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ABSTRACT

One of the problems with most approaches in the selection of wastewater treatment systems is that the wastewater characteristics which are often estimated are assumed to remain constant through the design period of the plant. The change in standard of living, water availability and change of industrial activities are some factors that can significantly alter the wastewater characteristics and possibly affect its treatability with existing systems. This study was carried out from March to May 2009 to assess the treatability of sewage at two wastewater plants in Harare which are more than 20 years old. Characteristics studied included pH, BOD, COD, TP, TS, TSS, TDS, TVSS, Ammonia and seven selected metals linked to bacterial toxicity. Composite samples were collected at the inlet works of Crowborough and Marlborough sewage treatment works and analyzed for the selected parameters according to standard methods. Crowborough which receives a mixture of domestic and industrial wastewater incorporates biological nutrient removal (BNR) and trickling filter (TF) processes. Marlborough Sewage Treatment Works, which treats only domestic wastewater, comprises a waste stabilization pond system. The ratios of key parameters were used to assess the treatability of the sewage including the potential to remove nutrients. The level of the metals was used to infer possible inhibition of biological processes in the plant while TVSS and BOD were used to ascertain the biodegradability of the sewage. It was found that the most ratios of key wastewater quality parameters were outside the range recommended for optimum treatment by BNR process while the composition was marginally suitable for trickling filters for most samples, with the raw sewage inflow to Crowborough being in the range weak to medium strength. Toxicity was found to be a potential problem for Crowborough. Factors affecting the composition of sewage could be industrial wastewater effluent and water availability. The raw sewage inflow to Marlborough was within the range medium to strong as a result of the recurrent water shortages in the area. It is recommended that appropriate process and operational modifications be made at the treatment plants to cater for the changes in wastewater characteristics. Stringent effluent requirements should be made for industries that produce effluent with toxic elements

Keywords: biological nutrient removal, pond, treatability, trickling filters, toxicity, wastewater characteristics.

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1. Introduction

Wastewater collection systems (sewer) and the wastewater treatment plants were originally constructed to minimize the “nuisance”, pollution effects, the sewage was having on the environment thereby protecting public health and preserving the environment (Waring, 1867; Cooper; Turneaure and Russel, 1916). It thus becomes imperative to characterize wastewater in order to predict the level of treatment for different reuse purposes. Municipal Wastewater Treatment Plants make use of naturally occurring water micro-organisms to (1) remove pollutants from wastewater, particularly the nutrients carbon, nitrogen and phosphorous, (2) remove biological pathogens and viruses that are detrimental to the health of the people that may use water polluted with untreated sewage, (3) remove chemical oxygen demand strength before discharging into receiving wastes to avoid eutrophication that will lead to destruction of aquatic life (Makaya et al., 2007). The activated sludge process is a suspended film process that makes use of suspended mixture of micro-organisms to oxidize the biodegradable organics in the sewage. The treatment of sewage by the activated sludge process is based more on the concentration of viable micro-organisms than on the organic loading of the sewage (Metcalf and Eddy Inc., 1991). Biological filters are an example of a fixed media processes whose efficiency of sewage treatment is based on the concentration of the organics to be oxidized. Also like the Activated Sludge system, biological filters use micro-organisms to effect treatment. Sewage treatment ponds use a variety of mechanisms that include aerobic, anaerobic and facultative micro-organisms for the removal of harmful substances from sewage (Hammer and Hammer, 1996). This biological removal of harmful pollutants from domestic and industrial sewage is affected by a number of factors which have a bearing on the optimum conditions for microbial activity like temperature, pH, the presence of toxic organics and inorganics including heavy metals and the amount of the waste to be removed (Mines et al, 2003; Deshpande et al, 1994; Ileri et al, 2003; Shon et al, 2006).

