xylem

Phosphorus solutions for wastewater treatment

Using advanced treatment options to make the most of a valuable resource

Phosphorus is an essential nutrient for all forms of life, performing a vital role in the operating functions of animal, plant and microbial cells. As such, it's a key component of the fertilizers we use in gardens, on golf courses, and, perhaps most importantly, on crops.

However, in the wrong place—the lakes and streams of our watersheds—too much phosphorus can be an environmental hazard, stimulating excess growth of algae and aquatic plants, which in turn deplete oxygen needed by fish and other aquatic life. According to the EPA, nutrient impairment prevails in 58% of the nation's rivers and streams, 45% of our lakes, about two thirds of our coastal areas, and more than one third of our estuaries.[1]

Too much of a good thing

We have all seen the effects of nutrient impairment in waterways in the late summer. High levels of nitrogen and phosphorus can cause eutrophication, which can lead to hypoxia ("dead zones"), causing fish kills and a decrease in aquatic life. Excess nutrients can cause harmful algal blooms in freshwater systems, which not only disrupt wildlife but can also produce toxins harmful to humans and animals. Closed beaches, hazardous waters and dying fish are all the result of too much of a good thing.

Nutrients enter the watershed from a variety of sources. Non-point sources include runoff from farms, parks, golf courses and lawns that use phosphorus-rich fertilizers. Phosphorus-containing manure from livestock and wildlife, as well as inadequate septic systems also add to the non-point waste stream. Because phosphorus is present in significant amounts in human waste and, to a lesser extent, household detergents, wastewater discharge is one of the most significant point sources of phosphorus in the watershed.

As nutrient impairment of lakes and streams increases, municipalities and government agencies nationwide are evaluating policies and options for reducing the amount of nutrients, including phosphorus, that enter

[1] 2022 EPA Nutrient Reduction Memorandum

the environment from all sources, including treatment plants.

Permitted levels are decreasing year after year. At the same time, because phosphorus has high value as fertilizer, and is a limited natural resource, new options are emerging for recovering it from the waste stream and returning it to service in agriculture.

This white paper is written for engineers and operators of wastewater treatment plants who face changing phosphorus limits as they explore options for meeting the current and future environmental needs of their communities.

Tighter phosphorus limits are coming

Across the U.S., more and more treatment plants are facing permitted phosphorus limits as low as 0.05 mg/L or less. According to the most recent EPA Integrated Compliance Information System database, approximately 29% of municipal wastewater treatment plants of 1 MGD or larger have either phosphorus-only or phosphorus and nitrogen limits. And of the small plants that account for most treatment facilities, less than 10% have discharge limits for P or N and P. However, the status quo is changing rapidly as the EPA implements its strategy to accelerate nutrient pollution reduction. While much of this strategy addresses non-point source pollution, there will also be increased efforts to further reduce nutrient loads from point sources. The EPA has made clear their commitment to working with states and regional permitting authorities to issue new water quality-based permits.

This initiative will present more and more publicly owned treatment works across the U.S. with new phosphorus limits, some as low as 0.05 mg/L or even less. In addition to municipal wastewater plants, the EPA will be promulgating revised effluent limitation guidelines for industries.[2, 3]

While new facilities are often designed for low phosphorus discharge, existing facilities that predate the current regulatory environment were not. Consequently, planners are looking for the best ways to upgrade their facilities for the lowest possible lifecycle cost.

Phosphorous in wastewater

Municipal wastewater typically contains 4–8 mg/L of total phosphorus, primarily in soluble form, as phosphate compounds. About half is present as orthophosphate, and close to 40% as polyphosphate, a string of phosphate molecules. The remainder is present as organically bound phosphorus.[4] Treatment system designers draw on five technologies for removing these phosphates: chemical removal, biological removal, ballasted clarification, filtration, and phosphorus recovery. Depending on plant configuration, projected growth, site limitations, and regulatory requirements, an effective solution for meeting lower phosphorus requirements will most likely employ a combination of these technologies.

