Designing a State-of-the-Art BNR Facility for Salt Lake City

Beverley Stinson[1], Michelle Barry[2,] Damian Kruk[3], Gerry Stevens[4], Keith Sears[5]
[1] AECOM, Laurel, Maryland
[2] Salt Lake City, Department of Public Utilities, Salt Lake City, Utah
[3] NEXOM, Winnipeg, Canada
[4] AECOM Canada, Kelowna, British Columbia, Canada
[5] AECOM Canada, Winnipeg, Manitoba, Canada
[1]Email: Beverley.Stinson@aecom.com
[5]Email: Keith.Sears@aecom.com

ABSTRACT

Salt Lake City has recently begun the design process for a new state of the art biological nutrient removal (BNR) facility. Prior to selecting their design engineer, the City made the important decision of preselecting the BNR process configuration. The selection of the Modified Westbank BNR process as the preferred BNR approach is a reflection of the relevant academic and full scale research that show the benefits of this process compared to conventional BNR configurations. Unique to the Westbank process is the ability to grow enhanced populations of the genus Testrasphaera, which are known to provide efficient and reliable BNR treatment. The objective of this paper is to present the approach used to assess the sensitivity of the kinetic and stoichiometric parameters within the process modeling software Biowin™, to optimize the bioreactor zone sizing as applied to the Westbank configuration for the new Salt Lake City Water Reclamation Facility.

KEYWORDS

Process design, modeling, enhanced biological phosphorus removal (EBPR), biological nutrient removal (BNR).

INTRODUCTION & BACKGROUND

The existing Salt Lake City Water Reclamation Facility (SLCWRF) is more than 55 years old and is reaching the end of its useful life. Multiple structures and components do not meet current code requirements and require replacement. The Technology Based Phosphorus Effluent Limit (TBPEL), implemented by the Utah Department of Environmental Quality, Division of Water Quality (DWQ), requires Water Reclamation Facilities within the state of Utah to meet an annual average phosphorus effluent limit of 1 mg/L. Based upon these key drivers, Salt Lake City has decided to replace their existing trickling filter/activated sludge treatment process with a new, Modified Westbank BNR process. The process will meet the new phosphorus permit limits and is being designed to be “future-ready” for potentially more stringent nitrogen limits. The selection of the Modified Westbank BNR process as the preferred BNR approach is a reflection of the relevant academic and full scale research that show the benefits of this process compared to conventional BNR configurations. While the understanding surrounding the complexities of the enhanced biological phosphorus removal (EBPR) process is improving, it is not yet fully developed in process models. Modeling of the Westbank process using widely accepted design software does not accurately reflect full scale observations, and the accuracy of biological phosphorus removal as estimated by the Activated Sludge Model (ASDM) model has been questioned by other practitioners (Barnard, Dunlap, & Steichen, 2016; Dunlap et al., 2016), who note that this is especially the case for systems incorporating fermenters and increased anaerobic solids retention time (SRT).

In studies of several BNR facilities, Onnis-Hayden et al. (2018) indicated that the Westbank process had the lowest, most consistent effluent total phosphorus concentrations. The unique Westbank process configuration with a return activated sludge (RAS) only anaerobic zone supplemented with primary sludge fermentate provides deep anaerobic conditions (i.e. ORP < -250 mV) which promote the growth of the bacteria from Tetrasphaera genus (Nguyen, Le, Hansen, Nielsen, & Nielsen, 2011; Onnis-Hayden et al., 2018). In conventional enhanced biological phosphorus removal (EBPR) systems, where primary effluent is passed through the anaerobic zone, the main phosphorus accumulating organism (PAO) is believed to be *Candidatus* Accumulibacter (Crocetti et al., 2000; Hesselmann, Werlen, Hahn, Van Der Meer, & Zehnder, 1999). Although there is certain variability between the members of the Tetrasphaera genus, most of the species tested by Kristiansen et al. (2013) have two metabolic capabilities; (1) they can ferment complex organic compounds such as carbohydrates or amino acids, producing stored carbon or releasing volatile fatty acids (VFA);and (2) they can use nitrates/nitrites as electron acceptors in the process of phosphorus uptake. These two features result in an improvement in overall phosphorus removal due to their ability to uptake phosphorus earlier in the treatment process anoxic zones, something that *Cadidatus* Accumulibacter does not have the ability to do, and also to source various forms of carbon other than volatile fatty acids (VFAs) to be used for phosphorus release. Although not fully understood at the time, observations of high rates phosphorus uptake in the anoxic zones and higher phosphorus releases per unit of VFA consumed at the Westbank BNR facility in British Columbia by Stevens et al. (1999) can now be explained through the identification and functional diversity of the Tetrasphaera bacteria. Optimization of the Westbank process has now led to a RAS only anaerobic zone which offers an innovative alternative to address the low carbon to phosphorus ratio in influent wastewater, which can become a challenge in EBPR plants. Normally, a RAS only anaerobic zones requires up to a 24 hour retention time, however when supplementing VFA into this zone through the use of primary sludge fermenters, the required retention time can be reduced to less than 90 minutes. The use of a RAS only anaerobic zone with fermentate allows for all primary effluent to be directed to the denitrification stage of the process, enhancing overall total nitrogen removal.

