This Fact Sheet was prepared to provide information on the types of biological nutrient removal technologies, nutrient removal efficiencies, and the associated costs for small and large municipal systems.

Biological Nutrient Removal Processes and Costs

Nitrogen and phosphorus are the primary causes of cultural eutrophication (i.e., nutrient enrichment due to human activities) in surface waters. The most recognizable manifestations of this eutrophication are algal blooms that occur during the summer. Chronic symptoms of over-enrichment include low dissolved oxygen, fish kills, murky water, and depletion of desirable flora and fauna. In addition, the increase in algae and turbidity increases the need to chlorinate drinking water, which, in turn, leads to higher levels of disinfection by-products that have been shown to increase the risk of cancer. Excessive amounts of nutrients can also stimulate the activity of microbes, such as *Pfisteria*, which may be harmful to human health (U.S. EPA, 2001).

Approximately 25% of all water body impairments are due to nutrient-related causes (e.g., nutrients, oxygen depletion, algal growth, ammonia, harmful algal blooms, biological integrity, and turbidity) (U.S. EPA, 2007). In efforts to reduce the number of nutrient impairments, many point source dischargers have received more stringent effluent limits for nitrogen and phosphorus. To achieve these new, lower effluent limits, facilities have begun to look beyond traditional treatment technologies.

Description

Biological nutrient removal (BNR) removes total nitrogen (TN) and total phosphorus (TP) from wastewater through the use of microorganisms under different environmental conditions in the treatment process (Metcalf and Eddy, 2003).

Nitrogen Removal

Total effluent nitrogen comprises ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen. The biological processes that primarily remove nitrogen are nitrification and denitrification (Jeyanayagam, 2005). During nitrification ammonia is oxidized to nitrite by one group of autotrophic bacteria, most commonly *Nitrosomonas* (Metcalf and Eddy, 2003). Nitrite is then oxidized to nitrate by another autotrophic bacteria group, the most common being *Nitrobacter*.

Denitrification involves the biological reduction of nitrate to nitric oxide, nitrous oxide, and nitrogen gas (Metcalf and Eddy, 2003). Both heterotrophic and autotrophic bacteria are capable of denitrification. The most common and widely distributed denitrifying bacteria are Pseudomonas species, which can use hydrogen, methanol, carbohydrates, organic acids, alcohols, benzoates, and other aromatic compounds for denitrification (Metcalf and Eddy, 2003).

In BNR systems, nitrification is the controlling reaction because ammonia oxidizing bacteria lack functional diversity, have stringent growth requirements, and are sensitive to environmental conditions (Jeyanayagam, 2005). Note that nitrification by itself does not actually remove nitrogen from wastewater. Rather, denitrification is needed to convert the oxidized form of nitrogen (nitrate) to nitrogen gas. Nitrification occurs in the presence of oxygen under aerobic conditions, and denitrification occurs in the absence of oxygen under anoxic conditions.

Exhibit 1 summarizes the removal mechanisms applicable to each form of nitrogen.

Exhibit 1. Mechanisms Involved in the Removal of Total Nitrogen

Form of Nitrogen	Common Removal Mechanism	Technology Limit (mg/L)
Ammonia-N	Nitrification	<0.5
Nitrate-N	Denitrification	1 – 2
Particulate organic-N	Solids separation	<1.0
Soluble organic-N	None	0.5 – 1.5

Source: Jeyanayagam (2005).

Note that organic nitrogen is not removed biologically; rather only the particulate fraction can be removed through solids separation via sedimentation or filtration.

Phosphorus Removal

Total effluent phosphorus comprises soluble and particulate phosphorus. Particulate phosphorus can be removed from wastewater through solids removal. To achieve low effluent concentrations, the soluble fraction of phosphorus must also be targeted. **Exhibit 2** shows the removal mechanisms for phosphorus.

Exhibit 2. Mechanisms Involved in the Removal of Total Phosphorus

Form of Phosphorus	Common Removal Mechanism	Technology Limit (mg/L)
Soluble phosphorus	Microbial uptake Chemical precipitation	0.1
Particulate phosphorus	Solids removal	<0.05

Source: Jeyanayagam (2005).

