Modeling biological phosphorus removal in activated sludge systems

_ The case of Crowborough Sewage Treament Works, Harare, Zimbabwe.

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Introduction

Effluent from wastewater treatment plants has been reported as the main cause of eutrophication in surface waters [1]. Small amounts of nutrients can lead to eutrophication and stimulate excessive production of chemical oxygen demand (COD) in the form of algae, loss of oxygen resources, changes in aquatic population and subsequent deterioration of water quality. Phosphorus and nitrogen concentrations in Lake Chivero, the main source of drinking water for Harare, the capital city of Zimbabwe, have been reported to be at alarming levels [2][3][4]. Their studies pointed out that effluent from wastewater treatment plants in and around Harare is the main source of nutrients in the lake.

Biological Nutrient Removal (BNR) processes have been developed and are being used as an effective method of treating municipal wastewater. Although BNR processes are an environmentally acceptable means of removing nitrogen and phosphorus from wastewater, they are more complicated and sensitive to operation than conventional activated sludge plants. In other words there are many factors that affect its performance, such as influent wastewater characteristics, nitrate and dissolved oxygen concentrations in the return activated sludge (RAS). , The design and operation of BNR plants can be simplified through the use of mathematical models [5]. A number of activated sludge models have been applied for full-scale wastewater treatment plants and found to be very useful tools[6][7]. These models are capable of describing the wastewater treatment processes in activated sludge systems.

Major towns and cities in Zimbabwe use activated sludge plants for treating municipal wastewater. The effluent is discharged into nearby streams and rivers. Crowborough Sewage Treatment Works (CSTW) in Harare is one of the treatment works in Zimbabwe that uses activated sludge treatment processes and disposes the effluent into surface waters.

Study Objectives

- To carry out a water quality assessment of the wastewater at CSTW based on the parameters for the selected modeling software.
- To investigate the effect of retention time on phosphorus removal efficiency through modeling.

Scope of study

The study mainly focused on the capabilities of BioWinV2 and SASSPro V2 simulation software to describe the treatment processes at the plant. The choice of software was based on its applicability to the modeling objective, price, user friendliness and availability of customer support services. BiowinV2 and SASSProV2 were used complimentary to each other. Characterisation of the wastewater to the plant was based on physico- chemical analysis of the major parameters considered most sensitive to model outputs. The competitive requirements of nitrogen removal on the efficiency of phosphorus removal were not considered. The plant was assumed to be operating under steady state conditions since it has been operational for a number of years. The bacteria in the system were therefore assumed to have adapted to the influent characteristics at the plant and the influence of industrial effluent on biological activities was not considered. Both simulation software used assume that the characteristics of the wastewater are constant and that there is no significant level of nitrates in the influent because of anaerobic conditions in sewer systems. For the purposes of modeling the clarifier is regarded as a point of separation of biomass and effluent implying that there are no biological activities occurring in the clarifier.

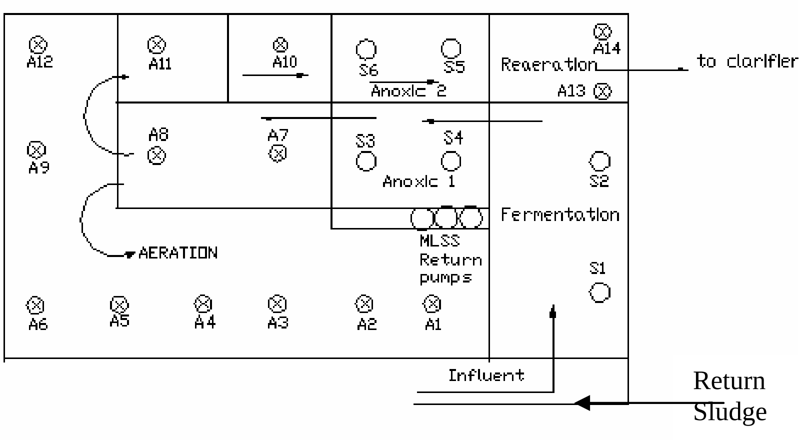
Study Site

Crowborough Sewage Treatment Works (CSTW) is located near the high-density suburb of Mufakose,right in the capital city of Zimbabwe ,Harare. The CSTW receives sewage from the surrounding high-density suburbs of Budiriro, Kuwadzana, Dzivarasekwa and Kambuzuma. Industrial effluent from the Workington and Willowvale industrial areas is also treated at CSTW.

Operation of the activated sludge plant at CSTW

The settled sewage from the set of primary settling tanks (PSTs) is directed to the activated sludge plant at an average flow of 10 000m^3/day to 14000m^3/day depending on the volume of influent to the plant. The design sludge retention time of the plant is 15 to 25 days with mixed liquor suspended solids (MLSS) concentration of between 4000 and 6000 mg/l in the bioreactor. The MLSS concentration is maintained at this range by sludge recycle from the clarifiers as well as sludge wastage. The three sludge recycle pumps are centrifugal pumps, which use a float switch system as a control to recycle the activated sludge from the clarifiers. The number of clarifiers working governs the volume of influent that can be directed to the activated sludge plant to avoid overloading the clarifiers. Three mixed liquor return pumps ensure internal recirculation of the MLSS. Sludge wasting also depends on the concentration of the MLSS in the reactor. If the concentration is below the 4000 mg/l, wasting is totally suspended to allow a build up of solids. The plant uses tapered aeration in which 14 aerators of different power rating are used to ensure the appropriate dissolved oxygen is supplied to the different zones of the basin. These aerators are switched on and off depending on the desired oxygen levels. Figure 1 shows a schematic representation of the BNR plant at Crowborough Sewage Treatment Works.

Figure 1 Schematic Layout of CSTW Activated Sludge Plant



Key
S1-S5 Stirrers
A1-A14 Aerators

The arrows in Figure 1 show the flow direction of wastewater in the bioreactor. The influent to the 5-stage BNR plant is settled sewage from the PSTs. Return sludge comes from the underflow of the clarifiers to maintain active sludge in the bioreactor by recycling mixed liquor suspended solids. From the aeration basin part of the flow is directed to the anoxic2 basin through the stages of aeration that are tapered towards the anoxic zones. The tapered aeration process ensures the desired oxygen levels. The other part of effluent from the aeration zone is recycled to the anoxic 1 basin where nitrified effluent is mixed with phosphorus rich effluent from the anaerobic zone as well as effluent rich in the carbon source and denitrification occurs in this stage. Effluent from the anoxic zone 2 passes through the reaeration basin to the clarifiers where solid-liquid separations mainly occur. The individual basin volumes are shown in Table.1. The individual volumes enable the calculation of the effluent hydraulic retention time (HRT) in the different basins. Individual

Table 1 Basin Volumes for the Activated Sludge Plant

Basin volumes also allow correct schematisation of the plant in simulation models.

