Leveraging the Existing Infrastructure to Achieve Sidestream Enhanced Biological Phosphorus Removal and Energy Efficiency Upgrades

[1*]Sara Arabi, Ph.D., P.E., BCEE, [1]Eric Lynne, P.E.

[1]Donohue & Associates, Inc., Chicago
[*]Email: Sarabi@donohue-associates.com

ABSTRACT

As Water Resource Recovery Facilities (WRRF) effluent nutrient limits are becoming increasingly strict, upgrades to Biological Nutrient Removal (BNR) is inevitable. Retrofitting existing plants to BNR on a tight budget is not unusual. WRRFs are required to meet the more stringent permit requirements for nutrients while under pressure from the communities to keep the user rates at a reasonable rate. Nutrient removal is often stereotyped with additional costs for WRRFs. A case study of a large WRRF in Illinois proves that a holistic review of the WRRF requirements can help facilities leverage larger projects that initiate improvements for regulatory changes, nutrient removal, energy efficiency, and equipment replacement. In this work, North Shore Water Reclamation District's (NSWRD) obtained energy savings and nutrient removal by leveraging their existing tankage to use for Sidestream Enhanced Biological Phosphorus Removal (S2EBPR) without sacrificing permitted capacity or operational simplicity.

KEYWORDS: Enhanced Biological Phosphorus Removal (EBPR), Sidestream EBPR, Energy efficiency, Nutrient Removal

INTRODUCTION

Biological Nutrient Removal and Energy Management

Biological Nutrient Removal (BNR) processes are widely employed at Water Resource Recovery Facilities (WRRFs) in order to meet the stringent final effluent discharge regulations for Nitrogen (N) and Phosphorus (P). Retrofitting an existing plant with BNR capabilities often results in additional medium to high capital measures as well as operational costs. BNR retrofits involves considerations for site-specific factors such as influent quality and existing treatment system layout and space availability that may cause costs to vary significantly between treatment plants with similar design capacities implementing the same BNR configuration.

Energy use will continue to be a significant operating cost for WRRFs. Energy costs have been viewed as simply part of the cost of doing business. More focus has been placed on meeting the effluent regulations than mitigating operational cost increases. As WRRFs are moving towards sustainability, it is prudent for WRRFs to consider energy management and nutrient removal as a combined approach. This combined approach might be of particular benefit if a WWRF is considering BNR upgrades and equipment replacement plans, using regulatory incentives and funding. Feasible practical energy conservation measures can be implemented at BNR plants that not only result in energy use reduction, but also ensure final effluent compliance with tighter discharge regulations; thus satisfying both the primary objective of WRRFs as well as energy conservation.

Enhanced Biological Phosphorus Removal (EBPR) and S2EBPR

The increasingly stringent nutrient limits and the desire to achieve effective phosphorus (P) removal requires more efficient, stable and optimized Enhanced Biological Phosphorus Removal (EBPR) process. EBPR relies on selecting Polyphosphate Accumulating Organisms (PAOs) that can accumulate phosphorus in excess of their normal growth requirements and is achieved by subjecting these microorganisms to alternating anaerobic and anoxic/aerobic conditions. The benefits of EBPR compared to chemical P removal include lower sludge production, reduced impact on pH, lower cost, and improved ability to recover P for beneficial use (e.g., struvite). An adequate supply of readily degradable carbon compounds in the form of readily biodegradable Chemical Oxygen Demand (rbCOD) in the anaerobic zone is critical for effective and reliable EBPR. Secondly, minimizing the quantity of nitrates returned to the anaerobic zone prevent inefficient use of the rbCOD for phosphorus removal. Increased rbCOD production though the use of primary sludge fermentation or through addition of an external carbon source have been used by WRRFs for improved EBPR.

An alternative method for improving EBPR process stability is implementation of a side-stream anaerobic biological sludge hydrolysis and fermentation reactor. This process configuration has been termed side-stream EBPR (S2EBPR). S2EPBR can be implemented in multiple process configurations which can be adapted to existing structures at WRRFs (Tooker et al., 2017). Example process types for S2EBPR includes: Side-stream RAS fermentation (SSR), Side-stream RAS fermentation with supplemental carbon addition (SSRC), Side-stream Mixed Liquor Suspended Solids (MLSS) fermentation (SSM), and unmixed in-line MLSS fermentation (UMIF). Some of the process types for S2EBPR such as SSR, SSM, and UMIF does not require primary sludge fermentate and is therefore applicable to WRRFs without primary clarifiers or those where primary sludge fermentation is not feasible. Another advantage of S2EBPR is that readily degradable carbon compounds in the influent that would have been used for EBPR can instead be used for denitrification. Currently, there are several key knowledge gaps related to S2EBPR related to standard design of S2EBPR processes including proportion of RAS or MLSS diversion, SRT and HRT in side-stream reactor, mixing conditions, and key parameters for process monitoring (Tooker et al., 2017).

Scope of Study

This study focuses on a WRRF for a large suburb of Chicago that obtained energy savings and nutrient removal by leveraging their existing tankage to use for (S2EBPR) without sacrificing permitted capacity or operational simplicity. The monthly power consumption for this WRRF was approximately 4,200 kWh which was over two times higher than the baseline/benchmark monthly energy usage of 1,760 kWh. The WRRF adopted a monthly energy use goal of 1,350 kWh.

The WRRF prepared to meet the near future effluent P limit of 1 mg/L as well as replacing aging equipment including positive displacement (PD) blowers with limited turn down capacity and old diffuser system. While the effluent TP limit of 1 mg/L is not typically considered stringent and can be achieved through simple EBPR processes such as anaerobic/aerobic process (simply adding anaerobic selectors), the WWRF considered EBPR upgrades, equipment efficiency and replacement plans and how to fund new improvements. The WRRF took a holistic approach of the WRRF requirements to leverage a larger project that initiate improvements for regulatory changes, energy efficiency, and equipment replacement. In preparation for the design upgrades for EBPR, the replacement of some existing energy intensive blowers and diffusers were considered as well as implementation of S2EBPR. To further improve energy efficiency, process changes for EBPR and process control upgrades were considered at the same time.

