PUBLIC WORKS TECHNICAL BULLETIN 420-49-39
1 SEPTEMBER 2001

BIOLOGICAL NUTRIENT REMOVAL

Public Works Technical Bulletins are published by the U.S. Army Corps of Engineers, Washington, DC. They are intended to provide information on specific topics in areas of Facilities Engineering and Public Works. They are not intended to establish new DA policy.

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
441 G Street, NW.
Washington, DC 20314-1000

CEMP-RI
Public Works Technical Bulletin 1 September 2001
No. 420-49-39

FACILITIES ENGINEERING
UTILITIES

BIOLOGICAL NUTRIENT REMOVAL

1. Purpose. This Public Works Technical Bulletin (PWTB) provides information on Biological Nutrient Removal (BNR) for Army wastewater treatment plants (WWTPs). BNR is the removal of nitrogen and/or phosphorous from wastewater using biological methods of treatment.

2. Applicability. This PWTB applies to all U.S. Army facilities engineering activities, and installations responsible for design, construction, and operation and maintenance of WWTPs and, for informational purposes, to installations that deliver wastewater off-post to regional treatment facilities or have privatized their WWTPs.

3. References.

a. Army Regulation (AR) 200-1, “Environmental Protection and Enhancement,” 21 February 1977.

b. AR 420-49, “Utility Services,” 28 April 1997.

4. Discussion. Army installations are obligated to meet the requirements of their National Permit Discharge Elimination System (NPDES) permits. These permits have become increasingly stringent as the United States strives to improve the quality of the nation’s waters. Nutrient limitations are becoming more common as the importance of nutrient control for improving the environment is realized on a national basis.

a. U.S. Army installations, especially in areas threatened with eutrophication, are being required to reduce nutrient loads in their wastewater effluent. Threatened areas such as the Chesapeake Bay and other large estuaries, and the Great Lakes have regional plans aimed at reducing nutrient loading.

b. This PWTB gives an overview of BNR, including the need for the technology, and other available and emerging technologies.

c. Appendix A explains the BNR technology in detail.

5. Points of Contact. The proponent for this document Mr. Bob Fenlason, CEMP-RI. Questions and/or comments regarding this subject should be directed to the technical POC; U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory for Mr. Richard J. Scholze (Richard.J.Scholze@erdc.usace.army.mil) at (800) USA-CERL .

FOR THE COMMANDER:

DWIGHT A. BERANEK, P.E.
Chief, Engineering and Construction Division
Directorate of Civil Works

APPENDIX A

BIOLOGICAL NUTRIENT REMOVAL AT ARMY WASTEWATER TREATMENT PLANTS

1. Introduction

a. Various programs exist throughout the world to control the effluent from wastewater treatment plants (WWTPs) and address the adverse effects of nutrients on water quality, both domestic and industrial. These WWTPs are called point sources as they release nutrients to the environment from a defined source such as a pipe, outfall, ditch, or similar conveyance. Typically during wastewater treatment, organic nitrogen and ammonia nitrogen are either converted to nitrates or removed as nitrogen gas to the atmosphere. Phosphorous is typically removed with the sludge following conversion to a chemical precipitate or incorporation into the biological cell mass.

b. Nonpoint sources also contribute significant quantities of nitrogen and phosphorous. Nonpoint sources for nutrients can be, for example, stormwater runoff, snowmelt, and atmospheric deposition. For water quality programs to be successful, it is often necessary to control these nonpoint sources as well. All sources of water entering lakes and reservoirs (i.e., rivers, creeks, groundwater, atmosphere, rainfall and wastewater effluent) can contribute nutrients. In some instances, contributions from nonpoint sources may be so great that benefits from removal of nitrogen or phosphorous from point sources become insignificant.

c. Typically, nutrient control strategies take advantage of a microorganism's necessity for nitrogen and phosphorous. Limiting the availability of either or both of these elements controls the growth of undesirable microorganisms. Nitrogen in the biomass of algae, for example, occurs in amounts ranging from 3 to 10 percent, largely in the form of protein. However, because several blue-green algae can fix elemental nitrogen dissolved in water, fixed forms of nitrogen available from aqueous sources may not be true growth restraints. Numerous studies have shown that nitrogen can become limiting in the control of algal growth during the summer growing season at a limiting level of 0.05 mg/L of inorganic forms (NH_3-N + $N0_3$-N). On this basis, nitrogen removal from wastewater may become necessary when receiving waters are insufficient in quantity to dilute inorganic forms to the limiting level.

d. Although phosphorous in algal cells occurs in small amounts in the biomass, it has been shown to be a limiting factor in the growth of algae. A value of less than 0.005 mg/L in the ortho form is recognized as a lower growth-limiting concentration. Its removal from wastewater is highly feasible because most organic and inorganic forms of phosphorous are readily removed by precipitation with the use of alum, ferric salts, or lime. Enhanced biological phosphorous removal processes can also remove it.

e. In instances where nutrient control for freshwater is deemed desirable, control of phosphorous is considered to be absolutely essential because, when nitrogen becomes limiting, any excess of phosphorous can support growth of nitrogen-fixing, blue-green algae. In such cases, the nitrogen budget of a body of water will be increased, thereby materially offsetting any benefits from nitrogen removal. In marine waters, it is considered desirable to control nitrogen inputs because phosphate is in abundant supply.

