Wastewater Treatment Optimization – Culling the Devil in the Details

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Abstract. Optimization of wastewater treatment facilities can result in achievement of desired efficiency at least cost along with the saving of the energy. In this study, three case studies of five wastewater treatment plants (WWTPs) in Ontario province of Canada have been presented. These WWTPs were monitored and their current operating conditions were analyzed using BioWin model. Optimization process revealed that reduced aeration tankage can be adopted for plants operating at capacities lesser than 70% and uncontrolled nitrification in the plants can cause complications resulting in high chlorine dosage.

1 Introduction

Non-optimal operation of Wastewater Treatment Plants (WWTPs) can lead to significant wastage of energy, non-compliance, high operational costs, and loss of treatment efficiency. Detailed analysis of a WWTP operation can reveal and help address these issues via optimization. The paper presents some common operational practices in wastewater treatment leading to the indicated issues, along with recommended good practices and remedial measures to address the same. The cases presented are based on process optimization projects completed by RVA on WWTPs in Southwestern Ontario.

2 Case Study #1 – Aeration Optimization

The WWTP in this case was a conventional activated sludge (CAS) plant with a rated capacity of 30,000 m^3/d. The plant was running at about 66% of its rated capacity at the time of this project. The plant was fully nitrifying and had no issues in meeting compliance with the effluent objectives. The aeration system at the plant operated with the blower speed controlled via VFDs based on DO set points. The objectives of the optimization study were to:

- Review the historic operational data of the WWTP with focus on air consumption, operating DO trends and aeration energy consumption;
- Identify opportunities for optimization of aeration; and
- Recommend measures to optimize the aeration energy use.

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2.1 Process Analysis

Plant recent historic data was used to prepare a roughly calibrated model of the plant. The model was prepared to establish the current average operating conditions and identify aeration-optimization opportunities. Table 1 gives a summary of the key inputs to the model, along with the key operating parameters and effluent quality predicted by the model. The model was roughly calibrated with all key operating parameters and the effluent quality matching or approximating the field data.

Table 1. Summary of the WWTP operation - Biowin model

Parameter	Unit	Value	Remarks
Input based on historic plant data			
Average day flow	m^3/d	20,000	
$cBOD_5$	mg/L	135	
TSS	mg/L	160	
TKN	mg/L	24	
Air supply rate	m^3/h	6,250	22% more than biological requirement
SRT	d	19	90% more than typical range of 8–12 d
BioWin output			
Aeration tank MLSS	mg/L	2,500	Matches field value
Aeration tank DO	mg/L	3.8	90% higher than the recommended 2 mg/L
Effluent $cBOD_5$	mg/L	1.9	Approximates field average
Effluent TSS	mg/L	3.9	Matches field value
Effluent Ammonia-N	mg/L	0.36	Matches field value

The following observations were made about the operation based on the BioWin model.

- Although the aeration tank MLSS of 2,500 mg/L was typical of a nitrifying plant in Ontario, operation with full aeration tankage at 66% of design flow corresponded to an SRT of 19 d which was significantly higher than the typical SRT range of 8–12 d used to meet the nitrification criteria in Ontario.
- The operating aeration tankage corresponded to an HRT of 20 h at the current average day flow of 20,000 m^3/d.
- The model was configured with an air supply rate of 6,250 m^3/h based on the average air consumption reported in the plant data. The aeration tank DO of 4 mg/L indicated by the model at this air supply rate was close to the average DO levels in the plant, and was indicative of the high DO range of 8–10 mg/L in the final effluent.
- The air required for biological BOD removal and nitrification was found to be approximately 4,600 m^3/d by setting the DO set point in the model to 2 mg/L.
- Theoretical mixing air requirement based on the MOECC guidelines was approximately 8,000 m^3/h. However, adequate mixing achieved with 6,250 m^3/h of air, indicated its sufficiency for at full tankage.

- Taking 6,250 m^3/h as the mixing air requirement with the full aeration tankage in operation, the mixing requirements at reduced aeration volumes was extrapolated and plotted as indicated in Fig. 1.

2.2 BioWin Analysis with Half Aeration Tankage

From the analysis of the plant's current operation it was evident that the usage of 100% aeration tankage at the current plant flow was non-optimal as it potentially led to significant excess use of aeration energy without providing any treatment benefit.