Process Unit	No of Units	Dimensions (m)	Volume (m^3)			
		Length	Width	Height	Diameter	
Fermentation 1	1	19.8	16.5	3.25		1062
Fermentation 2	1	19.8	12	3.25		748
Anoxic 1	1	45.1	14.3	3.05		1967
Anoxic 2	1	45.1	18.7	2.95		2488
Aeration basin	1	69.3	52	2.85		10270
Reaeration Basin	1	45.1	17.6	2.85		2262
(total basin Volume)		114.4	52	3.25		19334
Clarifier	3			8	26	2123

Research Methodology

Wastewater Characteristics

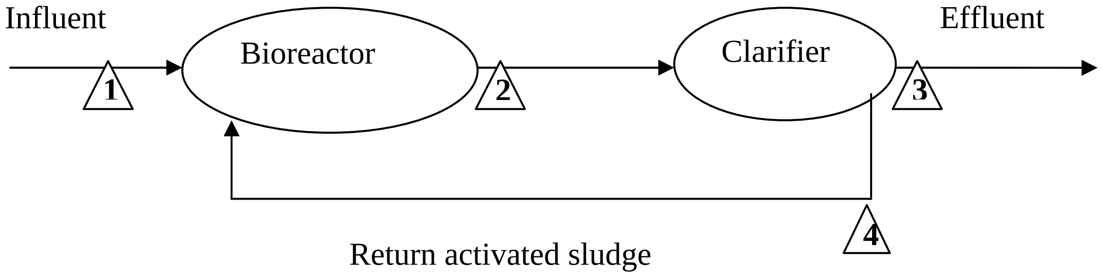
An analysis of the wastewater characteristics at Crowborough sewage treatment works was done using the historic weekly monitoring results for the period January 2001 to February 2005. The results were obtained from the City of Harare Laboratory. This period was chosen as it included the period during which the plant was operating with minimum breakdowns as well as adequately recorded breakdowns. The main parameters of the influent that were considered are, COD, Total Kiedjal Nitrogen (TKN), NH_3-N, Total Phosphorus (TP), and Total alkalinity as well as mixed liquor suspended solids concentration. These parameters are considered to be the most sensitive in the process of modeling activated sludge systems.

Sample Collection and Preservation

Two sampling programmes were undertaken. The first sampling program was carried out from 1800hrs on 3/16/05 to 0600hrs on 3/17/05. The samples were collected in plastic bottles washed with phosphorus free detergents and left with a few milliliters of 10M hydrochloric acid overnight. The sample bottles were rinsed three times with the sample and then filled with the sample to exclude air bubbles. Grab samples were collected after every two hours during the two sampling periods because it was assumed that the interval would allow the capturing of representative parameters and after considering that individual sample analysis was going to be done instead of composite sampling. The samples were preserved according to the standard methods of preserving samples. A second sampling programme was done for twenty-four hours from the 5th of April 2005 to the 6th of April 2005.The samples were carried to the University of Zimbabwe's Department of Civil Engineering Water and Wastewater laboratory in a cooler box with ice blocks and analysed within 24 hours.

Figure 2 shows a schematic representation of the sampling point for the plant. The sampling of MLSS in the bioreactor and return sludge was done randomly as the MLSS was not expected to vary much during the period of sampling.

Figure 2 Sampling points for the Activated Sludge Plant (during the period of study)



∆: Sampling point

Samples were stored in a cooler box filled with ice blocks to maintain a temperature of less than 4°C.

Analytical methods

The samples were analysed at the University of Zimbabwe's Department of Civil Engineering Water and Wastewater Laboratory. Analysis of the influent and effluent parameters including MLSS concentrations was done according to the Standard methods for the analysis of water and wastewater [8]. COD was analysed using the closed reflux Standard Methods 5220. Ammonia was analysed using the Ammonia-Selective Electrode Method (Standard Method 4500-NH_3 F). The Vanadate molybdate- phosphoric acid method (Standard Methods 4500) was used for the determination of Total Phosphorus and Ortho-Phosphates.

The Ultraviolet spectrophotometer method was used for the analysis of effluent nitrates. Effluent samples were first filtered using a 0.45μm filter paper to eliminate substances that may interfere with nitrate absorbance. One ml of 1M HCl was added to each sample and the sample absorbance was recorded under a UV spectrophotometer (Spectronic D21) set at 220 and 275nm wavelength. The absorbance of the nitrates was obtained by subtracting twice the absorbance value at 275nm from the absorbance at 220nm. This is because dissolved organic substances may also absorb at 220 but nitrates do not absorb at 275nm.The concentrations were obtained from a standard calibration curve obtained from the absorbance of standard samples.

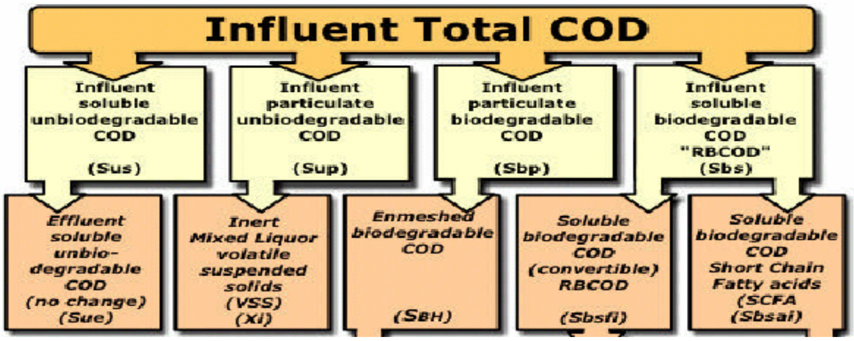
The Micro–Kjeldahl method (Standard Methods 4500-Nitrogen (organic)) was used to determine the TKN in samples. Total Alkalinity was analysed using the titration method as explained in the Standard Method 2320, the titrimetry method. Dissolved oxygen was analysed on site using a probe meter (Oximeter 340-A/SET –WTW). The Palin tests were also used as supplementary tests for ortho-phosphates ammonia and nitrates. These tests were carried out onsite and results verified with laboratory tests mentioned earlier for the different parameters.

The City of Harare Laboratory used the same Standard Methods for the analysis of water and wastewater for the mentioned parameters. The only notable difference was on the method for the analysis of ammonia and nitrates. The City of Harare laboratory uses the Nesslerisation method (Standard Method 4500D). The Nesslerisation method and the spectrophotometric method can give similar results in nitrate analysis if the colour produced in the Nesslerisation method is analysed under a UV spectrophotometer.

Influent Characterisation

The models used require influent wastewater characterization according to the influent parameters such as TKN, COD, TP, total alkalinity and influent dissolved oxygen. The wastewater is also characterized according to the different fractions of COD and TKN. The fractions for COD show basically biodegradable and non biodegradable components. These two components are further subdivided into soluble and particulate fractions. The influent COD is therefore divided into four components. The particulate soluble fraction is sometimes referred to as slowly biodegradable component. Figure 3 illustrates the four fractions of influent COD as given by SASSPro simulation software.

