Preliminary Engineering Report: Phosphorus Removal Upgrade Evaluation for Henrico County Water Reclamation Facility

Prepared for:

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Project Abstract Form

Project Title:
Phosphorus Removal Upgrade Evaluation for Henrico County Water Reclamation Facility

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Abstract

This report presents a design for upgrading phosphorus removal at the Henrico County Water Reclamation Facility (Henrico WRF) to meet increasingly stringent total phosphorus (TP) limits while reducing reliance on glycerol-dependent incidental biological phosphorus removal. Based on a holistic alternative analysis, the proposed design converts the existing process to intentional enhanced biological phosphorus removal by retrofitting out-of-service aeration tanks for return activated sludge (RAS) fermentation and reconfiguring the front end of the existing enhanced nutrient removal trains to provide dedicated anaerobic zones. The sidestream RAS fermentation process produces volatile fatty acids (VFA) to support phosphorus release and uptake by phosphorus-accumulating organisms and to serve as the primary external carbon source for downstream denitrification, with methanol retained only as a backup supplemental carbon source during periods of insufficient VFA in the facility influent. A new metal salt chemical storage and feed facility that is compatible with most of the available chemicals in the market was also designed to provide backup phosphorus polishing during secondary clarification as a contingency measure. Process modeling, hydraulic analysis, and cost evaluation altogether indicate that the proposed improvements provide a practical, resilient, and cost-effective pathway for long-term TP compliance at Henrico WRF.

Summary of Project Team

Yitao Li (Project Lead) led the overall coordination and technical direction of the design. He contributed to the development of design alternatives, guided major technical tasks, and reviewed team deliverables to ensure technical accuracy and consistency. He was specifically responsible for developing the process flow configuration and conducting BioWin model calibration and simulation.

Cyrus Li (Hydraulic Engineer) was responsible for the hydraulic analysis for the proposed process upgrades. This included evaluation of the sidestream RAS fermentation routing configuration and the sizing of associated conveyance infrastructure. He also conducted GIS-based analysis to support the integration of proposed amendments with existing facilities.

Jackson Becker (Project Engineer) was responsible for the cost estimation portion of the project. They determined the expected capital costs for the construction and development of this project and collated the estimated recurring operational costs.

Mingxi Wang (Senior Process Engineer) contributed to the enhanced biological phosphorus removal system design, including anaerobic zone configuration and HRT evaluation, and developed the nitrogen removal strategy. He also evaluated and selected chemical coagulants for phosphorus polishing and performed storage tank sizing and material selection.

Siyi Chen (Process Engineer) was responsible for the design of the RAS fermentation tanks, including evaluating their VFA production capacity for sustaining enhanced biological phosphorus removal activity, assessing sludge splitting ratio, and performing tank volume calculations needed for the system.

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Caroline Nguyen, PhD, PE (Innovation Program Manager)	*Zhiwu Wang, PhD, PE* (Associate Professor) Coach	*Yewei Sun, PhD, PE* (Adjunct Professor) Industry Coach
Malcolm Taylor, PhD, PE (Principal Environmental Engineer)	*John T. Novak, PhD, PE* (Professor Emeritus) Coach	*Molly Sayles, PE* (Principal Engineer)
Loudoun Water	**Fairfax County**	**HRSD**
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1. Executive Summary

Henrico County Water Reclamation Facility (Henrico WRF) must prepare for substantially more stringent phosphorus limits. Effective January 1, 2026, the facility's total phosphorus (TP) waste load allocation will be reduced from 92,623 to 45,689 pounds (lb) per year. Henrico WRF expects a future Virginia Pollutant Discharge Elimination System (VPDES) permit to require compliance with a further tightened annual-average TP concentration of 0.20 mg/L by the early 2030s. At the same time, the Owner has identified major implementation constraints: future compliance strategy should not rely on glycerol, existing chemical feed facilities are in poor condition, and any proposed solution must be cost-effective, flexible, and based on proven full-scale practice.

To address these needs, this Preliminary Engineering Report (PER) recommends converting the existing process from the current 4-stage Bardenpho process with unintentional biological phosphorus removal to a 5-stage Bardenpho process with intentional enhanced biological phosphorus removal (EBPR). The proposed design diverts 7.5% of the return activated sludge (RAS) flow to two abandoned aeration tanks, formerly BNR Trains 3 and 4, to provide approximately 2 days of fermentation hydraulic retention time (HRT) for volatile fatty acid (VFA) generation. The front end of the existing enhanced nutrient removal process was modified to provide dedicated anaerobic zones for enriching phosphorus-accumulating organisms (PAOs). The VFAs directly support EBPR while serving as the primary supplemental carbon source for downstream pre-anoxic denitrification. Methanol is selected as a backup carbon source for post-anoxic denitrification. Supplemental chemical phosphorus polishing using aluminum sulfate is retained as a contingency measure during peak phosphorus loading period or in case of unexpected EBPR upset. This approach leverages existing unutilized infrastructure to reduce capital investment while improving operational flexibility and reducing long-term dependence on chemical phosphorus removal.

Process modeling indicates that the proposed alternative can meet Henrico WRF's future permit requirement under all operating conditions. A hydraulic evaluation was conducted on the RAS fermentation routing, and the cost analysis estimated a capital cost of approximately $3.08 million and annual operating cost of $1,363,000/year, which generates an at least $2 million saving compared to the current condition. In long term, the report also recommends evaluating separation of the upstream water treatment residual stream from the WRF so that the EBPR platform can be paired with future phosphorus recovery technology and protect biosolids land application program. The proposed alternative is also highly compatible with other future mainstream process upgrades, such as densified activated sludge and partial denitrification anammox, and also compatible with solids process upgrades, such as thermal hydrolysis enhanced-anaerobic digestion. Overall, the proposed design provides Henrico WRF with a resilient, cost-effective, and forward-looking basis for meeting both near-term and future TP requirements.

2. Introduction and Problem Statement

2.1. Increasingly Stringent Phosphorus Limit

Henrico County Water Reclamation Facility (Henrico WRF) is a 75-million gallon per day (MGD) utility located in Henrico County, Virginia, serving a population of around 330,000 residents in the county and the surrounding Richmond metropolitan region. Treated effluent from Henrico WRF is discharged to the James River, which is part of the environmentally protected Chesapeake Bay watershed. Beginning January 1, 2026, Henrico WRF is facing a major tightening of its phosphorus requirements. Its total phosphorus (TP) waste load allocation (WLA) is halved from 92,623 to 45,689 pounds (lb) per year. Moreover, Henrico County expects its future Virginia Pollutant Discharge Elimination System (VPDES) TP permit limit to likely be lowered from its annual average of 0.50 mg/L to 0.20 mg/L by 2032 or 2033. Together, these near-term and longer-term regulatory changes in TP discharge limits are expected to create a substantial compliance challenge for the Henrico WRF in the coming years and will require upgrades to its phosphorus removal processes.

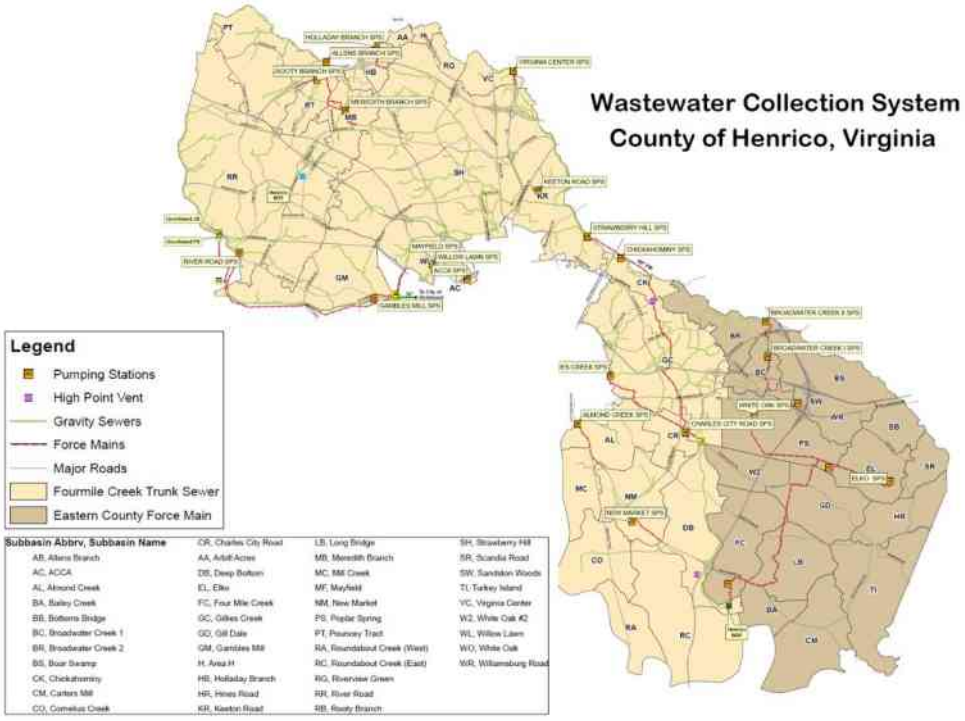


Figure 3-1. Sewershed map of Henrico WRF.

2.2. Henrico County WRF Aging Infrastructure and Chemical Change Implications

In addition to tightened TP limits, Henrico WRF faces uncertainty in the reliability of its existing phosphorus removal strategy. The utility currently uses glycerol as its supplemental carbon source for denitrification. However, it has been observed that stopping glycerol dosing is correlated with an increase in final effluent TP level, suggesting that the current phosphorus removal performance is enhanced by unintentional biological phosphorus removal (BPR) associated with glycerol. According to interviews with WRF staff, the unit price of glycerol has tripled over the past 18 months. Glycerol is traditionally generated as a coproduct of conventional biodiesel production; however, the increasing adoption of renewable diesel technologies, which do not produce glycerol as a coproduct, has likely tightened glycerol

supply and contributed to the recent increase in glycerol price (Department of Energy; US Energy Information Administration, 2023). Due to this market uncertainty surrounding glycerol, future TP compliance strategy should not rely on the unintentional BPR currently associated with glycerol addition. Furthermore, the facility has other aging phosphorus-removal infrastructures, including the polymer and aluminum sulfate storage and feed systems, that are in poor condition and past their expected service life. If metal salt addition is deemed necessary, a new metal salt storage and feed system should be designed given the condition of existing facilities. Henrico WRF desires the flexibility to use a variety of metal salts to better respond to future market conditions. Henrico WRF has also expressed interest in alternative TP removal technologies beyond conventional chemical phosphorus removal. However, based on interviews with WRF staff, the facility is not interested in serving as a demonstration site for emerging technologies. Any proposed alternative must therefore be cost-effective and supported by at least five years of proven full-scale operation.

2.3. Scope of Work

This Preliminary Engineering Report (PER) evaluates phosphorus removal alternatives capable of meeting both near-term and future effluent TP limits at Henrico WRF. The scope includes review of applicable regulatory requirements and design assumptions, site investigation and data collection, process modeling, and a holistic evaluation of candidate alternatives. This report considers carbon source implications with respect to glycerol and methanol, metal salt selection and feed configuration, and opportunities to repurpose existing underutilized facilities at Henrico WRF. Process alternatives are assessed under the assumption that a newly constructed methanol-capable supplemental carbon feed system and new tertiary deep-bed sand filters will be in place and are therefore outside the scope of this PER. The objective is to identify a resilient, forward-looking, and cost-effective phosphorus removal strategy that also maintains operational flexibility, system redundancy, and manageable implementation risk.

3. Regulations

3.1. Current Permit

Henrico WRF currently operates under a 75.0-MGD VPDES individual permit with an annual average TP limit of 0.50 mg/L. In addition to the concentration-based individual permit, the facility is also subject to a current TP WLA of 92,623 lb/year under the nutrient permitting framework. Normalized to the permitted design flow of 75.0 MGD, this current TP mass limit is equivalent to about 0.41 mg/L TP. Therefore, the current phosphorus regulatory framework is effectively governed by both mass-based and concentration-based limits. Total nitrogen (TN) is another important parameter considered as the new phosphorus removal strategy shall not sacrifice or compromise TN removal. Henrico WRF's current permit includes an annual-average TN limit of 5.0 mg/L. Based on analysis of the most recent six months of operating data, the average effluent TN concentration was 3.51 mg/L, consisting primarily of 2.56 mg/L NOx-N and essentially nondetectable level of ammonia-N.

3.2. New and Future Permit

Effective January 1, 2026, Henrico WRF's TP WLA will be reduced from 92,623 lb/year to 45,689 lb/year. At the permitted design flow of 75.0 MGD, this new load limit is equivalent to approximately 0.20 mg/L TP. Looking further ahead, Henrico WRF anticipates that when the current individual permit expires in

2028, the new individual permit will likely contain a compliance schedule requiring full compliance with an annual average TP concentration of 0.20 mg/L by 2032 or 2033. Based on the WRF staff interviews, this upcoming regulatory change is specifically focused on TP, and the regulations do not indicate a new reduced limit for TN or other analytes at that time.

4. Existing Facilities and Process Performance

4.1. Influent Containing Water Treatment Residuals: Benefits and Drawbacks

Henrico WRF receives aluminum-based sludge residuals from the upstream Henrico County Water Treatment Facility (WTF) through the collection system. An evaluation previously performed by Hazen and Sawyer shows that this waste stream in the WRF influent provides a meaningful phosphorus-removal benefit, because an average of 86% of the total aluminum was in the form of soluble aluminum hydroxide colloids which can remove phosphorus by precipitation and adsorption (Hazen and Sawyer, 2018). During the 2017 monitoring period, higher aluminum loading was associated with lower effluent TP loading (*See Appendix A Figure A1*). Based on analysis of the most recent operating data, about 34% of the total influent TP load was removed during primary settling as a result of WTF residuals enhancement (Figure 6). It was also concluded that WTF residuals may improve secondary sludge settleability and digestate dewatering performance (Hazen and Sawyer, 2018).

