Universal Journal of Environmental Research and Technology
 eISSN 2249 0256
Available Online at: **www.environmentaljournal.org**
2018 Volume 7, Issue 2: 61-71

Open Access **Research Article**

Phosphorus Removal in Mangrove Constructed Wetland

Anesi Satoki Mahenge

Environmental Engineering Department, Ardhi University (ARU), P.O.Box 35176, Dar-es-Salaam, Tanzania

Corresponding Author: anesimahenge@gmail.com

Abstract:
The probable application of Mangrove Constructed Wetlands as a suitable method for phosphorus removal from wastewater generated in coastal areas of Dar es Salaam city in Tanzania was examined. In-Situ examinations were made on horizontal surface-flow mangrove constructed wetland situated at Kunduchi coastline in Dar es Salaam. A wetland of 40 meters by 7 meters was built to collect domestic wastewater from septic-tank of Belinda Resort Hotel and was run in an intermittent continuous flow mode. It employed the existing mangrove specie known as *Avicennia Marina* which had an average breast height of 4 meter and it collected a mixture of wastewater and seawater at a ratio of 6 to 4. The efficiency of the wetland in removal of phosphorus was established. The removal rate of phosphorus informs of phosphate (PO_4-P) was found to be 35%. Mangrove Constructed wetland has a potential in phosphorus removal from domestic wastewaters when soils comprising minerals contents are used.

Keywords: Constructed Wetlands, Mangroves, Phosphorus, Removal rate, Wastewater.

1.0 Introduction:

Mangroves are woody trees, palm or bushes that possess shallow water and develop at the interface amongst land and ocean in coastal areas (Hogarth, 2015). They are described by silt or muddy deposit. These plants, and the related microorganisms, creatures, and abiotic factors (like minerals, carbon dioxide, nutrients, water, oxygen and natural substances) compose the mangrove environment (Semesi, 2001). Normally, mangrove ecological systems play imperative part in hindering poisons from entering the ocean (Frontier Tanzania, 2004) by uptake of contaminations and making favorable conditions for development of decomposing organisms (Cronk and Fennessy, 2016).

Majority of tropical urban areas that are built around natural waterways are lined by mangrove swamps (Zhang *et al.,* 2015). Cases from Africa are: Mombasa, Dar es Salaam and Maputo (Wolf *et al*., 2001; Kamau *et al.,* 2015). However peri-urban mangroves of most urban area like Tudor and Mtwapa creeks in Mombasa, the Msimbazi River and Kunduchi coastline area in Dar es Salaam (Mohammed, 2002), are receivers of wastewater-polluted streams and are extensively utilized for wastewater dumping. The outcome is a potential hazard to human healthy and ecological systems of estuaries and seas (Semesi, 2001; Ouyang, and Guo, 2016; Fusi *et al.,* 2016; Sanders *et al.,* 2014). This could be ascribed to absence of sufficient wastewater treatment infrastructure in these urban areas. For instance in Dar es Salaam, the coverage of sewerage system is 7% (DAWASCO, 2007) of administration zone. In order to protect receiving environment, improvement of the wastewater facilities is thus needed in Tanzania, where the majority of citizens cannot meet the expenses of conventional wastewater treatment technologies. The Waste Stabilization Pond and Constructed Wetland Research and Development Group in Tanzania has been developing cheap technologies like constructed wetlands and waste stabilization ponds. These technologies employ nature to remove pollutants and therefore they are feasible innovations in treatment of wastewater (Mbwette *et al.,* 2005; Kaseva, 2004; Njau *et al.,* 2014). Mangroves Constructed wetlands are in this manner considered perfect to protect mangrove ecological systems.

The pathways of natural mangrove wetlands to reduce pollutants from domestic wastewater are alike to other wetland systems that employ terrestrial plants (Leung *et al.,* 2016; Zhou *et al.,* 2016; Devis *et al.,* 2003). In this manner, it is expected that by adapting engineering methods to natural mangrove wetlands, the system can be employed in treatment of domestic wastewaters originating from urban areas along the coast (Boonsong and Patanapolpaiboon, 2003; Yang *et al.,* 2008).

