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Metropolitan Water Reclamation District of Greater Chicago

***MONITORING AND RESEARCH
DEPARTMENT***

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STICKNEY PHOSPHORUS TASK FORCE

TECHNICAL MEMORANDUM NO. 3

*SUMMARY OF INFLUENTIAL PARAMETERS FOR ENHANCED
BIOLOGICAL PHOSPHORUS REMOVAL AT THE
STICKNEY WATER RECLAMATION PLANT*

October 2014

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BIOLOGICAL PHOSPHORUS REMOVAL AT THE
STICKNEY WATER RECLAMATION PLANT**

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FORWARD

The Metropolitan Water Reclamation District of Greater Chicago (MWRD) recognizes the value of phosphorus as a non-renewable resource. In an effort to optimize the sustainable removal of phosphorus from its wastewater influents and the subsequent recovery of phosphorus in various forms suitable for use as an agronomic fertilizer, the MWRD initiated a Phosphorus Removal and Recovery Task Force in 2012. The Task Force initiated a study phase at several of the MWRD's Water Reclamation Plants (WRPs) to evaluate the feasibility of implementing enhanced biological phosphorus removal and to develop operational guidelines for optimizing its effectiveness. The Task Force has created WRP specific study workgroups that are focused on each of the WRPs that have been identified to participate in this initiative. As the workgroups complete various phases of their studies and evaluations they are documenting their findings and recommendations in technical memoranda. These memoranda are written by the WRP specific workgroups and vetted by the Task Force before being published. Their purpose is to capture the state of knowledge and study findings and to make recommendations for implementation of enhanced biological phosphorus removal as they are understood at the time the memoranda are published.

DISCLAIMER


The contents of this technical memorandum constitute the state of knowledge and recommendations developed by the MWRD's Phosphorus Task Force at the time of publication, and are subject to change as additional studies are completed and experience is attained, and as the full context of the MWRD's operating environment is considered.

Summary of Influential Parameters for Enhanced Biological Phosphorus Removal at the Stickney Water Reclamation Plant – Continued

Technical Memorandum 3

Date: March 28, 2014

To: Phosphorus Task Force & Advisory Committee

From: Phosphorus Study/Planning Team 

Subject: Summary of Influential Parameters for Enhanced Biological Phosphorus Removal at the Stickney Water Reclamation Plant

1.0. General

Technical Memorandum 3 (TM3) is a continuation of TM2; TM2 should be referenced for the design criteria of Stickney's enhanced biological phosphorus (P) removal (EBPR) process, the EBPR approach and phases of implementation, and the improvement of dissolved oxygen (DO) relative to the design criteria.

In summary, Battery D operations were modified in May 2012 to accommodate both the anaerobic zone followed by the aerobic zone in sequence. However, because Stickney is a single-stage nitrifying plant, it was necessary to implement an anoxic zone ahead of the anaerobic zone. In this anoxic zone, the nitrate (NO_3) being returned with the return activated sludge (RAS) can be denitrified. The EBPR battery diagram is illustrated in [Figure 1](#). At the inception of this demonstration project, the three zones described were generated through modifying the airflow in the air lift, RAS, mixing, and feed channels and the first half of pass 1 in each aeration tank.

[Table 1](#) summarizes the overall effluent total P (TP) results through the various phases of EBPR implementation for test Battery D. It shows an improvement throughout the phases of P removal.

The following design parameters are covered in this memorandum: mixed liquor (ML) suspended solids (MLSS) concentrations, volatile fatty acids (VFAs) or biodegradable carbon (C), and NO_3 .