f. The primary reason to reduce nutrients is to slow down eutrophication, which is a term that describes the natural process by which biological productivity increases with the age of a body of water. This increase is typically a result of algae and other aquatic plants capturing plant nutrients that are contributed by inflowing waters, resulting in new growth. These resultant organisms and plants eventually die and settle to the bottom, where they decompose to some degree. During decomposition, nutrients are released to the water and these nutrients eventually reach the upper waters. This continual enrichment from external and recycled sources perpetually produces new growth that dies and settles to the bottom. Residue from decomposition and silt carried by inflowing waters gradually fills the lake or reservoir.

g. The fertilizing effects of nitrogen and phosphorous in receiving waters vary in different depths as does the impact of ammonia nitrogen. Movement of the water and whether it is a stream or lake also play important roles in how serious is the effect of nutrient addition.

h. The most damaging and obvious effect of nutrients in lakes, ponds, and reservoirs is the stimulation of algal growths that typically occur in pulses referred to as blooms. Of particular concern are algae that tend to float to the water's surface at certain stages in their life cycles and that are moved about by gentle breezes to accumulate along shorelines or coves. Such aggregations can interfere with normal recreational activities such as swimming and can cause serious nuisances because of algal decay, subsequent odorous bacterial decomposition, and unsightliness. Odor problems can be particularly offensive when high-protein blue-green algae are involved.

i. When algae decompose under aerobic conditions they consume oxygen, which eventually becomes depleted. This condition is quite normal in lakes that are deep enough to stratify. When oxygen is reduced below certain levels, however, the effects on fish life and other oxygen-dependent organisms are disastrous. Nitrates in the water may temporarily prevent the formation of anaerobic conditions, but their subsequent depletion will allow anaerobic conditions to develop.

j. Bacterial decomposition under both aerobic and anaerobic conditions then leads to a phase that perpetuates the blooming process. The decaying bacteria release nitrogen as ammonia and phosphorous as phosphates. Small amounts are also released as soluble organic compounds, and fractions of the nutrients always remain as indigestible residues in bottom deposits. The predominant release is of prime nutrients, however, which are then recycled to the waters above.

2. Overview of Nutrient Removal Processes

a. Table 1 summarizes the various options for removing or converting nitrogen from one species to another. To completely remove nitrogen from the system, five processes are available:

(1) Conversion of nitrogen to nitrogen gas, N_2, which escapes into the atmosphere. This process is achieved in biological treatment systems through nitrification, followed by denitrification (breakpoint chlorination).

(2) Biological uptake of nitrogen for growth of biomass.

(3) Stripping of ammonia from the water because NH_3 (g) can be achieved at high pH.

(4) Ion exchange to chemically exchange nitrogen ions as NH_4+ or as $N0_3$- using a cation or anion exchange resin, respectively.

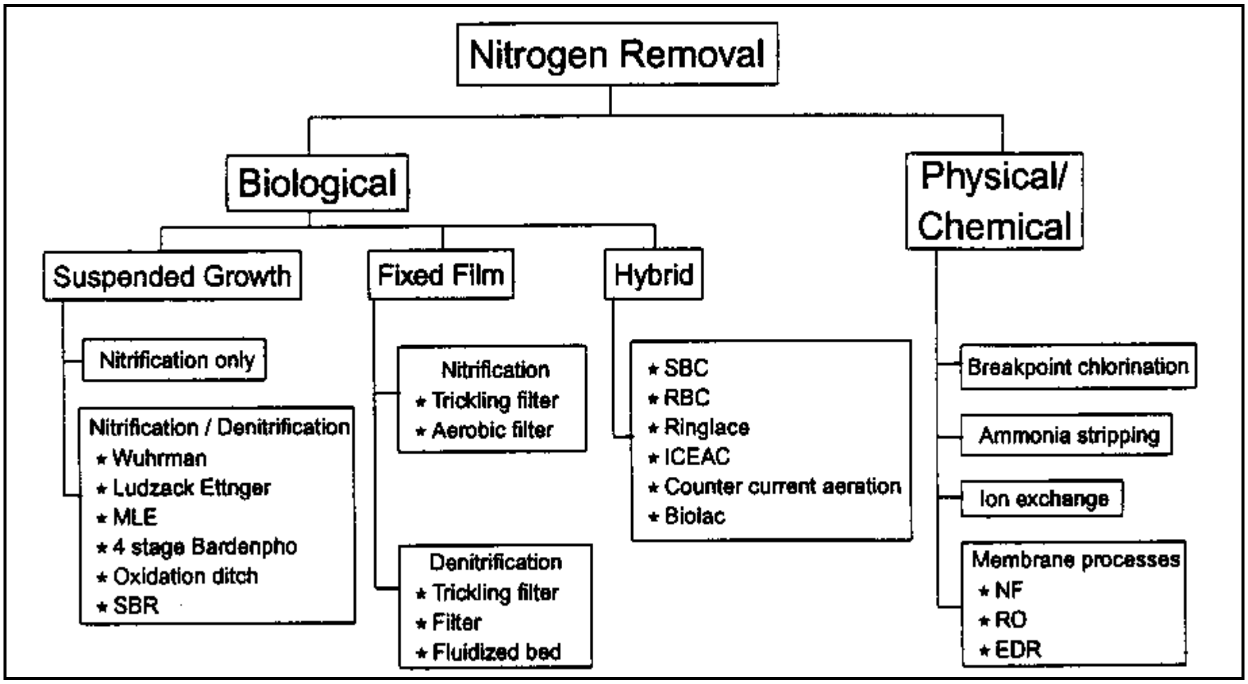
(5) Processes that will remove essentially all pollutants from water, such as reverse osmosis membranes, can be used to remove nitrogen. Efficiency varies with the type of membrane and nitrogen species.

