

CALIBRATION OF A WHOLE OF WORKS PROCESS SIMULATION MODEL FOR THE MANGERE WASTEWATER TREATMENT PLANT

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ABSTRACT

The Mangere Wastewater Treatment Plant (WWTP), situated on the Manukau Harbour, receives the wastewater flow from four municipalities of greater Auckland, treating a population equivalent of one million. The design average inflow to the plant is 390,000 m³/day and the current load to the plant consists of 120 tonnes/day of BOD₅, 130 tonnes/day of total suspended solids (TSS), 18 tonnes/day of total nitrogen (TN), and 1.8 tonnes/day of total phosphorous (TP). This large plant provides primary, secondary and advanced level treatment for all flows up to 9 m³/s and primary treatment and UV disinfection for further storm flows of 9 - 16.5 m³/s. The plant is designed to achieve an effluent standard of 15 mg/L TBOD₅, 15 mg/L TSS and a total nitrogen of 9.5 mg/L (summer) and 35 mg/L (winter).

A “whole of works” BioWin model was calibrated using the protocols and suggested analytical testing contained in “*Methods for Wastewater Characterization in Activated Sludge Modeling*”, WERF 2003.

This paper presents a summary of the testing results versus model for each unit process and a discussion of the SBR protocol and its application to a complex treatment process such as Mangere. The paper also discusses some of the key factors influencing the model calibration and some of the difficulties and uncertainties associated with collection, measurement and interpretation of analytical and SBR data for model calibration.

KEYWORDS

Process Simulation, calibration, uncertainty, SBR protocol

1 INTRODUCTION

The Mangere WWTP is the largest wastewater treatment facility in New Zealand with a population equivalent of approximately 1 million people (see figure1). It discharges, on average, 300,000 cubic metres of treated wastewater into the Manukau Harbour per day.

The treatment process consists of a number of unit operations including:

- Screening and grit removal
- Primary sedimentation
- Secondary biological treatment via activated sludge
- Tertiary filtration and UV disinfection
- Solids thickening, digestion and dewatering

Figure 1: Aerial View of the Mangere WWTP



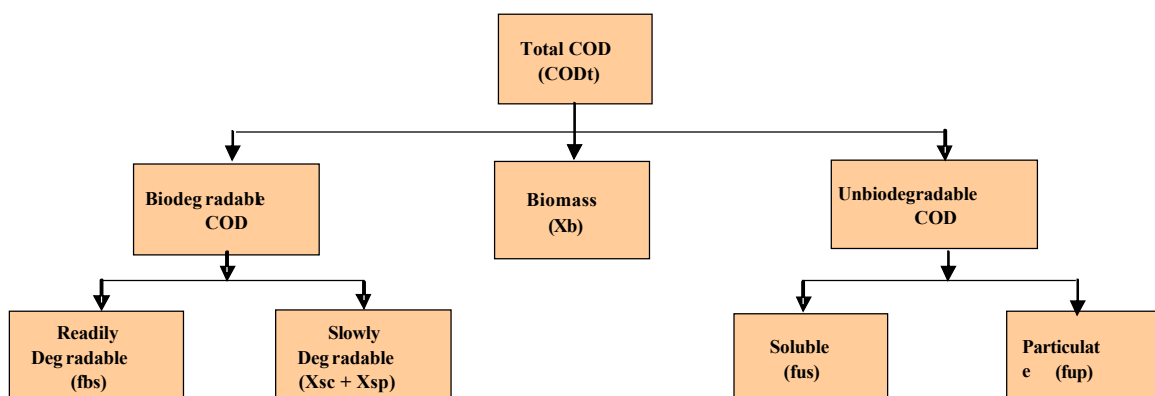
In order to understand the interrelationships between each unit process, the effect of effluent quality, solids production and operational cost, a process simulation model was built using BioWin simulation software. Details of the model build can be found in McCoy *et al* 2007.

BioWin simulation software provides a platform for the simulation of wastewater treatment processes via modified Activated Sludge Models (ASM) and an Anaerobic Digestion Model (AD).

The BioWin AS/AD model uses ASM variables and a digestion model that is based upon these variables. The key to these models is the “state variables” which make up the basis of the model predictions. The state variables include parameters that cannot be broken down into sub groups such as ammonia, reactor temperature, etc.

The AS/AD model is based on a Chemical Oxygen Demand, Nitrogen and Phosphorus mass balance. Each of these components is broken down in the model to a state variable. For example COD is broken down as shown in Figure 2:

Figure 2: Breakdown of COD fractions in BioWin

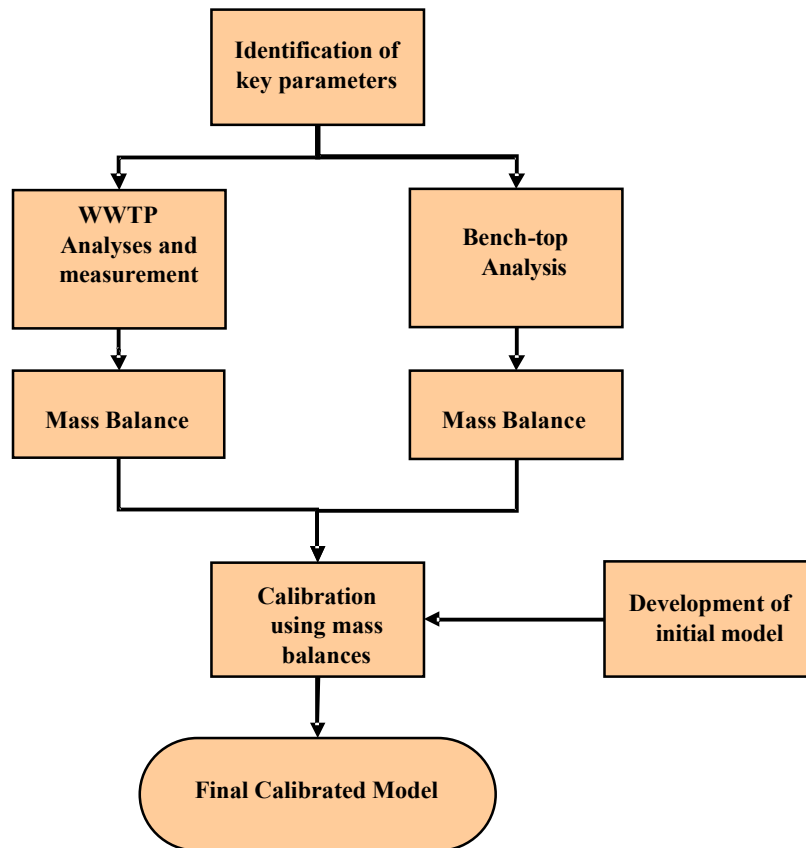


Calibration of the AS/AD model therefore includes measuring and estimating the wastewater “fractions” and in some instances measurement and modification of kinetic and stoichiometric parameters.

Measurement of the wastewater fractions and their application to the model can be complex and typically involves a range of standard and specialized laboratory tests. Guidelines for this testing have been developed over a number of case studies and research programs and are summarized in “*Methods for Wastewater Characterization in Activated Sludge Modeling*” published by the Water Environment Federation (WEF).

A general guideline for creating a calibrated model based on these methods is summarized in Figure 3 below.

Figure 3: Modelling Approach



The above approach was used as the basis for the calibration of the Watercare “whole plant” model (note that a “whole plant” model refers to the integrated modeling of all the main unit processes in an integrated simulation package, and can also be referred to as a “super” model).

This paper summarizes the techniques used to calibrate the Mangere model, provides a comparison of modelled versus measured data and an analysis of the challenges of integrating this information into a simulation.

2 METHODS

2.1 ANALYTICAL METHODS

The first stage of the model calibration was to identify the critical streams around the process and to develop a sampling program and protocol for each stream. As the Mangere plant has a large number of recycles and interdependent process streams, identification of the sample location and sample type was critical to the success of the calibration. A sampling program was developed that identified nine sample points around the process along with 28 points where flow measurements were recorded on the site SCADA or could be determined by calculation. Sample parameters are summarized in Table 1 below. Ten samples were taken at each of the nine sample points identified above.

Table 1: Analytical Samples

Parameter	Short Sample Name	Sample Frequency
Chemical Oxygen Demand COD _t (total COD)	COD _t	Daily
Filtered COD (125 micron)	COD _f	Daily
Filtered and Flocculated COD (modified UCT method)	COD _{ff}	Daily
Carbonaceous BOD ₅	BOD	Daily
Filtered Carbonaceous BOD ₅	BOD _s	Daily
Total Suspended Solids (125 micron)	TSS	Daily
Volatile Suspended Solids	VSS	Daily
Total Kiedhal nitrogen	TKN	Daily
Filtered TKN (125 micron)	TKN _s	Daily
Ammonia	NH ₄ -N	Daily
Nitrate	NO ₃ -N	Daily
Total Phosphorus	TP	Daily
Dissolved Reactive Phosphorus	DRP	Daily
pH	-	Daily
Flow	-	Daily

2.2 BENCH SCALE SBR

The limitation of the analytical methods for the fractionation of the COD components is the measurement of the unbiodegradable particulate COD fraction (Sup in Biowin or Xi in ASM models). The Sup fraction of the COD is very important for predictions of mixed liquor concentration, waste solids mass and the performance of anaerobic digesters. Using Mangere as an example, the over estimation of Sup by 25% would increase the solids inventory in the model by 20,000kgDS/d.

The best way to minimize the error in the estimation of the Sup concentration is to use a bench scale reactor. This enables a complete mass balance to be undertaken across the reactor under controlled loading and SRT conditions. A balance over the influent, waste solids and final effluent allows the Sup concentration to be fitted to the reactor data by means of a total COD balance. This balance can also be verified by modelling the bench scale system in BioWin.

One of the disadvantages of the SBR protocol is that the reactor cannot be run on all the wastewater streams at the same time. Hence one stream has to be identified for the SBR and the other streams that combine to make this stream evaluated by difference. At Mangere the interstage pump station (IPS) that feeds the nine reactor clarifiers was selected for the SBR trial. This is because the IPS:

- Receives primary treated wastewater that includes all recycles.

- Feeds the biological treatment stage (this has the longest solids retention time of any unit process).
- The composition of the WAS generated from the IPS flow determines the solids flux to secondary sludge thickening.
- The prediction of the reactor clarifier mixed liquor is most sensitive to the Sup concentration.

The influent feed to the SBR was taken from a 24 hour composite sample of the IPS. In order to ensure representative sampling, composite weekend samples were also included. The IPS wastewater sub-samples were combined and tested for COD. To achieve controlled reactor conditions the inlet COD concentration to the SBR must be maintained as constant as possible. This was achieved by diluting the raw composite samples to 400mgCOD/L with tap water. Each day, the SBR was fed a total of 4 litres of diluted wastewater. Baking soda (NaHCO_3) was also added to increase the alkalinity of the feed and raise the pH to above 7 in the decant. This was calculated based on the concentration of ammonia within the diluted wastewater and was around 250 mg per day.

2.2.1 SBR CYCLES

The cycles for the SBR were as follows:

- Fill 09:00 4 litres of diluted wastewater was pumped into the SBR;
- Aeration 09:20 Following end of feed period, aeration and mixing was begun and this react phase ran for 23 hours;
- Wasting 07:45 Approximately 270 mL of mixed liquor was manually wasted;
- Settling 08:00 Aeration and mixing were stopped and the system allowed to settle for 30 minutes;
- Decant 08:30 Following the settling of the system 4 litres was decanted from the reactor.

No denitrification phase was included in the SBR schedule. For calculation of the fractions required for the BioWin calibration denitrification was not required as the fractions are wastewater specific not process specific.