FIGURE 1: BATTERY D SAMPLE LOCATIONS

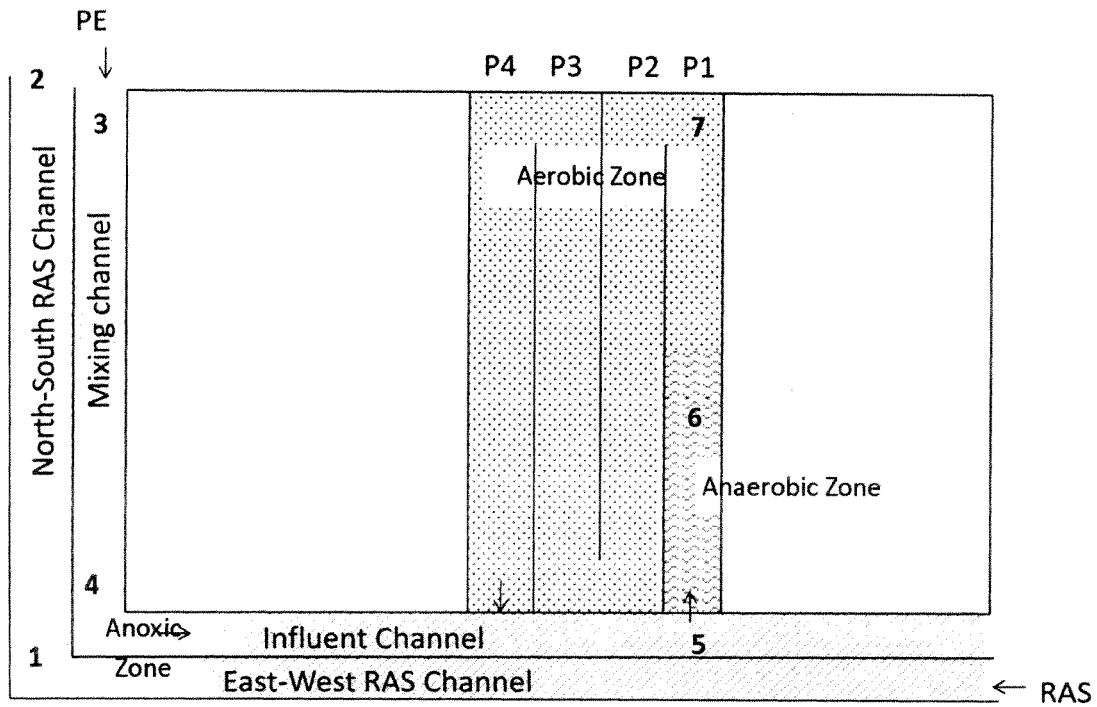


TABLE 1: BATTERY D EBPR PERFORMANCE THROUGH PHASES

	Phase I (5/1/12– 9/12/12)	Phase II (9/13/12– 10/9/12)	Phase III (10/10/12– 12/12/12)	Phase IV (1/28/13– 9/30/13)
Influent Flow (MGD)	193	112	133	172
Influent TP (mg/L)	4.91	3.69	4.17	4.89
RAS/Influent Flow	0.98	1.24	1.03	0.97
Test Battery Effluent TP (mg/L)	1.16	1.42	0.90	0.42
P Removal Efficiency (%)	76.4	61.5	78.4	91.4

The following sections highlight improvements with respect to each referenced parameter as well as the average concentrations for each parameter through the various phases.

2.0. Mixed Liquor Suspended Solids

The MLSS concentration can be used in the control of EBPR systems, although it must be balanced with a minimum solids retention time (SRT). With a higher MLSS, there is an increase in the phosphate-accumulating organism (PAO) population, which benefits the entire system. The improvement in MLSS occurred only in Phase III, but was maintained in Phase IV. The MLSS concentrations through the phases are summarized in [Table 2](#). In addition, the total volatile solids (TVS) percentages for each of the phases are included. MLSS is collected daily from the middle of the influent channel as a grab sample during the midnight shift.

TABLE 2: SUMMARY OF MLSS IN BATTERY D

	Phase I (5/1/12– 9/12/13)	Phase II (9/13/12– 10/9/12)	Phase III (10/10/12–12/12/12)	Phase IV (1/28/13–9/30/13)
Efforts Affecting MLSS Concentrations	No changes	No changes	Targeted concentration of 3,500 mg/L.	Maintained 3,500 mg/L target.
MLSS – Average (mg/L)	3,343	2,224	3,227	3,639
MLSS – Min (mg/L)	2,287	1,907	1,860	650
MLSS – Max (mg/L)	5,657	2,493	8,264	7,520
MLSS – Stdev	743	176	917	945
Number of Samples	136	26	62	270
ML TVS – Average (%)	64.4	68.7	68.5	64.4

The MLSS concentrations have a target of 3,500 mg/L for EBPR at the Stickney WRP (SWRP). Two statistical analyses were performed. The analysis of variance (ANOVA) showed that the MLSS concentrations were significantly different between the phases. The regression analysis indicated that the MLSS concentration has a significant impact on the effluent TP concentrations in each of the phases, meaning higher average MLSS concentrations assisted in lower average effluent TP.