The presence of heavy metals in wastewaters poses a serious problem for the environment as well as for the biological treatment processes that take place at sewage treatment plants (Spain and Alm, 2003). The disposal of both the treated effluent and sludge contaminated with heavy metals give rise to detrimental impacts on the environment and aquatic life in the receiving waters. Also, sewage sludge fertilizers containing these heavy metals lead to accumulation of these metals in soil and produce harmful effects on vegetation, and animals (Udom et al, 2004). In Wastewater treatment, heavy metals reduce the metabolic potential of microorganisms used in the treatment of sewage resulting in the discharge of highly nutritive effluent into the waterways which causes eutrophication, another major environmental problem (Gikas, 2008).

Numerous studies, especially on soils, have been carried out on the effects of heavy metals on microbial populations and their metabolism. According to Wyszowska et al. (2007) heavy metals change the population size and equilibrium of a number of microbial groups, depending on the type of heavy metal, soil species and pH of the soil. In their study on the effects of interactions between nickel and other heavy metals on the soil microbiological properties, they found that Cd and Cr were amongst the greatest inhibitors of microbial growth, especially in acidic soils, whether they occurred alone or in combination with other heavy elements. The genus *Acetobactor*, which is also found in water, was completely wiped out in sandy soils contaminated with Cr and/or Cd while the inhibition was reduced significantly in more compact soil. This is an indication that the toxicity could even be more enhanced in water since the availability and toxicity of a given metal ion is always much lower in soil than in water (Nwuche and Ugoji 2008). *Acetobactor* is responsible for denitrification and organic matter degradation in sewage treatment (Gerardi, 2006). Mazierski (1995) reported that the growth rate of denitrifying bacteria decreases when the concentration of Cr (VI) is 0.6 ppm.

In wastewater analysis there has also been studies carried out to assess the effects of heavy metals on the performance of the activated sludge processes. Using synthetic wastewater in a laboratory-scale activated sludge process in Turkey, Ozbelge et al. (2007) were able to find out that the performance of the activated sludge process was heavily compromised when seed micro-organisms acclimatized to combined heavy metal concentrations double the threshold levels for the micro-organism for a period of one to four months. Furthermore, they went on to discover that the inhibition of the activated sludge process was increased with an increase in the duration of acclimatization with low efficiencies of substrate removal being recorded for acclimatized microorganisms while high substrate removals were evidenced for non-acclimatized microorganisms (the acclimatized process efficiency in terms of COD removal was 20% lower than the non-acclimatized process). In a similar study carried out in 2008 in Taiwan, You et al. (2009) discovered that Ni and Cd inhibited the Specific Ammonia Utilization Rate (SAUR) of the aerobic-anoxic-oxic and Sequencing Batch Reactor (SBR) process with the SBR process being inhibited at much lower heavy metal concentration levels than SAUR process, 80 % inhibition was effected in SAUR process by 25mg/l Ni while only 5mg/l Ni caused the same percentage inhibition for the SBR process.

In Zimbabwe, studies on water pollution and wastewater characterisation have been limited to physiochemical composition with no reference to the effect of heavy metals on the biological treatment processes of wastewater yet two of the sewage works Crowborough and Firle receive a mixture of industrial and domestic sewage. Furthermore the emergence of backyard industries and home industries has also created potentials of heavy metal entrance into municipal sewers even in areas where the sewage is predominantly domestic. This present study aims to characterise influent sewage at two sewage treatment plants in terms of the physicochemical components and metal composition to assess the possible effects on the treatability of the sewage by the activated sludge process, the trickling filter and waste stabilization pond processes. Physico-chemical parameters studied included pH, BOD, COD, 4HR-PV, TP, ammonia, TS, TSS, TDS, TVSS while metals studied were Cd, Cr, Cu, Fe, Pb, Ni and Zn.