Based on a long term set of data and model calibration from the original Westbank BNR facility in West Kelowna, BC, two sets of kinetic and stoichiometric parameters related to the phosphate accumulated organism (PAO) activity were developed, one by Dunlap et al (2016) and a second by Stevens et al (internal AECOM work, unpublished). The objective of this paper is to present the results of a sensitivity analysis of the kinetic and stoichiometric parameters of the PAO process in Biowin^{TM}, and the optimization of bioreactor volume and zone sizing when applied to the new Salt Lake City Water Reclamation Facility (i.e, New WRF).

SENSITIVITY ANALYSIS OF THE PAO MODEL

Methodology

In BNR facilities operated in a Westbank configuration, it appears the most significant discrepancy between actual operating observations and desktop modeling studies are related to the phosphorus profiles through the various bioreactor zones. This is an important consideration in design, as constructing bioreactor zone sizes too large or small can result in a significant deterioration of effluent quality. For example, in the Westbank process where carbon is used efficiently, oversizing anoxic zones can result in conditions that become anaerobic and lead to secondary phosphorus release which in-turn increases effluent phosphorus concentrations.

To better understand the modeling complexities, one-year of detailed analysis of all relevant parameters from a Westbank BNR facility located in Kelowna British Columbia was conducted. Data was collected three times per week, with an analysis of up to 50 sampling points a day were used as the basis to develop kinetic and stoichiometric parameters related to PAO activity (Steven et al, unpublished data). A model was developed using the software Biowin^{TM} representing the BNR facility (Figure 1), and used to compare the impact of the adjusting PAO related parameters on the model estimates versus the actual plant data. A sensitivity analysis for each of the parameters was conducted to get a better understanding of the overall impacts.

This was then compared to a set of PAO kinetic and stoichiometric parameters developed in a similar fashion by Dunlap et al (2016).

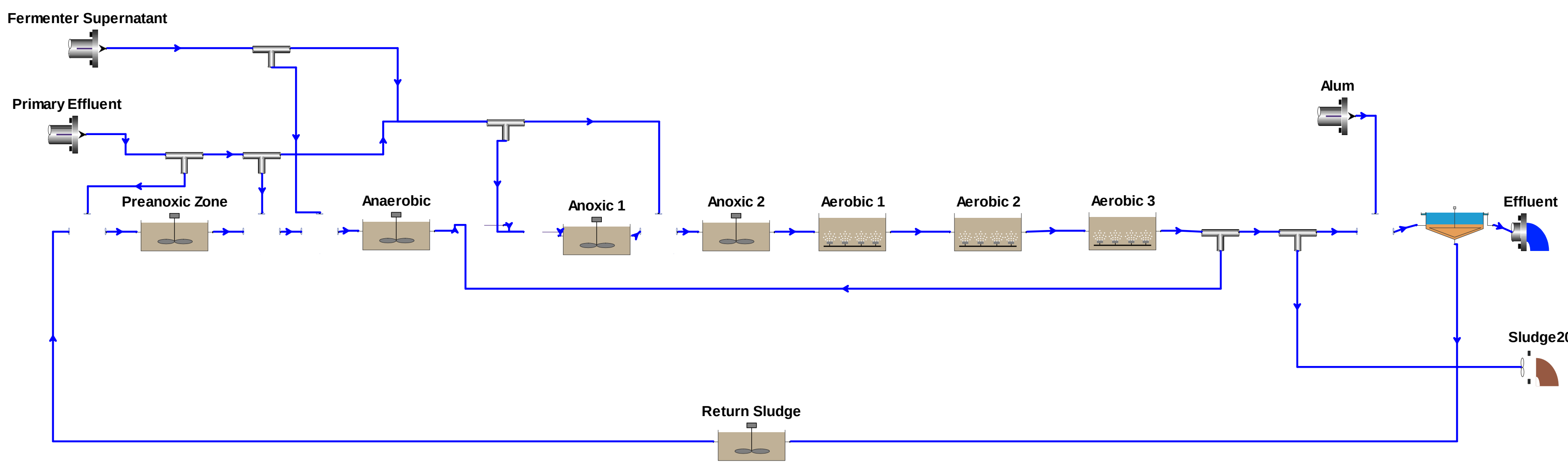

Figure 1. Biowin™ Model Flow Diagram Used for Westbank BNR Analysis

Results and Discussion

A summary of the kinetic parameters developed by Dunlap et al (2016) and this study are summarized in Table 1.