3.0. Biodegradable Carbon and Volatile Fatty Acids

Under the anaerobic conditions of EBPR process, the PAOs uptake VFAs to form intercellular poly- β -hydroxyalkanoates (PHAs) and cause P release. In the subsequent aerobic zone, PAOs obtain energy from breaking these stored PHAs, uptake large amounts of P into their cells, and thus remove P from the liquid phase and from the system through wasting the sludge.

In the EBPR approach at SWRP, C is necessary to drive both denitrification and P uptake as both denitrifiers and PAOs use the available C. The ML is first subjected to anoxic conditions where NO₃ is still present due to its presence in the RAS, and C is utilized for denitrification at that location. The ML passes next to anaerobic conditions where the PAOs can utilize the remaining C.

VFAs were measured throughout the study as an indicator of biodegradable C for the EBPR process, as well as biochemical oxygen demand (BOD), chemical oxygen demand (COD), soluble COD (solCOD), and readily biodegradable COD (rbCOD). The improvement in C was focused on Phases III and IV, as shown in Table 3.

TABLE 3: CARBON CONCENTRATIONS IN PRIMARY EFFLUENT THROUGH PHASES

	Phase I (5/1/12 – 9/12/12)	Phase II (9/13/12 – 10/9/12)	Phase III (10/10/12 – 12/12/12)	Phase IV (1/28/13 – 9/30/13)
Efforts Affecting Carbon Concentrations	No changes	No changes	<ul style="list-style-type: none"> All air turned off in the North-South RAS channel and mixing channel to allow some in line fermentation to occur 	<ul style="list-style-type: none"> Wasted less sludge from southwest preliminary tanks, thus increasing the SRT and more fermentation. Construction on southwest preliminary tanks reducing BOD removal
TP from PE, mg/L	4.85	3.69	4.24	4.92
VFA, mg/L (8/20/12–5/2/13)	14	18	23	11
BOD, mg/L	114	102	113	136
COD, mg/L	260	268	269	328
solCOD, mg/L	113	107	121	104

TABLE 3 (Continued): CARBON CONCENTRATIONS IN PRIMARY EFFLUENT THROUGH PHASES

	Phase I (5/1/12 – 9/12/12)	Phase II (9/13/12 – 10/9/12)	Phase III (10/10/12 – 12/12/12)	Phase IV (1/28/13 – 9/30/13)
rbCOD, mg/L (8/5/13–9/30/13)	ND	ND	ND	77
Influent Flow (MGD)	193	112	134	177
BOD Load (lb/day)	187,802	94,093	119,578	197,306
COD Load (lb/day)	409,400	249,919	280,346	474,194
solCOD Load (lb/day)	166,309	101,225	114,856	139,188
BOD:TP @ PE	24.1	26.4	27.2	29.2
COD:TP @ PE	66.6	69.9	68.6	68.1
solCOD:TP @ PE	27.7	28.6	29.9	23.5
rbCOD:TP @ PE*	ND	ND	ND	10.9

ND = No data.

*Number of samples for each parameter in each phase shown below, each listed from Phase I – IV: TP at PE – 68, 14, 36, 141; VFA – 16, 13, 27, 56; BOD – 134, 26, 58, 237; COD – 28, 7, 16, 59; solCOD – 28, 7, 16, 59; rbCOD – no data, no data, no data, 12; Influent flow – 135, 26, 63, 246.

3.1. Types of Carbon

Of note is that the VFA concentrations measured actually decreased from Phase III to Phase IV (1/28/13 to 5/2/13). Although the VFAs are ultimately used by the PAOs, the VFA sampling was stopped in May of 2013 because the data was deemed unreliable. During this period, samples were not filtered and preserved immediately after sample collection, resulting in loss of VFAs in the final analyses. Sampling procedures have since been adjusted to the proper preparation procedure. This analysis is based on the other organic measures.

As shown in Table 3, the BOD and COD concentrations in the primary effluent increased only slightly throughout the phases. The ANOVA analysis performed showed the COD concentrations were not statistically different throughout phases, while the BOD concentrations were similar in Phases I – III and were statistically higher in Phase IV.