3 RESULTS AND ANALYSIS

3.1 ANALYTICAL TESTING

To characterize the influent wastewater, the COD fractions were determined using the following method (based on WERF Manual “Methods for Wastewater Characterization in Activated Sludge Modelling” and STOWA).

3.1.1 COD FRACTIONS

1. Measurement of the COD_t (total COD), fCOD (filtered COD) and ffCOD (filtered and flocculated COD) concentrations.
2. Measurement of the ffCOD concentration in the effluent. The concentration of ffCOD in the effluent (plant discharge) is equivalent to the soluble, unbiodegradable concentration, S_{US}. The f_{US} fraction is the S_{US} / COD_t.
3. The difference between the influent ffCOD and S_{US} (determined as above) is the soluble biodegradable concentration S_{BS}. The f_{BS} fraction is the S_{BS} / COD_t.
4. The colloidal COD fraction (X_{SC}) is represented by the difference between the fCOD and the ffCOD concentrations.

5. The particulate concentrations are more difficult to determine. The User Manual for BioWin 2.1 (EnviroSim 1991) contains a section to calculate the BOD values associated with the soluble and particulate COD concentrations based on the slowly biodegradable particulate concentration X_{SP} as follows:

$$BOD_s = (1-Y).S_s + (1-f).Y.S_s.(1-e^{-b.t}) \quad (1)$$

$$BOD_{SP} = X_{SP} \left(\left((1-Y) + \frac{(1-f).b.Y}{(b-k)}.(1-e^{-k.t}) \right) - \frac{(1-f).Y.k}{(b-k)}.(1-e^{-b.t}) \right) \quad (2)$$

Where:

Y = Yield of active organisms (~ 0.666 mg cell COD/mgCOD)

S_s = Soluble (filtered) biodegradable COD (mgCOD/L) – includes colloidal

f = fraction of active mass remaining as endogenous residue (~0.20)

b = Endogenous decay rate constant (~ 0.24 d⁻¹)

k = first order rate constant for sbCOD degradation (~0.40 d⁻¹)

t = time (d)

Comparisons were made between the measured total BOD and filtered BOD and their calculated equivalents. The X_{SP} value was iterated to provide comparable BOD values.

6. The inert particulate fraction, f_{UP} , is also difficult to analytically quantify. However, by definition:

$$f_{UP} = 1 - f_{BS} - f_{US} - \frac{(X_{SC} + X_{SP})}{COD_t} \quad (3)$$

As f_{BS} and f_{US} have been calculated, X_{SC} and the COD_t measured, and X_{SP} estimated, f_{UP} can be calculated.

7. The last 'fraction' to be calculated is the amount of non-colloidal slowly biodegradable COD that is particulate.

$$f_{XSP} = \frac{X_{SP}}{X_{SC} + X_{SP}} \quad (4)$$

The major assumption in using this method is that while the f_{US} and f_{BS} fractions are measured variables the f_{UP} is calculated based on the particulate BOD (i.e. the X_{SP} concentration and the measured particulate BOD). Hence there is some error associated with this method as the BOD test is difficult to replicate and model accurately. The other assumption that has been made is that particulate COD that is degradable does not include biomass COD.

3.1.2 NITROGEN FRACTIONS

The nitrogen fractions that were calculated were:

1. f_{NA} TKN to ammonia ratio:

$$f_{NA} = \frac{[NH_4^+]}{[TKN]} \quad (5)$$

2. f_{NOX} Fraction of organic nitrogen that is particulate –

$$f_{NOX} = \frac{([TKN] - [NH_4^+]) - ([TKNf] - [NH_4^+])}{([TKN] - [NH_4^+])} \quad (6)$$

The SBR was operated for approximately three sludge ages (62days) in order to obtain “steady state” conditions. Following this a 10 day intensive sampling period was undertaken including samples for TSS; VSS; filtered COD; filtered and flocculated COD; filtered TKN; TKN; and TN. In addition, further testing was carried out on the mixed liquor of the reactor on Day 3 of the testing period (following 65 days of operation from initialization) – this involved taking samples of wastewater from the mixed liquor and doing ammonia and nitrate tests (and occasionally nitrite tests) every 30 minutes starting from the time of feeding the reactor (9.00am). This intensive testing was continued every half-hour until virtually all the ammonia in the reactor had nitrified (which occurred around 6.00pm).

From this testing a mass balance was calculated using concentration data from the decant, influent and waste streams and the volume of wastewater in each. Tables two and three below summarize the mass balance. In theory a perfect mass balance is achieved when there is 100% recovery of the inlet mass. Using this basis the amount of gas given off (carbon dioxide gas in the COD balance and nitrogen gas in the nitrogen balance) was determined. Table 2 and Table 3 below show the COD and nitrogen behavior over time for the different streams.

Table 2: SBR COD Balance

Parameter	Unit	3/06/2008 Day 1	4/06/2008 Day 2	5/06/2008 Day 3	6/06/2008 Day 4	7/06/2008 Day 5	8/06/2008 Day 6	9/06/2008 Day 7	10/06/2008 Day 8	11/06/2008 Day 9	12/06/2008 Day 10	Average
CODin	mg/L	555	529	508	601	610.8	569	540		443	653	556.53
COD dil	mg/L	407	393	385	419	394	373	379		402	389	393
Volume in	L	2.93	2.97	3.03	2.79	2.58	2.62	2.81	2.55	3.63	2.38	2.83
COD in	mg	1626	1571	1539	1677	1576	1491	1517		1610	1554	1573
CODwas	mg/L	1077	1208	1218	1161	1150	1162	1180	1260	1225	1354	1200
Volume was	mL	285	270	285	280	275	265	270	270	270	270	274
CODwas	mg	307	326	347	325	316	308	319	340	331	366	328
CODdecant	mg/L	91.0	64.0	73.8	73.6	91.0	77.5	84.0	54.0	50.0	75.0	73.4
Volume decant	L	3.97	4.45	3.52	4.19	3.97	3.91	3.86	3.86	4.15	3.81	3.97
CODdecant	mg	361	285	260	308	361	303	324	208	208	286	290
CO2	mg	958	960	932	1043	898	880	875		1071	903	947
SRT	days	8.06	9.89	10.03	9.16	8.49	9.51	9.18		11.38	10.39	9.57
CO2	mg/L	327	323	308	374	348	336	311		295	379	333
CO2%		59%	61%	61%	62%	57%	59%	58%		67%	58%	60%