Chemical removal: reliable and time tested

Chemical removal of phosphorus from wastewater is a proven, reliable, and relatively economical process. It primarily uses aluminum, iron coagulants, or lime to form chemical flocs with phosphorus. These flocs are then settled out to remove the phosphorus from the wastewater.[5]

Me_{dose}/P_{ini} Ratio

- Mole ratio holds true when effluent P is greater than 1 mg/L
- Stoichiometric doses
    - Ferric dose of 1.8 g Fe per g P
    - Alum dose of 0.8 g Al per g P
- Me_{dose}/P_{ini} ratios of 1.5–2.0 are needed to remove 80–98% of soluble P
- Me_{dose}/P_{ini} ratios of 6–7 are needed to get below 0.10 mg/L

Dosing guidelines for chemical phosphorous removal.[6]

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[2] EPA's April 5, 2022, Memorandum on Accelerating Nutrient Reduction in Our Nation's Waters
[3] EPA NPDES information
[4,5] EPA Design Manual on Phosphorus Removal
[6] Water Environment Federation Webinar – "Basics of Phosphorus Removal and Operational Lessons Learned, by the WEF Plant Operations and Maintenance Committee"

$$Al_2(SO_4)_3 \cdot (14H_2O) + 2H_2PO_4^- + 4HCO_3^- \rightarrow 2AlPO_4 + 4CO_2 + 3SO_4^{2-} + 18H_2O$$

$$FeCl_3 \cdot (6H_2O) + H_2PO_4^- + 2HCO_3^- \rightarrow FePO_4 + {}_3Cl^- + 2CO_2 + 8H_2O$$

Chemical removal is based on these aluminum- and iron-based reactions.

Chemical removal is, however, a complex, often multipoint process with competing reactions that can vary with pH, alkalinity, reaction time, and mixing intensity. Phosphorus occurs in several different forms throughout the process, and understanding its distribution is vital to monitoring and removing it. Chemicals are frequently added at both primary and secondary stages, and tertiary treatment is used in plants that have ultra-low phosphorus level requirements.

Typical process yields total suspended solids:

- 1 mg/L iron dosage = 1.9 mg/L TSS
- 1 mg/L aluminum dosage = 2.9 mg/L TSS

Volatile Suspended Solids:

- 1 mg/L iron hydroxide = 0.25 mg/L TSS
- 1 mg/L aluminum hydroxide = 0.35 mg/L TSS
- Affects digester VSS destruction

Typical yields. Successful removal ultimately depends on how well the process removes total suspended solids (TSS).

Biological phosphorous removal: lower cost, less sludge

In conventional biological treatment, phosphorus is removed as a normal part of aerobic biological growth. The microorganisms are then separated from the wastewater by settling or filtration. The biological yield of this process is approximately 0.5 lb. per pound of BOD removed, with phosphorus content of about 2% by weight.

Under typical conditions, the process will yield the following:

- Typical WW with 60 g BOD/cap/d, 1.5–2 gr P/cap/d, 0.3 m³/cap/d = 200 mg/L BOD, 6.7 mg/L P, 30:1 BOD:P

Assimilative uptake of P:

- Yield = 0.5 mg VSS/mg BOD, 2% P, 2 mg/L removed (30–40% removed)
- Effluent P = 3–4 mg/L

Enhanced biological phosphorous removal: lower costs and superior effluent quality

Enhanced Biological phosphorus Removal (EBPR), in which the series of reactor processes are optimized for high-efficiency phosphorus removal, can increase the biomass content of waste sludge to 3–6% phosphorus compared to conventional activated sludge systems (normally 1.5–2%) Under the right conditions (generally, a BOD:P ratio of 30:1 with anaerobic/aerobic cycling of biomass), EBPR can reduce or eliminate the need for chemical precipitation or filtration, achieving effluent phosphorus levels below 1 mg/L or even < 0.3 mg/L on its own.

EBPR can be achieved in continuous flow systems or batch systems. Continuous-feed oxidation ditches, such as Orbal®, systems can be designed with an aerated-anoxic zone with a strong oxygen deficit to achieve a strong reducing environment that favors phosphorus accumulating bacteria.