Table 1. Nitrogen removal and conversion processes.

Initial species	Ultimate species	Process
Organic-N	Ammonia, NH_4^+-N	Ammonification Biological conversion of organic nitrogen to ammonia
Ammonia, NH_4^+-N	Nitrate, NO_3^--N	Biological nitrification
	Ammonia gas, NH_3(g)	Stripping
	Organic nitrogen	Biological uptake during bacterial growth
	Nitrogen gas, N_2(g)	Breakpoint chlorination
	Resin	Ion exchange will exchange ammonia for another cation
Nitrate, NO_3^--N	Nitrogen gas, N_2(g)	Biological denitrification
	Resin	Ion exchange will exchange nitrate for another anion

(Source: WEF 1998.)

b. Figure 1 summarizes the various processes that can be used to remove nitrogen from wastewater.



(Source: WEF 1998.)

Figure 1. Processes used for nitrogen removal.

3. Biological Nutrient Removal

a. BNR is achieved through a series of biochemical reactions that transform nitrogen from one form to another. The key transformations are nitrification and denitrification.

(1) *Nitrification* – The conversion of ammonium, NH_4+, to nitrite, NO2-, and finally to nitrate, NO_3-. The conversion to nitrite is catalyzed by *Nitrosomonas* sp., and the conversion to nitrate by *Nitrobacter* sp. In practice, the kinetics of the overall process are limited by *Nitrosomonas* sp., and nitrite is rapidly converted to nitrate by *Nitrobacter* sp.; therefore, little nitrite is found in solution if the reactions occur under optimum conditions.

(2) *Denitrification* – In the absence of dissolved oxygen, bacteria will use nitrate as a terminal electron acceptor and convert it to nitrogen gas. Denitrification occurs under two distinct conditions:

a) Rapid denitrification is achieved when an external substrate (such as wastewater or methanol) is available for bacterial growth. Substrate level denitrification is relatively rapid and proceeds typically at 0.03 to 0.11 kg NO_3^-N/kg VSS-d. The concentration of available substrate (food to microorganism ratio) and type of substrate will affect the denitrification rate.

b) Slow denitrification occurs when bacteria use nitrate under conditions without an external substrate source, also known as endogenous-level denitrification. Endogenous-level denitrification is slow and proceeds typically at rates between 0.01 and 0.03 kg NO_3^-N/kg VSS-d. Endogenous-level denitrification rates are related to sludge age and the active mass fraction of denitrifying bacteria.

b. Suspended Growth Processes

(1) The activated sludge process is a typical suspended growth system, where bacteria are kept in suspension under appropriate conditions to allow the bacteria to grow and consume pollutants from the water. Earlier, nitrification was separated from carbon oxidation (biochemical oxygen demand [BOD] removal) in activated sludge plants in a two-stage process by using a high-rate, first-stage activated sludge process for BOD removal, followed by a low-rate nitrification stage. However, carbon oxidation and nitrification can proceed readily in the same aeration basin under favorable conditions.

(2) For a suspended growth system, it is important to maintain a sufficiently high sludge age to allow the slow-growth nitrifiers to reproduce in the aeration basin and prevent them from being washed out of the system. The minimum sludge age is determined by temperature, pH, and other operating conditions. When estimating the sludge age of nitrifier sludge mass, one must reduce the traditional sludge age by considering only the sludge mass that is kept under aerobic conditions, because nitrifiers are obligate aerobes and do not grow under anoxic or anaerobic conditions.

(3) After nitrification is established, effluent ammonia concentrations below 1 mg NH_4^+-N/L can be readily achieved using activated sludge at a high sludge age. The design and operation of a nitrification activated sludge system is similar to a normal activated sludge system operated for BOD removal only. The oxygen demand is significantly higher, however, and the operator must consider the effect of decreases in alkalinity and a possible drop in pH. Because the nitrifier growth is affected by pH, alkalinity supplementation may be required. Denitrification in suspended growth plants can be readily achieved by creating zones that are depleted of oxygen by replacing aeration with mixing in some areas. If these zones, without dissolved oxygen, are created at the feed end of the aeration basin, the presence of BOD in the feed water provides substrate for denitrification, and substrate level denitrification will occur. If the zone is created toward the end of the basin where the substrate level is low, endogenous-level denitrification will occur. An external substrate, such as methanol, can also be added to the denitrification basin to increase the denitrification rate.

(4) Denitrification in activated sludge secondary clarifiers will lead to the flotation of solids, because the gaseous N_2 produced in the process becomes entrapped in the activated sludge floccules and floats to the surface. This flotation of solids can be controlled by reducing NO_3 before the water enters the clarifier by denitrifying in the reactor, by a long solids retention time to produce a stable sludge, or by increasing the mixed liquor dissolved oxygen.

c. Fixed Film Processes

(1) Trickling filters and rotating biological contactors (RBCs) are fixed film processes that have been used effectively for nitrification. In this case, the process analysis is less straightforward than in activated sludge because bacteria are in direct competition for oxygen with heterotrophic bacteria. Because the heterotrophic bacteria typically outgrow the nitrifiers, heterotrophic activity tends to dominate areas where BOD is high, such as the top of a trickling filter and the front end of an RBC. An RBC is a type of fixed film treatment process – essentially a trickling filter turned on its side – which rotates through the wastewater as the

wastewater passes through the RBC or a series of RBCs. After the BOD loading decreases in either process, however, oxygen becomes more available for nitrifiers and nitrification begins.