Table 3: SBR Nitrogen Balance

Parameter	Unit	3/06/2008 Day 1	4/06/2008 Day 2	5/06/2008 Day 3	6/06/2008 Day 4	7/06/2008 Day 5	8/06/2008 Day 6	9/06/2008 Day 7	10/06/2008 Day 8	11/06/2008 Day 9	12/06/2008 Day 10	Average
TNin	mg/L	55.00	66.00	60.00	60.00	61.00	60.00	61.80	59.00	55.00	63.00	60.08
Volume in	L	2.93	2.97	3.03	2.79	2.58	2.62	2.81	2.55	3.63	2.38	2.83
TN in	mg	161.2	196.0	181.8	167.4	157.4	157.2	173.7	150.5	199.8	149.9	169.5
TNoutwas	mg/L	71.5	98.0	112.0	97.0	112.0	82.6	102.0	102.0	91.0	108.0	97.6
Volume was	mL	285.0	270.0	285.0	280.0	275.0	265.0	270.0	270.0	270.0	270.0	274.0
TN was	mg	20.4	26.5	31.9	27.2	30.8	21.9	27.5	27.5	24.6	29.2	26.7
TNdecant	mg/L	33.0	36.0	35.6	31.0	33.5	30.2	37.0	32.0	28.0	33.6	33.0
Volume decant	L	3.97	4.45	3.52	4.19	3.97	3.91	3.86	3.86	4.15	3.81	3.97
TNdecant	mg	131.0	160.2	125.3	129.9	133.0	118.1	142.8	123.5	116.2	128.0	130.8
N2	mg	9.76	9.36	24.57	10.35	-6.42	17.23	3.30	-0.61	59.07	-7.24	11.94
SRT	d	2.36	2.63	3.56	3.09	3.42	2.95	2.99	3.38	3.23	3.44	3.10
TN lost	mg/L	3.33	3.15	8.11	3.71	-2.49	6.58	1.17	-0.24	16.26	-3.04	3.65
N2 %		6.1%	4.8%	13.5%	6.2%	-4.1%	11.0%	1.9%	-0.4%	29.6%	-4.8%	6.4%

Figure 4: SBR Mass Balance - COD

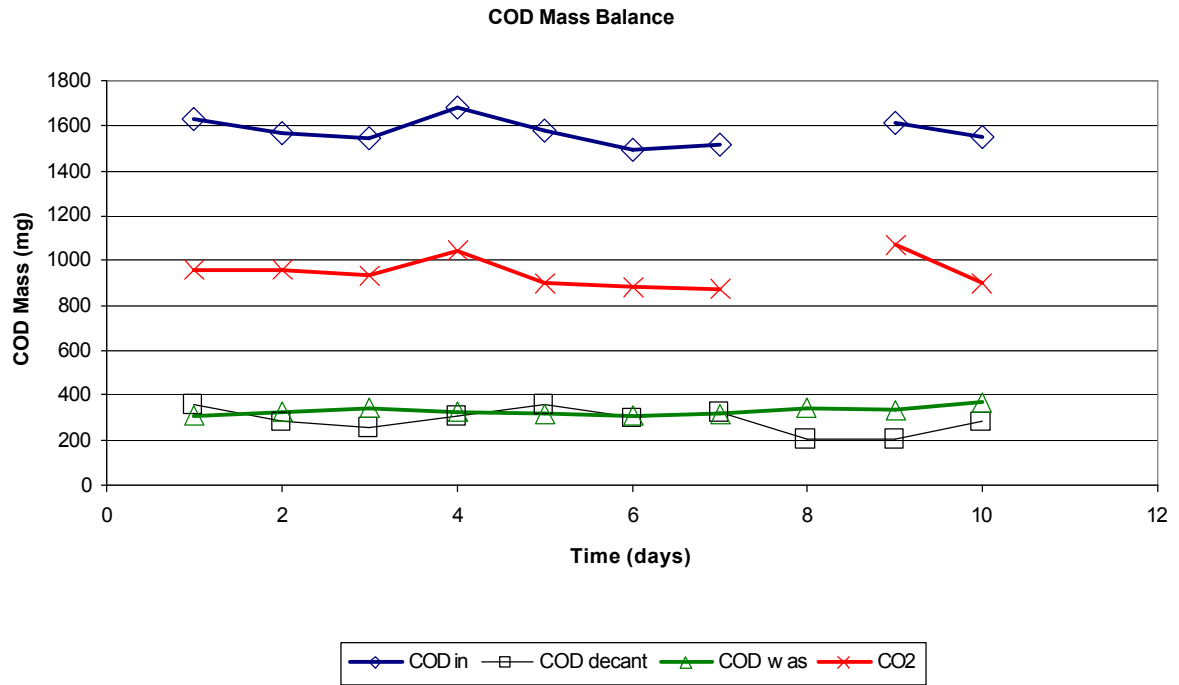
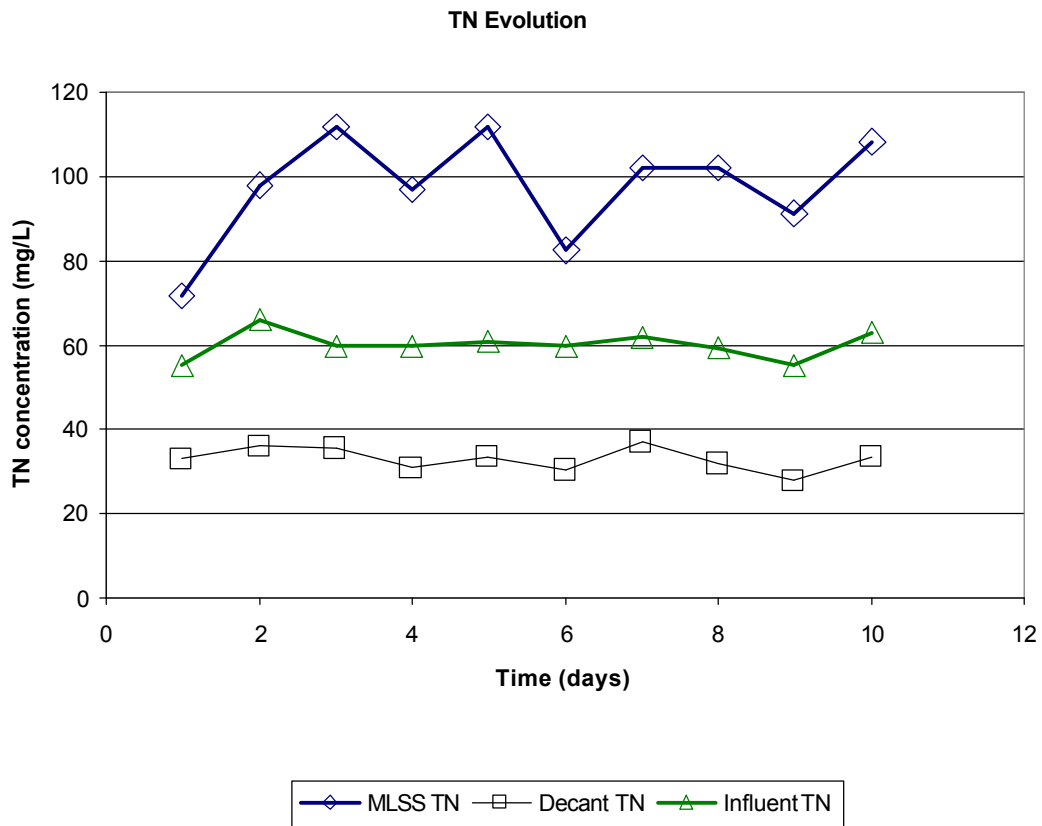