BACKGROUND

The North Shore Water Reclamation District (NSWRD) operates three WRRFs with a combined average design capacity of 63.4 Million Gallons per Day (MGD), serving over 300,000 residents in its service area in northern suburbs of Chicago. Future National Pollutant Discharge Elimination System (NPDES) permits for the WRRFs are anticipated to eventually include a P limit of 1.0 mg/L or lower. NSWRD investigated the options for the implementation of P removal, and specifically EBPR at each WRFs. Focus of this paper is on the Gurnee Water Reclamation Facility (WRF) with 23.6 MGD annual average daily capacity. Gurnee WRF was originally constructed as a 2-stage nitrifying activated sludge plant and discharges treated effluent to the Des Plaines River. Figure 1 shows the site plan for the Gurnee WRF and Figure 2 presents the schematic diagram of the Gurnee WRF prior to EBPR upgrades (BioWin®).

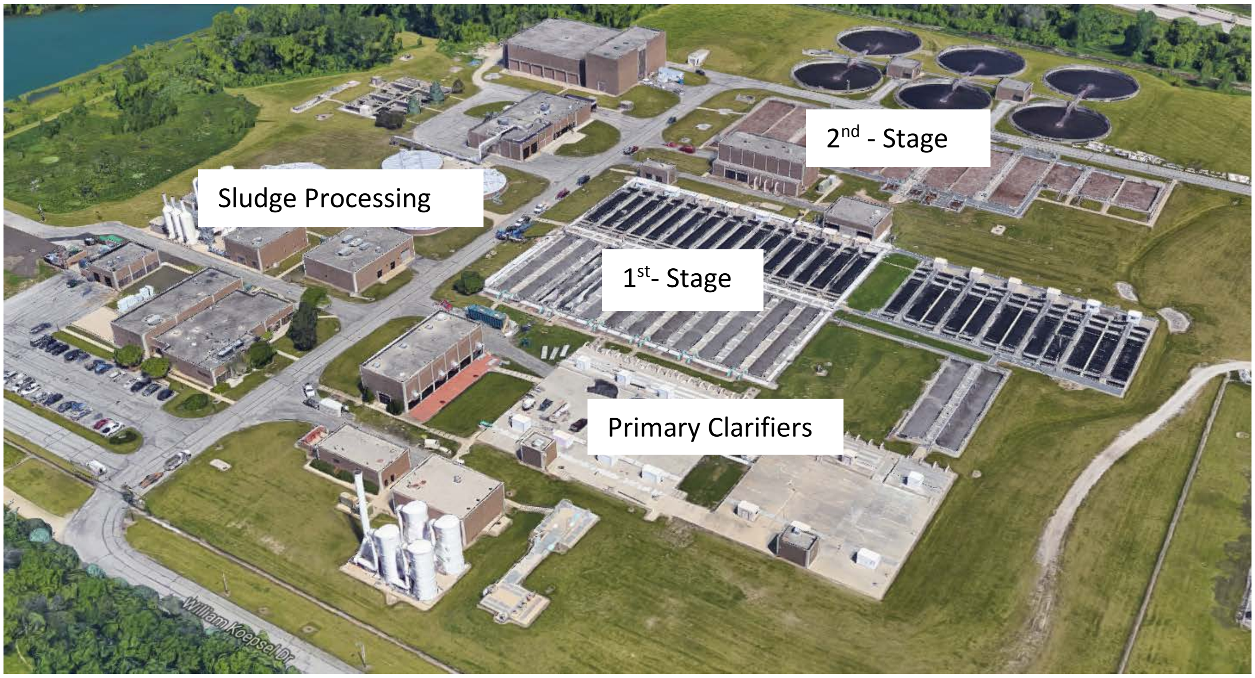

Figure 1 – Gurnee WRF Site Plan

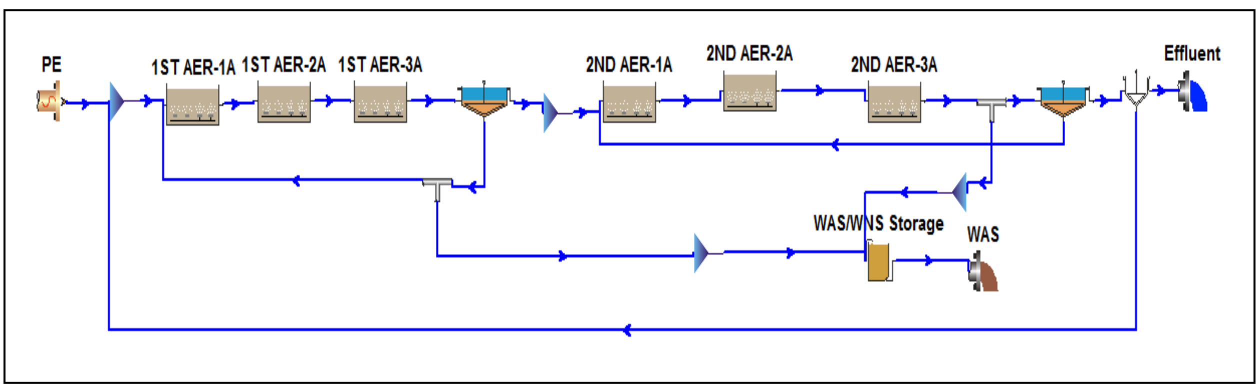

Figure 2 – Schematic Diagram of the Gurnee WRF Prior to EBPR Upgrades (BioWin®)

EBPR UPGRADES

The existing two-stage activated sludge system is designed to operate as BOD removal in the first stage and nitrification in the second stage. However, historical operating data indicated that much of the treatment, of which nitrification was of particular concern, in the first stage. Deviations from this historical operational practice required physical and operational changes to prevent the competitive impacts of nitrate in the anaerobic zone.

Average Primary Effluent (PE) BOD and TP for Gurnee WRF was 114 mg/L and 4.2 mg/L, corresponding to BOD:TP ratio of 27 which is favorable for EBPR without the need for S2EBPR; however, having the off-line storage of biomass was viewed favorable to avoid washing out the system. The WRF exhibited peak flows that were anticipated to dilute wastewater characteristics and reduce anaerobic zone contact times, thus the S2EBPR concept was recommended to preserve PAO biomass and develop additional VFA.

Table 1 shows the influent loading for maximum week and maximum day design conditions for Gurnee WRF which indicates lower than optimal BOD: TP for peak flow conditions. Detailed sampling and analysis of PE showed BOD concentration as low as 63 – 86 mg/L, and TP values of 3.5 –5.9 mg/L, which corresponds to BOD: TP values of 18 and 19. Based on special sampling results, the average readily biodegradable COD (rbCOD): P ratio was 9 which is less than the optimum value recommended for EBPR at 15:1 (WEF, 2010).