Table 1. Biowin^{TM} Adjusted PAO Related Process Parameters.

#	Adjusted Parameters	Unit	Default	AECOM	Dunlap Avg	Dunlap Range
1	PAO max spec growth rate	1/d	0.95	1.80	3.50	constant
2	Anoxic PAO growth rate factor	-	0.33	1.20	0.50	0.33-0.90
3	Anoxic P/PHA uptake ratio	mg P/mg COD	0.35	1.00	0.71	0.40-1.00
4	Aerobic P/PHA uptake ratio	mg P/mg COD	0.93	1.23	1.23	0.80-1.80
5	Anaerobic P/Ac release ratio	mg P/mg COD	0.51	0.56	0.56	constant
6	Hydrolysis rate factor (AS)	-	0.04	0.10	0.10	0.04-0.20

To understand the sensitivity of the various PAO related parameters are series of modeling runs were conducted and compared to the actual plant data.

PAO Maximum Specific Growth Rate

To understand the sensitivity of the PAO maximum specific growth rate, a series of modeling runs were conducted. The orthophosphate profiles through the various bioreactor zones illustrate the impact of adjusting these parameters. Figure 2 shows the sensitivity of the PAO maximum specific growth rate. It is apparent that the default value of 0.95/d for the PAO growth rate is too low as the model predicts lower uptake of phosphorus in the anoxic zones and an overall elevated aerobic zone orthophosphate concentrations. However, at a growth rate of 3.5/d as predicted by Dunlap (2016) the model over predicted the amount of phosphorus uptake in the anoxic zones. The best fit to the actual plant operating data occurred at a value of 1.8/d.

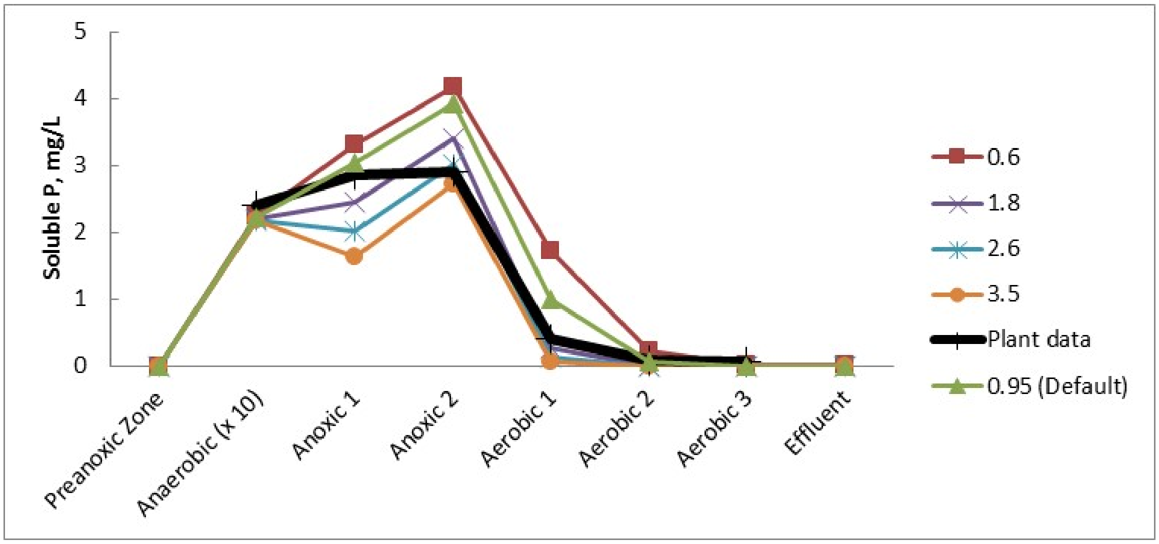

Figure 2. Impact of the PAO Maximum Specific Growth Rate on the Soluble Phosphorus Profile.

Note: concentrations in the anaerobic zone must be multiplied by 10 for the actual values.