Anaerobic selectors for EBPR

In other cases, the addition of an anaerobic selector can be used, either in SBR's or in suspended growth activated sludge processes with separate tanks. SBR systems can utilize common-wall construction, typically requiring less space compared to processes with separate secondary clarifiers. Additionally, SBR systems offer more flexibility in adjusting the reaction times for anaerobic, anoxic, and aerobic treatments than processes that rely on secondary clarifiers for liquid-solid separation.

OMNIFLO® SBR systems accomplishes equalization, aeration, and clarification in a timed sequence in a single reactor basin providing a treatment process to support efficient biological nutrient removal (BNR) of ammonia nitrogen, total nitrogen and phosphorus.

The OMNIFLO® SBR system with Jet Tech technology from Xylem is a batch-feed process that can be operated with a static fill step at the beginning of the treatment cycle creating a strong reducing environment. Similarly, a continuous flow SBR like the Sanitaire® ICEAS SBR system typically reduces nitrate levels in the mixed liquor to very low concentrations by the end of the settle/decant phase, allowing a strong reducing environment to be created with an unaerated mix sequence at the beginning of the treatment cycle. In either SBR system approach, the initial anaerobic period provides excellent conditions for fermentation, volatile fatty acid uptake, and phosphorus release. Subsequent anoxic and aerobic steps allow for uptake of phosphates. The continuous flow Sanitaire® ICEAS SBR system can typically tolerate higher peak flows with a smaller basin versus a batch-feed system, however the batch feed OMNIFLO® SBR system may be better suited for extremely low effluent ammonia limits (ie–less than 0.5 mg/L) and treating high-strength wastewater.

For suspended growth activated sludge processes with separate tanks for settling, a small anaerobic zone with a mechanical mixer has been used successfully to enhance P removal. One example is 2-channel Orbal® system, from Xylme, when a very low DO or ORP level cannot be maintained in the first channel. Similarly, anaerobic zones with a mechanical mixer can be employed in BioLoop® oxidation ditch systems as well as in CASPERON™ conventional activated sludge systems from Xylem with fine bubble aeration.

Orthophosphate levels in these selectors have been observed to rise to levels of 30–40 mg/L as P4. anaerobic selectors have also been used in systems requiring both low TN and TP levels to allow the anaerobic and aerated-anoxic environments to be optimized independently.

The continuous flow Sanitaire ICEAS® SBR System can typically handle higher peak flows within a smaller basin versus a true-batch SBR system.

In each case, by sequencing the biomass through a sufficiently anaerobic stage, and with a sufficient food source, prior to the reintroduction of oxygen, it is possible to selectively grow a biomass capable of storing phosphorus at a higher than conventional level.

The phosphorus is ultimately removed from the system by settling and removing sludge.

Any of the above methods can be effective in reducing treatment costs and optimizing the process to achieve superior effluent quality. As in any biological system, the processes can be negatively impacted by flow and temperature variations as well as shock loads, so a backup chemical precipitation system should be considered to ensure consistent performance.

Simultaneous nitrification and denitrification (SND)

To establish anaerobic conditions necessary to give phosphorus accumulating organisms an environmental advantage, nitrate concentrations in the mixed liquor must be reduced. Operating an activated sludge process with reactors in series allows the oxygen supply rate to the initial reactors, which will have with a higher F:M ratio, to be controlled so that the oxygen is quickly consumed (called an aerated-anoxic condition). Downstream reactors can be maintained in an aerobic state and will remove any residual ammonia, but the majority of the ammonia can be converted to nitrate in the upstream initial reactors. This approach results in simultaneous nitrification and denitrification (SND), reducing power consumption and basin volume by about 25% compared to conventional systems relying on unaerated anoxic zones and recirculation pumping of nitrates for denitrification.

