THE HIGHEST LEVEL OF PHOSPHORUS REMOVAL PRACTICABLE FROM MUNICIPAL WASTEWATER TREATMENT PLANTS

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ABSTRACT

This paper presents results of eleven (11) full-scale plant data on the reliability and efficiency of various phosphorus removal technologies. A selection of process options are offered that can be used to comply with a range of NPDES permit limits. They include biological phosphorus removal with or without chemical addition; chemical treatment at multiple application points, both with and without filtration; and a new membrane process with chemical addition. A discharge permit limit for phosphorus concentration below 0.1 mg/l has been achieved with a combination of chemical addition, followed by filtration and land application.

For a new phosphorous limit of 0.03 mg/l, pilot testing has shown that the target can be achieved by two-step chemical coagulation, followed by a new filtration process. A full-scale demonstration is recommended for generating reliability and efficiency data.

INTRODUCTION

Phosphorus removal from municipal wastewater treatment plants has been practiced in the Great Lakes Basin since the early 1970s. The International Joint Commission comprised of the eight Great Lakes states in the U.S. and two Provinces of Canada agreed to require treatment plants to remove 80 percent of incoming phosphorus, or down to 1 mg/l for those treatment plants with over 1 MGD influent flow.

Since then, other regions followed with similar requirements, based on analysis of particular water quality needs, notably the Chesapeake Bay Water Quality Agreement in the 1980s. This agreement included the states of Pennsylvania, Maryland, and Virginia, as well as the District of Columbia. More recent requirements are based on specific analysis of waste loads for phosphorus, under the total maximum load limitation (TMDL) for the specific watershed. These analyses often resulted in more stringent requirements for phosphorus removal below 1 mg/l, down to 0.10 mg/l and lower.

The purpose of this paper is to present a summary of technologies that have been developed and successfully implemented in meeting the phosphorus removal requirements. It will also present new options novel treatment options currently being developed.
METHODOLOGY

Plant performance and reliability data were collected and plotted for eleven (11) full-scale treatment plants in the U.S. for a full twelve month period. The monthly average concentration of phosphorus was used in this evaluation, because that is the typical compliance basis.

Beyond the full-scale plant analysis, a pilot study was run on a DualSand™ system designed to achieve very low phosphorous levels. Figure 1 contains a diagram of the flow path used during pilot testing of DualSand™ filters.

Figure 1 - Pilot Test Flow Path

The wastewater flowed through comminutors and screens prior to being split between the two oxidation ditches. The WWTP had three clarifiers, two smaller units and one larger unit. The DualSand pilot unit was connected to the larger clarifier, which was receiving 70 percent of the plant flow from the two oxidation ditches. The DualSand system consists of a deep bed Parkson Dynasand™ filter containing 2 meters (80 inches) of sand and a second standard bed filter containing 1 meter (40 inches) of sand. The filters were run in series. The filter effluent was discharged to one of the smaller clarifiers that was not in use. Supernatant from the sludge storage tanks was recycled to the head of the plant.
To aid proper operation of the filters, several chemicals were used. Ferric chloride was added at the head of the plant to reduce the total phosphorus concentration in the clarifier effluent. Sodium hypochlorite (NaOCl) and polyaluminum silicate sulfate (PASS) were added upstream of the filters. The sodium hypochlorite was added to minimize biological growth in the filter media. The sodium hypochlorite was diluted to 2.5 percent (as NaOCl) and added at a feed rate of 5 gpd. PASS served as a coagulant and was fed at a rate of 4 gpd. A flow meter and static in-line mixer were located downstream of the chemical feed points.

RESULTS

Full-Scale Performance

Biological Phosphorus Removal

Figure 2 presents flow diagrams and results for two plants using biological phosphorous removal (BPR). Both plants have an effluent limitation of 1 mg/l. Plant A, with Sequencing Batch Reactors (SBR), performed well, meeting the limitation all of the time. Plant B, performing treatment with A/O process, had an upset in one month and recovered by adjusting operating parameters. The plant staff went through further training and the operation subsequently became successful. P denotes primary sediment tanks and Sed represents secondary sedimentation tanks.

Figure 2 - Flow Diagrams and Phosphorus Removals for Plants A and B

Plant A

0.75 mgd  BPR  1 mg/L

Plant B

5 mgd  P  BPR  Sed  1 mg/L
Chemical Phosphorus Removal with a Single Application Point

Figure 3 presents flow diagrams and results for three plants using chemical phosphorous removal. All three plants have a single chemical application point and were successful in meeting their permit requirements; 1 mg/l for Plants C and D, and 0.6 mg/l for Plant E. Plant C is the most typical secondary treatment plant, succeeding with a single point application at the activated sludge (A.S.) process. The chemical coagulant dosage is the main control tool at this plant and many similar facilities. Plant D is a tertiary treatment plant with multi-media gravity filters. It was designed to meet a stringent BOD limitation, yet the system is effective at phosphorus removal as well. In this plant, the phosphorus removal is accomplished by a combination of coagulation in the primary sedimentation tanks, biological uptake in activated sludge, and filtration of solids, which contain phosphorus in the range of 1 to 2 percent by weight. F denotes filters in the figures. Plant E is similar to Plant D in the process configuration, except the permit limit was lowered down to 0.6 mg/l from the original limit of 1 mg/l, due to concerns about the receiving stream. This plant was successful in meeting the new limit by increasing the coagulant dosage at the activated sludge process.
Figure 3 - Flow Diagrams and Phosphorus Removals for Plants C, D, and E