Desktop analysis indicated that shutting down 50% of the tankage would still provide an HRT of 10 h at the current average flow, which is more to the typical HRT range of 6–8 h required for nitrifying plants. To predict the plant performance and operational parameters, the volume of the aeration tankage was reduced to 8,350 m^3 in the BioWin model, and the model was run at an SRT of 10 d, and a DO of 2.0 mg/L. Table 2 gives a summary of the key inputs to the model, along with the key operating parameters and effluent quality predicted by the model.

Table 2. Predicted operation with half aeration tankage

Parameter	Unit	Value	Remarks
Modified input parameters of calibrated model			
Aeration tank volume	m^3	8,350	50% tankage in operation
SRT	d	10	Within the typical range of 8–12 d for nitrification
Aeration tank DO	mg/L	2.0	Typical operating value
Output of the reconfigured model			
Aeration tank MLSS	mg/L	2,500	Same as with 100% tankage in operation
Aeration tank MLVSS	% of MLSS	61	
Air supply rate	m^3/h	4,628	25% less than with full tankage in operation
Effluent $cBOD_5$	mg/L	1.9	
Effluent TSS	mg/L	3.9	
Effluent Ammonia-N	mg/L	0.54	

The following observations were made based on the predicted operating and performance parameters:

- The air demand at 50% aeration tankage is 4,600 m^3/h, which is 36% lower than the current average air consumption of 6,250 m^3/h at 100% tankage. Figure 1 represents the first optimization opportunity where the air demand is reduced by reducing the aeration tankage in operation. Conventional systems are typically operated below the critical volume i.e. where the mixing requirements are less than the biological demand.

- The operation with 50% tankage at MLSS concentration of 2,500 mg/L would enable maintenance of the 10 d SRT for nitrification without increasing the solids loading rate to the secondary clarifiers. As such all operating parameters and effluent quality would remain unchanged with this change in operation.
- At 50% tankage, the mixing air requirement would be 3,125 m^3/h which is 33% lower than biological air demand of 4,650 m^3/h. This gap between the two requirements would provide further optimization opportunity via DO and ammonia based aeration control.

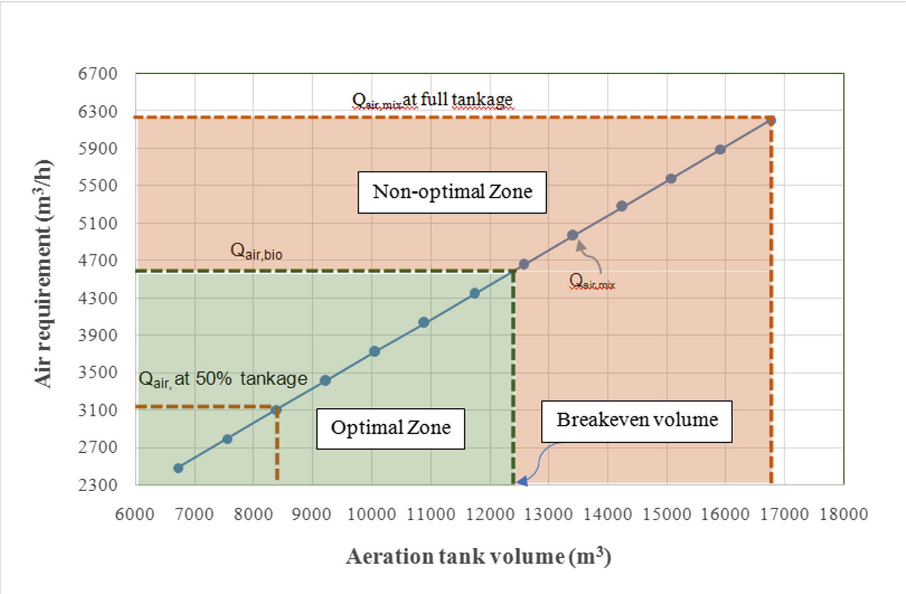

Fig. 1. Optimization via reduction in aeration tankage

2.3 Optimization Measures

Based on the above analysis, it was recommended to operate the WWTP with 50% aeration tankage at the current flows. and increase the tankage incrementally as the flows and loadings increase in future. In addition, since the existing blowers at the plant were too big to be turned down to the required airflow with reduced tankage, replacing the existing blowers with smaller blowers was recommended.

