Appendix 5-3. Phosphorus Evaluations

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1.1 PHOSPHORUS MANAGEMENT

The Metropolitan Council has been and continues to take a proactive approach to phosphorus management at each of its facilities. The Blue Lake WWTP has aspects on both the mainstream liquids and solids sidestreams that require a coordinated approach to consistently meet effluent phosphorus loading requirements. The current effluent phosphorus limits consist of both a monthly concentration (1 mg P/L) as well as yearly loading (58,024 kg/yr). Further, the Metropolitan Council is anticipating more stringent requirements in the future based on proposed River Eutrophication Standards (RES), these limits will reduce the loading impact on receiving streams to prevent future water body impairment.

The phosphorus management approach will have to consider the impact of the following:

- **Industrial Pretreatment Incentive Program (IPIP).** This program can impact the total phosphorus loading of the influent but can also impact the overall carbon and phosphorus ratios for biological phosphorus removal.

- **Phosphorus sequestration and/or harvesting.** Sidestream phosphorus loading from the solids digestion processes increase mainstream loading and contribute to phosphorus upcycling within a facility. In addition to these directly related parameters, impacts to dewatering, chemical usage, maintenance, and biological phosphorus removal stability can also be associated by sidestream phosphorus loading.

1.1.1 Historical EBPR Performance

The current EBPR performance of the facility has historically experienced periods of instability, a specific cause of the instability has not been identified. Figure 1-1 shows historical effluent total phosphorus concentrations and sidestream total phosphorus return concentrations

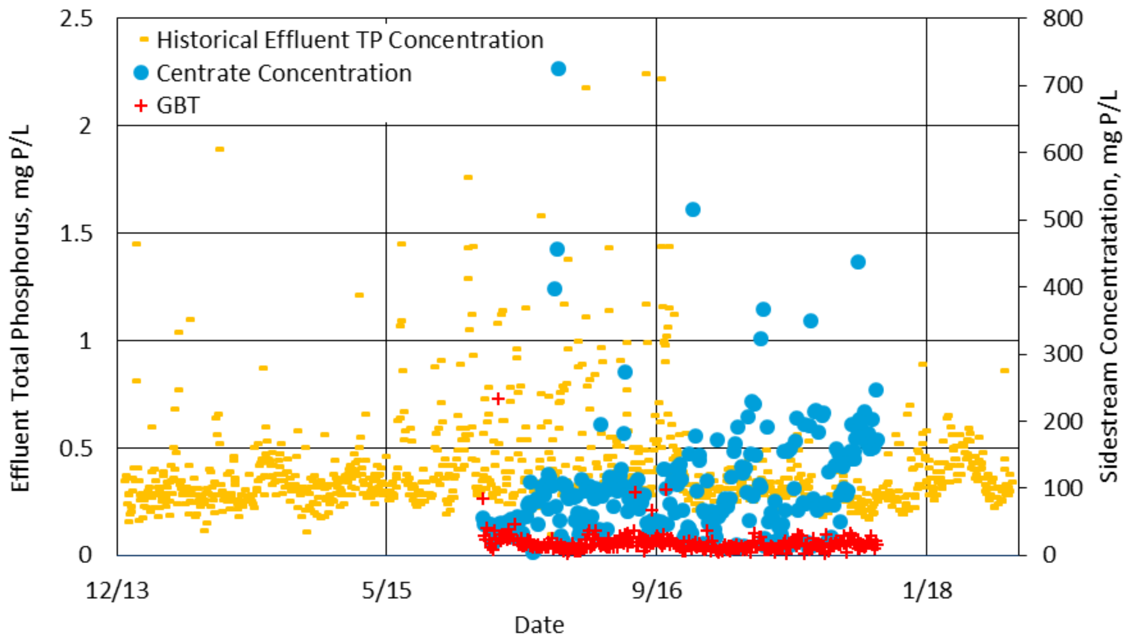

Figure 1-1: Blue Lake WWTP historical effluent and sidestream total phosphorus concentrations. Current permit limit is 1.0 mg P/L.

The effluent total phosphorus had increased instability during the period of March 2015 through September 2016 where spikes were continuous throughout a calendar year. Following September 2016 through 2018 effluent total phosphorus concentrations have stabilized near 0.5 mg P/L. Monthly effluent concentrations are currently and are expected to be part of a future permit, annual loading based on a 12-month rolling average is also in the current and expected to be in a future permit. Figure 1-1 summarizes the annual loading through the same time period.

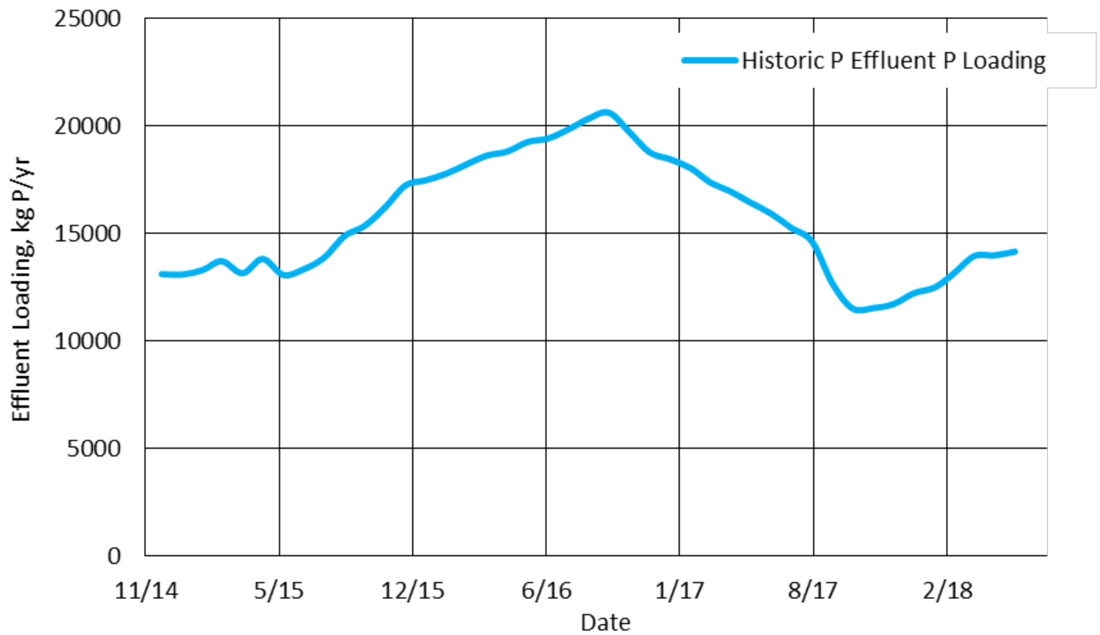

Figure 1-2: Blue Lake WWTP historical annual effluent total phosphorus loading. Current permit limit is 58,024 kg/yr.

The historical effluent total phosphorus concentration and loading do not appear to have a direct link to the sidestream return total phosphorus loading. However, it should be noted that staff have expressed rapid formation of struvite in the dewatering centrifuges suggesting that sidestream loading is higher than measured concentrations. Influent data was reviewed to determine any potential impacts of shifting influent characteristics that may lead to EBPR instability. Industry experience has found EBPR instability causes to the following:

- Readily available carbon (rbCOD/sBOD) to phosphorus ratios. The selective pressures for PAO selection and subsequent phosphorus removal are heavily dependent on adequate available carbon. Blue Lake WWTP raw influent and primary effluent data were reviewed to identify potential links. While the total COD and BOD values are often available for historical data review the critical parameters are VFA and rbCOD concentrations of the raw influent. A specific facility's influent characteristics can differ widely if only total COD and BOD values used.
- Wet weather flows. Wet weather flows can impact the anaerobic zone within the aeration basin that is required for phosphorus release and readily available carbon uptake. These peak flow events can reduce hydraulic retention time or potentially eliminate anaerobic zones.

Figure 1-2, Figure 1-3, Figure 1-4, Figure 1-5 and Figure 1-6 summarize the Blue Lake WWTP historical influent BOD, COD, and VFA and primary effluent BOD and COD to total phosphorus ratios vs. effluent total phosphorus, respectively.

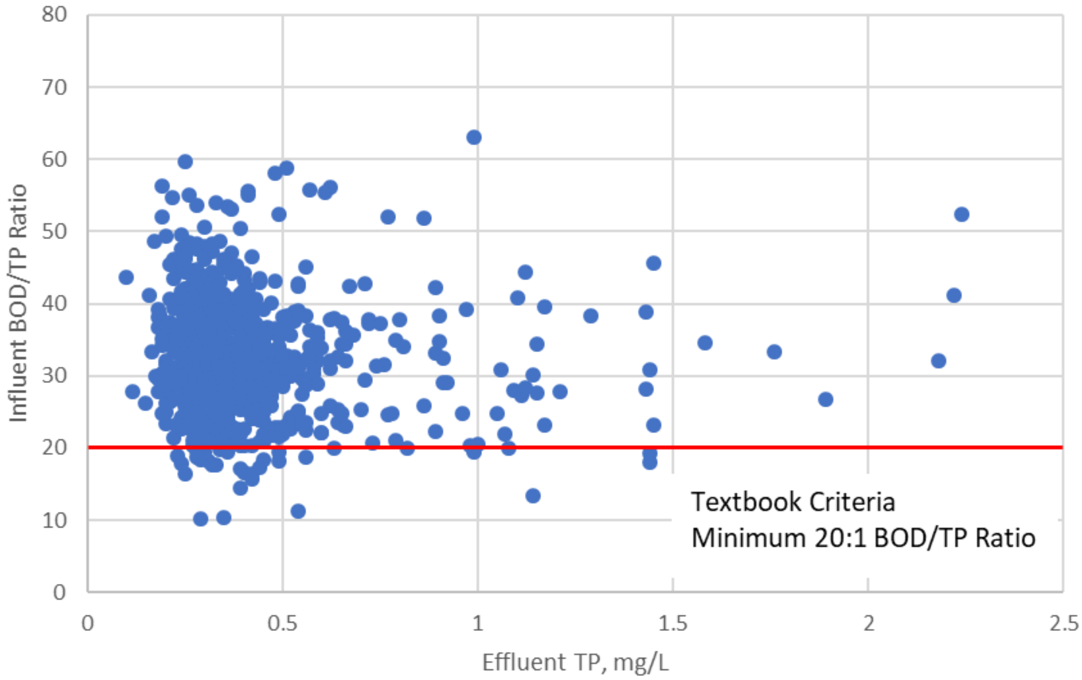

Figure 1-3: Blue Lake WWTP historical influent BOD/TP ratio vs. effluent total phosphorus. Data available from January 2014 through September 2018.