It is realized that mangroves wetlands somewhere else capture land-derived phosphorus and limit their spreading seaward and therefore preventing pollution to ecological systems in sea and estuaries (Wu *et al.*, 2008; Mahenge, 2014; Cochard, 2017; Guo *et al.,* 2016; MacDonnell *et al.,* 2017, De-León-Herrera *et al.,* 2015), however their treatment performance varies widely due to influence of a variety of factors brought by living and non living organisms. Moreover, in Tanzania, no efforts have been made to study the performance of constructed mangrove wetlands in the treatment of domestic wastewater; as a result no information is available on removal of phosphorus in this kind of technology. Although, similar studies of nutrients removal have been conducted in Tanzania, the differences are; one study was conducted by Pamba (2008) on small scale Mangrove Constructed Wetlands (microcosms) which were run in batch mode while others carried the study using subsurface constructed wetlands planted with terrestrial plants (Bigambo 2003; Senzia 2003).

2.0 Materials and Methods:

Mangrove wetland treatment system was built at Kunduchi coastline area to carry out secondary treatment of wastewater collected from septic tank of Belinda Resort Hotel. The study area inhabits tropical climate and a variable environment with tides (i.e the area is flooded during high tides and is just wet during low tides). It experiences maximum tide (spring tides) at new and full moon and minimum tide (neap tides) in the course of full moon and new moon. It is also dominated by mangrove type - *Avicennia marina* with average height of 4 meters.

2.1 Design of Surface Flow Mangrove Constructed Wetland:

A wetland cell (Cell 01) of length 40m and width 7m was designed and constructed (Figure 1) and its design criteria and features are described in Table1. The wetland cell received domestic wastewater by gravity from Belinda resort hotel through a pipe of 100 mm diameter at a flow rate of 5 m^3 /day. The cell collects a mixture of wastewater and seawater at a ratio of 6 to 4, respectively (i.e. wastewater was flowing at a rate of 3 m^3/day and seawater at a rate of 2 m^3/day). The ratio of wastewater to seawater was determined by Pamba (2008) who conducted pilot experiments in microcosms in year 2006 to 2007. Given that the study area is dominated by mangrove of type *Avicennia marina;* this plant was used as wetland vegetation (macrophytes) in the wetland cell.

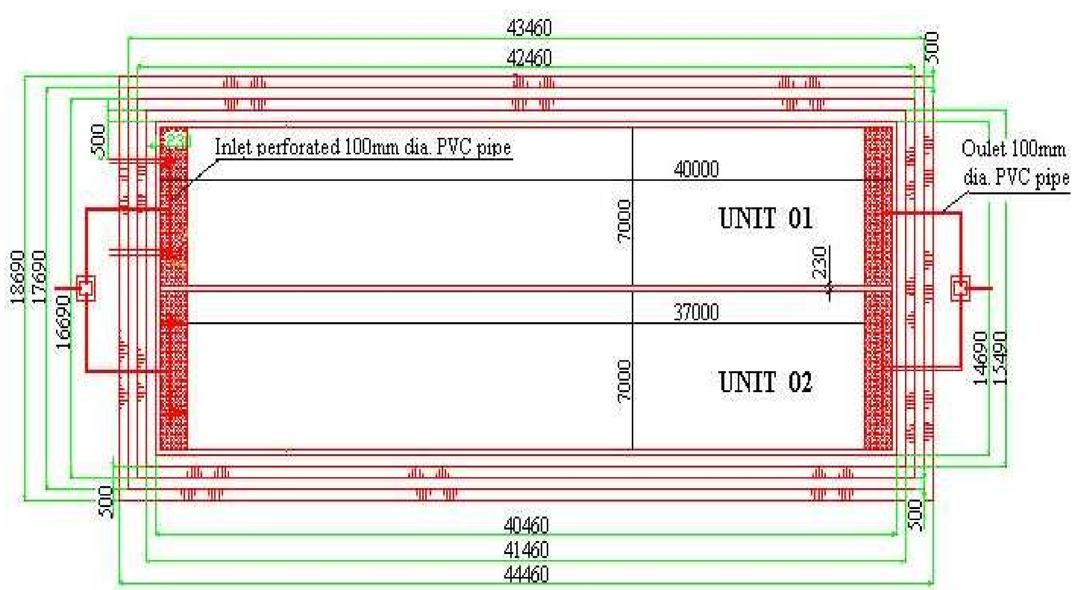

Figure 1: Plan horizontal surface flow Mangrove Constructed Wetland (units are in mm)