Biological phosphorus removal relies on phosphorus uptake by aerobic heterotrophs capable of storing orthophosphate in excess of their biological growth requirements. The treatment process can be designed to promote the growth of these organisms, known as phosphate-accumulating organisms (PAOs) in mixed liquor (WEF and ASCE/EWRI, 2006). Under anaerobic conditions, PAOs convert readily available organic matter [e.g., volatile fatty acids (VFAs)] to carbon compounds called poly-hydroxyalkanoates (PHAs). PAOs use energy generated through the breakdown of polyphosphate molecules to create PHAs. This breakdown results in the release of phosphorus (WEF and ASCE/EWRI, 2006).

Under subsequent aerobic conditions in the treatment process, PAOs use the stored PHAs as energy to take up the phosphorus that was released in the anaerobic zone, as well as any additional phosphate present in the wastewater. In addition to reducing the phosphate concentration, the process renews the polyphosphate pool in the return sludge so that the process can be repeated (Jeyanayagam, 2005).

Some PAOs use nitrate instead of free oxygen to oxidize stored PHAs and take up phosphorus. These denitrifying PAOs remove phosphorus in the anoxic zone, rather than the aerobic zone (Jeyanayagam, 2005).

As shown in Exhibit 2, phosphorus can also be removed from wastewater through chemical precipitation. Chemical precipitation primarily uses aluminum and iron coagulants or lime to form chemical flocs with phosphorus. These flocs are then settled out to remove phosphorus from the wastewater (Viessman and Hammer, 1998). However, compared to biological removal of phosphorus, chemical processes have higher operating costs, produce more sludge, and result in added chemicals in sludge (Metcalf and Eddy, 2003). When TP levels close to 0.1 mg/L are needed, a combination of biological and chemical processes may be less costly than either process by itself.

Process

There are a number of BNR process configurations available. Some BNR systems are designed to remove only TN or TP, while others remove both. The configuration most appropriate for any particular system depends on the target effluent quality, operator experience, influent quality, and existing treatment processes, if retrofitting an existing facility. BNR configurations vary based on the sequencing of environmental conditions (i.e., aerobic, anaerobic, and anoxic)[1] and timing (Jeyanayagam, 2005). Common BNR system configurations include:

- Modified Ludzack-Ettinger (MLE) Process – continuous-flow suspended-growth process with an initial anoxic stage followed by an aerobic stage; used to remove TN
- A^2/O Process – MLE process preceded by an initial anaerobic stage; used to remove both TN and TP
- Step Feed Process – alternating anoxic and aerobic stages; however, influent flow is split to several feed locations and the recycle sludge stream is sent to the beginning of the process; used to remove TN
- Bardenpho Process (Four-Stage) – continuous-flow suspended-growth process with alternating anoxic/aerobic/anoxic/aerobic stages; used to remove TN
- Modified Bardenpho Process – Bardenpho process with addition of an initial anaerobic zone; used to remove both TN and TP
- Sequencing Batch Reactor (SBR) Process – suspended-growth batch process sequenced to simulate the four-stage process; used to remove TN (TP removal is inconsistent)
- Modified University of Cape Town (UCT) Process – A^2/O Process with a second anoxic stage where the internal nitrate recycle is returned; used to remove both TN and TP
- Rotating Biological Contactor (RBC) Process – continuous-flow process using RBCs with sequential anoxic/aerobic stages; used to remove TN
- Oxidation Ditch – continuous-flow process using looped channels to create time sequenced anoxic, aerobic, and anaerobic zones; used to remove both TN and TP.

Although the exact configurations of each system differ, BNR systems designed to remove TN must have an aerobic zone for nitrification and an anoxic zone for denitrification, and BNR systems designed to remove TP must have an anaerobic zone free of dissolved oxygen and nitrate. Often, sand or other media filtration is used as a polishing step to remove particulate matter when low TN and TP effluent concentrations are required. Sand filtration can also be combined with attached growth denitrification filters to further reduce soluble nitrates and effluent TN levels (WEF and ASCE/EWRI, 2006).

Choosing which system is most appropriate for a particular facility primarily depends on the target effluent concentrations, and whether the facility will be constructed as new or retrofit with BNR to achieve more stringent effluent limits. New plants have more flexibility and options when deciding

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[1] Anoxic is a condition in which oxygen is available only in the combined form (e.g., NO_2^- or NO_3^-). However, anaerobic is a condition in which neither free nor combined oxygen is available (WEF and ASCE/EWRI, 2006).

which BNR configuration to implement because they are not constrained by existing treatment units and sludge handling procedures.

