area

Wetland Hydrology

All water inlets into and outlets from the Lubigi wetland were identified and geo-referenced using a Garmin Global Positioning System (GPS) device, in order to determine and record their co-ordinates. Then the locations and routes of these inlets and outlets were transferred to a digitized map of the wetland area. Their size (widths, depths, lengths) were also taken and recorded. Inflows and outflows from the wetland, were measured daily for a period of one calendar year from August 2016 to July 2017 inclusive, in order to closely follow temporal seasonal variations, using the following materials and methods:

(i) Staff gauges with established stage-discharge relationship rating curves.

(ii) Area-velocity methods using a current meter, propeller No. 1-135308 to 135513 attached to an OTT hydrometer z30 quartz timer.

(iii) Appropriate floating objects for measuring flow velocities, where the current meters could not be employed.

(iv) Filling buckets of known volumes during measured time periods.

Data for daily rainfall and evapotranspiration (ET) during the research period were obtained from the Uganda National Meteorological Authority (2016), for the nearby Makerere University meteorological station. The rainfall distribution into the system was subsequently estimated for each section of the wetland, by considering the catchment area of that section. Storm water run-off and sub-surface inflows into the wetland were measured at the respectively entry points.

Ground water flows i.e seepage and infiltration as defined in the wetland water balance Equation (1), were studied based on interpretations of earlier descriptions and analyses of the geology, hydrogeology and soils of the Lubigi wetland area, by the Uganda Geological Survey Department (1957). In addition, pertinent *in situ* measurements of resistivities applying the Wenner 4-point Test were made. The WDJD-4 low-frequency soil resistivity meter connected to WDZJ-4 soil electrodes was used in this test. Using the results from the determination of the water balance components as discussed above, the Lubigi wetland water balance was developed.

$$\frac{dV}{dt} = Q_i + Q_s + Q_{gs} + R - Q_e - Q_{gi} - ET \ldots(1)$$

Wetland Hydraulics

A tracer study was conducted to determine the major water flow paths and patterns, and to find out the wetland hydraulic retention times, flow velocities, flow depths, volumetric efficiency and dispersion number. This was conducted in the wetland in September 2016 during the rainy peak flow season. In this study, 20 kg of sodium chloride as the tracer, were dissolved in 20 litres of water drawn from the wetland main central drainage channel in a plastic container. The sodium chloride tracer solution, was then released as a pulse into the main central drainage channel in transect T2.

Subsequently, *in situ* recordings of Electrical Conductivity (EC) values were made at the main effluent outlet O1, at 10 minute intervals for a period of about 6 hours. At the start of this experiment, it was noted that the background Electrical Conductivity (EC) values of the water in the wetland at main effluent outlet O1, had remained persistently between 498 μS/cm and 502 μS/cm. Hence, subsequent major increases in Electrical Conductivity (EC) values, which were recorded after a period of time after the release of the tracer solution, were largely attributed to the arriving sodium chloride ions.

For purposes of further analyses, these recorded Electrical Conductivity (EC) values were converted to equivalent NaCl, Total Dissolved Solids (TDS) concentrations, applying the procedure adopted by Hubert and Wolkersdorfer (2015). The interpretation of the results obtained from these measurements, were based on the fact that the allochthonous wastewaters entering into the wetland, tend to have considerably higher Electrical Conductivity (EC) values, than the background Electrical Conductivity (EC) values of the autochthonous wetland waters (Kansiime and Nalubega, 1999).

To facilitate the confirmation, interpretation and explanation of the results of the tracer study described above, another similar study was carried out in January 2018 during the dry low flow season. *In situ* wetland water Electrical Conductivity (EC) values, were measured using an Electrical Conductivity (EC) electrode TetraCon 325 WTW, connected to an Electrical Conductivity (EC) meter WTW 3310.

Data Analyses and Presentation

Numerical data generated from the investigations and studies in this research study, have been presented where appropriate in the form of Ranges, Means, Standard Deviations and percentages. All data were preliminarily examined to check for their correctness. Those found to be obviously erroneous, by virtue of appearing to be incongruous with the rest of the data in their respective sets, were discarded. For data found to be normally distributed, their arithmetic means and arithmetic standard deviations were computed and applied as necessary.

RESULTS AND DISCUSSION

Wetland Hydrology

Inflows and outflows

All the identified water inlets into and outlets from the Lubigi wetland, are as shown in Figure 1. Inlet 1 is a box culvert with 12 cells crossing the Hoima Road, and it is the main water inlet into the wetland, receiving flow from a canalised stream, which receives discharges from the newly constructed Nsooba-Lubigi drainage channel. The channel collects municipal and industrial wastewater, storm water run-off and sub-surface water flow from the upstream densely populated, unsewered informal settlements. In addition, the stream receives effluent discharges from the Lubigi Sewage Treatment Plant. Inlets 2, 3 and 4 are small circular culverts crossing the Hoima Road, practically dry during most periods and discharging small volumes of storm water run-off and sub-surface inflows from the Nabweru zone into the wetland, only during heavy rain periods.