Table 1: Design Criteria, Dimensions and Characteristics of CMW system

FACTOR	DESIGN CRITERIA FOR SURFACE FLOW WETLANDS	WETLAND CELL DESIGN DIMENSIONS AND CHARACTERISTICS
Length (m)	-	40
Width (m)	-	7
Substrate (soil) depth (m)	Maximum, 1	0.6
Water depth (cm)	Maximum, 10	4
Organic Loading Rate, OLR (kg/ha.d)	Maximum, 80	44.6
Hydraulic Loading Rate, HLR (cm/d)	7-60	4.5
Aspect ratio (L/W)	2-10	
Retention time (d)	5 – 14	7
Slope (%)	Maximum 1	1

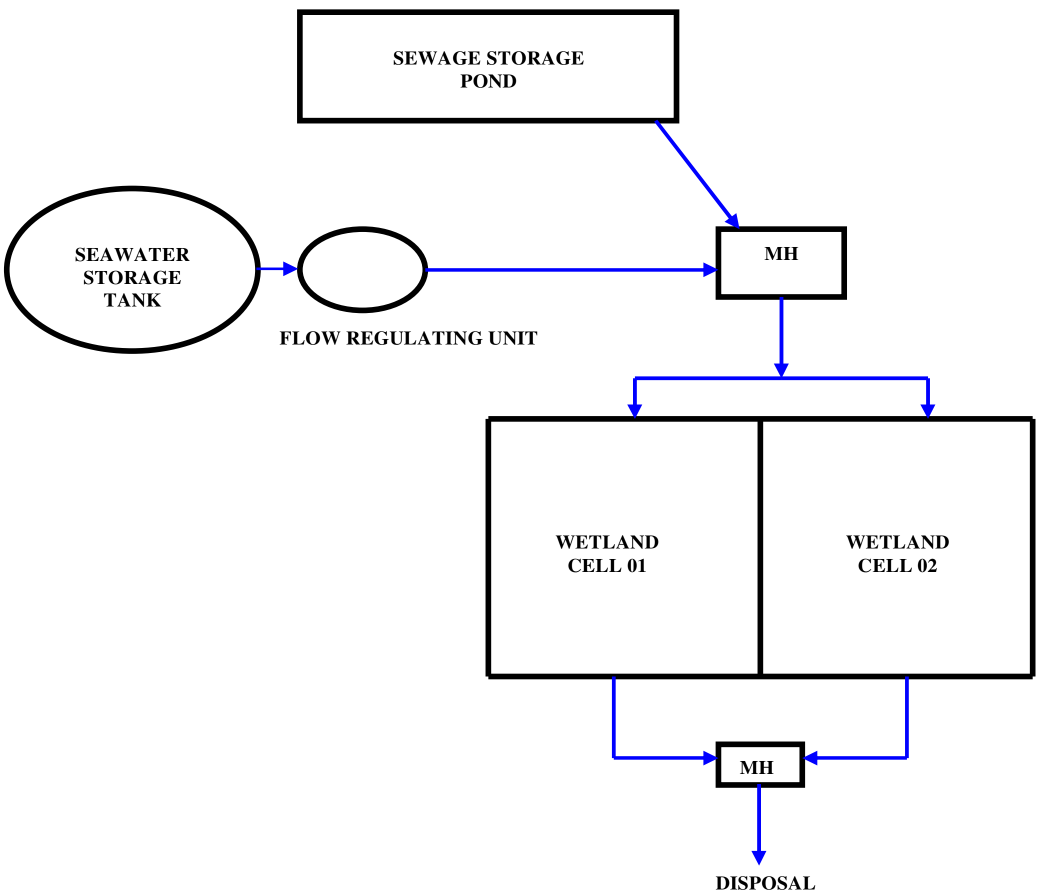

Figure 2: Layout of Mangrove Constructed Wetland Systems

2.2 Operation of Surface Flow Mangrove Constructed Wetland:

In order to mimic the natural occurrence of alternating flooding with seawater and drying-up of mangroves, the wetland cell was operated in an intermitted continuous flow mode of 3 days flooding (inundation) and 3 days drying-up cycles. The cell via its inlet pipe, was receiving a mixture of 60% wastewater and 40% seawater which was flowing by gravity at a rate of 5 m^3/day. In order to enable roots of mangrove to take breaths, the depth of wastewater flow was kept to 4 centimetres.

2.3 Experimental Set-Up:

The set-up of the experiment is as described in Figure 2 and the details of some features in the set-up are as described in Figure 3.