Table 1 - BOD and Phosphorus Loading for Design Conditions (2015 Data)

Design Condition	***Flow (MGD)***	***BOD (ppd)****	***TP (ppd)***	***BOD/TP***
Annual Average	14.53	13,741	486	28.3
Maximum Month	19.99	15,985	621	25.7
Maximum Week	47.2	45,100	1,970	22.9
Peak Day	47.2	67,800	3,570	19.0

*ppd: pounds per day

Several EBPR alternatives were considered and the optimal configuration was selected considering BNR performance and energy demand with the goal of using an innovative use of existing infrastructure. Figure 3 shows the schematic flow diagram for Gurnee WRF after the EBPR upgrades.

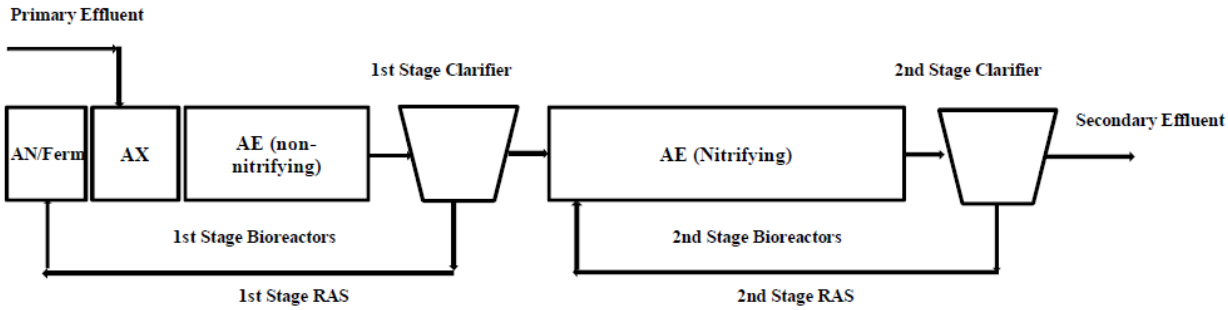

Figure 3 – Gurnee WRF Process Flow Diagram after EBPR Upgrades

Figure 4 shows a schematic of the upgrades for the 1st-stage. The total selector volume was 50% of total 1st- stage basin volume, both for energy efficiency and for superior nutrient removal performance. Two of the four passes in each tank were converted to un-aerated zones. The 1st pass consists of two unaerated zones (Pass A) where 100% of RAS is added. PE is added to the 2nd pass, which consists of two anaerobic zones. Dissolved Oxygen (DO) in the subsequent aerobic zones is kept at 0.5 mg/L to minimize nitrification occurrence. Therefore, the RAS entering the anaerobic RAS tanks have no/low nitrate concentration. This makes the Pass A selectors function as RAS fermentation zones which simulates the S2EBPR process/Sidestream RAS fermentation. P release and uptake take place respectively in the anaerobic zones and the aerobic zones of the 1st-stage. However, operational data for anaerobic RAS reactor exhibits significant orthophosphate release does occur, depending on the retention time in this zone.

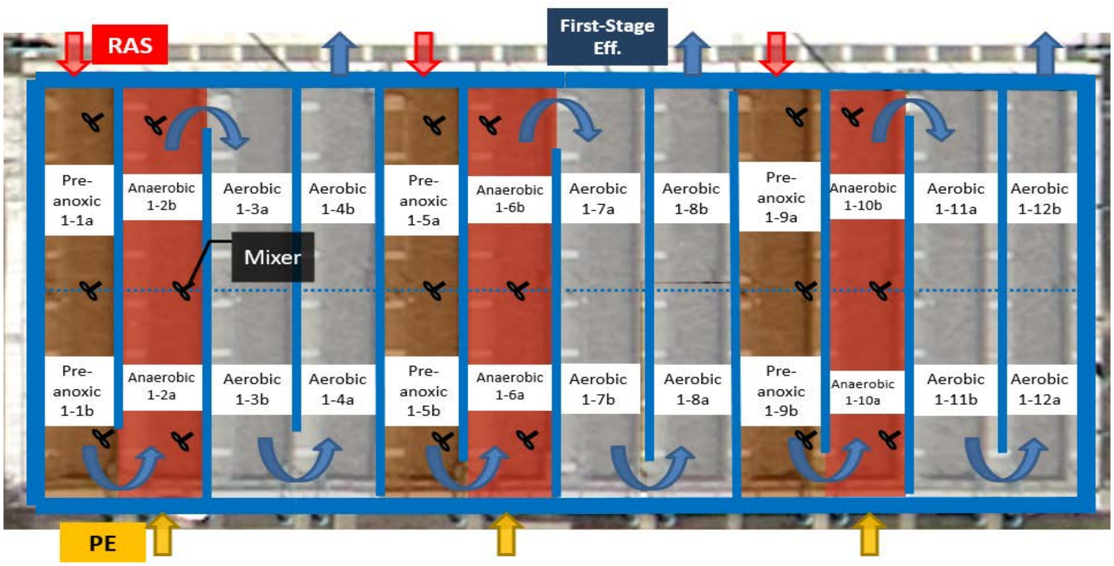

Figure 4 – Gurnee WRF EBPR Upgrades for the 1st -Stage Activated Sludge

BioWin® modeling was conducted for the EBPR upgrades. Default model parameters for PAOs were used in simulations. The schematic flow diagram of the WRF with EBPR upgrades are shown on Figure 5. Figure 6 shows the mass fraction of tanks based on BioWin® modeling. For conventional BNR, anaerobic mass fraction is generally less than 10% and for processes involving fermentation could be as high as 50% (Barnard et al., 2011). The mass fraction for anaerobic zones are 45.5% (Figure 6).