However, the WTF residuals in the WRF influent have been highly variable and not fully controlled because its loading depends on WTF flow, aluminum dose, raw water turbidity, sludge production, and periodic sludge holding tank cleaning events. Based on historic influent aluminum data, the measured influent aluminum concentration ranged from approximately 1.0 to 20.9 mg/L (5.0 mg/L on average), with higher values generally occurring during mid-summer through early winter. The evaluation by Hazen and Sawyer also reported a typical seasonal pattern with higher summer aluminum loads, which was proven to provide seasonably better TP removal at WRF. For days with relatively low aluminum loads, WRF had to dose aluminum sulfate metal salt during secondary clarification to compensate for the TP removal. In addition, the evaluation reported that WTF aluminum residuals increased the inert sludge production at WRF during primary settling (*See Appendix A Figure A2*), which in turn lowered digester volatile solids reduction (VSR) (Hazen and Sawyer, 2018). The hypothesized mechanisms were: (1) more inert solids increase sludge mass and volume, effectively reducing digester solids retention time (SRT), and (2) aluminum may bind digestible proteins and reduce sludge digestibility (Hazen and Sawyer, 2018). This is an important consideration in this design project because if digester VSR falls below 38%, Henrico WRF may fail to meet the 40 CFR Part 503 vector attraction reduction (VAR) criterion for land application and could be forced to divert biosolids to landfill at a higher cost. According to Henrico WRF, the cost of landfilling biosolids ($85.23/wet ton) is approximately 2.4 times that of land application ($35.25/wet ton). Therefore, for the purpose of this PER, it is reasonable to hypothesize that proactively equalizing or wasting WTF residuals into the collection system based on WRF TP removal demand can optimize metal salt usage for phosphorus removal at WRF and equalize the negative impact on digester VSR.

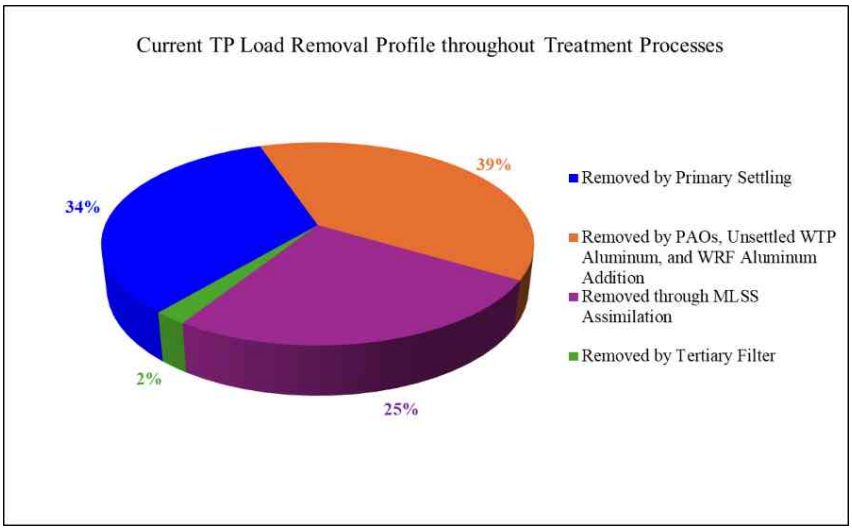


Figure 4-1. Average percentage of TP load removal by different stages of treatment processes

4.2. Unintentional Biological Phosphorus Removal and Nitrogen Removal

As shown in Figure 4-2, Henrico WRF's existing enhanced nutrient removal (ENR) system generally follows a 4-stage Bardenpho process with a small RAS fermentation zone prior to the pre-anoxic zone. Using the most recent six months of operating data provided, the existing enhanced nutrient removal (ENR) system appeared to remove a substantial portion of both phosphorus and nitrogen upstream. As shown in Figure 4-1, the ENR system removed about a total of 64% of influent TP on average with around 25% removed through MLSS assimilation and 39% removed either by phosphorus accumulating organisms (PAOs), unsettled WTP aluminum, and/or WRF aluminum dosing. According to WRF staff, because majority of WTP aluminum has already been settled during primary clarification and WRF only adds aluminum sulfate occasionally for chemical phosphorus removal, this suggests that Henrico WRF's current process already achieves considerable BPR with glycerol. However, since nitrate recycle (NRCY) flow is currently returned to Cell 2, it suggests that the observed BPR activities are unintentionally achieved without dedicated anaerobic zones for PAOs selection. Previous full-scale studies have reported that glycerol might be able to promote the selection of microorganisms that store carbon, such as PAOs (Katya Bilyk, 2011). This may explain the observed unintentional BPR with glycerol at Henrico WRF's ENR process.

As shown in Figure 4-2, the current piping arrangement already provides flexibility for future conversion. Although both PE and NRCY flow are currently fed to Cell 2, the WRF has the capability to redirect NRCY flow to Cell 3 or Cell 4 if a true upstream anaerobic selector (i.e., 5-stage Bardenpho) is needed. Figure 4-2 also suggests that external carbon sources can be fed either to the NRCY channel or to the start of the second anoxic zone.

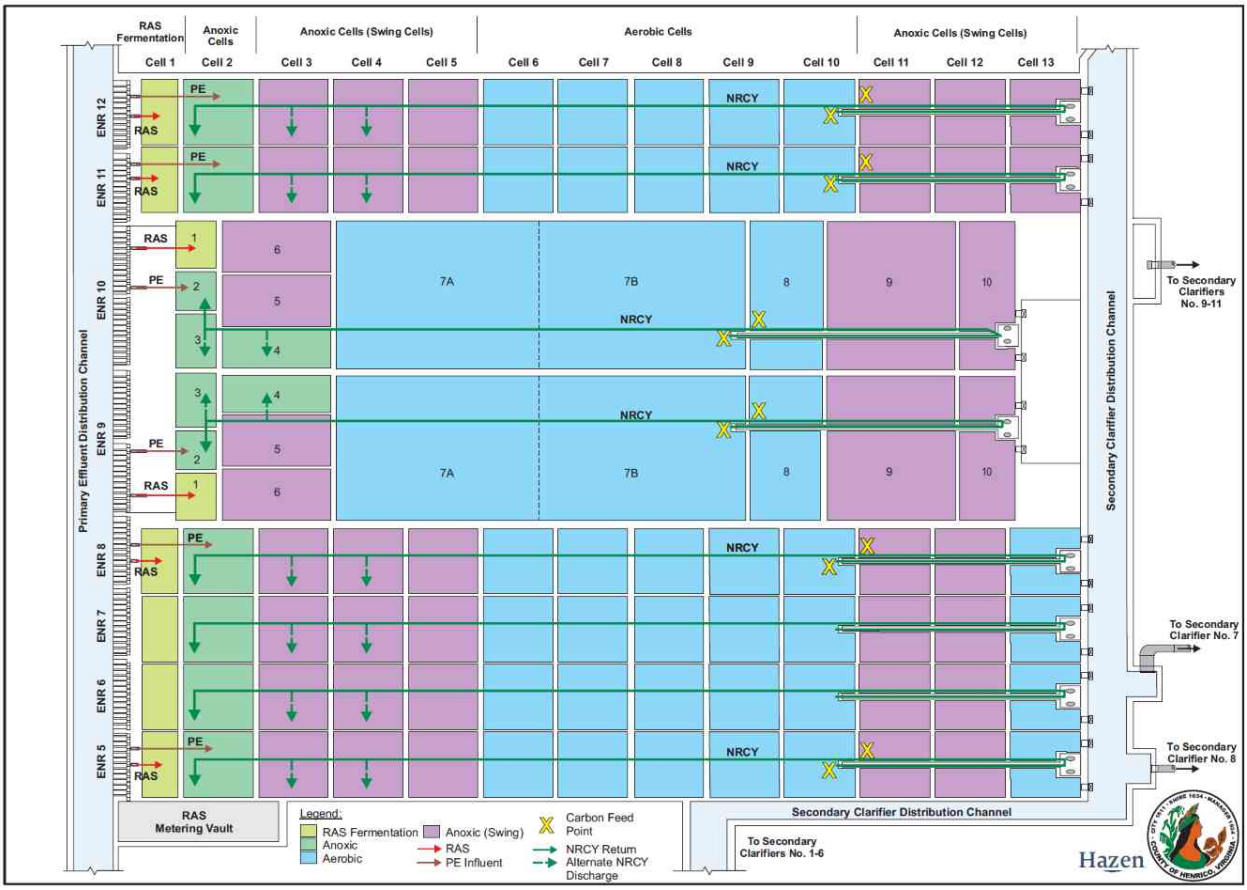


Figure 4-2. Detailed configuration of Henrico WRF's ENR process

4.3. Temporary Chemical Phosphorus Removal using Aluminum Sulfate

Henrico WRF was originally designed with the capability to add aluminum sulfate during primary clarification and to add aluminum sulfate and polymer during secondary clarification for chemical phosphorus removal and settling enhancement. However, according to WRF staff, the secondary polymer system has been difficult to operate reliably because polymer distribution through the manifolds is uneven. Operation staff indicated that polymer underdosing can lead to poor settleability, while overdosing can impair downstream tertiary filterability.

Based on observations during site survey, the three original aluminum sulfate storage tanks with a total volume of 30,000 gallon (gal) and feed system have been taken out of service (*See Appendix B Figure B1*). In recent years, the WRF has instead retrofitted the polymer storage feed system for temporary aluminum sulfate storage and feeding, using it to dose aluminum sulfate to the secondary clarifier process on an as-needed basis to supplement phosphorus removal at around 20 gallons per hour (gph) (*See Appendix B Figure B2*). The current unit cost of aluminum sulfate provided by Henrico WRF is $1.09/gal; however, the total consumption of aluminum sulfate was not recorded by Henrico WRF's Wastewater Information Management System.

4.4. Anaerobic Digestion and Biosolids Land Application as the Phosphorus Outlet

Biosolids cake disposal currently remains as the only permanent sink for phosphorus removal from Henrico WRF's treatment process. The overall solids process flow is shown in *Appendix A Figure A3*. Thickened waste activated sludge (WAS) is blended with primary sludge (PS) in a sludge blending tank before being fed to three anaerobic digesters (with an average SRT of 27.5 days). Digested sludge from these three primary digesters overflows to a fourth digester used as a sludge holding tank prior to centrifuge dewatering. The dewatered biosolids cake averaged about 22.9% TS from July through December 2025 and is currently managed by a land application vendor.

As shown by the most recent digester volatile solids reduction (VSR) data analyzed in Figure 4-3, Henrico occasionally experiences digester VSR below 38%, which is the regulatory threshold commonly used to demonstrate vector attraction reduction (VAR) for land-applied biosolids. As previously discussed in Section 5.1, this risk is associated with the adverse impacts of aluminum residuals on digestion performance. Again, if biosolids can no longer be land applied and must instead be landfilled or incinerated, the facility would spend 140% more cost for biosolids disposal. That being said, for the purpose of this PER, the potential impact of proposed P-removal alternatives on digester VSR should be considered as biosolids landfill costs are generally much higher than annual chemical costs.

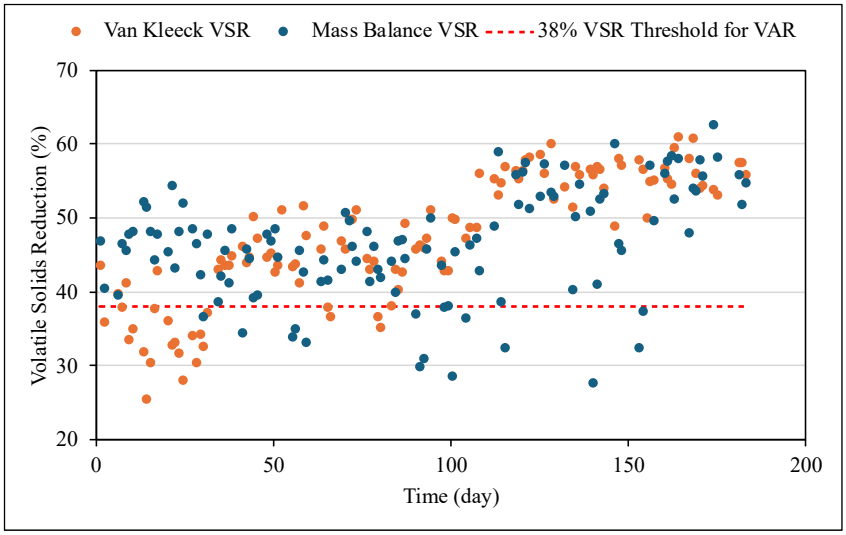


Figure 4-3. Digester VSR calculated by Van Kleeck and mass balance methods during July 1-December 31, 2025

4.5. Other Processes Relevant to P Removal Upgrade

In general, because ordinary activated sludge microbes contain up to 2% P content and PAOs can contain up to 40% P content, secondary clarification solids loss via overflow is a substantial P contributor to effluent TP concentration (WEF Plant Operations and Maintenance Committee, 2017). Tertiary filtration remains to be the last process to remove TP from secondary effluent at Henrico WRF. The WRF has recently replaced granulated carbon filters with new deep-bed sand filters; therefore, the new tertiary filtration process is expected to exhibit better total suspended solids (TSS) and particulate P removal. In addition, Henrico WRF has newly constructed five methanol-compatible carbon source storage tanks with a 100,000-gal total capacity (20,000 gal each). Therefore, the design of these aforementioned facilities is not within the scope of this PER. Other processes that are not directly relevant to this design are briefly summarized in Appendix C.