2. Study Area



Crowborough Sewage Treatment Works (CSTW) is situated about 20km southwest of Harare City centre. It has the capacity to handle an average of about 54 000 m³/day of sewage per day when fully functional (Nhapi et al., 2002). The CSTW receives sewage from the surrounding high-density suburbs and the western middle and low-density suburbs of Harare. Industrial effluent from the Workington and Willowvale industrial areas is also treated at CSTW. The sewage works consists of a modified Activated Sludge Plant commissioned in 1984 and the Old Conventional Plant commissioned in 1960 (O'Dwyer & Partners, 1993). Table 1 shows a list of the industries located in Workington and their nature. Treated and untreated industrial effluent is discharged to the municipal sewers which drain to sewage works operated by the municipality. The Trade Waste Section of the City of Harare is mandated to monitor the effluent releases by industries to the municipal sewers in line with the Trade Waste by-laws. Thus CSTW receives sewage from domestic, commercial and industrial areas.

Table 1: Partial list of industries at Workington Industrial area.

Industry	Production
Dairy Marketing Board (DMB)	Dairy Products
UNILEVER (Lever Brothers)	Detergents, edible fats and oils
Harare Power Station	Power
Windmill	Fertilizers and Agricultural Chemicals
Sugar Refinery	Sugar refining
National Foods	Assorted food production
Chemical Plating	Electroplating
Clover	Electroplating
Coal Chromium	Electroplating
Lion Match	Matches
Zimbabwe United Passenger Company (ZUPCO)	Repair and maintenance of buses
Chloride Zimbabwe	Lead acid battery manufacture

3.2 Marlborough Sewage works

Marlborough Sewage Treatment Works (MSTW) is a waste stabilization pond sewage treatment system located about 10km north-west of the Harare City centre (Fig. 1). MSTW caters mainly for domestic sewage from the surrounding medium and low-density areas and shops and offices. With the emergence of home industries within the area, the sewage treatment plant has been exposed to mostly untreated electroplating, detergent and rubber effluents according to reports from the Trade Waste Inspectorate of the Harare City.

3. Materials and Methods

3.3 Study Design

The sampling sites were the inlet works of the two sewage treatment works studied. Samples were collected before any preliminary treatment such as screening so as to determine the composition of the raw sewage. These two treatment works are representative of all the different treatment designs being used in Harare and also the type of sewage treated within Harare. The parameters assayed, BOD, COD, 4HR-PV, TP, Ammonia, TS, TSS, TDS, TVSS are indicative of the organic, and to some extent the inorganic, content of the sewage, the bulk of which is removed by the biological action of the microbes (Ujang, 2007). The heavy metals Cd, Cr, Cu, Fe, Pb, Ni and Zn including pH are indicative of the state of the environment the microbes are working in. Their concentrations, oxidation state, combined and cumulative effects could enhance, inhibit, shift the population and

change the diversity of the microbes used for the biological treatment of wastewater thus affecting the potential removal of the waste loads from the sewage (Spain and Alm, 2003).

3.4 Data Collection

Influent 24 hour composite samples were collected in 1 L polythene bottles in triplicate once a week for five weeks on hourly bases to give five sampling campaigns. These campaigns were conducted from 0600 hrs Monday mornings to 0600 hours Tuesdays mornings on 20 April to 21 April, 27 April to 28 April, 4 May to 5 May, 11 May to 12 May and 18 May to 19 May 2009. Samples of 500 ml from two of the 1 L bottles were abstracted and preserved with concentrated sulphuric acid for COD analysis and the remaining 500ml assayed for the rest of the physical parameters. The third sample was preserved with 1.5ml conc. HNO_3 for heavy metal analysis according to APHA(1989).

3.5 Sample analyses

BOD, COD, 4HR-PV, TP, Ammonia, TS, TSS, TDS, TVSS, pH and total trace metal concentrations were determined according to methods prescribed in APHA (1989). For total metal concentration, the samples were first digested with concentrated HNO_3 and concentrated by a factor of four (4) before determination by the Atomic Absorption Spectroscopic method.

4. Results and Discussion

4.1 Sewage Strength

The results for the physics-chemical characterisation of the wastewater from the two sewage treatment plants are shown in Tables 2 to 5. Based on the classification shown in Table 5, the average values of ammonia, Total Dissolved solids and phosphates (Table 4) at both the Marlborough and Crowborough influents were in the weak to medium range. The BOD_5 and TS for Crowborough was falling in the weak to medium range while the same parameters for Marlborough were in the medium to strong range, including the COD. The Total Suspended and Total Volatile suspended solids for Crowborough were in the medium to strong range while the same parameters for Marlborough were strong and the COD for Crowborough was of medium strength.