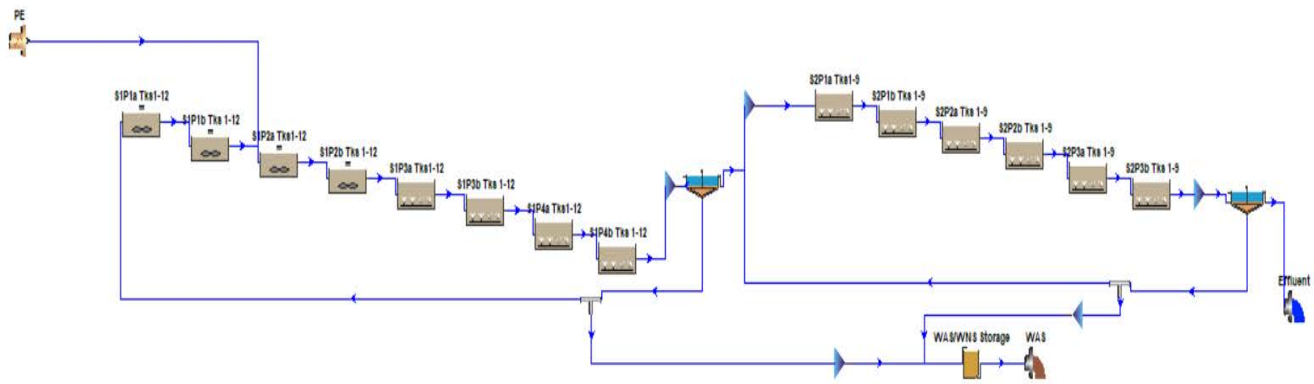

Figure 5 –Modeling Diagram for Gurnee WRF using BioWin® with EBPR Upgrades

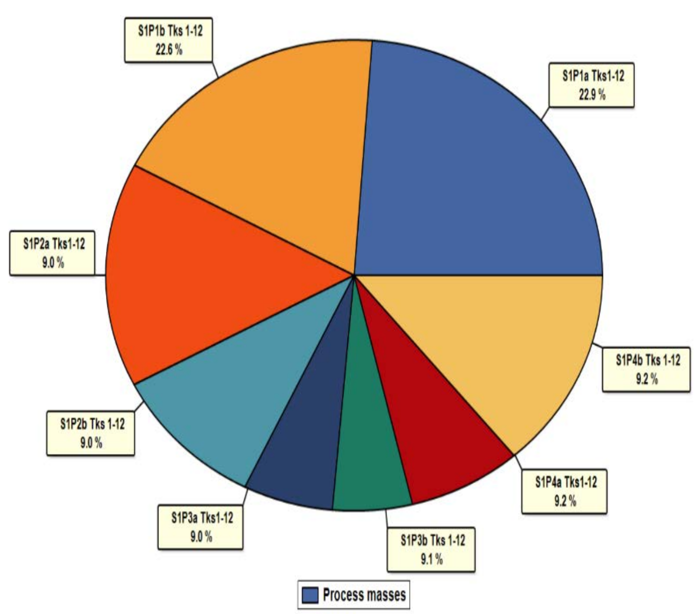

Figure 6 – Mass Fractions for the 1st - Stage Activated Sludge

Figure 7 shows the 1st- stage, denoting the processes occurring in each pass. The 1st-stage aerobic SRT is maintained at 4 d to limit nitrification in the 1st-stage. The DO setpoints in the 1st-stage were maintained at 0.5 mg/L in the aerobic zones to reduce airflow requirements. Table 2 presents the volume and retention time for zones in the 1st-stage system. The HRT in the anaerobic RAS reactor is 2.5 hours, and anaerobic zone HRT drops to under 1 hr due to the added PE flow. Nitrification occurs in the 2nd-stage system. With avoiding nitrification in the 1st-stage and no nitrate in the RAS for the 1st-stage, the RAS anaerobic zone provides the environment for RAS fermentation. Grab sampling of VFA in the inlet and outlet of the RAS fermentation zone shows VFA generation in this zone.

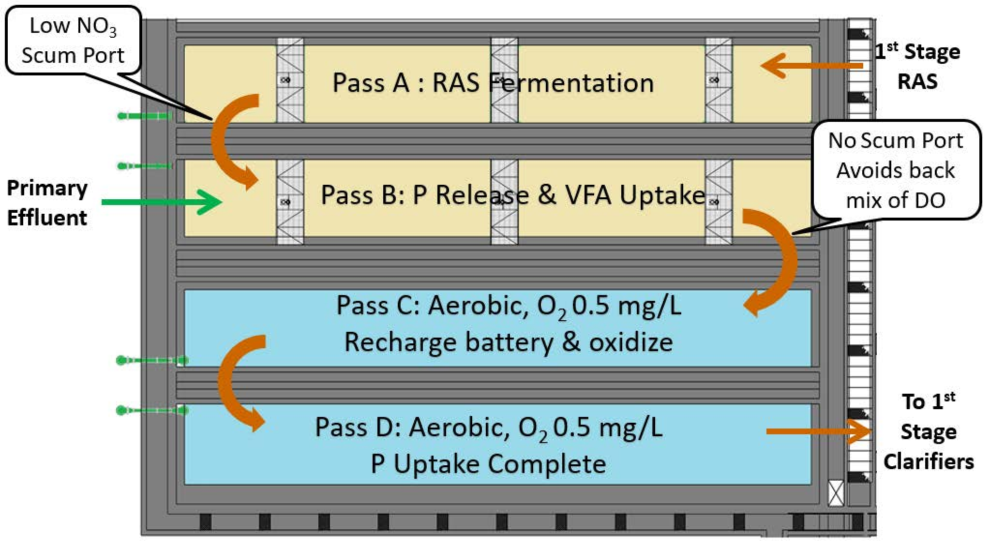

Figure 7 – Gurnee WRF 1st-Stage Activated Sludge, Passes A-D

Table 2- Volume and Retention Time for Zones in the 1st-Stage System

Gurnee WRF	*Volume (MG)*	*Avg HRT (hrs)**
RAS Anaerobic Tank Volume - Pass A	0.9	2.48
Anaerobic Selector Volume - Pass B	0.9	0.92
Aerobic Zone Volume - Pass C and D	1.8	1.82

*Calculated based on average flow of 14.53 MGD and RAS rate of 60%, excludes RAS time in clarifier

Figures 8 and 9 show the result of dynamic simulation for P removal in the 1st-stage. The preliminary results for implementation of EBPR in 2017 is presented in Figure 10. After the steady-state operation of EBPR process, high Soluble P (SP) concentration was observed in the effluent of the 1st-stage. It was found that this was due to release or Ortho-P in the clarifier as a result of relatively long retention time of RAS in the 1st-stage clarifier. Therefore, RAS rate increased from 40% to 60% in early September, which resulted in low SP in the 1st- stage effluent. This configuration achieved future P goal of 1 mg/L (12-month rolling average) well in advance of permit requirements. This provided significant leverage for ongoing permit negotiations.

