Nitrogen Transformation and Removal in Horizontal Surface Flow Constructed Mangroves Wetland

A. S. Mahenge
Environmental Engineering Department, Ardhi University (ARU), P.O.Box 35176,
Dar-es-Salaam, Tanzania
Cell: ***+255-713-447131 / +255-762-279612/+255-687-296986***
E-mail: ***anesimahenge@yahoo.com***

Abstract: *The potential use of Constructed Mangrove Wetlands (CMWs) as a cheaper, effective and appropriate method for Nitrogen removal from domestic sewage of coastal zone in peri-urban cities was investigated from August 2007 to September, 2008. Field investigations were made on horizontal surface flow constructed mangrove wetland located at Jangwani beach in Dar es Salaam. A wetland of 40m x 7m was constructed to receive domestic sewage from septic tank of Belinda Beach Hotel and was operated in an intermittent continuous flow mode. The wetland was loaded by sewage of strength 60% and 40% was seawater. The wetland used the already existing mangrove plant specie Avicennia Marina. The performance of the wetland in removal of nitrogen species was determined. The observed removal rates of TKN, NH3-N and NO3-N, and were 61%, 85% and 76%, respectively. The removal of TKN was contributed by mineralization of organic nitrogen to NH3-N. The removal of NH3-N was contributed by nitrification, volatilization and mangrove uptake processes. Nitrification process transformed NH3-N to NO3-N at aerobic conditions while volatilization process transformed NH3-N in gaseous form that finally escaped from a water phase to the atmosphere. The removal of NO3-N was contributed by de-nitrification process that transformed NO3-N to nitrogen gas which escaped to the atmosphere. The removal processes were attributed by the forcing functions pH, temperature and DO with averages of 7.75, 29oC and 1.55 mg/L, respectively. Constructed Mangrove wetland has shown high potential in Nitrogen removal from sewage, therefore it can be used for sewage treatment.*

Keywords: Constructed Wetlands, Mangroves, Sewage, Treatment Performance

SYMBOLS AND ABBREVIATIONS

NH_3-N	Ammonia Nitrogen
NO_3-N	Nitrate Nitrogen
TKN	Total Kjeldahl Nitrogen
DO	Dissolved Oxygen
HSFCMW	Horizontal Surface Flow Constructed Mangroves Wetland

INTRODUCTION

Mangroves are woody trees, palm or shrubs that occupy shallow water and grow at the interface between land and sea in tropical and subtropical coastal regions. They are characterized by muddy or fine sediment substrata. These plants, and the associated microbes, animals, and abiotic factors (like nutrients, minerals, water, oxygen, carbon dioxide, and organic substances) constitute the mangrove ecosystem

(Semesi, 1998). Naturally, mangrove ecosystems play important role in preventing pollutants from entering the water body (Frontier Tanzania, 2004) by up-taking of pollutants and creating conducive environments for growth of decomposing microorganisms. Many tropical cities that are built around natural harbours or waterways are lined by mangrove swamps. Examples from Africa are: Mombasa, Dar es Salaam and Maputo (Wolf *et al.,* 2001). However peri-urban mangroves (*A. Marina*, *R. Mucronata* and *S. Alba*) of most coast cities *examples are Tudor and Mtwapa creeks in Mombasa, and the Msimbazi River and Jangwani beach area in Dar es Salaam (Mohammed, 2002),* are recipients of sewage-polluted rivers and are extensively used for sewage dumping.

The consequence is a potential risk to human health and ecosystems of estuaries and oceans (Semesi, 2001). This could be attributed to lack of adequate sewage treatment facilities in these cities. For example in Dar es Salaam, the coverage of sewerage system is 7% (DAWASCO, 2007) of service area. Upgrading of the sewage infrastructure therefore, is urgently required in developing countries, where majority of these cannot afford conventional wastewater treatment systems in order to protect receiving environment. The Waste Stabilization Pond and Constructed Wetland (WSP and CW) Research Group at the University of Dar es Salaam in Tanzania has been developing low-cost technologies such as waste stabilization ponds and constructed wetlands. These systems use nature to treat waste, are easy to maintain, are simple to construct and they are very effective technologies in treatment of wastewater (Mbwette *et al.,* 2005). Mangroves constructed wetlands are therefore considered ideal to protect peri-urban mangrove ecosystem.

The mechanisms of natural mangrove wetlands to remove nitrogen and other pollutants from sewage are similar to wetland treatment systems using other types of vegetation. Therefore, it is expected that by applying appropriate engineering design and construction, the natural mangrove wetland can be used as an efficient sewage treatment system of the wastes generated from urban and peri-urban areas located along the coast as example in Thailand and China (Boonsong and Patanapolpaiboon, 2002).

It is known that mangroves wetlands elsewhere intercept land-derived nitrogen and limit their spreading offshore and hence preventing risk to estuariesô and oceansô ecosystems (Wu *et al*, 2008), however their treatment performance varies widely due to influence of various forcing functions like pH, temperature, DO on the transformation and removal processes of nitrogen. Furthermore, in Tanzania, no efforts have been made to study the performance of constructed mangrove wetlands in the treatment of sewage; as a result no information is available on transformation routes and removal of nitrogen in this kind of treatment system. However, similar studies of nitrogen transformation have been conducted in Tanzania the differences are; one study was conducted on small scale constructed mangroves cells (microcosms) operated in batch while others conducted the study by using subsurface constructed wetlands planted with terrestrial plants.

MATERIALS AND METHODS

Experimental Set-up

Site description:

Mangrove wetland treatment system was constructed at Jangwani beach area in Dar es Salaam to perform secondary treatment of domestic sewage discharged from septic tank. The sewage was collected from Belinda Resort Hotel. The climate of the area is typically tropical. The site area inhabits a changeable environment with tides (at low tides the area is just wet and flooded during high tide). The area receives maximum tide range at new and full moon (spring tides) and minimum tide (neap tides) in between full moon and new moon. Also, the site area is dominated by mangrove type - *Avicennia marina* with average height of 4m.

Design and Operation of Surface Flow Constructed Mangrove Wetland

Design of Surface Flow Constructed Mangrove Wetland:

A wetland cell (**unit 01**) of *40m x 7m* was designed and constructed (Figure 1) and its design criteria and features are shown in Table 1. The wetland cell received sewage by gravity from Belinda hotel via a 100 mm diameter pipe at a flow rate of 5 m^3 /day. The wetland cell was loaded by sewage of strength 60% (i.e. 40% was seawater that was flowing at a rate of 2 m^3/day; and 60% was sewage that was flowing at a rate of 3 m^3/day). The sewage strength of 60% was established from pilot experiments that were carried out from August 2006 up to March 2007 (Pamba, 2008). Since study area is dominated by mangrove type *Avicennia marina;* this mangrove specie was used as macrophytes for the wetland cell.