Using just the BOD and COD to classify the influents, the Marlborough sewage is medium to strong while the Crowborough sewage is of weak to medium strength. The high strength of the Marlborough sewage can be attributed to the low water usage due to shortages in Marlborough. According to literature, industrial sewage has a greater polluting strength than domestic sewage (Waites and Morgan, 2001; Metcalf and Eddy 1991; Hammer and Hammer, 1996). The high strength of the Marlborough sewage, which is formally of domestic origin, could be an indication of the pollution being caused by the insurgence of home industries in the area.

Table 2: Levels of the assayed wastewater parameters for Marlborough for the period 21 April – 19 May 2009.

Parameter	Marlborough				
Date	21/04/09	27/04/09	5/05/09	12/05/09	19/05/09

Temp °C	17.2	18	15	20.5	22
Ph	6.95	7.04	6.82	7.07	6.72
BOD (mg/l)	210	310	132.5	194.6	420
COD (mg/l)	270	404.9	513.8	595	2843.8
4HR PV (mg/l)	27.6	32	9.2	70.2	110.8
TS (mg/l)	558	553.5	507	884	3075.1
TSS (mg/l)	227.5	368.1	137.5	715	2011.9
TDS (mg/l)	330.5	185.4	369.5	169	1063.2
TVSS (mg/l)	218.8	336.3	122.4	564.4	1705
PO ₄ ³⁻ (mg/l)	5.65	8.9	1.3	1.75	5
NH ₃ (mg/l)	18.75	15.5	12.5	16.75	23.75

Table 3: wastewater characteristics for Crowborough for the period 21 April – 19 May 2009

Parameter	Crowborough				
Date	21/04/09	27/04/09	5/05/09	12/05/09	19/05/09

Temp °C	19.5	19	21.2	21	22.5
Ph	7.16	7.07	7.08	6.96	6.72
BOD (mg/l)	150	390	121.3.	188.3	230.6
COD (mg/l)	384.2	425	414.4	663	635.4
PV (mg/l)	42.4	51.2	28.4	28.6	97.6
TS (mg/l)	623.1	680.5	611.5	636	721.1
TSS (mg/l)	221.3	416.1	200	316	376.3
TDS (mg/l)	401.8	264.4	411.5	320	344.8
TVSS (mg/l)	210	335.6	184.4	256.9	371.3
PO ₄ ³⁻ (mg/l)	4.50	4	1.75	2.6	3
NH ₃ (mg/l)	14.25	13	9.5	18.5	24.5

Table 4: Mean levels of the parameters of the two sampling sites for the period 21st April to 19th May 2009

Parameter	Marlborough	Crowborough
Temp °C	18.54±2.76	20.64±1.40
pH	6.920±0.148	6.998±0.171
BOD (mg/l)	253.42 ± 112.82	216.04 ± 105.57
COD (mg/l)	925.5±1079.27	504.4±133.39
4HR PV (mg/l)	49.96±40.61	49.64±28.50
TS (mg/l)	1115.52 ± 1105.73	654.44 ± 45.52
TSS (mg/l)	692±769.87	305.94±94.31
TDS (mg/l)	423.52±368.19	348.5±60.64
TVSS (mg/l)	589.38±645.11	271.64±80.08
PO ₄ ³⁻ (mg/l)	4.52±3.11	3.17±1.10
NH ₃ (mg/l)	17.45±4.19	16 ±5.79
Flows (m ³ /DAY)	123 805 ± 0	^a Aprox 10 000 ± 0
COD:BOD	3.26:1	2.67:1

a: this is an approximate value as the flows for Marlborough were not measured during the course of the study

Table 5: Sewage strength for selected parameters ((Metcalf and Eddy Inc., 1991)