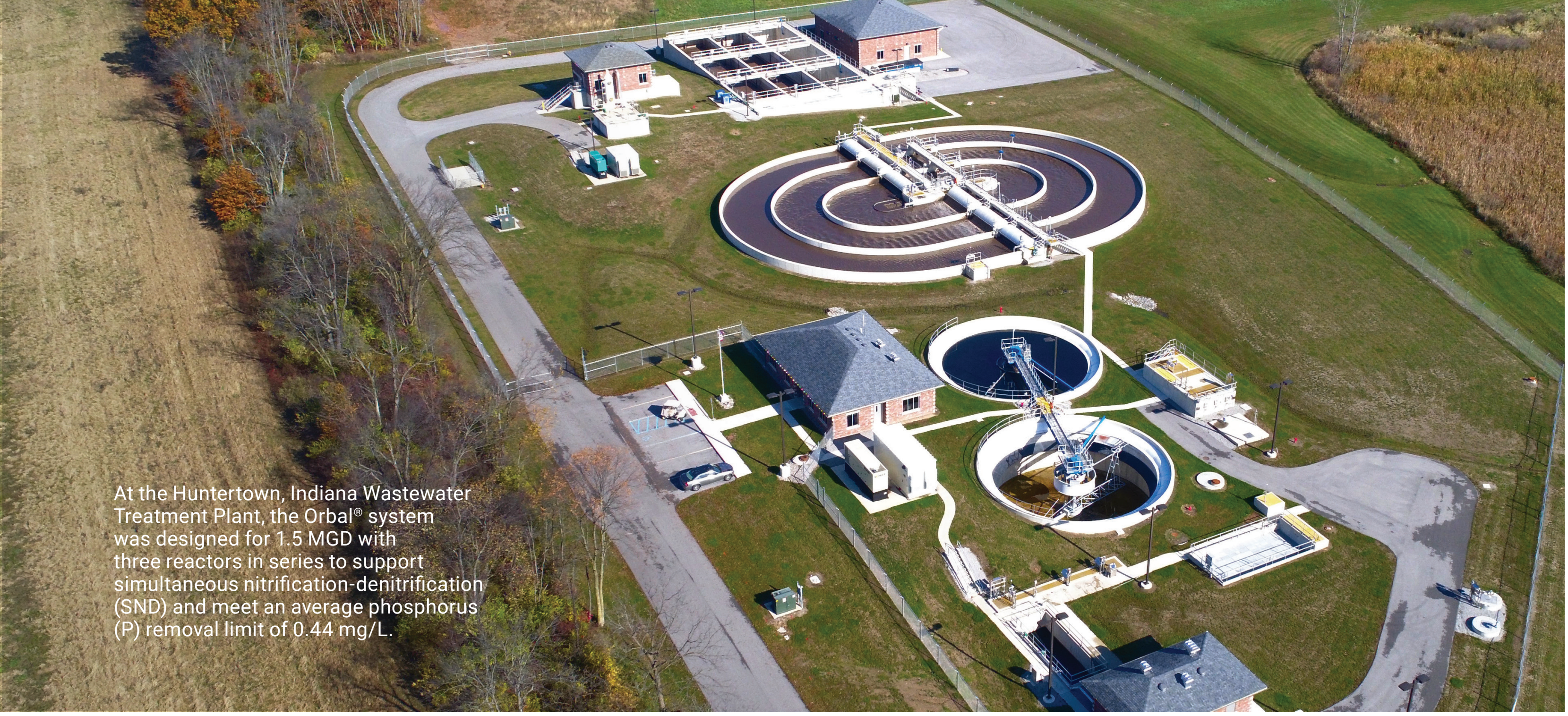
In the Orbal® and VLR® systems from Envirex® a Xylem brand, aeration and mixing is provided with disc aerators, allowing maintenance of aeration equipment without the use of dewatering basins. Compared to other types of mechanical aeration devices, disc aerators offer a significantly broader turn-down range, keeping mixed liquor solids in suspension even when transferring minimal oxygen. This ability helps maintain conditions conducive to SND, even under low loads and temperatures.

The Bioloop® oxidation ditch system utilizes fine bubble diffusers which can be more energy efficient versus mechanical aeration systems depending on the basin depth. The Bioloop® system uses a combination of fine bubble diffused aeration and submersible mixers to allow independent control of the mixing and oxygen supply rates. This provides good turndown in aeration rates necessary to maintain conditions ideal for SND at low loads and temperatures. Although it is common for a diffused aeration system to operate for 10 or more without the need to drain a basin for maintenance, the Bioloop® system should be designed to provide treatment with a basin out of service to allow fine bubble diffuser replacement when required.