**Plant C**
- 60 mgd
- Flow: P → A.S. → Sed → 1 mg/L

**Plant D**
- 47 mgd
- Flow: P → A.S. → Sed → F → 1 mg/L

**Plant E**
- 29 mgd
- Flow: P → A.S. → Sed → F → 0.6 mg/L

Graph showing a scatter plot of percent less than or equal to total phosphorus (mg/L) against total phosphorus (mg/L). The data points are labeled C, D, and E, corresponding to Plants C, D, and E, respectively.
Biological Phosphorus Removal with Chemical Addition

Figure 4 presents a flow diagram and results for a plant using biological phosphorous removal with some chemical addition. This plant, with modified activated sludge, removes phosphorus biologically on a semi-continuous mode and adds alum on an as-needed basis. The effluent met the permit limit in all but one month during the year.

Figure 4 - Flow Diagrams and Phosphorus Removals for Plant F

Plant F

0.8 mgd  →  BPR  →  1 mg/L
Chemical Phosphorus Removal with Multiple Application Points

Figure 5 presents flow diagrams and results for two plants using chemical phosphorous removal with multiple application points. For these and similar plants with low effluent limits, a combination of coagulation, biological uptake, and filtration are practiced. Plant G adds ferric chloride at both the primary and secondary sedimentation tanks, provides biological uptake in Rotating Biological Contactors (RBC), and is followed by a gravity filter process. This filter was designed primarily for phosphorus removal, down to 0.3 mg/l, as contrasted to Plants D and E, which were primarily for BOD removal purposes. Plant H is unique in that the limit was lowered down to 0.18 mg/l, which was one of the first instances of such a low limit for a large plant. The first and third application points are for ferric chloride or pickle liquor, while the second application is for lime, which is added to maintain proper pH during nitrification under low alkalinity conditions. The filter is essential in order to meet the effluent phosphorus and BOD limits. In both plants, the limits are met at all times. It is worth noting that the effluent limit for Plant H subsequently was lowered down to 0.12 mg/l and the performance remained in compliance while using the same processes.

Figure 5 - Flow Diagrams and Phosphorus Removals for Plants G and H

Plant G

1.8 mgd → P → RBC → Sed → F → 0.6 mg/L

Plant H

380 mgd → P → Sed → A.S. 1 → Sed → A.S.2 → Sed → F → 0.18 mg/L
Special Processes

Figure 6 presents flow diagrams and results for three plants using unusual processes. Plant I is the first membrane plant constructed to meet a limit of 0.2 mg/l. Ferric chloride is added into the aerobic zone of an old SBR, which had been converted into two zones (anaerobic and aerobic). The membrane unit is installed in the aerobic zone. The performance has been excellent, meeting the permit limit and attaining measurements of 0.05 mg/l.

Figure 6 - Flow Diagrams and Phosphorus Removals for Plants I, J, and K

Plant I

1.0 mgd  BPR  2.0 mg/L
Plant J has a unique permit limit based on the load limit, proportional to the flow of the receiving stream. The limit generally is approximately 0.14 mg/l. Phosphorus removal is accomplished by a combination of chemical coagulation in Claricone™ settlers, followed by a slow sand filtration, and finally a combination of ion exchange and precipitation from land application of the effluent. The final discharge sample is collected from the underdrainage of the land application site. The exchange capacity of the site soil was tested during design and the useful life of the land was one of the
key considerations. The performance has been excellent, with effluent concentrations ranging from 0.07 to as low as 0.02 mg/l.

Plant K is required to meet an effluent limit of 0.21 mg/l. The plant uses a single point application of coagulant, followed by an additional stage of clarification using lamellas, and then filtration using Dynasand™ filters. The performance has been good in compliance with the permit requirement. The difference in the process design between this plant and Plants D and E are additional stages of clarification (Plant K) and the different type of filters (gravity, multi-media filters vs. upflow Dynasand). The differences are recognized in the media size and hydrodynamics during filtration and backwashes.

Pilot Test Results

A pilot test was conducted to determine if a total phosphorus limit of 0.03 mg/L could be met by optimizing chemical usage with a new filtration process. The selected process used DualSand™ filters. Two different coagulants were used during the pilot test. Ferric chloride was fed to the head end of the plant to reduce the amount of phosphorus entering the filters. Polyaluminum silicate sulfate was fed upstream of the filters, along with sodium hypochlorite to minimize biological growth in the filters.

