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FULL-SCALE ACTIVATED SLUDGE BIOWIN MODELLING. A CASE STUDY OF FIRLE SEWAGE TREATMENT PLANT, HARARE, ZIMBABWE

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Abstract— Activated sludge process control is a major challenge to plant operators given the need for correct balance of parameters to achieve plant optimum conditions. A good example is a correct Mixed Liquor Suspended Solids (MLSS) balance necessary to retain the Food to Microbe (F/M) ratio within the desired range. In this regard, mathematical models play an important role in assisting plant process control. Thus, a research on a full scale activated sludge nutrient removal plant was carried out in Harare, Zimbabwe at Firle Sewage Treatment Works (FSTW) Unit 4. The main objective was to investigate opportunities for optimizing nutrient removal through the use of BioWin Simulator. This paper presents the results of calibration, simulation and validation of the BioWin modeling tool for optimum nutrient removal from a study carried out during the period 2012 to 2015 at FSTW. BioWin Simulator is complex because it attempts to simulate simultaneously biological processes of different organisms in addition to being built-up from a large number of model parameters with only few being able to be measured directly. To overcome this challenge the International Association on Water Quality (IWAQ) approach was used. In accordance with this approach a stepwise procedure starting with sludge composition and production, nitrification and finally denitrification was used. Critical attention was on the plant model set-up before any detailed measurement and calibration program started in order to reduce tedious cycles. To validate the model, data was collected for periods comparable with the period from which data for input and calibration was obtained. The initial simulation did not predict well the effluent quality, thus data reconciliation and plant revisits were conducted. This assisted in detecting where potential errors in the process could have been made. By using this method the number of components that need to be analyzed and the number of analyses was reduced. After validation the model predicted Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphate (TP) effluent concentrations reasonably well. Thus, it was concluded the calibrated simulator could be used to inform operations and for process control.

Keywords— Activated Sludge, BioWin Simulator, Full-scale calibration, Nutrient removal, Validation

1. INTRODUCTION

1.1 *Background*

Approximately two million ton of untreated wastewater are discharged annually into the world’s waterways resulting in annual deaths of over 1.8 million children below the age of five years (Corcoran et al., 2010). This scenario presents wastewater engineers with a huge task to reduce wastewater generation, develop sustainable treatment methods including potable and non potable reuse of treated effluents. In the early 70s scientists and engineers responded to the

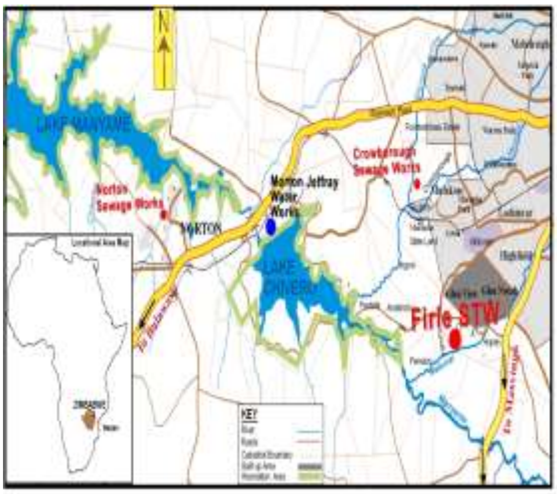

Fig. 1: Locality map for Firle Sewage Works

wastewater challenges by introducing new technologies to improve nutrient removal in wastewater treatment (Reardon et al., 2015). In the late 70s activated sludge processes which could effectively remove nutrients i.e. nitrogen and phosphorus were introduced, resulting in reduction in poor effluents discharge (Poschl et al., 2010). However, these activated sludge processes have their own challenges that include complicated process control requirements resulting from the need for correct balance of operational parameters (Thorin et al., 2012). To address these challenge, Activated Sludge Models (ASMs) were developed, starting with the Activated Sludge Model No. 1 (ASM1) in 1987 (Barker and Dold, 1987). The ASMs which include ASM1 (Barker and Dold, 1987), ASM2 (Henze et al., 1994), ASM3 (Gujer et al., 1999) presented operators and designers with a common platform for knowledge transfer particularly in process control, design, trouble-shooting and technology transfer. Today ASMs are vital tools in revealing and interpreting wastewater treatment process control problems, designing and providing computer generated solutions (Esposito et al., 2011).

Activated sludge modeling is a tool used to simulate the performance of a wastewater treatment plant, predict potential effects of operational changes such as changing sludge age, and to evaluate the comparative effectiveness of proposed facility upgrades (EnviroSim, 2000). Therefore, activated sludge modeling serve as a low cost means of developing computer generated changes without the risk of causing actual treatment process upset which may result in violating plant permit regulations. Activated sludge processes being complex, modeling should offer high level of flexibility to be of high benefit to its users as recommended by Jeppsson (1996). To achieve modeling flexibility, powerful graphics software that have made tremendous progression are to be fully utilized in assisting object oriented modeling (Barker and Dold, 1987). Where these powerful graphic software have been used they have helped to present and visualize key benefit in modeling in areas such as appreciation of system responses to changes in control variables (O'Shaughnessy et al., 1998). Use of dynamic simulation models has become standard practice in The Netherlands and since its introduction some five years ago more than 100 full scale wastewater treatment plants have been modelled (Hulsbeek et al., 2001). At the beginning, there were different approaches that were used varying in calibration approach, amount of sampling and time investment according to Barker and Dold (1997). Of late the accumulated practical experiences by the Dutch Foundation of Applied Water Research (STOWA) has stimulated the development of a protocol to aid in the set-up and calibration of models for full scale wastewater treatment plants.