The CASPERON™ system from Sanitaire® a Xylem brand is an activated-sludge process designed to work with a full-floor fine bubble aeration system. The challenge for maintaining Aerated Anoxic conditions with full-floor fine bubble aeration has been the need to limit the oxygen supply rate during low temperatures and/or low influent load while maintaining mixing. The CASPERON system addresses this need with the variable energy mixing aeration (VEMA) controller, which intermittently pulses the air supply rate to the aeration grids to maintain mixed liquor solids in suspension while operating most of the time at lower airflow rates. As the VEMA controller does not provide as wide a range of oxygen transfer turndown as Orbal or BioLoop oxidation ditch systems, it may be necessary to design initial reactors as “swing” zones to allow the turndown needed for SND when very low loads and temperatures are expected. CASPERON systems should also be designed to provide treatment with a basin out of service to allow diffuser replacement when required.

Experience with all Xylem biological treatment technologies show that increasing wasting rates can elevate sludge production rates above normal and increase biological production for best phosphorus removal. A young sludge will result in better phosphorus removal compared to older sludges (high MLSS) that contain more dead cells.

- Proper design and operation of the final clarifiers is essential to enhanced biological phosphorus removal. To minimize the risk of high-effluent phosphorus, the sludge retention time (SRT) within the final clarifier should be less than 30 minutes. This is accomplished by using higher recirculation rates and a suction sludge removal device, and maintaining a low or “zero” (less than 1 ft) sludge blanket. SBR settings can limit the length of settle and idle times to minimize phosphorus release.
- If discharge permits require phosphorus limits less than 1.0 mg/L, tertiary solids removal by filtration may be necessary.



At the Huntertown, Indiana Wastewater Treatment Plant, the Orbal® system was designed for 1.5 MGD with three reactors in series to support simultaneous nitrification-denitrification (SND) and meet an average phosphorus (P) removal limit of 0.44 mg/L.

- When both phosphorus and nitrogen removal are required at a plant, some design and operating parameters required to achieve these goals conflict with each other. To effectively operate both processes, it is necessary to maintain tight control over operating parameters. Xylem's PLC-based SmartBNR™ and OSCAR™ process control systems are recommended for this purpose.
- Suboptimal biosolids management can impair the efficiency of an entire plant. But the Vorelodos® aerobic digester system can cut nitrogen, and phosphorus returns to the main treatment process by up to 50%. The Vorelodos system reduces nutrient spikes for greater stability while it trims the consumption of chemicals and energy.
- Anaerobic digestion is generally incompatible with EBPR. Digester supernatants have very high soluble phosphorus. If EBPR is used in a plant with anaerobic digestion, it is usually necessary to chemically treat the digester supernatant to precipitate the soluble phosphorus. However, EBPR waste sludge does offer an opportunity for phosphorus recovery, as discussed below.

Clarifier enhancements and tertiary treatment: ballasted clarification and disc filtration

Ballasted clarification dramatically increases biological treatment capacity, helping to meet enhanced nutrient removal (ENR) limits and produce effluent quality far superior to conventional alternatives, and at lower life-cycle costs. Ballasted clarification uses a high-density inert material such as microsand or magnetite—fully inert iron ore particles—to ballast biological floc or conventional chemical floc, enhancing settling rates and increasing the performance of wastewater and water treatment facilities, while substantially reducing costs to upgrade process performance. The ability to handle a wide variation in flows and loads minimizes the risks of upsets.

BioMag® system: ballasted clarification for biological processes

Xylem's innovative BioMag® system uses magnetite to deliver the world's fastest proven settling clarification technology for biological floc, allowing capacity expansion and performance improvement with minimal plant modifications at the lowest cost possible. It consistently achieves a sludge volume index (SVI) of less than 50. The BioMag® system is a cost-effective solution for activated sludge systems with an average design capacity of 5 million gallons per day (MGD) or larger providing up to 300% more treatment capacity in existing tankage.