The results indicate that the total phosphorus in the filter effluent ranged from 0.061 mg/L to 0.14 mg/L from April 9 through April 15. During this same time period the filter influent ranged from 1.5 to 2.3 mg/L. On April 16, the ferric chloride feed rate was increased to reduce the influent total phosphorus to below 1 mg/L. From April 17 through April 27, the effluent total phosphorus concentration was less than 0.03 mg/L, as shown in Figure 7. The feed rate to the filters was maintained between 30 and 36 gpm.
The stress test began on April 28. The effluent total phosphorus concentration increased from 0.015 mg/L to 0.027 mg/L when the flow rate was increased to 45 gpm. The second day of stress testing increased to flow to 50 gpm and produced an effluent total phosphorus concentration of 0.032 mg/L. The total phosphorus concentration remained below 0.03 mg/L once the flow was decreased to 40 gpm.

**DISCUSSION**

Three key factors are critical in achieving low phosphorus concentration: the solubility of coagulants, choice of polymer for best flocculation, and ability to remove these coagulation products.

**Table 1 - Chemical Reactions of Al(III) and Fe(III)**

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<th>Reaction</th>
<th>Equilibrium constants</th>
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<tr>
<td></td>
<td>Al(III)</td>
</tr>
<tr>
<td>1. Me$^{3+}$ + 3 H$_2$O ⇌ Me(OH)$_3$(s)</td>
<td>pK$_{MeOH}$ =</td>
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<tr>
<td>2. r Me$^{3+}$ + H$_2$PO$_4^-$ + (3r-1) OH$^-$ ⇌ Me$_r$(H$_2$PO$<em>4$)(OH)$</em>{3r-1}$(s)</td>
<td>pK$_{r}$ =</td>
</tr>
<tr>
<td>3. Me$^{3+}$ + H$_2$PO$_4^-$ ⇌ MeH$_2$PO$_4^{2+}$</td>
<td>pK$_{MP1}$ =</td>
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<tr>
<td>4. Me$^{3+}$ + HPO$_4^{2-}$ ⇌ MeHPO$_4^{+}$</td>
<td>pK$_{MP2}$ =</td>
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<tr>
<td>5. H$_3$PO$_4$ ⇌ H$^+$ + H$_2$PO$_4^-$</td>
<td>pK$_{1}$ =</td>
</tr>
<tr>
<td>6. H$_2$PO$_4^-$ ⇌ H$^+$ + HPO$_4^{2-}$</td>
<td>pK$_{2}$ =</td>
</tr>
<tr>
<td>7. HPO$_4^{2-}$ ⇌ H$^+$ + PO$_4^{3-}$</td>
<td>pK$_{3}$ =</td>
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An examination of phosphorous solubility relationships for Fe and Al ions revealed that theoretical equations are close to, but not exact mimics of, “real world” conditions, as shown in Figures 8 and 9 for each ion, respectively.

Figure 8 - Phosphorus Solubility Relationship for Iron Ions
From these figures, one can observe two important points:

1. The lowest concentration achievable with Fe addition is approximately 0.07 mg/l at pH of approximately 6.9 and 7.0; the pH relationship in actual data from three (3) treatment plants, however, differ from the theoretical one, due to other chemical reactions concurrent with the phosphorus reactions.

2. From Figure 9, it can be observed that the lowest phosphorus concentration achievable with Al ion is even lower than that with Fe ion, approaching 0.01 mg/l at the pH range of 6.6 and 7.2.

The choice of polymer was also found to be important. From prior experience in cold temperature, a polymer with silicate often gives the best results.

For removing coagulation products and particles generated from chemical addition, DualSand™ filters seemed to offer enhanced benefits compared to more conventional systems. These benefits include the two-stage configuration that showed enhanced solids capture efficiency, as well as the particular size distribution of the selected media in each stage.
By combining use of Al salt as the principal coagulant and a corresponding polymer for maximum flocculation, followed by an efficient two-stage filtration process, it appeared that the best system for achieving extremely low phosphorus levels was identified. Future work will include scaling-up the pilot system and demonstrate its reliability and long-term efficiency.

CONCLUSIONS

Based on the performance review of eleven full-scale treatment plants and a pilot study, the following conclusions and recommendations are made:

- For plants with NPDES permit limits of 1 mg/l or higher, either chemical or biological options will be effective. Biological options generally are more economical, but need a chemical backup to assure full compliance. No filtration is required.

- For plants with NPDES permit limits of 0.5 to 1 mg/l, either a chemical option with a single application point, or a biological process with chemical addition will work. Filtration is not a requirement.

- For plants with NPDES permit limits of 0.1 to 0.5 mg/l, a chemical option with multiple application points and a good filtration process, or a biological membrane process with a single point chemical application will work.

- For plants with NPDES permit limits of less than 0.09 mg/l, a site specific test is needed to optimally select the coagulant, corresponding flocculant and the filtration system. Aluminum salt is favored over Fe salt as a coagulant if the target phosphorous concentration is below 0.07 mg/l.

- The results of the pilot testing indicated that the target concentration of 0.03 mg/l could be reliably achieved. A full-scale demonstration is recommended for verification of its reliability and efficiency on a long-term basis.

- Further research is recommended for the solubility limits of Fe and Al and relevant factor under varying environmental conditions.

ACKNOWLEDGEMENTS

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At the time of the pilot testing, John Porter was the project manager at Tetra Tech MPS.
REFERENCES