4.6. Underutilized Facilities

There are three notable underutilized facilities that could potentially be leveraged in this project: four high-purity oxygen activated sludge tanks (BNR 1 to 4), an aluminum sulfate & polymer storage and distribution system, and a secondary process control building (SPCB), depicted below in Figure 4-4. The four BNR tanks were used prior to the addition of ENR 5-12. These tanks were sealed but not demolished due to the high cost of doing so for little gain. If a reaction tank is to be needed for this P-removal upgrading effort, using one or more of these tanks would be much more economically viable than the construction of a new large reaction tank. The tanks would be relatively easy to reopen and repurpose for an alternative use, which makes them an attractive option for this project. The tanks each can contain 2.02 MG, for a total of 8.08 MG, and an engineering drawing is shown in Appendix A Figure A4.

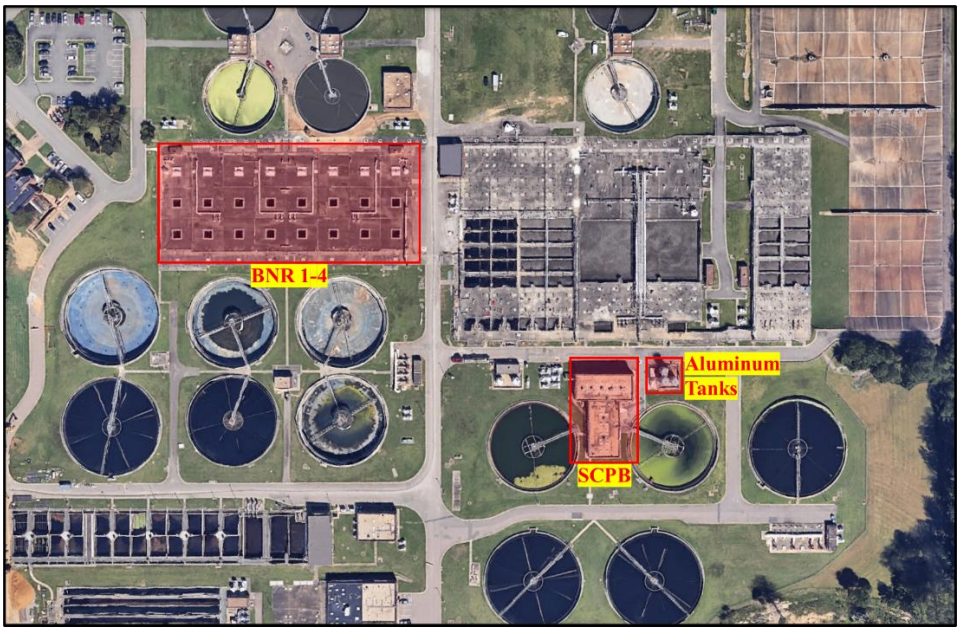


Figure 4-4. Three underutilized facilities that have the potential to be re-utilized for this design.

Another facility worth considering is the aluminum sulfate & polymer storage and distribution system. This system was not maintained due to only being needed in uncommon circumstances and for being split by a simple manifold with inconsistent distribution as mentioned earlier. In addition, the alum storage tanks have leaks and would need to be replaced if the system were to be used for this project. However, the distribution system appears to be intact and has access to distribution points throughout the facility, which could be repurposed if combined with new tanks and a better method to control distribution. These storage tanks and pumps are shown in Appendix B Figure B1.

The last notable underutilized facility is the secondary process control building. The building currently has pumps and tanks connected to the aluminum & polymer distribution system that are unused. This is a wired and plumbed building that could be used as an accessory to any revamps to the aluminum & polymer distribution system. It is largely unused except for being used for temporary aluminum feeding. Any components that need cover or power could be housed in this building, especially those connected to the distribution system. The interior of this building can be seen in Appendix B Figure B3.

5. Alternatives Evaluation

5.1. Design Considerations

The alternative development process emphasizes the following design considerations to meet all requirements from Henrico WRF:

- Guarantee future TP compliance without glycerol, preferably with methanol as the carbon source for denitrification
- Offer operational redundancy and flexibility with metal salts
- Reduce long-term operational cost, including chemical cost and biosolids disposal costs
- Leverage existing facilities if possible to reduce capital cost
- Ensure that proposed alternatives have at least 5 years of proven full-scale performance
- Ensure that the proposed alternatives are compatible with future upgrade and expansion

5.2. Alternative 1 – Mainstream and Sidestream Chemical Phosphorus Removal

Alternative 1 focuses primarily on expanding chemical phosphorus removal through mainstream metal salts dosing based on Henrico WRF's effluent TP removal demand. Under this alternative, metal salt addition would be utilized at the secondary clarifier process to supplement losses in unintentional BPR resulting from the switch from glycerol to methanol. Additional chemical polishing can also be applied during dewatering of anaerobic digester sludge to reduce centrate TP loads back to the mainstream flow. This alternative would require designing and constructive a new metal salt feeding facility with a larger capacity due to loss of unintentional BPR removal capacity.

5.3. Alternative 2 – Controlled Upstream Water Treatment Residual Equalization

Alternative 2 focuses on deliberately leveraging the upstream water treatment alum residuals present in the wastewater influent at Henrico WRF as a means for TP removal. Under this concept, mixing and equalization would be implemented in the sludge holding tank at the upstream Henrico WTF such that alum residuals are discharged in a more controlled and predictable manner based on Henrico WRF's TP removal demands. According to the evaluation by Hazen and Sawyer, the transport time for alum residuals from the upstream WTF to Henrico WRF is around 11.0 to 18.5 hours, making controlled alum equalization and release based on TP removal feasible (Hazen and Sawyer, 2018). While this alternative is attractive from a chemical cost perspective, it requires a high degree of coordination between the upstream Henrico County WTP and Henrico WRF and may further contribute to high alum loading entering the solids process.

5.4. Alternative 3 – Expanded RAS Fermentation and Implementation of Intentional EBPR with Chemical P Removal as Polishing or Backup

Alternative 3 retrofits the out-of-service BNR tanks on site to expand RAS fermentation while implementing true anaerobic selectors ahead of the first anoxic zones, thereby converting the ENR process from unintentional BPR to intentional enhanced biological phosphorus removal (EBPR). Under this

alternative, a portion of the RAS is diverted to retrofitted BNR trains, where sufficient HRT is provided to generate volatile fatty acids (VFAs) for both EBPR and pre-anoxic denitrification. In the active ENR trains, Cell 1 and Cell 2 would be converted to dedicated anaerobic zones, while NRCY is rerouted to Cell 3 as to allow for upstream PAO activity. Methanol is retained only as a backup carbon source for denitrification during cold winter months, seasonal peak loading, or periods of insufficient VFA production. A small ferric chloride storage and feed system is also included as a contingency polishing measure at the secondary clarifier influent.

5.5. Evaluation Basis and Decision Matrix

The three P removal alternatives were compared using a decision matrix in Table 5-1 that reflected the project's primary objectives and the aforementioned design considerations for Henrico WRF. The evaluation criteria included metal salt savings, methanol savings, compatibility with future P recovery, protection of digester VSR and biosolids land applicability, system redundancy and resiliency, operational simplicity, and capital cost favorability. Each criterion was assigned a weighting factor based on its relative importance to long-term TP compliance, operability, and cost after incorporating opinions from WRF staff. Each alternative was then qualitatively scored according to its relative ability to satisfy these criteria, and weighted scores were calculated accordingly to determine the recommended alternative for Henrico WRF.

Table 5-1. Qualitative comparison of phosphorus removal alternatives

Objectives	Weight	Alternative 1: Chemical P Removal	Alternative 2: Chemical P Removal with WTF Residual Control	Alternative 3: EBPR with RAS Fernentation and Chemical P as a backup
Metal Salt Savings	15%	● ○ ○	● ● ○	● ● ●
Methanol Savings	15%	○ ○ ○	○ ○ ○	● ● ○
Compatibility with Future P Recovery	10%	○ ○ ○	○ ○ ○	● ● ○
Protection of Digester VSR/Land Applicability	10%	● ○ ○	● ● ○	● ● ●
System Redanduncy and Resiliency	10%	● ○ ○	● ● ○	● ● ●
Operational Simplicity	20%	● ● ●	● ○ ○	● ○ ○
Capital Cost Favorability	20%	● ● ○	● ● ●	● ○ ○
Total Score		***1.35***	***1.5***	***1.95***

Based on this semi-qualitative analysis in Table 5-1, Alternative 3, intentional EBPR with expanded RAS fermentation and chemical P removal as a backup polishing process, received the highest total score of 1.95, compared with 1.50 for Alternative 2 and 1.35 for Alternative 1, both of which highly rely on chemical P removal. Alternative 3 ranked most favorably because it offered the greatest reduction in long-

term chemical dependence in terms of both metal salts and methanol, the strongest compatibility with future P recovery technologies, the best protection of digester VSR and biosolids land applicability, and the highest degree of P-removal redundancy. Although it was less favorable in operational simplicity and capital cost, its overall advantages in resilience, sustainability, and long-term P control made it the preferred alternative for Henrico WRF. Therefore, a more detailed conceptual design is performed for Alternative 3 herein.

6. Recommended Design – Alternative 3

6.1. Proposed Process Flow

The overall process flow for Alternative 3 is shown in Appendix G Figure G2. In summary, a 5-stage Bardenpho process with designated anaerobic zones and an expanded sidestream RAS fermentation zone is proposed. The sidestream RAS fermentation process is designed to produce readily biodegradable carbon for EBPR. In addition, methanol is used as the external carbon source for post-anoxic denitrification with a backup capability of dosing in pre-anoxic zone. Metal salt is dosed to prior to secondary clarification to chemical P polishing as needed based on actual EBPR performance. Other processes will remain unchanged compared to the current Henrico WRF's process flow. Detailed explanation and implementation measures are further described in following sections.

6.2. Retrofit Out-of-Service BNR Tanks for Expanded RAS Fermentation

In EBPR, the process depends on the availability of readily biodegradable carbon, or VFA, in the anaerobic stage. As previously mentioned, Henrico WRF currently removes around 39% of total influent TP loading during ENR process, with the assumption that majority were attributed to unintentional BPR with glycerol (Figure 4-1). As glycerol is replaced with methanol, it is reasonable to assume the Henrico WRF would lose 39% of TP removal capacity as methanol is not a carbon source that can support BPR. Therefore, for the purpose of this design, the intentional EBPR process should receive sufficient VFA to remove 39% of influent TP load. It should be noted that Henrico WRF currently does not monitor VFA anywhere on a regular basis. However, based on limited historical influent VFA data provided, it appears that influent VFA (including digester dewatering centrate VFA) varies substantially (*See Appendix A Figure A5*). Based the VFA-to-P ratio of 7.5 mg VFA per mg P removed in typical full-scale operation (Dold, 2019), the influent VFA is only sufficient to support the required BPR about 50% of the days where VFA was monitored. During the remaining 50% of the days, the naturally available VFA supply is substantially inadequate (*See Appendix A Figure A5*) and therefore requires VFA supplementation. Under this condition, fermenting a portion of the RAS provides a practical way to generate supplemental VFAs on site and provide consistent substrate for PAOs. The current RAS fermentation cells shown in Figure 4-2 only have an HRT of around 0.4 hours, which is far below the requirement for acting as a fermenter to produce VFA. Therefore, it is determined that the RAS fermentation cells will need to be expanded substantially to provide the capability of generating VFA for supporting the EBPR process and helping maintain more consistent PAO activity across varying influent conditions.

The out-of-service BNR tanks are suitable candidates for this purpose because they already provide the basic physical footprint needed for a fermentation system. Since the tanks already have covers, they are better positioned to maintain the low-oxygen conditions needed for fermentation and odor control. This significantly reduces the amount of new infrastructure required and makes the retrofit more cost-effective than constructing a new dedicated fermenter. The main retrofit effort should focus on restoring the tanks

to dependable service, including repairing cracks, checking structural condition, and replacing appurtenances such as piping, valves, mixing, and access features as needed. According to WRF staff, the BNR tanks have been unused for years without regular inspection and maintenance, the exact conditions of the BNR tanks are currently therefore unknown. More detailed retrofitting strategies should be provided upon detailed in-tank inspections.