As noted in TM2, the BOD load was determined to be statistically different throughout the phases, and also to have a statistically significant impact on the effluent TP. It is important to note, however, that increases in BOD do not always correspond to increases in usable C. While C is beneficial, it also needs to be in a readily available, usable form.

Ultimately, the most reliable C measurement is rbCOD. The rbCOD indicates the C that can be easily fermented to VFAs in the system. At SWRP, rbCOD analyses were conducted in a portion of Phase IV. The ratio of rbCOD/solCOD was approximately 0.65 during the test period. This value may change with the seasons and needs to be further verified.

3.2. Location

In addition to the C concentrations in the primary effluent, the C concentrations at the beginning of the anaerobic zone also have an impact on the effluent TP concentrations. While the solCOD:ortho P at primary effluent (PE) ratios were 65, 52, 79, and 60 for Phases I – IV, respectively, the average solCOD:ortho P ratios at the beginning of the anaerobic zones were 14, 7, 12, and 36 for Phases I – IV, respectively, showing significant decreases from the ratios entering the battery. At the beginning of the anaerobic zone, denitrification is theoretically completed, leaving all remaining solCOD available to the PAOs for their use.

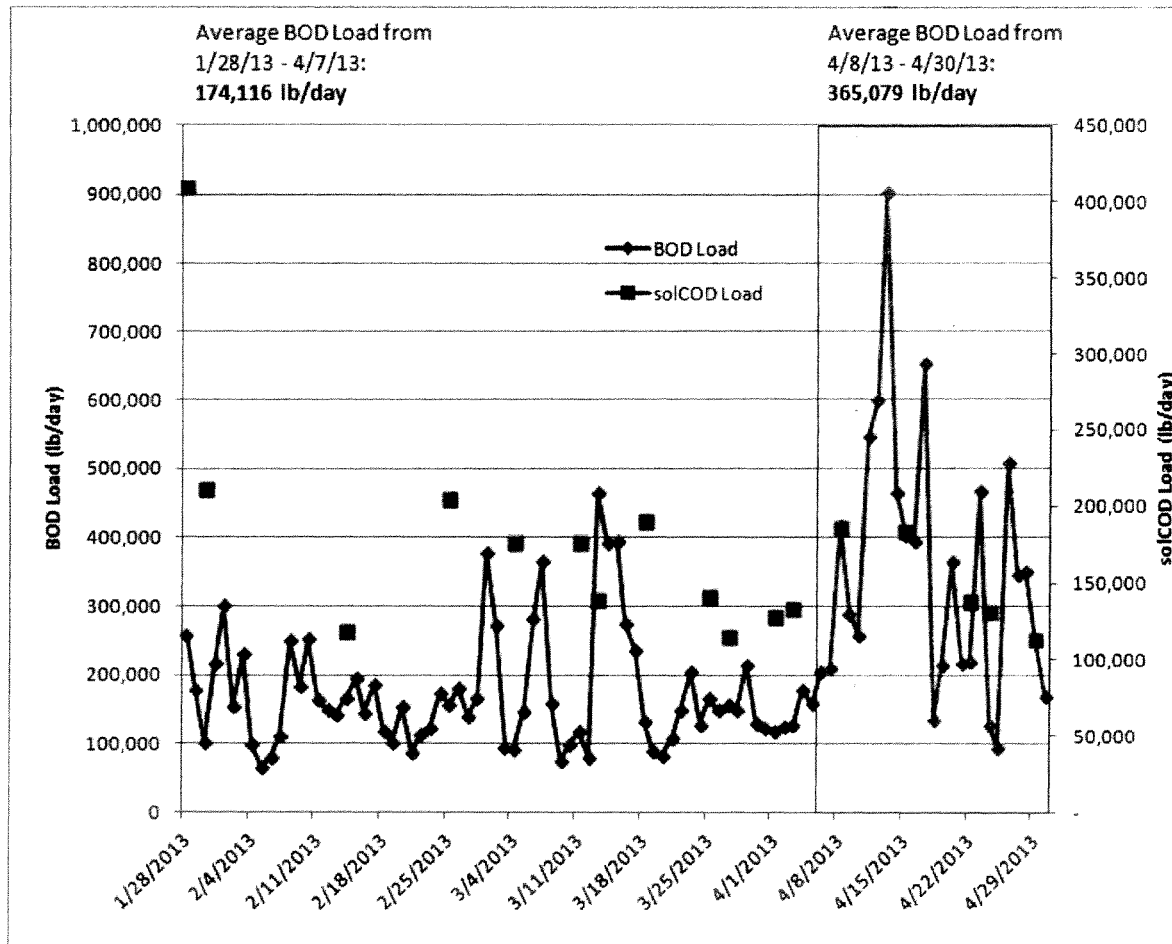
3.3. Efforts

Figure 2 highlights Phase IV changes made to increase available C. Operations began to hold the preliminary sludge longer, thus wasting less, increasing the SRT, and promoting fermentation of the settled primary sludge and ultimately VFA release, around January 24 through March 2013. However, laboratory-scale tests using primary sludge from SWRP indicated that to see appreciable differences in VFA release holding times on the order of days is

required, rather than the additional hours that the existing primary tank infrastructure can provide.

Half of the Southwest preliminary tanks were also shut down for a construction project in April 2013. Capacity was cut in half, but the flows remained nearly the same. This action essentially forced more flow through the preliminary tanks in service, shortened the residence time, therefore reducing BOD removal. This period is shaded in [Figure 2](#); the average daily BOD load increased from 174,116 lb/day during 1/28/13–4/7/13 to 365,079 lb/day during 4/8/13–4/30/13. Between these two methods, the most effective way to increase BOD proved to be through decreasing the residence time in the preliminary tanks, rather than holding the preliminary sludge in the tanks for longer periods of time. However, as shown in [Figure 2](#), increases in BOD loads did not correspond to increases in solCOD loads.