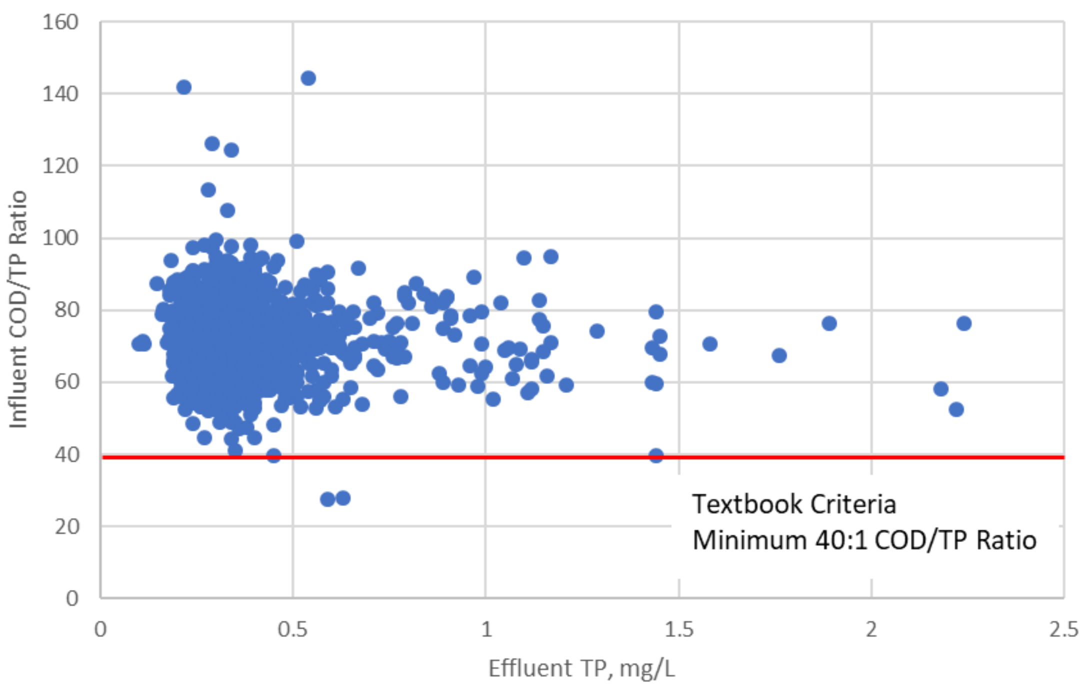

Figure 1-4: Blue Lake WWTP historical influent BOD/TP ratio vs. effluent total phosphorus. Data available from January 2014 through September 2018.

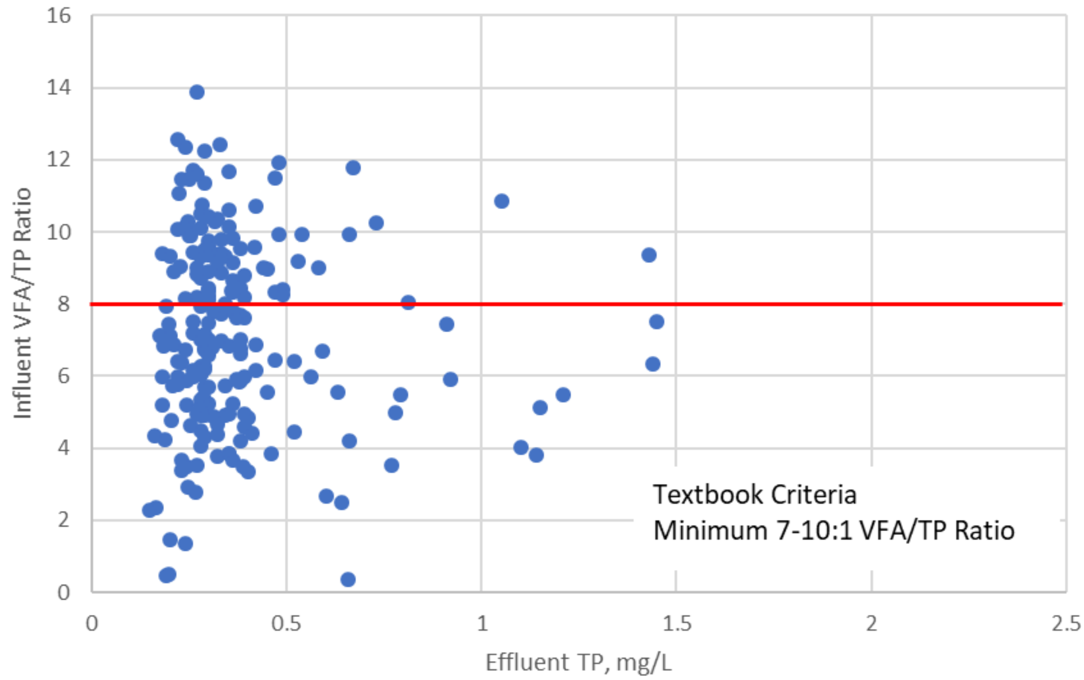

Figure 1-5: Blue Lake WWTP historical influent filtered COD/TP ratio vs. effluent total phosphorus. Data available from January 2014 through February 2016.

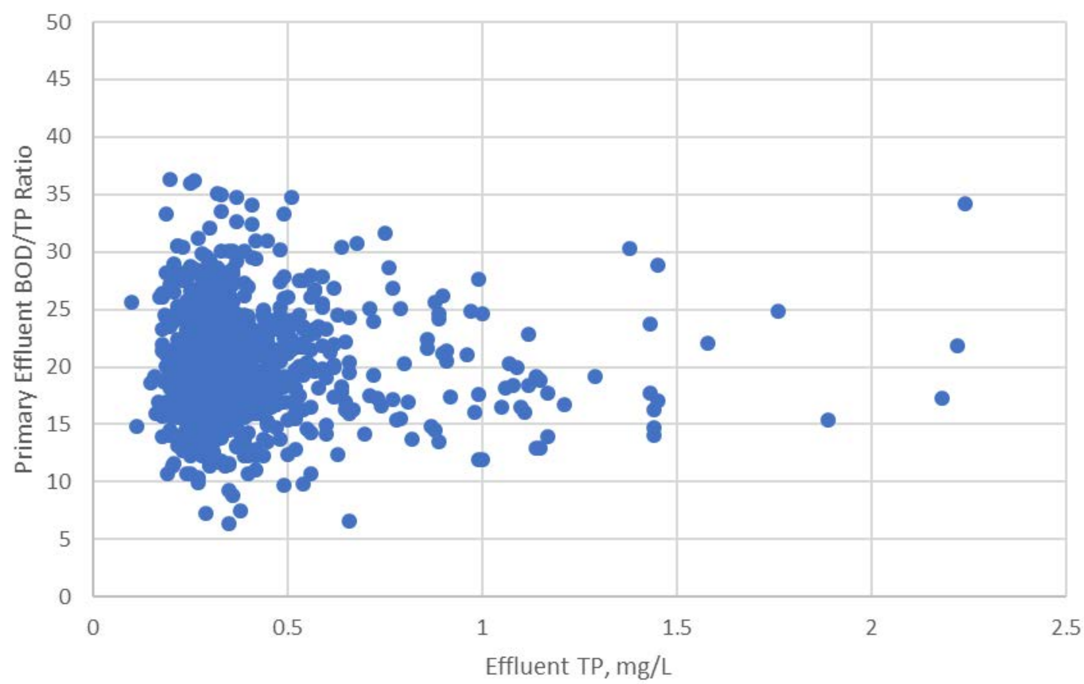

Figure 1-6: Blue Lake WWTP primary effluent BOD to influent TP ratio vs. effluent total phosphorus. Data available from January 2014 through September 2018.

