The Efficacy of a Tropical Constructed Wetland for Treating Wastewater During the Dry Season: The Kenyan Experience

Khisa Kelvin · Mwakio Tole

Abstract Constructed wetlands have recently received considerable attention as low cost and efficient means of cleaning up many different types of wastewaters at secondary and tertiary levels. This is an environmentally sound method of wastewater treatment that does not use hazardous chemicals, and is based on the high productivity and nutrient removal capability of the wetland that strongly relies on its intricate ecosystem structure and function. Research work was conducted on a tropical constructed wetland to establish its capability to treat wastewater during the dry season. A comparison of its efficacy with that of conventional wastewater treatment plants was made on the basis of the measured water quality parameters. Temperature, pH, dissolved oxygen, and conductivity were measured in situ. Total suspended solids (TSS), total dissolved solids (TDS), biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), phosphorus, ammonia, and nitrites were analyzed in the laboratory. Fecal coliforms were enumerated and *Escherichia coli* counts were determined. The TSS values reduced from a mean of 102 mg/l at the influent point to 16 mg/l at the effluent point, depicting a reduction of 84.3%. Influent TDS averaged 847 mg/l, while the effluent averaged 783 mg/l. Dry season BOD$_5$ levels were reduced from an average of 286 at the inlet point to 11 mg/l at the outlet representing a reduction efficiency of 96.2%. COD levels were reduced from a mean of 2,002.5 to 47.5 mg/l depicting a removal efficiency of 97.6%. Phosphorus was reduced from a mean of 14 to 11 mg/l representing a percentage removal of 21.4%. Levels of ammonia reduced from a mean of 61 at the influent point to 36 mg/l at the effluent point representing a percent reduction of 41.0%. There was a 99.99% reduction for both the fecal coliforms and *E. coli* counts. Conductivity of wastewater increased from 1.08 to 1.98 mS, while the pH increased from 6.23 at the inlet point to 7.99 at the outlet of the system. Temperature and dissolved oxygen measurements showed a diurnal variation. The dry season wastewater heavy metal concentrations were in the following ranges: Pb (0.7–6.9 ppm), Cr (0.2–0.5 ppm), Zn (0.1–2.3 ppm), Ni (0.1–1.3 ppm) with Cd and Cu not being detected in the wastewater streams. Overall, tropical constructed wetlands are effective in treating wastewater streams and they perform a lot better than the popularly used waste stabilization ponds. This paper recommends that they can be widely used within the tropics.

Keywords Constructed wetlands · Wastewater treatment · Environmentally sound methods · Hazardous chemicals · Heavy metals · Tropical

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1 Introduction

The Splash Water World wastewater treatment facility is one of the pioneering constructed wetland (CW) systems in Kenya. It was constructed in 1993 and commissioned in 1994 and is designed to treat up to 80 m^3 of restaurant wastewater per day with an approximate retention time of 11 days. This wastewater treatment facility presents a low technology, low-energy, non-mechanical, chemical free, and environmentally friendly option for the treatment of different streams of wastewater (Khisa 1997).

Wetlands in Kenya mean different things to different people. To some, they are important habitats for numerous kinds of waterfowl and fish whereas to others, they are the kidneys of the earth. Pollutants are removed by a complex variety of biological, chemical, and physical processes. Critical processing of pollutants is done by wetland microbial populations. Micro-organisms in the wetland cause a metabolic breakdown of the organic matter in the wastewater by rapidly adapting to and exploiting new nutrient or energy sources. The foundations of the three wetland cells are profiled to maximize water travel distance between the inflow and the outflow of each cell to ensure that both aerobic and anaerobic microbial activities are enabled to go on.