3 Case Study #2 – Uncontrolled Nitrification

The objective of this study was to review the existing chlorination/dechlorination systems at three (3) WWTPs of a Regional Municipality. The systems were to be reviewed in terms of their adequacy for the current and design flows, compliance with the MOECC guidelines, provide recommendations to optimize the processes, and addressing deficiencies if any. The analysis performed on the WWTPs considered operation of the liquid trains, effluent characteristics and requirements, and the design and operating parameters of the disinfection facilities.

While all three systems were observed to be adequate for the design flows and compliant with the MOECC guidelines (barring minor discrepancies), a major anomaly was found with regards to exceptionally high chlorine dose at one of the plants (Fig. 2). The said plant, indicated as Plant 2 in Fig. 2, had a chlorine dose ranging from 30 to 60 mg/L which was up to twenty (20) times higher than the doses at Plants 1 and 3 with typical chlorine doses.

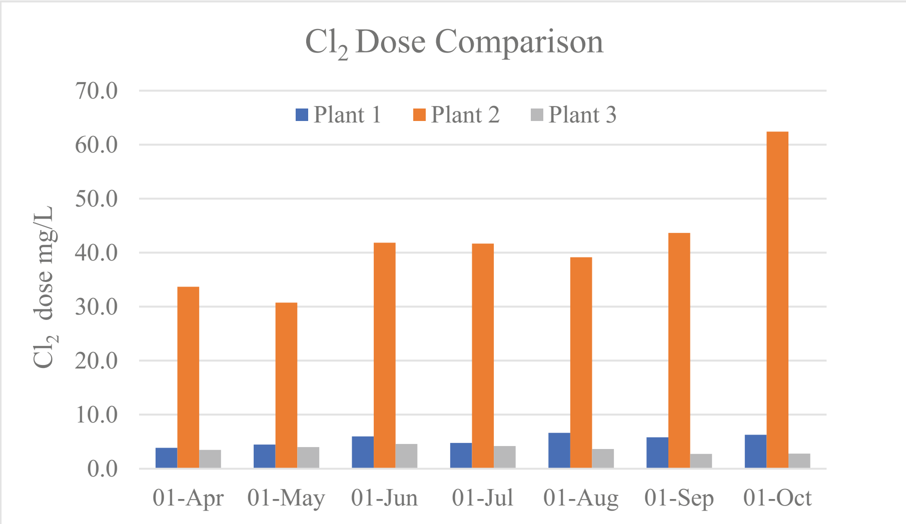

Fig. 2. Chlorine dose comparison at the three WWTPs

3.1 Process Analysis

The reason for this anomaly was found via analysis of the liquid train operation of Plant 2. Since the influent characteristics at all three (3) plants were similar, the reason for the exceptionally high dose was thought to lie in the process of the liquid train. The effluent criteria for Plant 2 indicated that the plant is not required to nitrify. However the plant was being operated at an SRT of 15 d. The aeration tanks were mechanically aerated with the DO consistently below 1 mg/L in the summer months, and dropping to 0.5 mg/L in some months (Fig. 3) with several days recording as low as 0.2 mg/L. While the high SRT and high temperature in summer encourages nitrification, the low DO is known to inhibit nitrite oxidizing bacteria (NOB) in the nitrification process. As such, the Nitrites tend to accumulate in the process under such conditions.

A roughly calibrated BioWin model was prepared for Plant 2 based on the available historic data. When the model was run at a low DO and high temperature observed in the summer months, it predicted Nitrites increasing to as high as 18 mg/L in the effluent at DO of 0.2 mg/L, which confirmed the hypothesis of partial nitrification. With Nitrites having a high chlorine demand of 5 mg/L for oxidation, 18 mg/L of Nitrites in the effluent indicated a Chlorine demand of 90 mg/L, resulting in the high chlorine dose range of 40–60 mg/L observed at Plant 2.