Figure 5: SBR Nitrogen Balance



The wastewater fractions for the IPS were calculated based on the data above and the analysis of the SBR reactor. This information was then put into BioWin and the process simulated at steady state without primary sedimentation, digestion and dewatering/thickening recycles. This allowed the predictions of the reactor clarifiers to be confirmed without interference from the solids or primary tank stream. Note that this method was only valid because the IPS is the confluence of all the recycles and the primary wastewater. Therefore the concentration data obtained during the intensive sampling campaign included all these flow without the need for all of the unit processes to be modeled.

Subsequent to the IPS and reactor clarifier models being simulated with the intensive sampling data and the SBR information, the next step on the model was to include the primary sedimentation system and digestion/dewatering. The simulation outputs of these processes were matched against the analytical data and the model simulated to verify that the predictions of each stream of the model matched the sampling data. As a next step all recycles were connected in the model and the final effluent, MLSS and digester performance modeled to ensure that simulation of these processes matched the sampling data.

As a final step the mass of COD, nitrogen and phosphorus from the plant recycles (primary sludge thickening and dewatering) were subtracted from the plant inlet flow as these recycles join the flow upstream of the raw wastewater sampling point.

A summary of the calibrated and default model parameters are shown in table 4.

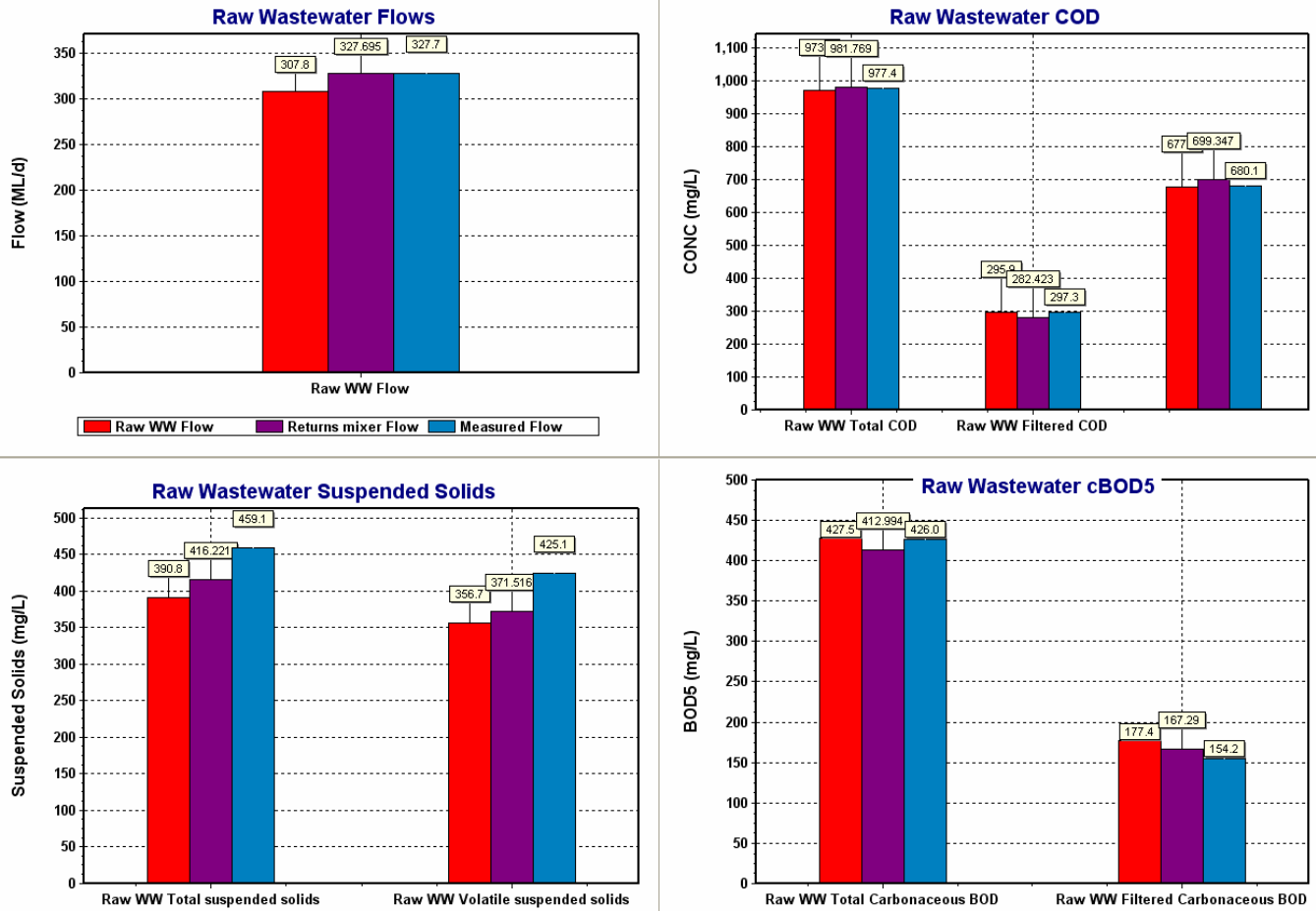
Table 4: Calibrated Fractions

Name	Description	Default Value	Calibrated Value	Calculated (Analytical)
Fbs	Readily biodegradable (including Acetate)	0.16	0.210	0.219
Fac	Acetate	0.15	0.000	
Fxsp	Non-colloidal slowly biodegradable	0.75	0.910	0.910
Fus	Unbiodegradable soluble	0.05	0.046	0.054
Fup	Unbiodegradable particulate	0.13	0.210	0.199
Fna	Ammonia	0.66	0.550	0.553
Fnox	Particulate organic nitrogen	0.5	0.918	0.882
Fnus	Soluble unbiodegradable TKN	0.02	0.000	0.035

Note that Acetate is set at zero as this was not measured during the intensive testing regime due to the expense of volatile fatty acid (e.g. acetate) tests. The acetate COD fraction is included in soluble readily biodegradable complex COD fraction and will not affect the performance of the model, as complex is converted to acetate in the process.

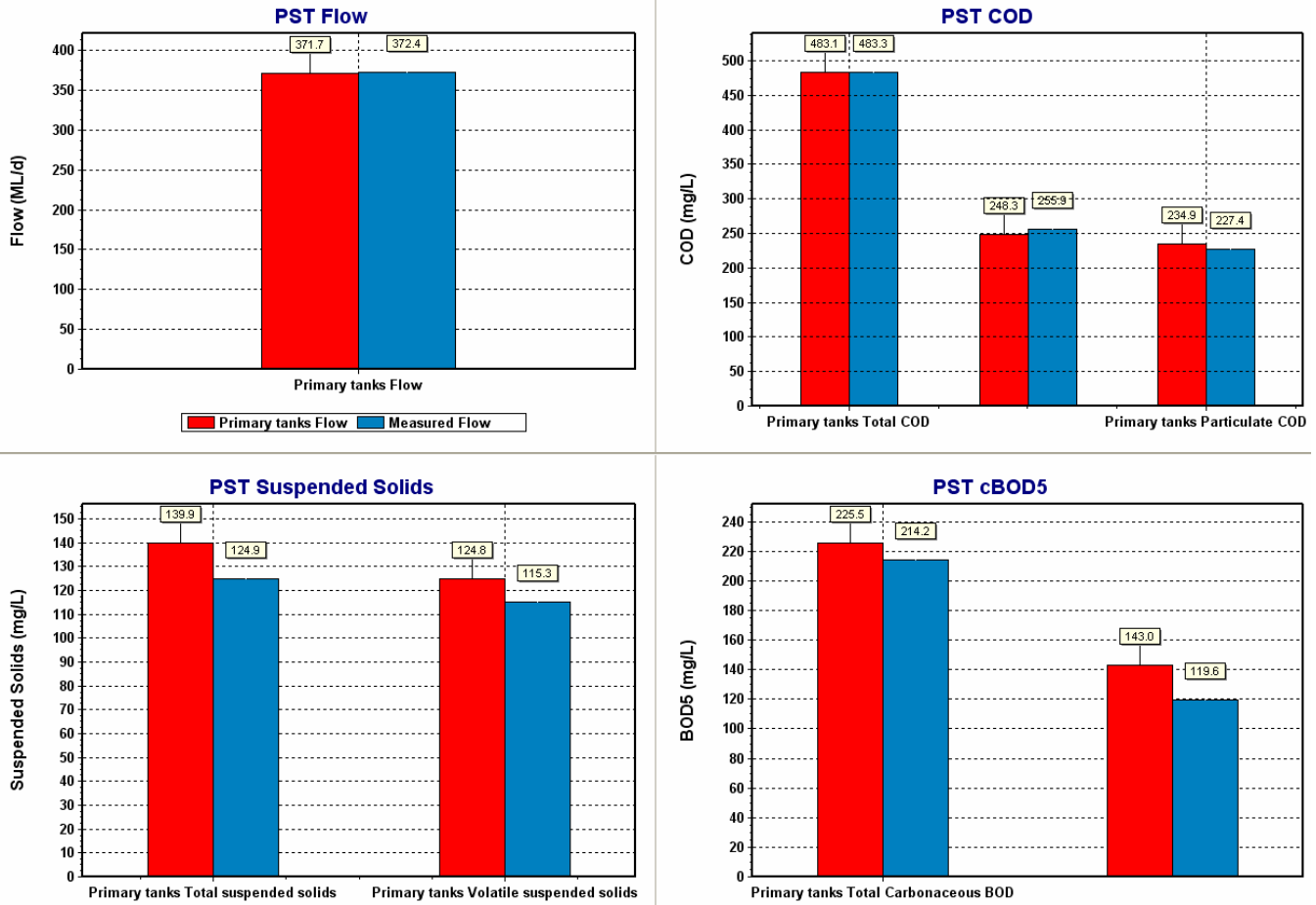
Figure 6 shows a comparison between model and sample data for the raw wastewater and the primary tank effluent.