The set-up in figure 2 comprise of seawater tank, flow regulating unit, wastewater storage pond, manholes (MH), wetland cells and pipe network

The details for dosing of wastewater and seawater to the wetland cell are as illustrated in Figure 3 whereby, wastewater was flowing from the wastewater pond at a rate of 3 m^3/day and seawater was flowing from seawater tank at a rate of 2 m^3/day and to make a total flow rate of 5 m^3/day of wastewater that is flowing into the wetland.

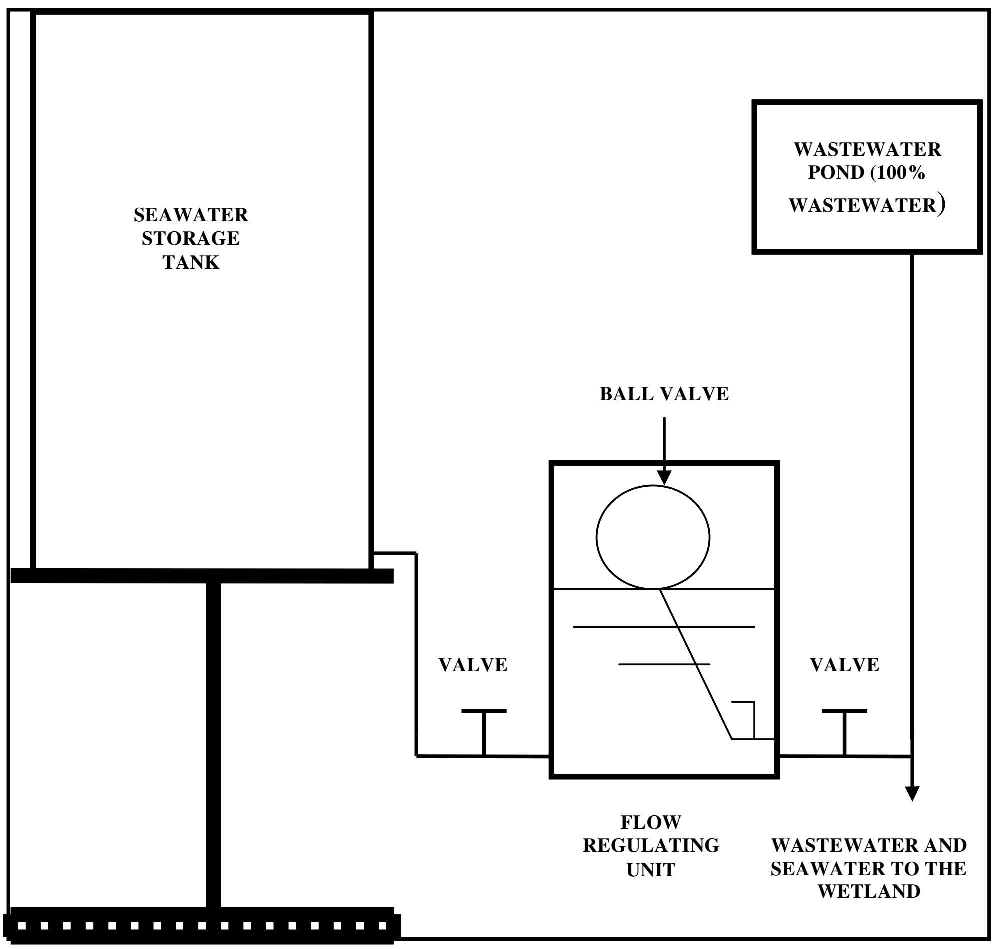

Figure 3: Seawater Dosing Unit for Controlling Seawater Flow to Dilute the Wastewater

2.4 Sampling procedure for physical and chemical parameters:

The samples were collected twice per week on the first day when wastewater enters into the wetland cell and on the last day (3rd day) when the wastewater gets out of the wetland cell. The samples were collected at 6:00 am in the morning, 12:00 noon, 6:00 pm in the evening and 11:30 pm in the night. Five (5) sampling locations were established inside the wetland cell as presented in Figure 4. In this manner the cells were divided into four sections and the sampling locations were designated "Inlet, A1, A2, A3 and Outlet". The distances from each sampling location was 10 meters and at each sampling point a composite sample was taken crosswise the cell.