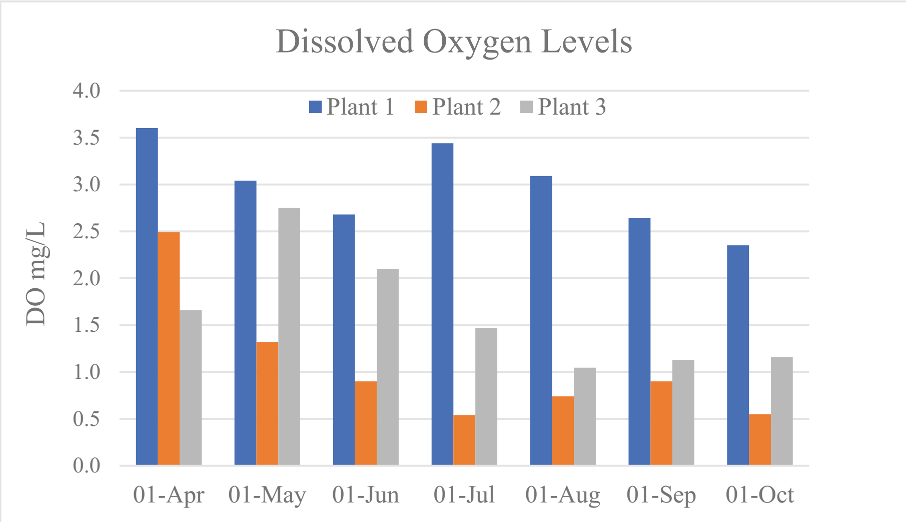

Fig. 3. Aeration do levels at the three WWTPS

3.2 Optimization Measures

Based on this finding, the following recommendations were made to prevent uncontrolled nitrification leading nitrite accumulation and high chlorine doses.

3.2.1 Reduce SRT to 4–6 d Range

This could be achieved by reducing the mixed liquor suspended solids (MLSS), or using less aeration volume. Reduction in SRT to this range would reduce aeration demand due to reduced endogenous respiration that occurs at high SRTs. This would help maintain a higher DO in summer, which would mitigate inhibition of the NOB and the resulting Nitrite accumulation in the system. It was also realized through BioWin that nitrification could not be prevented by reducing the SRT to the above range, as it would occur even at an SRT as low as 3 d at summer temperatures close to 20 °C. As such the recommendation was to have the nitrification occur in a predictable and controlled manner as opposed to trying to prevent it, and still have it occurring in an uncontrolled manner in summer months.

3.2.2 Improve DO

While the reduced SRT would mitigate the aeration demand to some extent, it was determined through desktop and BioWin analysis that this measure will not fully resolve the partial/uncontrolled nitrification issue on its own. As such additional air would be required to ensure a DO of 2 mg/L in summer months. This was recommended to be achieved by switching from mechanical aeration to fine bubble aeration.

4 Case Study #3 – Nutrient Limitation

In this case, the Municipality had a high rate activated sludge plant with a rated capacity of 79,000 m^3/d. The WWTP had the capability to reduce total suspended solids (TSS) and biological oxygen demand ($cBOD_5$). The WWTP had no effluent limit for total phosphorous (TP) and total ammonia nitrogen (TAN) but had objectives to maintain TP and TAN less than 0.5 mg/L and 7 mg/L respectively. See Table 3 for details.

Table 3. Effluent criteria

Parameter	Unit	Objective	Limit
$cBOD_5$	mg/L	15	25
Total suspended solids	mg/L	15	25
Total phosphorus	mg/L	0.5	–
Total ammonia nitrogen	mg/L	7.0	–

Historically the plant had no compliance issues. However, two months preceding this study the operating staff had started observing frequent operational issues concerning exceedances of effluent compliance limits for TSS and $cBOD_5$. These issues were observed to coincide with a change in the solids train process and introduction of solids side-streams and septage loads to the liquid train. General observations about these issues by the plant operations staff included:

- High effluent BOD_5 and TSS, with occasional exceedances of both parameters;
- Aeration tanks nearly black and septic, with DO ranging between 0.06 and 0.5 mg/L;
- Poor sludge settleability with the sludge volume index (SVI) of 150–200 mL/mg; and
- Foam in the aeration tanks.

The objective of this study was to investigate and review the biological process at the plant and identify the potential operational issues leading to non-compliance.

4.1 Process Analysis – Base Loading

A BioWin Model was generated for the WWTP to determine its approximate operating conditions and identify any potential performance or capacity issues at base loading, i.e. without the extraneous and side-stream loads. The model was approximately calibrated to match the field effluent quality and operating conditions. For calibration, the settling parameters of the clarifier model were adjusted to match the predicted effluent TSS value with the field value. In addition, the ferric dose was set at 100 L/d to approximately match the field TP value. Table 4 summarizes the historic average influent and effluent characteristics of the Plant without the side-stream and extraneous loads. Table 5 gives the operating conditions of the plant at base loading and Table 6 compares the key effluent parameters observed in the field with predicted by BioWin.