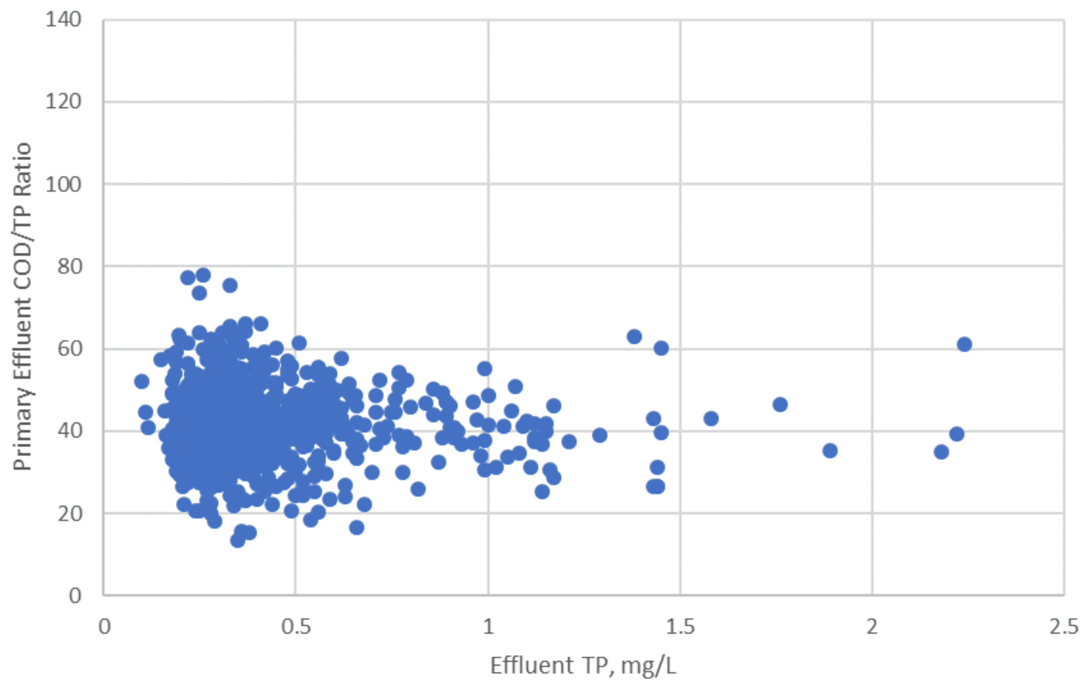

Figure 1-7: Blue Lake WWTP primary effluent COD to influent TP ratio vs. effluent total phosphorus. Data available from January 2014 through September 2018.

The raw influent carbon (total BOD and COD) to total phosphorus concentrations are consistently above traditional industry understanding for stable EBPR performance. However, the influent VFA to total phosphorus ratios appear to be below required ratios for stable EBPR performance. While this data could point to a cause for EBPR instability the data is only available from 2014 through 2016 and the effluent total phosphorus concentration doesn't not show correlation to this ratio. If the influent VFA to total phosphorus ratio to the Blue Lake WWTP was representative of these ratios it would be expected to see a high correlation with effluent total phosphorus. EBPR stability will be directly linked to this parameter and significant ratios below 7 should be correlated with elevated phosphorus concentrations. Potential causes of the inconsistency are sample or sample preparation that is not representative of the raw influent or other constituents (metal salts) contained within influent or recycle streams that bind up available phosphorus. Similar to the raw influent, the primary effluent carbon ratio does not indicate potential EBPR instability. It should be noted to produce the primary effluent ratios raw influent total phosphorus data was used as primary effluent total phosphorus data was not available.

Another source of EBPR instability can be related to peak flow events that reduce the hydraulic retention time within the anaerobic zone. Figure 1-7 summarizes the historical influent flow rate vs. the effluent phosphorus concentration.

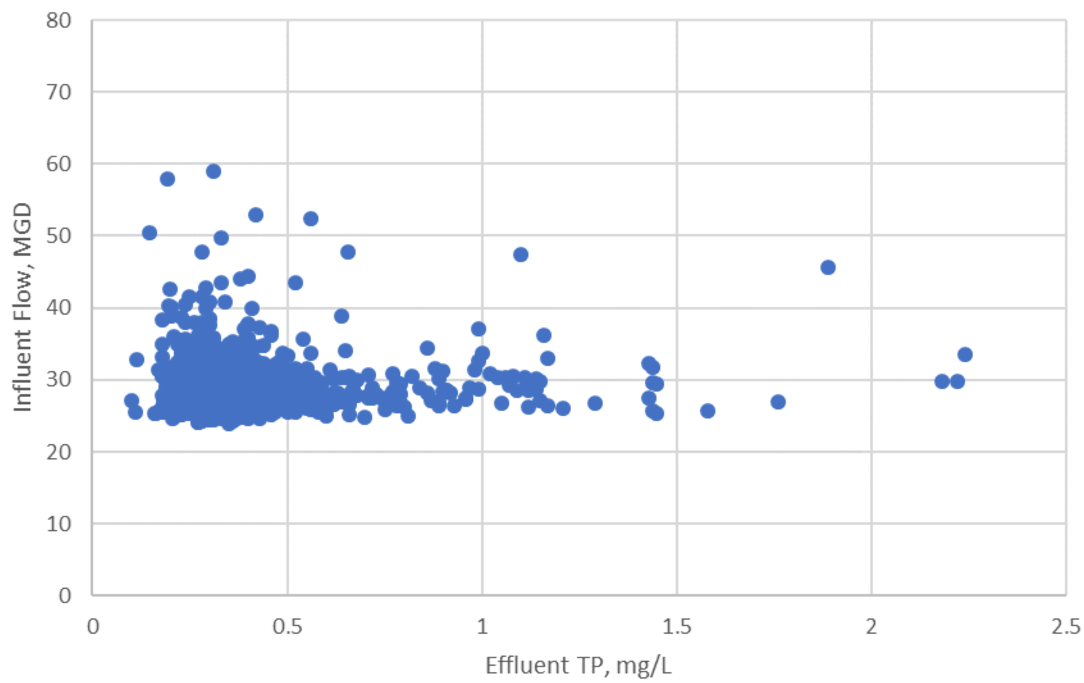

Figure 1-8: Blue Lake WWTP influent flow vs. effluent total phosphorus concentration. Data available from January 2014 through September 2018.

Peak flow events do not have a correlation with elevated effluent phosphorus concentrations, further it appears elevated phosphorus concentrations occur more often at average day flows.

The Blue Lake WWTP EBPR instability does not appear to be correlated with influent available carbon and phosphorus nor to peak flow events. As part of the recommendations and further evaluations the following are areas of outstanding interest.

- **Sidestream recycle loading.** Historical measurements do not appear to be correlated directly with effluent phosphorus, however, struvite formation has been observed and is an indication of return streams with higher phosphorus concentrations. Subsequent sections will review potential sidestream phosphorus mitigation approaches.
- **Operational and/or infrastructure.** The aeration basins have separate RAS denitrification zones followed by anaerobic zones where primary effluent is introduced. The efficiency of these zones is critical to achieving deep anaerobic conditions that select for PAOs and maintain EBPR stability. A sampling protocol will be developed for operations to monitor the conditions and to better define the conditions within these zones.
- **Industrial loading.** The Blue Lake WWTP does have significant industrial contributions, these range from food processing to water treatment chemical sludge. These industries can contribute to available carbon, total phosphorus loading, and metal salts that can bind available phosphorus. Subsequent sections provide a review of the current Industrial Pretreatment

Incentive Program (IPIP), both impacts of known changes and consideration for future industry pretreatment systems.

1.2 SIDESTREAM PHOSPHORUS SEQUESTRATION OR HARVESTING

The current sidestream and solids process phosphorus management approach is ferric chloride dosing to the anaerobic digesters. This provides not only a means of struvite mitigation but also H_2S control. Recent operations have indicated the potential need to add more ferric chloride to the anaerobic digesters to further reduce the sidestream phosphorus loading, however, the pH within the digesters is preventing a significant increase from the current dosing rate. While there has not been a direct link of the sidestream phosphorus loading with EBPR stability and effluent phosphorus concentrations alternative management approaches could provide other benefits. Struvite formation at the dewatering centrifuges and anaerobic digestion health (related to pH) are drivers to consider alternatives to ferric chloride dosing for struvite mitigation. The alternatives evaluated here include:

- Ferric chloride ($FeCl_3$) addition to the anaerobic digestion and sidestream centrate.
- $FeCl_3$ and magnesium hydroxide ($Mg(OH)_2$) combined addition to the anaerobic digesters. $FeCl_3$ addition may not be required to control H_2S formation.
- Struvite harvesting or sequestration technologies within the solids stream.

The first two alternatives are similar, in that both are chemical addition, while the third alternative would be a more significant capital investment. The addition of $FeCl_3$ and MgOH would require operations and maintenance staff to manage two chemicals, rather than one. An evaluation that considers the impacts and total life cycle costs of each incorporates uncertainty, specifically related to the phosphorus harvesting or sequestration technology was used to provide insight to the following questions:

- How does a decreased phosphorus concentration in the centrate affect plant phosphorus balance, capacity and stability?
- What is the impact of an increased phosphorus loading to Blue Lake WWTP?
- If a phosphorus harvesting technology is selected what is the market value?
- What is the impact to phosphorus harvesting or sequestration to the final sludge dried pellets?
- What are ancillary benefits of phosphorus harvesting? Dewatering impacts? Chemical usage? Solids production?

The Extended Pearson-Tukey (PT) was the selected method to define the uncertainty and probability of likely outcomes. This approach is comparable to a Monte Carlo modeling technique that typically uses thousands of simulations to define a probability distribution. Due to the sheer number of simulations required to perform Monte Carlo evaluations feasibility related to time and data management can become resource consuming, whereas the PT approach provides a similar uncertainty evaluation with significantly less simulations. Evaluating the impact or sensitivity of four variables, for example, would require only 81 simulations per scenario. The PT approach utilizes a branching method with each branch corresponding to a variable (parameter selected for review), more branches require more simulations, Figure 1-8.