Macrophytes remove the pollutants by directly assimilating them into their tissues; providing a suitable environment for microbial activity; slowing down water movements (flow rates) and thereby allowing for sedimentation and adsorption of substances to their shoot systems. CW technology for treating wastewater offers a relatively low cost treatment system in terms of operation and maintenance (Scholz and Lee 2005; Hedmark and Jonsson 2008). This makes it suitable for treating wastewater in the economically disadvantaged third world. Apart from ensuring effective and reliable wastewater treatment, the system also affords a habitat for different varieties of flora and fauna. The lush and opportunistic tropical vegetation of the wetland has served to attract a number of resident and migratory bird

species, a development that has turned the constructed wetland into an ornithological site with more than 120 bird species recorded (Ng'weno 1994)

2 Description of the Constructed Wetland

The constructed wetland is located at an altitude of over 1,500 m above sea level within a tropical highland climate setting. It consists of a Gravel Bed Hydroponics (GBH) and three open surface wetland cells in series. The mean annual rainfall is 1,080 mm, falling in two seasons: March to June and October to December. This study was carried during the dry seasons from July to September and from January to March. The mean annual temperature of the site is 18.9°C with a mean maximum of 24.9°C. Wind speeds average 6.4 m/s while the mean relative humidity is approximately 58%. In total, the entire wetland covers an area of 0.5 ha of land and was build to treat up to 80,000 l of wastewater per day with the aid of the force of gravity. This is achieved after a residence time of approximately 11 days.

The GBH is almost rectangular in shape and measures approximately 70×25 m. It has an average depth of less than 1.5 m. Its design incorporates a large graded ballast-filed subsurface flow section that is suitably designed to minimize the smell nuisance. Alternating wall embankments within the GBH ensures that wastewater meanders through the gravel as it is being broken down. The large surface area for the microbial attachment provided by the ballast pieces assist in microbial breakdown of organic wastes. The GBH top is planted with macro hydrophytes that absorb nutrients and also aids in the transportation of oxygen to the underground bacteria through their rooting systems, hence enhancing the growth of these useful bacterial colonies.

Wetland cell 1 has a maximum possible area of 480 m^2 and is ringed with suitably selected macro-

Table 1 Areas of the main sections of the constructed wetland

Section of the constructed wetland	Maximum possible area (m^2)
Gravel bed hydroponics (GBH)	1,750
Wetland cell 1	480
Wetland cell 2	1,080
Wetland cell 3	990
Total area	4,300

Fig. 1 TSS values of influent (before treatment) and effluent (after treatment) wastewater streams
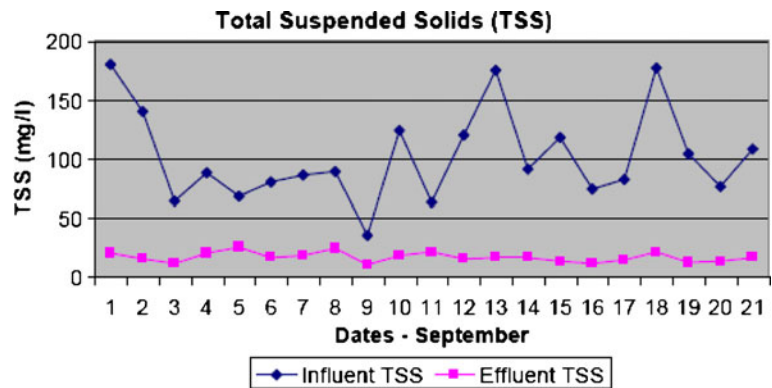
phytes that assist in wastewater treatment by absorbing nutrients and heavy metals and also providing a conducive environment for aerobic and anaerobic microbial activity. Aquatic plants are an essential component of a wetland and contribute to the nutrient transformation by abetting in the physical, chemical, and microbial processes besides removing nutrients for their own growth (Brix 1997). They offer mechanical resistance to the flow, increase the retention time, and facilitate the settling of suspended particulates.