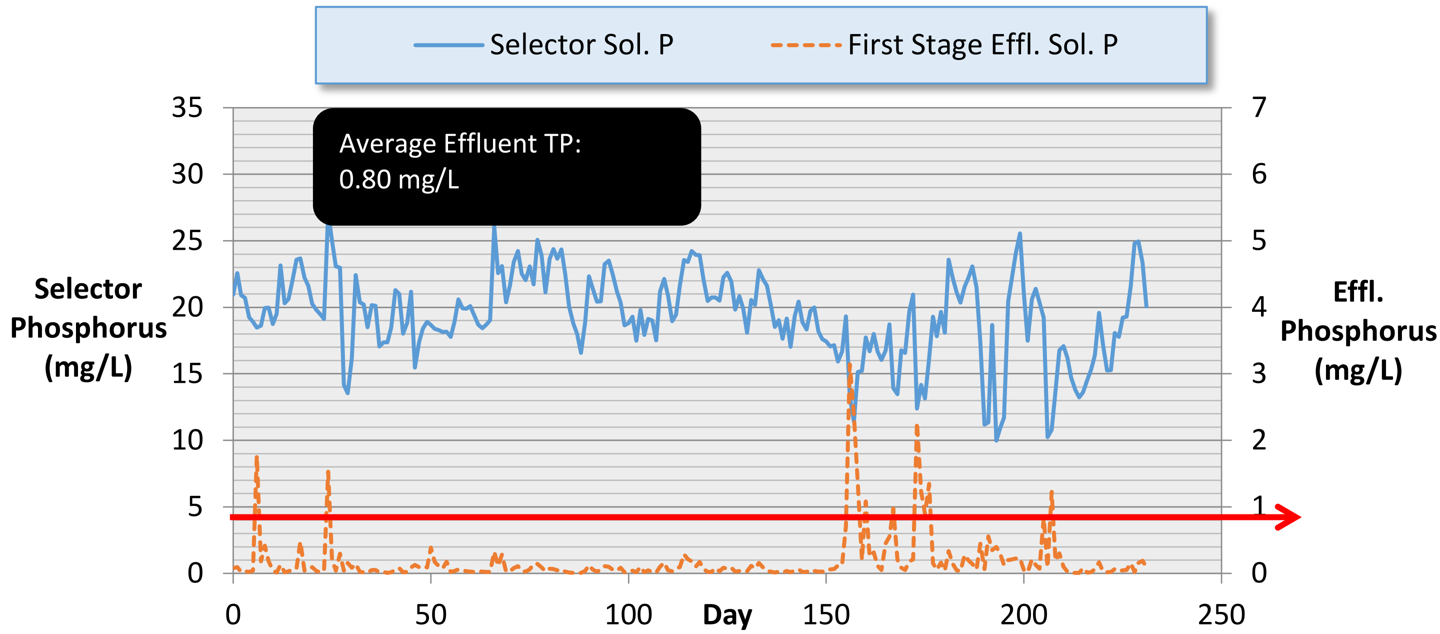

Figure 8 – Dynamic Modeling Results for P Removal in 1st-Stage System

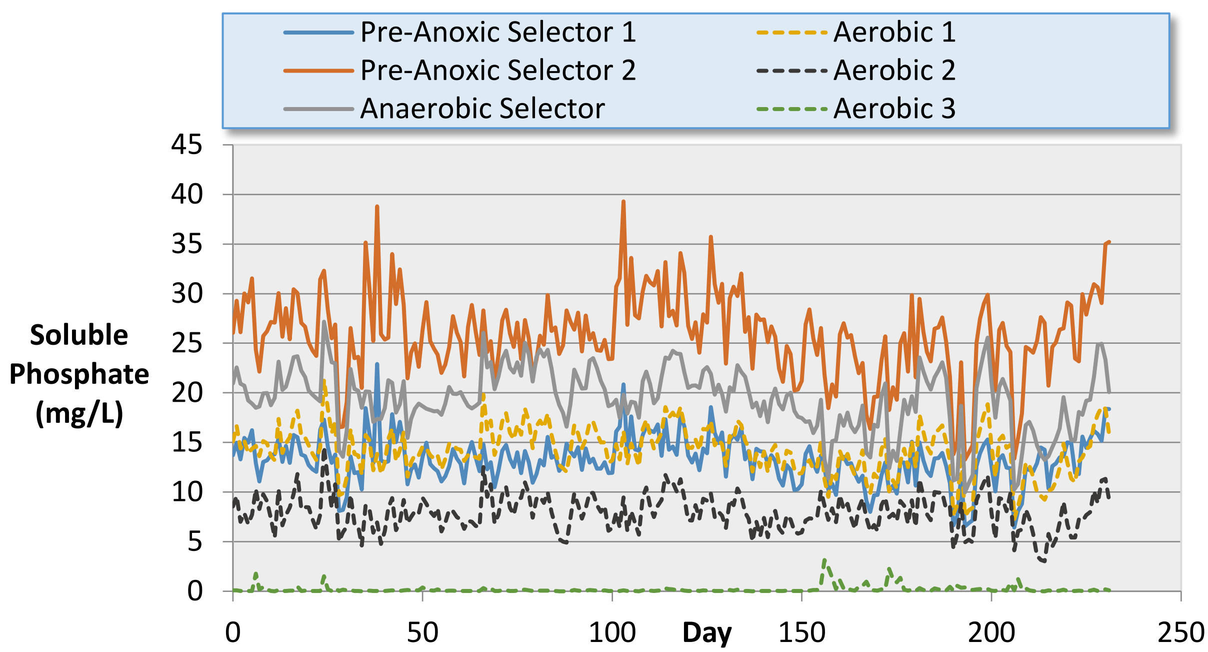

Figure 9 – Dynamic Modeling Results for P Profile in 1st-Stage System

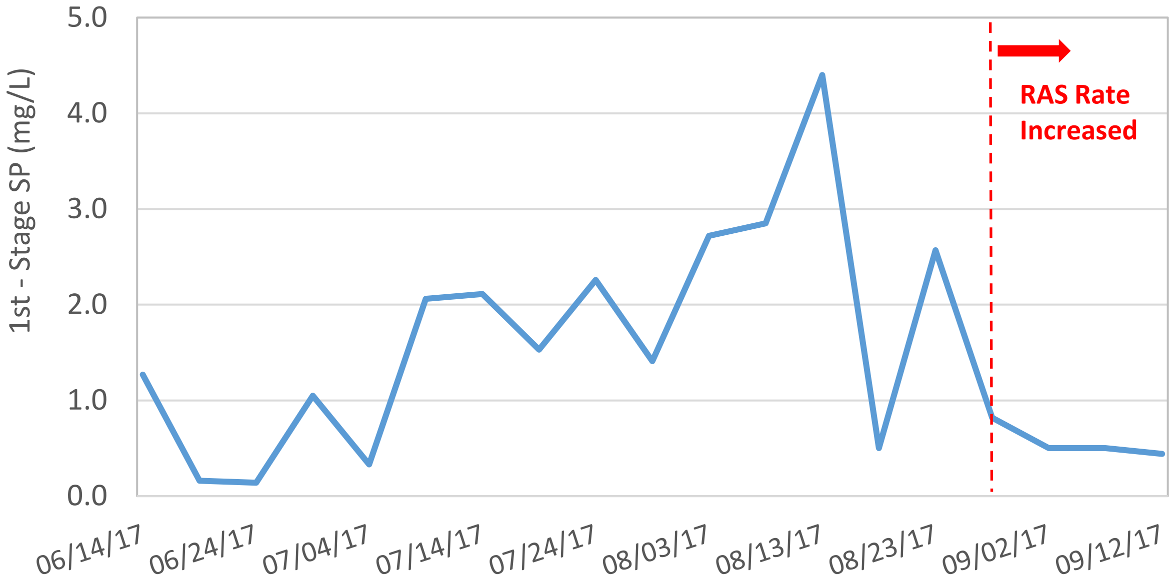

Figure 10 – Preliminary Results for P Removal in 1st-Stage System

Figure 11 summarizes the results for the final effluent TP after the EBPR upgrades in Winter 2017 and Spring 2018. The average final effluent TP was 0.72 mg/L which is similar to the model predicted effluent TP of 0.8 mg/L. The results indicated that WRF can meet the future TP requirement without chemicals.

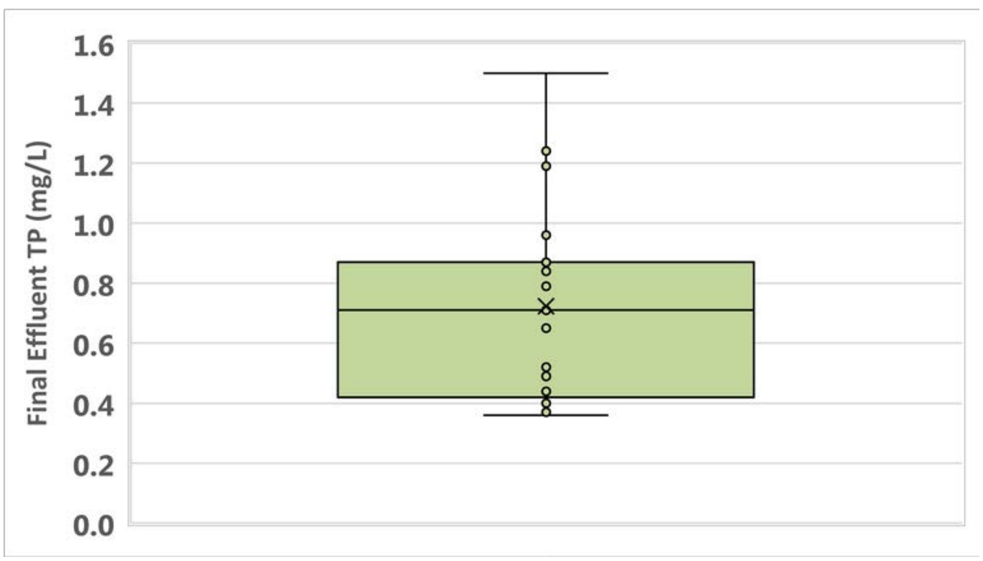

Figure 11 – Final Effluent TP Results after EBPR Upgrades

Energy Efficiency Improvements

The monthly power consumption for Gurnee WRF was approximately 4,200 kWh which was over two times higher than the baseline/benchmark monthly energy usage of 1,760 kWh. The WRRF adopted a monthly energy use goal of 1,350 kWh. The high energy usage for this WRF was attributed to medium voltage PD blowers, some with Variable Frequency Drives (VFD) and some with 2-speed option, but limited turndown and efficiency. The fine bubble aeration system was also old and required replacement.

The previous desktop studies focusing only on replacement of diffusers or blowers independently showed very long payback period and therefore, it was not considered by the WRF. Replacement of diffusers with the existing blowers, was not expected to result in significant savings because of the limited turn down of the existing blowers. Replacement of blowers and diffusers together resulted in a marginal payback, but still struggled due to the inefficient distribution of mixing energy and process demand.