(2) Trickling filters have been used successfully to achieve nitrification. Heterotrophic growth will typically dominate the top of the trickling filter, and nitrification will occur at the lower end. Nitrifying trickling filters are typically tall, and forced ventilation is provided to improve oxygen supply.

(3) Trickling filter effluent ammonia concentrations of 1 mg/L are achievable under favorable conditions. Below this concentration, however, the confidence level of the process decreases and additional facilities may be required to ensure that effluent limits are consistently met. Pilot testing for specific applications should be considered to determine the process performance under site-specific conditions. After site-specific processes are established, nitrification remains efficient in trickling filter plants.

(4) Because denitrification requires the absence of oxygen, it can be achieved in fixed film reactors in a deep film or by operating in a submerged mode. Both upflow and downflow modes of operation can be used. An external carbon source, such as methanol, is often added to increase the denitrification rate and reduce the reactor size.

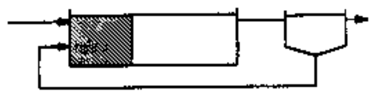
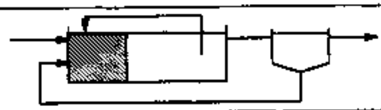
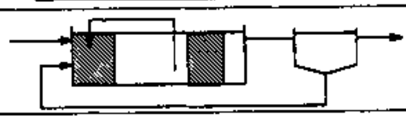
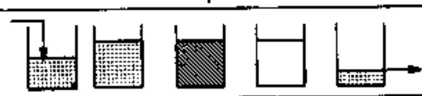
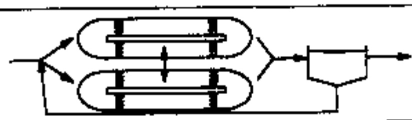
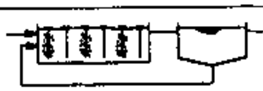
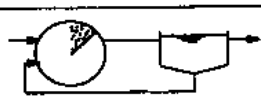
(5) Denitrification can be achieved in trickling filters and fluidized-bed reactors following any nitrification process. A fluidized-bed reactor is a type of mobile bed where uniform expansion of the media is caused by upflowing liquid. As with fixed film reactors, an external substrate such as methanol is typically added to increase denitrification rates. Koopman et al. (1990) found that complete denitrification (effluent nitrate plus nitrite < 1 mg/L) can be achieved with addition of 3.3 to 3.5 g methanol/g N. Madireddi et al. (1994) achieved nitrate concentrations below 1 mg/L in an upflow fluidized-bed reactor receiving nitrified trickling filter effluent and adding methanol as a carbon source.

4. BNR Schemes

a. Figure 2 shows several of the BNR schemes used to take advantage of the biological nitrogen transformations. This list is by no means complete, but it demonstrates the variety of possible ways to achieve nitrogen removal. These processes are not explained in depth in this PWTB. Further details and comparisons of the processes may be found in the WEF Manual of Practice No. 8, *Design of Municipal Wastewater Treatment Plants* (1998) and *Biological and Chemical Systems for Nutrient Removal* (WEF 1998). In general, the various schemes achieve nitrogen removal by:

(1) Sequential nitrification followed by denitrification (schemes 1, 4, 5, 6, and 12) — Because denitrification rates are slow, large reactors are required or a chemical substrate is added, as shown for the post-denitrification fluidized bed or filter in schemes 5 and 6.

(2) Denitrification using influent organics to achieve substrate level denitrification (schemes 2, 3, 4, and 12) – These schemes rely on the return activated sludge and are often an internal recycle to return nitrate from the nitrification zone to the denitrification zone.

Symbolic Representation	Process	Substrate Level Denitrification	Endogenous Level Denitrification	Separate Stage Nitrification	Mixed Nitrification/Denitrification	Fixed Film	Chemical (methanol) Addition	Internal Recycle
	1. Wuhrman		✗					
	2. Ludzack-Ettinger	✗						
	3. MLE	✗					✗	✗
	4. Bardenpho	✗	✗				✗	✗
	5. Trickling Filter Filter			✗		✗	✗	
	6. Activated Sludge Fluidized Bed			✗		✗	✗	
	7. SBR				✗			
	8. Oxidation Ditch				✗			
	9. Biodenitro				✗			
	10. Biolac				✗			
	11. Counter Current Aeration				✗			
	12. Step Feed Denitrification	✗	✗					

(Source: WEF 1998.)

Figure 2. Typical biological nitrogen removal schemes.

(3) Mixed systems (schemes 7, 8, 9, 10, and 11), where nitrification and denitrification occur within the same reactor. Two types of schemes are used:

a) Change the environment and feed pattern to achieve nitrification and denitrification at various times. Schemes 7 and 9 are examples of the feed and aeration cycles being manipulated to achieve nitrification and denitrification.

b) Operate the system to achieve simultaneous nitrification and denitrification at different locations within the same reactor by controlling environmental (such as dissolved oxygen) and hydrodynamic (mixing) conditions. Schemes 8, 10, and 11 are examples of aerobic and anoxic regions being created within one system.

b. BNR essentially replaces physical/chemical nitrogen removal processes with biological processes.