Figure 3 Influent COD fractions (Adopted from SASSPro manual)



The different COD fraction values were obtained using the in-built COD fraction calculator in SASSPro simulation software. The inputs to the calculator were obtained from the routine laboratory tests for wastewater on influent COD, effluent COD, influent filtered COD and ultimate BOD of the effluent.

Table 2 shows the different wastewater fractions that were used for the purposes of modeling the wastewater characteristics. The fractions were obtained through physico-chemical analysis of the influent and sludge for the parameters given in Table 2. The last column shows the typical range for municipal wastewater.

Table 2 Influent and Sludge Characterisation

Parameter	Wastewater Fraction (Symbol)	Typical Ranges
Unbiodegradable particulate COD	f_{up}	0.01 – 0.5
Unbiodegradable soluble COD	f_{us}	0.01 – 0.5
Readily biodegradable soluble COD	f_{bs}	0.01 – 0.99
Influent Total P and Ortho-P ratio	f_{pa}	0.2 – 0.9
COD/VSS ratio	f_{cv}	0.2 – 2.5
Nitrogen fraction of the biomass MLVSS	f_n	0.005 – 0.15
Phosphorus fraction in the biomass	f_{xbhp}	0.01 – 0.1
MLVSS/MLSS ratio	f_i	0.4 - 1
Influent TKN and NH_3-N fraction	f_{na}	0.2 – 0.6

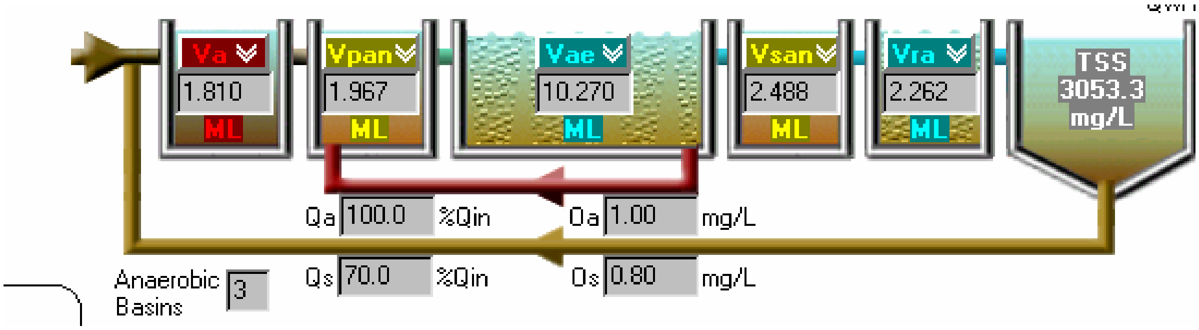
Modeling software

SASSProV2 and BioWin V2 were used for modeling the treatment processes. SASSProV2 is a steady state simulator that provides a solution for the system based on flow-weighted average influent loading to the system, while BioWinV2 is a dynamic simulator that shows the time varying system response based on the time varying influent loading to the system. Computing time for BioWin was up to 2 minutes from full start up to steady state. After attaining the plant's steady state conditions in BioWin, the dynamic simulations were then run using the attained steady state conditions. All plant simulations were performed using the temperature of mixed liquor of 25°C as observed in the activated sludge units. Simulations of low temperature conditions were carried out at a temperature of 15 °C. This temperature was used as it was considered the lowest temperature recorded for sewage at the plant.

Plant Configuration in the Simulation Software

The plant configuration of the activated sludge plant is a 5-stage modified Bardenpho. The SASSPRoV2 simulation software has an in-built configuration of a 5-stage Bardenpho that was used for simulating the activated sludge process. BiowinV2 has drag and drop units that were used to build the plant configurations in the simulator. Figure 4 illustrates the process configuration model in SASSPro simulation software.

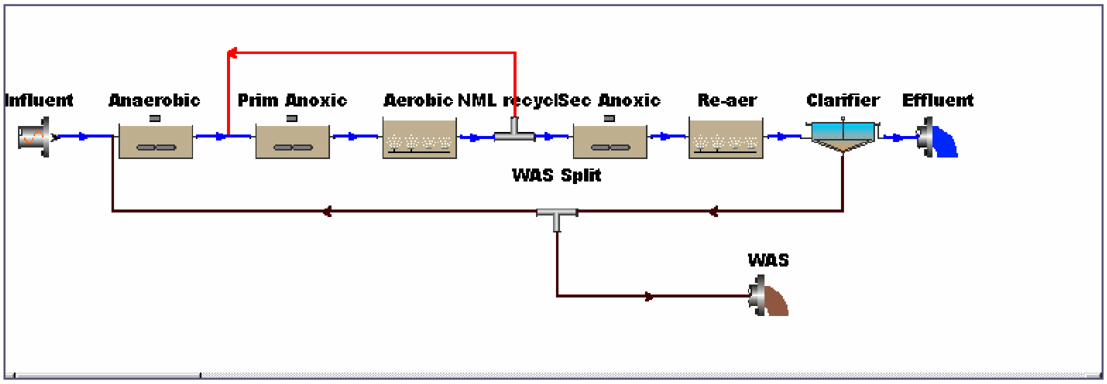
Figure 4 Hydraulic scheme of the Activated sludge plant model at CSTW in SASSPro



Va 1.810 ML
Vpan 1.967 ML
Vae 10.270 ML
Vsan 2.488 ML
Vra 2.262 ML
TSS 3053.3 mg/L
Qa 100.0 %Qin
Oa 1.00 mg/L
Qs 70.0 %Qin
Os 0.80 mg/L
Anaerobic Basins 3

The volumes of the individual basins in the bioreactor given in Figure 4 are in megalitres (ML). In the model hydraulic scheme, Q_a and Q_s represent the internal and overall recycle rates respectively as percentage of the influent. Figure 5 below shows the hydraulic scheme of CSTW in BioWin simulation software.

Figure 5 Hydraulic scheme of the Activated Sludge Plant at CSTW in BioWin model



The NML recycle in Figure 7 represents the internal recycle for the plant. The WAS split and the WAS unit model the sludge wasting route of the plant.

Model Calibration

Calibration of the models was based on proper influent and sludge characterisation and evaluation of the flow scheme. Calibration for SASSProV2 was done on flow weighted average values using the in-built SASSPro influent flow weighted calculator. The calibration of BioWin was done on dynamic data from the sampling programmes. The calibration procedure included matching the model results with the measured results using the wastewater fractions obtained as well as default parameters for quantitative coefficients, kinetic constants and similar constants.