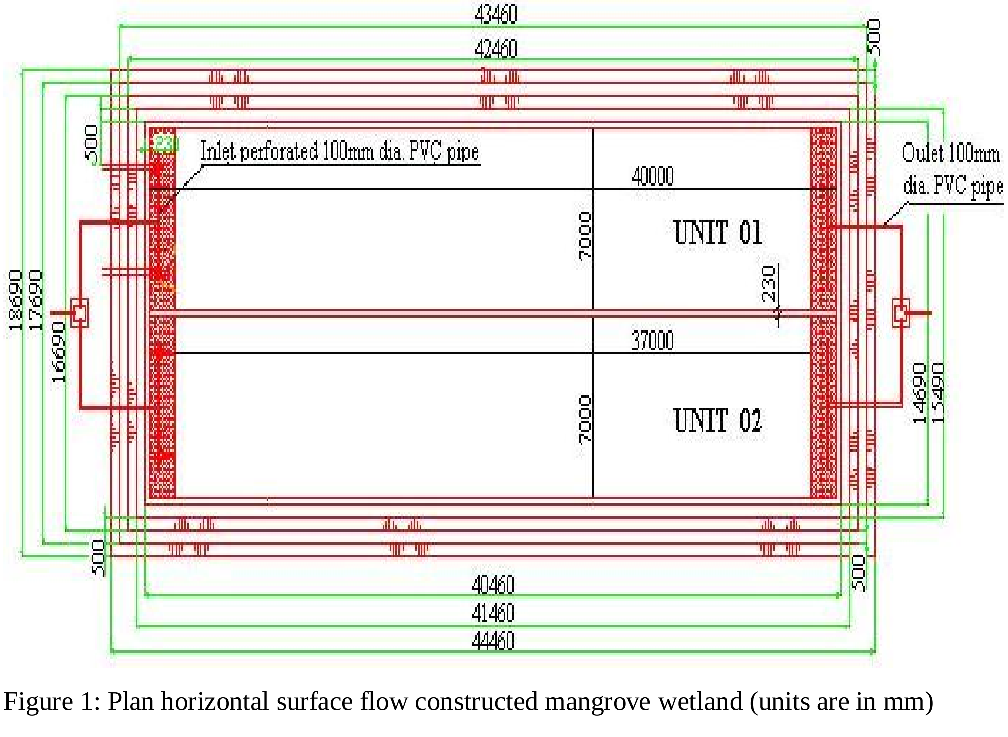

Figure 1: Plan horizontal surface flow constructed mangrove wetland (units are in mm)

Operation of Surface Flow Constructed Mangrove Wetland

In order to imitate the natural phenomenon 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 with sewage (inundation time) and 3 days drying up cycles. The cell through its inlet pipe, was receiving 60 % sewage and 40% seawater flowing by gravity at a rate of 5 m^3/day. In order to enable mangrove roots to respire, the depth of sewage flow was kept 4 cm.

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	44.64
Hydraulic Loading Rate, HLR (cm/d)	7-60	4.5
Aspect ratio (L/W)	2-10	
Retention time (d)	5 ï 14	7
Slope (%)	Maximum 1	1

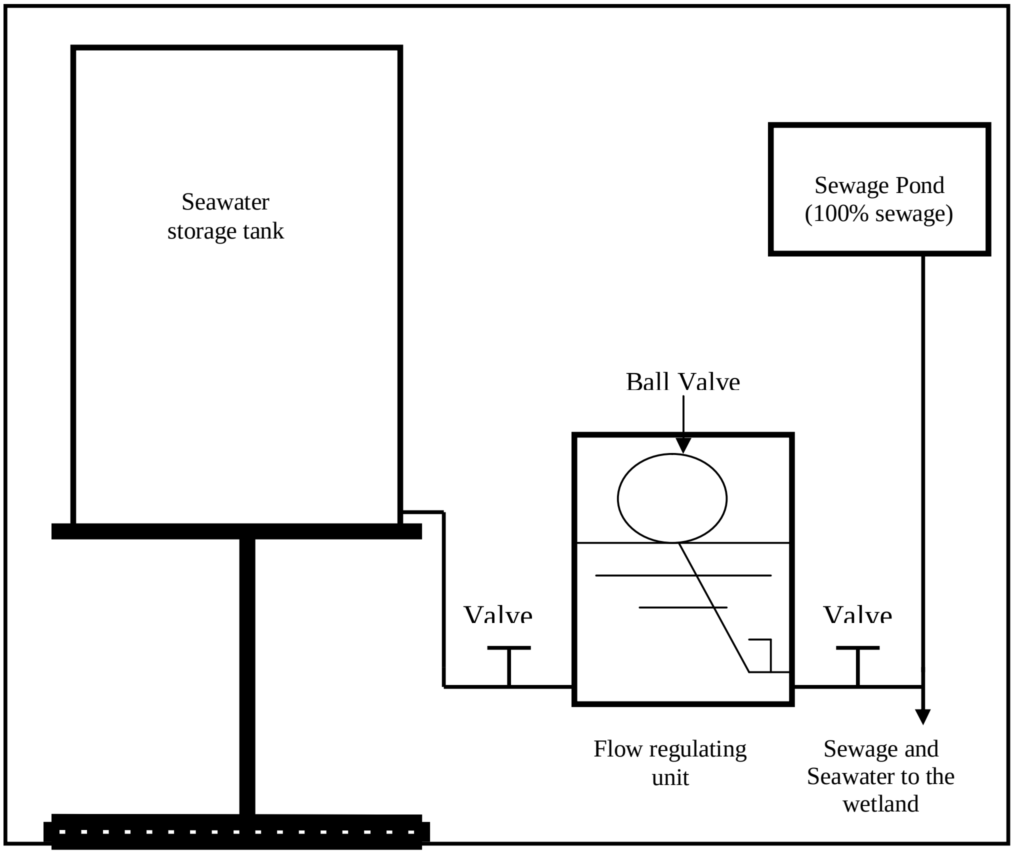

Figure 2: Seawater Dosing Unit for Controlling Seawater Flow to Dilute the Sewage

The dosing of sewage and seawater is as presented in Figure 2 where by, sewage was flowing from the sewage 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 sewage flowing into the wetland.