Published guidance for sidestream RAS fermentation commonly points to a fermenter HRT of about 35–50 hours, and one widely cited rule-of-thumb is that fermenting approximately 5–10% of the RAS flow at an HRT of 2 days can provide enough VFA to sustain EBPR in the mainstream process (Bryce Figdore, 2019). Therefore, the proposed RAS split flow to the fermenter is selected as midpoint value of 7.5%, and a total of two old BNR tanks are needed for the RAS fermentation (*See calculations in Appendix D*). Previous studies on secondary sludge and RAS fermentation shows that the expected VFA yield is typically around 0.04 mg VFA/mg VS at the 2-day HRT (Cecconi et al., 2024; James E. Huff, 2015). Using this yield and the proposed RAS split, the system design can be used to estimate both the designed VFA production capacity and the corresponding designed EBPR capacity. Under worst-case conditions where no influent VFA is available as mentioned above, the designed RAS fermentation tank is capable of supporting EBPR to carry out about 60%-70% of the required P removal capacity. Therefore, while the RAS fermenter can substantially enhance EBPR capacity and reduce dependence on chemicals, it is not expected to fully meet the phosphorus removal target under the worst-case conditions. The remaining 30%-40% phosphorus load under these worst-case conditions would need to be removed through chemical phosphorus polishing downstream at secondary clarification. However, it should also be noted that an unnecessarily large RAS fermentation volume can lead to excess ammonia production, which would in turn increase the carbon demand for post-anoxic denitrification. A conceptual design of the RAS fermentation and pipeline routings are demonstrated in **Figure 6-1.**

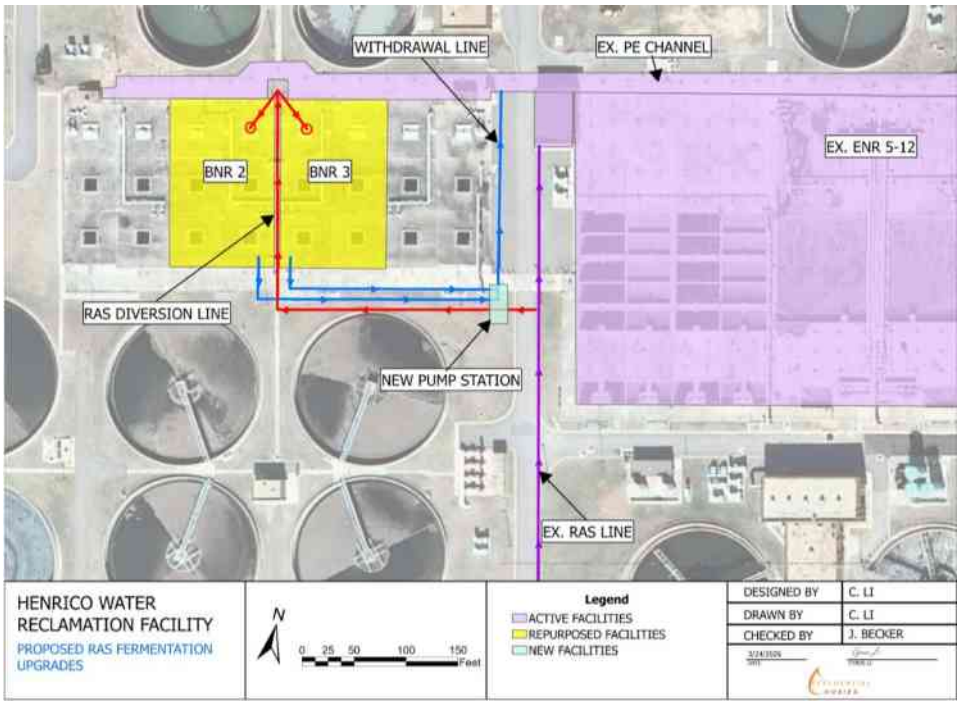


Figure 6-1. GIS map showing proposed layout of RAS fermentation sidestream pipe routing and facilities.

6.3. Designated Anaerobic Zone for Intentional EBPR

The existing Henrico ENR system currently achieves unintentional biological phosphorus removal. This means that phosphorus removal occurs as a byproduct of the process configuration, rather than through a dedicated design for PAOs. Without a true anaerobic selector, PAO enrichment remains inconsistent, and process performance becomes sensitive to influent and external carbon availability. This instability is reflected in the observed decline in P removal when glycerol addition is discontinued. To achieve stable and efficient phosphorus removal, a dedicated anaerobic zone at the very beginning of each ENR train is required. Under anaerobic conditions, PAOs release intracellular polyphosphate while taking up VFA from the primary effluent and storing them as polyhydroxyalkanoates (PHAs). This phosphorus release phase is essential, as it enables subsequent aerobic uptake, during which PAOs utilize stored PHA and accumulate phosphorus beyond normal cellular requirements. To enable this configuration, NRCY flow is proposed to be diverted from Cell 2 to Cell 3, preventing nitrate from entering the anaerobic zone. Since the facility already has the capability to redirect NRCY in this manner, no additional piping is required. In addition, the primary effluent, currently introduced at Cell 2, can be redirected to Cell 1 by operating existing slide gates according to Henrico WRF staff. Therefore, the proposed modification can be implemented using the existing infrastructure without the need for new construction.

The minimum anaerobic HRT required to reliably induce PAO phosphorus release has been established at around 0.25-1 hour in the literature (Barnard, 1984; C. P. Leslie Grady, 1999). The following scenarios evaluate whether the proposed anaerobic zone configuration meets this threshold under varying flow and operational conditions. A flow of 40 MGD is evaluated for average-condition scenarios rather than the calculated six-month average of 36.7 MGD, to provide a conservative planning margin. A peak flow of 75 MGD is evaluated for peak-flow conditions. All calculations in different scenarios are be shown in Appendix E. The combined HRT of Cells 1 and 2 under different conditions are summarized below, and the calculations show that the anaerobic HRT is sufficient at all conditions including peak:

- Anaerobic zone HRT of 1.1 hours at 40 MGD flow with one train not in service
- Anaerobic zone HRT of 1.0 hours at 40 MGD flow with two trains not in service
- Anaerobic zone HRT of 0.7 hours at 75 MGD flow with all trains in service

6.4. Nitrogen Removal using Methanol

The selection of an external carbon source is a key operational decision because it directly affects both denitrification performance and long-term cost. Henrico WRF currently uses glycerol as the supplemental carbon source. Glycerol supports efficient denitrification and has been shown to achieve higher specific denitrification rates than many alternatives (Chen et al., 2013), making it suitable for meeting stringent nitrogen limits. However, its relatively high unit cost results in substantial annual expenditure at full-scale operation.

Methanol is a widely used alternative that offers a clear cost advantage. Although methanol-fed systems require an acclimation period due to the slow growth of methylotrophic bacteria (Yin and Guo, 2022), stable performance can be achieved once the microbial community is established. Therefore, while glycerol provides faster kinetics, its cost disadvantage makes methanol a more economical option, particularly for long-term operation or supplemental use.

Current glycerol usage at Henrico WRF is 972,360 gal/year at $3.52/gal, resulting in an annual cost of approximately $3,425,381. In comparison, methanol at $1.80/gal, based on procurement costs reported by two WRRFs in Virginia, leads to significantly lower costs. Because RAS fermentation also produces ammonia due to mineralization of decayed biomass, it can increase NO_3 production during nitrification and, in turn, increase denitrification demand in anoxic zones. After considering the additional denitrification demand with RAS fermentation, the estimated methanol usage is 333,573 gal/year, with a total cost of $600,431 per year. As can be seen, these values represent a substantial cost reduction compared to current glycerol use. Detailed calculations are shown in Appendix E.

Because of the ammonia production during RAS fermentation, feeding RAS fermentate to post-anoxic zones for denitrification may cause ammonia and NO_3 breakthrough due to the nature of the 5-stage Bardenpho process as shown in *Appendix G Figure G2*. Therefore, the fermentate containing internally produced VFAs and ammonia is only designed to serve as the supplemental carbon source for pre-anoxic zones, while methanol serves as the external carbon source for the post-anoxic zones if necessary. In this role, the lower unit cost of methanol provides a clear long-term operational advantage over continued glycerol use.

6.4.1. Nitrogen Removal Configuration

Under Alternative 3, the nitrogen removal configuration downstream of the new anaerobic zone (Cells 1–2) remains structurally identical to the existing ENR process. The treatment sequence from Cell 3 onward is as follows.

Cells 3–6 (Pre-anoxic Zone): Denitrification is driven by the readily biodegradable COD present in the incoming primary effluent, supplemented by the internally produced VFAs generated in the expanded RAS fermentation system. NRCY from the end of the first aerobic zone is redirected to Cell 3, delivering nitrified mixed liquor for denitrification while keeping Cells 1–2 strictly anaerobic. No methanol is required in this zone for denitrification under normal operating conditions.

Cells 7–10 (Pre-aerobic Zone): Nitrification of ammonia to nitrate occurs in the aerobic zone. Dissolved oxygen is maintained to ensure complete nitrification before flow enters the post-anoxic zone.

Cells 11–13 (Post-anoxic Zone): By the time mixed liquor reaches the post-anoxic zone, influent COD has been substantially consumed in the pre-anoxic and pre-aerobic zones. An external carbon source is therefore required to drive denitrification in this stage. Under Alternative 3, methanol is dosed to the post-anoxic zone as the clean external carbon source, replacing the glycerol currently used at Henrico WRF.

6.4.2. Methanol Demand Estimation

To size the methanol feed system, the NOx removal demand in the post-anoxic zone was estimated from July–December 2025 daily plant operating data. For each sampling day, the NOx concentration difference between the post-anoxic influent and effluent represents the daily NOx removal demand that must be met by the external carbon source. The methanol dosing requirement for biological denitrification is established at 3 g methanol per g NO_3-N removed (Bryce Figdore, 2019; Methanol Institute, 2015). This value is used as the basis for estimating the methanol demand in the post-anoxic zone.

Based on sampling days between July and December 2025, the average daily NOx removal demand in the post-anoxic zone was 3.83 mg/L at an average flow of 36.75 MGD, corresponding to an average NOx load of 1,173.9 lb/day. At the stoichiometric ratio of 3 g methanol per g NO_3-N, the baseline methanol

demand is 533.6 gal/day, or 194,760 gallons/year. The expanded RAS fermentation system releases additional ammonia through biomass decay, which increases the downstream NOx load reaching the second anoxic zone; including this additional load of 836.59 lb/day, the total NOx removal demand is 2,010.5 lb/day and the methanol demand is 913.9 gal/day, or 333,573 gallons/year, which serves as the basis for the carbon source cost presented in Section 7.2. Detailed calculations are provided in Appendix E.

6.5. New Metal Salt Feeding Facility as the Backup Phosphorus Polishing Process

Metal Salt Selection

Three candidate metal salts were evaluated for chemical phosphorus polishing under Alternative 3: aluminum sulfate, polyaluminum chloride (PACl), and ferric chloride ($FeCl_3$). The evaluation considered unit chemical cost, annual chemical cost, and sludge production, with annual chemical cost identified as the primary selection criterion since chemical polishing serves as a supplemental process to EBPR and minimizing long-term operational cost is a key objective.

Because the chemical unit costs used in this analysis are provided by two WRRFs in Virginia in addition to Henrico WRF, the determined costs are considered closely representative of regional market conditions. As shown in Table 6-1, although aluminum sulfate requires a higher annual consumption volume than PACl (117,460 gal/year vs. 82,867 gal/year), its unit cost of $1.09/gal is significantly lower than PACl ($2.73/gal) and $FeCl_3$ ($2.52/gal), resulting in the lowest annual cost of $128,031/year. This corresponds to savings of approximately $98,000/year compared to PACl ($226,226/year) and $89,000/year compared to $FeCl_3$ ($217,400/year). Sludge production was also evaluated, as increased sludge generation leads to higher solids handling costs. Ferric chloride produces less sludge (1.914 g sludge/g metal) compared to aluminum sulfate and PACl (2.891 g sludge/g metal), which is a potential advantage. However, ferric chloride has several drawbacks, including the potential to cause discoloration in equipment and treated water, which may cause extra maintenance efforts and effluent aesthetic issues (Edzwald, 2010). Aluminum sulfate has been used by Henrico WRF for chemical P removal and settleability improvement for decades; therefore, the operators have sufficient experience with it. Altogether, based on this evaluation, aluminum sulfate is selected as the preferred metal salt polishing chemical for Alternative 3 due to its lowest annual cost and consistent performance in Henrico WRF's P removal history.

Table 6-1, Chemical Coagulant Comparison for Phosphorus Polishing under Alternative 3.

	Aluminum Sulfate	PACl	Ferric Chloride
Chemical Formula	$Al_2(SO4)_3 \cdot 14H_2O$	Proprietary	$FeCl_3$
Metal Concentration (% wt)	4.99	7.14	13.8
Sludge Production (g sludge/g metal)	2.891	2.891	1.914
Consumption (gal/month)	9,654	6,811	7,091
Consumption (gal/year)	117,460	82,867	86,270
Unit Price ($/gal)	$1.09	$2.73	$2.52
$/Year	$128,031	$226,226	$217,400

Metal Salt Storage Tank Sizing and Material Selection

Virginia Administrative Code 9VAC25-790-840 requires that chemical treatment facilities maintain a minimum on-site supply of 30 days of chemical storage (Commonwealth of Virginia). Based on Table 6-1, the monthly aluminum sulfate consumption rate of 9,654 gal/month was used as the sizing basis, corresponding to the average demand projected under Alternative 3. This yields a minimum code-compliant storage volume of approximately 9,654 gallons. To satisfy both regulatory requirements and the owner's request for operational flexibility, the storage system has been designed with a total capacity of 22,500 gallons, equivalent to approximately 70 days of supply at average alum usage. This additional storage volume provides a practical safety margin to account for supply chain disruptions, delivery scheduling variability, and short-term fluctuations in chemical demand, all of which are common in full-scale wastewater treatment operations.

Regarding tank materials, the storage tank for aluminum sulfate will be constructed from crosslinked polyethylene (XLPE). XLPE is a thermoset material widely used in municipal water and wastewater treatment for chemical storage due to its excellent chemical resistance, durability, and compatibility with a wide range of coagulants, including aluminum sulfate, ferric salts, and polymer-based chemicals. The selection of this material allows for temporary or supplemental use of alternative chemicals without requiring significant modification. It provides the owner with the ability to respond to changes in chemical pricing, availability, or performance needs, while maintaining reliable phosphorus removal and compliance with effluent limits. Additional tank material selection considerations were included in Appendix F.