The sludge retention time (SRT) of the plant was estimated using the activated sludge concentration. During the calibration in SASSProV2, the biomass concentration (as represented by the (MLSS) was adjusted to the observed values in the plants by varying the sludge-wasting rate without taking into account the amount of biomass leaving the plant via the effluent. A similar SRT estimation procedure was done for BioWin by adjusting the sludge wastage modes.8 until the MLSS concentration in the model reactor was equal to the measured MLSS concentration for the plant

Modeling Strategy

The simulation of the wastewater treatment plant was performed in two steps. In each step the characteristics of both liquid phase and activated sludge were compared with measured data. The steps included;

- Simulation of the treatment plant operations (both liquid phase and biomass) without calibration of the parameters *(i.e.* using default parameters) and simulation of the treatment processes with calibrated parameters based on measured data
- Simulation of different options for alternative process design using calibrated parameters

Model verification and validation

Model verification was based on checking the capability of the models to describe the liquid phase of the plant flows using static and dynamic influent data and the mixed liquor suspended solids. A comparison of the simulated effluent concentrations with the measured effluent concentrations was done to verify the models. Percentage differences between the measured and simulated values were calculated to check the capabilities of the models to simulate the wastewater treatment processes. The sampling programme during the period 1200hrs on 4/5/05 to 1200hrs on 4/6/05 was used to validate the models. Historic data for the plant was also used to validate the models.

Verification and validation of the software to simulate the phosphorus profiles in the bioreactor was done using the results obtained from the City of Harare Laboratory. These results showed the concentrations of phosphorus as ortho-phosphates in the different basins of the Bardenpho. The simulations were done using the recorded influent characteristics and bioreactor phosphorus concentrations of 5/11/04.

Results and Discussion

Settled influent characteristics

The characteristics of settled influent to the activated sludge plant at Crowborough were obtained by calculating average values from weekly monitoring data on the BNR plant. The data used was for the period from January 2001 to February 2005. The calculated average values are shown in Table 3. The values for Total Alkalinity are in mg $CaCO_3$/L the rest are in mg/L. The last column represents the Zimbabwean standards for safe disposal of effluent into surface waters.

Table 3 Average Wastewater Characteristics

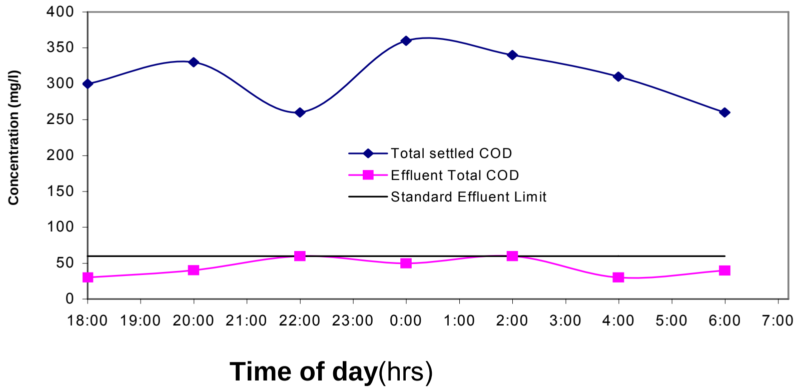
YEAR	**2001**		**2002**		**2003**		**2004/5**		**Zimbabwe Stds for Effluent**
Parameter	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	
COD	380±77	43±4	388±51	38±4	320±22	42±5	375±35	43±6	60
TKN	27.5±5	1.8±1	24±3	1.21±0.3					No set limit
NH_3-N	25.2±1.5	3±1.8	25±2	3±2	21±3	4±2	21±1.7	2.8±1.2	0.5
TP	5.2±0.6	0.8±0.1	5±0.8	0.92±0.1	4.4±0.5	1±0.3	4.0±0.5	1.7±0.3	0.5
Alkalinity	210±20	139±15	248±21	153±10	216±14	144±10	222±10	186±17	No set limt

The influent values in Table 3 represent settled sewage. The effluent values are for the effluent from the clarifiers of the BNR plant. From Table 4 it can be observed that there has been a gradual decrease of phosphorus removal from the BNR plant during the five-year period. The average effluent TP in 2001 was 0.8±0.2 and it gradually increased to an average of 1.7±0.3. This could be partly due to the increasing number of breakdowns at the plant.

Sampling Programme Results

Figure 6 below shows the variation of COD during the first sampling period

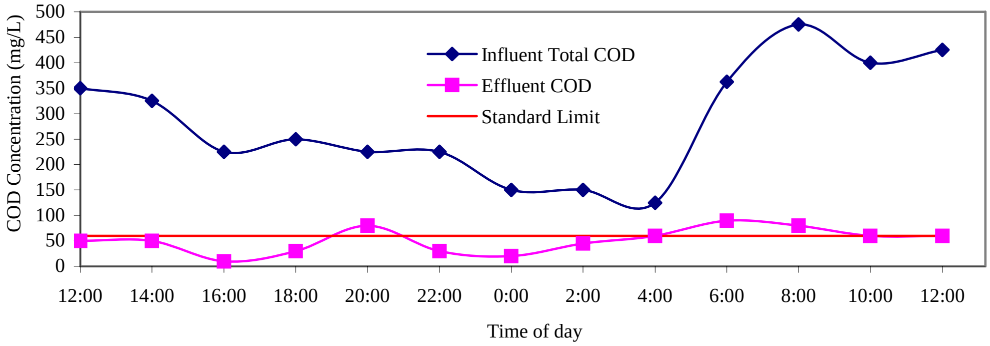
Figure 6: COD variation.



The flow to the bioreactor was kept at a constant rate of 10 000m^3/day (417m^3/h) during the period of sampling. The influent COD was 308mg/l± 38 The effluent COD concentration was 44mg/L ± 13.During the period of sampling the effluent COD concentration met the national water authority effluent COD concentration standard for safe disposal of wastewater effluent into surface waters. This can be seen from Figure 6 where the horizontal line represents the standard limit of 60 mg COD/L. All samples along and below the horizontal line met the effluent standard for safe disposal. Despite the fact that out of the 14 aerators only 6 were operating, the COD effluent met the national water authority standard limit. This could be due to the fact that COD oxidation requires lower levels of oxygen (about 0.5mg of O_2/L dissolved oxygen).About 50% of influent COD is assimilated by biomass in the bioreactor[9].

Figure 7 shows the variation of COD during the second sampling programme. The influent settled COD concentration shows a gradual decrease as the day progressed and reaches a peak around midday. This variation is evident of the water usage during a typical day. The effluent concentration showed little diurnal variation as compared to the influent. This could be due to the fact that there were stable conditions in the bioreactor and the buffering action of the hydraulic retention time (HRT) of the plant. The flow to the bioreactor was kept at constant flow of 10 000 m^3/ day (417m^3/day) as during the first sampling period .The HRT of the plant was calculated as 28 hours during the sampling period. This effectively means whatever comes in is maintained in the bioreactor for at least 28 hours.