The WRF decided to take a holistic approach and not only consider the equipment upgrade options but engage in evaluation of whole plant understanding and consider process changes. A whole plant BioWin® model (Figure 2) was used to evaluate options. The WRF considered the following options as energy reduction measures: reducing the DO set-points, balancing the demand and mixing, improve Standard Oxygen Transfer Efficiency (SOTE), improve blower efficiency, improve blower turn down, improve aeration control options using control valves, reduce the header pressure, and remove un-needed tanks from service. Process evaluation for Gurnee WRF showed that the facility was operated in a mixing limited aeration mode for majority of the year. Due to site groundwater concerns, tanks are not taken off-line for extended periods of time. In order to reduce the quantity of air required, conversion of 50% of the existing aerobic zone in 1st-stage to selector zone was considered. The benefit of the selector zones was two-fold: reduce the aeration demand of the 1st-stage and direct the demand to the 2nd-stage and achieve EBPR to meet the future P limit of 1 mg/L. This resulted in a large un-aerated zone for RAS. Process modeling and experience from other facilities also indicated that keeping DO at 0.5 mg/L in the second 50% of the 1st-stage is sufficient for P uptake and it helps the WRF save aeration energy. With this strategy, all tanks are kept in service while reducing the air demand significantly and achieving EBPR.