The strength of computer based models to simulate activated sludge processes rest on good calibration of the model, in this way good understanding of the underlying biological reactions is achieved (de Haas and Wentzel, 2002). The development of models has continued to improve through fractionation of Chemical Oxygen Demand (COD), description of active biomass growth and population dynamics of floc forming and filamentous bacteria, a phenomenon of enhanced biological phosphorus removal (Gujer et al., 1999). Models such as BioWin have been used successfully since mid-80s to model operations of various plants worldwide according to Jeppsson (1996). Potential capital cost reductions, substantial operational cost cutting measures and energy savings in activated sludge plants have been achieved by using activated sludge models (Barker and Dold, 1995). The New York City wastewater treatment plants and Blue Plains wastewater treatment plant in Washington are good examples where models such as BioWin have been used successfully in capital cost estimates and operational cost reductions (Thermo Energy Corporation, 2007). Thus, use of activated sludge models brought closure to the previous challenges experienced in trying to optimise activated sludge processes. It therefore means that, where plant process designers were solely relying on reported values of wastewater characteristics, kinetic, stoichiometric and other model parameters they can now validate these model parameters through model simulations according to Water Environment Research Foundation (2003). Furthermore, through observing full-scale treatment plants and application of activated sludge models designers and operators are able to gain useful information that increases confidence in their designs for future plants and in optimisation of existing systems (de Haas and Wentzel, 2002).

The activated sludge model developments come against low inflow of fresh water, in addition to the influx in human waste, which has outpaced the development of wastewater management systems, leading to worldwide pollution of natural water bodies and irregular water supply (van Rooijen et al., 2009). On the other hand, Africa is faced with huge challenges that are adversely affecting public health, one such challenge is the inability of urban Africans to access clean water supply (WHO, 2006). The majority of SADC cities are now grappling with the problems of high volumes of waste, low capacity to manage waste and the high costs involved in the management of these wastes (SADC, 2016). The SADC region water resources play a critical role in sustaining economic and social development to approximately 200 million people in the region (UNEP, 2005). In Harare, the capital city of Zimbabwe, the poor waste management has resulted in pollution of water sources (Chivero and Manyame) according to Muisa et al. (2011). Thus, pollution of water sources has complicated and also increased water treatment costs in Harare, compromising on potable water quality resulting in user rejection according to Hoko and Makado (2011). A survey of Firle Sewage Treatment Works (FSTW) in Zimbabwe showed that the plant's aeration and anoxic zones, are regularly covered with foam suggesting growth of filamentous bacterium. This poor process control at FSTW is contributing to poor quality effluents which then pollute Lake Chivero, the source of raw water for Harare as reported by Muisa et al. (2011). It is against this background that a research was carried out at FSTW to optimize nutrient removal at the plant through the use of BioWin Simulator as a decision making tool. The study was carried out during the period 2012 to 2015.

1.2 *Background on activated sludge models and BioWin*

A literature survey of seven major simulators available worldwide was carried out. A simulator is a computer program which allows the user to link various unit processes together and then mimic the performance of the plant for specified operational and influent loading conditions (Water Environment Research Foundation, 2003). These simulators include ASIM by Swiss Federal Institute for Environmental Science and Technology of Switzerland, BioWin by EnviroSim Associates Limited of Canada, EFOR by DHI Inc of Denmark, GPS-X by Hydromantis Inc of Canada, SIMBA by IFAK-System GmbH of Germany and STOAT by WRc Group of United Kingdom and WEST by Hemmis N.V. of Belgium (Water Environment Research Foundation, 2003). All these simulators have a library of various activated sludge models where the user can select from depending on the simulator intended purpose (for example with GPS-X the model variants include the IWA models (ASM1, ASM2, ASM3), when using STOAT the model selection include modified versions of ASM1, ASM2d, unmodified ASM3 and models based on BOD (Stokes et al., 2000), while with BioWin the models variants include ASM1, ASM2, ASM3, ADASM according to Barker and Dold (1997) and the IWA models (ASM1-3) (Henze et al., 1995). Considering that each model outputs is heavily dependent on assumptions made and values specified to activated sludge models parameters (Copp, 2001), evaluating the impact of using different models for a specific task is an extremely difficult task. Thus, selection of BioWin Simulator for this research was principally based on the simulator's ability to achieve this research objectives. The ability of BioWin Simulator to satisfactorily track changes over time for the various wastewater parameters that include key research parameters e.g. COD, TN and TP in addition to other relevant parameters such as ammonia, nitrates, suspended solids etc. was the major consideration.

2 STUDY AREA

2.1 *Background to study area*

The study was carried out at FSTW Unit 4 which is a 3-stage activated sludge plant constructed in 1984 in Harare, the capital city of Zimbabwe (Stewart Scott International, 1984). Harare is located in the upper Manyame sub-catchment and draws water from Lakes Chivero and Manyame that are located on the downstream of the city (Fig. 1). The raw water yields from these two lakes are no longer adequate for city of Harare water requirements given that the treated water is also pumped to neighboring towns namely Chitungwiza, Ruwa, Norton and Epworth jointly known as Greater Harare (GH).

Fig 1

2.2 *Population and socio-economic issues*

The current population for GH is estimated at 2.4 million distributed as follows Harare 1,8 million, Chitungwiza 0.4 million, Epworth 0.2 million, Norton 0.07 million and Ruwa 0.06 million (Zimbabwe National Statistics Agency, 2012), These figures indicates that Harare strongly dominates the overall population in the GH, accounting for 71 % of the 2.4 million people.

2.3 *Wastewater management in Harare*

The City of Harare is tasked by the Urban Council's Act to manage wastewater in its area of jurisdiction, thus, the local authority is responsible for wastewater collection from both domestic and industrial areas (Government of Zimbabwe, 1997). The Harare Water Department in the City of Harare is responsible for collection, treatment and safe disposal of the treated effluents to the environment. On the other hand the Environmental Management Act mandates the Environmental Management Agency (EMA) to monitor discharge of effluents into the environment. The agency's roles include issuing wastewater effluent discharge permits and monitoring compliance with permit conditions (EMA, 2007). Under this arrangement the users of sewer infrastructure are accountable to City of Harare while the city is accountable to the Environmental Management Agency for effluent disposal to the environment. Over the years the City of Harare has been paying fines as a result of poor effluent quality from its wastewater plants which has generally been classified as high environmental risk.