The same conditions are replicated for wetland cells 2 and 3 whose areas are as stated in Table 1 below:

By design, the three surface cells have open surfaces at their centers for purposes of facilitating natural aeration due to exposure to winds and the destruction of pathogenic organisms through ultraviolet irradiation. Wind action improves the dissolved oxygen levels of the water. Wind induces vertical mixing of the wetland cell water. There are no characteristic malaria problems as each component of the system is contained in an intricate predator-prey relationship.

3 Objectives of the Study

This study was undertaken to establish the effectiveness of this constructed wetland for wastewater treatment during the dry season and also identify the major operational and management challenges associated with the use of constructed wetlands for purposes of establishing a database against which future changes in the wetland can be compared.

The IUCN in the Ramsar Convention adopted the following definition of wetlands (Navid 1989): "Areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static of flowing, fresh, brackish, or salt including areas of marine water, the depth of which at low tide does not exceed 6 metres". A constructed wetland, on the other hand is defined as follows: "A Constructed Wetland consists of former terrestrial environments that have been modified to create poorly drained soils and wetland flora and fauna for the primary purpose of contaminant or pollutant removal from waste water. Constructed wetlands are essentially wastewater treatment systems and are designed and operated as such, though many systems do support other functional values" (Hammer (1989)).

4 Field and Laboratory Methods

Duplicate water samples were collected from the inlet and outlet of the GBH. Additional water samples were then collected in sampling bottles along a transect at approximate 10 m intervals along the entire profile of the three wetland cells. There were a total of 11, 11, and eight samples, respectively, for wetland cells 1, 2, and 3. Measurements were made in situ for the dissolved oxygen, temperature, conductivity, total dissolved solids, and pH. pH was

Table 2 TDS variation through the wetland profile

Wetland section	TDS	% Change
Into GBH	900	
Out of GBH	1,050	+16.7
End of wetland cell 1	900	−14.0
End of wetland cell 2	850	−6.0
End of wetland cell 3	850	0.0
Cummulative		−6.0

Table 3 Variation of temperature and pH along the Wetland profile

Sampling Site	Temperature	pH
1	24.2	6.10
2	23.4	6.10
3	23.9	6.37
4	24.6	7.74
5	25.1	7.87
6	26.2	7.95
7	25.5	7.76
10	26.1	7.88
12	29.0	7.89
13	29.1	7.72
14	30.7	7.66
15	29.9	7.43
16	28.6	6.81
17	29.1	6.80
18	29.4	7.65
19	29.5	7.85
20	29.2	7.94
24	30.1	7.92
25	30.6	7.80
26	29.4	7.79
27	28.5	7.72
28	28.4	7.83
29	29.0	7.85
30	28.7	7.98

measured with a standard digital pH meter (Jenway model 3100) while conductivity was measured with a conductivity meter (Jenway model 4070), both with automatic temperature compensation. Jenway Dissolved oxygen (DO) meter model No. 4490 was used for determining the oxygen levels.

Fig. 2 Conductivity and temperature variation along the wetland profile
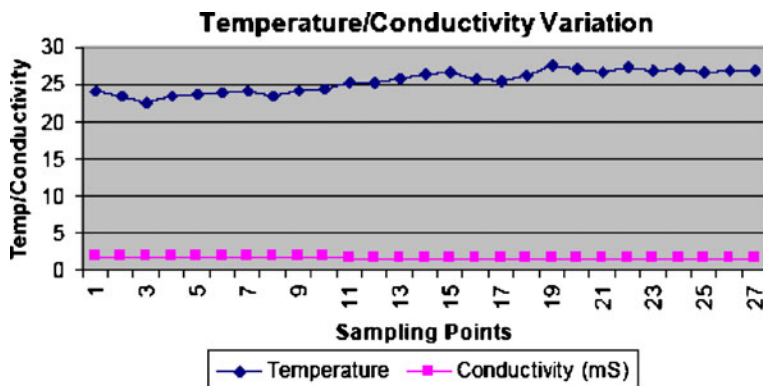
Samples for heavy metal analysis were preserved by acidifying with concentrated nitric acid and storing in a freezer at 4°C. To 20 cm³ wastewater was added 30 ml of nitric acid and digested for 3 h at 70°C. The samples were then cooled, filtered, and made up to the 100 cm mark and the following heavy metals [lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), nickel (Ni), and copper (Cu)] were determined using a Perkin Elmer 2380 Atomic Absorption Spectrophotometer. Wastewater samples were also stored in a portable freezer at 4°C and transported to the laboratory and analyzed for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), nutrients (NO_2-, PO_4^{3-} - P, and NH_3), and fecal coliforms and *Escherichia coli* were determined using standard APHA (1992) procedures.