Retrofitting an existing plant with BNR capabilities should involve consideration of the following factors (Park, no date):

- Aeration basin size and configuration
- Clarifier capacity
- Type of aeration system
- Sludge processing units
- Operator skills

The aeration basin size and configuration dictates which BNR configurations are the most economical and feasible. Available excess capacity reduces the need for additional basins, and may allow for a more complex configuration (e.g., 5-stage Bardenpho versus 4-stage Bardenpho configuration). The need for additional basins can result in the need for more land if the space needed is not available. If land is not available, another BNR process configuration may have to be considered.

Clarifier capacity influences the return activated sludge (RAS) rate and effluent suspended solids, which in turn, affects effluent TN and TP levels. If the existing facility configuration does not allow for a preanoxic zone so that nitrates can be removed prior to the anaerobic zone, then the clarifier should be modified to have a sludge blanket just deep enough to prevent the release of phosphorus to the liquid. However, if a preanoxic zone is feasible, a sludge blanket in the clarifier may not be necessary (WEF and ASCE/EWRI, 2006). The existing clarifiers also remove suspended solids including particulate nitrogen and phosphorus, and thus, reduce total nitrogen and phosphorus concentrations.

The aeration system will most likely need to be modified to accommodate an anaerobic zone, and to reduce the DO concentration in the return sludge. Such modifications could be as simple as removing aeration equipment from the zone designated for anaerobic conditions or changing the type of pump used for the recycled sludge stream (to avoid introducing oxygen).

The manner in which sludge is processed at a facility is important in designing nutrient removal systems. Sludge is recycled within the process to provide the organisms necessary for the TN and TP removal mechanisms to occur. The content and volume of sludge recycled directly impacts the system's performance. Thus, sludge handling processes may have to be modified to achieve optimal TN and TP removal efficiencies. For example, some polymers in sludge dewatering could inhibit nitrification when recycled. Also, because aerobic digestion of sludge produces nitrates, denitrification and phosphorus uptake rates may be lowered when the sludge is recycled (WEF and ASCE/EWRI, 2006).

Operators should be able to adjust the process to compensate for constantly varying conditions. BNR processes are very sensitive to influent conditions which are influenced by weather events, sludge processing, and other treatment processes (e.g., recycling after filter backwashing). Therefore, operator skills and training are essential for achieving target TN and TP effluent concentrations.

Performance

Exhibit 3 provides a comparison of the TN and TP removal capabilities of common BNR configurations. Note that site-specific conditions dictate the performance of each process, and that the exhibit is only meant to provide a general comparison of treatment performance among the various BNR configurations.

Exhibit 3. Comparison of Common BNR Configurations

Process	Nitrogen Removal	Phosphorus Removal
MLE	Good	None
A^2/O	Good	Good
Step Feed	Moderate	None
Four-Stage Bardenpho	Excellent	None
Modified Bardenpho	Excellent	Good
SBR	Moderate	Inconsistent
Modified UCT	Good	Excellent
Oxidation Ditch	Excellent	Good

Source: Jeyanayagam (2005).

The limit of technology (LOT), at least for larger treatment plants, is 3 mg/L for TN and 0.1 mg/L for TP (Jeyanayagam, 2005). However, some facilities may be able to achieve concentrations lower than these levels due to site-specific conditions.

Exhibit 4 provides TN and TP effluent concentrations for various facilities using BNR processes.

Exhibit 4. Treatment Performance of Various BNR Process Configurations

Treatment Plant (State)	Treatment Process Description	Flow (mgd)	Average Effluent Concentration (mg/L)[1]	
			TN	TP
Annapolis (MD)	Bardenpho (4-Stage)	13	7.1	0.66
Back River (MD)	MLE	180	7.6	0.19
Bowie (MD)	Oxidation Ditch	3.3	6.6	0.20
Cambridge (MD)	MLE	8.1	3.2	0.34
Cape Coral (FL)	Modified Bardenpho	8.5	1.0	0.2
Cox Creek (MD)	MLE	15	9.7	0.89
Cumberland (MD)	Step Feed	15	7.0	1.0
Frederick (MD)	A^2/O	7	7.2	1.0
Freedom District (MD)	MLE	3.5	7.8	0.51
Largo (FL)	A^2/O	15	2.3	ND
Medford Lakes (NJ)	Bardenpho (5-stage)	0.37	2.6	0.09
Palmetto (FL)	Bardenpho (4-stage)	1.4	3.2	0.82
Piscataway (MD)	Step Feed	30	2.7	0.09
Seneca (MD)	MLE	20	6.4	0.08
Sod Run (MD)	Modified A^2/O	20	9.2	0.86
Westminster (MD)	MLE-A^2/O	5	5.3	0.79

Sources: EPA (2006); Gannett Fleming (no date); Park (no date).
mgd = million gallons per day
ND = no data

[1] Represents the average of average monthly values from 2003 to 2006, where available.