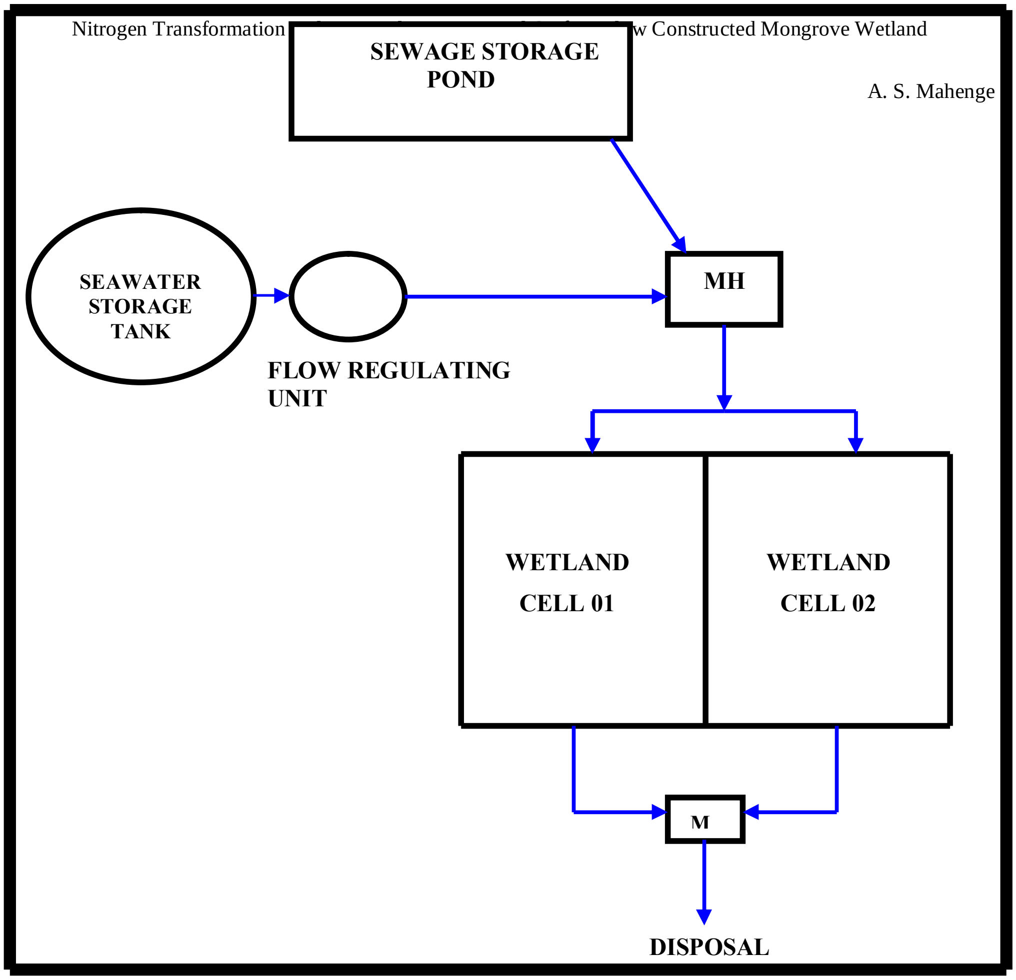

Figure 3: Layout of Constructed Mangrove Wetland Systems

Sampling procedure and analysis of physical & chemical parameters

Sampling procedure Plot layout

The samples for sewage analysis were taken twice per week on the first day during discharge into the wetland cell and on the last day (3rd day) during discharge out of the wetland cell. The samples were taken at 6:00 am in the morning, 12:00 noon, 6.00 pm in the evening and 11:30 pm on the night. Five sampling points were established inside each cell at locations as shown in Figure 4. In this manner the cells were divided into four sections and the sampling points were designated ñInlet, A1, A2, A3 and Outletò. The distances from each sampling location was 10m. At each sampling point a composite sample was taken across the cell.

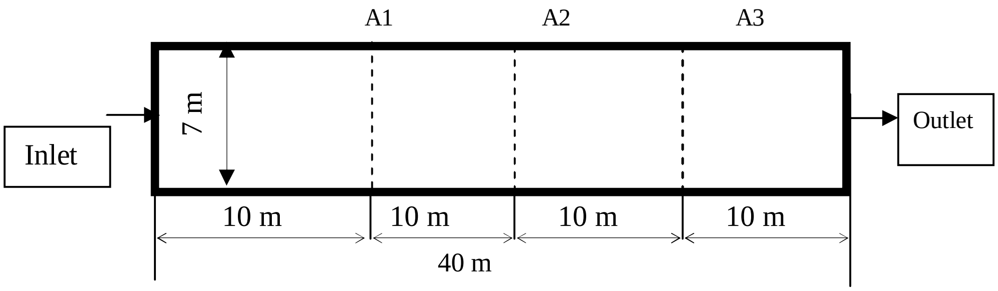

Figure 4: Partitioning of the test wetland into sampling sections

Analysis of physical and chemical parameters:

Analysis of both physical and bio-chemical parameters followed the standard procedures for analysis of water and wastewater (APHA, 1998).

Physical parameters (Dissolved Oxygen (DO), salinity, water temperature, pH and depth of water flow) were measured at the site, then the samples were covered and stored in a box and transported from the experimental site to the Chemical and Process Engineering laboratory at the University of Dar es salaam for analysis of NH_3-N, NO_3-N, NO_2-N and TKN (nitrogen species).

At the laboratory, samples were filtered through a Whatmen No. 42 filter paper (110 mm in diameters) to remove possible particulate that probably might interfere with analysis of nitrogen species and were immediately analysed on the same day. Samples that were not able to be analysed on the same day of sampling, were preserved by being acidified and stored in the refrigerator.

Analysis of physical parameters:

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

Analysis of TKN:

TKN was determined by Kjeldahl method. A heating device known as Gerhardt Kjeldthem (German, Accuracy is ± 0.5% of the value) and distillation device by Gerhardt Vapodest German (Accuracy is ± 0.2% of the value), were used.

Analysis of NH_3-N:

Ammonia nitrogen was determined by Phenate method (Accuracy is ± 0.01 mg/L). A spectrophotometer type PYE UNICAM PU 8610 UV/VIS (Accuracy is ± 0.5% of the value), was used

Analysis of NO_3-N & NO_2-N:

Nitrate was determined by cadmium reduction method (Accuracy is ± 1.1% of the value). Nitrate was reduced almost quantitatively to nitrite when a sample was run through a column containing amalgamated cadmium fillings. Thus nitrite produced is determined by diazoting with sulphanilamide and coupling N-(1-naphthyl) ethylemediamide to form a highly coloured azo dye which was measured calorimetrically by using kinematics spectrophotometer type PYE UNICAM PU 8610 UV/VIS (Accuracy is ± 0.5% of the value).

Determination of the treatment efficiency of constructed mangrove wetland in NH3-N, NO3-N, and TKN removal

For determination of the treatment efficiency of the constructed mangrove wetland, the inlet and outlet water samples into and out of the wetland system on the first and last day of the specified inundation (retention) time were studied and the percentages removal of NH_3-N, NO_3-N, and TKN were determined.