5 Results and Discussions

5.1 Total Suspended Solids

The removal of suspended solids by the constructed wetland system was highly variable during the entire dry season period. The average TSS effluent levels were reduced from an average of 102-16 mg/l over the 21-day monitoring period representing a mean removal rate of 84.31% (Fig. 1). The efficiency of removal ranged from 63% to 91%.

5.2 Total Dissolved Solids

The total dissolved solid levels showed tremendous variability with large deviations from the mean. However, differences between the mean influent TDS and the mean effluent

TDS were not very significant. The TDS values showed an increase of 16.7% on passing through the GBH. This is attributed to the wastewater reacting with the soils and rocks, to dissolve some solids as it meandered through the profiled embankments (Table 2).

5.3 pH and Temperature

The pH of the wastewater along the profile varied from 6.1at the influent to 7.98 at the final effluent. The accompanying temperature readings varied from 24.2°C at the influent to 28.6°C at the effluent point (Table 3).
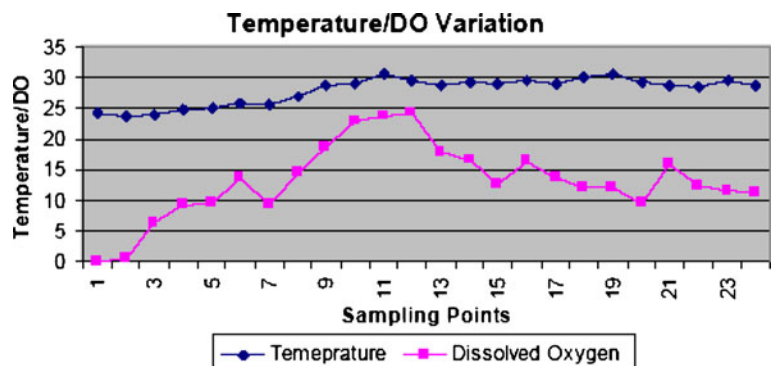
5.4 Electrical Conductivity

The conductivity ranged from 1.90 mS at the influent to 1.57 mS at the effluent. Figure 2 shows the conductivity variation along the entire wetland profile together with the accompanying temperatures. The change in conductivity of 17.4% is reflective of the minimal change in the TDS, though it can be argued that the more conducting ions remained in solution as the less conducting ions were removed from the wastewaters.

5.5 Dissolved Oxygen

The levels of DO were measured for 5.5 h along the wetland profile at a constant depth of 20 cm together with the temperature profile (°C). Wastewater entering the constructed wetland had the lowest concentration of DO (0.1 mg/l). This concentration increased along the profile to super saturation levels due to the photosynthetic activities of the wetland algae and other submerged and above-surface macrophytes (Fig. 3).

5.6 Biochemical Oxygen Demand

The average effluent levels of BOD_5 were reduced from an average of 286 to 11 mg/l over the course of the 20-day sampling period, representing a cumulative reduction rate of 96.15%. The dry season BOD_5 in the raw influent ranged from 150 to 385 mg/l as compared to the range of 9.4 to 13.5 mg/l for the final effluent (Fig. 4).

5.7 Chemical Oxygen Demand

The influent levels of COD were reduced from an average of 2,002.5-47.5 mg/l at the effluent, representing a cumulative reduction rate of 97.63%. The septic tank, GBH, wetland cell 1, 2, and 3 gave average reductions of 37%, 15%, 82% and 45%, respectively.