LOT levels (i.e., TN less than 3 mg/L and TP less than 0.1 mg/L) have not been demonstrated at treatment plants with capacities of less than 0.1 mgd (Foess, et al., 1998). BNR for TN removal may be feasible and cost effective. However, BNR for TP removal is often not cost effective at small treatment plants (Keplinger, et al., 2004). Therefore, performance data for TP removal at small treatment plants is limited. **Exhibit 5** summarizes the TN levels achievable with various BNR configurations.

Exhibit 5. BNR Performance for Small Systems (Less than 0.1 mgd)

BNR Process	Achievable TN Effluent Quality
MLE	10 mg/L
Four-Stage Bardenpho	6 mg/L
Three-Stage Bardenpho	6 mg/L
SBR	8 mg/L
RBC	12 mg/L

Source: Foess et al. (1998).

Operation and Maintenance

For BNR systems to result in low TN and TP effluent concentrations, proper operation and control of the systems is essential. Operators should be trained to understand how temperature, dissolved oxygen (DO) levels, pH, filamentous growth, and recycle loads affect system performance.

Biological nitrogen removal reaction rates are temperature dependent. Nitrification and denitrification rates increase as temperature increases (until a maximum temperature is reached). In general, nitrification rates double for every 8 to 10°C rise in temperature (WEF and ASCE/EWRI, 2006). The effect of temperature on biological phosphorus removal is not completely understood (WEF and ASCE/EWRI, 2006), although rates usually slow at temperatures above 30°C (Jeyanayagam, 2005).

DO must be present in the aerobic zone for phosphorus uptake to occur. However, it is important not to over-aerate. DO concentrations around 1 mg/L are sufficient. Over-aeration can lead to secondary release of phosphorus due to cell lysis, high DO levels in the internal mixed liquor recycle (which could reduce TP and TN removal rates), and increased operation and maintenance (O&M) costs (Jeyanayagam, 2005).

There is evidence that both nitrification and phosphorus removal rates decrease when pH levels drop below 6.9. Nitrification results in the consumption of alkalinity. As alkalinity is consumed, pH decreases. Thus, treatment plants with low influent alkalinity may have reduced nitrification rates (WEF and ASCE/EWRI, 2006). Glycogen-accumulating organisms may also compete with PAOs at pH values less than 7.

Filamentous growth can cause poor settling of particulate nitrogen and phosphorus in final clarifiers. However, many conditions necessary to achieve good BNR rates, such as low DO, longer solids retention times, good mixing, also promote filament growth (Jeyanayagam, 2005). Therefore, operators may need to identify the dominate filaments present in the system so that they can design strategies to target their removal (e.g., chlorinating recycle streams, chemical addition as polishing step) while still maintaining nutrient removal rates.

Nitrogen and phosphorus removal efficiencies are a function of the percentage and content of the mixed liquor recycle rate to the anoxic zone and the RAS recycle rate to the anaerobic zone (WEF and ASCE/EWRI, 2006). The mixed liquor recycle stream supplies active biomass that enables nitrification and denitrification. Optimizing the percentage and content of this recycle stream results in optimal TN removal. The RAS recycle rate should be kept as low as possible to reduce amount of nitrates introduced to the anaerobic zone because nitrates interfere with TP removal. In addition, the type of pump used to recycle the activated sludge is important to avoid aeration and increased DO concentrations in the anaerobic zone (WEF and ASCE/EWRI, 2006).

Costs

BNR costs differ for new plants and retrofits. New plant BNR costs are based on estimated influent quality, target effluent quality, and available funding. Retrofit costs, on the other hand, are more site-specific and vary considerably for any given size category. Retrofit costs are based on the same factors as new plants, in addition to the layout and design of the existing treatment processes.

Exhibit 6 provides capital costs to upgrade wastewater treatment plants in Maryland with BNR. These costs represent retrofits of existing facilities.