2.4 *Firle Wastewater Treatment Plant*

The study was carried out at FSTW which is the biggest sewage treatment plant in the country. The plant treats domestic and industrial effluent and is situated at Firle Farm, south west of Harare City Musona et al. (2011). FSTW has five units with a total design capacity of 144,000 m^3/day and these units are numbered 1 to 5 in order of their construction (Stewart Scott International, 1984). Units 1 and 2 were constructed around 1969 and use biological trickling filters with a combined design capacity of 36,000 m^3/day, Unit 3 was constructed in 1980 with a design capacity of 18,000 m^3/day and uses a 5-stage biological nutrient removal process, Unit 4 the study site was constructed in 1984, has a design capacity of 18,000 m^3/day and uses 3-stage biological nutrient removal process. Finally Unit 5 which was constructed in 1998 has a total design capacity of 72,000 m^3 /day with four sub-units each with a design capacity of 18,000 $m^{3/}$day and uses 3-stage process similar to the one used at Unit 4 (Stewart Scott International, 1984).

A simplified process flow diagram for FSTW Unit 4 that was used for model calibration is shown in Fig. 2.

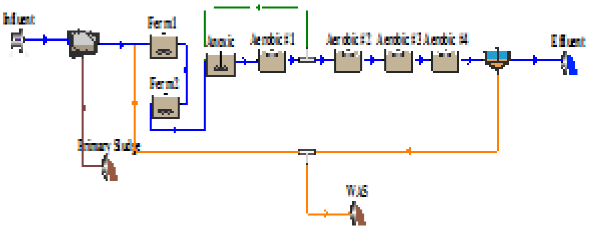

Fig. 2: BioWin Abstract Process Flow Diagram (PFD): FSTW Unit 4 (see study design for rational of aeration divisions)

3 MATERIALS AND METHODS

3.1 *Study design*

The study was arranged in accordance with The Dutch Foundation of Applied Water Research (STOWA) guidelines where five phases namely the inception phase, initial model construction, data acquisition and evaluation, model calibration and simulation and model validation were used.

The bioreactor comprises three stages, the anaerobic stage with two physically demarcated tanks in series each with a capacity of 900 m^3, the anoxic and the aerobic stages which are in one tank with no physical demarcation (Stewart Scott International, 1984). Based on the bioreactor configuration, the biological reactions taking place along the bioreactor and the assumption i.e. that the area influenced by each aerator constitute a completely mixed reactor, the bioreactor was then assumed to be a plug flow tank. Given, that the kinetic model of the plug flow system is mathematically complicated, to overcome this challenge, two assumptions were proposed as suggested by (Lawrence and McCarty, 1970). The first assumption was that the concentration of microorganisms in the influent to the reactor was approximately equal to that in the effluent to the reactor, when the ratio of Sludge Retention Time (SRT) to Hydraulic Retention Time (HRT) was greater than 5. The second assumption was that the rate of substrate utilization is constant as the waste passes through the reactor.

A true plug flow recycle system is theoretically more efficient in the stabilization of most soluble waste than a continuous flow stirred tank recycle system according to (Williamson and McCarty, 1976). Nevertheless, in practice it is essentially impossible to obtain a true plug flow regime (Metcalf and Eddy, 2003). Consequently, by dividing the aeration tank into a series of reactors, the process approaches plug flow kinetics and improved treatment efficiency compared to a completely mixed process as suggested by (Grady et al., 1997). In this regard, it was justified to divide the bioreactor into five completely mixed reactors in series. The anoxic tank having no physical boundary separating it from the aeration zone, the 1 400 m^3 anoxic tank capacity was estimated from plant physical dimensions. The anoxic zone was assumed to be completely mixed reactor. Considering that the reactor model and the transport model of the bioreactor were clearly defined, it was therefore, simple to describe the process flow diagram. The assumption was to divide the 5,600 m^3 aeration tank into four completely mixed reactors in series with each reactor volume influenced by a particular surface aerator. The three clarifier units were modelled as one ideal separator, in this way the solids loading rate and the clarifier underflow rate were specified. The simulator then calculate the mass balances around the clarifier, thus, determining the effluent and underflow concentrations.

3.1.1 *Selection of study site*

Harare, the capital city of Zimbabwe, has an estimated population of 1,8 million and accommodates more than 16% of the country's population (Zimbabwe National Statistics Agency, 2012). The city generates approximately 219,000 m^3/day of raw sewage, out of this quantity approximately 150,000 m^3/day drains to FSTW (Gauff, 2014). This treatment plant sits upstream of Lake Chivero, Harare's raw water source, hence the poor performance of this plant impacts on the lives of more than 1.8 million people (Zimbabwe National Statistics Agency, 2012). From the 150,000 m^3 /day of sewage arriving at FSTW, a total of 98,000 m^3/day is treated using 3-stage activated sludge process, which means optimizing this treatment process has the highest impact. It was therefore, important to assess the opportunities for optimizing nutrient removal of the 3-stage activated sludge process. Therefore, selecting FSTW Unit 4 was ideal for this purpose principally because it uses a 3-stage activated sludge process. Furthermore, the quality effluent from FSTW is generally classified in the high environmental risk according to Environmental Management Act quality standards (Muserere et al., 2014).

3.1.2 Selection of sampling sites

A well prepared measurement plan should give the type and location of the measurement among other attributes (Meijer and Brdjanovic, 2014). In model calibration, simulations and validation the sampling sites are generally the same as those selected to demonstrate compliance with environmental discharge standards and for process control according to Water Environment Research Foundation (2003). Plant process control and routine monitoring is carried out at FSTW hence existing sampling points were selected for calibration and validation sampling campaigns. To validate the sampling points, these routine monitoring sampling points were assessed to ensure that samples collected from these points were representative, reproducible, defensible and useful for the research. Furthermore, other factors considered in selection of sampling sites are the process used i.e. batch or continuous process, accessibility and safety of sampling sites (EPA, 2003). Based on these factors, wastewater samples were collected from upstream and downstream points of process units i.e. PSTs, BNR and clarifiers, and for sludge analysis sampling points were located at the centers of the units.