5.8 Albuminoid Ammonia

The concentration of albuminoid ammonia when the wastewater was entering the septic tank was 16.92 mg/l. It underwent a cumulative percentage reduction of 86% so that the final effluent at the end of wetland cell 3 had 2.3 mg/l of albuminoid ammonia. The GBH achieved 80% reduction of albuminoid ammonia from 16.92 to 3.44 mg/l (see Table 4).

5.9 Nitrites

Nitrite concentrations during the dry season were 0.13 mg/l at the influent point and below detection levels at the wetland cells 1 and 2. At the effluent point, however, a concentration of 0.1 mg/l was detected. This was probably due to the microorgan-

Fig. 3 Variation of temperature and dissolved oxygen along the wetland profile

Fig. 4 Variation of BOD5
along the wetland profile
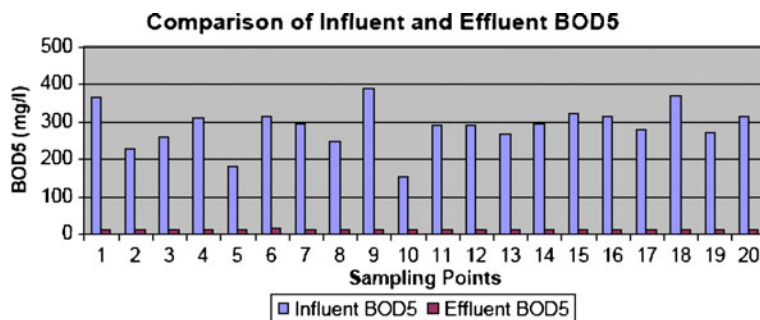
isms and macroorganisms residing in wetland cell three. This wetland cell had the greatest ecological succession.

5.10 Soluble Phosphorus

Mean soluble phosphorus concentrations decreased from 13.8 at the influent point to 11.2 mg/l at the effluent point, indicating a removal efficiency of 18.8% during the monitored dry season.

5.11 Coliforms

Coliform counts showed a decrease from 3,450/ 100 ml at the influent point to 95/100 ml at the effluent point, representing a removal rate of 97.2%.

5.12 E.Coli

E. coli counts decreased from 1,215/100 ml at the influent point to 28/100 ml at the effluent point, achieving a removal rate of 97.7%.

5.13 Heavy Metals

Lead removal efficiency was 89.9% (with levels of concentration decreasing from 6.9 to 0.7 ppm).

Chromium removal efficiency was 60% (from 0.5 to 0.2 ppm). Zinc removal efficiency was 96% (from 2.3 to 0.1 ppm). Nickel removal efficiency was 92% (from 1.3 to 0.1 ppm). Cadmium and copper were not detected in the wastewater.

5.14 Conclusion and Recommendations

The absence of extreme cold temperature conditions in the tropics ensures that the functionality of constructed wetlands for wastewater treatment is not disturbed all the year round. High tropical temperatures also ensure that the ecological succession is much faster with an abundant mix of tropical biodiversity. These results demonstrate that constructed wetlands are capable of treating domestic wastewater to acceptable standards using the power of nature and not chemicals.

Constructed wetlands rely on the intricate cycles of nature to treat wastewater in an environmentally sound manner and enjoy greater treatment efficiencies than the popularly used waste stabilization ponds. It is recommended that their adoption be encouraged where land requirements allow. In particular, they are recommended for tourist camps and lodges located within tropical National Parks and Game Reserves.

Table 4 Albuminoid
ammonia

Wetland section	Albuminoid ammonia concentration (mg/l)	% Change
Into GBH	16.92	
Out of GBH	3.44	−80
End of wetland cell 1	7	+103.5
End of wetland cell 2	5.26	−24.9
End of wetland cell 3	2.3	−56.3
Cumulative		−86.4

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