6.6. BioWin Process Modeling

BioWin modeling was employed to simulate whether the proposed design can comply with Henrico WRF's new permitted effluent limit as described in Section 3.2. To ensure the simulated results are representative of the performance in practice, the BioWin model representing the current Henrico WRF's process flow (*See Appendix G Figure G1*) was first calibrated to its actual treatment process performance by adjusting influent wastewater fractions and process kinetic parameters. The calibrated model performance for each process was compared against the performance data provided by Henrico WRF (*See Appendix G Table G1*). Nearly all process performance parameters were within 10% of the actual process performance, suggesting the model is calibrated. Then, process flow in Alternative 3 was implemented to the calibrated model (*See Appendix G Figure G2*). The simulated effluent quality shown in Table 6-2 indicates that the designed process flow in Alternative 3 was able to achieve TP and TN concentrations below the discharge permit limit under both the 40-MGD normal flow and the 75-MGD peak flow conditions. It should be mentioned that the designed process is capable of further reducing the effluent TP and TN levels but at a higher chemical cost.

Table 6-2. Effluent quality modeled using BioWin for Alternative 3

Effluent Parameter	Normal Flow (40 MGD)	Peak Flow (75 MGD)	Discharge Permit (monthly average)
pH	6.7	6.5	6.0 - 9.0
TP (mg/L-P)	0.02	0.09	0.2
TN (mg/L-N)	3.82	4.88	5.0
TSS (mg/L)	0.0	0.0	8.0

6.7. Hydraulic Analysis

The hydraulic analysis for Alternative 3 is focused on the proposed RAS fermentation sidestream, as the recommended modifications are not expected to materially alter the existing hydraulic grade line through Henrico WRF's mainstream process. Under the proposed routing, 7.5% of the combined RAS flow from east and west secondary clarifiers is diverted from the main header to repurposed BNR trains 2 and 3 for sidestream fermentation, then returned to the PE channel upstream of the active ENR trains after required fermentation detention time has been achieved.

Hydraulic losses were estimated using the Darcy-Weisbach equation for pipe friction and standard minor-loss coefficients for valves, bends, branch connections, and flow division. Detailed loss calculations are included in Appendix H. Based on this evaluation, the proposed sidestream layout uses 12-inch HDPE for the common RAS diversion and return headers, and 8-inch HDPE for the individual BNR train branches. The pipe diameters were selected to prevent the settling of RAS solids during normal operation and consistent with 9VAC25-790-690(F)(3) of the Virginia Administrative Code, which requires suction and discharge piping for sludge return facilities to maintain a velocity of not less than 2 ft/s at normal sludge return rates. HDPE was selected as it is well suited for buried installation, provides strong corrosion resistance and durability, and offers a smooth interior reducing friction losses.

Two pump services were identified: The RAS diversion pump, which withdraws flow from the main RAS header and conveys it to the repurposed BNR fermentation tanks, and the fermentation tank withdrawal pumps, which return fermented sludge upstream to the PE channel. One withdrawal pump is recommended for each active fermentation train. Using the design flow basis of 7.5% of total RAS (or 1.96 MGD under historical average RAS flow conditions), the preliminary total dynamic head (TDH) of these pump services was estimated at approximately 6.9 ft for the RAS diversion pump and 2.9 ft for each fermentation tank withdrawal pump, with safety margin. For conservative pump sizing with worst-case peak RAS flows, TDHs of approximately 21.5 ft and 18.8 ft corresponded with flow rates of 4.0 and 2.0 MGD, respectively.

Under the proposed pipe routing, RAS fermentation inflow and outflow lines to the BNR tanks are routed in close proximity, allowing the RAS diversion pump and the fermentation tank withdrawal pumps to be grouped within a single local pump station area. This arrangement is expected to simplify access and improve the maintainability of the proposed pumps, valves, and associated piping. Other routing alternatives can be considered if Henrico WRF prefers a different tie-in location, access arrangement, or maintenance configuration. Final design should confirm pump selection, tie-in elevations, and detailed layout once owner preferences and field constraints are finalized.

7. Cost Analysis for Alternative 3

7.1. Capital Costs

There are two major categories that the capital expenses on this project fall into: the cost of converting BNR tanks 2 and 3 to fermenters and reconstructing the alum distribution system. Costs were estimated using RSMeans where possible and by seeking out vendors where RSMeans didn't have data.

In order to estimate the cost of retrofitting the BNR tanks, four main components were identified as making up the total cost. These were the inspection and repair of the tanks, the new piping design, new pumps, and the reinstallation of mixers. The tanks have not been maintained since their use was discontinued, so an important step is inspecting the condition of the tanks and making any necessary repairs. For example, there may be structural issues in the concrete or leaks in the plumbing that would prevent simply piping RAS into them. However, reusing old infrastructure will avert much of the major expense compared to constructing a new tank, since the earthmoving and initial laying of concrete will have comprised a significant fraction of the initial construction costs. We estimated that the inspection and any necessary repairs would only cost 20% of the cost to construct a new tank, since a recent project repurposed a tank that had been unused from the same time as the BNR tanks and required little work. The new pipe system, as depicted in Figure 6-1 in Section 6.2 above, was simple to cost. After selecting the pipe types (12" HDPE pipes for handling combined flows and 8" HDPE pipes for flows to and from the individual tanks), identifying a representative per-foot cost, and applying a factor of 0.3 to account for fittings (as recommended in RSMeans), the cost was calculated for the lengths depicted in the schematic. The pumps were similarly easy to cost once the hydraulic profile was completed, since the main factors in selecting a pump were the hydraulic head and the flow volume. Lastly, the cells of each tank already have an opening in the top to allow a mixer to be installed, and so after identifying a reasonable representative cost for each mixer, the cost to install a mixer in each cell was directly calculated.

The current alum storage and distribution system is sufficient for this project, but it is past its design life, so repairs and replacements will be needed in order to continue operation. The three major components of the restoration will be the new piping, the feed pump, and the chemical storage tank. The piping estimation was conducted in the same way as that of the BNR retrofit, but for 2" PVC pipe in place of the HDPE pipes. The current design only requires one peristaltic pump connected to the distribution system, since the flows are quite low and variable. Since the inability to precisely control the amount of alum going to each clarifier was a concern, the design includes a valve and flow meter in front of each distribution point to manually control the amount of alum entering each clarifier. The cost of the alum storage tank was estimated by deriving a reasonable cost per gallon for large tanks, since most commercially available tanks do not reach the 22,500 gallon capacity required for this design, and then calculating the cost based on our desired capacity.

After applying a factor of 0.25 to account for overhead and additional expenses, such as labor, permits, etc., as well as adjusting the prices found in RSMeans for inflation based on consumer price indexes, the final estimated cost for this project is $3,076,000. The cost estimation spreadsheet is in Appendix I.

7.2. Operating Cost Comparison Between Alternatives

There are three primary recurring operating costs to consider for this project: aluminum sulfate, methanol, and electricity. An estimated annual chemical cost comparison is performed for all three alternatives listed in Section 5. The estimation was based on BioWin simulations for the three alternatives. As shown in Table 7-1, Alternative 3 exhibits the lowest annual aluminum sulfate and methanol costs, totaling to around $728,000/year, among the three alternatives. This is attributed to the partial replacement of metal salts by EBPR for P removal and partial replacement of methanol by internally generated carbon source

via RAS fermentation. In addition to the chemical cost, the last significant new recurring cost is the electricity requirement of the pumps and mixers. Between these two categories, the expected electricity cost is approximately $635,000/year, which is further broken down in Appendix I. Together, for Alternative 3, the combined annual operating cost is estimated to be approximately $1,363,000/year, which is even substantially lower than the current glycerol cost of $3,425,381/year.

Table 7-1. Comparison of annual chemical cost between three alternatives

Alternatives	Alum. Sulfate ($/year)	Methanol ($/year)	Total ($/year)
Alternative 1: Chemical P Removal	$512,124	$919,800	$1,432,000
Alternative 2: Chemical P Removal with WTF Residual Control	$409,699*	$919,800	$1,329,500
Alternative 3: EBPR with RAS Fernentation and Chemical P as a backup	$128,031	$600,431	$728,000

*Assumed a 20% aluminum sulfate saving attributed to WTF residual discharge optimization

7.3. Nutrient Credit Exchange Revenue

Henrico County WRF is actively participating in the Chesapeake Bay nutrient credit exchange program. The fraction of the nitrogen and phosphorus permissible waste load allocations that are used by Henrico County WRF can be sold to other industry or municipal dischargers in the Chesapeake Bay area for revenue. Based on the nutrient removal performance modeled using BioWin as shown in Table 6-2, the estimated waste load from Henrico WRF is expected to be 487,056 lb N/year and 4,870 lb P/year (Table 7-2), leaving approximately 654,482 lb N/year and 40,819 lb P/year of sellable nutrient load. Subsequently, according to Henrico WRF's most recent nutrient credit selling prices of $0.80/lb for N and $4.73/lb for P, the future annual revenue from nutrient credit trade for Henrico WRF is estimated to be $716,659/year if Alternative 3 is adopted (Table 7-2), which can offset approximately 53% of the annual operating cost.

Table 7-2. Estimated annual revenue from nutrient credit exchange for Henrico WRF

Nutrient	Waste Load (lb/year)	Nutrient Credit Exchange Revenue ($/year)
N	487,056	$523,585**
P	4,870	$193,074**
Total	--	$716,659

Estimated based on Henrico WRF's historical nutrient credit selling prices of *$0.80/lb for N*** and ***$4.73/lb for P***

8. Future Considerations

Phosphorus is increasingly viewed as a strategic mineral rather than only a pollutant. Continued import of alum residuals from the WTP helps current phosphorus removal, but it also binds phosphorus into an aluminum-rich solids matrix that is unfavorable for future phosphorus recovery and can interfere with technologies such as struvite recovery. The same imported aluminum also harms digester VSR, which directly affects biosolids beneficial use.

From a long-term resource-recovery perspective, the facility should ultimately aim to reduce or eliminate the WTP residual stream entering the WRF, or at minimum isolate it from the liquid and solids processes that control digestion and phosphorus recovery. Once that stream is removed or substantially reduced, the intentional EBPR platform proposed in Alternative 3 becomes much more valuable. Biological phosphorus can then be released during digestion in a form that is much more compatible with downstream phosphorus-recovery technologies. This creates the opportunity to produce marketable phosphorus products, generate offsetting revenue, and reduce recycle loading to the mainstream process.

Accordingly, the recommended strategic roadmap for Henrico WRF is: first, implement Alternative 3 to establish stable intentional EBPR and reduce dependence on glycerol; second, evaluate long-term isolation of WTP alum residuals from the Henrico WRF; and third, pair the resulting EBPR-rich digestion sidestream with phosphorus recovery. That integrated roadmap would improve TP compliance, protect the biosolids land application program, lower recirculated phosphorus load, and create a future revenue opportunity rather than treating phosphorus solely as a compliance cost. Furthermore, the proposed Alternative 3 is also highly compatible with other future mainstream process upgrades, such as densified activated sludge and partial denitrification anammox, and also compatible with solids process upgrades, such as thermal hydrolysis enhanced-anaerobic digestion.

Appendix A:

Supplemental Figures

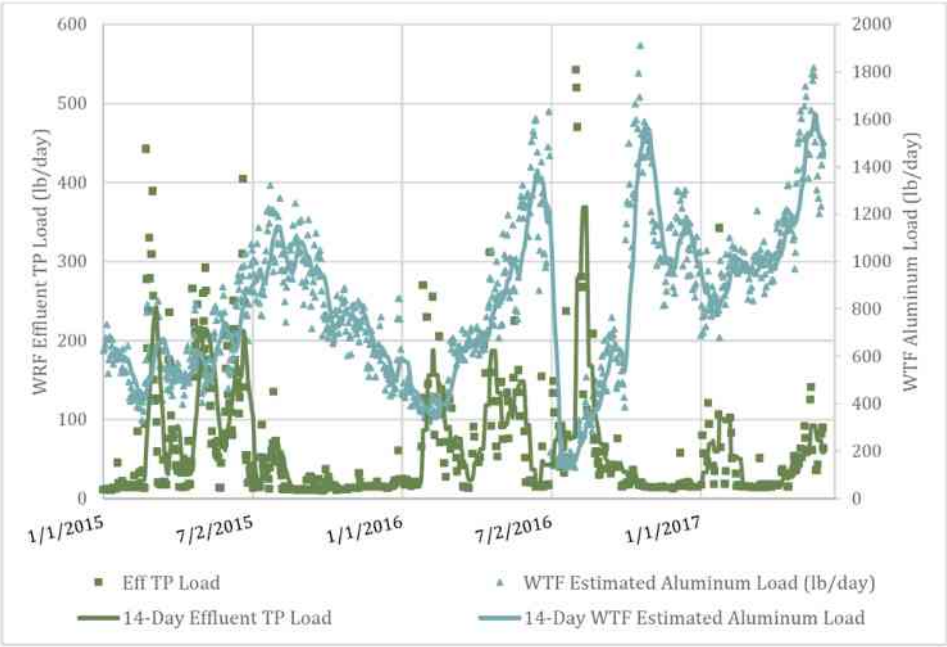


Figure A1. Effluent TP load relative to aluminum load during the 2017 monitoring period reported by Hazen and Sawyer demonstrates TP removal capability by WTF residuals (Hazen and Sawyer, 2018)