Inlets 5, 6 and 7 are medium-size man-made channels, practically dry during most periods and discharging moderate volumes of storm water run-off and sub-surface inflows from the Nansana and Ganda towns into the wetland, only during heavy rain periods. Inlets 8, 9, 10 and 11 are medium-size circular culverts crossing the Northern By-pass Highway, practically dry during most periods and discharging moderate volumes of storm water run-off and sub-surface inflows from the Namungoona and Masanafu towns into the wetland, only during heavy rain periods. Outlets 1 and 2 are large culverts crossing the Sentema Road, and they are the main effluent outlets from the wetland. Outlets 3, 4, 5, 6, 7, 8 and 9 are small culverts crossing the Sentema Road, discharging moderate volumes of effluent from the wetland.

The Lubigi wetland field flows measurements data are presented in Figure 2. The wetland inflow discharges range from 1.052 m^3/s to 23.207 m^3/s, with a mean value of 2.574±1.532 m^3/s. The inflow velocities range from 0.110 m/s to 0.841 m/s, with a mean value of 0.441±0.112 m/s. The wetland outflow discharges range from 0.506 m^3/s to 22.062 m^3/s, with a mean value of 2.562±1.415 m^3/s. The effluent velocities range from 0.242 m/s to 0.954 m/s, with a mean value of 0.523±0.123 m/s. It was observed that 94 wetland outflow discharge measurements out of 370 (25.4%) greatly exceeded the inflow discharges. This was attributed to temporary excessive increases in wetland basin water storages, during previous heavy rain storm events; which storages are then released through the effluent outlets later and over longer periods of time. This demonstrates the considerable impounding reservoir and flood buffering effects of the Lubigi wetland. This is an important role played by wetlands, to alleviate possible negative impacts of storms and floods events (Mitsch and Gosselink, 2007).