Figure 7 COD concentration during the period 1200hrs on 4/5/05 to 1200hrs on 4/6/05

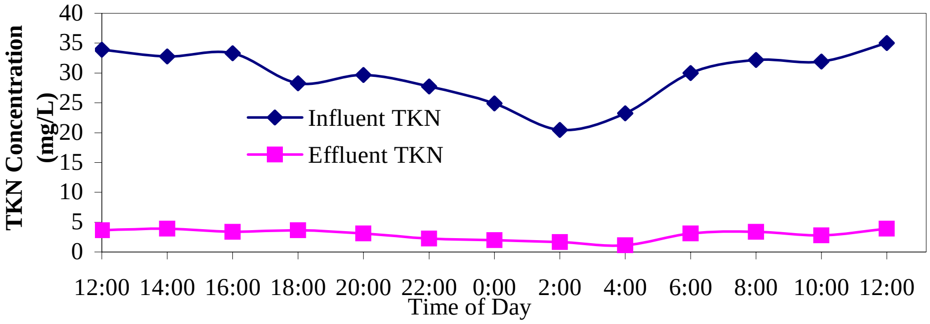


Total Kiedjal Nitrogen Concentration

The average influent TKN during the first sampling period was 26.2 ± 5mg/L .The average effluent TKN was found to be 8mg/L± 2. Effluent TKN as well as effluent NH_4-N is an indication of the nitrification and aeration process of the plant. Effluent TKN and ammonia that does not meet the standard limit may be indicating low aeration capacity. This can be explained from the state of the plant where only 6 of the 14 aerators were functioning. According to [10][9], surface aerators, on average transfer oxygen at 1.5kg

O_2/KWh in municipal wastewater. Nitrification requires 4.57 kg of oxygen for every kilogram of nitrogen nitrified. The influent TKN would require 262*4.57kg=1197kg of oxygen/day. The six aerators that were operational had a total energy of 5900 KW per day. With an average oxygen transfer of 1.5 kg O_2/KWh, about 9000 kg of oxygen is transferred per day if the efficiency of the aerators is 100%. However, the distribution of the working aerators would also affect the oxygen transfer rate. The figures presented imply that with effective distribution of aerators, the oxygen would be adequate for both nitrification and carbonaceous oxidation. Figure 8 shows the TKN concentration for CSTW during the period second sampling period

Figure 8 TKN concentration during the second sampling period

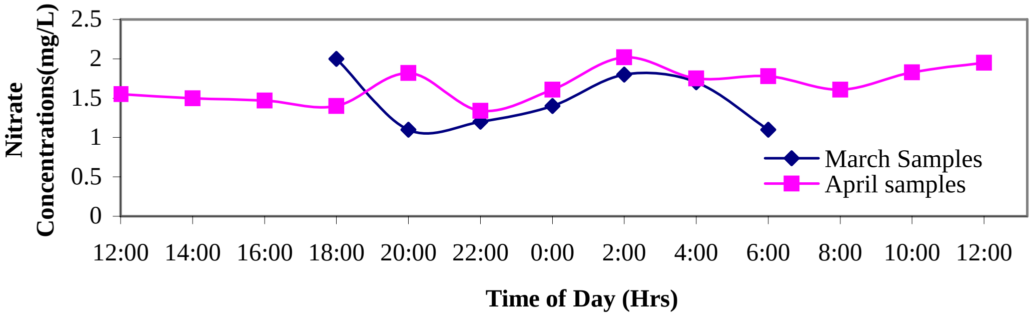


The influent TKN at Crowborough during the second sampling program from 1200hrs on 4/5/05 to 1200hrs on 4/6/05 was 29mg/L ±5.The effluent TKN during this period was 2.9mg/L ±0.9. During plant operations it would be appropriate to increase aeration input during the peak periods and also to monitor phosphorus removal efficiency during peak periods, as increased nitrogen levels would negatively affect phosphorus removal in the plant.

Effluent NO_3-N Concentration

Figure 9 illustrate the effluent nitrate concentration variation during the two sampling programmes at the CSTW activated sludge plant.

Figure 9 Effluent Nitrates during the two sampling periods

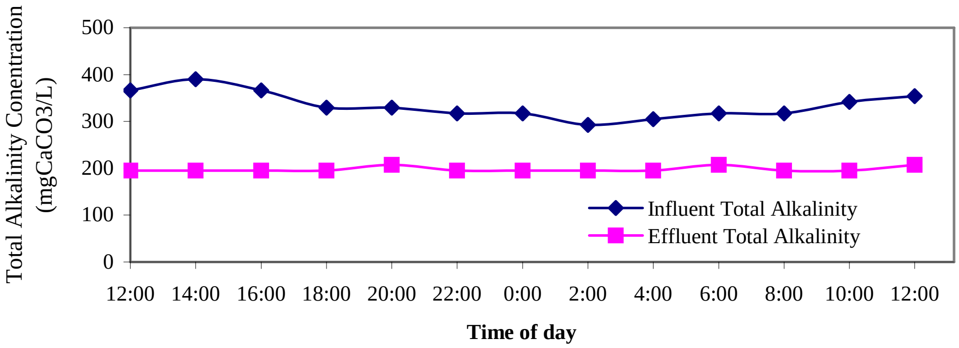


The effluent NO_3-N/L concentration during the first sampling period at Crowborough was 1.2 ± 0.5.mg NO_3-N/L. During the second sampling program the effluent nitrates were 1.7± 0.2mg NO_3-N/L. The results of effluent nitrates suggest that the effluent is meeting the standards for safe disposal of nitrates as all samples had effluent nitrate concentration less than the standard 3 mg/L set by the national water authority for safe disposal of effluent into surface waters. On the other hand low nitrate effluent could suggest poor aeration capacity, as the influent TKN and NH_4-N would not be fully nitrified. Effluent Total Nitrogen, which is the sum of TKN and Nitrates, was above the limit of 10mg/L and this could suggest low nitrification resulting from poor aeration.

Alkalinity Variation

The influent Total Alkalinity during the first sampling period was 358 ± 23 mg $CaCO_3$/L. The effluent Total Alkalinity was 143 ± 19 mg $CaCO_3$/L. The influent Total Alkalinity during the second sampling program was 334 ±28.mg $CaCO_3$/L. The effluent Total Alkalinity for the second sampling period ranged from 198 ± 5 mg $CaCO_3$/L. Total Alkalinity acts as a buffer to any pH changes that might occur in the activated sludge system. There is no prescribed limit for effluent Total Alkalinity but values in excess of 500 mg $CaCO_3$ /L in the effluent are considered toxic to aquatic life. If Total Alkalinity in the bioreactor goes below 40 mg $CaCO_3$/L, the system will begin to experience problems due to pH changes. Figure 10 shows the influent and effluent Total alkalinity during the second sampling period.