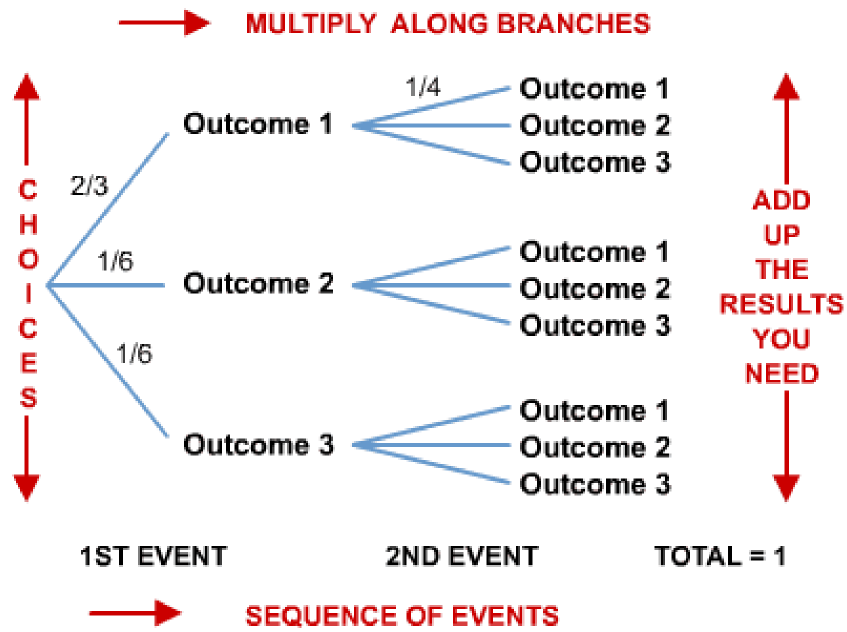

Figure 1-9: Example Extended Pearson-Tukey evaluation tree, with two variables.

A range of parameters was selected for the Blue Lake WWTP, Table 1-1, related to influent characteristics.

Table 1-1: Blue Lake WWTP influent characteristics selected for sensitivity assessment of each alternative.

PARAMETER	5TH PERCENTILE	50TH PERCENTILE (MEDIAN)	95TH PERCENTILE
cBOD (mg/L)	165	250	340
TP (mg/L)	5.4	7.9	11.2
TKN (mg/L)	36	48	61

Note: Evaluations were performed at an average influent of 30 mgd to represent future conditions.

The values are representative of historical data, each parameter will become a branch of the evaluation PT tree, Figure 1-9.

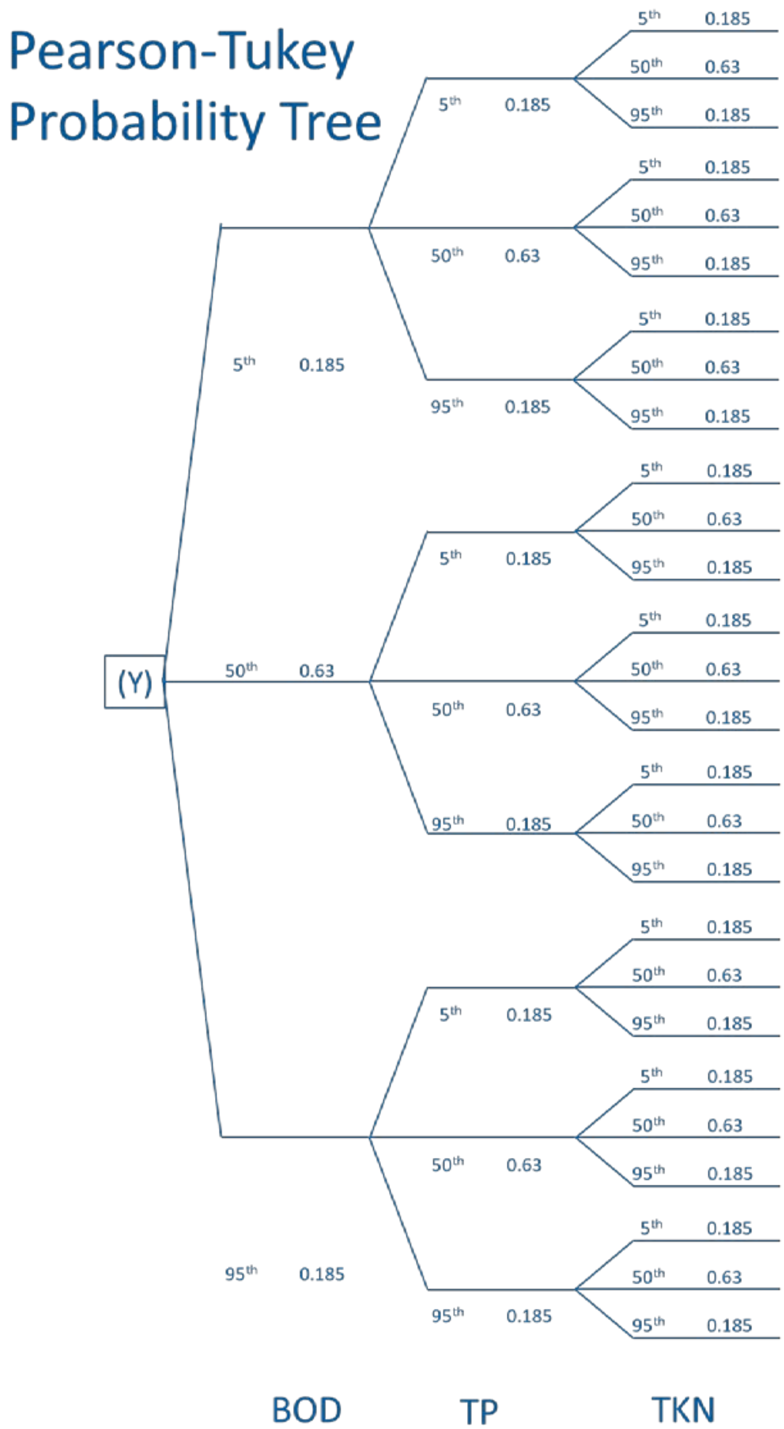

Figure 1-10: Phosphorus management alternative uncertainty evaluation approach.

The evaluation tree is used to provide uncertainty and a probability range of expected performance for eight selected scenarios requiring a total of 216 simulations (27 simulations per scenario). The eight scenarios evaluated are summarized in Table 1-2.

Table 1-2: Extended Pearson-Tukey phosphorus management uncertainty scenarios summary.

SCENARIO	DESCRIPTION
1	Status quo influent and operational conditions, model verification of approach
2 thru 4	Influent TP load increases of 10%, 20%, and 30% with status quo operations
5	Status quo conditions with struvite harvesting/sequestration
6 thru 8	Influent TP load increases of 10%, 20%, and 30% with struvite harvesting/sequestration

The initial status quo simulations (Scenario 1) were to provide proof and verification of the approach, a representative output is expected and required prior to further evaluation. Scenarios 2 through 4 will then provide a comparison of increased total phosphorus loading if the status quo operational approach remains versus an alternative approach using struvite harvesting/sequestration. The increased phosphorus loading assumes only an increase in total phosphorus, nitrogen and carbon loading do not equally increase. This will result in an increasingly less favorable sBOD/TP ratio for stable EBPR performance. Figure 1-10 summarizes the simulation outputs comparatively against the historical data distribution.

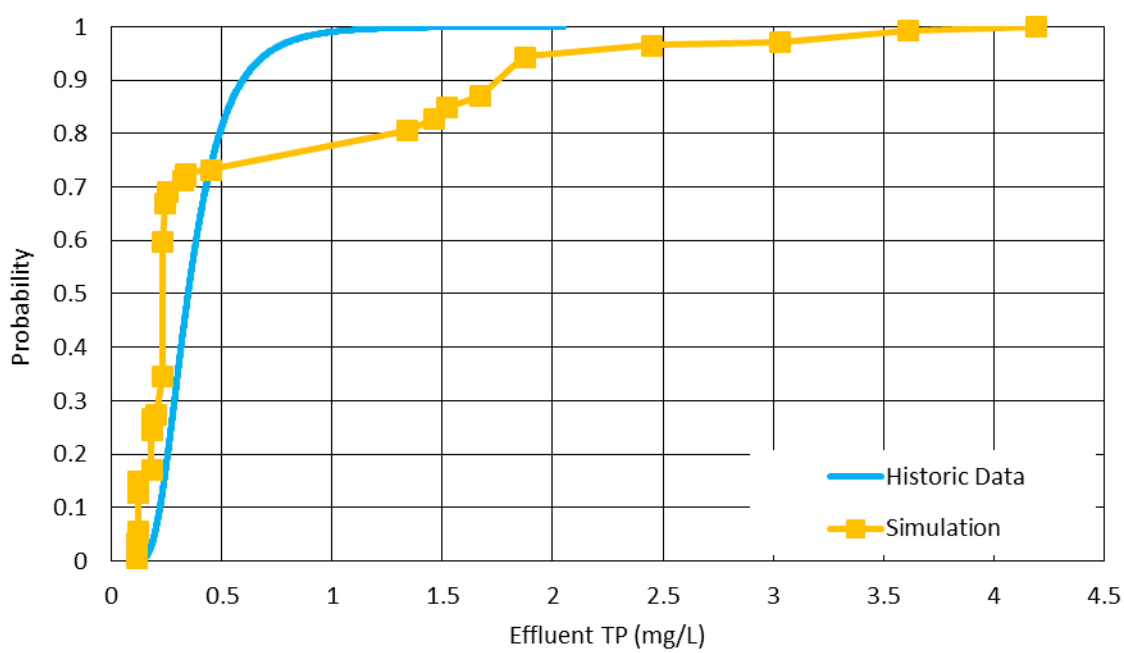

Figure 1-11: Scenario 1 - Status Quo uncertainty simulations compared to historical effluent data.