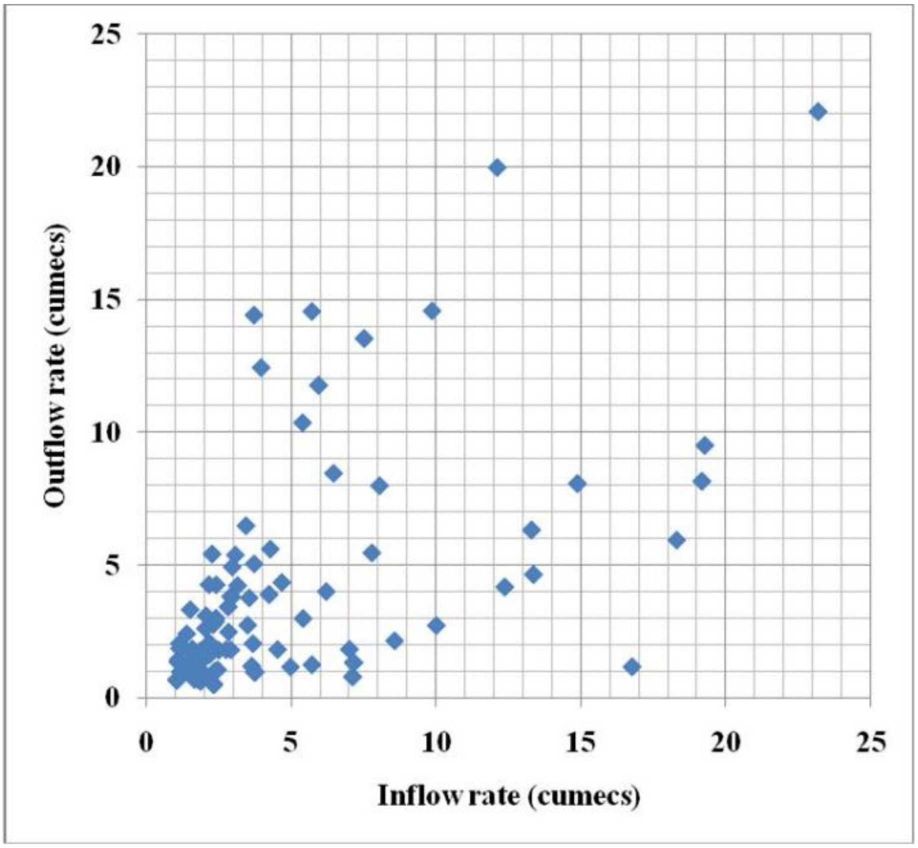

Figure 2: Wetland Enfluent versus Effluent flow rates

Rainfall

The Lubigi wetland rainfall data are presented in Figure 3, which shows that Lubigi wetland conforms to the typical rainfall patterns of areas within the equatorial belt, particularly in the Central and East African regions. These areas experience a moist sub-humid climate, characterised by bi-seasonal rainfall in the periods of March to June and September to November. This rainfall is linked to the Inter Tropical Convergence Zone (ITCZ), the altitude, local topography and adjacent water bodies like lakes. The periods June to September and November to March are typically the dry seasons of the year. Indeed in the Lubigi wetland, rainfall in June to September and November to March i.e the dry seasons, is significantly lower ($p = 0.006$) than that in March to June and September to November i.e the rainy seasons. Mean annual rainfall within the equatorial belt, particularly in the Central and East African regions tends to vary between 250 mm and 2,000 mm. The Lubigi wetland annual rainfall as measured during this research study is 1,417 mm.

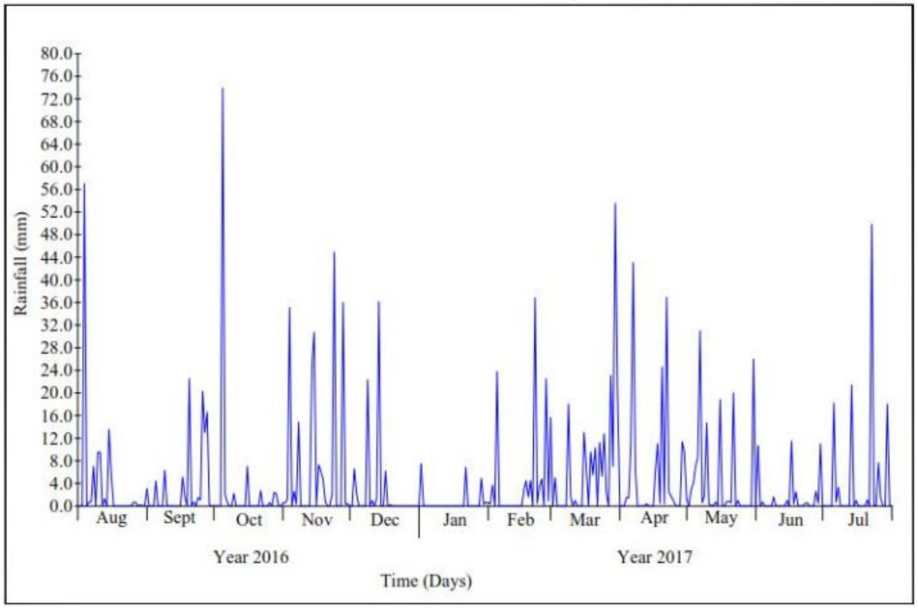

Figure 3: Lubigi Wetland Rainfall

Water losses

Evapotranspiration (ET) and infiltration into the ground are the two major sources of water loses. As already discussed, the contribution of ground water fluxes into the wetland water body via seepage, and the loss of water from the water body via infiltration through the soils down into the rocks, are insignificant and negligible for the water balance considerations. Figure 4 shows that Evapotranspiration (ET) in the Lubigi wetland, varies considerably throughout the year, irrespective of whether the season is rainy i.e March to June and September to November or dry i.e June to September and November to March.

Wetland Water Balance

The water balance of the Lubigi wetland main study area for the period of 1 July 2016 to 3 July 2017 is summarized in Table 1 and Figure 5. Generally, the bulk of the residual component of the water balance, represents the rate of change of the volume of water stored in the wetland over the period of the study. A positive residual value indicates water storage replenishment, whereas a negative value indicates water storage depletion. However, the residual component also includes elements related to uncertainties, associated with estimates of the major components of the water balance. These uncertainties include random type errors due to measurement precision, the application of rainfall and evapotranspiration (ET) data not measured *in situ*, and ground water fluxes, which have been considered to be negligible (Sriwongsitaton *et al.*, 2009; Bateganya, 2010).