Table 4. WWTP performance data – base scenario

Parameter	Unit	Influent	Effluent
Flow	m^3/d	77,153	75,331
$cBOD_5$	mg/L	129	15.2
Total suspended solids	mg/L	153	18.5
Total phosphorus	mg/L	2.84	0.73
TKN	mg/L	23.5	14.9
Total ammonia nitrogen	mg/L	14.7	14.7

Table 5. Base scenario operating parameters - field versus BIOWIN

Parameter	Unit	Value		Remarks
		Field	BioWin	
Input parameters of calibrated model				
SRT	d	2.8	2.8	
DO	mg/L	1.5	1.5	
Ferric	L/d	1800	100	Adjusted to match effluent TP
RAS flow	m^3/d	38,576	38,576	Ok. Less than firm RAS pumping capacity of 140,000 m^3/d
Output parameters of calibrated model				
MLSS	mg/L	1,700	1675	Ok
Air supply	m^3/h	11,000	11,000	Ok. Less than aeration capacity of 13,087 m^3/h
Surface overflow rate (SOR)	m^3/m^2-d	14	14	Ok. Less than the lower limit recommended range of 16–28 (Metcalf Eddy)
Solids loading rate (SLR)	kg/m^2-d	36	36	Ok. Less than the lower limit recommended range of 96–144 (Metcalf Eddy)

Table 6. Effluent quality under base loading - field versus BIOWIN

Parameter	Unit	Effluent	
		Field	BioWin
$cBOD_5$	mg/L	15.2	10
Total suspended solids	mg/L	18.5	18.5
Total phosphorus	mg/L	0.73	0.66
Total ammonia nitrogen	mg/L	14.7	13.0

The following observations were made from this analysis:

- The required air supply at base loads was 84% of the firm aeration capacity, and maintained DO of 1.5 mg/L.
- All effluent quality parameters apart from $cBOD_5$ predicted by the calibrated BioWin model were close to the field values. The field $cBOD_5$ value was 50% higher than the one predicted by BioWin despite identical effluent TSS values in the field and those predicted by BioWin.
- Effluent TSS value of 18.5 mg/L with 74% VSS translated into approximately 9.7 mg/L particulate $cBOD_5$. This left a soluble $cBOD_5$ concentration of 8.7 mg/L in the effluent, which was significant.
- Ferric dose in the field is 15 to 20 times higher than predicted by BioWin and desktop calculations.

4.2 High Ferrous Dose and Phosphorus Limitation

The calibrated BioWin model was run with no Ferric addition to determine Phosphorus removal via biomass assimilation. The model predicted 188 kg/d of TP removed via biomass assimilation (sum of TP in waste sludge and effluent TSS) out of an influent load of 216 kg/d. This translated into 28 kg/d or 0.36 mg/L of soluble P in the effluent TP concentration of 0.71 mg/L. This value was very close to the field value of 0.73 mg/L observed in 2014. This meant that the effluent TP levels at base loading could be achieved without addition of any Ferric to the system, indicating that the high Ferric dose in the field potentially limited soluble P availability to the cell mass for oxidation of the BOD and synthesis of cell mass. It was inferred from this analysis that P limitation was the reason of high effluent $cBOD_5$ values observed in the effluent in spite of lower TSS values. In addition, since Phosphorus deficiency is a known cause of sludge bulking and even foaming in the aeration tanks, this condition was also potentially responsible for relatively poor sludge settleability and high effluent TSS despite the secondary clarifiers operating within the design guidelines for SOR and SLR.

4.3 Performance with Side Stream Loads

The performance of the plant with side-streams in the field was observed for two months prior to the study. Table 7 shows the average flow and characteristics of the

Table 7. Blended wastewater flow and characteristics

Parameter	Unit	Value
Low	m^3/d	60,000
$cBOD_5$	mg/L	197
TSS	mg/L	189
TKN	mg/L	32.6
TP	mg/L	2.6

Table 8. Operating parameters with side-streams

Parameter	Unit	Value	Remarks
SRT	d	3.0	
MLSS	mg/L	2,131	
DO	mg/L	0.06–0.75	Wide range in all 4 cells. Near anoxic conditions in most cells
Ferric	L/d	2,400	High, especially with potential phosphorus limiting conditions

Table 9. Observed effluent quality with side-streams

Parameter	Unit	Value
$cBOD_5$	mg/L	20.5
Total suspended solids	mg/L	31.5
Total ammonia nitrogen	mg/L	19.0
Total phosphorus	mg/L	0.39

blended wastewater observed during these months. Tables 8 and 9 summarize the operational parameters of the WWTP and average effluent quality during these months.