Figure 6: Raw wastewater and mixed influent comparison



The wastewater from the PST, following settlement within the tanks, was also compared (7). These graphs show that the accuracy of the predicted model was very high.

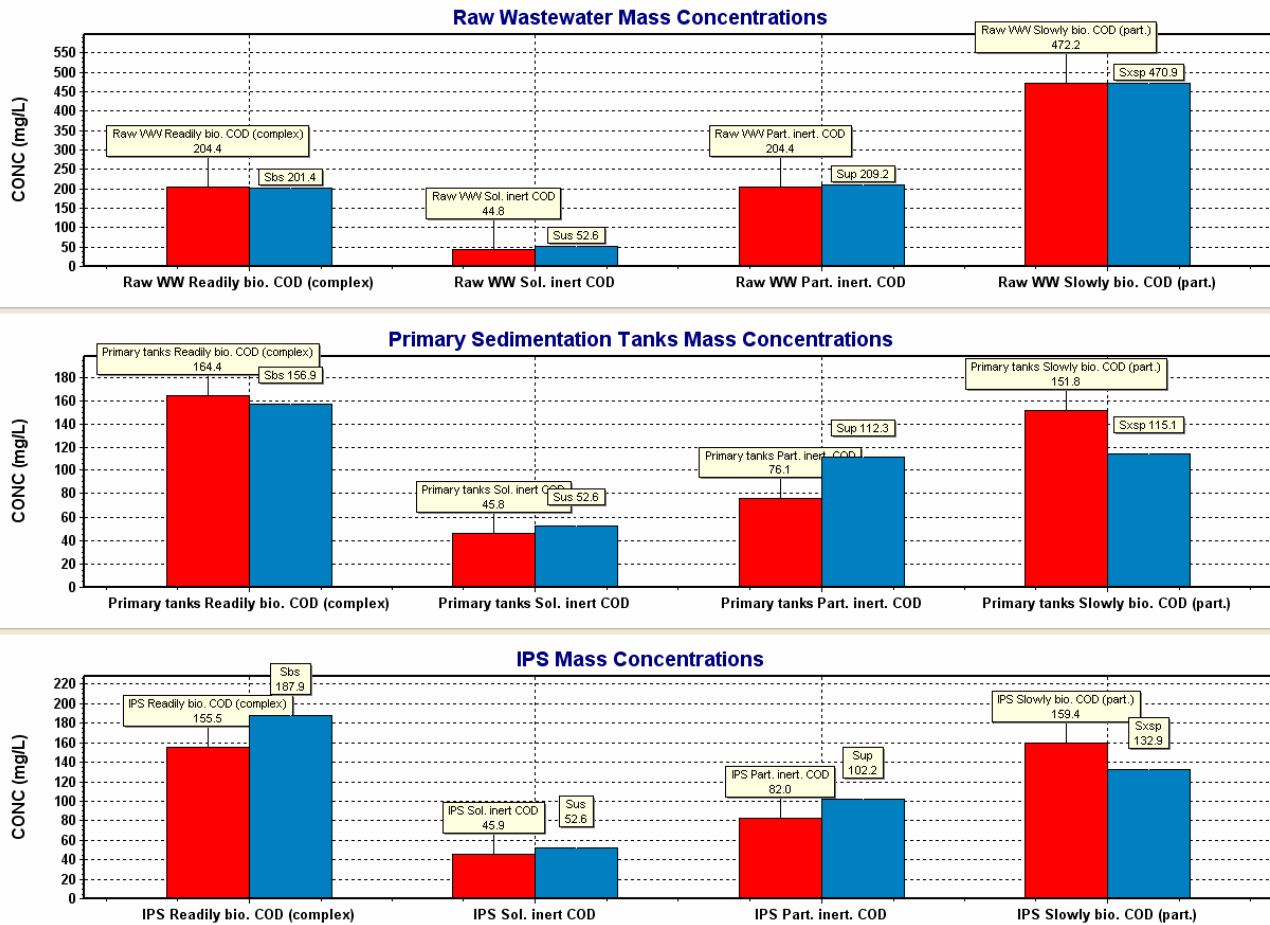
Figure 7: Liquid stream from PST prior to mixing in the IPS



3.1 FRACTION COMPARISONS

Figure 8 shows the comparison of mass fractions calculated from the measured values and predicted by BioWin. For the incoming wastewater the differences between predicted and measured fractions is very small. However, variations in the PST and IPS streams are more significant. Within the PST and IPS this can be traced back to the uncertainty with the predicted cBOD concentrations. Increased cBOD increases the amount of slowly biodegradable substrate available and decreases the inert COD fractions.