Figure 10 Total Alkalinity during the second sampling period

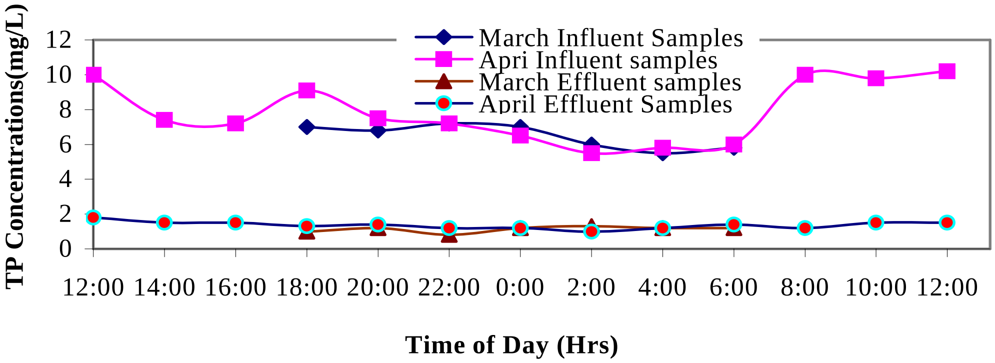


Nitrification releases hydrogen ions that destroy alkalinity in the order of 7mg alkalinity (as $CaCO_3$) for every gram of NH_4-N nitrified. For every mg of NO_3-N denitrified 3.5 mg of alkalinity as CaCO3 is restored. The effluent during the two sampling periods shows that the wastewater alkalinity was adequate to offset any pH drops. Bacteria responsible for phosphorus removal are affected by pH change according to the bell shaped curve where the optimum activity occurs in the 6.5 to 7.5 pH range. The effluent pH was found to be 7.2 ± 0.2 during the two periods of sampling. The results suggest that the wastewater had enough buffering capacity to maintain the pH at the desired range for bacterial activity.

Total Phosphorus Concentration

The influent phosphorus concentration during the first sampling period in March was 6.4±0.7 mg TP/L while the effluent TP was found to be 1±0.2 mg TP/L The influent TP concentration during the second sampling period+ was 7.9 ±1.8 mgTP/L and the effluent TP concentration was 1.33 ±0.2 mgTP/L. The standard limit for effluent TP is 0.5mg/L for safe (blue band) disposal but the effluent met the low hazard (green band) Zimbabwe National Water Authority standard of less than 1.5mgTP/L. The effluent TP could be affected by the low aeration capacity of the plant as evidenced by the high TKN values in the effluent. The presence of nitrogen in the return sludge from the clarifiers could also affect phosphorus release in the aerobic zone. There is a linear relationship between phosphorus release in the anaerobic zone and phosphorus uptake in the aerobic zone [11]. The presence of nitrogen in the anaerobic zone would negatively affect phosphorus release and the overall phosphorus removal efficiency. Figure 11 illustrates the variation of Total P concentration during the 2 sampling programmes.

Figure 11 TP concentrations during the sampling periods at CSTW



During the March sampling programme seven samples were collected for influent TP and seven samples for effluent TP. Thirteen samples for influent TP and effluent TP were collected for the second sampling programme, which was carried out in April. The influent TP showed a gradual decrease from daytime to nighttime as shown by low influent TP values during the night compared to daytime values. The two sampling periods showed the same trend in influent and

effluent concentration variation. The effluent concentration showed a small variation compared to the influent. As discussed for effluent COD variation, the small variation could be due to the buffering effect of the hydraulic retention time of the bioreactor. All the samples analyzed for effluent TP during the two sampling periods did not meet the standard limits for the blue band set by the Zimbabwe National Water Authoriy(ZINWA) for safe disposal of effluent into surface waters.

Influent Dissolved Oxygen and pH

The influent dissolved oxygen was measured onsite using a probe meter. The average dissolved oxygen was found to be 0.03mgO_2/L during the two sampling programs at Crowborough Sewage Treatment Works. The low DO in the influent is attributed to the anaerobic conditions developed in the long trunk sewers. This also provides fermentation conditions for biodegradable COD. This makes the volatile fatty acids required for phosphorus release in the anaerobic basin readily available. The influent pH was measured using a pH meter and the average pH during the sampling periods was found to be 7.8 ±0.3.

Summary of Settled Influent Characteristics.

The average wastewater characteristics obtained during the sampling programmes showed that parameter concentrations were in the same range. The plant was operating at dry weather flow during the two sampling periods. The flow of settled sewage to the bioreactor was kept at a constant rate of 10 000 m^3/ day (417 m^3/hr). Table 4 summarises the settled influent characteristics obtained during the two sampling programmes. Concentration units in Table 4 are in mg/L.

Table 4 Settled Sewage Characteristics for CSTW (Obtained during sampling periods)

Parameter	Average	Standard Deviation	Range	City of Harare Results
Total COD	384	14	370 - 398	400
TKN	26	5	21 - 31	
TP	7	2	5 – 9	5
Alkalinity	343	16	327 - 359	280
NH_3-N	23	3	20 - 26	27
MLSS	5000	50	4900 - 5100	4500
MLVSS	2600	80	2500- 2700	

The last column shows the concentration of the settled sewage obtained by the City of Harare Laboratory. Results of effluent analysis were also compared with those obtained by the City of Harare Laboratory during the second sampling period that was carried out in April. Results of most parameters were in the same ranges.

Influent parameter ratios are usually used in selecting process configuration for given wastewater characteristics. The parameter ratios also give an indication of the possibility of enhanced biological phosphorus removal in activated sludge systems. The minimum COD/TP that is recommended in literature for effective P removal in BNR plants as discussed in Section 2.2.1 is 35. A COD/TP ratio of 49 ± 10 was obtained during the sampling programmes that were carried out at CSTW during the period of study. The obtained range implies that the influent wastewater was suitable for biological phosphorus removal. Most of the ratios were in the recommended literature range for municipal wastewater characteristics suitable for biological phosphorus removal. The average values that were obtained are summarized in Table 5.

Table 5 Influent Parameter ratios

Ratio	Average value	Standard deviation	Range	Software Recommended Range
COD/TP	49	10	40 - 60	35 - 50
TKN/COD	0.07	0.02	0.05 – 0.09	0.07 – 0.08
Ortho-P/TP	0.8	0.12	0.68 – 0.92	0.7 – 0.9
NH_3-N/TKN	0.85	0.09	0.76 – 0.94	0.8 – 0.9

The influent TP during the three days of sampling was 5.7±1.8mg TP/L. The effluent TP during the same period was average was 1.4±0.6mg/ L. During the time of sampling the effluent did not meet the standard limit for safe disposal, which is 0.5mg/[12].

Modeling Results

Influent and Sludge Characterisation

Influent and sludge wastewater characteristics were obtained from the parameter ratios in obtained earlier on for the wastewater treatment plant, as well as physico-chemical analysis on the settled influent for the different Nitrogen and COD fractions such as the biodegradable and non biodegradable fractions. The nitrogen and phosphorus fractions of the biomass were obtained using analysis of the MLSS for the two nutrients. Most of the fractions fell in the range considered to be for settled municipal wastewater according to the manuals of BioWin and SASSPro simulation software that was used for modeling. Although the MLVSS/MLSS (f_i) ratio was within the software range of 0.4 to 1, the average value was less than the recommended average of 0.85 for settled municipal sewage. Table 6 shows the wastewater fractions for the activated sludge plant at CSTW. The last column in Table 6 represents the software recommended range for the parameters.