RESULTS AND DISCUSSION

Treatment Performance of Constructed Mangrove Wetland

Sewage characteristics:

The sewage characteristics during pumping to the systems are presented in *Table 2.*

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

Parameters	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
TKN (mg/L)	23.16± 8.29
NH_3-N (mg/L)	4.70±1.87
Organic Nitrogen (Org-N) (mg/L)	18.46
NO_3-N (mg/L)	0.0126±0.0102
NO_2-N (mg/L)	0.0055±0.004

Physical parameters:

The physical and chemical environment (abiotic factors) of a wetland affects all biological processes. In turn, many wetland biological processes modify this physical/chemical environment. Four most important abiotic factors in mangrove wetlands are temperature, dissolved oxygen (DO), salinity and pH.

Dissolved Oxygen, DO:

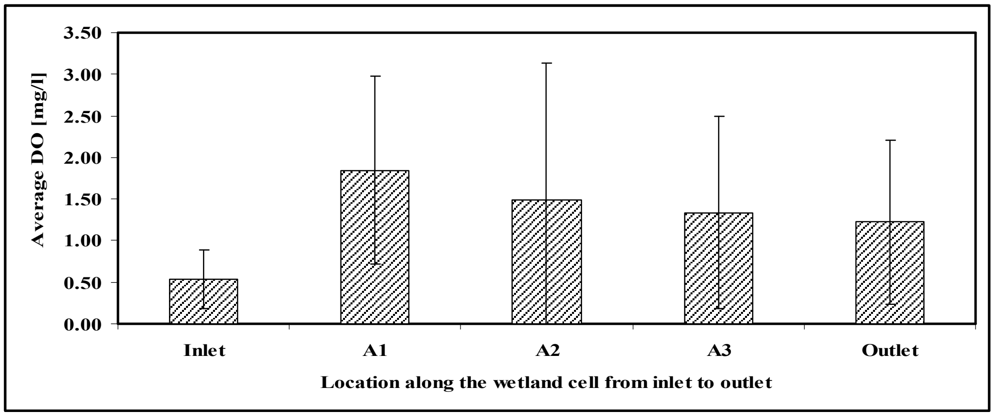

Figure 5: Variation of Average DO Concentration along the Wetland Cell from Inlet to Outlet

The average DO concentrations 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. along the location A1 ï A3), was 1.55 mg/L. The levels of DO within the wetland cell were significantly lower than the ones reported in the newly planted mangrove wetlands (experimental microcosms, DO was 18.75±2.82 mg/l) (Pamba, 2008). This may attributed to the lack of sunlight penetration into the water column and wind effect due to plant cover over the trial wetland which was not the case with microcosms. Oxygen is introduced into water column during photosynthesis process of algae. 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 nitrification processes.

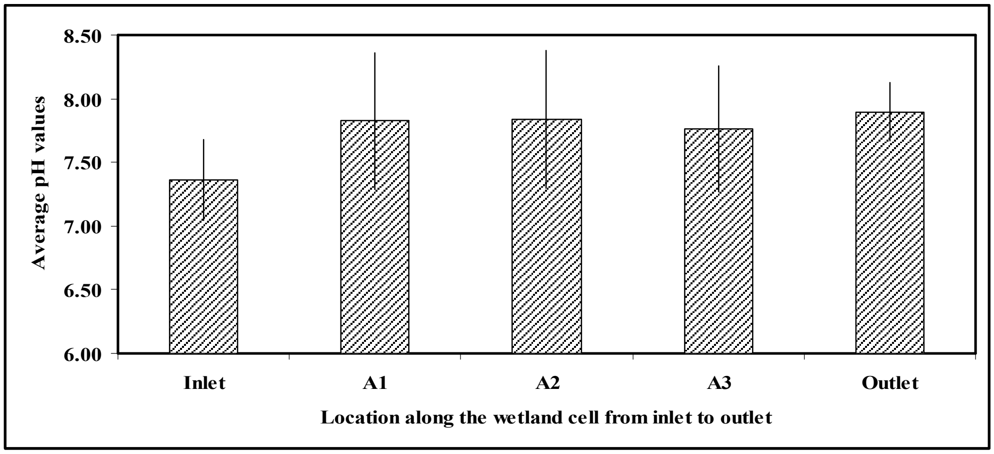

Figure 6: Variation of pH Values along the Wetland Cell from Inlet to Outlet

The variation of pH with location along the wetland is shown in 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 ï 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). Difference 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, 2002). 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, 1991). Since average pH in wetland system was 7.75 during the day, this pH favours most of the decomposing bacteria to decompose nitrogen.

Salinity:

The average salinity concentrations as a function of location along the wetland is shown in Figure 7. 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 (i.e. along the location A1 ï A3), was 10 ppt. The low salinity in the inlet is explained by dilution of the seawater by rainwater. As the sewage was travelling through the wetland salinity increased most likely due to evapo-transpiration from the fully grown *Avicennia* mangrove plants.

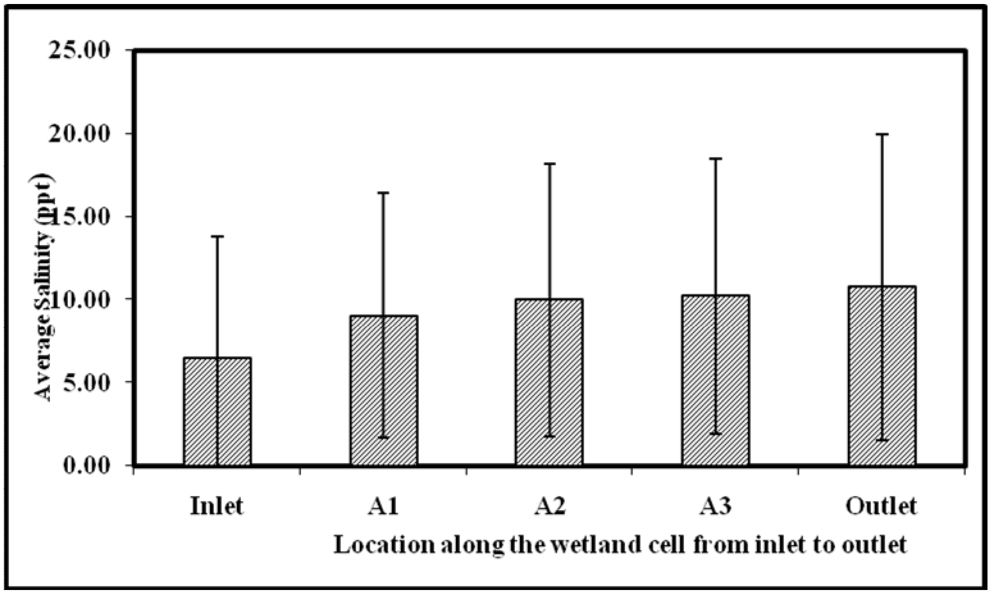

Figure 7: Variation of Average Salinity along the Wetland Cell from Inlet to Outlet

Temperature:

Variation of temperature was as presented in Figure 8. During the day, average inflow temperature was 30.1 ± 0.22 and average temperature in the system was 29.3 ± 0.27. During the night, average inflow temperature was 29 ± 0.45 and average temperature in the system was 28.9 ± 0.46. Generally temperature in the wetland cell was slightly lower during the day and night compared to influent water temperature because of the shading effect of plants. The growth rate constants of decomposing bacteria are influenced by temperature changes within the wetland system. The optimum temperature for the growth of nitrifying bacteria ranges from 28 to 36^{o} C (Senzia, 2003). Since average temperature in wetland system was 29.3 ^{o} C during the day, this temperature favours the decomposing bacteria to decompose nitrogen.