PAO Anoxic growth factor

This parameter dictates the growth rate of PAO under anoxic conditions. The anoxic growth rate is calculated a product of the anoxic growth factor and the maximum specific growth rate. The impact of the PAO anoxic growth factor on the soluble phosphorus profile is presented in Figure 3. Based on these profiles, the model default value of 0.33/d results in a significant under prediction of the orthophosphate removal in the anoxic zones. Based on measurements from the BNR facility, the best fit occurred at a value of 1.2/d.

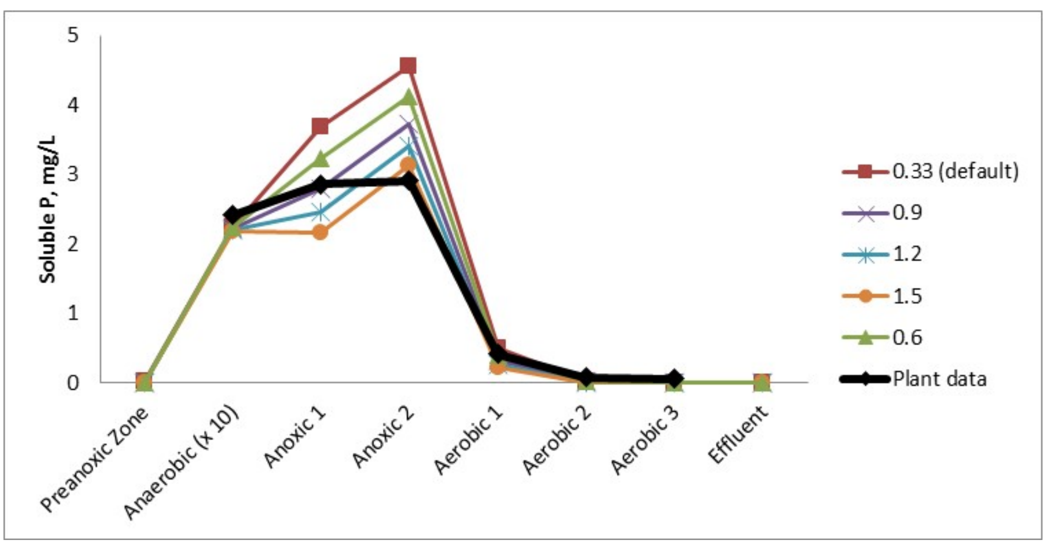

Figure 3. Impact of the PAO anoxic growth factor on the soluble phosphorus profile.

Note: concentrations in the anaerobic zone must be multiplied by 10 for the actual values.

P/PHA Anoxic Uptake Ratio

This parameter dictates the efficiency of phosphorus update under anoxic conditions. The ratio indicates how much phosphorus is picked up and stored in the PAO biomass per unit of utilized internal storage of polyhydroxyalkanoates. The impact of the ratio on the soluble phosphorus profile is presented in Figure 4. Similar to the anoxic growth rate factor, the default parameter of 0.35 over predicted the amount of orthophosphate in the anoxic zone. The best fit occurred at a ratio of 1.0.