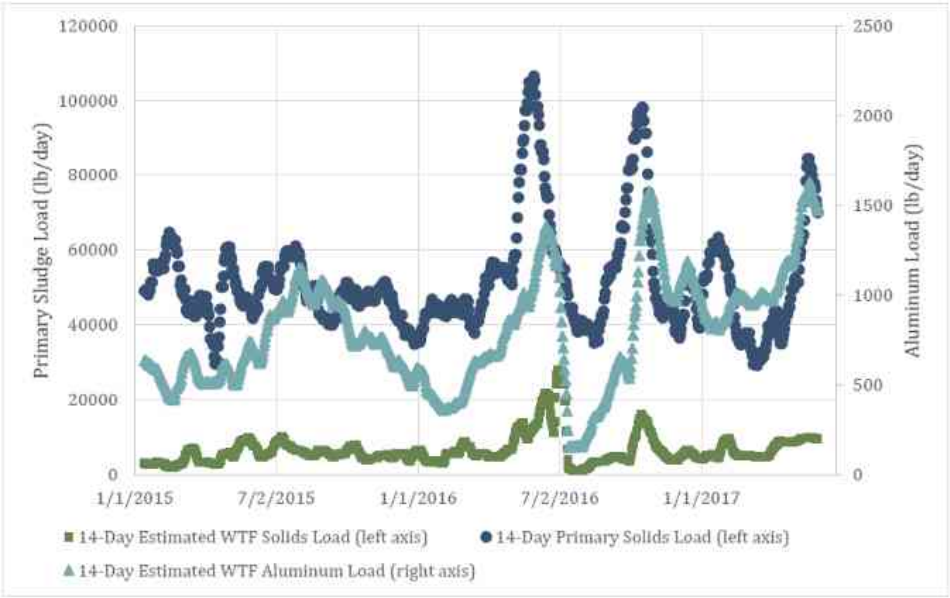


Figure A2. Higher WTF aluminum load correlates with higher WRF primary sludge production (Hazen and Sawyer, 2018)

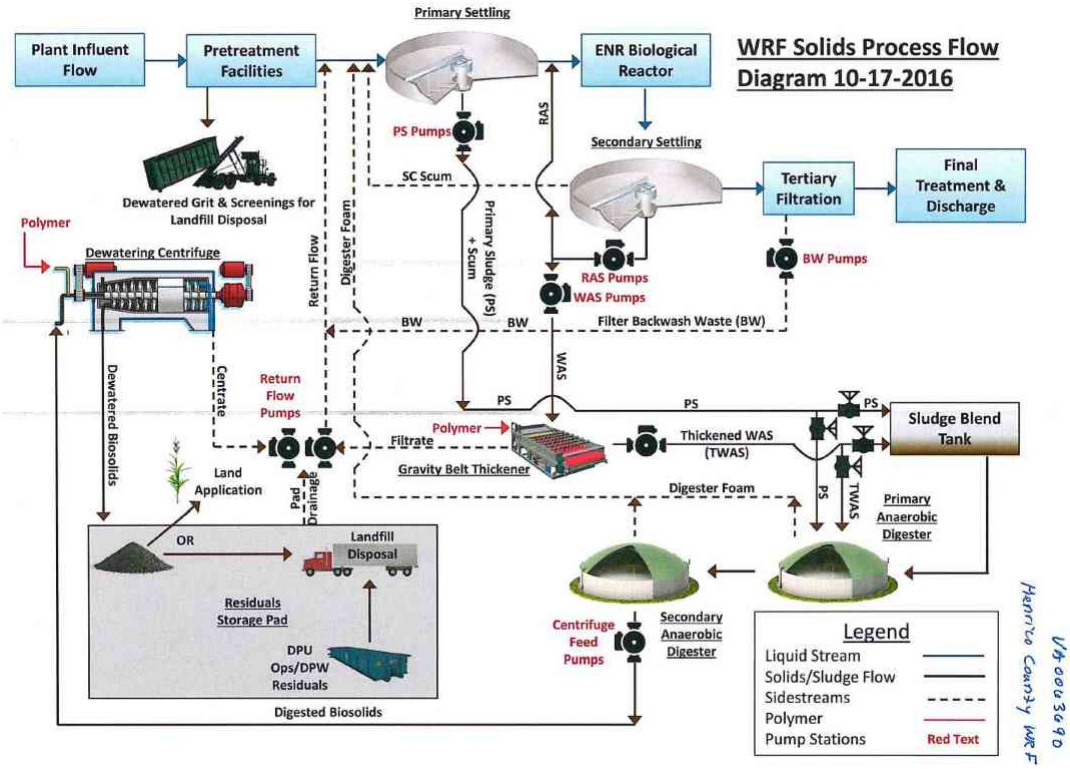


Figure A3. Henrico WRF solids process flow diagram

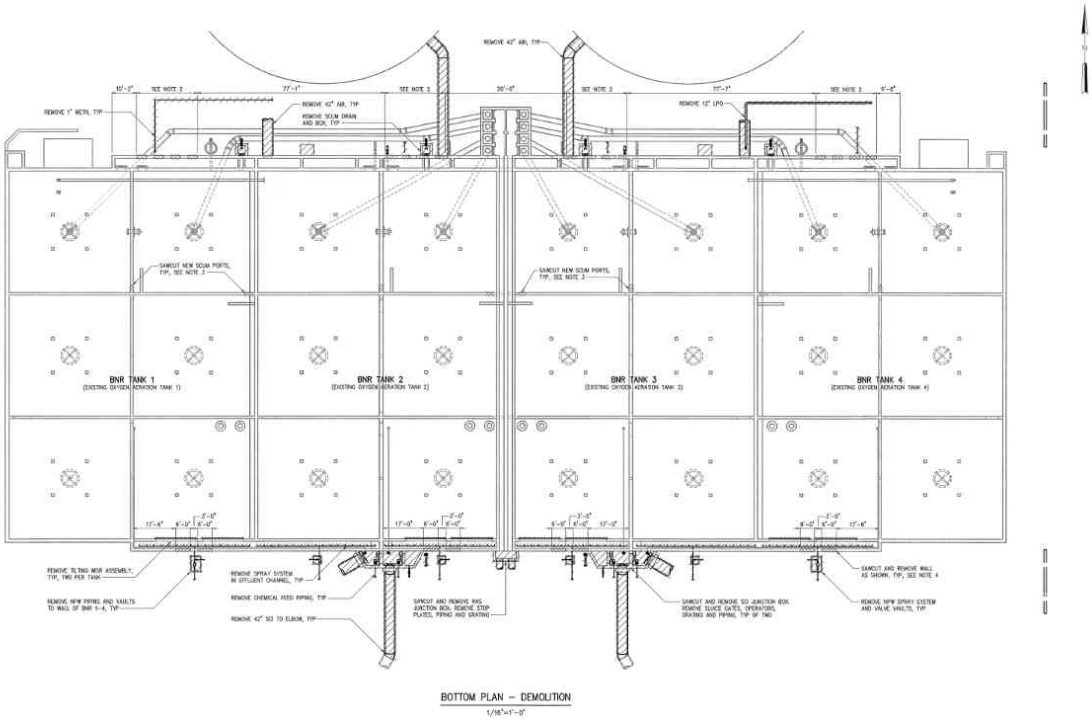


Figure A4. Engineering draw and configuration of BNR 1-4

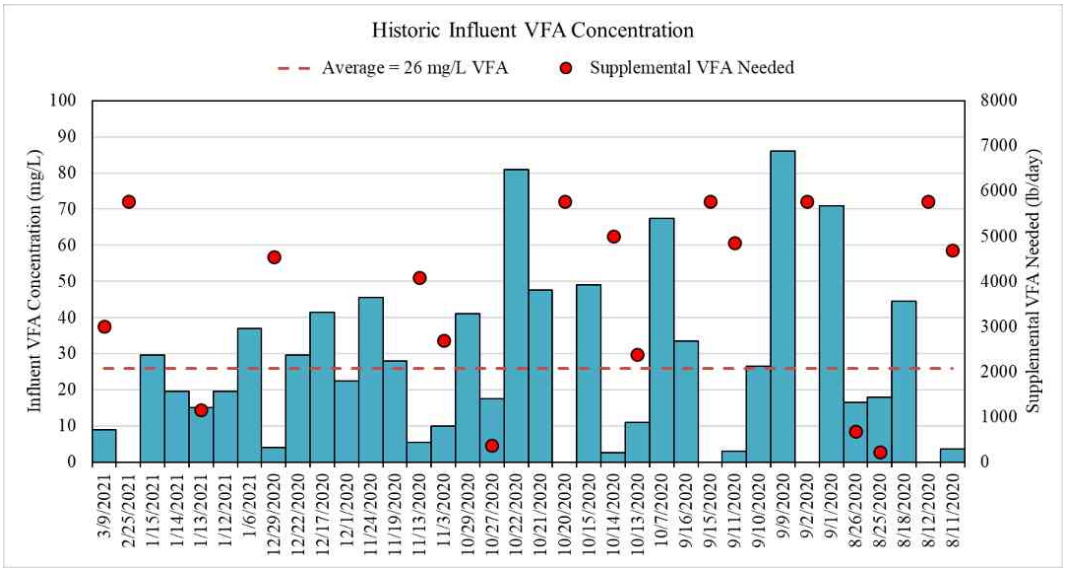


Figure A5. Historical influent VFA and corresponding supplemental VFA needed for required P removal

Appendix B:

Site Survey Photo



Figure B1. Underutilized 30,000-gal aluminum sulfate storage tank, transfer pumps, and metering pumps.



Figure B2. The original polymer storage tank and feed system was retrofitted to serve as temporary aluminum sulfate storage and feed system at a capacity of 20 GPH.



Figure B3. Interior, electrical connections, and underutilized pumps and tanks in SCPB

Appendix C:

Summary of Other Processes at Henrico WRF

In addition to the main ENR, chemical, and solids handling systems discussed in Section 5 above, Henrico WRF also includes several conventional headworks and downstream tertiary treatment processes. Ahead of secondary treatment, Henrico WRF employs bar rack screening, grit removal, and primary clarification in its headworks. Excess flows during peak wet-weather events can be diverted to an excess flow lagoon following primary clarification and can be returned to the mainstream via a pump station. Henrico WRF does not have a raw influent equalization tank ahead of primary clarifiers. Tertiary filtration is also employed following secondary treatment, with the facility actively replacing its older granular carbon filters with new deep-bed sand filters. Following tertiary filtration, disinfection is carried out through a chlorination/dechlorination process. Six chlorine contact tanks are operated using sodium hypochlorite, with dechlorination carried out using a sodium bisulfite spray header prior to the final effluent outfall splitter box. In anticipation of the loss of glycerol, Henrico WRF recently completed a new carbon feeding system capable of handling various supplemental carbon sources including methanol.

Appendix D:

BPR Ability in RAS Fermenter and Tank Volume Calculations

$$BPR\ required = Average\ TP\ Load \times f_1 = C_{\text{inf,TP}} \times Q_{inf} \times 8.34 \times f_1$$

$$= 1{,}739\ lb/day \times 39.31\% = 683.6\ lb/day$$

Where:

- $C_{inf,\ TP}$ = total influent phosphorus (mg/L)
- Q_{inf} = influent flow (MGD)
- Average TP Load = average TP mass load in influent
- f_1 = average percentage of TP removal in the ENR

$$BPR\ provided\ by\ RAS\ fermenter$$

$$= \frac{C_{RAS} \times f_2 \times Q_{RAS} \times \%RAS\ split \times 8.34 \times Y_{VFA}}{f_3}$$

$$= \frac{\left(6854.52 \frac{mg}{L}\right) \times (77.43\%) \times (25.69\ MGD) \times (7.5\%) \times 8.34 \times 0.04}{8} = 430.7 \frac{lb}{day}$$

Where:

- C_{RAS} = average total solids concentration in RAS (mg/L)
- f_2 = average VS/TS ratio in RAS
- Q_{RAS} = average RAS flow rate (MGD)
- %RAS split = percentage of RAS flow diverted to the RAS fermenter (%)
- Y_{VFA} = how many mg of VFA can be produced by 1 mg of VS (mg VFA/mg VS)
- f_3 = VFA-P removal ratio

$$BPR\ percentage\ by\ RAS\ fermenter$$

$$= \frac{BPR\ provided\ by\ RAS\ fermenter}{total\ BPR\ required} \times 100\%$$

$$= \frac{430.7 \frac{lb}{day}}{683.6 \frac{lb}{day}} \times 100\% = 63\%$$

$$Required\ tank\ number = \frac{Q_{RAS} \times \%RAS\ split \times HRT}{V_{tank}}$$

$$= \frac{(25.69\ MGD) \times (7.5\%) \times 2\ day}{2.02\ MG} = 1.91$$

Where:

- Q_{RAS} = average RAS flow rate (MGD)
- %RAS split = percentage of RAS flow diverted to the RAS fermenter (%)
- HRT = hydraulic retention time (day)
- V_{tank} = old BNR tank volume (MG)

Appendix E:

Anaerobic Zone and Nitrogen Removal Design Calculations

Designated Anaerobic Zone HRT for Intentional EBPR

Scenario 1:

$$\text{HRT} = \frac{0.37654\ MG\ + 0.69515\ MG + 0.0941\ MG + 0.1738\ MG + 0.267\ MG + 0.267\ MG}{40\ MGD} \times 24\ \text{hr}$$
$$= 1.1\ \text{hr}$$

Scenario 2:

$$\text{HRT} = \frac{0.37654\ MG + 0.69515\ MG + 0.267\ MG + 0.267\ MG}{40\ MGD} \times 24\ hr = 0.96\ \text{hr}$$