3.1.3 Selection of parameters to be analyzed

In activated sludge plant modeling, influent flow rate, wastewater characteristics, sludge production, operational and key design parameters are essential data (Randall et al., 1992, Weijers and Vanrolleghen, 1997, Barker and Dold, 1995). Key information for supporting influent wastewater characteristics, its fractionation and determination of inorganic solids that impact sludge production include free and saline ammonia (NH_3), Biological Oxygen Demand (BOD_5), Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) (Water Environment Research Foundation, 2003). Thus, COD, BOD_5, TP, TSS, ISS, TN, NH_3, Total Kedhjal Nitrogen (TKN), Total Alkalinity (TA), Mixed Liquor Suspended Solids (MLSS) and pH were selected for analysis

3.1.4 Methods of sampling and frequency

The sampling was carried out primarily to collect routine operating data for the overall plant performance, to acquire information to use in assessing performance of specific treatment processes and check regulatory compliance of the plant. To achieve this, samples were analyzed in accordance with APHA-AWWA-WEF (2005). Specifically COD, BOD, TKN, TP, TSS, NH_3, pH and alkalinity were according to APHA (5220), APHA (5210), APHA (4500-N), APHA (4500-P), APHA (2540), APHA (4500- NH_3), APHA (4500 – H^+), (2320B) respectively. Grab samples and 24-hour composite samples were collected as recommended by (Tjandraatmadia et al., 2009). The analytical measurements of suspended solids were depended on sludge concentrations. For concentrated sludge > 20%, filtration, drying and weighing was no longer possible, the dry mass method was used.

When an extensive measurement campaign is performed, very little effort is required to execute model simulations yielding substantial information on plant operations according to (Meijer et al., 2001b). To achieve this a series of sampling campaigns were carried out from 2012 to 2015. On 6 March 2012 sampling was carried out, taking 24-hour composite samples for steady state analysis, at the same time hourly grab sampling were collected for use in dynamic simulations. A second set of 24-hour composite samples were collected and analyzed over a 9-day period from 27 June to 6 July 2012. The main purpose of this sampling program was to support and confirm the historical data. Furthermore, in model design it is critical to fractionate wastewater according to (Hulsbeek et al., 2001), to that effect two sampling campaigns were carried out from 3 to 16 July 2013 and 1 to 14 October 2013. For the purposes of the model calibration samples were taken from the routine plant monitoring during the period 2012 to 2015 and validated through taking additional samples during the period 23 to 30 August 2014 and 7 to

21 January 2015. Model validation requires the use of checked and balanced data usually taken under different conditions than the data used for calibration according to (Vanrolleghem et al., 2003). To validate the model hourly grab and 24-hour composite samples were collected during the first 7-day week in January 2016, the sample results were checked and balanced and used to validate the model.

It must be noted that this paper is a third in a series, therefore results on wastewater characterization and fractionation were published in the previous two papers Muserere et al. (2014) and Muserere et al. (2015). Therefore, the reader is referred to these two published papers for more information on wastewater characteristics and fractionation of FSTW wastewater.

3.2 *Data collection methods*

3.2.1 *Sampling*

The samples were collected manually using a calibrated beaker tied to a 2m long steel rod and samples were collected at the mid-depth of each sampling point. The beaker was rinsed with acidified water first then three times with sample water before sample collection as suggested by (Tjandraatmadia et al., 2009). The sampling containers were filled to capacity and tightly closed. For quality control samples were split into two.

3.2.2 *Model calibration, simulation and validation data*

The Dutch Foundation of Applied Water Research (STOWA) protocol's Model-Based Design (MBD) based on the work by (Hulsbeek et al., 2001) and (Meijer et al., 2001a), was adopted in this research. The work was further applied and studied in practice by (Meijer et al., 2001b), based on this extensive practical experience with full-scale and plant-wide MBD studies adjustments were made in the Dutch Foundation of Applied Water Research (STOWA) protocol. Using MBD both historical and additional data were selected in accordance with the research problem and objectives as suggested by (Hulsbeek et al., 2001). To establish physical process boundaries, process flow diagrams of the wastewater plant was used as recommended by Water Environment Research Foundation, (2003). In addition, through plant visits the plant inventory namely important design information, historical operational data, indicative average operational information, process flow diagram, and other relevant information such as contact details, photographs, design reports, guidelines, etc. were compiled. Using this preliminary information, the preliminary plant model was constructed, the preferred simulation platform and the activated sludge model were selected as suggested by (EnviroSim, 2007). This was followed by construction of a simplified model flow diagram in the simulation platform. The model was then fed with plant design data and preliminary flow data to perform preliminary simulations as proposed by (Vanrolleghem et al., 2003). The main purpose of this simulation was to get an early indication of whether the assumptions made especially of the flow scheme are valid as well as checking if the operational data can be fitted into the model. The process was used for early feedback to the plant operators and resolving potentially critical problems at early stages. Additional measurements were taken primarily to check the main operational parameters, in particular flows and sludge production. In addition the important plant data for design calculations, model input data to the simulation study and data to validate the model simulation results were collected. The data was measured within a preselected system of mass balances, determined from the initial definition of the process boundaries. The data were checked using multiple empirical design calculations and traditional key design and operational parameters such as the SRT, sludge loading, and oxygen consumption. After this process data report with checked and balanced input data were ready for the model input and calibration.

From the mathematical modeling perspective, the activated sludge model is the most complicated part of the plant-wide model (Meijer et al., 2001b). Thus, data were further refined during model validation. The calibrated simulation results were subjected to multiple empirical design calculations, calculation of key design parameters such as SRT, sludge loading, oxygen consumption. This process helped to check information for accuracy and detecting inconsistencies, plant operational assessments, and determining whether the model simulation results were within acceptable design boundaries. For model validation, the checked and balanced data were then compared with simulation results of the calibrated model.

4 RESULTS AND DISCUSSIONS

4.1 *Model calibration*

4.1.1 Plant input data (2012 to 2015)

Calibration is a process where model parameters are adjusted until model predictions match the selected set of data linked to actual plant performance (Water Environment Research Foundation, 2003). In evaluating the match between model predictions and actual plant data, it was critical to pay attention to all model variables (EnviroSim, 2007). The aim was to fit most of the measured variables reasonably, instead of fitting perfectly one selected component concentration. In this way the model was calibrated to establish the design space, which then indicate the expected accuracy of the model under the specific circumstances. Under steady state the variables were matched within 5 to 20%, while under dynamic runs the match was within 10 to 40% according to (Nowak et al., 1999).