5. Phosphorous Removal Processes

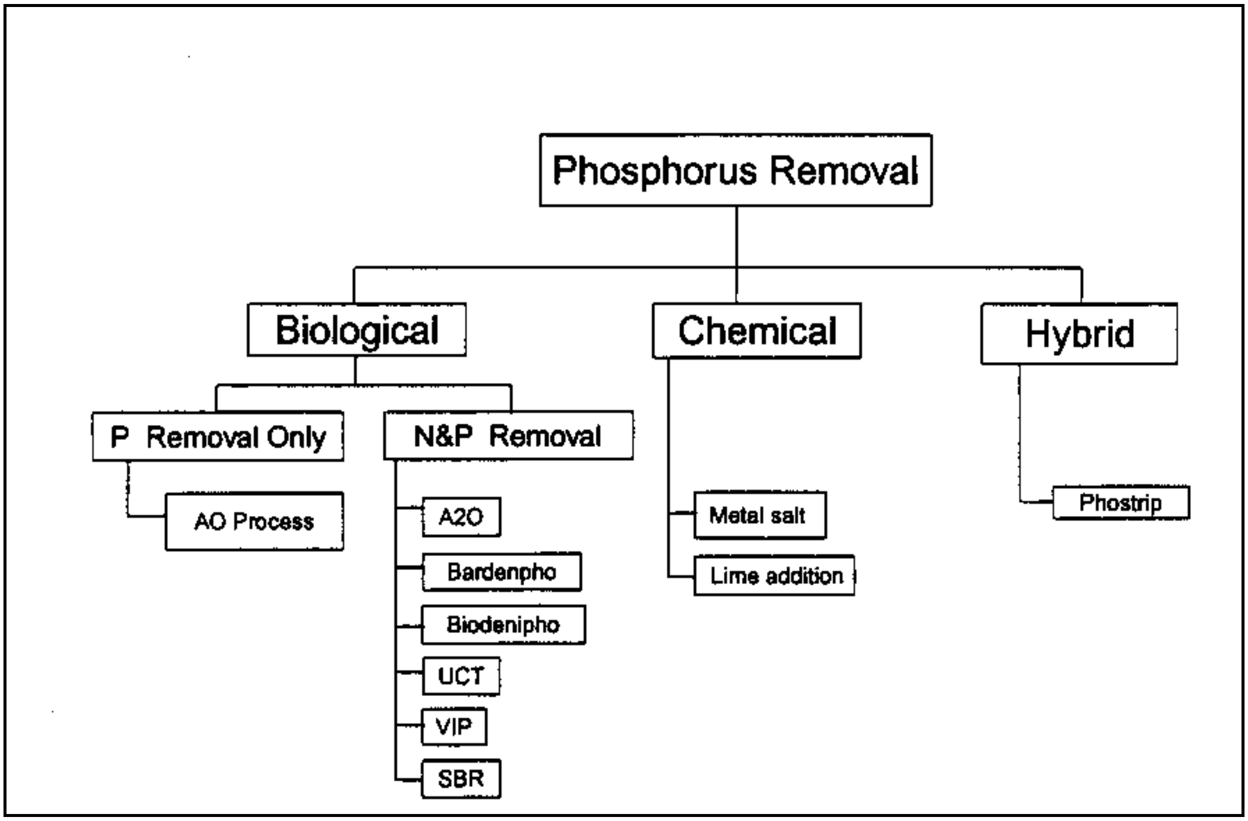
a. Unlike nitrogen, phosphorous has no gaseous form that can be removed from wastewater. Consequently, phosphorous must either be converted to a particulate form and removed as a particulate by sedimentation, filtration, or some other solids removal process or be concentrated into a sidestream using membrane treatment. Figure 3 summarizes the various options for removing or converting phosphorous species. Three options are available to remove phosphorous from the system:

(1) Convert the phosphorous to a chemical species by adding a metal salt or lime. The efficiency of phosphorous removal through conversion depends on two factors: the chemical equilibrium between the phosphorous liquid and solid phases, and the efficiency of the solids removal process. Typically, the latter process controls the removal efficiency.

(2) Incorporate the phosphorous into the biomass. Typically, biomass contains 1.5 to 2.5 percent (w/w) phosphorous per volatile solids. Under certain conditions, the biomass will accumulate phosphorous levels of 6 to 8 percent, far in excess of the nutritional requirements. This process is referred to as enhanced biological phosphorous removal (EBPR). The phosphorous removal efficiency for biological systems depends on the phosphorous content of the sludge removed and the efficiency of the solids separation process.

(3) Remove with membrane treatments. Processes that will remove essentially all pollutants from water, such as reverse osmosis, or nanofilters, can be used to remove phosphorous. Membrane treatment is expensive and not used for mainstream phosphorous removal; however, membranes used for another objective (e.g., total dissolved solids removal) will also remove phosphorous.

b. The different chemical species must be considered when considering NPDES permit requirements and evaluating process options. Typically, phosphorous limits are stated in terms of total phosphorous, which includes all phosphorous species, dissolved and soluble. In such cases, removal of the chemical or biological bound solid-phase phosphorous is critical in meeting effluent standards. If the discharge limit is based on orthophosphate only, suspended solids removal is less critical.



(Source: WEF 1998.)