The simulation outputs using the PT method provides an approximation of stability that follows the general trend of historic data. The main objective of the PT approach is to provide an estimate of the mean with the selected variable parameters. The historical mean of 0.4 mg P/L is lower than the predicted PT mean of 0.7 mg P/L, the higher predicted effluent is due to the steady state simulation approach. The range of inputs selected are representative of the historical range, however, the extreme loading events simulated will last for shorter durations under field conditions. These extreme loading events result in worse performance when performed as a steady state simulation.

For comparison of the status quo to implementation of a struvite harvesting or sequestration technology the CNP AirPrex system was selected as the representative technology. This was selected due to its implementation at similarly sized facilities and proven ability to improve dewaterability. Other phosphorus management approaches that could be considered should implementation move forward are the CNP CalPrex system, Schwing's NuReSys, and Renewables Nutrients Quick Wash. The general Blue Lake WWTP proposed process flow diagram would look similar to Figure 1-11.

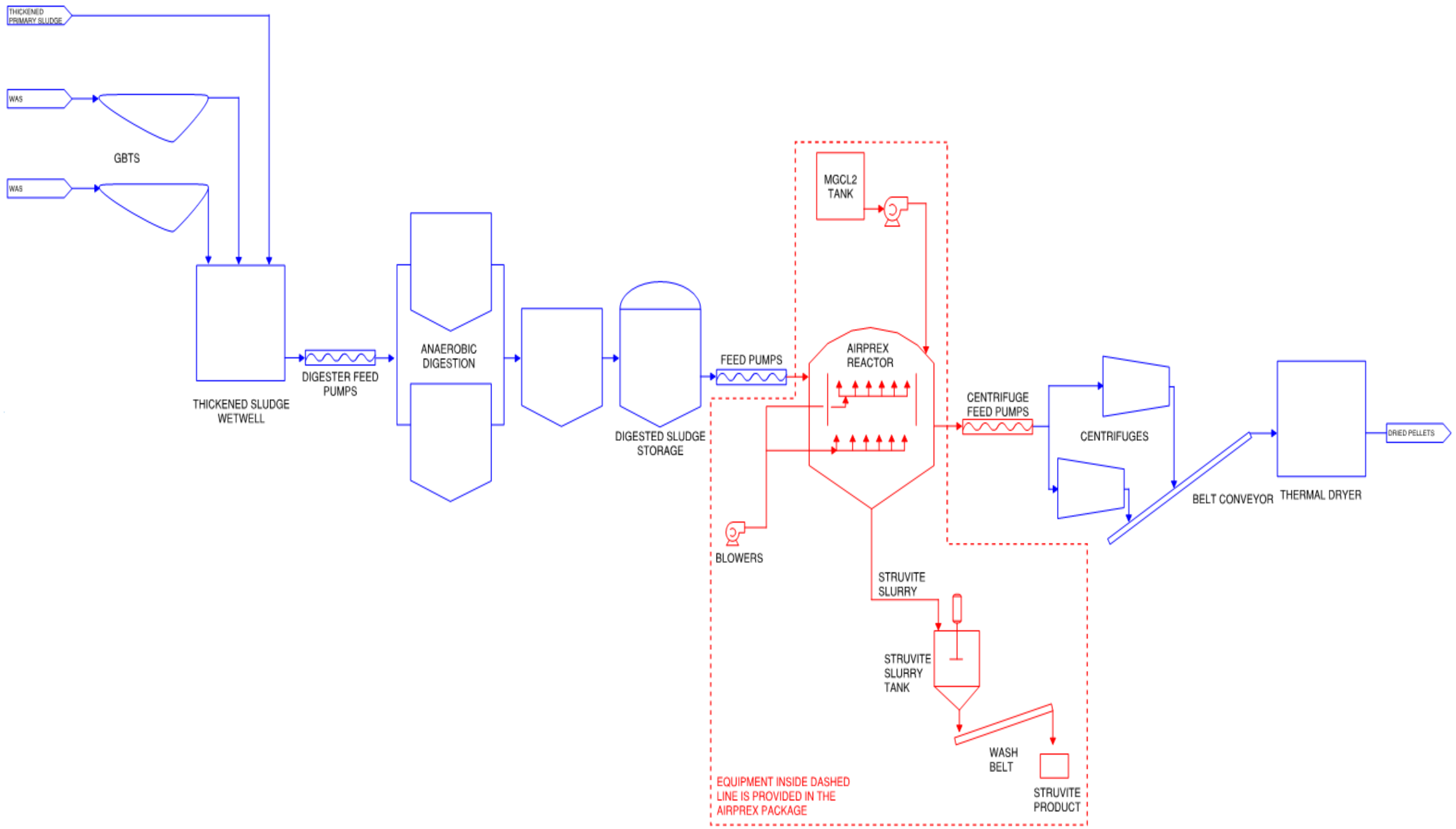

Figure 1-12: Blue Lake WWTP proposed flow diagram for phosphorus management approaches using biosolids harvesting/sequestration technologies.

Figure 1-12 summarizes the outputs from Scenarios 5-8 using a struvite harvesting/sequestration technology similar to Airprex.

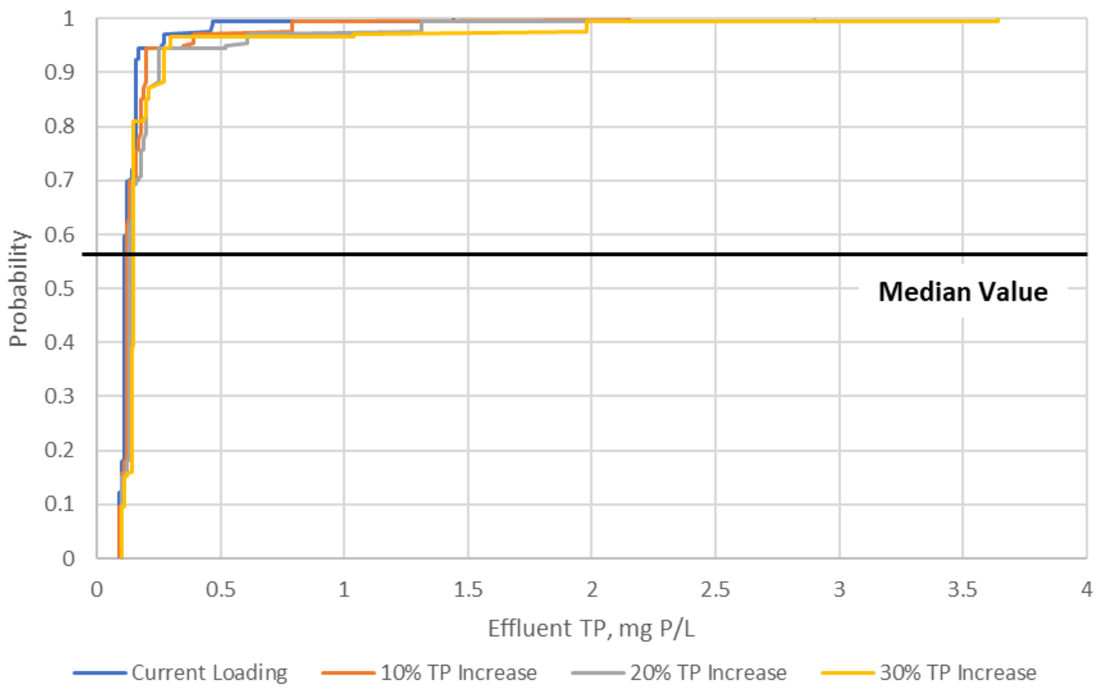

Figure 1-13: PT simulation results of Scenarios 5-8 with struvite harvesting/sequestration technologies.

The results of Scenarios 5-8 demonstrate an increase in effluent phosphorus stability compared to the baseline simulations that showed increasing instability beginning at 30% of the time (0.7 probability). A comparison of all eight Scenarios is shown in Figure 1-13.