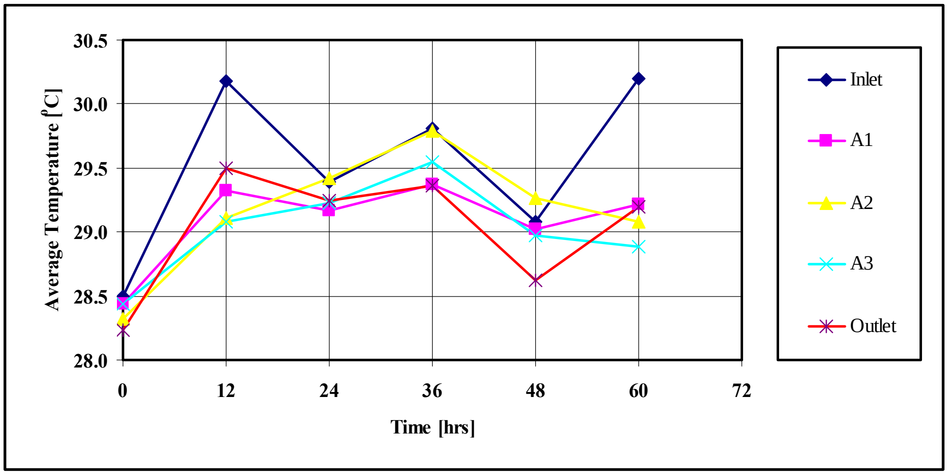

Figure 8: Variation of Average Temperature with Inundation Time

Ammonia Nitrogen (NH3-N):

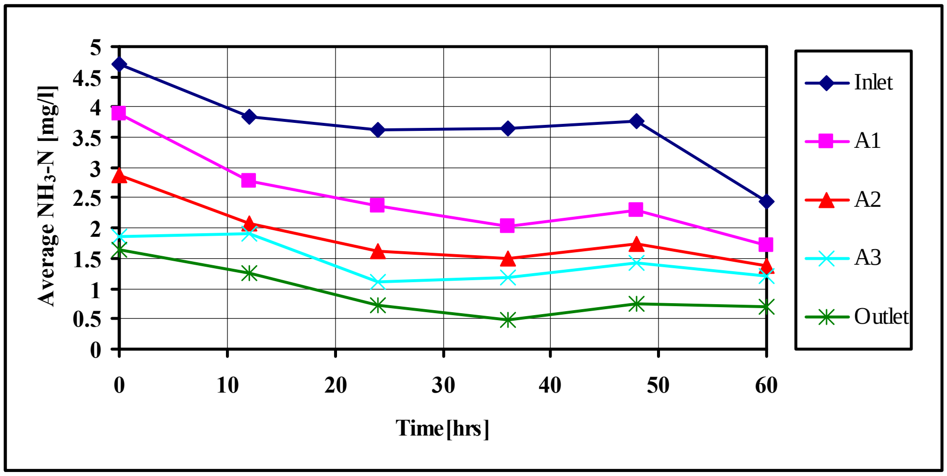

Figure 9: Variation of Average NH3-N Concentrations with Inundation Times

Figure 9 shows the variation of average NH_3-N concentration with time at different sections in the wetland and figure 12 shows the variation of NH_3-N along the wetland cell. It is clear from these figures that the concentration of NH_3-N in the water column typically varied with time and distance from the inlet to the outlet. This observation was made from the five sampling points namely Inlet, A1, A2, A3 and Outlet. The distribution of NH_3-N along the mangrove field wetland was less uniform within the wetland region indicating that there was an inefficient surface circulation pattern.

High NH_3-N concentration were determined at the inlet and tended to be varying with time due to non-uniform quality of the feed. At the inlet the average concentration of NH_3-N was 4.7 ± 1.87mg/l. The average outlet concentration of NH_3-N after 60 hours was 0.7 ± 0.9 mg/l and the average percentage removal was 85.11.

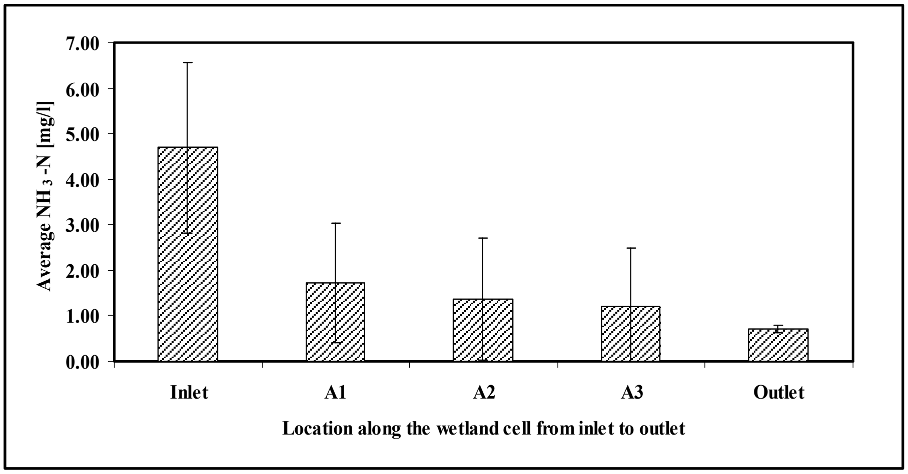

Figure 10: Variation of Average NH3-N Concentrations along the Wetland Cell from Inlet to Outlet

Ammonia showed very good distribution from inlet to outlet (Figure 10). The average effluent NH_3-N concentration from the system was 0.7 mg/l which is within the allowable discharge limit used for design (1.5mg/l). The calculated NH_3-N removal rate of the system ranged from 0.31 to 0.57 kg/ha.d with an average removal rate of 0.49 kg/ha.d. The removal of NH_3-N might be achieved by mangroves and algal uptake, volatilization, nitrification and sedimentation (Senzia, 2003). Based on the results of NH_3-N distribution it is evident that, despite the non-steady state operation of the wetland, the continuous removal of NH_3-N over the cell within three days indicated satisfactory performance of the system.