Yearly performance data for FSTW Unit 4 biological nutrient removal plant with Primary Settling Tanks (PSTs) on-line for the period 2012 to 2015 were examined. Graphs for flowrates, concentrations and loadings for all measured variables over the 4 year period were plotted. This period was selected for this case study because all components of this system were in continuous operation and its performance showed that relatively stable operations prevailed. Graphs of the 2012 to 2015 wastewater results recorded by the plant were plotted. In analyzing data for these plots, the obvious outliers were deleted from the database.

The input variables for the simulator taken from the database are as follows:-

1. Wastewater temperature (Fig. 3)

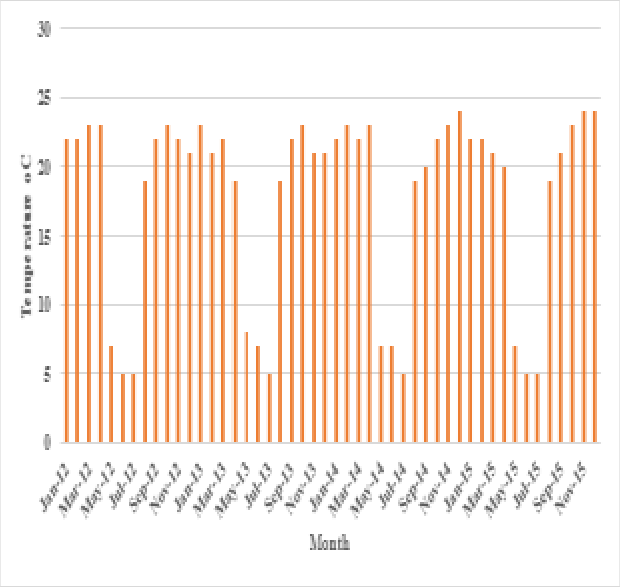

Fig. 3: Wastewater temperature for the period 2012 to 2015: FSTW Unit 4

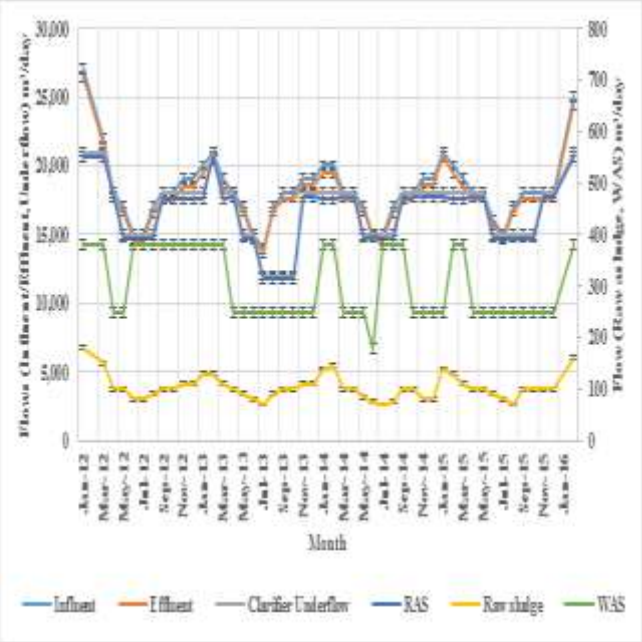

Fig. 4: Flowrates at Firle Sewage Treatment Works: 2012 to 2015

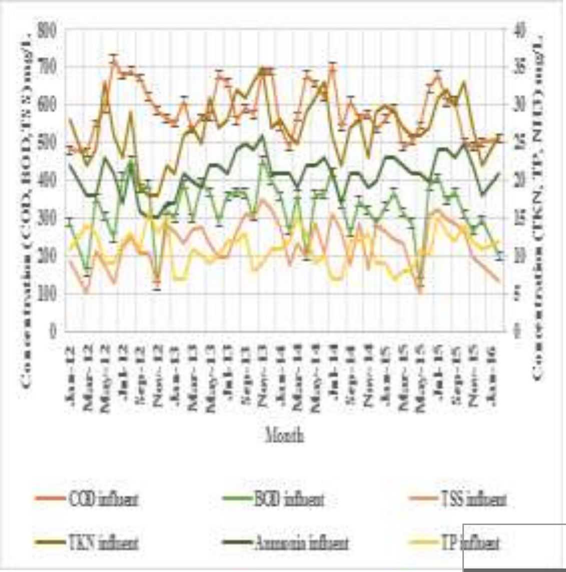

Fig. 5: Influent wastewater parameters concentrations for the period 2012 to 2015: FSTW Unit 4

2. Flowrates for influent, effluent, clarifier underflow, waste activated sludge and return activated sludge (Fig. 4)
3. Concentrations for influent COD, BOD, TSS, TKN, Ammonia, and TP (Fig. 5)

Fig 2 to 5

The flow rates were plotted to check the hydraulic model of the plant (Figure 4):-

The average temperatures suggested high biological activity, however, the minimum temperatures were very critical. Biological activity of the autotrophs, mesophilic type, will be affected at such low minimum temperatures of 5 ^{O}C according to Metcalf and Eddy, (2003).

Statistical analysis were performed using the 2012 to 2015 quality results and average, maximum, minimum and standard deviations were reported (Table 1 and 2)

Table 1 and 2

The influent quality suggested a generally highly biodegradable wastewater. The wastewater was treatable with 3-stage activated sludge, thus the process of calibrating the model was supported. The FSTW Unit 4 typical effluent results for randomly selected dates to demonstrate the plant behaviour under different operating conditions were tabulated (Table 3).

Table 1: Temperature and flow rates boundary values for Firle Sewage Treatment Works Unit 4 for the period 2012 to 2015

Item	Temperature °C	Flow rates m			
		Influent	Raw Sludge	WAS	F
Average	20	18,229	104	261	15
Maximum	24	27,000	150	380	20
Minimum	5	14,000	100	250	11
Standard Deviation	7	3,508	21	55	3

Table 2: Influent concentrations for COD, BOD5, TKN, NH_3 and TP for the period 2012 to 2015: Firle Sewage Treatment Works

Item	Influent concentrations mg/L				
	COD	BOD_5	TKN	NH_3	TP
Average	587	353	27	21	11
Maximum	720	455	35	26	16
Minimum	475	123	18	15	7
Standard Deviation	113	84	6	4	3

From the additional samples taken to fill in the gaps in COD, BOD effluent results and to validate the 2012 to 2015 historical records it was found that the plant was not consistently within the low environmental risk category (Table 4). According to Environmental Management Act read in conjunction with Statutory Instrument 6 of 2007 the stipulated quality is COD < 60 mg/L, BOD < 20 mg/L, TN < 10 mg/L and TP < 1 mg/L. thus, the average values for COD and BOD were higher than the stipulated average values suggesting poor effluent results.