For equipment replacement with more efficient equipment, the WRF considered new fine pore aeration diffuser system. For the upgrades, EPDM diffusers were bid competitively with PTFE coated diffusers, however EPDM were recommended to have a lower return on investment based on received pricing and limited concern for fouling. Tapered aeration arrangement was selected for diffusers for better distribution of DO based on loading and to maintain uniform diffuser efficiencies at diffuser airflow rates at or below 1 scfm/diffuser. High efficiency turbo blowers were also considered for equipment upgrades. This resulted in an energy efficiency increase from 20-27 scfm/kW for the existing PD blowers to 30-35 scfm/kW for the new turbo blowers. Replacement of the existing underground and corroded air supply piping with new overhead air piping and associated foundation and supports were done. High efficiency mixers were considered. The mixers installed in the selector zones were sizes to provide low mixing energy of 0.011 HP/kgal (2W/m3) to keep the RAS in suspension yet minimizing surface exchange of oxygen. The upgrades were coupled with operational changes and operator training for new systems, with the goal of developing mindset changes to focus on energy efficiency.

Multi-year simulations of historical data were used as input into BioWin® and GPS-X process modeling software to provide a relative comparison of the energy savings and nutrient removal performance. Similar process model simulations can be developed for any plant configuration to account for pumping and blower energy and nutrient removal associated with activated sludge or attached growth system. The approach of applying advanced process modelling to evaluate aeration energy conservation measures yields other benefits, the most significant of which is to ensure that final effluent compliance with regulatory requirements is met satisfying the primary wastewater treatment objective of protecting the environment as well as conservation of energy. The process modeling revealed aeration energy savings of 65-75% for all three NSWRD facilities. The significant energy savings were pursued for grant funding, which was identified to cover 25% of total project costs, bringing total project payback within 10-years on just energy savings alone. Grant funding also provided 22% project coverage ($1.5M from IL CEF and $0.9M from DCEO/ComEd). Figure 12 shows the summary of economic evaluation for the life cycle cost and net present worth for the upgrades. Application of a superior economic evaluation technique such as life cycle cost analysis, which takes into account all the costs incurred during the project life, so that the most cost effective measures can be selected for implementation. The overall payback considering the grant funding was 9 years for Gurnee WRF.

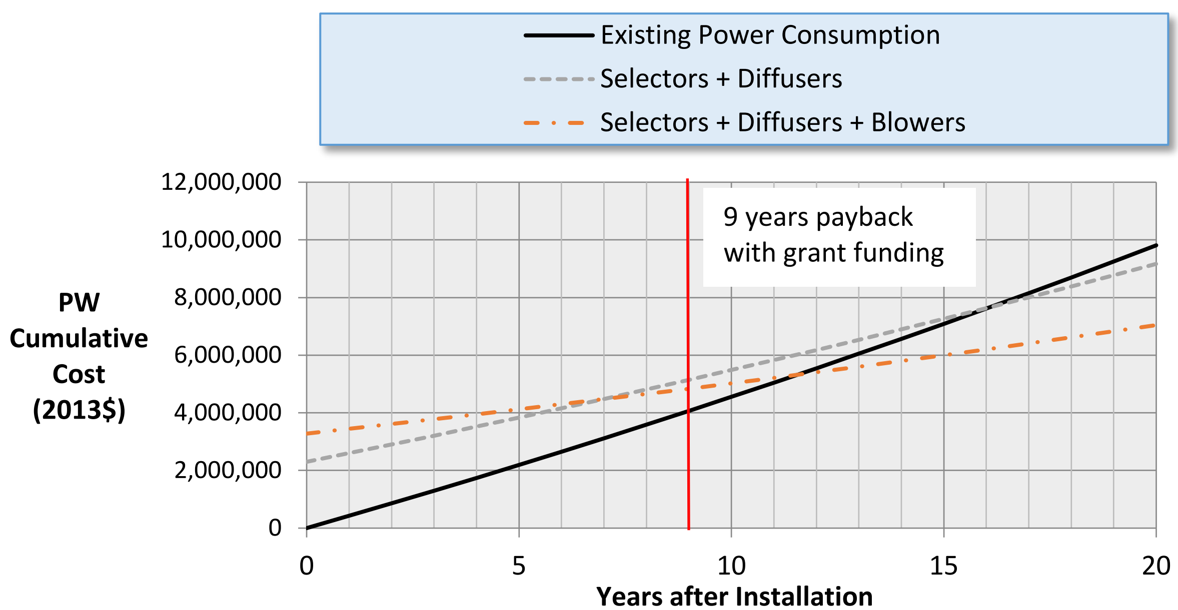

Figure 12 – Life-Cycle Costs and NPW for Energy Efficiency Upgrades

Actual energy use after implementation of EBPR upgrades and energy efficiency upgrades are calculated at 3,300 kWh on a monthly basis which is an improvement from the original 4200 kWh on a monthly basis before the upgrades. This resulted in total annual electric saving of $260,000 for Gurnee WRF. While the monthly power usage of 3,300 kWh is still higher than the bench mark and goal values of 1,760 and 1,350 kWh, respectively, the WRF continues the optimization efforts both for EBPR performance and energy usage.

It should be noted that that NSWRD operates two other WRFs, Waukegan (22 MGD) and Clavey Road (17.8 MGD) with the same biological process configuration. The same EBPR and equipment upgrades were conducted for the other two WRFs with similar results for EBPR and energy efficiency. Figure 13 shows the energy use for the three WRFs before and after the upgrades. Annual energy saving for Waukegan and Clavey Road WRFs was $310,000 and $385,000, respectively. The payback period was estimated at 9 years without funding and 6 years with funding for Waukegan and Clavey Road WRFs