Contaminants, mg/l	Concentration, mg/l		
	weak	medium	strong
BOD ₅	110	220	400
COD	250	500	1000
TS	350	720	1200
TSS	100	220	350
TDS	250	500	850
TVSS	80	165	275
NH ₃	12	25	50
TP	4	8	15

4.2 Treatability of the influent sewage

Tables 6 and 7 show the COD: BOD ratios of the five sampling campaigns of the two sampling sites. The ratios for the first two sampling campaigns for Marlborough show a high level of treatability, over 70%, while those for the last three sampling campaigns have treatability ratios that show biodegradability of less than 35%. For Crowborough, all sampling campaigns except for the second one done on the 27th of April 2009 which has a treatability level higher than 90% have less than 40% biodegradability.

Table 6: The COD: BOD ratio for the Marlborough Sewage and the approximate biodegradable percentage of the observed COD

Parameter	21/04/09	27/04/09	05/05/09	12/05/09	19/05/09
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COD: BOD	1.29:1	1.31:1	3.88:1	3.06:1	6.77:1
% biodegradability achievable	79.995	76.56	25.79	32.70	14.77
% non-biodegradable	20.005	23.44	74.21	67.3	85.23

Table 7: The COD: BOD ratio for the Crowborough Sewage and the approximate biodegradable percentage of the observed COD

Parameter	21/04/09	27/04/09	05/05/09	12/05/09	19/05/09
COD: BOD	2.56:1	1.09:1	3.42:1	3.52:1	2.76:1
% biodegradability achievable	39.04 %	91.76 %	29.27 %	27.65 %	36.29 %
% non-biodegradable	60.96 %	8.24 %	70.73 %	72.35 %	63.71

The COD: BOD ratios for the Crowborough influent shown in table 3 generally suggest that the sewage is treatable by biological processes for all sampling campaigns with the exception of the sample collected on the 27th of April 2009 which had a ratio less than 2. Classification of the Crowborough influent based on the simple average shown in Table 4 also suggests that the sewage is readily biodegradable hence can be treated efficiently with the existing biological process systems. The low levels of ammonia and phosphorous levels indicate that the biological removal of these nutrients is relatively feasible to a notable extent. However, the treatability of the sewage by trickling filters is greatly compromised if the sewage flows are considered since the treatment capacity of the Crowborough Sewage treatment works is approximately 54 000 m³/day compared to the current flows of about 123 805 m³/day.

4.3 Heavy metal content

Tables 8 to Table 12 show the metal composition of the samples collected from the 21st of April to the 19th of May 2009. The levels of Cd, Cr, Pb and Fe are generally higher for the Marlborough sewage, while those for Ni, Zn, and Cu are lower than they are for the Crowborough sewage as shown in table 11. The higher levels of Ni, Zn and Cu, in the Crowborough influent could be as a result of the common use of all these metals in electroplating industries in the Workington industrial (Table 1). The presence of all the seven metals in the Marlborough sewage in significant quantities is evidence of some unmonitored industrial activities (home industries) in the area.

Table 8: Levels of trace heavy metals in the Marlborough wastewater samples collected over the 5 - week sampling period from 21 April to 19 May 2009, units in µg/l

Parameter	Marlborough				
Date	21/04/09	27/04/09	5/05/09	12/05/09	19/05/09

pH	6.95	7.04	6.82	7.07	6.72
Cd	15.84	71.5	11.31	11.5	12.65
Cr	77.81	61.21	144.74	149.04	216.39
Pb	311.60	257.8	518.56	572.16	620.04
Ni	74.5	41	60.25	67.63	107.63
Zn	76 957.15	102 304.4	164 675	141 200	166 912.5
Fe	1542.25	1391.96	1632.43	2045.25	10 021.88
Cu	1705	2252.5	1971.25	1730	1975
TOTAL	80 684.15	106 380.37	169 013.54	145 775.58	179 866.09

Table 9: Levels of trace heavy metals in the Crowborough wastewater samples collected over the 5 - week sampling period from 21 April to 19 May 2009, units in µg/l