2.5 Analysis of physical and chemical parameters:

Analysis of physicochemical parameters was according to standard procedures for analysis of water and wastewater (APHA, 2012). The physical parameters such as Dissolved Oxygen (DO), salinity, water temperature, pH and depth of water flow, were measured in situ, then the samples were covered, stored in a box and transported from the site to the laboratory for analysis of chemical parameter PO4-P (phosphate phosphorus). In order to remove probable particulate matters that might interfere with analysis of phosphorus, samples were filtered before analysis by using a Whatmen No. 42 filter paper. Most of samples upon reaching the laboratory were immediately analysed. Samples that were not able to be analysed on the same day of sampling, were preserved by being acidified and stored in the refrigerator.

2.5.1 Analysis of physical parameters:

Temperature and pH were measured by the pH probe meter (WTW ino-Lab, pH Level 1 type, German, Accuracy is ± 0.01). DO was measured by DO probe meter (WTW inoLab type, German, Accuracy is ± 0.5% of the value). Salinity measured by WTW Cond probe meter (inoLab, Cond Level 1 type, German, Accuracy is ± 0.5% of the value).

2.5.2 Analysis of Ortho-Phosphate (PO_4-P):

Phosphorus was determined as phosphate by the method known as ***Ascorbic Acid*** (the accuracy for method was ± 3% of the value) according to American Standard Test Method APHA, 2012).

2.6 Determination of the treatment efficiency of Mangrove Constructed Wetland in PO_4-P removal:

For determination of the efficiency of Mangrove Constructed Wetland in wastewater treatment, the influent and effluent wastewater samples on the first and last day of the specified inundation (retention) time were analysed for phosphorus and the removal percentages of phosphate phosphorus (PO_4-P) was determined.

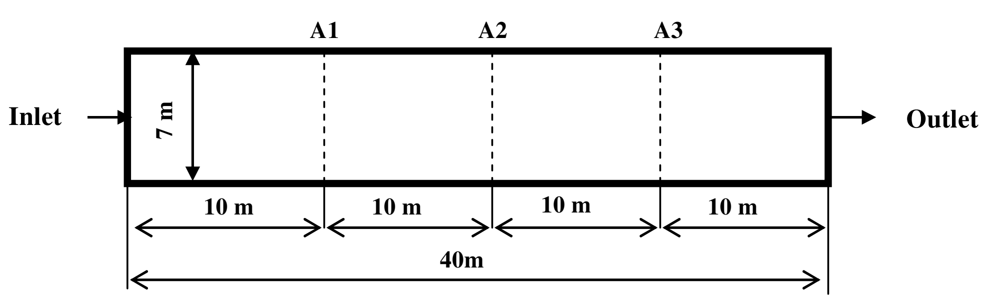

Figure 4: Partitioning of the test wetland into sampling sections

3.0 Results and Discussion:

3.1 Wastewater characteristics

The characteristics of the mixture of wastewater and seawater during loading to the wetland cell, are shown in Table 2.

Table 2: Wastewater Characteristics at the Inlet of a wetland cell

Parameter	Mean ± SD
pH	7.36±0.31
Salinity (ppt)	11.46±10.03
DO (mg/L)	0.54±0.35
Temperature (^{o} C)	29.3 ±0.87
PO_4-P (mg/L)	3.27±2.00

3.2 Physical and Chemical parameters:

Four most important abiotic factors (i.e physical environment) in mangrove wetlands are temperature, salinity, dissolved oxygen (DO) and pH. The physical environment in a wetland cell affects the chemical and biological processes that are responsible for phosphorus removal in the cell. Dissolved Oxygen, PH, temperature affect the solubility of phosphate. Insoluble inorganic phosphorus is not readily available for mangrove uptake.

3.2.1Dissolved Oxygen (DO):