Table 6 Settled Sewage Wastewater Fractions (obtained during sampling period)

Wastewater Fraction	Symbol	Average	Standard Deviation	Range	Recommended Range
Soluble biodegradable COD	f_{bs}	0.231	0.05	0.47 - 0.57	0.01 - 0.99
Soluble unbiodegradable COD	f_{us}	0.13	0.04	0.051 - 0.131	0.01 - 0.5
Particulate unbiodegradable COD	f_{up}	0.122	0.001	0.121-0.1223	0.01 - 0.5
MLVSS/MLSS	f_i	0.65	0.07	0.49 - 0.65	0.4 - 1
Nitrogen fraction of the biomass	f_n	0.07	0.001	0.069 - 0.071	0.005 - 0.15
NH3-N/TKN ratio	f_{na}	0.85	0.02	0.83 - 0.87	0.6 - 0.9
Ortho-P/TP ratio	f_{pa}	0.65	0.04	0.61 - 0.80	0.2 - 0.9

Biomass characteristics such as yield factors; temperature coefficients and kinetic constants were adopted from the default values of the simulation software. This was necessitated by the unavailability of the experiments that are required to obtain these constants such as respirometry. However, biomass nitrogen and phosphorus fractions were obtained from the analysis of the two nutrients on mixed liquor suspended solids.

Model Calibration

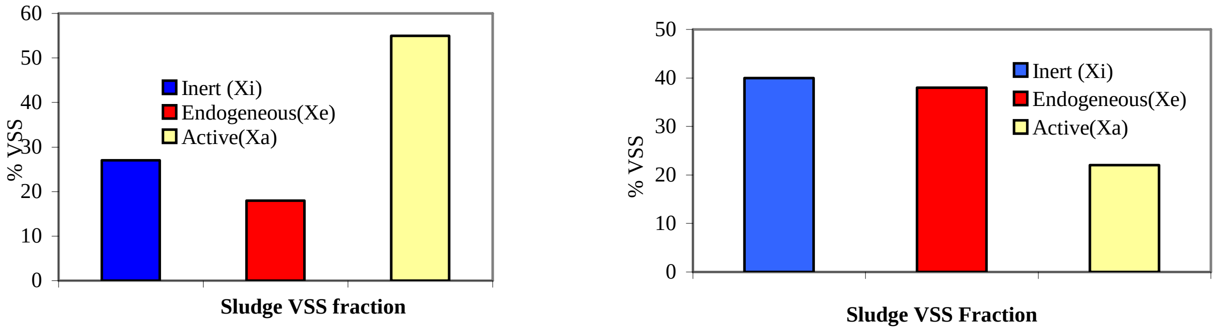
The first step in calibrating SASSPRoV2 and BioWin simulation software was to calibrate the sludge retention time (SRT). Table 7 summarizes the SRT simulated for the BNR plant. The high sludge retention times obtained from the simulations were as a result of the absence of sludge wastage at the plant due to pump breakdowns.

Table 7 Simulated Sludge Retention Time (days)

Simulation Software	Sludge retention time
SASSPro	45
BioWin	42
Design SRT	15 to 25

The concentration of the mixed liquor suspended solids is greatly affected by the sludge retention time of the plants. Normally at high sludge retention times the concentration of mixed liquor suspended solids will be high. This was observed during the sampling period where the MLSS concentration was on average 5000mg/L while the design MLSS concentration is 4500mg/L. However, when the plant is not experiencing sludge wastage the Mixed Liquor Volatile Suspended Solids (MLVSS) concentration will be low compared to the desired situation. This was observed from the low MLVSS/MLSS (f_i) ratio obtained. Figure 12 simulated distributions of the different volatile suspended solids (VSS) fractions at two different sludge retention times using SASSPro simulation software. The first figure shows the simulated VSS fractions at a sludge retention time of 15 days and the other shows the simulated VSS fractions at a sludge retention time of 45 days.

Figure 12 Simulated components of activated sludge MLVSS fraction at CSTW



From the above Figure, it is be observed that at low sludge retention time (15 days), about 55% of the volatile suspended solids are in the active stage compared to only 22% at high sludge retention time of 45 days. Volatile suspended solids in activated sludge systems have a variable Phosphorus content mass per mg of VSS [9]. The active polyphosphorus accumulating organisms (PAO) fraction is estimated to accumulate 0.38mg P/mg VSS; endogenous and inert PAO fractions accumulate on average 0.03mgP/mg VSS.The figures suggest that if a higher percentage of VSS is in the endogenous and inert fraction, there would be reduced phosphorus content in the VSS, resulting in low phosphorus removal efficiency.

Model Verification

Table 8 shows the simulated and measured values of the effluent and the error values in SASSProV2 software. In Table 8, simulated 1 represents results obtained without calibrating the model while simulated 2 represents the results obtained after calibrating the model.

Table 8 Comparison of simulated and measured values

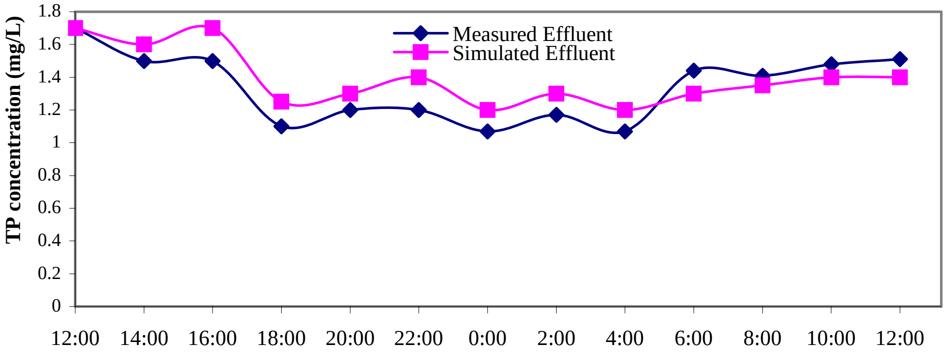
			COD	TKN	TP	Alkalinity	NO3-N	NH_4-N
Average Values Of Effluent	mg/L	Measured	51±24	2.9±0.9	1.3±0.2	198±5	1.7±0.2	3.8±2.8
		simulated 1	45	3.7	1.8	205	1.3	1.8
		simulated 2	49	2.3	1.4	200	1.4	3.2
Average Values Of Error	mg/L	simulated 1	6	0.8	0.5	7	0.4	1.1
		simulated 2	2	0.6	0.1	2	0.3	0.6
	%	simulated 1	11	28	30	4	23	29
		simulated 2	4	21	8	1	18	16

The error values (i.e. difference between the simulated and measured values) decreased by an average of 5% for most parameters when the simulations were run with calibrated model parameters. This indicates that most of the default parameters could be used to simulate the treatment processes at the plants. The large percentage error difference of 22% for effluent total phosphorus between simulated 1 and simulated 2 could be as a result of phosphorus removal sensitivity to the COD fractions. The amount of biodegradable COD for a particular influent is greatly affected by the f_{bs} fraction used. SASSProV2 manual recommends that for good simulation results, the average simulated results should be within 1 standard deviation of the measured values. All the simulated 2 values in Table 8 are within 1 standard deviation of the average measured values.