By increasing the water retention time up to about 7-14 days, it is expected that the system will reach equilibrium and the ammonia removal rates would have been even better (Wu, 2008). This has been proven from the intermittent flow system (operated in inundation time of 3 days), where by this system has shown better performance in removal of NH_3-N compared to the batch system of which was operated in inundation time of 12 hourly cycles.

Nitrite Nitrogen and Nitrate Nitrogen (NO2-N & NO3-N):

The average concentrations of NO_2-N and NO_3-N at the inlet was 0.006 ± 0.004 mg/l and 0.126 ± 0.1 mg/l, respectively. The average outlet concentrations after 60 hours were 0.055 ± 0.007 mg/l for NO_3-N and 0.012 ± 0.007 mg/l for NO_2-N (Figure 11 & Figure 12). The average percentage removal for the NO_3-N was 76.2 and the average NO_3-N removal rate was 0.26 kg/ha.d. NO_2-N showed non-uniform behavior within the wetland, since there was a net production of NO_2-N in the system (Figure 12). NO_3-N also showed non-uniform behavior within the wetland (Figure 11). However, good removals were observed. Non-uniform behavior of NO_2-N and NO_3-N in the wetland cell was also observed by Senzia (Senzia, 2003) could also be caused by co-existence of aerobic and anaerobic areas in the bed that encourages losses of nitrogen through nitrification and denitrification process (Vymazal and Kropfelova, 2009).

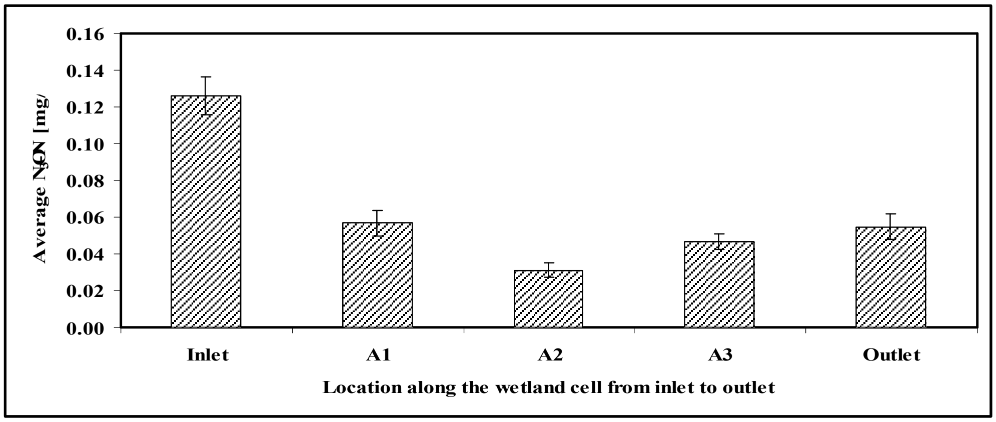

Figure 11: Variation of Average NO3-N Concentration along the Wetland Cell from Inlet to Outlet

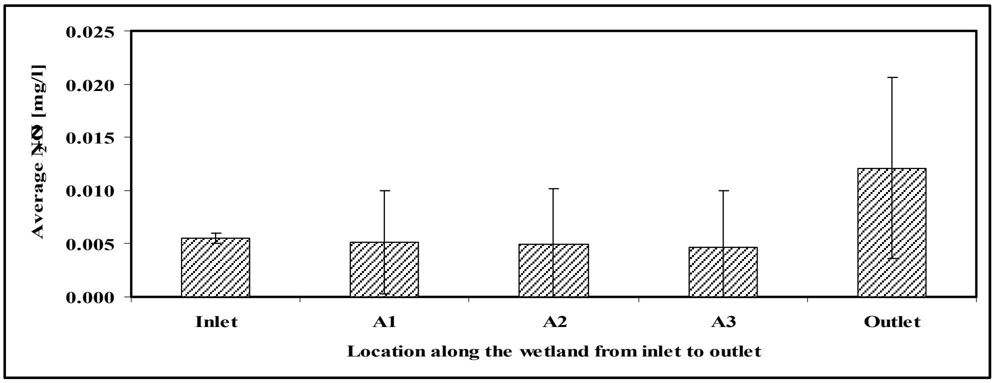

Figure 12: Variation of Average NO2-N Concentration along the Wetland Cell from Inlet to Outlet

The main removal mechanism of NO_2-N in the system is through oxidation to NO_3-N. The removal of NO_3-N in system is mainly through denitrification, plant and algal uptake. According to Hoffman and Lee (1953), the optimum pH for *Nitrosomonas* (i.e. bacteria that oxidize NH_3-N to NO_2-N) and *Nitrobacter* (i.e. bacteria that oxidize NO_2-N to NO_3-N) is 8.3, and that the nitrification rate falls almost to zero at a pH of 9.6. Experiments by Senzia (2003) concluded that the optimum pH range for *Nitrosomonas* was from 7.5 to 8.5 and that for *Nitrobacter* was from 8.3 to 9.3. Hoffman and Lee (1953) quote the optimum pH for *Nitrosomonas* as 8.3 and affirm that the nitrification rate falls to zero at a pH of 9.6. About 90% of the maximum nitrification occurs between pH 7.8 and 8.9.

The maximum average pH finding in this research was 7.9, therefore according to others researcherŝs results indicate that the pH of 7.9 favored more *Nitrosomonas* oxidation than *Nitrobacter* oxidation and hence there was net productivity of NO_2-N in the system (Bigambo, 2003).

Total Kjeldahl Nitrogen (TKN):

Total Kjeldahl Nitrogen (TKN) is a parameter that includes organic nitrogen and Ammonia Nitrogen. At the inlet the average concentration of TKN was 23.16 ± 8.29 mg/l. The average outlet concentration of TKN after 60 hours was 7.10 ± 2.50 mg/l.

Wetland system showed good removals in TKN as the sewage was travelling through the wetland (Figure 13). The average removal of TKN from the system was 61%. The value of TKN concentration was above the allowable discharge limit used for design (5mg/l). The calculated TKN removal rate of the system ranged from 0.83 to 2.33 kg/ha.d with an average removal rate of 1.26 kg/ha.d. The removal of TKN is attributed to mineralization of organic nitrogen (decomposition of organic nitrogen to ammonia), nitrification (decomposition of ammonia to nitrite then nitrate) and uptake of ammonia nitrogen by algae and plant and sedimentation (Tam *et al,* 2009).