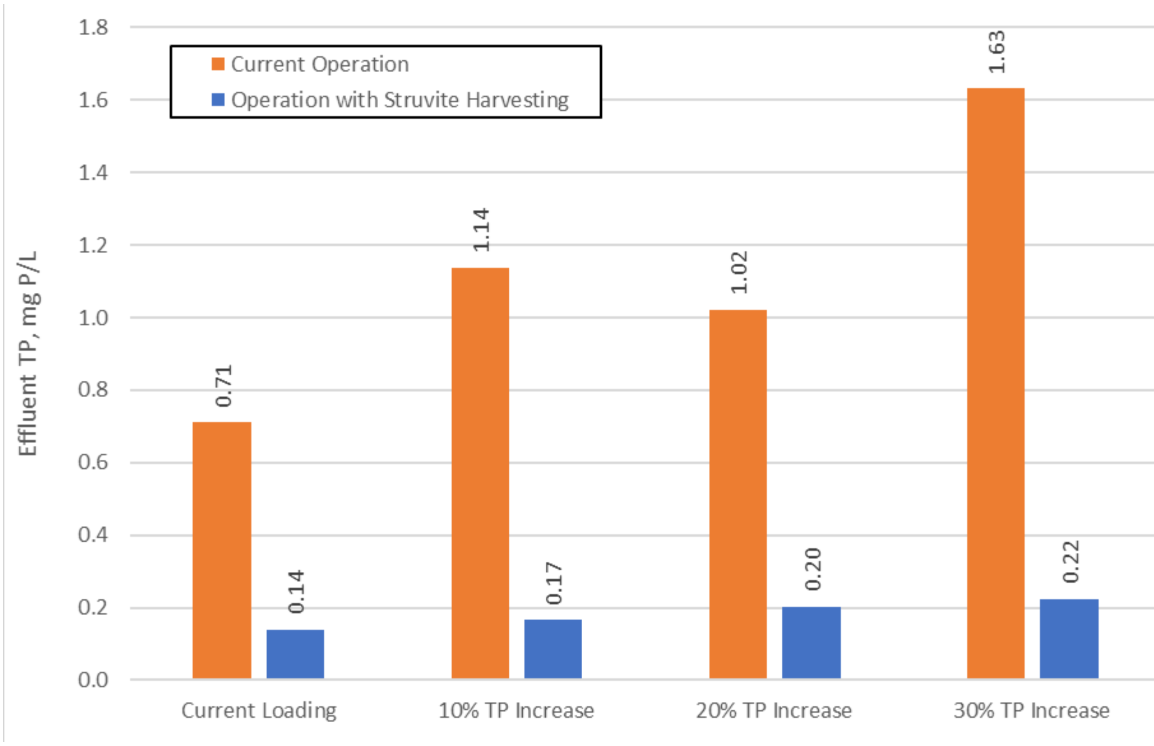

Figure 1-14: Blue Lake WWTP alternative phosphorus management approach comparison to current strategies for Scenarios 1-8.

As influent total phosphorus loading is increased to Blue Lake WWTP, operation at the current mitigation strategy using $FeCl_3$ result with increasingly unstable mainstream EBPR performance. As the phosphorus loadings continue to increase each Scenario will approach a breaking point where effluent phosphorus concentrations drastically increase. The current operational approach is starting to demonstrate a significantly increasing effluent concentration whereas the struvite harvesting continues to show stable performance at a 30% phosphorus load increase. It should be noted that the struvite harvesting technology approach will also begin showing increasing effluent performance if loading continues to increase but it will provide continued stable performance at higher loadings than the current operational approach.

A comparison of chemical usage for the alternatives and scenarios used is summarized in Figure 1-14.

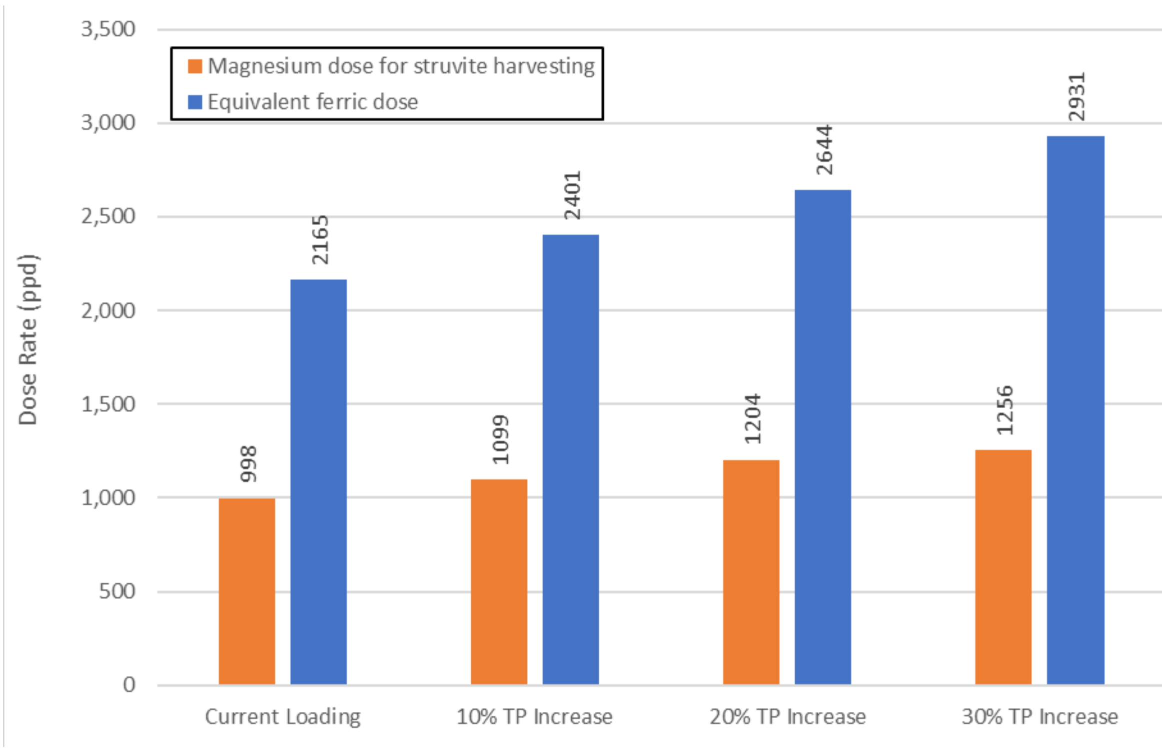

Figure 1-15: Predicted chemical usage of eight scenarios evaluated.

The chemical dosing required for each scenario used the following assumptions to estimate the expected use:

- $FeCl_3$ dosing was not optimized in the simulations
  - Dose rates matching current loading and usage were escalated with respect to the increasing load
  - $FeCl_3$ dosing was added to the centrate stream to match the equivalent return phosphorus loading provided by struvite harvesting technologies
- $MgCl_2$ dosing for the struvite harvesting technology maintained a constant ratio
  - Assumed 1.1 to 1 for the Mg:P ratio
  - Full scale experience indicates ratios as high as 1.4 to 1

The primary objective for consideration when evaluating the alternatives is the impact to mainstream EBPR performance and potential impact to new, more stringent effluent requirements in the future. While this is primary, the implementation of a struvite harvesting technology does provide additional ancillary benefits such as:

- Reduced digester struvite production, reducing strain on maintenance and digester capacity.
- A recoverable, marketable product that can provide an offset to a portion of operational cost and meet resource recovery initiatives. If sequestration is chosen as the approach this would not be an ancillary benefit.

- Final biosolids phosphorus content reduction. Typically, phosphorus content of biosolids is in excess of that required for fertilization and excessive phosphorus application can increase nutrient runoff where phosphorus is often the limiting nutrient.
- Biosolids dewaterability. Implementation of struvite harvesting technologies has shown an increase in solids dewaterability, this is predicted in this evaluation with comparing the soluble phosphorus and magnesium concentrations of the biosolids. Downstream drying facilities mitigate the potential impact of higher solids dewatering potential because of the target solids content desired. However, decreased chemical usage can also be an ancillary benefit applicable to Blue Lake WWTP.

Figure 1-15, Figure 1-16, Figure 1-17, and Figure 1-18 summarize the impact of struvite harvesting to these ancillary benefits as compared to the current operational approach. Note if struvite sequestration is the selected technology approach both the struvite harvesting and phosphorus content of the sludge do not exist.

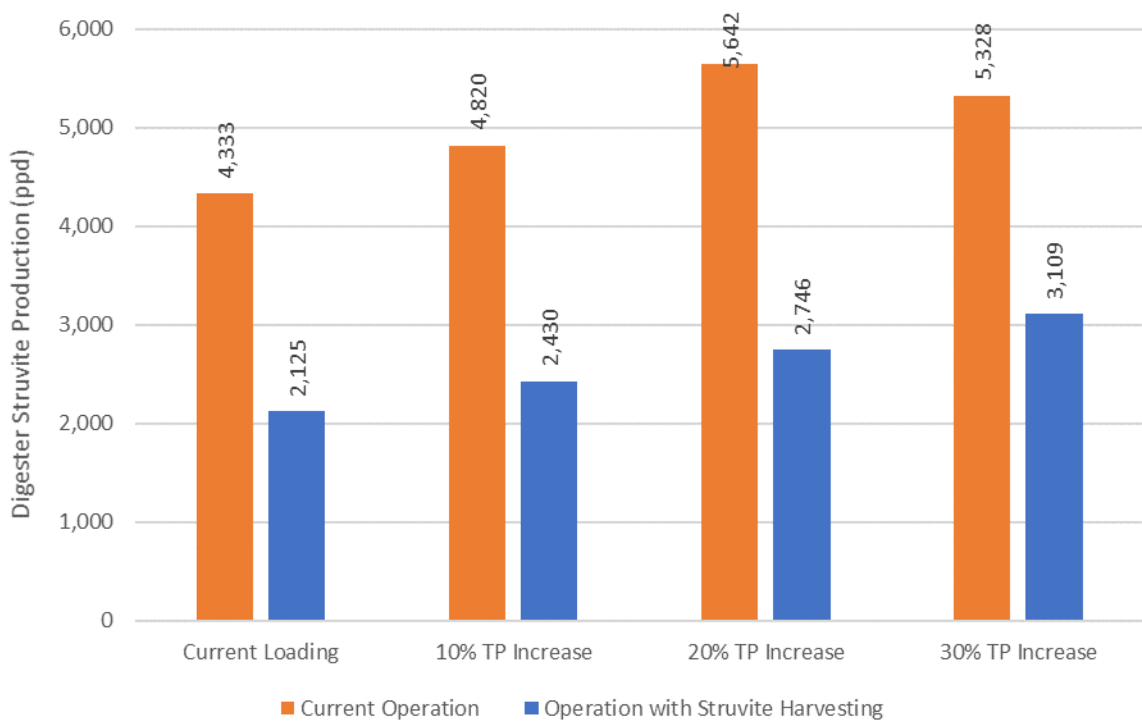

Figure 1-16: Comparison of struvite harvesting/sequestration technologies vs. current operation of digester struvite production with increasing phosphorus loading.