FIGURE 2: PRIMARY EFFLUENT CARBON LOAD



3.4. Carbon Deficit

As discussed in TM2, C is utilized for both denitrification and EBPR. Because of this, there is considerable demand placed on the available C at SWRP, and the available C load is split between PAOs to reduce influent TP and denitrifiers to reduce the RAS NO₃ nitrogen (NO₃-N) load. Given the flows and BOD concentrations measured over the course of this study, SWRP appears to be C-limited roughly 45 percent of the time in Phase IV as shown in [Table 4](#). The calculation is based upon literature ratios for BOD:TKN of 3 and BOD:TP of 25 as reported in “Nutrient Removal, WEF Manual of Practice No. 34,” (Water Environment Federation, 2011). Other literature indicates that prolonged periods of low BOD:TP ratios can result in an extended recovery period for an EBPR system (“Optimization of Enhanced Biological Phosphorus Removal after Periods of Low Loading”, by Miyake and Morgenroth, [Water Environment Research 2005, 77, 117–127]). This means that after BOD:TP ratios are increased, effluent TP takes additional time to decrease because of decreased ortho P uptake rates in the recently starved PAOs.

The average C deficits in the C-limited days are comparable throughout phases. However, the percentage of C-limited days was greatly reduced from over 70 percent during Phases I through III to about 45 percent in Phase IV. This deficit could be reduced by the addition of about 30 mg/L BOD to the primary effluent as shown in [Table 4](#). Also, the average BOD concentration left after denitrification and TP usage shows that Phase IV was the only phase which had average excess BOD when averaging all days, including both deficits and excesses.

TABLE 4: BOD CARBON DEFICIT ANALYSIS

	Phase I (5/1/12 – 9/12/12)	Phase II (9/13/12 – 10/9/12)	Phase III (10/10/12 – 12/12/12)	Phase IV (1/28/13 – 9/30/13)
Number of Data Points	30	7	14	42
Percentage of Samples where Deficit Calculated (%)	73	71	86	45
Average Deficit from Carbon Limited Days (lb BOD/day)	-60,093	-26,894	-36,179	-41,171
Average BOD after Denitrification & TP Usage (lb/day)	-36,359	-1,979	-30,307	6,082
Amount of BOD needed to add to PE ¹ (mg/L)	37.3	28.8	32.4	27.9

¹Using only days when a deficit was calculated.