4.4 Process Analysis with Extraneous and Side-Stream Loads

- The effluent TSS was high despite the SOR and SLR in the secondary clarifiers being well below the design guidelines. This indicated poor sludge settleability. High effluent TSS was also a contributing factor to high effluent $cBOD_5$.
- Influent $cBOD_5$ of 197 mg/L translated into a bCOD of 315 mg/L. At this bCOD and the recommended bCOD to TP ratio of 100:1, the required TP concentration to carry out $cBOD_5$ removal is approximately 3.15 mg/L for aerobic biological treatment. However, the influent TP of 2.6 mg/L indicates that the biological system was P limited to start with. Phosphorus deficiency was another key reason for BOD_5 spikes in effluent as the inadequacy of phosphorus prevents complete removal of $cBOO_5$ from the influent.
- With the effluent TSS of 31.5 mg/L and typical effluent TSS carrying 2% P, the effluent particulate P was predicted to be approximately 0.63 mg/L. The observed

effluent TP value of 0.39 mg/L indicated that the effluent TP was entirely constituted of particulate P, i.e. all soluble P had been consumed by the biological system leading to a P limited biological system.

- Phosphorus limitation is also known to cause viscous bulking which contributed to high effluent TSS. Such bulking is known to be caused by extracellular polymeric substances (EPS) that get accumulated around the cell mass and reduce its settleability. This type of bulking is usually accompanied by whitish foam which was a common occurrence at the plant.
- Low DO in the aeration tanks further worsened the above conditions, as filamentous organisms are known to proliferate under low DO and nutrient limiting conditions.
- Poor sludge settleability was confirmed by the high average SVI value of 180 mL/g, which on several days during the observation period exceeded 200 mL/g.
- Considering the solids lost in effluent, the biological system operated at an effective SRT of about 2.6 d during this period. In addition to the low DO and nutrient deficiency, low SRT could be another contributing factor towards sludge bulking.

4.5 BioWin Analysis for Process Issues

BioWin modeling was used to confirm the Phosphorus limitation issue identified above in the desktop analysis. The influent flow and characteristics in the base model were modified based on the actual flow and characteristics of the blended influent indicated in Table 7. The air supply was set at 9,200 m^3/h, simulating the field conditions indicated by the operating staff. All remaining input operating parameters including SRT, DO, Ferric dose and settling characteristics were kept unchanged in the base model.

The influent TP concentration of 2.6 mg/L was observed to generate an alarm of "Phosphorus limitation in aeration tank". The model was subsequently run by increasing the influent TP concentration in the model by increments of 0.05 mg/L above the field value until reaching a critical concentration of 3.0 mg/L that did not generate the above alarm. This concentration is close to limiting phosphorus concentration of 3.15 mg/L predicted in desktop analysis. Table 10 compares the effluent quality observed in the field to that predicted by BioWin at Influent TP concentration of 3.0 mg/L (critical concentration) and 2.95 mg/L (just below the critical TP concentration).

Table 10. Influent phosphorus impact on effluent quality

Parameter	Unit	Value		
		Field	BioWin TP 2.95 mg/L	BioWin TP 3.0 mg/L
$cBOD_5$	mg/L	20.5	28.5	12.3
Total suspended solids	mg/L	31.5	19.0	19.1
Total ammonia nitrogen	mg/L	19.0	20.6	20.4
Total phosphorus	mg/L	0.39	0.34	0.36

Following key observations were made from the BioWin Model predictions:

- At influent TP of 3.0 mg/L, the effluent $cBOD_5$ of 12.3 mg/L is well below the field value of 20.5 mg/L. However, by a small decrease of 0.05 mg/L in the influent TP concentration, the effluent $cBOD_5$ increases sharply to 28.5 mg/L and even exceeds the field value. This clearly shows that the biological system performance is highly sensitive to adequacy of phosphorus in the influent and TP concentration marginally below the critical TP value can trigger a sharp drop in $cBOD_5$ removal.
- The aeration tank DO at the configured air supply of 9,200 m^3/h was 0.13 mg/L which is in the low range observed in the field. Increasing the air supply in the model to the system capacity (13,000 m^3/h), the DO increases to 2 mg/L, but the "phosphorus limitation" alarm was generated again. This indicated that increasing the air supply switches the aeration tank operation from near anoxic mode (DO at 0.13 mg/L) to oxic mode (DO more than 1.0 mg/L), which leads to higher TP assimilation by the biomass, thereby causing phosphorus limitation. At the same time, effluent $cBOD_5$ increased due to phosphorus limitation. The influent TP had to be adjusted to 3.25 mg/L to remove the P limitation alarm, and bring the effluent $cBOD_5$ to a normal level (below 15 mg/L). However, since the soluble BOD_5 is fully removed at TP of 3.25 mg/L, the aeration tank DO dropped to 1.0 mg/L under these conditions. In summary, the WWTP with its current aeration capacity could provide up to 1.0 mg/L of DO when operating with the side stream loads, provided there was no phosphorus limitation.
- The effluent TSS values predicted by BioWin were well below the field values. The higher field values in the field were likely due to deterioration the sludge settleability (caused by phosphorus deficiency and low DO), which was not factored in the configured model.

4.6 Optimization and Remedial Measures

Given below is the list of optimization measures recommended to address the process issues.

Optimize Ferric dose by

- Including measurement of soluble P in influent and effluent in the regular monitoring plan of the plant;
- Optimizing the Ferric dose to maintain a minimum soluble P concentration of 0.1 mg/L in the effluent; and
- Reducing the Ferric dose in the influent by decrements of 25% and monitoring soluble P in the effluent, and continuing with the process until around 0.1 mg/L of soluble P is achieved in the effluent.

Optimize Influent Phosphorus by

- Addition of phosphorus to the influent if the residual soluble P of 0.1 mg/L is not achieved by even with complete stoppage of Ferric dose.
- Phosphorus could be added in the form of $NaHPO_4$. Soluble P in the effluent should be observed daily and the influent Phosphorus dose increased in increments of 5 kg/d until a soluble P of 0.1 mg/L is observed in the effluent

Increasing DO the Aeration Capacity by

- Running the existing blowers at their rated capacity; and
- Replacing one or more blowers with higher capacity blower(s) and enable the aeration system to maintain a DO of 2 mg/L at design loads.

5 Key Optimization Lessons

- Larger aeration tanks are not necessarily better and can lead to significant wastage of energy if the mixing requirements are higher than the biological aeration demand. Existing plants with significantly less flows (less than 70%) than their rated capacity are good candidates for aeration optimization via reduced aeration tankage. Before implementing this measure however, the process impacts with regards to maintenance of viable SRT for nitrification and the loading on the secondary clarifiers should be checked for all loading conditions.
- Uncontrolled nitrification in plants with no limit for total effluent ammonia (TAN) can cause complications with control of chlorination based disinfection, and lead to exceptionally high doses of chlorine due to Nitrite accumulation in the effluent. Operating strategy of running at low SRT of 3–4 d to limit nitrification and reduce aeration requirement does not work under all conditions, as nitrification occurs even at such low SRTs in the summer months. Since the system is not equipped to provide the additional air for nitrification, the DO in the aeration tanks drops to levels which would cause partial nitrification (nitritation) with resulting accumulation of nitrites in the effluent. Apart from the explained issues due to nitrite accumulation, the low DO can also lead to sludge bulking and effluent compliance issues. As such, plants with no TAN criteria should design their aeration systems for full nitrification nonetheless so they have enough air to provide for spontaneous nitrification in summer, and thereby prevent the above issues due to uncontrolled nitrification.
- The biological process for BOD removal and nitrification requires a minimum dose of phosphorus to carry out these processes, failing which the process can suffer from inefficient BOD removal, sludge bulking and other associated issues. The ratio of BOD to be removed and the minimum phosphorus required for that must be analyzed to ensure that sufficient phosphorus is available. The metal addition for TP removal is only required when available phosphorus is more than the biological requirement. Monitoring and maintaining a minimum reactive P level of 0.1 mg/L in the effluent ensures that the biological process is not P limited.

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