Scenario 3:

$$\text{HRT} = \frac{0.56481\ MG\ +\ 1.04272\ MG\ +\ 0.267\ MG\ +\ 0.267\ MG}{75\ MGD} \times 24\ hr = 0.69\ \text{hr}$$

Annual Demand and Cost for Nitrogen Removal

Glycerol as carbon source:

Glycerol usage = 2,664 gal/day, Glycerol price = $3.52/gal

Annual cost: $2664 \times 3.52 \times 365 = 3{,}425{,}381$ USD/year

Methanal as carbon source:

- NOx removed (baseline) = 3.83 mg/L × 36.75 MGD × 8.34 lb/gal = 1173.9 lb/day

  Methanol required (3 g MeOH/g NO3-N) = 1173.9 lb/day × 3 g MeOH/g NO3-N = 3521.7 lb/day

  Methanol required (volume, 6.6 lb/gal) = 3521.7 ÷ 6.6 = 533.6 gal/day

  Methanol consumption (gal/year) = 533.6 gal/day × 365 = 194,760 gal/year

  Annual cost = 194,760 × 1.80 = 350,568 USD/year

- NOx removed (with RAS ferment.) = 3.83 mg/L × 36.75 MGD × 8.34 = 1173.9 lb/day

  Total NOx removed = 1173.9 + 836.59 = 2010.5 lb/day

  Methanol required (3 g MeOH/g NO3-N) = 2010.5 × 3 = 6031.6 lb/day

  Methanol required (volume, 6.6 lb/gal) = 6031.6 ÷ 6.6 = 913.9 gal/day

  Methanol consumption (gal/year) = 913.9 × 365 = 333,573 gal/year

  Annual cost = 333,573 × 1.80 = 600,431 USD/year

Appendix F:

Supplementary Information for Metal Salt Storage Tank Material Selection

A key consideration in material selection was long-term structural integrity under continuous chemical exposure. Compared to fiberglass reinforced plastic (FRP) tanks, which rely on an internal corrosion-resistant liner, XLPE provides a homogeneous, one-piece structure in which the chemical resistance is inherent throughout the tank wall. In FRP systems, aggressive chemicals can gradually penetrate the internal resin barrier and reach the structural fiberglass layer, leading to material degradation and eventual failure. In contrast, XLPE tanks are rotationally molded as seamless units, eliminating joints and preventing chemical wicking into the tank wall, thereby significantly improving long-term reliability (Assmann Corporation, 2024).

From a cost and lifecycle perspective, XLPE also offers clear advantages. FRP tanks typically have a higher initial cost, often three to five times that of XLPE tanks, and require longer lead times for fabrication and delivery. In addition, FRP systems require ongoing maintenance such as inspection of the internal liner and periodic recoating for UV protection, whereas XLPE tanks require minimal maintenance due to their corrosion-resistant and UV-stabilized construction (Polyprocessing, 2024).

Operational considerations further support the selection of XLPE. FRP tanks are more rigid and susceptible to cracking during handling or installation, while XLPE tanks exhibit higher impact resistance and flexibility, reducing the risk of damage during transport and installation. Additionally, fittings in FRP tanks are typically attached after fabrication, creating potential leak points, whereas XLPE tanks can incorporate integrally molded fittings, minimize leakage risk and improving system integrity (Polyprocessing, 2024).

For these reasons, XLPE is selected as the material of construction for the aluminum sulfate storage tank, providing a more reliable, cost-effective, and flexible solution for long-term chemical storage in this application.

Appendix G:

Supplemental Information for BioWin Process Modeling

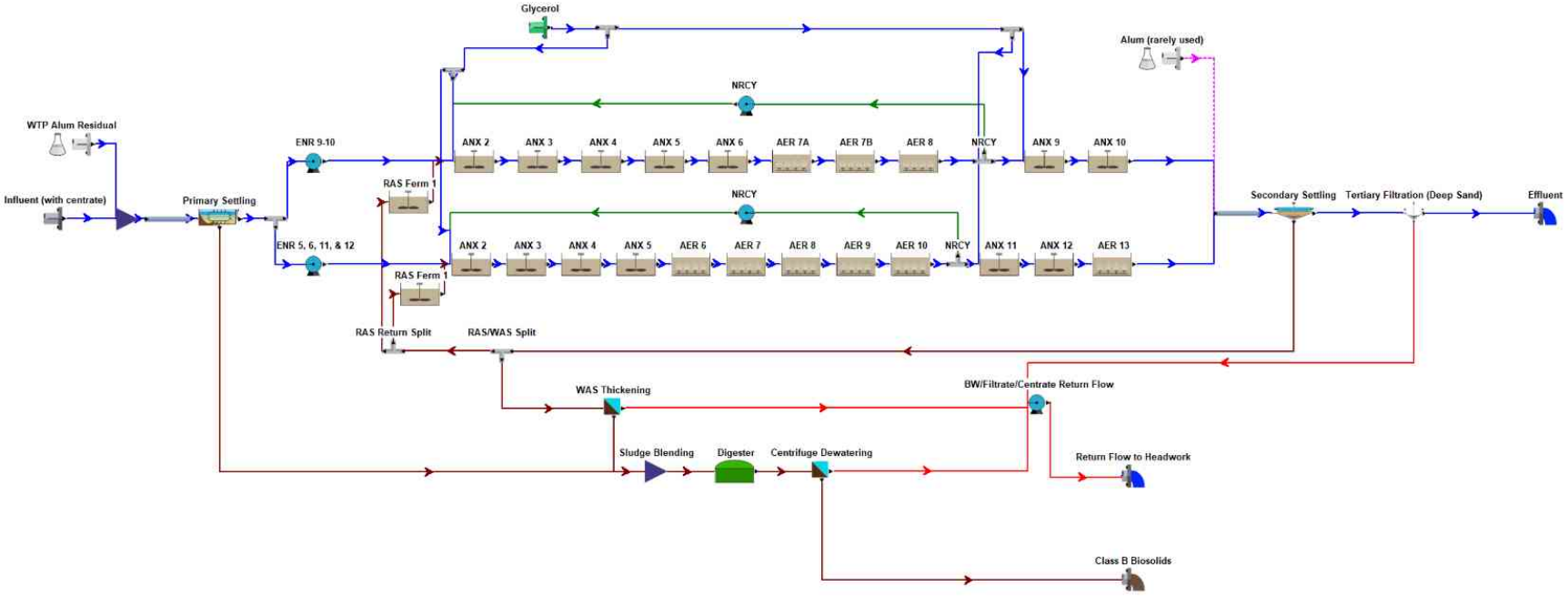


Figure G1. BioWin process flow setup for calibrating to Henrico WRF's current treatment performance

Locations		Parameters	Unit	Actual	Model	% Difference
Influent		Flowrate	MGD	36.92	36.92	0.01%
		TSS	mg/L	309.67	307.33	0.76%
		TP	mg/L	5.78	5.78	0.06%
		Ammonia	mg/L	29.29	29.26	0.09%
		TKN	mg/L	44.34	44.33	0.03%
		COD	mg/L	465.39	465.28	0.02%
		sCOD	mg/L	112.56	112.57	0.01%
		Alkalinity	mg/L	232.95	232.58	0.16%
Primary Settling	Overflow	Flowrate	MGD	36.75	36.75	0.01%
		TSS	mg/L	118.98	117.34	1.38%
		TKN	mg/L	41.15	39.08	5.04%
		TP	mg/L	3.86	3.81	1.35%
		Ammonia	mg/L	30.14	29.26	2.91%
		COD	mg/L	285.92	250.81	12.28%
		sCOD	mg/L	122.17	112.57	7.86%
		Alkalinity	mg/L	243.11	232.58	4.33%
	Sludge	Flowrate	MGD	0.17	0.17	2.77%
		TS	%	3.91	4.02	2.92%
		VS/TS	%TS	71.96	71.71	0.34%
Enhanced Nutrient Removal	Pre-Anoxic Effluent	NOx (ENR 9-10)	mg/L	1.29	1.33	3.10%
		NOx (ENR 5, 6, 11, &12)	mg/L	0.85	0.67	21.18%
	Aerobic Effluent	Ammonia (ENR 9-10)	mg/L	0.22	0.22	0.00%
		NOx (ENR 9-10)	mg/L	8.53	6.3	26.14%
		Ammonia (ENR 5, 6, 11, &12)	mg/L	0.68	0.4	41.18%
		NOx (ENR 5, 6, 11, &12)	mg/L	4.6	4.91	6.74%
	Post-Anoxic Effluent	NOx (ENR 9-10)	mg/L	2.34	2.52	7.69%
		NOx (ENR 5, 6, 11, &12)	mg/L	2.3	2.44	6.09%
		MLSS	mg/L	3204.68	2965.21	7.47%

Locations		Parameters	Unit	Actual	Model	% Difference
Secondary Clarification	Overflow	TSS	mg/L	9.08	10.17	12.06%
		TKN	mg/L	1.61	1.85	14.57%
		TP	mg/L	0.27	0.4	49.51%
		NOx	mg/L	2.54	2.48	2.23%
		Ammonia	mg/L	0.00	0.02	–
		COD	mg/L	32.19	32.17	0.06%
	Sludge	Flowrate	MGD	25.69	25.69	0.01%
		RAS TSS	mg/L	6854.52	7087.10	3.39%
		TWAS TS	%	4.80	4.82	0.29%
Effluent		pH	s.u.	7.13	6.88	3.53%
		TSS	mg/L	0.03	0.03	12.38%
		TP	mg/L	0.11	0.11	0.34%
		TKN	mg/L	1.05	1.27	20.97%
		NOx	mg/L	2.56	2.48	3.09%
		COD	mg/L	21.29	22.00	3.36%
Post-dewatering		Centrate TSS	mg/L	2558.63	2425.69	5.20%
		Centrate TKN	mg/L	927.36	881.71	4.92%
		Centrate TP	mg/L	87.71	95.2	8.54%
		Cake Dryness	%	22.92	23.23	1.35%

Table G1. Calibrated BioWin model prediction vs. Henrico WRF's actual performance

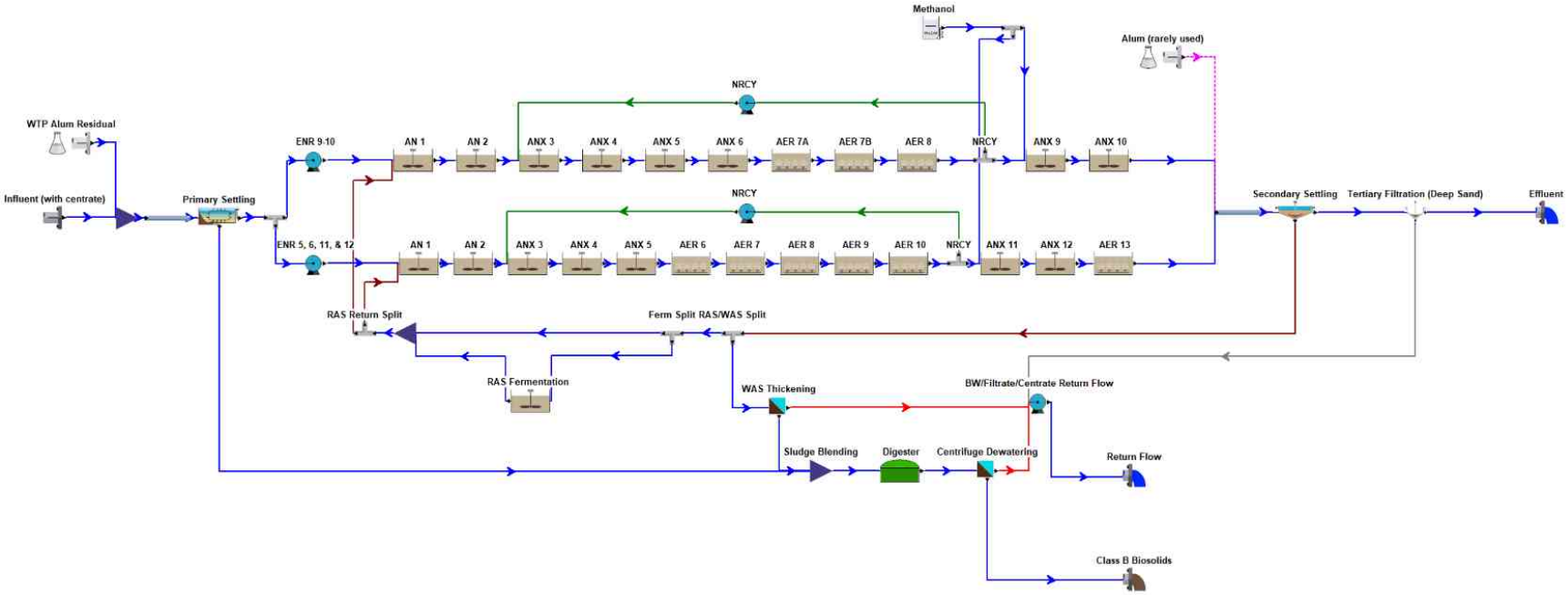


Figure G2. Process flow for Alternative 3 – EBPR with RAS fermentation and chemical P polishing

Appendix H:

Hydraulic Profile Calculations

For this preliminary engineering report (PER), major losses within the RAS fermentation sidestream were calculated using the Darcy-Weisbach Equation and verified with calculations using the Hazen-Williams Equation.

The pipes implemented are HDPE with a constant Darcy friction factor of f = 0.016 was selected for all pipe segments.

This is representative of fully turbulent flow in smooth HDPE pipe and represents a reasonable, conservative estimate for friction losses.