3.5. Conclusions

The decreases in air and the other efforts seem to be helpful in increasing the C available to the overall system; however, when balanced against the demand on the available C, the system cannot be considered optimized for Bio-P at this point as the system is still in a C deficit roughly half of the time. Utilizing the existing infrastructure in all ways possible to further generate C, including shutting off air in influent channels and anaerobic zones to further promote inline ML fermentation, is a worthwhile effort, as such changes have shown some improvements; this will be studied in Phase V starting December 2013. In the long term, to consistently meet C needs, this may also require either mixers or automated air valves to give more consistent release of the VFAs from the fermenting portions of MLSS. To generate the usable forms of C more reliably, utilization of fermentation tanks for primary sludge or RAS should also be considered.

4.0. NITRATE

TABLE 5: SUMMARY OF AVERAGE RETURN ACTIVATED SLUDGE NITRATE NITROGEN IN BATTERY D

	Phase I (5/1/12– 9/12/13)	Phase II (9/13/12– 10/9/12)	Phase III (10/10/12– 12/12/12)	Phase IV (1/28/13– 9/30/13)
Efforts Affecting Nitrate	Initial DO reduction in the RAS channel – assists in lower DO concentrations and increasing simultaneous denitrification rates.	Turned off every other valve completely in RAS and mixing channel while other valves kept at minimum – largely for DO concentrations, but would help denitrify faster.	Turned off all air valves in RAS and mixing channel – largely for reducing DO concentrations, but would help denitrify faster.	Same as Phase III.
NO ₃ -N (mg/L)	6.75	6.72	6.28	5.77
NO ₃ -N Load (lb/d)	9,944	7,389	6,589	6,736
Number of Samples	30	7	16	42

Only RAS NO₃-N results measured during the M&R profile sampling in each phase of the study are used for evaluation here. M&O NO₃-N data in the RAS channel will not be used

because the samples were not coarse filtered immediately on-site and, therefore, were not representative. Typical $\text{NO}_3\text{-N}$ concentration in the RAS return is about 6 mg/L in Battery D throughout the four phases, as shown in [Table 5](#). RAS flows to the Stickney batteries are also relatively constant. The ratio of RAS flow to PE flow is about 1, which means there is a significant NO_3 load entering the EBPR tank. Statistical analysis showed no difference in both RAS $\text{NO}_3\text{-N}$ concentration and RAS $\text{NO}_3\text{-N}$ load observed through the four phases.

During the profile sampling events, ML samples were collected along each location shown in [Figure 1](#) for laboratory analytical tests. [Figure 3](#) shows the $\text{NO}_3\text{-N}$ profile during each phase. NO_3 production levels in the anoxic zone were reduced through Phases III and IV because simultaneous nitrification was eliminated between sampling points WAS (1) and RS (2) by completely turning off air valves in the RAS channel in Phase III. Meanwhile, the DO reductions in Phase III did not result in a reduced $\text{NO}_3\text{-N}$ concentration in the mixing channel between sampling points MCC (4) and MC (5). Only 60 percent of time was $\text{NO}_3\text{-N}$ completely gone before the anaerobic zone (Point 5 MC as shown in [Figure 1](#)) in Phase IV. The anaerobic zone of an EBPR bioreactor is expected to perform two functions. The primary function is the PAO selection. When NO_3 is present in the anaerobic zone, heterotrophic anoxic organisms, e.g. denitrifiers, can use this combined oxygen as the electron acceptor and will compete with the PAOs for VFAs. This results in less VFA uptake and storage by PAOs and, subsequently, less EBPR. For example, denitrification of 1.0 mg of $\text{NO}_3\text{-N}$ requires the biodegradable C needed for the removal of 0.7 mg of P. In some instances, the anaerobic zone can also perform a secondary function – that of VFA generation through fermentation; here, the presence of NO_3 in the anaerobic zone could potentially inhibit VFA production and PAO selection. The optimal $\text{NO}_3\text{-N}$ concentration in the anaerobic zone is zero (0) mg/L. Our laboratory detection limit of $\text{NO}_3\text{-N}$ is 0.15 mg/L. We consider reported $\text{NO}_3\text{-N}$ concentration below 0.15 mg/L as meeting the EBPR requirements in the study. Based on profile sampling data, 40 percent of the time during the Phase IV period, the $\text{NO}_3\text{-N}$ concentrations have been greater than 0.15 mg/L in the anaerobic zone of Battery D tank 4.