Exhibit 6. BNR Upgrade Costs for Maryland Wastewater Treatment Plants

Facilities with BNR (as of 10/30/06)	Design Capacity (mgd)	Treatment Process	Completion Date	Total Capital BNR Cost (2006$)[1]
Aberdeen	2.8	MLE	Dec-98	$3,177,679
Annapolis	10	Ringlace	Nov-00	$14,687,326
Back River	180	MLE	Jun-98	$138,305,987
Ballenger	2.0	Modified Bardenpho	Aug-95	$2,891,906
Broadneck	6.0	Oxidation Ditch	1994	$3,165,193
Broadwater	2.0	MLE	May-00	$6,892,150
Cambridge	8.1	Activated Sludge	Apr-03	$11,740,209
Celanese	1.25	Sequential step feed	Jun-05	$7,424,068
Centreville	0.375	SBR/Land Application	Apr-05	$7,336,020
Chesapeake Beach	0.75	Oxidation Ditch	1992	$2,158,215
Conococheague	2.5	Carrousel	Nov-01	$6,620,888
Cox Creek	15	MLE	May-02	$11,466,657
Cumberland	15	MLE	Aug-01	$12,929,990
Denton	0.45	Biolac	Dec-00	$4,203,767
Dorsey Run	2.0	Methanol	1992	$3,967,307
Emmitsburg	0.75	Overland	1996	$2,562,722
Frederick	8.0	MLE	Sep-02	$11,916,504
Freedom District	3.5	Activated Sludge	1994	$1,462,798
Fruitland	0.50	SBR	Jul-03	$7,546,764
Hagerstown	8.0	Johannesburg Process	Dec-00	$11,190,344
Havre DeGrace	1.89	MLE	Nov-02	$7,596,882
Hurlock	2.0	Bardenpho	Aug-06	$5,200,000
Joppatowne	0.95	MLE	Jul-96	$2,433,205
La Plata	1.0	MLE	Jun-02	$4,952,150

Exhibit 6. BNR Upgrade Costs for Maryland Wastewater Treatment Plants

Facilities with BNR (as of 10/30/06)	Design Capacity (mgd)	Treatment Process	Completion Date	Total Capital BNR Cost (2006$)[1]
Leonardtown	0.65	Biolac	Oct-03	$2,811,448
Little Patuxent	18	A^2/O	1994	$7,263,879
Marlay Taylor (Pine Hill Run)	4.5	Schreiber	Jun-98	$4,986,641
Maryland City	2.5	Schreiber	1990	$1,375,866
Maryland Correctional Institute	1.23	Bardenpho	1995	$2,703,932
Mt. Airy	0.60	Activated Sludge	Jul-99	$5,235,575
Northeast	2.0	Activated Sludge	Oct-04	$4,225,029
Parkway	7.5	Methanol	1992	$15,869,228
Patuxent	6.0	Oxidation Ditch	1990	$2,106,763
Piscataway	30	MLE	Jul-00	$24,778,239
Pocomoke City	1.4	Biolac	Sep-04	$3,924,240
Poolesville	0.625	SBR	Jan-05	$1,593,640
Princess Anne	1.26	Activated Sludge	2002	$4,311,742
Seneca	5.0	MLE	Dec-03	$34,886,034
Sod Run	12	MLE	2000	$21,999,198
Taneytown	0.70	SBR	Apr-00	$3,808,298
Thurmont	1.0	MLE	Dec-96	$3,122,264
Western Branch	30	Methanol	Jul-95	$47,132,782
Westminster	5.0	Activated Sludge	Jan-01	$5,274,444

Source: MDE (2006).

mgd = million gallons per day

[1] Total capital BNR upgrade costs eligible for Maryland Department of the Environment 50% cost share (http://www.mde.state.md.us/Programs/WaterPrograms/WQIP/wqip_bnr.asp) including engineering, pilot study, design, and construction, updated to 2006 dollars using the ENR construction cost index assuming that the completion date represents the original year dollars (2006 ENR index = 7910.81).

Exhibit 7 shows BNR retrofit costs for wastewater treatment plants in Connecticut.