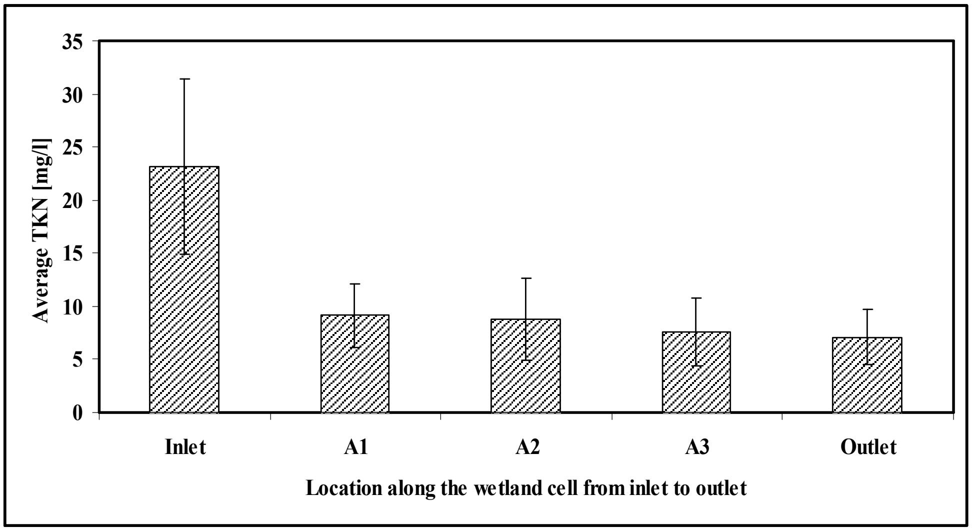

Figure 13: Variation of TKN Levels along the Wetland Cell from Inlet to Outlet

Plates Describing Existing Situation of Constructed Mangrove Wetland during sewage treatment

Plate 2a:Inlet area

Plate 2b:Inlet area

Plate 1: Side view of CMW

Plate 3: Oulet area

CONCLUSIONS AND RECOMENDATIOS

Conclusions and Recommendations

Based on the results presented, reduction in concentration of nitrogen was observed. The removal rates of NH_3-N, NO_3-N and TKN 85%, 76% and 61%, respectively. The removal processes were attributed by the forcing functions pH, temperature and DO with averages of 7.75, 29°C and 1.55 mg/L, respectively.

For optimization of system treatment performance with respect to nitrogen and other pollutants removal, it is recommended that;

- Inundation time should be long enough to allow the system to operate more in a steady state conditions (> 5 ï 15 days) for treatment of sewage to acceptable levels for safe use or discharge.
- For mangrove root-nodes respiration, water depth must be as low as possible (< 10 cm).

- Since raw sewage may cause anaerobic conditions in which may produce Hydrogen Sulphide gas (H_2S) which is harmful to mangroves, only primary treated sewage should be used. The primary treatment can be achieved in oxidation ponds, septic tanks, UASB reactors etc.

- For maintaining of saline conditions, the wetland system should be located in a point where it can receive tidal seawater both neap and spring tide.

Based on the above recommendations, it is recommended that further research on nitrogen removal in HSFCMW should be conducted on long term basis in order to establish a best database, which will be useful for design of constructed mangrove wetlands in coastal zones in tropical and subtropical countries.

REFERENCES

Along, D.M., Christoffersen P. and Tirendi, F. (1993). ñThe influence of forest type on microbial-nutrient relationships in tropical mangrove sedimentsò *Journal of experimental marine Biology and Ecology*, Vol. 171.

APHA, AWWA and WEF (1998). *Standard Methods for the Examination of Water and Wastewater*, 20th ed., Washington, DC.

Billore, S.K., Singh, N., Sharma, J.K., Dass, P. and Nelson, R.M. (1999). ñHorizontal subsurface Flow Gravel Bed Constructed Wetland with *Phragmites karka* in Central Indiaò, *Wat. Sci. Tech*., Vol. 40, No. 3, pp. 163-171.

Bigambo, T. (2003). *The effects of biofilm activities on nitrogen transformation in horizontal subsurface flow constructed wetland,* MSc. Dissertation, Water Resources Department, University of Dar es Salaam, Tanzania.

Biota, (2005). ñYannarie Salt Project: Mangrove and Coastal Ecosystem study ï Baseline Ecological Assessmentò. *Unpublished report to Straits Salt,* Pty Ltd., Perth.

Boonsong K. and Patanapolpaiboon P. (2002). ñUsage of Mangroves in Constructed Wetlands Municipal Wastewater Treatment Systemò, *Proceedings from 8th international conference on wetland systems for pollution control*, Eds. Mbwette, T.S.A, Katima, J.H.Y., Kayombo, S. and Pratap, H.B., Arusha - Tanzania, Vol. 2, pp 952 -960.

Bruun, E. and Poulsen, M. (2003). *A performance Evaluation of a Subsurface Flow Constructed Wetland in the Tropics,* Thesis, University of Pharmaceutical sciences.

Canfield, D.E., Pfizer, J., Trott, L.A., Tirendi, F., Dixon, P. and Klumpp D.W. (2005). *Rapid sediment accumulation and microbial mineralization in forests of the mangrove Kandelia candel in the Jiulongjiang Estuary - China,* Elsevier Science Ltd, Oxford, UK.

Chazarenc, F., Merlin, G. and Gonthier, Y. (2003). ñHydrodynamics of horizontal subsurface flow constructed wetlandsò*, Journal of Ecological Engineering*, Volume 21, pp 165-173.

Clough, B.F., Boto, K.G. and Attiwill, P.M. (1983). ñMangroves and sewageò a re-evaluation, In Teas, H.J. (Ed.), *Tasks for Vegetation Science*, Dr W. Junk Publishers, The Hague, Vol. 8, pp. 151-161.

Corridor, J.E. and Morell, J.M. (1994). ñNitrate Depuration of Secondary Sewage Effluents in Mangrove Sedimentsò, *Journal of Estuaries:* Vol. 17, No. 16, pp 295-300.

Crites, R.W., Reed, S.C., and Middlebrooks, E.J. (2000). *Natural systems for waste management and treatment*. McGraw Hill, New York, NY.

DAWASCO, (2007). DAWASCO annual report, Dar es Salaam, Tanzania

EPA (2000). ñ*Wastewater Technology Fact Sheet"*, Free Water Surface Wetlands, Office of Water Washington, D.C.

Gerba, C. P., Thurston, J. A.; Falabi, J. A.; Watt, P. M. and Karpiscak, M. M (1999). ñOptimisation of artificial wetland design for removal of indicator microorganisms and pathogenic protozoaò, *Water Science* and *Technology*, 40: 363 - 368. Elsevier Publishers Ltd

Gilvear, D. and Bradley, C. (2000). *Hydrological Monitoring and Surveillance for Wetland Conservation and Management,* a UK Perspective.