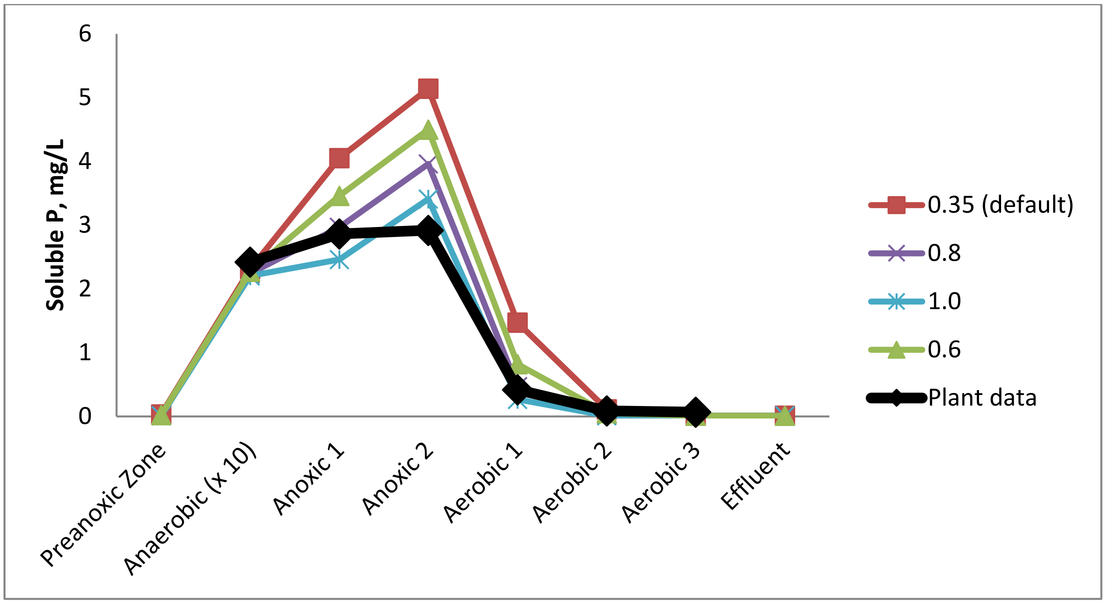

Figure 4. Impact of the P/PHA Anoxic Uptake Ratio on the soluble phosphorus profile.

Note: concentrations in the anaerobic zone must be multiplied by 10 for the actual values.

P/PHA Aerobic Uptake Ratio

This parameter dictates the efficiency of phosphorus update under aerobic conditions. The impact of the ratio on the soluble phosphorus profile is presented in Figure 5. Similar to the anoxic P/PHA the ratio had to be increased from the default value of 0.35 to 1.23 to match the observations from the full scale facility.

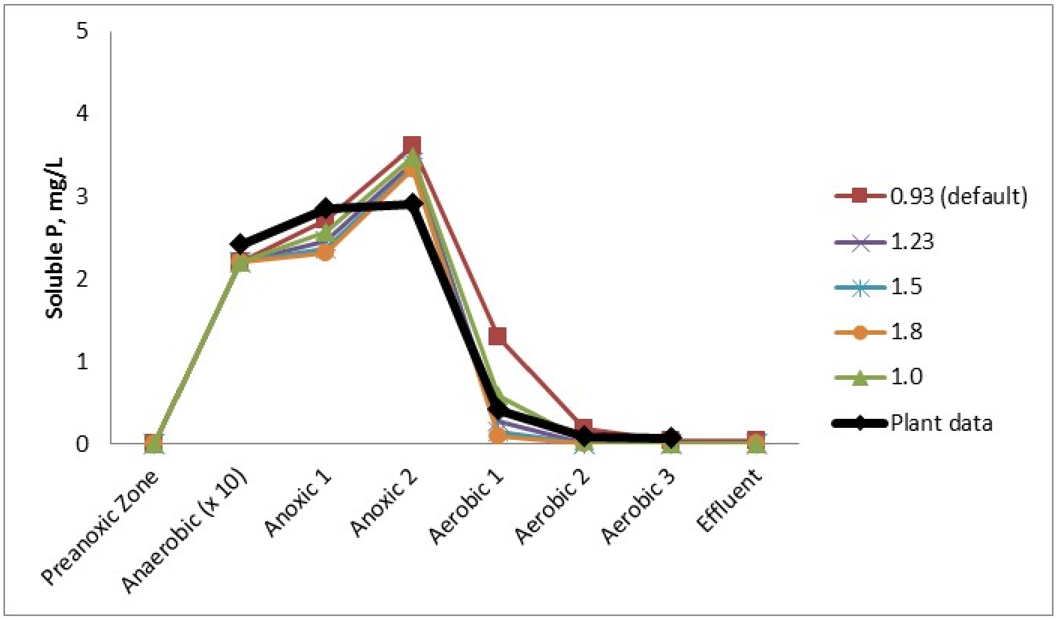

Figure 5. Impact of the P/PHA Aerobic Uptake Ratio on the soluble phosphorus profile.

Note: concentrations in the anaerobic zone must be multiplied by 10 for the actual values.

P/Ac Release Ratio

This parameter dictates the efficiency of phosphorus release. The ratio indicates how much phosphorus is released per unit of acetate express as COD. The impact of the ratio on the soluble phosphorus profile is presented in Figure 6. To match the full scale plant data, this parameter had to be increased from the default value of 0.51 to 0.56. Coincidentally, this was the same value derived by Dunlap et al (2016).