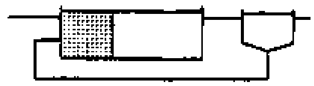
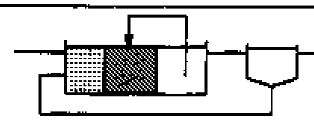
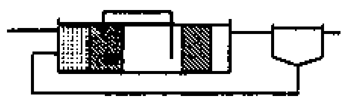
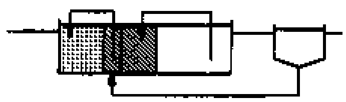
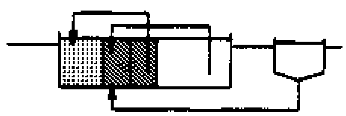
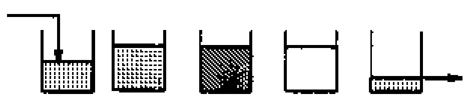
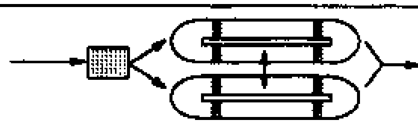
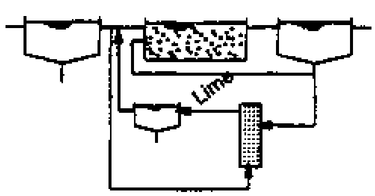
Figure 3. Overview of phosphorus removal processes.

c. Phosphorous removal processes can be sorted into two basic groups: chemical processes and biological processes. Figure 4 gives a brief overview of these processes. The selection of the specific process must be based on case-by-case evaluation of the system economics, including both capital and operating costs. The chemical processes will not be reviewed in this PWTB on biological processes.

d. Biological Phosphorous Removal

(1) Typically, biomass in the activated sludge process will contain 1.5 to 2.5 percent phosphorous based on dry weight. Under certain conditions, however, some bacteria will accumulate phosphorous in the cell in excess of typical nutritional requirements. As stated earlier, this enhanced efficiency is referred to as EPBR.

(2) A proposed mechanism for EBPR has acetate and other fermentation products (mostly volatile fatty acids [VFAs]) produced from fermentation reactions catalyzed by facultative microorganisms (able to use various types of electron donors) in the anaerobic zone. The fermentation products are readily assimilated by these microorganisms capable of enhancing phosphorous removal and stored as intracellular hydrocarbons. Assimilation and storage is aided by the energy made available from the hydrolysis and release of polyphosphates previously stored in the cells, which causes an increase in the soluble phosphorous concentration.

Symbolic Representation	Process	Nitrification	Nitrogen Removal	Internal Recycle	Chemical Addition
	AO Process				
	A20 Process	✗	✗	✗	
	Bardenpho	✗	✗	✗	
	UCT	✗	✗	✗	
	VIP	✗	✗	✗	
	SBR	✗	✗		
	Biodenipho	✗	✗		
	PhoStrip				✗

Aerobic
Anoxic
Anaerobic

(Source: WEF 1998.)

Figure 4. Biological phosphorus removal processes.

This accumulation of storage products gives the *Acinetobacter*, and other phosphorous removal organisms, a competitive edge for growth and survival, which it needs because of its extremely low growth rates under normal activated-sludge conditions. The anaerobic stage, therefore, serves two important purposes: it provides a fermentation zone to produce simple hydrocarbons used by phosphorous removal bacteria, and it provides an environment that gives these organisms a competitive edge to ensure their survival in the system.

(3) During the aerobic phase, polyhydroxybutyrates stored inside the cells are depleted and soluble phosphorous is taken up, with excess amounts stored as polyphosphates inside the cells. The phosphate-using bacterial population increases during this time because of substrate use and growth. Therefore, the level of phosphate accumulation in the cells is related to the amount of substrate assimilated and stored in the anaerobic phase.

(4) The conditions required for EPBR therefore include the following:

a) Provide an anaerobic zone (i.e., free of dissolved oxygen and devoid of nitrate). In this zone, phosphate is released from the cell with accompanying substrate uptake.

b) Soluble substrate such as VFA must be present in significant quantities. The initial phosphorous release is accompanied by soluble chemical oxygen demand (COD) uptake. It is now known that simple organics such as VFAs are most effective in contributing to phosphorous release and uptake.

(5) All biological phosphorous removal schemes include an anaerobic zone in the process. The proper functioning of the anaerobic zone requires the absence of dissolved oxygen and nitrate. Consequently, the various processes use different approaches to eliminate oxygen and nitrate from the anaerobic zone.

(6) Some process schemes also include a fermentation step to generate VFAs and feed the VFA-rich stream to the anaerobic zone. These VFAs can also be supplemented by chemical addition. Figure 4 shows a summary of the various biological phosphorous removal processes.