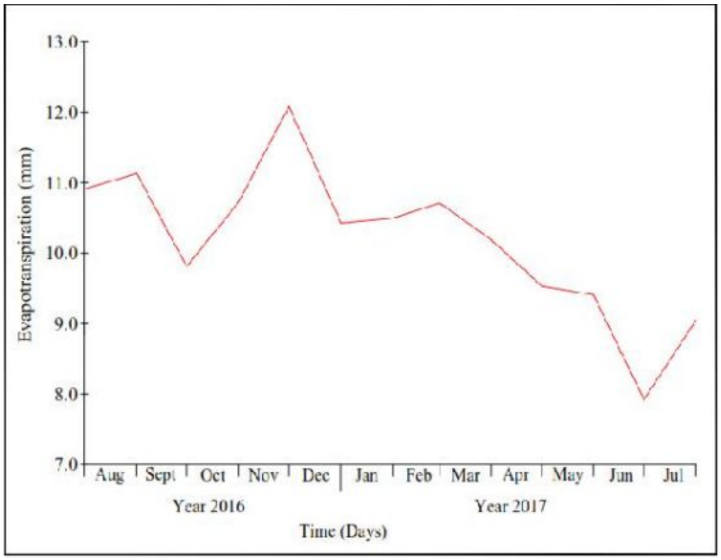

Figure 4: Lubigi Wetland Evapotranspiration

Table 1: Lubigi Wetland Main Study Area Water Balance – 1/7/2016 to 3/7/2017

Water Fluxes	**Quantity (m^3/d)**	**% of Total Influx**	**% of Total Outflux**	**% of Influent Discharge**
Influent Discharges	222,377.60	93.21		
Rainfall	3,566.54	1.49		
Storm water run-off and Sub-surface inflows	12,656.00	5.30		
Total Influx	**238,600.14**	**100**		
Effluent Discharges	221,356.80		97.71	
Evapotranspiration (ET)	5,195.26		2.29	
Total Outflux	**226,552.06**		**100**	
Residual (Total Influx – Total Outflux)	+12,048.08			−5.42

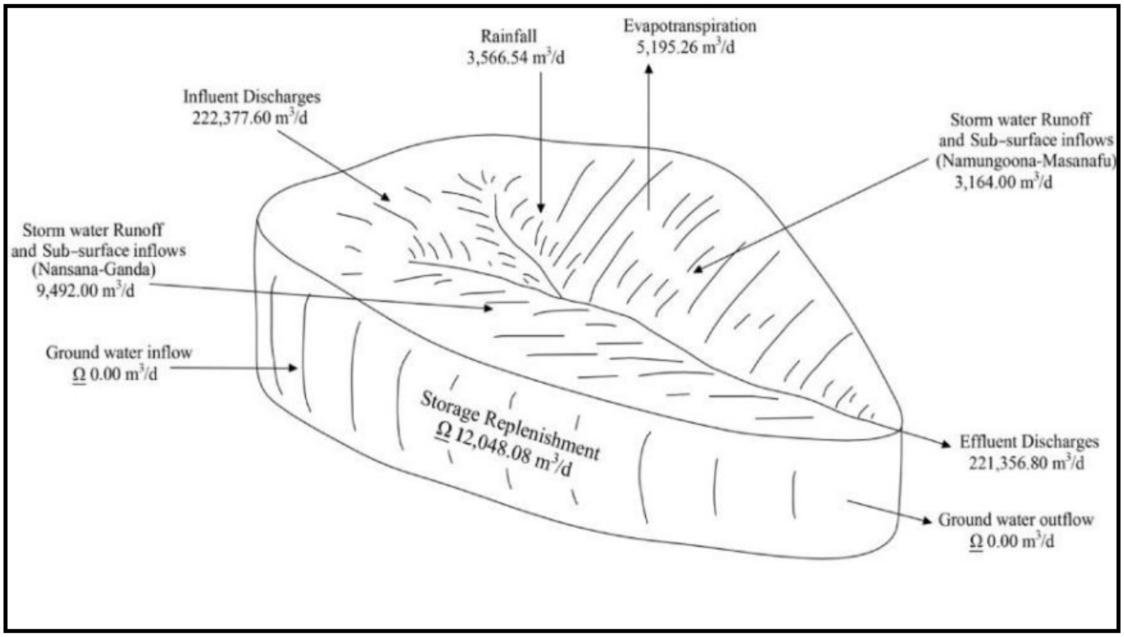

Figure 5: Lubigi Wetland Main Study Area Water Balance – 1/7/2016 to 3/7/2017

From Table 1, it is evident that the Lubigi wetland water balance is dominated by the influent discharges, which account for 93.21% of total water influx, and the effluent discharges, which account for 97.71% of total water outflux. Rainfall, storm water run-off and sub-surface inflows and evapotranspiration (ET), constitute minor components of the wetland water balance, accounting for 1.16% and 4.10% of total water influx and 2.29% of total water outflux, respectively. The positive residual volume of +12,048.08 m^3/d which is 5.42% of influent discharges, indicates a net wetland water storage replenishment during the study period. According to Kadlec and Wallace (2009), it is only with great care that you can obtain residuals of =5.0% to ±10.0% of influent discharges in water balance studies.