Hogarth, P. (1999). *The Biology of Mangroves*, Oxford University Press.

Holguin, G., Vazquez, P. and Basham, Y. (2001). ñThe role of sediment microorganisms in productivity, Conservation and Rehabilitation of Mangrove ecosystem: an overviewò *Journal of Biological and Fertilized soil,* Volume 33.

IIka C. F. and Sitnik, M. (2002). *Mangrove ecology: A Field Manual Focused on the Biocomplexity on Mangrove Ecosystems,* Smithsonian Institution, Washington.

Kadlec, R.H., and Knight, R.L. (1996). *Treatment Wetlands,* Lewis publishers, Michigan.

Kadlec, R.H., Knight, R.L., Vyamazal, J., Brix. H, Cooper, P. and Haberi, R. (2002). ñConstructed Wetlands for pollution Controlò in IWA Processes*, Performance and design and operation IWA Specialist Group on use of Macrophytes in water pollution Control,* IWA Publishing

Kathiresan K. and Bingham B. (2001). óóBiology of Mangroves and Mangrove Ecosystemsôô, *Advances in Marine Biology,* Vol. 40, pp 81-251.

Katima, J.H.Y. (2005). ñConstructed Wetlands: A Chemical Engineering Perspectiveò, *Professorial Inaugural Lecture series No. 46*, University of Dar es Salaam, Tanzania.

Kimwaga, R. J. (2003). *Optimization of waste stabilization pond effluents treatment by use of Coupled dynamic roughing, filter and Horizontal Subsurface flow constructed wetlands* Ph.D Thesis: Department of water Resources Engineering, University of Dar es Salaam, Dar es Salaam.

Kiwanuka, S. (2001). Coliform removal in a tropical integrated pilot constructed wetland, University of Dar es Salaam, Tanzania.

Kristensen, E., Andersen, F. O., Holmboe, N., Holmer, M. and Thongtham, N. (2000). ñCarbon and nitrogen mineralization in sediments of the Bangrong mangrove area, Phuket, Thailandò, *Mar. Ecol.Prog. Ser.*, Vol. 22, pp 199ï 213.

Maggie, M. (2003). ñSimple user guide for building and operating a constructed wetlandò. *Unpublished report*, University of Dar es Salaam Tanzania.

Mandura, A.S. (1997). ñA mangrove stands under sewage pollution stressò *Journal of Red Sea Mangroves and Salt Marshes*: Volume 1.

Mbwette, T.S.A., Katima, J.H.Y. and Jorgensen, S.E. (2001). *Application of wetland systems and waste stabilization ponds in water pollution control*, IKR, Dar es Salaam, Tanzania, pp 233.

Mbwette, T.S.A., Kayombo S., Katima, J.H.Y. and Jorgensen, S.E. (2005). *Waste stabilization ponds and Constructed Wetlands Design Manual,* IKR, Dar es Salaam, Tanzania.

Metcalf, F. and Eddy, J. (1991). *Wastewater Engineering, Treatment, Disposal and reuse,* Tata and McGraw-Hill Pub. New Delhi.

Mitsch W. and Gosselink J. (2000). *Wetlands*, 3rd ed, John Wiley & Sons ,New York.

Mng'anya, E.S. (2002). *Suitability of pumice (murram) soils for wastewater treatment in subsurface flow constructed wetland (SSFC)*. MSc. Dissertation, Environmental Engineering Department, University of Dar es Salaam, Tanzania.

Mohammed S. (2002). ñReview of water quality and pollution studies in Tanzaniaò, *Ambio*, Vol. 31, pp 617- 620.

Ottova, V., Balcarova, J. and Vymazal, J. (1997). ñMicrobial characteristics of constructed wetlandsò, *Water Science Technology*, Elsevier Publishers Ltd, Vol. 35, pp 117 - 123.

Pamba S. (2008). *The Assessment of Potential Use of Mangrove Constructed Wetland for Domestic Wastewater Treatment,* MSc. Dissertation, University of Dar es Salaam, Tanzania.

Rangwala, S.C. (2004). *Water supply and sanitary engineering*, Charotar Publishing House, India.

Reed, S.C., Crites, R.W. and Middlebrooks, E.J. (1995). *Natural systems for waste management and treatment,* McGraw-Hil Book Company New York.

Semesi, A. (1998). óóMangrove Management and Utilization in Eastern Africaöö, *Ambio,* Vol. 27, pp 620-626.

Senzia, M. (2003). *Modeling of nitrogen transformation and removal in horizontal subsurface flow constructed wetlands during treatment of domestic wastewater,* PhD. Dissertation, University of Dar es Salaam, Tanzania.

Shunula J., Skov M., Vannini M. and Cannicci S. (2002). óóQuantifying the density of mangrove crabs: Ocypodidae and Grapsidaeöö, *Marine Biology* Vol. 141, pp 725-732.

Tam, N. F. Y., Wong, A. H. Y. Wong, M.H. and Wong, Y. S. (2009). Mass balance of nitrogen in constructed mangrove wetlands receiving ammonium-rich wastewater: Effects of tidal regime and carbon supply, Department of Biology and Chemistry, City University of Hong Kong, China

Vymazal, J. and Kropfelova, L. (2009). Removal of Nitrogen in Constructed Wetlands with Horizontal Sub-Surface Flow: A Review, Czech University of Life Sciences in Prague, Faculty of Environmental Sciences, Department of Landscape Ecology, Namesti Smirickych Czech Republic.

Wekwe, W.W. (1990). *A study of East African marine and freshwater algae as indicators of heavy metal pollution*. MSc. Dissertation, University of Dar es Salaam, Tanzania.

Wu, Y. A., Chung, N. F. Y., Tam, N. Pi, Wong, M. H. (2008). Constructed mangrove wetland as secondary treatment system for municipal wastewater, Ecological Engineering; 34(2):137-146.

Yang, Q., Tam, N. F. Y., Wong, Y. S., Luan, T. G., Su, W. S. Lan, C. Y., Shin, P. K. S. and Cheung, S. G. (2008). Potential use of mangroves as constructed wetland for municipal sewage treatment in Futian, Shenzhen, China, *Marine Pollution Bulletin*, State Key Laboratory of Biocontrol, School of Life Sciences, Sun Yat-Sen University.

Ye Y., Tam N. and Wong Y. (2001). ñLivestock wastewater treatment by a mangrove pot-cultivation system and the effect of salinity on the nutrient removal efficiencyöö, *Mar Poll Bull*, Vol. 42, pp 513-521.

Zakrzewski, S.F. (2002). *Environmental toxicology,* (3rd edition) Oxford University press Inc. New York.