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The Efficacy of a Tropical Constructed Wetland for Treating Wastewater during the Wet Season: The Kenyan Experience

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Abstract
Constructed Wetlands are among the most promising treatment options for domestic and industrial wastewater streams in places where land is available. They need more land than conventional wastewater treatment plants but occupy less space when compared to waste stabilization ponds. They are generally affordable in operational and maintenance costs while offering effective and reliable service. Constructed Wetlands are manmade wastewater treatment systems that consist of shallow ponds and channels that have been planted with macrophytes. They rely on natural, microbial, biological, physical and chemical processes to treat wastewater. They normally comprise of impervious clay liners clay liners and engineered structures to control the flow direction, wastewater retention times and water levels. Research wok was conducted on a tropical constructed wetland to establish its capability to treat wastewater during the wet season. A comparison of its efficacy with that of conventional wastewater treatment plants was made on the basis of 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. Faecal coliforms were enumerated and *Escherichia coli* counts were determined. The TSS values were reduced from a mean of 116 mg/l at the influent point to 24 mg/l at the effluent point, depicting a reduction of 79.31%. Influent TDS averaged 847 mg/l, while the effluent averaged 783mg/l. Wet season BOD_5 levels were reduced from an average of 472 mg/l at the inlet point to 24 mg/l at the outlet, depicting a reduction efficiency of 94.9%. COD levels were reduced from a mean of 2174.2 mg/l to 71mg/l, representing a removal efficiency of 96.7%. Phosphorus was reduced from a mean of 14 mg/l to 11 mg/l representing a percentage removal of 21.4%. Levels of ammonia reduced from an influent mean of 61 mg/l to an effluent mean of 48 mg/l representing a percentage reduction of 21.3%. There were a 99.99% reduction for both the faecal coliforms and *E.coli* counts. Conductivity of wastewater increased from 1.08mS to 1.98mS, while the p H 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 wet season wastewater heavy metal concentrations were in the following ranges: Pb (7.9-11.9ppm), Cd (1.0-3.8ppm), Cr (1.4-8.8ppm), Zn (0.1-10.4ppm), Ni (2.2-8.3ppm) with Cu not being detected in the wastewater samples. 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 their widespread use within the tropics as the prevalence of warm temperatures all the year round enhances their performance.
Keywords: Constructed Wetlands, Microbial, Physical, Chemical, Heavy metals, Tropics

1 Introduction

The Splash Water World wastewater treatment facility is one of the pioneering Constructed Wetland (CW) systems in Kenya. This constructed wetland comprises of a sub-surface gravel bed hydroponics planted with emergent macrophytes and a free water surface system that comprises of three pond cells with emergent macrophytes planted around them. Having been constructed in 1993 and commissioned in 1994, the system is designed to treat up to 80 m3 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. In short, macrophytes do contribute to nutrient transformation, offer mechanical resistance to flow, increases the retention time, facilitates settling of suspended particulates, and improves conductance of water through the media as the roots grow. Particularly, the rhizomes of the reeds grow vertically and horizontally, opening up the soil to provide a hydraulic pathway through the media. Furthermore, they transport oxygen to the deeper layer of the media via the leaves and stems of the reeds down through the hollow rhizomes and out through the roots and hence help in oxidation and precipitation of heavy metals on the root surfaces (Gopal, 1999).

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. A part from ensuring an 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 wet seasons from March to May and from October to December. 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 m2 and is ringed with suitably selected macrophytes 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.

Table 1: Areas of the Main Components of the Constructed Wetland

Section of the Constructed Wetland	Maximum Possible Area (m2)
Gravel Bed Hydroponics (GBH)	1750
Wetland Cell 1	480
Wetland Cell 2	1080
Wetland Cell 3	990
Total Area	4,300

Wastewater treatment processes at the Splash Water World constructed wetland incorporates several physical, chemical, and biological processes. The major physical process is the settling of suspended particulate matter which is a major cause of BOD reduction. The chemical processes involve adsorption, chelation, and precipitation, which are responsible for the major removal of phosphorus and heavy metals. In term of biological processes, the treatment is achieved by microorganisms (Gopal, 1999). Due to fixed film or free bacterial development, biological processes allow the degradation of organic matter, nitrification in aerobic zones and denitrification in anaerobic zones. The **microbiological activity** is the key parameter for their performance. The principle removal mechanisms in subsurface flow constructed wetlands for some constituents in wastewater are bioconversion by facultative and anaerobic bacteria on plant and debris surfaces for biodegradable organics; filtration and sedimentation for suspended solids; nitrification/ denitrification, plant uptake ad volatilization for nitrogen; adsorption to plant roots and debris surfaces as well as sedimentation for heavy metals; adsorption and biodegradation for trace organics and natural decay, physical entrapment, filtration, predation, sedimentation, excretion of antibiotics from roots of plants for pathogens (Crites and Tchobanoglous1998).