Table 4

4.1.2 Initial model calibration

The first step was to examine the plant gravity separation units i.e. the PSTs and clarifiers as suggested by Water Environment Research Foundation (2003). The PSTs performance was

Table 3: Randomly selected effluent results for the period 2012 to 2015: FSTW Unit 4

	Date	COD	NH_3	Ortho- P	MLSS	pH	TP
	19-Aug-12		0	0.1	116		
	27-Aug-12		0.7	0.8	89		
	26-Mar-13		0.2	0.2	64		1
	13-May-13		0.52	0.1	25		
	19-Aug-14	27	27	0	4	7.2	13.6
	2-Dec-14		0.5	0	10	7.2	9
	13-Aug-15	22.4	0.5	0	18.5	8.2	0.5
	21-Aug-15	11	0	0	4	8.5	1.5
	10-Sep-15	63	0	0	13	7	0.5
	18-Sep-15	15.7	7	0	101	7.3	3.5
	30-Sep-15	3	0.11	1.2	7.5	7.2	3
	13-Oct-15	28.6	0.1	0	2	7.6	7
	20-Oct-15		0.8	0	4.6	7.2	1
	30-Nov-15	27.1	0.2	1	10	6.92	1
	1-Dec-15	53.8	0.2	0	10	7.6	1.2
	19-Aug-12		0		8280		
	27-Aug-12		0.3		6310		
	26-Mar-13		0.2		2640		
	13-May-13		0.5		1350		
	19-Aug-14		20		31500		
	27-Aug-14		1.7		3880		
	1-Dec-14				5600		
	13-Aug-15		6		4570		
	21-Aug-15				5030		
	10-Sep-15				4120		
	18-Sep-15		30		5500		
	30-Sep-15				4100		
	13-Oct-15		0.8		4480		
	20-Oct-15		0.3		3200		
	30-Nov-15		0.04		2860		
	19-Aug-12		0		10300		
	27-Aug-12		0.6		13000		
	26-Mar-13		0.9		3500		
	13-May-13				3450		
	19-Aug-14				17500		
	27-Aug-14				7350		
	1-Dec-14				10000		
	13-Aug-15		5		11000		
	21-Aug-15				10260		
	10-Sep-15		0		6180		
	18-Sep-15		12.7		19460		
	30-Sep-15		0		10200		
	13-Oct-15		0.4		8800		
	20-Oct-15		1.2		7630		
	30-Nov-15		0.2		4330		

Table 4: Effluent concentrations for COD, BOD5, TKN, NH3 and TP for the period 2012 to 2015: Firle Sewage Treatment Works

Item	Effluent concentrations mg/L					
	COD	BOD_5	TKN	NO x	TN	TP
Average	86	32	2	8	10	1.0
Maximum	130	55	4	11	12	1.4
Minimum	40	12	1	5	7	0.6
Standard Deviation	24	11	1	2	2	0.3

Note: NO_x is Nitrates and Nitrites concentrations

examined in the first published paper of this research and the reader is referred to Muserere et al. (2014). The clarifier removal efficiency was took from the operational manual of the plant by Stewart Scott International (1984). The estimates of these two parameters entered into the simulator are shown in Table 5.

Table 5

Volatile Suspended Solids (VSS) were estimated using the measurements for TSS and ISS since VSS concentrations were not directly measured. The TSS and ISS concentrations values were obtained from the plant database, these values were measured at least once a week during the period 2012 to 2015. Generally the ratio of ISS: TSS was approximately 0.3. On the other hand, there were no site specific information to estimate nitrification rates. However, the plant performance values during the period 2012 to 2015 suggested the plant was completely nitrifying hence the simulator default values were selected as the initial estimate.

The raw sewage fractions were measured and reported in the second published paper of this research work and the reader is referred to Muserere et al. (2015). The International Association for Water Quality (IAWQ) approach was used in fractionation. In this approach the slowly biodegradable COD is hydrolysed to

Table 5: Removal efficiency of gravity units for Firle Sewage Treatment Works Unit 4

Item	Unit	Removal efficiency %
1	Primary Settling Tanks	55
2	Clarifiers	99.8

readily biodegradable COD and thus conceptually released from the active site into a pool of readily biodegradable COD (de Haas and Wentzel, 2012). The assumption in this approach was that heterotrophic growth took place from the readily biodegradable COD substrate hence when the readily biodegradable COD was depleted it was the hydrolysis of the slowly biodegradable COD which governed heterotrophic growth rate (Ekama *et al.*, 1986). In model calibration the model parameters are adjusted for model predicted results to match actual plant performance according to (Hulsbeek et al., 2001). BioWin Simulator incorporates two factors namely Neta (Anoxic Hydrolysis) for hydrolysis of slowly biodegradable COD and Neta (Anoxic Growth) for the growth process of readily biodegradable COD according to de Haas and Wentzel (2012). Thus, BioWin during dynamic simulations slows down hydrolysis rate against the growth rate since these two processes have significantly different rates. Denitrification in activated sludge process is modelled as a heterotrophic growth process under anoxic conditions (Ekama and Wentzel, 2008), thus from the above hypothesis this process depends on the proportions of readily biodegradable COD to slowly biodegradable COD (Water Research Foundation, 1984). Sensitivity analysis of the two fractions was performed and it confirmed denitrification is sensitive to readily biodegradable COD fraction. The BioWin Neta factors took these dynamic processes into consideration and recent versions of BioWin have revised default settings for several parameters according to de Haas and Wentzel (2012). Thus, the assumption to use default values for stoichiometric and kinetic model parameters in this research as initial conditions was justifiable.