CoMag® system: ballasted clarification for chemical processes

Xylem's CoMag® system is an innovative technology that infuses magnetite as a weighting agent into traditional chemical floc to efficiently reduce the total phosphorus (TP) levels far below that of conventional treatment. The CoMag system settles floc up to 30 times faster than conventional treatment, enabling plants to increase capacity and clarifier performance. It can reduce total phosphorus down to 0.05 mg/L and can achieve UV transmittance greater than 75% when integrated into any type of coagulation/flocculation process or clarifier.

Disc Filtration

Forty-X® Disc Filter systems provide a solution to meet low level phosphorus effluent requirements by removing particulates associated with phosphorus. Designed with a unique woven optimum tertiary mesh (OTM) filter panel, the Forty-X Disc Filter uses an inside-out flow pattern for high-quality tertiary filtration.

In lieu of relying on gravity settling of chemical phosphorus flocs, the Forty-X Disc Filter actively filters floc particles out of the effluent stream.

Effluent from a WWTP's secondary solid-liquid separation process is blended with aluminum or iron coagulants in a rapid mix tank. The development of large, filterable chemical phosphorus flocs is done in a flocculation.

Taron® Activated Sludge Filter

The Taron® Activated Sludge Filter supplements or replaces secondary clarifiers, while producing effluent quality as low as 3 to 5 mg/L. As mixed liquor solids contain both nitrogen and phosphorus, the low TSS levels in the effluent produced by the Taron® system help achieve low phosphorus and nitrogen limits. The Taron® system can operate at mixed liquor concentrations from 6,000–12,000 mg/L, allowing the footprint of treatment plants to be decreased. The system is installed directly into aeration basins, making it easy to expand capacity of existing treatment plants with minimal disruption of treatment. The current generation of the Taron® system is designed for plants with an average flow of about 1.5 MGD or less, however plans are underway to scale up this technology to treat higher flows.

Advanced Phosphorus Recovery

With phosphorus recovery technology from Ostara Nutrient Recovery Solutions by Xylem, wastewater treatment facilities can do more than meet new lower limits for phosphorus: They can recover this valuable resource and return it to service as fertilizer.

Ballasted clarification systems dramatically increase biological treatment capacity, helping meet ENR limits and produces effluent quality far superior than conventional alternatives, and at lower life-cycle costs.

Ostara's Pearl® system is a fluidized bed reactor that recovers phosphorus and ammonia from high-strength nutrient streams that include sludge, dewatered liquor, and WAS thickening liquors. Within the Pearl system reactor, the growth of struvite (magnesium ammonium phosphate) is facilitated by the addition of magnesium in a controlled pH setting. This allows nutrients to crystallize into fertilizer granules which are harvested, dried and then distributed and sold by Ostara as Crystal Green® Fertilizer. The treated effluent is then discharged from the top of the reactor and returned to the plant with significantly reduced nutrient content.

Crystal Green® fertilizer is only 4% water soluble versus ~90% water solubility for typical phosphorous fertilizers. This greatly reduces the runoff and leaching of phosphorous into our waterways and groundwater. The nutrients are accessible from acid release of the crop roots allowing the fertilizer to remain in the root zone longer, requiring less phosphorous application for greater crop yields.

Ostara's Pearl® system is a nutrient recovery solution to help transform wastewater treatment plants into true resource recovery facilities

Now is the time to invest in a greener future…in the right places

Society is battling nutrient impairment—to which phosphorus is a key contributor—to reduce its impact on waterways and aquatic life. New farming practices, stormwater and runoff management, phosphate-free detergents, and other tactics are helping accelerate the progress of nutrient management.

The 2021 Bipartisan Infrastructure Law provides new opportunities for many communities to invest in clean, safe water, with the potential to accelerate progress on nutrient pollution even further. In this environment, wastewater treatment plant operators and designers have access to new resources, in the form of technologies like chemical removal, EBPR, and tertiary treatments, for keeping phosphorus in green spaces and farms where it can foster growth…and out of our watersheds, where it can be simply too much of a good thing.

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