The theoretical hydraulic residence time of a wetland, depends on the volume of the wetland basin, and the wetland water flow rates. Based on the volume of the Lubigi wetland main study area basin, the theoretical hydraulic residence time during the peak outflows (1,906,157 m^3/d) was about 6 hours. However, during low outflows (43,718 m^3/d) the theoretical hydraulic residence time increased to about 10 days. The theoretical hydraulic residence time based on the mean outflow of 221,357 m^3/d was about 2 days.

From all the foregoing hydrological features presented, it is evident that the Lubigi wetland has the endowment of a rheotrophic hydrological system, fairly abundant water fluxes, water impounding capacity and fairly adequate hydraulic retention times. Kansiime and Nalubega (1999) reported that hydrological characteristics like these, favour the biogeochemical mechanisms and processes mediating the transformation and removal of pollutants in a wetland.

For comparison purposes, in the water balance of the Nabajjuzi natural wetland in Uganda, Bateganya (2010) reported the direct rainfall input to be 5,396.96 m^3/d during the peak flow regime and 2,564.98 m^3/d during the low flow regime. Evapotranspiration (ET) was found to be

8,455 m^3/d. Influent discharges accounted for approximately 96.0% of total water influx, and the effluent discharges accounted for approximately 88.0% of total water outflux.

LUBIGI WETLAND HYDRAULICS

Tracer Studies

The field Electrical Conductivity (EC) measurements data for the Lubigi wetland tracer study conducted in September 2016 i.e the rainy peak flow season. The results of this tracer study, are presented as the resultant Sodium Chloride Total Dissolved Solids (TDS) Concentration versus Time response curve in Figure 6. The curve indicates that the tracer initially exited the wetland as an impulse, i.e a fairly sharp spike of Sodium Chloride Total Dissolved Solids (TDS) concentration. However, the tracer was still detectable as smaller peaks, sometime after the main peak. The initial sharp main tracer peak, indicates that there was little mixing and dispersion of the Sodium Chloride solution and the wetland water, and thus the Sodium Chloride solution moved predominantly in a "plug flow" hydraulic regime.

This can be attributed to the short-circuiting effect of the visibly prominent central drainage channel, running throughout the wetland from the main water inlet to the effluent outlets. The subsequent additional smaller peaks are indicative of smaller water flow paths, indicating that later there occurred more mixing and dispersion of the Sodium Chloride solution and the wetland water, leading to several other preferential flow paths in which the solution mixture meanders in re-circulation or dead zones for some time, before it gets back into the main flow channel (Kadlec, 2007; Kadlec and Wallace, 2009). This could be attributed to the presence of visibly prominent open water ponds just upstream of the Sentema Road.

Similar observations were made in a tracer study carried out by Abira (2007) in a constructed wetland in Kenya, whereby the tracer also emerged after time delays as a sharp spike, followed by smaller peaks. The time delays were caused mainly by a severe decline in the wetland hydraulic conductivity, due to the deposition of sediments and detritus and the presence of plant roots and rhizomes (Kadlec and Knight, 1996). Also according to Kadlec and Wallace (2009), riverine ecosystems are often conceptualised as having "plug flow" with some dispersion, such as was observed in this Lubigi wetland tracer study. Other tracer studies performed in constructed wetlands systems, have also reported significant amounts of dispersion, with tracer concentration versus time response curves similar to Figure 6 (Sanford *et al.*, 1995; Bhattarai and Griffin, 1998; Liehr *et al.*, 2000; George, 2000).

To facilitate further confirmation, interpretation and explanation of the results of the above-mentioned Lubigi wetland tracer study of September 2016, another similar study was carried out in January 2018 during the dry low flow season. However, in this study additional measurements of Electrical Conductivity values were carried out in the visibly prominent open water ponds, located approximately 300 m downstream of transect T3 and approximately 80 m away from the main central drainage channel towards the Nansana-Ganda edge of the wetland. The main objective of these additional Electrical Conductivity observations, was to test the hypothesis that these open water ponds act as alternative preferential flow paths and re-circulation or dead zones, in which the Sodium Chloride solution and the wetland water mixture, meanders first before returning to the main flow channel and ultimately out through the wetland effluent outlets; and that it is this phenomenon which manifests itself as additional smaller peaks of Sodium Chloride Total Dissolved Solids (TDS) concentration, detected after the main peak as shown in Figure 6.

The measurements of Electrical Conductivity values in the open water ponds, were carried out simultaneously with the main *in situ* recordings of Electrical Conductivity values at the main effluent outlet O1, at 10 minute intervals for a period of approximately 9 hours. The field Electrical Conductivity (EC) measurements data for the Lubigi wetland tracer study conducted in January 2018. The results are presented as the resultant Sodium Chloride, Total Dissolved Solids (TDS) Concentration versus Time response curves in Figure 7. A close examination and study of the behavior of the main wetland effluent outlet O1 curve, concurrently with the behavior of the open water ponds curve, confirms that indeed the tracer initially exited the wetland as an impulse, i.e a fairly sharp spike of Sodium Chloride Total Dissolved Solids (TDS) concentration.