6. Benefits of BNR

a. Reasons for using BNR processes for the treatment of wastewaters may be classified as environmental benefits, economic benefits, and operational benefits. The most important of these is the control of eutrophication in the effluent receiving water – an environmental benefit. Historically, treatment requirements were determined by the need to protect the oxygen resources of the receiving water, and this was accomplished primarily through the removal of putrescible solids and dissolved organics from the wastewater before discharge. More recently, considerable emphasis has been placed on also reducing the quantities of nutrients discharged (nitrogen and phosphorous) because they stimulate growth of algae and other photosynthetic aquatic life, which leads to accelerated eutrophication, excessive loss of oxygen resources, and undesirable changes in aquatic populations.

b. The potential impact of discharged nutrients on the oxygen resources of receiving waters can be best illustrated by looking at the amounts of organic matter that can be generated by these nutrients compared to the amount of organic matter in untreated sewage. The COD of raw sewage in the United States is typically about 400 mg/L, whereas the phosphorous content is 6 to 10 mg/L, and the nitrogen content is 30 to 40 mg/L. If 1 kg of phosphorous was completely assimilated by algae and used to manufacture new biomass from photosynthesis and inorganic elements, a biomass of 111 kg with a COD of 138 kg would be produced. Thus, the discharge of 6 mg/L phosphorous could result in COD production equivalent to 828 mg/L, or more than double the COD of the organic matter in untreated sewage.

c. Much of the algal biomass will slowly biodegrade, but the organics will build up in the bottom sediments where long-term biodegradation occurs, and it is likely that a high percentage of sediment oxygen demand (SOD) will eventually be exerted. The rate of SOD will also accelerate as the algal biomass accumulates. As was shown by the preceding comparison, removing only biodegradable organics from wastewaters lessens the potential effect on the oxygen resources of the receiving water by less than half. Considering that phosphorous is a conservative substance (i.e., never used up, keeps recycling) that will accumulate within the system, it is clear that all comprehensive eutrophication control efforts should include phosphorous removal from discharged wastewaters.

d. Either nitrogen or phosphorous can be the nutrient that determines the limit (limiting nutrient) of algal growth. A kilogram of nitrogen could potentially stimulate the manufacture of 16 kg of algal biomass, which would be equivalent to 20 kg of COD. Thus, 30 mg/L of discharged nitrogen could result in the production of COD equivalent to 600 mg/L. This amount is less than the potential production by phosphorous, but still greater than the COD of the organics in untreated wastewater.

e. Either nitrogen or phosphorous will probably be the limiting nutrient that controls eutrophication because of the relatively large quantities required for biomass growth compared to other nutrients such as sulfur, potassium, calcium, and magnesium. Conventional wisdom in recent years has been that phosphorous is typically the limiting nutrient in freshwater environments, whereas nitrogen is typically limiting in estuarine and marine waters. The relationships are actually considerably more complex than this generalization states because conditions in most lakes, reservoirs, and estuaries are dominated by bottom sediment conditions and seasonal changes.

f. Because the limiting nutrient dynamics are generally poorly understood for most bodies of water, the best eutrophication control policy is simultaneous reduction of both nitrogen and phosphorous inputs. Also, because of seasonal changes, it is typically necessary to control both point and nonpoint sources in a complex watershed to attain the desired water quality. BNR processes provide a capability for the removal of nitrogen and phosphorous that is both environmentally and economically superior to other options.

g. Additional environmental benefits of BNR compared to phosphorous precipitation and methanol nitrogen removal are reduced chemical consumption, reduced waste sludge production, and reduced energy consumption by the treatment system. Such reductions lessen overall operational and disposal requirements and provide the primary economic benefits of BNR.

h. Converting activated sludge systems to provide biological phosphorous removal (BPR) by incorporating an anaerobic zone ahead of the aerobic zone will result in substantial aeration energy cost reductions of possibly 10 percent. A biological nitrogen removal process is always more economical to operate than a fully aerobic one accomplishing complete nitrification. Typically, nitrification will increase energy costs by 50 percent for the treatment of domestic wastewaters, compared to requirements for COD removal only. Incorporation of an anoxic zone ahead of the aerobic zone in such a system will always result in a reduction of the total aeration energy costs. Anaerobic and/or anoxic zones placed ahead of aerobic zones help discourage the growth of filamentous microorganisms in activated sludge and generally improve the sludge settling properties.

7. Effects of Wastewater Characteristics

a. The performance of a BNR system is strongly affected by the characteristics of the wastewater influent to each zone of the process.

b. Neither biological nitrogen removal nor biological phosphorous removal can be accomplished without sufficient biodegradable organic substrate (i.e., as measured by COD or BOD). Efficiency of BPR varies with the specific organic compound available in the anaerobic zone. The efficiency of both nitrogen removal and phosphorous removal can be reduced by conditions that result in the metabolism of usable substrate by other biochemical pathways.

c. Primary settling will substantially reduce the ratio of organic matter to phosphorous in the wastewater, and reduce the amount of phosphorous and nitrogen that can be removed by the treatment plant. Recycle streams from sludge processing will have the same effect.

8. Effluent Limitations

a. There has been considerable confusion concerning the lower limits of phosphorous and nitrogen concentrations possible with BNR processes. That is, how low can the final concentrations be if the microorganisms have an abundance of substrate available compared to the nutrient concentrations (i.e., when the system is nutrient-limited rather than substrate-limited). Soluble effluent phosphorous concentrations averaging less than 0.35 mg/L can be achieved (Randall et al. 1992) and concentrations below 0.50 possible with only secondary clarification for suspended solids removal. Barnard (1988) stated that effluent-soluble phosphorous concentrations below 0.1 mg/L could be reliably obtained by phosphorous-limited BPR processes. BNR process effluents typically contain soluble organic nitrogen concentrations of 1.0 to 1.5 mg/L. Nevertheless, effluent Total Kjeldahl Nitrogen (TKN) concentrations of less than 1.5 mg/L are possible. Effluent concentrations of Total Nitrogen (TN) of about 6 mg/L can be achieved much more economically than concentrations of less than 3 mg/L because of the reactor volumes required to ensure complete nitrification at low temperatures.

b. Effluent nutrient standards for wastewater treatment plants should be set only after full consideration of the seasonal nature of nonpoint nutrients, the magnitude of atmospheric inputs, and the economics of different levels of wastewater treatment.