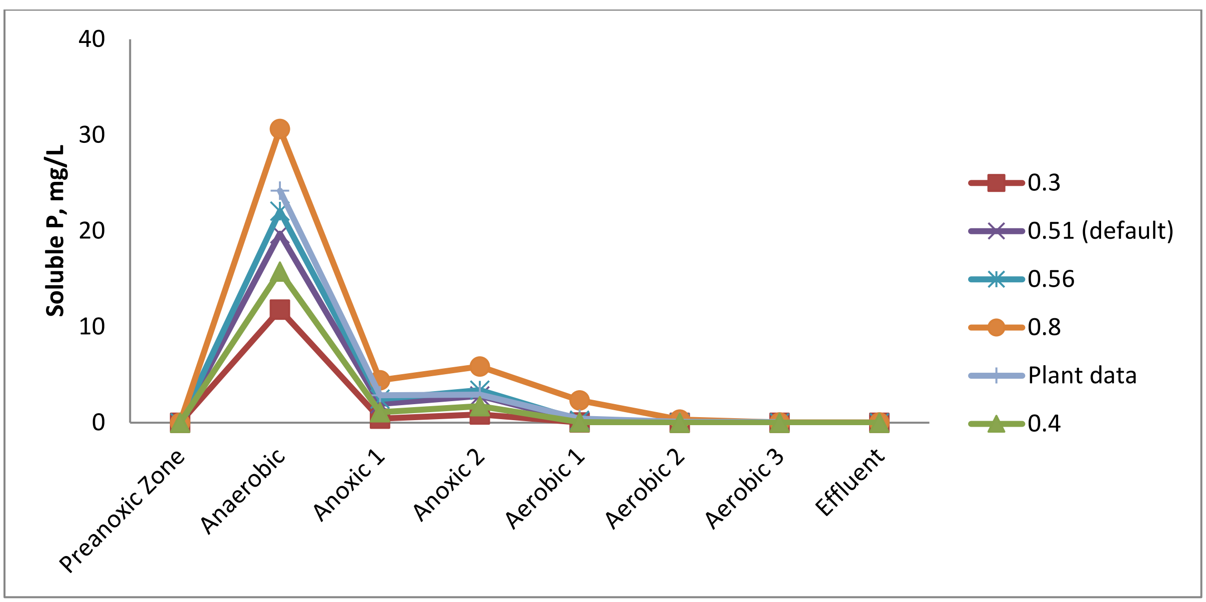

Figure 6. Impact of the P/Ac Release Ratio on the soluble phosphorus profile.

Combined impact of adjusted PAO parameters

Figure 7 illustrates the orthophosphate profiles from runs the PAO parameters listed in Table 1. The profiles for the BiowinTM defaults, the values derived by Dunlap et al (2016) and those developed in this study are compared against the actual full scale Westbank plant data.

Although the final effluent results are very similar, the dynamics of the process are noticeably different for all three sets of parameters. The default parameters significantly underestimate the anaerobic release of phosphorus and anoxic uptake. The values estimated by Dunlap et al (2016) provide much better match of the phosphorus release and aerobic uptake rates, but the anoxic uptake rate is still lower than the observed at the full scale Westbank BNR facility. The best fit of the phosphorus profile was achieved with the adjustments developed in this study.