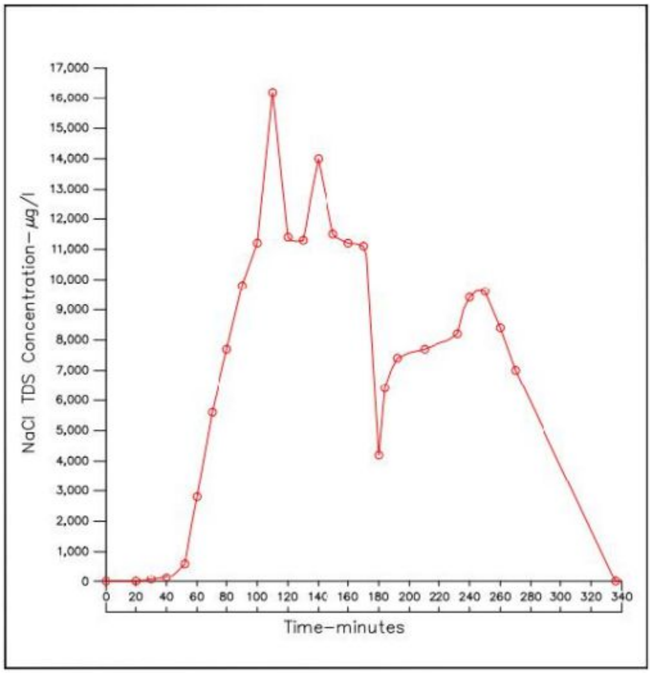

Figure 6: Lubigi Wetland NaCl Concentration versus Time Response Curve- Sept. 2016

Initially, there was minimal mixing and dispersion of the Sodium chloride solution and the wetland water, and the Sodium chloride solution moved predominantly in a "plug flow" hydraulic regime. This was caused by the short-circuiting effect of the prominent central drainage channel, running throughout the wetland from the main water inlet to the effluent outlets. However, sometime after the main tracer sharp peak of Sodium Chloride Total Dissolved Solids (TDS) concentration, more mixing and dispersion of the Sodium Chloride solution and the wetland water occurred, leading to the formation of diverse smaller water flow paths. These paths led to several other preferential flow routes in which the Sodium chloride solution mixed with the wetland waters entered and circulated within the open water ponds for some time, before it flowed back into the main central drainage channel. The solution mixture then exited the wetland, and it kept being detected as additional smaller peaks of Sodium Chloride Total Dissolved Solids (TDS) concentration at the main effluent outlet O1, several hours after the main tracer peak had subsided.

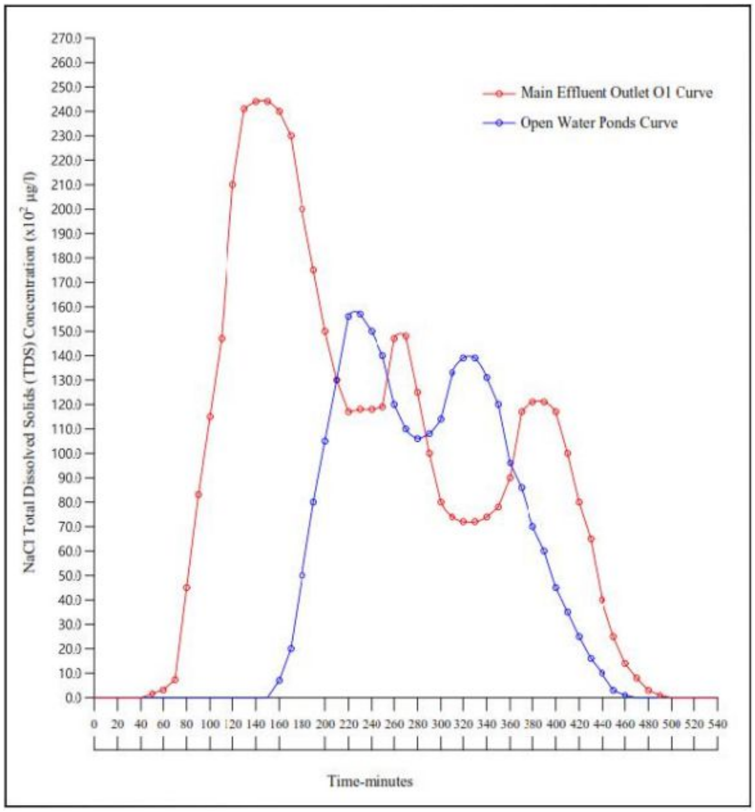

Figure 7: Lubigi Wetland NaCl Concentration versus Time Response Curves-Jan. 2018