[Figure 4](#) indicates that Battery D effluent TP concentration correlates with RAS $\text{NO}_3\text{-N}$ concentration in Phase IV. Effluent TP trended up when higher RAS $\text{NO}_3\text{-N}$ concentrations were present. Statistical analysis also shows that RAS $\text{NO}_3\text{-N}$ concentrations have an impact on effluent TP, i.e. higher $\text{NO}_3\text{-N}$ level in RAS leads to higher effluent TP concentration. When $\text{NO}_3\text{-N}$ in RAS was lower than 6 mg/L, effluent TP was less than 1 mg/L.

4.1. Conclusions

At this point, the removal of NO_3 in the return sludge is not considered to have been optimized with respect to the current infrastructure, as the $\text{NO}_3\text{-N}$ levels in anaerobic zone are not meeting recommended EBPR criteria of 0 mg/L all the time. This is logical, as no direct efforts have been made to change the NO_3 load. In Phase V, the RAS returning flow to Battery D will be reduced by running thicker secondary sludge blankets and thus lowering the RAS to PE ratios and the NO_3 load to ensure minimal NO_3 load entering the anaerobic zone.

FIGURE 3: FIELD NITRATE-NITROGEN PROFILE IN BATTERY D DURING ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL IMPROVEMENT PHASES

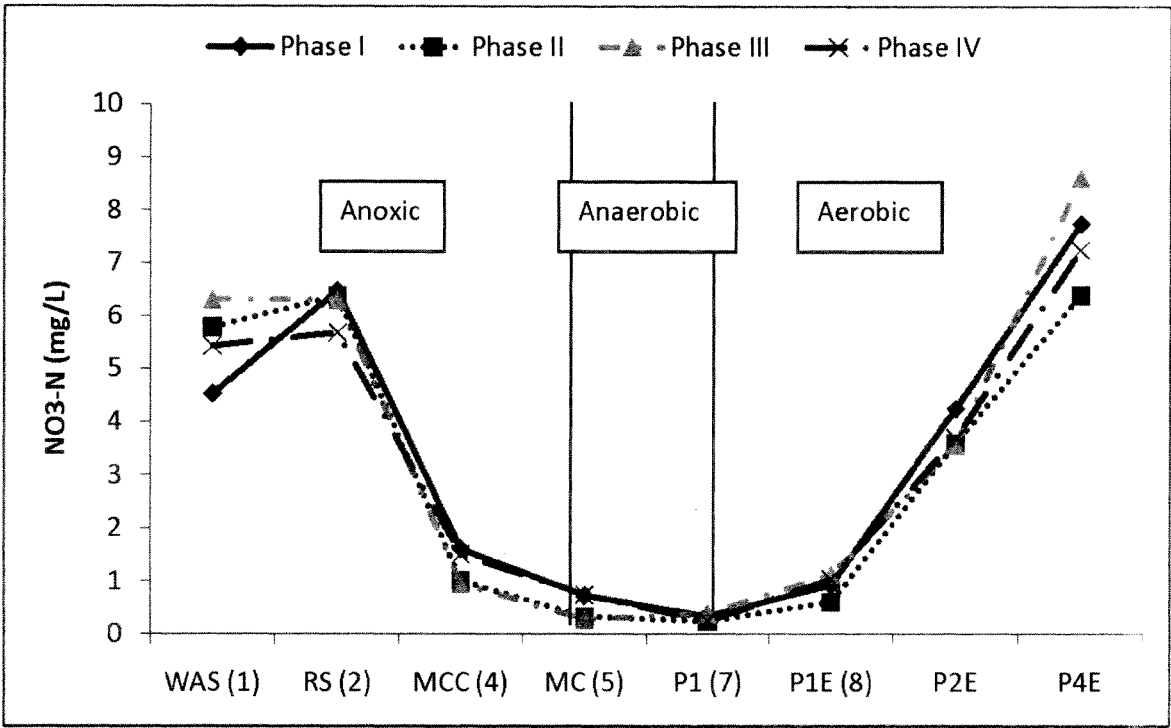


FIGURE 4: CORRELATION OF RETURN ACTIVATED SLUDGE NITRATE NITROGEN CONCENTRATIONS VERSUS BATTERY D EFFLUENT TOTAL PHOSPHORUS CONCENTRATIONS IN PHASE IV