BioWin Simulation software shows the time varying responds of the system to a given time varying input. The effluent Total Phosphorus concentration simulated during the second sampling period was compared with the actual measured effluent concentration variation during the same period.

Figure 13 shows the BioWin simulated results together with the measured effluent results. The simulated results in Figure 13 were obtained after calibrating the model.

Figure 13 Simulated and Measured Effluent TP



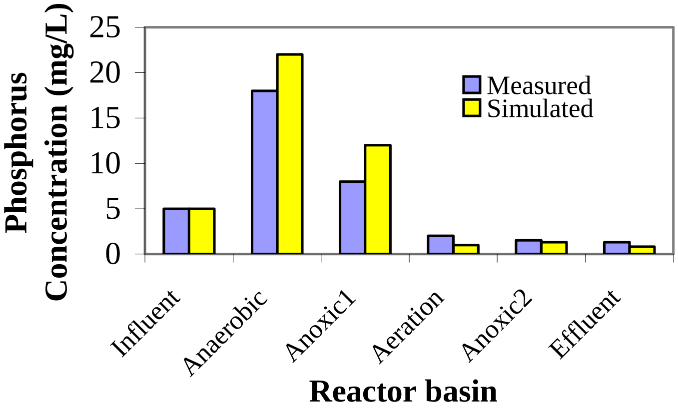
Both the simulated and measured values showed similar patterns although the simulated results were slightly higher than the measured results

Model validation

Simulations of phosphorus profile in the BNR plant were compared with the council weekly monitoring results of the individual basins in the bioreactor. The phosphorus concentration in the bioreactor is monitored as ortho-phosphate concentrations in the different basins. The concentration of ortho-phosphates with respect to total phosphorus in the anaerobic zone illustrates the efficiency of the phosphorus release of the biomass in this zone. On average the ratio of Ortho-P to total P is on average 0.9 for settled municipal wastewater. Monitoring the concentration in each basins helps in tracking the process of phosphorus removal in the bioreactor.

Figure 14 shows the phosphorus profile in the Biological Nutrient Removal plant. The influent and reactor basin data was obtained from the City of Harare monitoring results of 5/11/2004.

Figure 14 Simulated and Measured Phosphorus profile in the Activated Sludge at CSTW



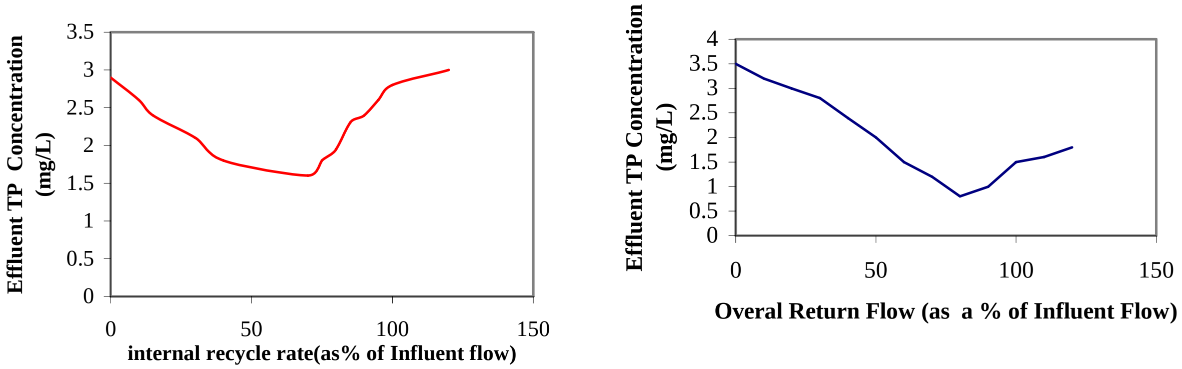
Results in Figure 14 show that the phosphorus profile for the sampled day on 5/11/04 was well described by the BioWin software as shown by the small difference between the simulated and measured phosphorus concentration in the BNR plant .The trend from one basin to the next is also the same for the measured and simulated values

Simulation of optimum recycle ratios

The removal of phosphorus is affected by the retention time among other important parameters in activated sludge processes. The flow volume as well as the recycle ratios determines the hydraulic and sludge retention times in activated sludge systems. Simulations of optimum recycle ratios were carried out in SASSPro simulation software. Results showed that increase in the recycle rates resulted in decrease in the hydraulic retention time as well as sludge retention time.

The internal recycle is meant to achieve denitrification in the anoxic1 zone for 5-stage plants. Ortho-phosphorus rich effluent from the anaerobic zone is mixed with nitrified effluent in the anoxic zone. It is believed that in this zone some phosphorus accumulating bacteria capable of utilizing nitrate as an electron accepter simultaneously remove nitrogen and phosphorus from the liquid phase of the wastewater. However, continued increase in internal recycle results in the heterotrophic non-phosphorus accumulating bacteria having a competitive advantage over phosphorus accumulating bacteria. This results in reduced phosphorus removal efficiency. Increased internal recycle is also believed to result in increased Dissolved oxygen levels in the anoxic 1 zone of the bioreactor and the heterotrophic bacteria would end up using oxygen as an electron acceptor instead of NO_3.Figure 15 shows the change in effluent TP as the recycle ratios increase. A similar relationship could be observed for effluent nitrates and recycle rates. The first Figure shows the effect of internal recycle on the concentration of effluent TP. The lowest point shows the optimum TP effluent that can be achieved at the given internal recycle rate. In the other Figure, the minimum point of the curve coincides with the optimum operating overall recycle ratio.

Figure 15 Simulated optimal recycle rates for CSTW



As the recycle rate increases, the effluent Total Phosphorus concentration decreases. Increasing the overall return flow decreases the HRT and SRT in the bioreactor and generally phosphorus removal increases as SRT and HRT decreases. However, as the recycle ratio continues to increase, the HRT in the basin becomes too low to allow the processes to occur at optimum levels

Conclusion

The influent wastewater characteristics for the Biological Nutrient Removal plant are suitable for the process configuration as recommended by the developers of BioWin and SASSPro simulation software. The influent parameter ratios were within the ranges that allow effective phosphorus removal in activated sludge systems. BioWin and SASSPro simulation software can be used for the simulation of the treatment processes at Crowborough Sewage Treatment Works with minimum parameter calibration.The phosphorus removal efficiency at the plant was greatly affected by the high sludge retention time at which the plant was operating. Simulation results showed that optimum phosphorus removal could be achieved through proper operation of internal and overall recycle ratios.

Recommendations

The BNR plant should be operated at its design sludge retention time to achieve phosphorus removal. The optimum Sludge Retention Time for optimum phosphorus removal should be set at 15 days. . At this SRT the percentage of volatile suspended solids can be maintained at the recommended level of 85% of the mixed liquor suspended solids

Accuracy of the models can be improved through the calculation of the biomass coefficient constants such as yield factors and temperature coefficients using respirometry.

The estimation of the aeration process during modelling could be improved if such information as the oxygen transfer rate (mass of O_2/KWh) of the individual aerators is known.

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