Lubigi Wetland Actual Hydraulic Residence Times, Dispersion Numbers, Volumetric Efficiencies and Flow Paths

Detailed analyses of the Sodium chloride Total Dissolved Solids (TDS) concentration versus time response curves, were done using the approach adopted by Metcalf and Eddy Inc. (2003), and based on the hydraulic flows and physical conditions prevailing on the particular days on which the September 2016 and January 2018 tracer studies were conducted. The actual retention time was obtained from the trace studies by plotting residence time distribution (RTD) curves. The tracer technique used was pulse input using NaCl, which was injected at the inlet of the study area. Nacl was measured at the outlet from which RTD curves were plotted. RTD curves were truncated when tracer concentration reached the background levels in which case the curve is normalized in such a way that the area under if is unity.

The actual tracer mean hydraulic residence times derived from the curves were determined by Equation (2), and the variances used to define the spreads of the distributions was determined by Equation (3) (Metcalf and Eddy Inc., 2003).

$$\bar{t}_c = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt} \text{............(2)}$$

Where $\bar{t}_c$ = the actual tracer mean hydraulic residence time in minutes, t = time in minutes, C(t) = the tracer concentration at time t in µg/l.

$$\sigma_c^2 = \frac{\int_0^\infty (t-\bar{t})^2 C(t)dt}{\int_0^\infty C(t)dt} = \frac{\int_0^\infty t^2 C(t)dt}{\int_0^\infty C(t)dt} - (\overline{t_c})^2 \text{..(3)}$$

Where σ^2_c = the variance used to define the spread of the distribution in minutes^2, t = time in minutes, C(t) – the tracer concentration at time t in µg/l.

If the curves are defined by a series of discrete time-step measurements, the actual tracer mean hydraulic residence times were typically approximated by Equation (4), and the corresponding variance by Equations (5) (Metcalf and Eddy Inc., 2003).

$$\overline{t_{\Delta c}} \approx \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \text{.................................(4)}$$

Where $\bar{t}_{\Delta c}$ = the actual tracer mean hydraulic residence time, based on a series of discrete time-step measurements in minutes, t_i = the time at the *i*th measurement in minutes, C_i = the concentration at the *i*th measurement in µg/l, Δt_i = the time increment about C_i in minutes.

$$\sigma^2_{\Delta c} \approx \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} .- (\overline{t_c})^2 \text{...........(5)}$$

Where $\sigma^2_{\Delta c}$ – the variance used to define the spread of the distribution, based on discrete time measurements in minutes^2, t_i = the time at the *i*th measurement in minutes, C_i = the concentration at the *i*th measurement in µg/l, Δt_i – the time increment about C_i in minutes.

The theoretical hydraulic residence times were computed by Equation (6) (Metcalf and Eddy Inc., 2003).

$$\tau = \frac{V}{Q} \text{...(6)}$$

Where τ = the theoretical hydraulic residence time in minutes, V = the volume of the wetland basin in m^3, Q = the water flow rate in m^3/minute.

The wetland volumetric efficiencies were calculated by Equation (7) (Bateganya, 2010).

$$e_v = \frac{V_{active}}{V_n} = \frac{\overline{t_c}}{\tau} \text{..............................(7)}$$

Where e_v = the wetland volumetric efficiency, V_{active} = the active volume of the wetland basin, calculated from the actual tracer mean hydraulic residence time in m^3, V_n = the nominal/actual wetland basin volume in m^3, $\bar{t}_c$ = the actual tracer mean hydraulic residence time in minutes, τ = the theoretical hydraulic residence time in minutes.

The wetland dispersion numbers were computed by Equation (8) (Metcalf and Eddy Inc., 2003).

$$d = \frac{1}{2}\frac{\sigma^2_{\Delta c}}{\tau^2} \text{...(8)}$$

Where d = the wetland dispersion number, $\sigma^2_{\Delta c}$ = the variance used to define the spread of the distribution, based on discrete time measurements in minutes^2, τ = the theoretical hydraulic residence time in minutes.

From the foregoing analyses using Equations (2) to (8), the theoretical hydraulic residence times for the Lubigi wetland main study area, based on the September 2016 and January 2018 tracer studies were found to be approximately 8 hours and 24 hours, respectively. The corresponding actual tracer mean hydraulic residence time based on the September 2016 and January 2018 tracer studies were found to be approximately 5 hours and 9 hours, respectively. Actual hydraulic residence times have frequently been reported to vary between 40% and 80% of the theoretical hydraulic residence times (Persson, 2000; Persson, 2005; Kadlec, 2007).