3 Objectives of the Study

This study was undertaken to establish the effectiveness of this constructed wetland for wastewater treatment during the wet 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 or 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: "…consisting 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, 8 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 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.

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 hours 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)] 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 NH3) and Faecal Coliforms and Escherichia Coli were determined using standard APHA (1992) procedures.

Table 2 TDS Variation through the wetland profile during the wet season

Wetland Section	TDS (mg/l)	% Change
Into GBH	946	
Out of GBH	1220	+ 29.0
End of Wetland Cell 1	920	- 25.0
End of Wetland Cell 2	843	- 8.0
End of Wetland Cell 3	840	-0.4
Cumulative		- 11

Table 3 Variation of temperature and pH along the Wetland Profile

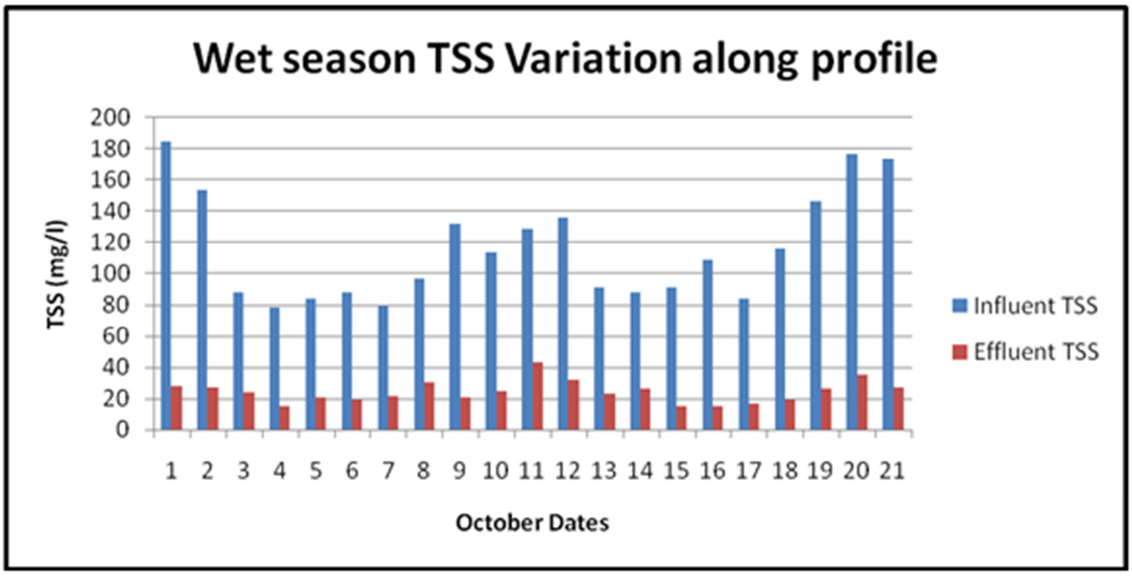
Sampling site	Temp °C	pH
1	22.3	6.23
2	21.1	6.36
3	20	6.37
4	23.5	7.74
5	23.6	7.77
6	24.6	7.91
7	23.7	7.76
8	22.9	7.68
9	31.7	7.89
10	22.6	7.73
11	23.3	7.88
12	21.6	7.70
13	18.8	6.79
14	16.8	6.80
15	20.7	7.65
16	22.8	7.83
17	22.0	7.66
18	24	7.86
19	22.7	7.80
20	23.4	7.79
21	23.9	7.97
22	23.3	7.72
23	23.2	7.83
24	20.9	7.85
25	22.2	7.38
26	20.8	7.20
27	22.5	7.12
28	23.6	7.31
29	23.3	7.90
30	23.7	7.97
31	25.4	7.99

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 wet season. The average TSS effluent levels were reduced from an average of 116 mg/l to 24 mg/l over the 21 day monitoring period, representing a mean removal rate of 79.31% (Fig. 1). the efficiency of TSS removal ranged from 66% to 86%.