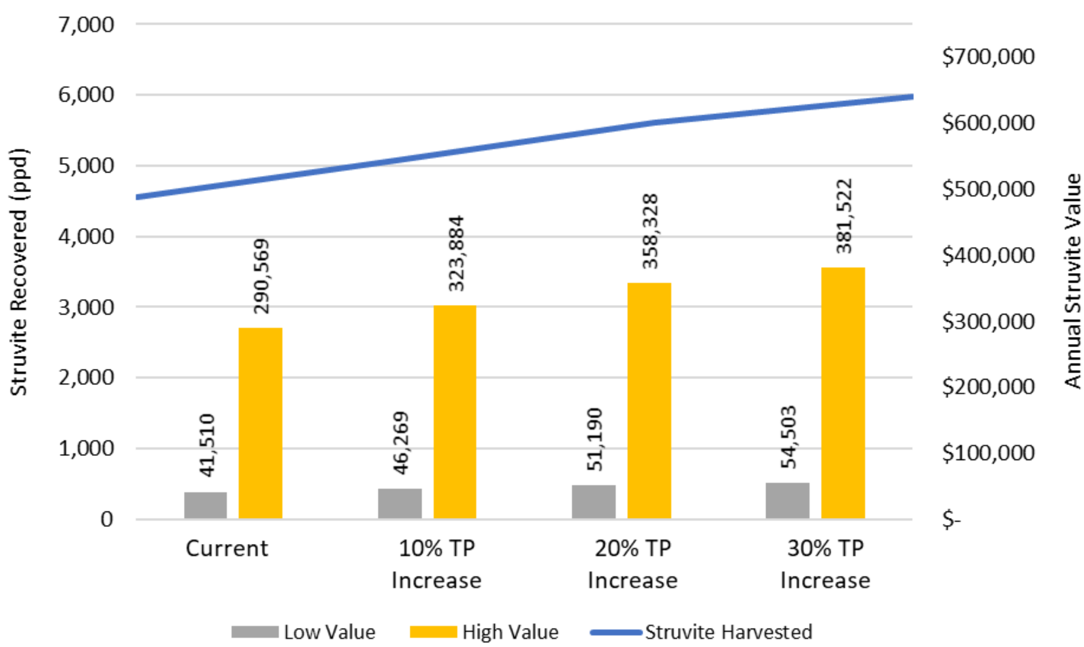

Figure 1-17: Potential value of struvite harvesting technologies based on the percent of struvite recovered. Percent recoveries assumed a range including 30%, 40%, and 50%.

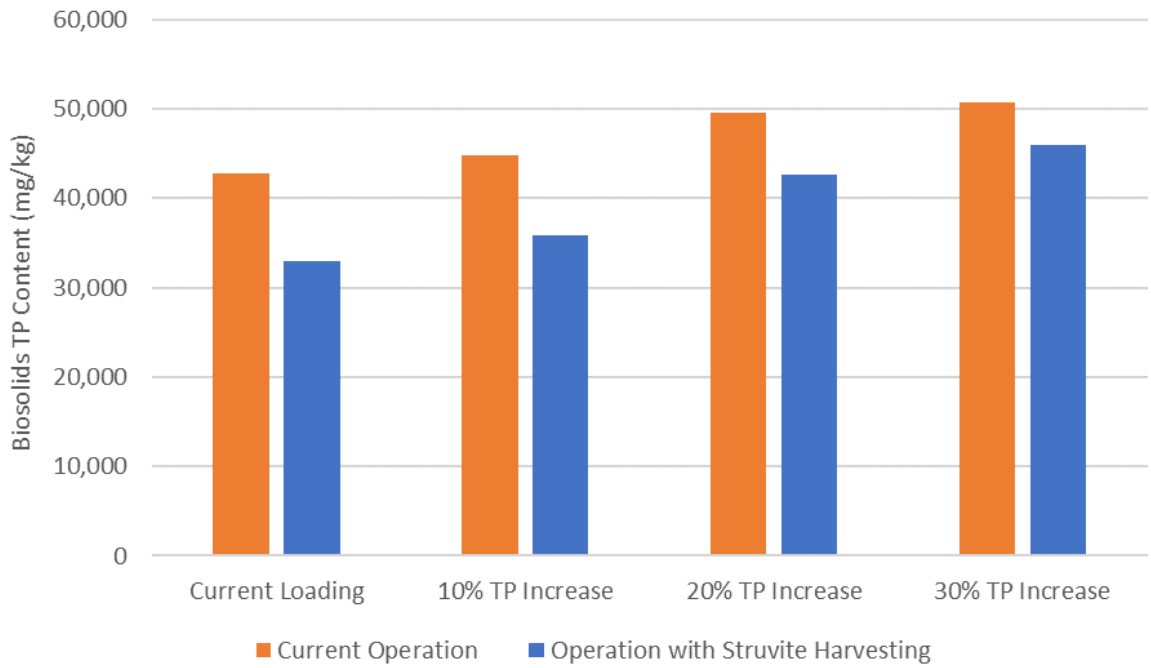

Figure 1-18: Final biosolids phosphorus content of current operation vs. struvite harvesting technologies for the eight evaluation scenarios.

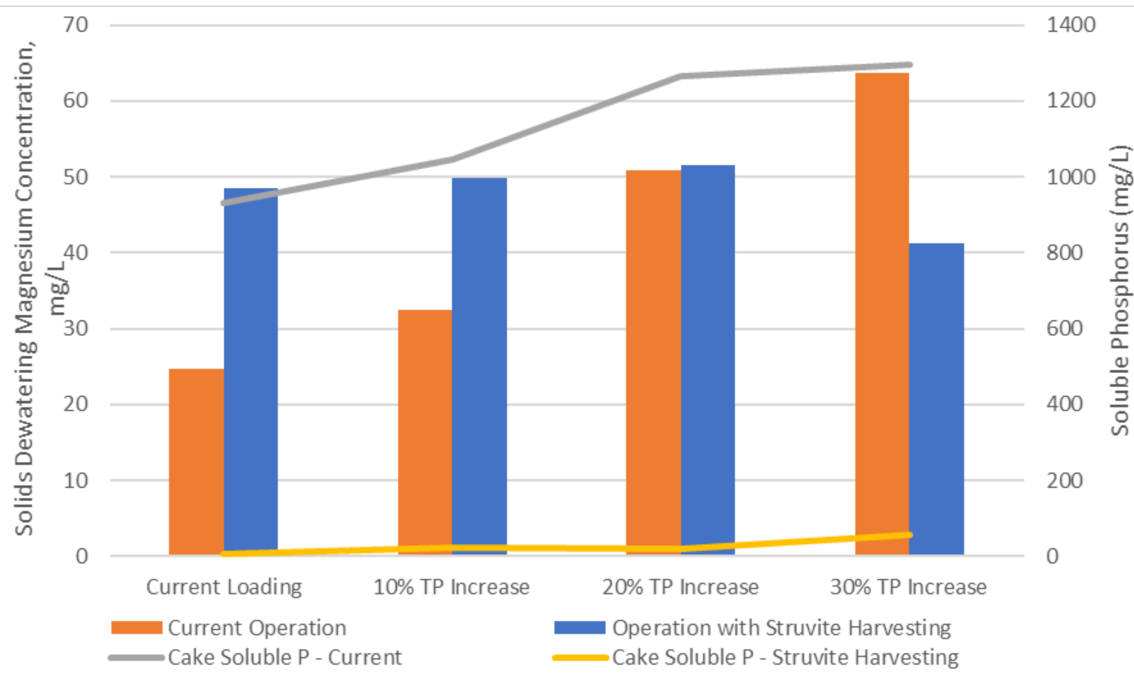

Figure 1-19: Final biosolids phosphorus and magnesium concentrations for both current operation and implementation of a struvite harvesting/sequestration technology.

The four ancillary benefits can provide additional return on investment if a struvite harvesting or sequestration technology is selected.

The PT uncertainty evaluation focused on comparison of the current operational approach versus the implementation of a struvite harvesting technology, however, alternative chemical addition is another approach that can have benefits. $MgCl_2$ is the chemical added for the struvite harvesting technologies requiring additional infrastructure, but some facilities are also exploring the potential to dose $Mg(OH)_2$ directly to anaerobic digesters similar to feeding $FeCl_3$. In lieu of using $MgCl_2$ used in struvite harvesting technologies or $FeCl_3$ dosed to digesters, $Mg(OH)_2$ can provide additional benefits:

- Provides a booster operational pH above 7.5 to drive struvite reaction rates higher.
- The increase of additional pH can provide additional alkalinity and improved digester performance.
- Improved dewaterability with the increased magnesium concentration and decreased soluble phosphorus of the final biosolids. This can increase cake percentage as well as reduced polymer usage.