Hence, applying Equations (7) the Lubigi wetland main study area volumetric efficiencies based on the September 2016 and January 2018 tracer studies, were found to be approximately 63% and 38%, respectively. Applying Equation (8), the corresponding dispersion numbers based on the September 2016 and January 2018 tracer studies were found to be approximately 0.03 and 0.01, respectively. The volumetric efficiencies obtained, indicate that only about 38% to 63% of the Lubigi wetland main study area, plays a part in the transformation and removal of pollutants. Furthermore, the low dispersion numbers of 0.03 and 0.01 are also indicative of the "near-plug flow" hydraulic conditions prevailing in the wetland. Low dispersion numbers i.e 0 to 0.05 are indicative of "near-plug flow" hydraulic conditions, moderate dispersion numbers i.e 0.05 to 0.25 are indicative of a blending of "plug-flow" and dispersive "mixed flow" hydraulic conditions, and high dispersion numbers i.e 0.25 to ∞ are indicative of "completely mixed flow" hydraulic conditions (U.S. Environmental Protection Agency, 2000).

As already discussed, the Lubigi wetland volumetric efficiencies and the dispersion numbers results are well-supported by actual visual and also experimental observations within the wetland. These observations show the bulk of the water in the wetland, tending to flow within and close to the main central drainage channel, from the main water inlet all the way up to transect T2. From transect T2, the water starts to spread out more laterally and getting more dispersed and distributed within the visibly prominent open water ponds just upstream of the Sentema Road, all the way to the effluent outlets. Clearly, the main central drainage channel has a strong short-circuiting effect in the upstream portion of the wetland. Such canalisation effects, have been reported to induce "near plug-flow" hydraulic conditions and thus also cause a considerable decrease in the effective volume of a wetland. These developments in turn lead to the reduction of the effectiveness of the wetland, and its capacity and potential of its function of transforming and removing pollutants from water (Kadlec, 2000; Persson and Wittgren 2003).

All these results show that wastewater flow through the wetland, is not well-distributed over the whole expanse of the wetland. There are zones of the wetland system, which seem to have little or no interaction with pollutants at all. This means that a lesser volume of the wetland is involved in the mechanisms and processes for the transformation and removal of pollutants. The findings also show that there are channelised preferential water flow paths in the wetland system, attributed mainly to the differential resistances due to the deeper water zones, spatial differences in vegetation types and densities, and water flow depths.

CONCLUSIONS

Based on the results of this work, all the various hydrological phenomena as observed in the Lubigi wetland, demonstrate the considerable impounding reservoir and flood buffering effects of the wetland. This is an important service provided by the wetland, to alleviate possible negative impacts of storms and floods events. The Lubigi wetland total influents and effluents discharges, have mean values of 222,377.60±132,365 m^3/day and 221,356.80±122,256 m^3/d. The wetland water balance is dominated by the influent discharges which account for 93.2% of the total water influx, and the effluent discharges which account for 97.7% of the total water outflux. The wetland main study area hydraulic residence times, vary between 6.0 hours and 10 days. Hence, the wetland is endowed with abundant water fluxes, water impounding capacity and adequate hydraulic retention times.

The wetland main study area volumetric efficiency is 63% and 38% during wet season and dry season, respectively. This indicates that on average only about 50.0 %, of the volume of the Lubigi wetland main study area plays a part in the transformation and removal of pollutants as the other 50% is practically dormant. The dispersion number is 0.01, indicating a "near-plug flow" hydraulic regime prevailing in the wetland. However, the Sodium chloride Total dissolved solids (TDS) concentration versus time response curve from the tracer study, also exhibits evidence of the presence of a degree of dispersion, in the wetland hydraulic flow conditions. Hence, the Lubigi wetland can be conceptualised as being "plug flow" with some degree of dispersion. Based on all the foregoing conclusions, it is evident that the hydrology and hydraulics of the Lubigi wetland play a vital role in the transformation and removal of nitrogen and faecal coliforms in the wetland. Furthermore, the hydrology and hydraulics of the wetland are also important sources of data, which provide key essential inputs into the pollutant removal models.

ACKNOWLEDGMENTS

The authors wish to thank the management and staff of The Uganda National Water and Sewerage Corporation laboratory, the Kawanda National Agricultural Research Organization laboratory in Uganda, The Makerere University Department of Plant Sciences, Microbiology and Biotechnology staff and herborium and The Uganda National Meteorological Authority, for helping the authors in the sampling and sample testing and analyses procedures, and in providing the authors with pertinent documents and recorded data.

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