9. New Developments

a. As populations increase and permit conditions become increasingly stringent, wastewater treatment facilities are under pressure to commit scarce financial resources to upgrade and expand the facilities. This requires the development of cost-effective technologies to meet those needs. Hybrid systems offer just those cost-effective alternatives. Hybrid systems are defined as activated sludge systems that incorporate some form of technology, either media or membrane, in the suspended growth reactor to enhance the level of treatment provided.

b. A review of hybrid systems was conducted by Sen et al. (2000) to upgrade existing WWTPs for nitrogen removal. The same technologies, however, may also be used to expand plant capacity and to improve BOD removal. Their review emphasized the use of hybrid systems for enhanced nitrification and denitrification.

c. The three basic hybrid system types are:

(1) Integrated Fixed-Film Activated Sludge (IFAS)
(2) Moving Bed Biofilm Reactor (MBBR)
(3) Membrane Bioreactor (MB).

d. Several types of IFAS hybrid systems are differentiated by the type of fixed-film media used. The media systems include rope media, sponge media, and plastic media. The rope media are fixed in frames and installed in the aerobic zone of the activated sludge basin. Several types of plastic trickling filter-type media have also been installed in cages in activated sludge basins. Sponge cubes and other types of plastic sections have been used as free floating media retained by screens in the aerobic zone of the activated sludge basin. Each system has its own advantages and disadvantages but the basic effect is the same: to increase the amount of biomass available for treatment without having to build additional activated sludge basins.

e. The MBBR uses plastic media suspended in the wastewater and retained within the aerobic zone by screens or sieves. It differs from the IFAS process in that there is no return activated sludge, which means that all of the treatment is accomplished in the biofilm.

f. The third type of hybrid system, MB, uses strictly the mixed liquor suspended solids to accomplish the treatment. It is classified as a hybrid system, however, because of the greatly elevated levels of mixed liquor suspended solids achieved by using membrane filters to separate the clarified permeate from the suspended solids in the activated sludge basin.

10. Summary

a. The nutrients nitrogen and phosphorous are a major pollution concern for the nation’s waters. Regulators are becoming more stringent in attempts to control the rate of eutrophication in lakes, estuaries, and the marine environment. Small amounts of phosphorous and nitrogen can effectively be multiplied into biomass twice the strength of domestic sewage, resulting in damage to the environment. Nitrogen and/or phosphorous can be the limiting factors in algal growth depending upon a number of factors: type of environment (freshwater, estuarine, or marine), season, water depth, and sediment characteristics. Residue from algal and other aquatic plant decomposition and silt carried by inflowing waters will gradually fill a lake or reservoir.

The most damaging effect of nutrients is stimulation of algal blooms, which result in interference with recreational activities, unsightliness, decay and its subsequent offensive odor, and depletion of available dissolved oxygen that causes fish kills and changes in the composition of faunal species.

b. A variety of nutrient removal processes exist: chemical, physical, and biological. This PWTB focused on the most cost-effective process, biological. Within the biological processes, a variety of treatment options exist for both nitrogen and phosphorous.

c. Benefits from BNR processes can be classified as environmental, economic, and operational. The most important environmental benefit is control of eutrophication so as to avoid excessive loss of oxygen and undesirable changes in aquatic populations. BNR has additional economic and operational benefits compared with other types of nutrient reduction through reduced chemical consumption, reduced waste sludge production, and reduced energy consumption by the treatment system. BNR will cost more than conventional reduction of COD, but that process does not reduce nutrients.

d. Effluent nutrient standards are becoming more of a factor in military installation NPDES permits. States and regional regulatory authorities are becoming more stringent in the amount of nutrients being allowed to pass through to the nation's waterways. Literally dozens of treatment options are available, including a number of innovative developments that not only assist in meeting more restrictive permit conditions but also increase treatment plant capacity within the existing footprint. Effluent standards should be set only after full consideration of the seasonal nature of nonpoint nutrients, the magnitude of atmospheric inputs, and the economics of different levels of wastewater treatment.

11. References

Barnard, J.L. (1988) "Case Studies in Phosphate Removal," *Proc. Intl. Workshop Wastewater Treatment Technol.*, Danish Assoc. Consult. Eng., Copenhagen, Denmark.

Koopman B. et al. (1990) "Denitrification in a Moving Bed Upflow Sand Filter," *Water Environment Research*, 62, p 239.

Madireddi, K. et al. (1994) "Denitrification in a Fluidized Sand Column: Lake Arrowhead Water Reclamation Pilot Study." Paper presented at the 67th Annual Water Environment Federation Conference, Chicago, IL.

Randall C.W. et al. (1992) "Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal." *Water Quality Management Library*, Vol. 5, Technomic Publishing Co., Lancaster, PA.

Sen, D. et al. (2000) *Investigation of Hybrid Systems for Enhanced Nutrient Control*, Water Environment Research Foundation, Alexandria, VA.

WEF (1998) *Biological and Chemical Systems for Nutrient Removal*, Water Environment Federation, Alexandria, VA.