4.2 *Model simulation and calibration*

The first initial model simulation suggested there were no significant differences between the predictions and actual plant performance. The model predictions showed that the clarifier underflow TSS concentration were within the average of the actual plant measurements. The actual plant measured values were in the range 6,200 to 10,330 mg/L compared with the model predictions which were generally below 8,000 mg/L (Fig. 6). The percentage difference ranged from 10 to 40%.

Fig. 6

In the initial model conditions the clarifier removal efficiency was set at maximum of 99.8% hence adjusting this parameter had no impact. The clarifiers were modelled using modified Vesilind velocity and the settling parameters were at the optimum values hence adjusting them could not be justified. The raw sewage at FSTW had a very high ISS content due to grit disposal into the system according to Muserere et al. (2014), The PSTs were not performing well according to historical database. Thus, the VSS: TSS ratio was adjusted from 0.7 to 0.5 to further improve the fit.

The effluent TSS concentration was also well predicted with model predictions concentrations below 20 mg/L (Fig. 7) compared with the actual plant performance which were in the same range (Table 3).

Fig 7

To try and further improve the fit of results, adjustments were made in the removal efficiency of the clarifiers from 99.8% to 97%, however this yielded very minimal improvements. The particulate COD fraction was also adjustment since it has an impact on VSS concentration according to Water Research Environment Federation (2003). However, adjustment of this fraction necessitated adjusting other related fractions input to the model. The model input values for TSS concentration were analysed and were observed to be generally 125 mg/L. Thus, the input values for TSS concentrations were reanalysed in the laboratory and it was found that the concentration value for TSS ranged from 125 mg/L to 175 mg/L. Thus, the constant input value for TSS concentration was corrected as it was

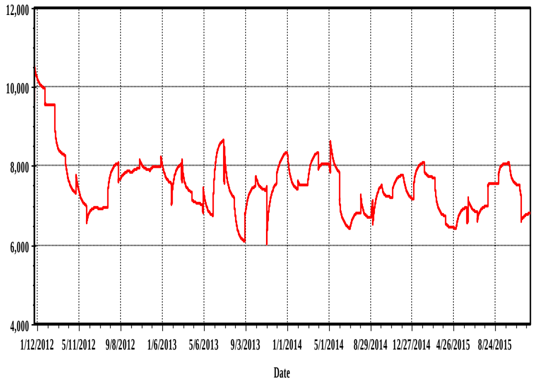

Fig. 6: Model predicted clarifier underflow for the period 2012 to 2015: FSTW Unit 4

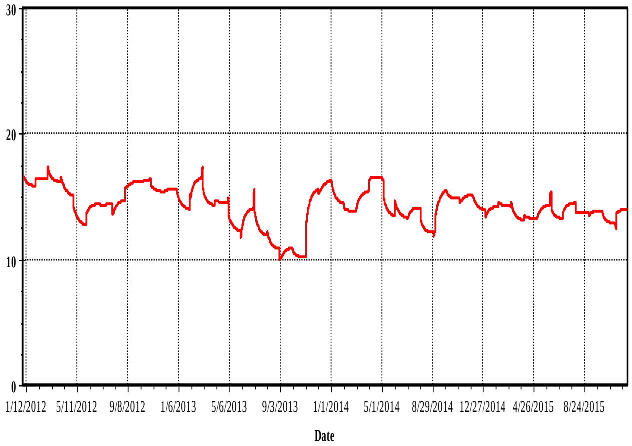

Fig. 7: Model predicted effluent TSS concentration for the period 2012 to 2015: FSTW Unit 4

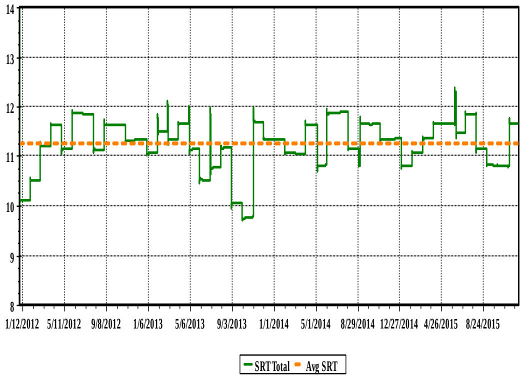

Fig. 8: Predicted SRT for the period 2012 to 2015: FSTW Unit 4

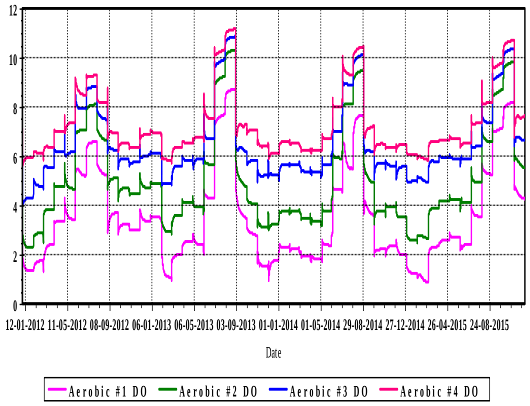

Fig. 9: Predicted DO concentrations in the aeration zone FSTW Unit 4: 2012 to 2015

suspected to be the reason for the slight variation resulting in under prediction by the model.

The plant SRT was calculated using TP mass balance i.e. TP profile had a good fit between the simulated results and the actual plant performance which was found to average 11.5 days. The SRT model prediction was in the same range (Fig. 8).

Fig. 8

The model predicted SRT had a good fit with the actual plant values hence there was no need to adjust on sludge wasting rates. Furthermore, with the adjustment in input value for TSS the values for SRT improved its fit.

The Dissolved Oxygen (DO) concentrations model predictions suggested high DO concentration value of 10 mg/L during winter periods (Fig. 9). These high DO concentrations were not supported by measured concentration values where the highest measured DO concentration was 5.5 mg/L. The DO concentrations at the plant were measured using a mobile DO probe since there are no fixed DO probes at the plant.