Exhibit 7. BNR Upgrade Costs for Connecticut Wastewater Treatment Plants

Facilities with BNR	Design Capacity (mgd)	Treatment Process[2]	Year Process In Service	Total Capital BNR Cost (2006$)[1]
Branford	4.5	4-Stage Bardenpho	2003	$3,732,049
Bridgeport East Phase 1	12	MLE*	2004	$2,323,766
Bridgeport West Phase 1	29	MLE*	2004	$2,640,643
Bristol Phase 1	10.75	MLE*	2004	$649,320
Derby	3.03	MLE*	2000	$3,513,514
East Hampton	3.9	MLE*	2001	$860,548
East Windsor	2.5	MLE	1996	$1,407,617
Fairfield Phase 2	9	4-Stage Bardenpho	2003	$14,235,676
Greenwich	12	MLE*	1996	$703,809
Ledyard	0.24	SBR	1997	$4,752,461
Milford BB Phase 1	3.1	4-Stage Bardenpho	1996	$1,407,617
New Canaan	1.5	MLE	2000	$1,570,463
New Haven Phase 1	40	MLE*	1997	$11,134,336
New London	10	MLE*	2002	$3,495,615
Newtown	0.932	MLE*	1997	$1,436,601
Norwalk Phase 1	15	MLE*	1996	$1,548,379
Norwalk Phase 2	15	MLE	2000	$7,042,287
Portland	1	MLE	2002	$1,266,843
Seymour	2.93	MLE*	1993	$379,597
Stratford Phase1	11.5	4-Stage Bardenpho	1996	$1,126,094
Thomaston	1.2	SBR	2001	$1,451,708
University of Connecticut	1.98	MLE	1996	$1,489,259
Waterbury	25	4-Stage Bardenpho	2000	$22,074,225

Source: CT DEP (2007).

mgd = million gallons per day

[1] Total capital BNR upgrade projects financed by the Clean Water Fund through 2006, updated to 2006 dollars using the ENR construction cost index assuming that the year in service date represents the original year dollars (2006 ENR index = 7910.81).

[2] Treatment process with an "*" are designed to meet interim TN limits of 6 – 8 mg/L; all other facilities designed to meet TN limits of 3 – 5 mg/L.

Site-specific factors such as existing treatment system layout and space availability may cause costs to vary significantly between treatment plants with the same design capacities implementing the same BNR configuration. For example, the La Plata and Thurmont wastewater treatment plants in Maryland both have design capacities of 1 mgd and upgraded to a modified Ludzack-Ettinger (MLE) BNR system. However, total capital costs to retrofit the La Plata facility ($5.0 million) exceed those for the Thurmont facility ($3.1 million) by more than $1.8 million.

Despite this variability in costs, unit costs (i.e., total capital cost per mgd) generally decrease as the size of the plant increases due to economies of scale. **Exhibit 8** illustrates this relationship for the Maryland and Connecticut facility upgrades presented in Exhibits 6 and 7 for three system size categories.

Exhibit 8. Average Unit Capital Costs for BNR Upgrades at MD and CT Wastewater Treatment Plants (2006$)[1]

Flow (mgd)	Cost/mgd
>0.1 – 1.0	$6,972,000
>1.0 – 10.0	$1,742,000
>10.0	$588,000

Source: Based on MDE (2006) and CTDEP (2007).

mgd = million gallons per day

[1] Calculated from cost information from Maryland Department of the Environment for 43 facilities and Connecticut Department of Environmental Protection for 23 facilities; costs updated to 2006 dollars based on project completion date using the ENR construction cost index (2006 index = 7910.81).

BNR systems for smaller facilities (i.e., flow less than 0.1 mgd) are usually pre-engineered, factory-, or field-assembled package systems (Foess, et al., 1998). In most cases, chemical phosphorus removal is preferred over biological removal because most small systems lack the operational oversight necessary to achieve low phosphorus levels with biological treatment. In addition, small systems will likely need effluent polishing filtration for added nitrogen removal (Foess, et al., 1998).

Exhibit 9 summarizes average BNR costs for small systems. The construction costs include all required facilities for a new plant on a new site, including filtration. O&M costs include labor, electricity, maintenance and repair materials, solids handling and disposal, administration labor, laboratory analytical requirements, and chemical costs (Foess, et al., 1998).