Fig 1: TSS values of influent (before treatment) and effluent (after treatment) of the waste water streams

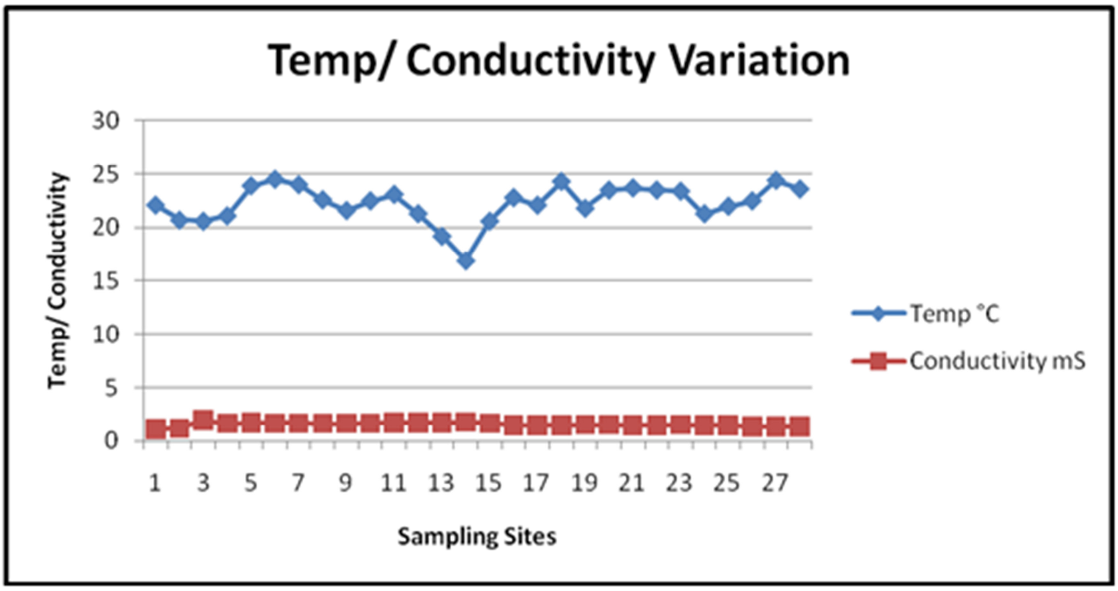


5.2 Total Dissolved Solids
The total dissolved solid levels showed tremendous variability with large deviations from the mean. However, differences between the mean influent TDS and the mean effluent TDS were not very significant. The TDS values showed an increase of 29% on passing through the GBH. This is attributed to the wastewater reacting with the soils and rocks, to dissolve some solids as it meandered through the profiled embankments. It is probable that the prevailing wet season at the time might have aided this process (Table 2).

5.3 pH and Temperature
The p H of the wastewater along the profile varied from 6.23 at the influent to 7.99 at the final effluent. The accompanying temperature readings varied from 22.3° C at the influent to 25.4 °C at the effluent point (Table 3).

5.4 Electrical Conductivity
The conductivity along the profile increased from 1.08 mS at the influent to 1.33 m S at the effluent. Fig. 2. Shows the conductivity variation along the entire wetland profile together with the accompanying temperatures. The increase in conductivity by up to 23% can be attributed to more additional ions being dissolved from the rocks along the constructed wetland regime.

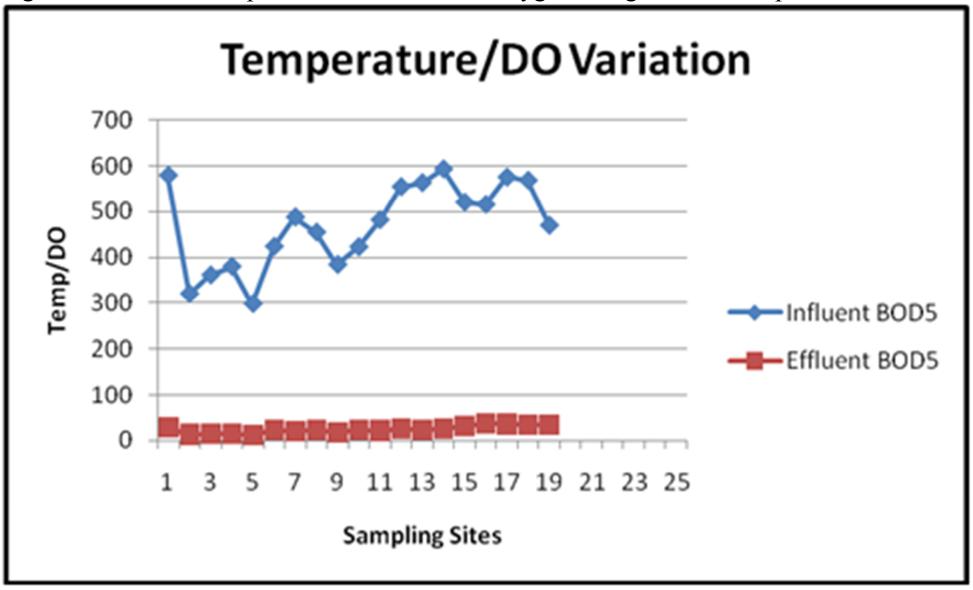
Fig. 2 Conductivity and Temperature Variation along the wetland profile



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 (0.1mg/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).