Figure 8: Predicted and measured mass fraction comparisons



4 APPLICATION

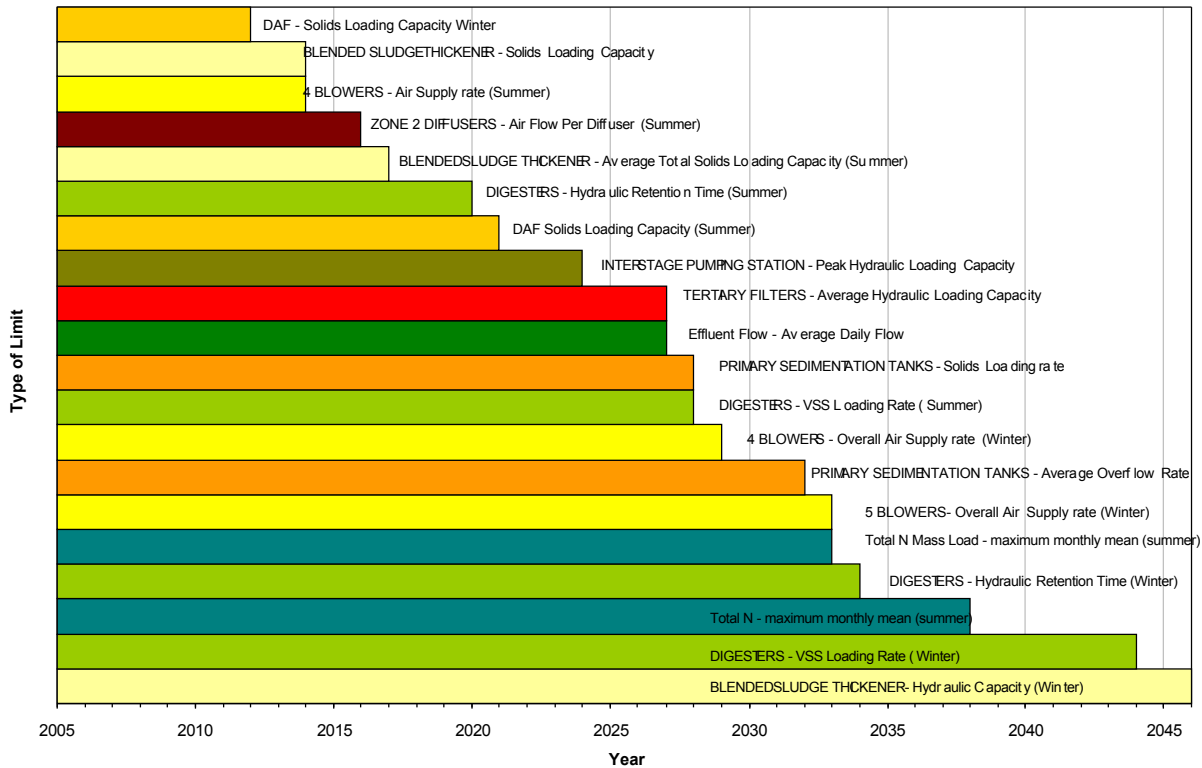
The calibrated BioWin model was sought after to enable its assistance with asset management and operations decision-making. Watercare was familiar with the application of modelling to other parts of the business, and the importance of calibration and also validation was recognised from this experience. Fundamentally:

- A model without calibration is a fantasy-world view, and is useful for demonstration of concept only
- A calibrated model without validation is an invalid real-world view and is useful for proof of concept
- A calibrated, validated model is a valid real-world view and is useful for future prediction

4.1 ASSET MANAGEMENT USE

Watercare applied the calibrated model to prove the concept of capacity limit prediction within the Mangere WWTP. The results generated by this application allowed Watercare to reprioritise the assets under review for future expansion to meet expected growth in the wastewater catchments. It is now planned to periodically repeat the concept of capacity limit prediction using BioWin. The model may evolve and be updated to reflect significant plant or process changes, and if so re-calibration will be required ahead of the next capacity review.

Figure 9: Predicted process limits from capacity modelling in BioWin and Excel



4.2 OPERATIONS USE

Watercare also applies the calibrated model to test the whole-plant effect of proposed process changes and refinements. As discussed above, there are significant effects on downstream processes from altering the activated sludge process, and due to the plant recycles, there are significant upstream effects as well. It is very difficult to evaluate these effects without trialling and testing, which is expensive, slow and risky compared to evaluation using a calibrated model. The model may not predict accurately without being validated, but it does highlight what needs to be checked out from an operational view, and provides sufficient guidance to determine whether the modification is a good idea for Watercare to pursue.

4.2.1 STRUVITE DEPOSITION

One concrete example of this is struvite deposition on equipment from the WAS. Prior to the BioWin model, the quantities of struvite that were deposited on the inside of certain pipes and tank walls were known to be at nuisance levels. Measurement after the various cleans indicated that there was hundreds of tonnes per year, although the measurement was prone to error because the deposition was not uniformly struvite, and the deposition was scattered during clean-up. It was observed that a significant proportion of the struvite that was produced was not deposited at all, instead exiting the process as biosolids.

The BioWin model predicted that there was thousands of tonnes of struvite produced per year, and has led to an evaluation (in progress) of whether there is an opportunity for process improvement to either eliminate or extract the struvite before it becomes a nuisance.

4.2.2 REACTOR TUNING

In a related application, the activated sludge process is designed to remove nitrogen, and it is believed that unexpected "luxury uptake" of phosphorus provides the substrate for struvite formation. The reactors are configured as step feed, with four anoxic and four aerobic zones interspersed with each other prior to clarification. The consent for discharge to the harbour carries a condition that the plant will limit total nitrogen, so any scarcity of COD for the nitrifying and denitrifying bacteria threatens this.

Watercare plans to use the BioWin model to investigate minor reconfigurations to the reactors to limit phosphorus uptake and maximise nitrogen removal to meet consent. The calibrated BioWin model, as mentioned above, predicts significant struvite formation from the WAS. It has been seen that “turning off” the phosphorus accumulating organisms (PAOs) reduces this, and therefore in its calibrated form, the model predicts phosphorus uptake in the reactor.

5 CONCLUSIONS

A calibrated full plant model of the Mangere wastewater treatment plant has been developed using the methods and protocols developed by WERF. In particular the intensive sampling and SBR protocols were used to build the calibration. The complexity of the treatment process and the interdependence of the unit processes meant that a large number of samples and analyses were needed around the plant to establish the calibrated wastewater fractions.

The model has been successfully used for future capacity planning and has been used for the investigation of struvite formation at the plant. The model is also being used by process controllers to evaluate “what if” scenarios and support process decisions.

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