Parameter	Crowborough				
Date	21/04/09	27/04/09	5/05/09	12/05/09	19/05/09
pH	7.16	7.07	7.08	6.96	6.72
Cd	13.7	70.1	7.8	9.2	9.85
Cr	74.5	75.45	79.45	130.86	77.08
Pb	256.37	191.48	426.89	480.56	563.8
Ni	61.5	66.5	84	102.13	93
Zn	142 191.7	121 525.05	137 325	192 162.5	100 675
Fe	2292.43	1982.35	2429.65	2296.96	2483.68
Cu	2880	2277.5	1706.25	1938.75	1578.75

TOTAL	147 770.2	126 188.43	142 059.04	197 120.69	105 481.16
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Table 10: Mean concentrations of the heavy metals in the wastewater samples from the two sampling points for the period 21 April to 19 May 2009, units in µg/l

Parameter	Marlborough	Crowborough	WHO recommended limits For drinking water
pH	6.920 ± 0.148	6.998 ± 0.171	6 – 9
Cd	24.56 ± 26.30	22.13 ± 26.91	50
Cr	129.84 ± 62.25	87.47 ± 24.33	50
Pb	456.03 ± 161.59	383.82 ± 155.60	50
Ni	70 20 ± 24.38	81.43 ± 17. 24	50
Zn	130 409.81 ± 39 591.91	138 775.85 ± 33 960. 17	5000
Fe	3 326.75 ± 3 750.52	2 297.01 ± 194.60	300
Cu	1 926.75 ± 222.66	2 076.25 ± 521.97	1000
TOTAL	136 343.94 ± 43 839.61	143 723.96 ± 34 900.82	6500

Table 11 shows the heavy metal tolerance levels of the activated sludge microbial population.

Table 11: Threshold concentrations of metal pollutants inhibitory to the activated sludge process (Hammer and Hammer, 1996)

metal	Concentration, µg/l	
	Carbonaceous removal	nitrification
Cd	10 000 – 100 000	-
Cr(VI)	1000 – 10 000	250
Cr(III)	50 000	-
Ni	1000 – 2 500	250
Zn	800 – 10 000	80 - 500

The Cd, Cr (VI) and Ni levels (Table 11) of influent at both plants were far too low to inhibit carbonaceous material removal. According to studies carried out by Gikas (2008) suggest that the levels of Ni observed could actually stimulate growth of activated sludge and enhance carbonaceous removal. This is also in agreement with the findings of the study done by Yetis and Gokcay (1989). Their results indicated that treatment efficiency was not significantly affected by the presence of Ni up to concentrations of about 10mg/l with the maximum specific growth rate of the experimental batch culture they used having doubled when the nickel concentration was 5.0 mg/l and better floc formation was noticed at this nickel concentration. The levels of all the other six heavy metals are above the WHO recommended levels for drinking water. Given that the treatment processes enable the removal of 40-60% of the metal, the levels that may be characteristic of the effluent will be still above the WHO recommended limits for drinking water. This poses a threat to human and animal

health who may use the water from the public waterways into which the sewage effluent is discharged. Zn levels for both Marlborough and Crowborough respectively are more than nine (times) the maximum threshold levels for exhibition of the biological process. . Given also the threshold levels for inhibition of the nitrification process, it is evident that Zn is an apparent threat to the nitrification processes of activated sludge processes at Crowborough.

5. Conclusion and recommendations

This study has revealed that the treatability of the influent sewage may not necessarily be related to the strength of the sewage but rather the level of the biodegradable fraction of the influent. This is evidenced by the fact that, though the Marlborough Sewage is more concentrated than the Crowborough sewage, it is relatively more biodegradable (hence more treatable) than the low strength Crowborough sewage. It is also evident that heavy metals have a negative impact on the biological treatment processes used for the removal of organic load of sewages.

There is need to carry out the study intensively over a longer period and when the treatment works are operating at full scale in order to ascertain how the treatability of the sewage is affected by seasonal and hourly variants.

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