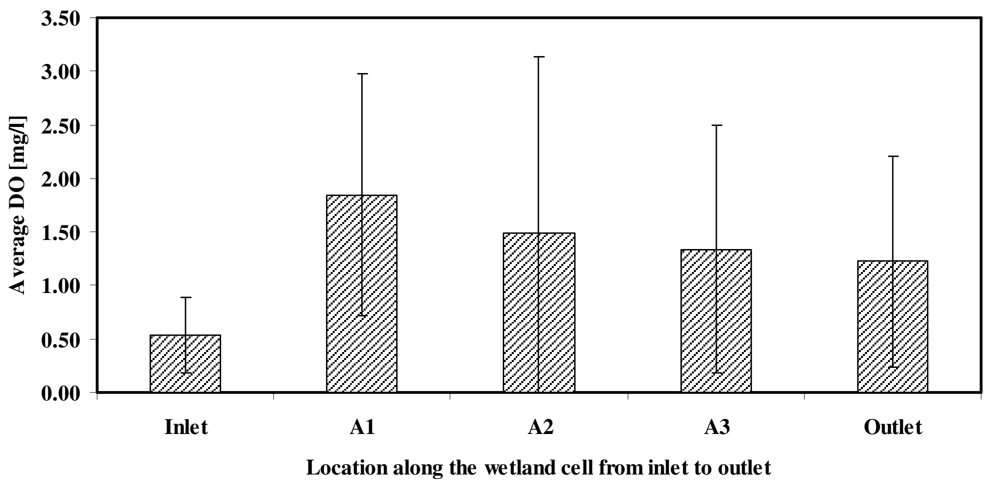

Figure 5: Variation of Average DO Concentration along the Wetland Cell

The average DO concentration as a function of location along the wetland is presented in Figure 5. The average inlet DO was 0.54 ± 0.35 mg/L and the average outlet DO was 1.22 ± 0.99 mg/L. The average DO within a wetland cell (i.e. from A1 to A3) was 1.55 mg/L. The levels of DO within the wetland cell were significantly low compared to the ones reported by Pamba (2008) in the newly planted mangrove wetlands (experimental microcosms, DO was 18.75 ± 2.82 mg/l). This may be due to the lack of sufficient penetration of sunlight and wind effect due to plant cover in the water column of this wetland which was not the case in microcosms. Oxygen is normally introduced into water column from atmosphere and during photosynthesis process of algae and mangroves. Since average DO in wetland system was 1.55 mg/L during the day, this DO creates aerobic conditions that favour growth of aerobic bacteria. Aerobic bacteria are responsible for mineralization of organic phosphorus to phosphate (inorganic form). Mangroves are able to uptake the inorganic form of phosphorus and not the organic form. Uptake of phosphorus by mangroves helps to remove the phosphorus in wastewater.

3.2.2 pH:

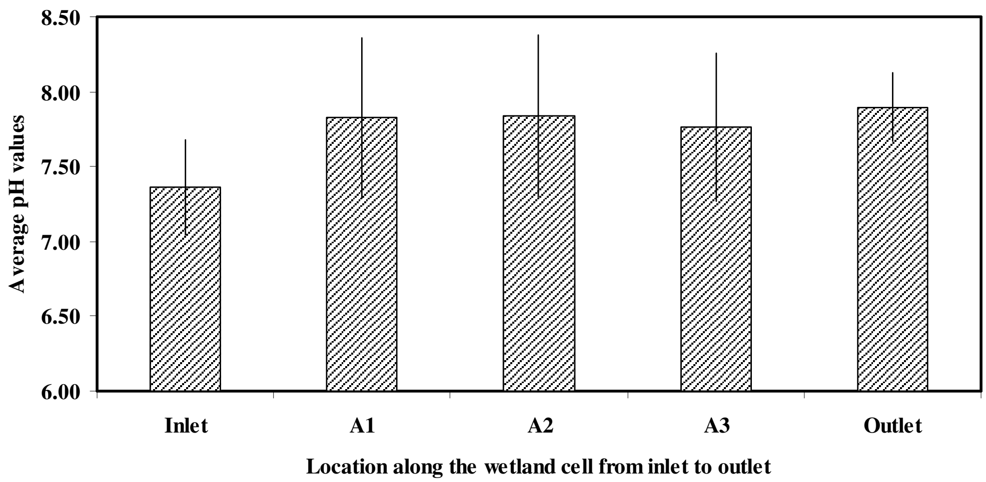

Figure 6: Variation of pH Values along the Wetland Cell

The variation of pH with location along the wetland is illustrated by Figure 6. The average pH value in the inlet was 7.36±0.32 and it improved slightly through the wetland to a pH of 7.90±0.23 in the outlet. The average pH within the wetland cell (i.e. along the location A1 – A3), was 7.75. Comparing the pH values obtained in this wetland cell to the values obtained in the experimental microcosms (Pamba, 2008) it is noticed that the later was slightly higher (pH was 8.26 ±0.37). Variation of pH between these two systems could be due to decomposition of detritus plant tissues on forest floor and the penetration of light through plant canopy. In new-planted system where plants were small and not fully covered the area, the light could penetrate to the bottom and make the water treatment to be more photosynthetic driven system which is accompanied with pH rise (Yang *et al*, 2008). The decomposition of a large amount of detritus in this wetland cell resulted in acid production (Boonsong and Patanapolpaiboon, 2003; Yang *et al.,* 2008). Usually, the microorganisms work better at certain ranges of pH values. Most bacteria operate well at the pH range of 7.0 to 9.5 (Metcalf and Eddy, 2003). Since average pH in wetland system was 7.75 during the day, this pH favours most of the decomposing bacteria to mineralize organic phosphorus. Mineralization is more in acidic to neutral conditions.