The addition $Mg(OH)_2$ could potentially replace the use of $FeCl_3$ completely but field testing would have to confirm the level of H_2S is acceptable. Increased pH from $Mg(OH)_2$ addition will slow the rate of H2S production but with the heavy industrial loading noted by operations staff within the collection system $FeCl_3$ addition may still be required.
New York City's Wards Island WRRF performed a comparison of $FeCl_3$ to $Mg(OH)_2$ addition to their anaerobic digesters. The following were noted takeaways from the comparison:

- $Mg(OH)_2$ addition was heavily influenced by the quality of the digested sludge, poor stabilization with lower pH resulted in higher VFA concentrations. These conditions led to higher required dosing rates to reach pH values near 8.
- The Mg to PO_4 dose ratio was 1.5 to achieve a recycle stream phosphate concentration of 40 mg P/L.
- Increased dewaterability was observed with $Mg(OH)_2$ addition.

The existing caustic feed system could potentially be repurposed for the $Mg(OH)_2$ feed system, existing pumps and piping would provide the capacity required with approximately 27 days of storage. The anticipated feed rate assuming a 1.5 molar ratio is approximately 18 gph. Due to the unknowns a pilot study with $Mg(OH)_2$ would be recommended to gain further insight on the site specific molar ratio required to determine if additional equipment is required. Piping modifications and pump modifications were assumed as capital costs input to account for modifications and equipment that has been out of service.

Capital and O&M costs were produced for the three sidestream phosphorus mitigate alternatives for comparison against the current status quo, these were then used to produce 20-year net present value costs. The status quo alternative assumes additional $FeCl_3$ feed to the centrate stream to match equivalent sidestream loading of all the alternatives. Table 1-3 provides a summary comparison of these costs for each alternative.

Table 1-3: Alternative capital and O&M cost summaries.

PARAMETER	STATUS QUO W/ $FECL_3$ ADDITION TO DIGESTERS AND CENTRATE	ANAEROBIC DIGESTION W/ STRUVITE HARVESTING	ANAEROBIC DIGESTION W/ P SEQUESTRATION	STATUS QUO W/ $MG(OH)_2$
Capital Costs[1]	$0	$6,849,000	$5,183,000	$222,000
Net Present Value (NPV) of Annual O&M[2]	$22,883,000	$13,041,000[3]	$15,177,000	$19,852,000
Total	$22,883,000	$19,890,000	$20,360,000	$20,074,000
Payback Period to Current Status Quo4	N/A	6 years	5.5 years	<1 year

1) Capital costs assume a 30% contingency and engineering fees.
2) Assumed payback NPV of 10 years with 3% discount and 3% escalation.
3) Struvite recovery was assumed at 30% with a value of $100 per ton.

Payback periods assumed to status quo with FeCl3 feed to both the digester and centrate stream to provide equivalent levels of treatment phosphorus loading in the return stream.

The least cost alternative from a capital cost is the status quo and alternative adding $Mg(OH)_2$. The addition of $Mg(OH)_2$ alternative requires minimal capital investment due to the existing caustic feed and storage equipment that is assumed for repurposing with the $Mg(OH)_2$. With this alternative, a consistent $FeCl_3$ feed of 4.5 gph is assumed which is less than 15% of current usage; the specific dosing rates of both chemicals would have to be determined during a field pilot to determine site specific dosing ratios. Field implementation of $Mg(OH)_2$ addition to refining the operational costs of this alternative, operations and maintenance staff may have to handle two chemicals.

The alternatives each have a component of uncertainty related to the specific dose rates required, site specific or bench scale testing would be recommended to better understand what the expected dose ratios are. Figure 1-19 provides an example of the payback period compared to the status quo of ferric dosing for the struvite harvesting (Airprex) alternative.

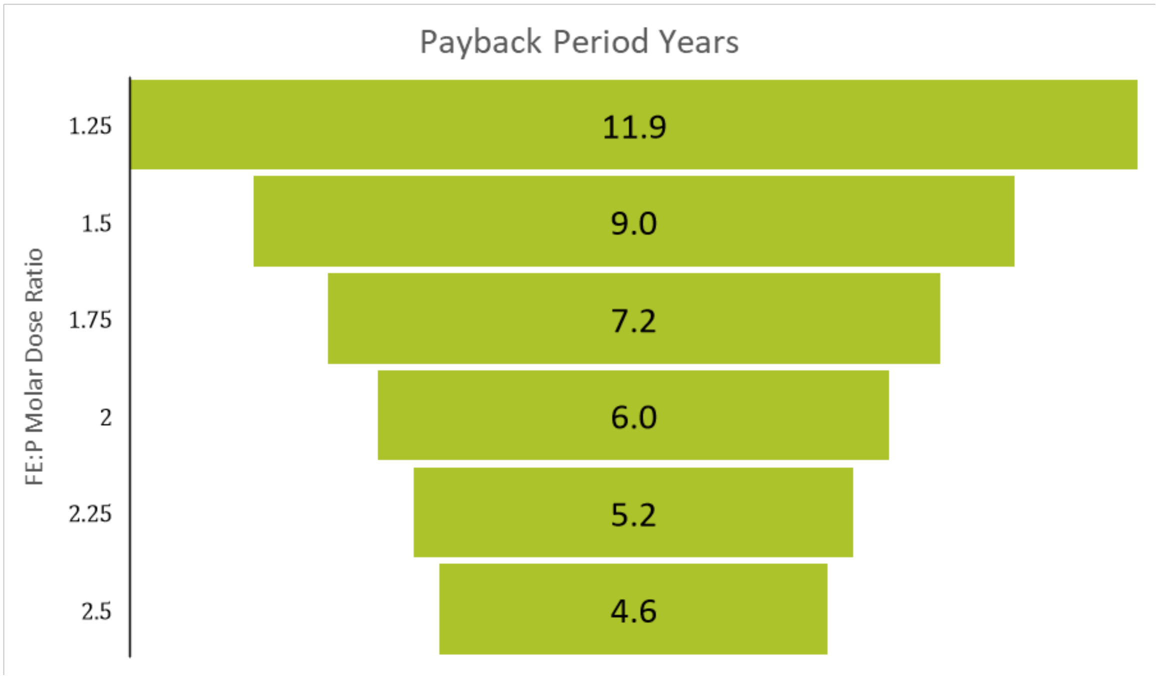

Figure 1-20: Struvite harvesting alternative payback period impact related to comparison of the status quo and ferric dosing ratio. Payback period used for cost comparisons was 6 years, a molar ratio of 2.0.

Further struvite harvesting technology (Airprex) also has an uncertainty level related to the capture efficiency and value of final struvite product, Figure 1-21 provides an example of the impact this can have on payback periods.

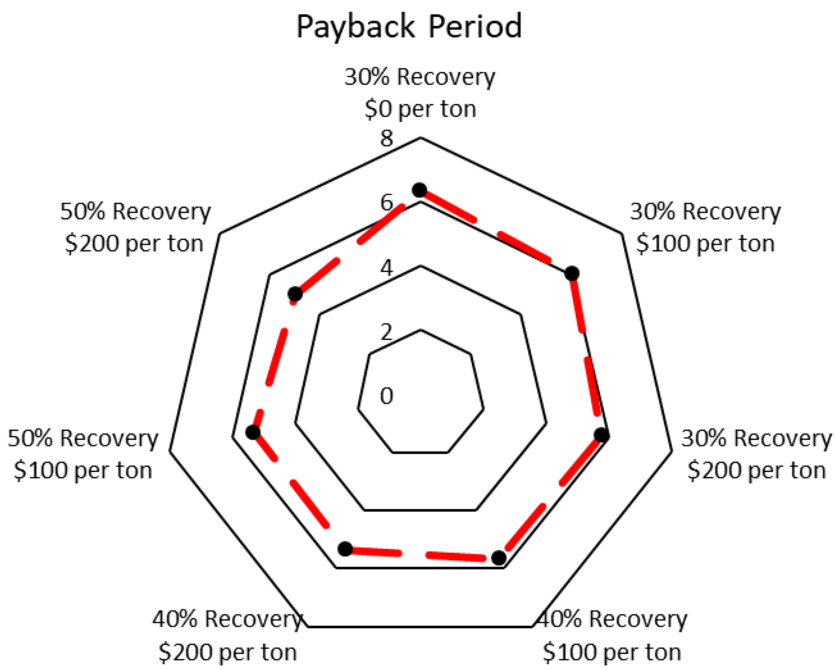

Figure 1-21: Struvite harvesting alternative payback period variability related to product recovery and value. Payback period used for cost comparisons assumed 30% recovery at a value of $100 per ton.

Due to the relative uncertainty related to the dose ratios of all three proposed alternatives it is recommended that Metropolitan Council further refine the assumptions of all or the most preferred alternative. These can be refined with pilot testing in the field and/or bench scale testing to reduce overall cost implications. The addition of $Mg(OH)_2$ is likely the most applicable to field pilot testing due to the presence of unused caustic feed and storage equipment. The struvite harvesting/sequestration alternatives can be refined with some field sampling (identify phosphorus concentrations without addition of $FeCl_3$) and bench scale testing to better identify site specific ratios.

Additionally, due to the relatively unknown causes of EBPR instability special sampling during well and poorly performing periods is recommended. This special sampling could provide better insight into focus areas to improve EBPR performance and the relative impact of the existing sidestream phosphorus loading. If it is determined during this sampling that the sidestream recycle loading does have a significant impact on the mainstream process performance and ultimately effluent water quality piloting of a revised operational approach is recommended.