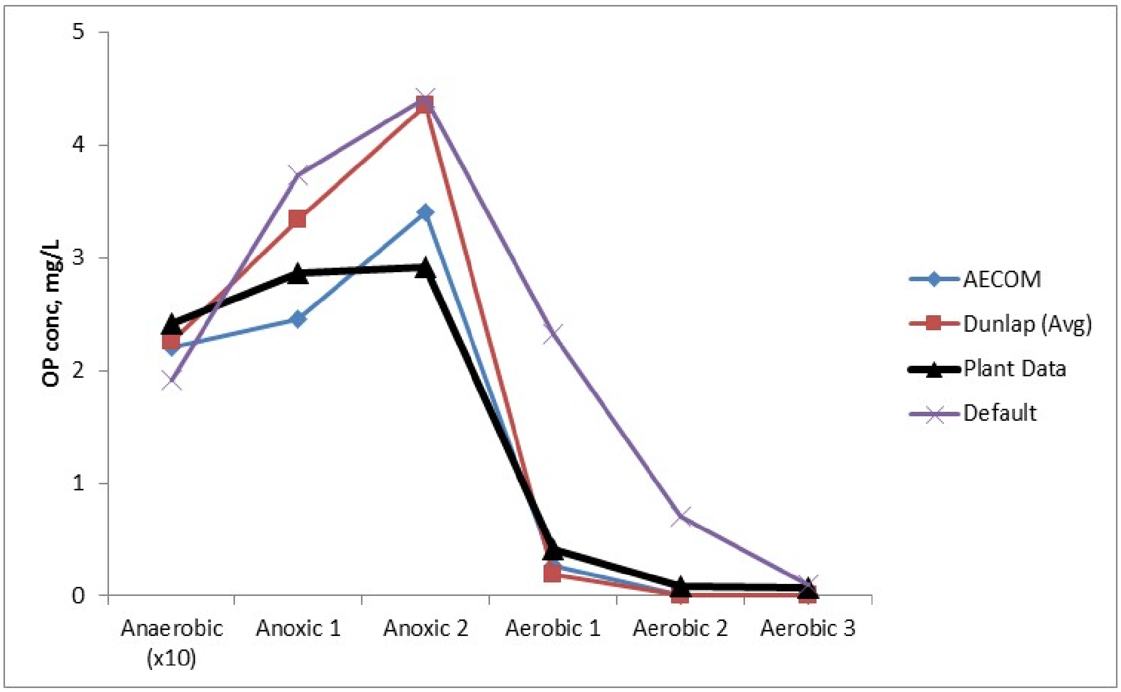

Figure 7. Comparison of impact of the adjustments of PAO related parameters between AECOM and Dunlap.

Note: concentrations in the anaerobic zone must be multiplied by 10 for the actual values.

As discussed the PAO related process parameters have a significant impact on the orthophosphate profile through the various zones of a BNR reactor. Modeling of the Westbank process using default kinetic and stoichiometric parameters may lead to an underestimation of biological phosphorus removal capacity which in-turn could lead to larger reactors, improper zone sizing, and an overall less stable EBPR process.

APPLICATION TO SALT LAKE CITY WRF FULL SCALE DESIGN

The New WRF in Salt Lake City will be designed to treat an average daily flow of 56 mgd. A general summary of the influent flows and loads are presented in the Table 2.

Table 2. Salt Lake City WRF Influent Design Flows and loads.

Parameter	Unit	Annual Average	Maximum Month
Flow	MGD	56.0	68.3
TSS	mg/L	180	175
COD	mg/L	480	455
TN	mg/L	30	25
TP	mg/L	4.0	4.0
Temperature (min/avg/max)		10/17/24°C	

Process modeling for the new Salt Lake City WRF project was conducted using Biowin™ version 5.3 by Envirosim. The model flow diagram is presented in Figure 7.

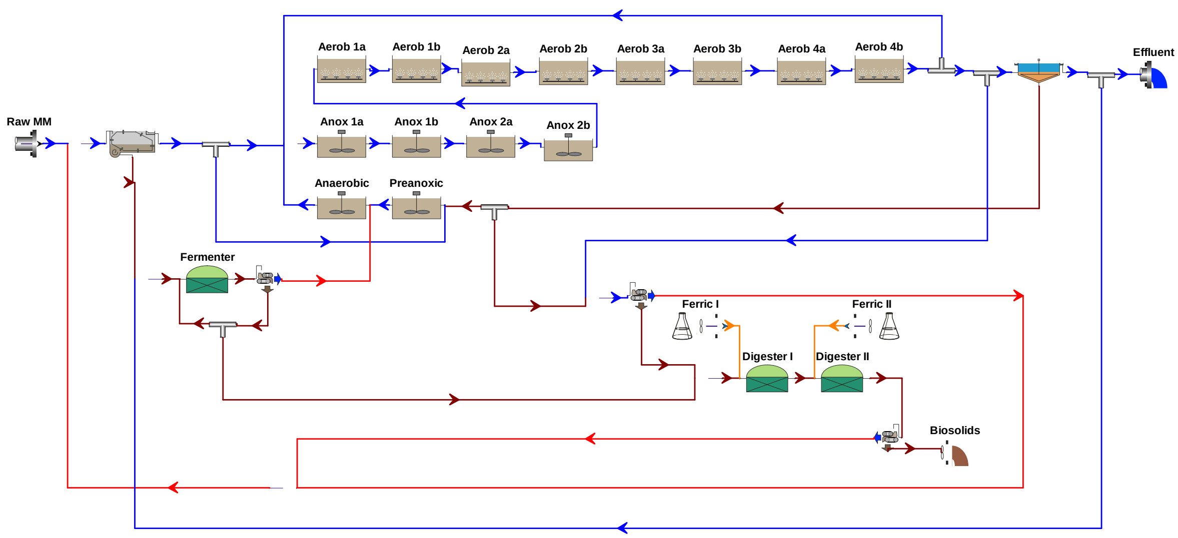

Figure 7. New Salt Lake City WRF Full Plant Model Flow Diagram.

The sizing of the bioreactor zone sizes and aeration system were based on dynamic simulations representing two consecutive years. The influent profiles were created using historical daily influent data which were adjusted to reflect the future design capacity. Two annual profiles were selected to represent a dry and wet year. Daily diurnal variability was built into the flows and concentration profiles with separate diurnal patterns used for weekday and weekends.