3.2.3 Salinity:

The spatial variation of salinity along the wetland is shown in Figure 7. As the wastewater was travelling through the wetland, there was a gradual increase of salinity from 7.21 ± 5.24 ppt in the inlet to 13.75 ± 3.10 ppt in the Outlet. The average salinity within the wetland cell was 10 ppt. The low salinity in the inlet is explained by dilution of the seawater by rainwater. The increase in salinity was most likely caused by evapo-transpiration from the fully grown mangrove plants. Higher salinity favours the growth of mangroves (Shiau *et al.,* 2017; Sun *et al.,* 2017).

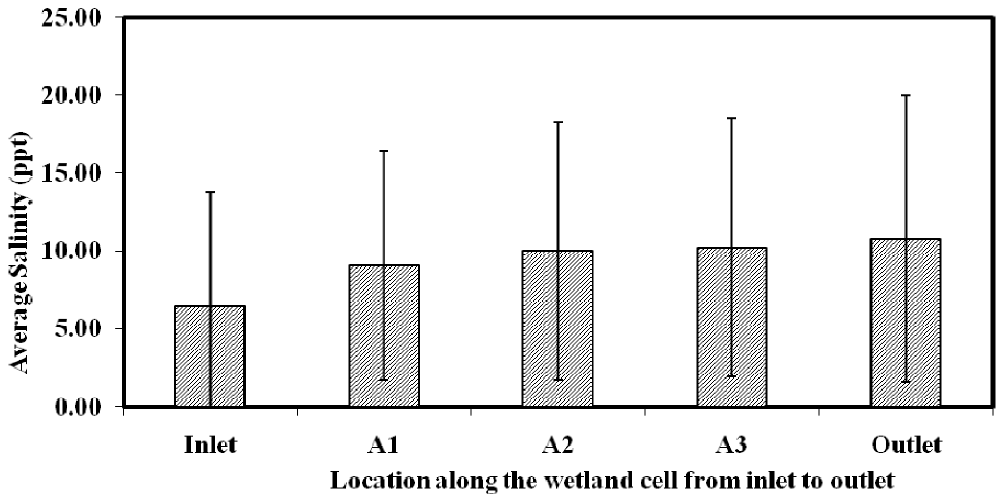

Figure 7: Variation of Average Salinity along the Wetland Cell

3.2.4 Temperature:

Variation of temperature with time in the wetland cell is as shown in Figure 8. During the day, average inflow temperature was 30.1 ± 0.22 and the average temperature in the wetland cell was 29.3 ± 0.27. During the night, the average inflow temperature was 29 ± 0.45 and the average temperature in the wetland cell was 28.9 ± 0.46. Generally, the temperature inside the wetland cell was slightly low during the day and night compared to influent water temperature because of the shading effect of the plants. The growth rate constants of decomposing bacteria are affected by temperature changes within the wetland cell. The optimum temperature for the growth of mineralizing bacteria ranges from 28 to 36^{o} C (Senzia, 2003). Since average temperature in wetland system was 29 ^{o} C during the day and night, this temperature favours the bacteria to mineralize organic phosphorus to inorganic phosphorus.