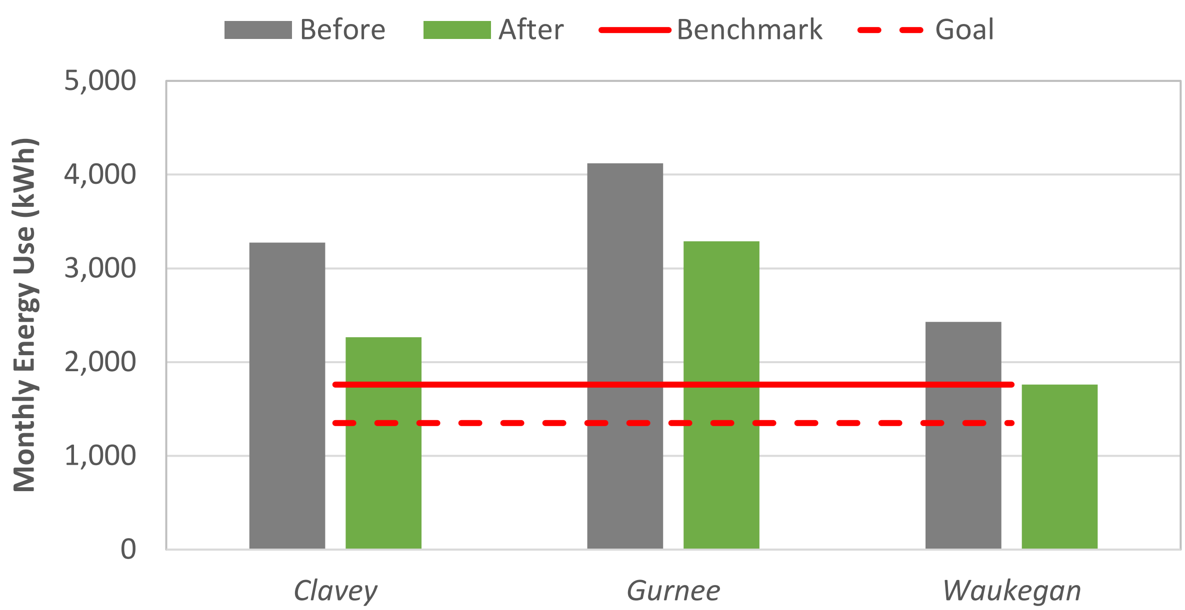

Figure 13 – Before and After Results for Energy Efficiency Upgrades for NSWRD

Figure 14 compares the result of EBPR upgrades for the three WRFs in terms of final effluent TP. P removal performance for the Waukegan and Clavey Road WRFs was similar to the Gurnee WRF with final effluent TP concentration of 0.35 and 0.85 mg/L, respectively. The P profiling and VFA analysis for the three WRFs indicated the highest VFA production in the fermentation zone for the Clavey Road WRF with fermentation zone HRT of 4.6 hours.

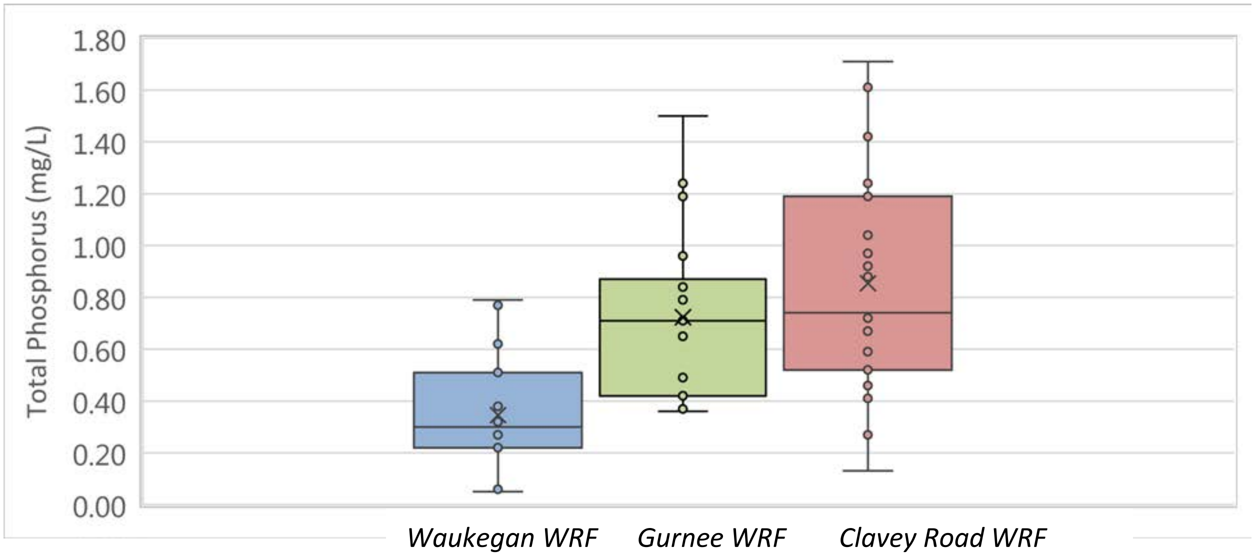

Figure 14 – Final Effluent TP for the Three WRFs for NSWRD

CONCLUSIONS

NSWRD maximized the existing infrastructure with the focus on energy savings and upgrades for nutrient removal. While the effluent TP limit of 1 mg/L is no longer considered stringent and can be achieved through simple EBPR processes such as anaerobic/aerobic process (simply adding anaerobic selectors), NSWRD utilizes existing infrastructure to leverage S2EBPR. Using the existing tanks/valves, S2EBPR was implemented which required tighter process control to avoid nitrate in first stage and achieve RAS fermentation. While being innovative in upgrading to EBPR with S2EBPR, NSWRD applied a risk averse approach by maintaining all tanks in service, and additional DO programming and diffusers for effluent protection. Given the flexibility in the design, NSRWD took the initiative to implement the S2EBPR upgrades before effluent TP limits are in effect, thus enabling time to experiment and establish the best operating point for both energy efficiency and effluent quality

REFERENCES

Barnard, J.; D. Houweling; H. Analla; and M. Steichen (2010) "Fermentation of Mixed Liquor for Phosphorus Removal." *Proceedings of the 83th Annual Water Environment Federation Technical Exposition & Conference*; New Orleans, Louisiana, October 2 - 6; Water Environment Federation: Alexandria, Virginia, 59 – 71.

Tooker, N.B.; Li, G.; Bott, C. ; Dombrowski, P. ; Schauer, P. ; Menniti, A., ; Shaw, A. ; Barnard, J.L. ; Stinson, B. ; Stevens, G. ; Dunlap, P. ; Takács, I. ; Phillips, H. ; Analla, H. ; Russell, A. ; Ellsworth, A. ; McQuarrie, J. ; Carson, K. ; Onnis-Hayden, A. ; Gu, A.Z. (2017) "Rethinking and Reforming Enhanced Biological Phosphorus Removal (EBPR) Strategy – Concepts and

Mechanisms of Side-Stream EBPR", *Proceedings of the 90th Annual Water Environment Federation Technical Exposition & Conference*; Chicago, Illinois, September 30–October 4; Water Environment Federation: Alexandria, Virginia, 2547 - 2564.

Water Environment Federation (WEF). 2010. *Nutrient Removal – WEF Manual of Practice No. 34.* Alexandria, VA.