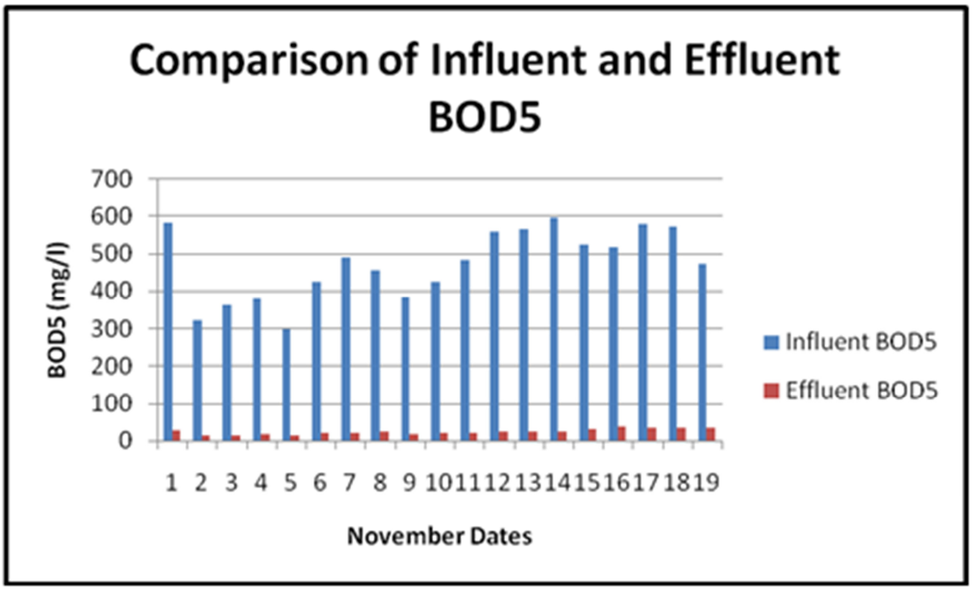
Fig 3 Variation of Temperature and dissolved oxygen along the wetland profile



5.6 Biochemical Oxygen Demand

The average effluent levels of BOD_5 were reduced from an average of 472 to 23 mg/l over the course of the 20-day sampling period, representing a cumulative reduction rate of 95.1%.

Fig 4 Variation of BOD along the wetland profile



5.7 Chemical Oxygen Demand

The influent levels of COD were reduced from an average of 2174.2 to 71.5 mg/l at the effluent, representing a cumulative reduction rate of about 96.5%. The septic tank, GBH, Wetland Cells 1, 2 and 3 registered average reductions of 30%, 27.5%, 85% and 71% 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).

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

5.9 Nitrites

Nitrite concentrations during the wet 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 microorganisms 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 wet season.

5.11 Coliforms

Coliform counts showed a decrease from 3,260/ 100 ml at the influent point to 85/100 ml at the effluent point, representing a removal rate of 97.3%.

5.12 E. Coli

E. Coli counts decreased from 1,500/100 ml at the influent point to 29/100 ml at the final effluent point, registering a removal rate of over 98%.

5.13 Heavy Metals

Lead removal efficiency was 18.5% with levels of concentration decreasing from 11.9 to 9.7 ppm. Zn concentration reduced by 98.4% with levels dropping from 6.3 to 0.1 ppm as Ni concentration reduced by 50.6% with levels dropping from 8.3 to 4.1 ppm. This can be attributed to the removal processes explained above. Although Cu was totally not detected in the wastewater stream, the concentrations of Cd and Cr increased along the constructed wetland profile. It is probable that this can be due to rock leaching occasioned by the wet season.

5.14 Conclusion and Recommendations

The tropical temperature differences between the wet season and the dry season are not so great as for the temperate region, meaning that the wastewater treatment performances of tropical wetlands in the two seasons do not vary significantly. This absence of extreme cold temperature conditions in the tropics ensures that the functionality of constructed wetlands for wastewater treatment is not disturbed at all the whole year round. Comparatively higher tropical temperatures all year round ensure that the constructed wetland's 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 manmade chemicals. These systems rely on the intricate cycles of Mother Nature to treat wastewater in an environmentally sound manner and also 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.

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