Since the bioreactors will be operated in a Westbank configuration, the kinetic and stoichiometric parameters developed in this study were used as inputs into the model to establish overall bioreactor volumes and zone sizing, As compared to a conventional BNR configuration using default parameters, this will lead to a facility with a smaller footprint, and will provide a reliable and stable phosphorus removal process.

To optimize the management of carbon in the system, the bioreactors will also be designed with the flexibility of step feeding RAS to either the pre-anoxic zone (upstream of the anaerobic zone) or the first anoxic zone. This will allow a portion or all of the RAS to be fermented and will provide the ability to meet lower nitrogen and phosphorus standards in the future.

It is also known that the Westbank process provides many of the environmental conditions needed to promote the growth of aerobic granular sludge (AGS). With the rapid advancement in AGS flow through technology, the bioreactors will be designed with the depth needed to facilitate granulation. The system is being arranged so that a single train can be operated independently, allowing plant staff to optimize the conditions for AGS growth. More details regarding the features provided in the SLC WRF BNR design will be provided in the presentation.

CONCLUSIONS

The design of the new Salt Lake City WRF BNR facility will be based on the Modified Westbank BNR process. Based on recent academic and full scale research, benefits of this configuration include the ability to growth enhanced populations of the genus Testrasphaera, which are known to provide efficient and reliable BNR treatment. The design of the facility is based on adjusted kinetic and stoichiometric parameters unique to the Westbank process. The application of real plant data obtained from an established Westbank process provided the ability to optimize bioreactor volumes and zone sizes leading to a more cost effective design. To accommodate recent advances in RAS fermentation and flow through AGS technology, the design will also incorporate features to allow operations staff the flexibility to research these on a full scale independent basis.

REFERENCES

Barnard, J. L., Dunlap, P., & Steichen, M. (2016). Rethinking the Mechanisms of Biological Phosphorus Removal. *Proceedings of IWA/WEF Nutrient Removal and Recovery Conference*. Denver, CO.

Crocetti, G. R., Hugenholtz, P., Bond, P. L., Schuler, A., Keller, J., Jenkins, D., & Blackall, L. L. (2000). Identification of Polyphosphate-Accumulating Organisms and Design of 16S rRNA-Directed Probes for Their Detection and Quantitation. *Applied and Environmental Microbiology*, *66*(3), 1175–1182. https://doi.org/10.1128/aem.66.3.1175-1182.2000

Dunlap, P., Martin, K., Stevens, G., Tooker, N., Barnard, J., Gu, A., … Li, Y. (2016). Rethinking EBPR: What do you do when the model will not fit real-world evidence? *5th IWA/WEF Wastewater Treatment Modeling Seminar, Annecy, France 2016*, 39–62.

Hesselmann, R. P. X., Werlen, C., Hahn, D., Van Der Meer, J. R., & Zehnder, A. J. B. (1999). Enrichment, phylogenetic analysis and detection of a bacterium that performs enhanced biological phosphate removal in activated sludge. *Systematic and Applied Microbiology*, *22*(3), 454–465. https://doi.org/10.1016/S0723-2020(99)80055-1

Kristiansen, R., Nguyen, H. T. T., Saunders, A. M., Nielsen, J. L., Wimmer, R., Le, V. Q., … Nielsen, P. H. (2013). A metabolic model for members of the genus Tetrasphaera involved in enhanced biological phosphorus removal. *ISME Journal*, *7*(3), 543–554. https://doi.org/10.1038/ismej.2012.136

Nguyen, H. T. T., Le, V. Q., Hansen, A. A., Nielsen, J. L., & Nielsen, P. H. (2011). High diversity and abundance of putative polyphosphate-accumulating Tetrasphaera-related bacteria in activated sludge systems. *FEMS Microbiology Ecology*, *76*(2), 256–267. https://doi.org/10.1111/j.1574-6941.2011.01049.x

Onnis-Hayden, A., Srinivasan, V., Tooker, N., Li, G., Wang, D., & Gu, A. Z. (2018). Survey of Full Scale Side-Stream EBPR Facilities and Comparison with Conventional EBPR:Process Stability, Kinetics and Microbial Ecology. *Preprints*. https://doi.org/10.20944/preprints201808.0241.v1

Stevens, G. M., Barnard, J. L., & Rabinowitz, B. (1999). Optimizing biological nutrient removal in anoxic zones. *Water Science and Technology*, *39*(6), 113–118. https://doi.org/10.1016/S0273-1223(99)00129-8