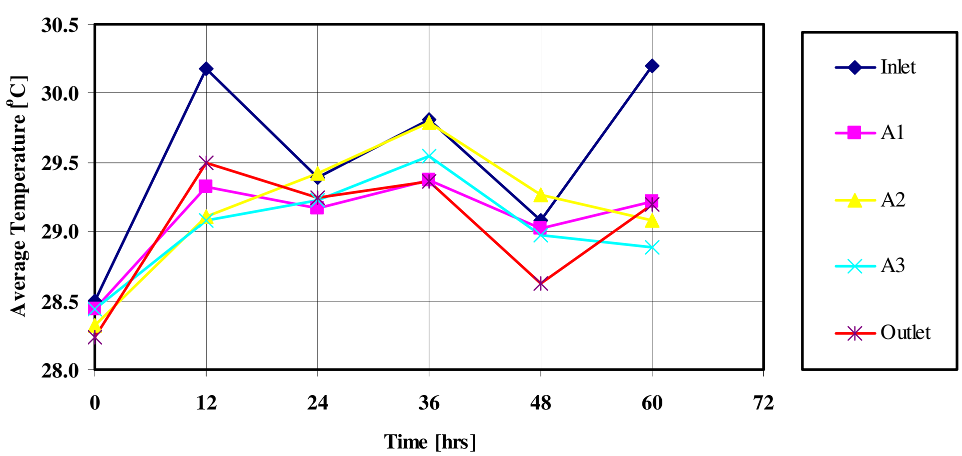

Figure 8: Variation of Average Temperature with Inundation Time

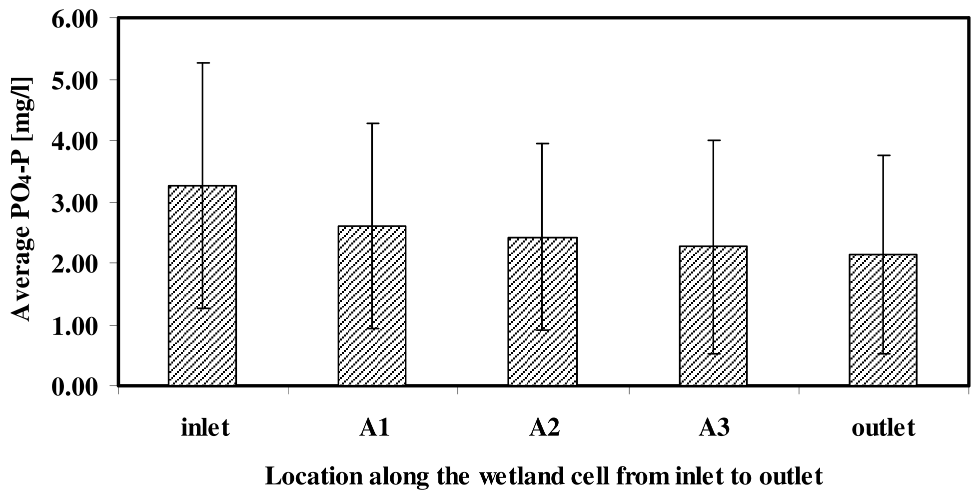

Figure 9: Variation of average PO4-P concentration along the wetland cell

3.2.5 Phosphate Phosphorus (PO_4-P)

Variation of phosphorus along the wetland cell is shown in Figure 9. The spatial decrease of concentration of PO_4-P along the wetland cell was observed. The average PO_4-P removal after 3 days is 35%. Again this is only a transient value since steady state situations have not been reached in the system.

Biotic processes which directly regulate removal or net gain of phosphorus in the system include uptake by vegetation and microbes, mineralization of both plant litter and soil organic phosphorus. Microbes can work in certain ranges of pH and temperature in absence or presence of oxygen and hence these factors directly affect biotic processes, which ultimately affect removal of phosphorus.

Abiotic processes which directly regulate removal or net gain of phosphorus include sedimentation and burial; adsorption and precipitation; and exchange processes between soil and overlying water column. pH directly affects these abiotic processes and hence indirectly affects the removal of phosphorus in the wetland system.

The average effluent PO_4-P concentration from the system was 2.1 ± 1.6 mg/l which was below the allowable discharge limit (6 mg/l) to the receiving water bodies (according to Tanzania Standards). The average PO_4-P removal rate of the system was 1.8kg/ha.d.

4.0 Conclusions:

Based on the results presented, reduction in concentration of phosphorus was observed. The removal rate was 35%. The removal processes were directly attributed by biotic process such as plants and microbial uptake. These biotic process are affected by the forcing functions pH, temperature and DO with averages of 7.75, 29^{o}C and 1.55 mg/L, respectively. The removal processes were also directly attributed abiotic processes such as sedimentation and burial; adsorption and precipitation; and exchange processes between soil and overlying water column.

For optimization of system treatment performance with respect to phosphorus removal, it is recommended that: Inundation (retention) time should be long enough i.e. between 5 and 15 days to allow the system to operate more in a steady state conditions for reduction of phosphorus to acceptable levels for safe use or discharge. It is also recommended that soils which contain minerals should be used as wetland substrate to enhance sorption of phosphorus

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