Fig. 10

The prevailing environmental conditions of pH and temperature plays an important role in the selection, survival and growth of microorganisms according to Metcalf and Eddy (2003). The lowest reported winter temperature during the period under review was 5 ^{o}C. While theoretically the autotrophic organisms, mesophilic organisms, will have low activity below 10 ^{o}C in real practice nitrification could have been taking place. This could account for the differences in model predicted DO concentration compared with actual plant performance. The Oxygen Uptake Rate (OUR) during the winter period decreased in response to the decrease in the ammonia oxidizing biomass concentration.

4.3 *Model validation*

After necessary adjustments were made the effluent TSS remained at values below 20 mg/L, however certain isolated effluent concentrations values exhibited poor performance of the plant at certain intervals. The clarifier operations were closely monitored and it was observed that the sludge blanket was not being properly monitored and controlled. Through frequent plant visits it was noticed that during certain time intervals the sludge blanket depth would rise to depth less than 0.5m, with floating scum as evidence of sludge bulking. The optimization of clarifiers operations in activated sludge processes are currently not well defined and represents a major operational challenge according to (Severin and Poduska, 1985). The situation becomes difficult to manage when sludge settleability is poor, influent hydraulic and solids fluxes approach the clarifier design capacity. The other contributing factor to isolated poor effluent results was unreliable power supply resulting in long durations of power cuts. Durations as high as 6 hours were recorded during the period 2012 to 2015 which was then attributed the isolated poor results. The power cuts records were kept at the treatment plant and on analysis it was noticed that in most cases power cuts periods coincided with the higher mixed liquor suspended solids concentrations and low underflow MLSS concentrations, poor nitrification, and sludge bulking. Thus the effluent results with higher values of TSS were discarded from the database particularly where long durations of power cuts were reported. The average measured TSS concentrations during the period 2012 to 2015 reduced significantly such that the model predictions fitted well with actual plant performance.

Similarly, the 2012 to 2015 monthly average measured clarifier underflow TSS concentrations reduced significantly after discarding high concentrations due to power cuts.

Further assessments of the activated sludge plant indicated the activated sludge process undergoes anaerobic ammonia oxidation where ammonia nitrification is coupled with nitrate reduction a concept which is not yet clearly known according to Metcalf and Eddy (2003). Microbial studies of the similarities and differences between aerobic and anoxic respiration in pure cultures indicate that essentially the same pathways are followed, but with lower ATP generation when nitrate is the electron acceptor versus oxygen according to (Madigan, 1997). According to this theory direct relationship do exist between ATP production and biomass production, therefore sludge production should be lower under anoxic conditions. ATP (Adenosine-5-triphosphate) is an unstable molecule which hydrolyses to ADP and inorganic phosphate when it is in equilibrium with water. ATP is the primary energy transfer for most energy requiring reactions in a cell. Thus, by analyzing the mixed liquor in the aeration basin it was observed that nitrification and denitrification took place along the reactor. This trend was noticed after assessing the combined effect of the hydraulic and activated sludge models. In the hydraulic model nitrified sewage is recycled from the first quarter of the tank to the anoxic tank, yet under the activated sludge model, nitrification and denitrification continued to take place along the reactor further downstream. The reduction in nitrates concentration along the reactor length suggested denitrification was taking place. It then means sludge production was reduced due to the anoxic processes which have lower ATP production. It was therefore necessary to further scrutinizing results and it was then noticed that higher sludge production was reported during periods of power cuts. It then became critical to take additional samples to validate this observation. The TSS concentration results suggested that when the plant was uninterrupted to achieve steady state conditions the average TSS concentrations in the bioreactor was 4,800 mg/L and the clarifier underflow TSS concentration was approximately 8,000 mg/L, which was in agreement with the model predictions. The existence of anoxic pockets along the bioreactor could have necessitated incorporation of an anoxic reactor downstream of the aeration zone or somewhere in between the aeration zone to describe process flow. This was not done because the flexibility of the anoxic zone and the hypothetical dimensions of this reactor adequately compensated for the downstream anoxic pockets. It could have been interesting to carry out a

Table 6: Model predicted against actual plant performance at FSTW: October 2015

Item	Parameter	Predicted Results	Plant Measured results	Percentage difference
1	COD	66	72	8%
2	TN	9	11	18%
3	TP	0.9	10	10%
4	SS	18	21	14%
6	SRT	11	12	8%

computational fluid dynamics of the anoxic and aeration zone of this configuration but time and budgetary constraints of the research were limiting. There were no adjustment to the kinetic and stoichiometric model parameters as there were no justifications to do so. In a study de Haas and Wentzel (2002) using measured diurnal influent, reactor and effluent data, a good agreement between observed and predicted data was found which confirmed that the more recent default settings in BioWin are more realistic for certain types of plants, compared to previous model versions. The calibrated simulation results were subjected to multiple empirical design calculations and calculation of traditional key design parameters such as SRT as suggested by Meijer and Brdjanovic (2014). This process helped to give plant operational assessment, check the information for accuracy as well as detect inconsistencies and check if the model simulations were within acceptable design boundaries. Subsequently for model validation, the checked and balanced data, key operational and design parameters were compared with the results of the calibrated model (Table 6).

The following table shows the plant SRT and effluent results of a validated model:-

Table 6

The results were within acceptable range for dynamic simulations, percentage difference below 20% is acceptable according to Water Environment research Foundation (2003).

CONCLUSIONS AND RECOMMENDATIONS

The approach which was used of making an initial fit of the model predictions to check for significant issues followed by adjusting the model parameters and other input conditions as appropriate was very effective in model calibration. This procedure gave a reasonably good fit of the model predictions to Firle Sewage Treatment Works plant data for the period 2012 to 2015.

Critical examinations of TSS, DO and operational issues especially clarifier monitoring were essential to ensure that a realistic description of the true plant conditions were used. Adjustments to input data to get an improved fit of the model is permissible as long as there is appropriate justification to do so according to Water Environment Research Foundation (2003). The default values for kinetic and stoichiometric appeared to be appropriate to use in this model and no further adjustments were necessary. The default model parameters are based on several experiments and model calibrations hence should allow reasonable estimations of process performance in most situations according to Haas and Wentzel (2002).

Thus, it was recommended to apply BioWin modelling tool to FSTW Unit 4's 3-stage activated sludge process to assess the treatment processes at each stage in order to determine optimum treatment conditions for COD and nutrient removal.

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