Exhibit 9. Average BNR Costs for Small Systems: New Plants (2006$)[1]

System	4,000 gpd	10,000 gpd	25,000 gpd	50,000 gpd	100,000 gpd
MLE Process					
Construction	$348,771	$415,585	$563,912	$803,108	$1,167,914
O&M	$37,263	$43,515	$60,553	$81,636	$122,699
4-Stage Process					
Construction	$448,992	$491,753	$634,736	$889,966	$1,293,524
O&M	$64,353	$70,604	$90,462	$117,551	$162,169
3-Stage Process					
Construction	$388,859	$444,983	$589,302	$837,851	$1,220,029
O&M	$44,005	$51,360	$69,133	$93,403	$142,066
SBR Process					
Construction	$448,992	$509,125	$644,090	$931,391	$1,290,852
O&M	$34,321	$41,799	$60,185	$82,862	$122,577
Intermittent Process					
Construction	$306,009	$499,771	$780,391	$1,150,542	$1,371,029
O&M	$34,321	$41,799	$60,185	$82,862	$122,577

Exhibit 9. Average BNR Costs for Small Systems: New Plants (2006$)[1]

System	4,000 gpd	10,000 gpd	25,000 gpd	50,000 gpd	100,000 gpd
MLE and Deep Bed Filtration					
Construction	$411,576	$491,753	$649,435	$887,294	$1,280,161
O&M	$45,231	$52,340	$71,217	$93,036	$136,550
Submerged Biofilter Process					
Construction	$330,063	$395,541	$601,328	$1,131,834	(2)
O&M	$23,902	$29,909	$50,379	$74,036	(2)
RBC Process					
Construction	$351,443	$457,010	$704,222	$1,159,896	$1,459,224
O&M	$25,006	$31,747	$53,198	$75,385	$109,584

Source: Foess, et al. (1998).
gpd = gallons per day
[1] Construction costs updated from 1998 dollars using the ENR construction cost index (2006 index = 7910.81); O&M costs updated from 1998 dollars using the Bureau of Labor Statistics consumer cost index (2006 index = 199.8).
[2] Exceeded manufacturer's sizes.

Retrofit opportunities are more limited at smaller facilities; however two retrofit alternatives may exist for nitrogen removal. The MLE process can be retrofitted by adding an anoxic basin upstream of the existing influent point and adding recirculation pumping from the existing aeration basin to the new anoxic basin. Also, deep-bed denitrification filters can be added downstream of an existing package plant. The retrofit involves installation of new pumping facilities to pump secondary effluent to the filters, methanol feed equipment, and chemical feed equipment (for phosphorus removal) (Foess, et al., 1998). O&M costs represent only the incremental costs associated with the additional equipment. **Exhibit 10** summarizes these costs.

Exhibit 10. Average BNR Costs for Small Systems: Retrofits (2006$)[1]

System	4,000 gpd	10,000 gpd	25,000 gpd	50,000 gpd	100,000 gpd
Anoxic Tank for MLE Upgrade					
Construction	$28,062	$32,071	$52,115	$76,168	$80,000
O&M	$14,832	$15,445	$16,425	$22,922	$21,100
Deep Bed Denitrification Filter					
Construction	$145,655	$161,691	$196,434	$217,815	$213,000
O&M	$21,573	$22,309	$24,883	$30,399	$28,600

Source: Foess, et al. (1998).
gpd = gallons per day
[1] Construction costs updated from 1998 dollars using the ENR construction cost index (2006 index = 7910.81); O&M costs updated from 1998 dollars using the Bureau of Labor Statistics consumer cost index (2006 index = 199.8).

Similar to large facilities, unit costs for smaller facilities also tend to decrease as flow increases. **Exhibit 11** summarizes average unit costs across all treatment processes for new plants and retrofits based on the cost information in Exhibits 9 and 10.

Exhibit 11. BNR Unit Costs for Small Systems (2006 Dollars)

Component	4,000 gpd	10,000 gpd	25,000 gpd	50,000 gpd	100,000 gpd
New Plants					
Construction	$70.97/gpd	$34.66/gpd	$19.34/gpd	$14.58/gpd	$8.50/gpd
O&M	$7.86/gpd	$3.70/gpd	$2.10/gpd	$1.43/gpd	$0.94/gpd
Retrofits					
Construction	$16.25/gpd	$7.25/gpd	$3.72/gpd	$2.20/gpd	$1.47/gpd
O&M	$3.71/gpd	$1.54/gpd	$0.67/gpd	$0.44/gpd	$0.25/gpd

Source: Foess, et al. (1998).
gpd = gallons per day

[1] Construction costs updated from 1998 dollars using the ENR construction cost index; O&M costs updated from 1998 dollars using the Bureau of Labor Statistics consumer cost index.

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