H.1 Major Headloss (Darcy–Weisbach)

$$h_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2g}$$

Where:

- h_f = major head loss (ft)
- f = Darcy friction factor (dimensionless)
- L = pipe length (ft)
- D = pipe diameter (ft)
- V = velocity (ft/s)
- g = 32.2 ft/s²

An example of major head loss calculated with Darcy–Weisbach with 12-inch HDPE pipe, where Q = 1.93 MGD (7.5% of average historical RAS flow), V = 3.8 ft/s, and L = 100 ft;

$$h_f = 0.016 \cdot \frac{100}{1.00} \cdot \frac{(3.8)^2}{2(32.2)}$$

$$h_f \approx 0.36 \text{ ft per } 100 \text{ ft}$$

Similarly, a Hazen-Williams coefficient of C = 150 was used for HDPE piping.

H.2 Major Headloss (Hazen–Williams)

$$h_f = 4.73 \cdot \frac{L}{C^{1.852} \cdot D^{4.87}} \cdot Q^{1.852}$$

Where:

- h_f= major head loss (ft)
- L= pipe length (ft)
- C= Hazen–Williams roughness coefficient
- D= pipe diameter (ft)
- Q= flow rate (ft³/s)

An example of major head loss calculated with Hazen–Williams with 12-inch HDPE pipe, where Q = 1.93 MGD (7.5% of average historical RAS flow), V = 3.8 ft/s, and L = 100 ft;

$$h_f = 4.73 \cdot \frac{100}{150^{1.852}(1.00)^{4.87}} \cdot (2.99)^{1.852}$$

$$h_f \approx 0.34 \text{ ft per } 100 \text{ ft}$$

Minor losses within the system are calculated for inlet, outlet, pipe bends, valves, splitters, and junction occurrences. These minor losses occur along as RAS and fermented sludge are carried through the RAS fermentation sidestream.

H.3 Minor Losses

$$h_m = K \cdot \frac{V^2}{2g}$$

Where:

- h_m= minor head loss (ft)
- K= loss coefficient (dimensionless)
- V= velocity (ft/s)
- g= 32.2 ft/s²

The RAS flow velocity through piping was calculated to ensure adequate flow and prevent solids settling in pipes, in accordance with 9VAC25-790-690(F)(3) of the Virginia Administrative Code. The flows through the sidestream were calculated using average historical RAS flows and a peak value of 4.0 MGD given piping infrastructure constraints.

H.4 Water Velocity Through Pipes

$$V = \frac{Q}{A}$$

Where:

- V= velocity (ft/s)
- Q= flow (ft³/s)
- A= cross-sectional area (ft²)

H.5 Pipe Cross-sectional Area

$$A = \frac{\pi D^2}{4}$$

Where:

- A= pipe area (ft²)
- D= pipe diameter (ft)

The total dynamic head (TDH) represents the total head required to convey flow through the RAS fermentation sidestream and evaluates the hydraulic feasibility and pump requirements. TDH accounts for both elevation differences and energy losses encountered during transport in the form of major and minor losses.

H.6 Total Dynamic Head

$$TDH = h_{static} + \sum h_f + \sum h_m$$

Where:

- h_{static}= static head due to elevation differences (ft)
- $\sum h_f$= total major headloss (ft)
- $\sum h_m$= total minor headloss (ft)

The following pages are Excel spreadsheets that were created to calculate the headloss and TDH for pump sizing along the RAS fermentation sidestream. Note that TDH calculations BNR trains 2 and 3 differ given piping length differences along the withdrawal line; these differences are not present in the inflow, as the proposed inflow route follows an existing parallel RAS return line.

Table H-1. TDH Calculations for RAS Diversion Pump under Historic Average RAS Flow Conditions

RAS Diversion Line to Splitter (Historic Average RAS Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	12.00	1.93	2.99	3.80	460.00	0.02	1.00	1.65
Branch Connection	-		-	-	-	0.50	1.00	0.11
Check Valve	-	-	-	-	-	2.00	1.00	0.45
Isolation Valve	-	-	-	-	-	0.15	1.00	0.03
Pipe 90 Bend	-	-	-	-	-	0.45	3.00	0.30
Flow Division	-	-	-	-	-	0.20	1.00	0.04
							Total:	**2.59**
RAS Diversion Line from Splitter to Trains 2 & 3 (Historic Average RAS Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	8.00	0.97	1.49	4.28	65.00	0.02	1.00	0.44
Pipe 90 Bend	-	-	-	-	-	0.45	3.00	0.38
Outlet to RAS Tank	-	-	-	-	-	1.00	1.00	0.28
							Total:	**1.11**
TDH Summary								
Hydraulic Grade Line at Diversion (ft)	63.00							
RAS Tank Elevation (ft)	65.00							
Static Head (ft)	2.00							
RAS Diversion Pump TDH (ft)	5.70							
Safety Factor (1.2)	**6.85**							

Table H-2. TDH Calculations for RAS Diversion Pump under RAS Fermentation Sidestream Peak Design Flow Conditions

RAS Diversion Line to Splitter (Peak Design Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	12.00	4.00	6.19	7.88	460.00	0.02	1.00	7.09
Branch Connection	-		-	-	-	0.50	1.00	0.48
Check Valve	-	-	-	-	-	2.00	1.00	1.93
Isolation Valve	-	-	-	-	-	0.15	1.00	0.14
Pipe 90 Bend	-	-	-	-	-	0.45	3.00	1.30
Flow Division	-	-	-	-	-	0.20	1.00	0.19
							Total:	**11.14**

RAS Diversion Line from Splitter to Trains 2 & 3 (Peak Design Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	8.00	2.00	3.09	8.86	65.00	0.02	1.00	1.90
Pipe 90 Bend	-	-	-	-	-	0.45	3.00	1.65
Outlet to RAS Tank	-	-	-	-	-	1.00	1.00	1.22
							Total:	**4.77**

TDH Summary	
Hydraulic Grade Line at Diversion (ft)	63.00
RAS Tank Elevation (ft)	65.00
Static Head (ft)	2.00
RAS Diversion Pump TDH (ft)	17.91
Safety Factor (1.2)	**21.50**

Table H-3. TDH Calculations for Fermentation Tank Withdrawal Pumps under Historic Average RAS Flow Conditions

Fermentation Withdrawal Line from BNR Train 2 to Junction (Historic Average RAS Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	8.00	0.97	1.49	4.28	265.00	0.02	1.00	1.81
Branch Inlet	-	-	-	-	-	0.50	1.00	0.14
Check Valve	-	-	-	-	-	2.00	1.00	0.57
Isolation Valve	-	-	-	-	-	0.15	1.00	0.04
Pipe 90 Bend	-	-	-	-	-	0.45	3.00	0.38
Junction	-	-	-	-	-	0.20	1.00	0.06
							Total:	**3.00**

Fermentation Withdrawl Line from BNR Train 3 to Junction (Historic Average RAS Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	8.00	0.97	1.49	4.28	215.00	0.02	1.00	1.47
Branch Inlet	-	-	-	-	-	0.50	1.00	0.14
Check Valve	-	-	-	-	-	2.00	1.00	0.57
Isolation Valve	-	-	-	-	-	0.15	1.00	0.04
Pipe 90 Bend	-	-	-	-	-	0.45	2.00	0.26
Junction	-	-	-	-	-	0.20	1.00	0.06
							Total:	**2.53**

Fermentation Withdrawal Line from Junction to PE Channel (Historic Average RAS Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	12.00	1.93	2.99	3.80	200.00	0.02	1.00	0.72
Outlet	-	-	-	-	-	1.00	1.00	0.22
Pipe 90 Bend	-	-	-	-	-	0.45	1.00	0.10
							Total:	**1.04**

TDH Summary	
RAS Tank Elevation (ft)	65.00
PE Channel Elevation (ft)	63.33
Static Head (ft)	-1.67
Fermentation Withdrawal Train 2 Branch TDH (ft)	**2.37**
Fermentation Withdrawal Train 3 Branch TDH (ft)	1.90
Safety Factor (1.2)	**2.85**

Table H-4. TDH Calculations for Fermentation Tank Withdrawal Pumps under RAS Fermentation Sidestream Peak Design Flow Conditions

Fermentation Withdrawal Line from BNR Train 2 to Junction (Peak Design Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	8.00	2.00	3.09	8.86	265.00	0.02	1.00	7.76
Branch Inlet	-	-	-	-	-	0.50	1.00	0.61
Check Valve	-	-	-	-	-	2.00	1.00	2.44
Isolation Valve	-	-	-	-	-	0.15	1.00	0.18
Pipe 90 Bend	-	-	-	-	-	0.45	3.00	1.65
Junction	-	-	-	-	-	0.20	1.00	0.24
							Total:	**12.88**

Fermentation Withdrawl Line from BNR Train 3 to Junction (Peak Design Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	8.00	2.00	3.09	8.86	215.00	0.02	1.00	6.29
Branch Inlet	-	-	-	-	-	0.50	1.00	0.61
Check Valve	-	-	-	-	-	2.00	1.00	2.44
Isolation Valve	-	-	-	-	-	0.15	1.00	0.18
Pipe 90 Bend	-	-	-	-	-	0.45	2.00	1.10
Junction	-	-	-	-	-	0.20	1.00	0.24
							Total:	**10.87**

Fermentation Withdrawal Line from Junction to PE Channel (Peak Design Flow)								
Pipe/Process Unit	Diameter (in)	Flow (MGD)	Flow (cfs)	Velocity (ft/s)	Pipe/Channel Length (ft)	K or *f*	Count	Headloss (ft)
Pipe Friction	12.00	4.00	6.19	7.88	200.00	0.02	1.00	3.08
Outlet	-	-	-	-	-	1.00	1.00	0.96
Pipe 90 Bend	-	-	-	-	-	0.45	1.00	0.43
							Total:	**4.48**

TDH Summary	
RAS Tank Elevation (ft)	65.00
PE Channel Elevation (ft)	63.33
Static Head (ft)	-1.67
Fermentation Withdrawal Train 2 Branch TDH (ft)	**15.69**
Fermentation Withdrawal Train 3 Branch TDH (ft)	13.68
Safety Factor (1.2)	**18.83**

Appendix I:

Cost Analysis Calculations

Capital Costs:

BNR Retrofit				
Category	**Unit Cost Estimate**	**Units**	**Adjustment Factor**	**Total Cost**
Inspection & Repair	$ 141,992.00	12	0.2, 1.3	$ 443,015.04
Piping - 12" HDPE	$ 26.58	660	1.3	$ 22,805.64
Piping - 8" HDPE	$ 20.54	545	1.3	$ 14,552.59
Pump 1	$ 27,280.53	1	1.4	$ 38,192.74
Pump 2/3	$ 19,826.18	2	1.4	$ 55,513.30
Mixer	$ 150,000.00	12		$ 1,800,000.00
Total Cost				**$ 2,374,079.32**

Aluminum Sulfate System				
Category	**Unit Cost Estimate**	**Units**	**Adjustment Factor**	**Total Cost**
Storage	$ 3.50	22500		$ 78,750.00
Piping - 2" PVC	$ 7.34	450	1.3	$ 4,293.90
Flow Meter	$ 520.80	6		$ 3,124.80
Pump	$ 595.96	1		$ 595.96
Total Cost				**$ 86,764.66**

Grand Total				
Category	**Unit Cost Estimate**	**Units**	**Adjustment Factor**	**Total Cost**
Base Cost				$ 2,460,843.98
Overhead & Expenses			0.25	$ 615,210.99
Final Cost				**$ 3,076,054.97**

*Adjustment factors include inflation in certain categories (Bureau of Labor Statistics, 2026), pipe fittings, and other expected reductions or increases in cost

Electricity Costs:

Mixer Costs				
Power (kW)	**Duration (hours)**	**Price ($/kW-h)**	**Units**	**Total Cost**
40	8760	$0.15	12	**$ 630,720.00**

Pump Costs						
Pump	**Flow Rate (gpm)**	**Head (ft)**	**Efficiency**	**Price ($/kW-h)**	**Duration (hours)**	**Total Cost**
1	1610	6.85	0.85	$0.15	8760	$3,165.62
2 / 3	809	2.85	0.85	$0.15	8760	$ 661.81
Total						**$4,489.25**

For Mixer Power:

Selected G value of 70

$G = \sqrt{\frac{P}{\mu \cdot V}}$ rearranges to $P = G^2 \cdot \mu \cdot V$

$$P = \left(70\frac{1}{s}\right)^2 \cdot 0.00105\frac{N \cdot s}{m^2} \cdot 7570m^3 = 38947.65\,W \approx 40\,kW$$

Appendix J:

Acronyms and Abbreviations

Abbreviations	Definitions
WRF	Water reclamation facility
TP	Total phosphorus
VPDES	Virginia Pollutant Discharge Elimination System
BPR	Biological phosphorus removal
MLSS	Mixed liquor suspended solids
PER	Preliminary Engineering Report
TN	Total nitrogen
NOx-N	Nitrate and nitrite nitrogen
WTF	Water treatment facility
VSR	Volatile solids reduction
VAR	Vector attraction reduction
SRT	Solids retention time
PE	Primary effluent
NRCY	Nitrate recycle
gal	Gallon(s)
gph	Gallon(s) per hour
PAOs	Phosphorus accumulating organisms
TSS	Total suspended solids
BNR	High-purity oxygen activated sludge tanks
SPCB	Secondary process control building
ENR	Enhanced nutrient removal
MGD	Million gallon(s) per day
lb	pound(s)
VFA	Volatile fatty acid
PHAs	Polyhydroxyalkanoates
PACl	Polyaluminum chloride
$FeCl_3$	Ferric Chloride
XLPE	Crosslinked polyethylene

Appendix K:

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