WASTEWATER TREATMENT PERFORMANCE AND COST DATA TO SUPPORT AN AFFORDABILITY ANALYSIS FOR WATER QUALITY STANDARDS

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1.0 Introduction

The Montana Department of Environmental Quality (MT DEQ) is currently developing preliminary, geographically-based nutrient standards for state waters. Some of the preliminary criteria, which were developed consistent with U.S. Environmental Protection Agency (USEPA) guidance, are low relative to commonly used municipal treatment technologies. Therefore, MT DEQ has initiated an evaluation of the potential economic impacts of the preliminary nutrient criteria on public and private wastewater treatment entities.

MT DEQ began its economic analysis of preliminary nutrient criteria by researching and evaluating existing economic impact assessment methodologies for water quality criteria (ICF 2006). That phase of the analysis recommended that MT DEQ develop an affordability assessment based on *Interim Economic Guidance for Water Quality Standards Workbook* (USEPA 1995), which was developed for use by states and USEPA Regions in implementing water quality standards programs.

In the current phase of the analysis, MT DEQ is compiling information about nitrogen and phosphorus reduction technologies for municipal wastewaters. Specifically, this report summarizes previously-published information on the performance (e.g., attainable effluent concentrations of total nitrogen and total phosphorus), availability, technical feasibility, and cost of nutrient reduction technologies that may be used at municipal wastewater treatment plants (WWTPs). This information will be used to identify additional treatments and associated costs for communities of various sizes if the preliminary nutrient criteria were codified.

The research methodology used for this report is summarized in Section 2. Section 3 provides a discussion of nitrogen and phosphorus removal processes and a summary of technologies considered representative of the diverse technologies on the market and that are potentially applicable to small- and medium-sized publicly owned treatment works (POTWs). Although more than 20 relevant information sources on technology performance and costs were identified during research efforts, none provided information that was both comprehensive (e.g., addressing both phosphorous and nitrogen reduction) and current. However, sufficient information to support the MT DEQ affordability assessment can be compiled from key sources (e.g., those that presented comparative cost or performance data for multiple technologies). Section 4 summarizes the relevant information available in the key sources. In Section 5 provides conclusions and recommendations concerning potential next steps in the affordability analysis. References cited in this report are identified in Section 6.

2.0 Research Methodology

Research for this report consisted of a literature search, extensive internet searches, and consultations with USEPA, state environmental departments, trade organizations, and wastewater treatment technology vendors. Information on technologies was gathered, as well as information on performance (e.g., attainable effluent concentrations of total nitrogen [TN] and total phosphorus [TP]), technical feasibility, and cost. As available, information was collected on factors relevant to the MT DEQ affordability analysis, including: (1) relationships between community size (e.g., population, influent volume) and performance, feasibility, and cost, (2) compatibility with other technologies and combined system costs, and (3) regional cost information relevant to Montana.

3.0 Nitrogen And Phosphorus Removal Processes

3.1 Wastewater Treatment Processes

The initial stage of wastewater treatment is known as primary treatment, where coarse solids that easily settle out are removed from the wastewater. Secondary treatment is the second stage in wastewater treatment systems in which bacteria consume the organic material in wastewater. Secondary treatment processes can remove up to 90 percent of the organic matter in wastewater using biological processes. The most common conventional methods to achieve secondary treatment are "attached growth" processes and "suspended growth" processes (USEPA 2004). Attached growth or "fixed film" processes provide a material on which microorganisms attach to form a biofilm. Trickling filters and rotating biological contactors are common aerobic attached growth processes. Suspended growth processes utilize mixing and/or aeration to promote a liquid suspension of the microbial community within a reactor. The most common wastewater suspended growth process is the activated sludge treatment process. Other process units include oxidation ditches and sequencing batch reactors (Opus International Consultants Limited 2005; USEPA 2004).

Advanced methods of wastewater treatment beyond secondary treatment can be extensions of conventional secondary biological treatment (as discussed above) to further remove nutrients, such as nitrogen and phosphorus. Advanced treatment may also involve physical-chemical separation techniques such as flocculation/precipitation and membrane filtration (USEPA 2004).

Some biological treatment processes called biological nutrient removal (BNR) can achieve significant nutrient reduction, removing both nitrogen and phosphorus. Most of the BNR processes involve modifications of suspended growth treatment systems so that the bacteria in these systems also convert nitrate nitrogen to inert nitrogen gas and trap phosphorus in the solids that are removed from the effluent (USEPA 2004). In general, BNR processes are incorporated into wastewater treatment systems to reduce effluent TN to an average level of 8 to 10 mg/L and TP to an average of 1 to 3 mg/L before being discharged into a receiving water body (Freed 2007). In many cases, BNR technologies can be retrofitted to existing plant configurations and are adaptable to climate extremes. Disadvantages include greater cost than conventional secondary treatment, and they also tend to be more sophisticated to operate and require greater operation training and skill (Hydromantis Inc. 2006). Enhanced nutrient removal (ENR)[1] refines the BNR process and removes TN to levels as low as 3 mg/L and TP to 0.3 mg/L or less. ENR relies on the same conventional processes as BNR, with modifications to enhance the microbial activities to achieve higher levels of efficiencies and greater reductions in nitrogen and phosphorus (Freed 2007).

[1] Various names and acronyms are used in the literature for related biological treatment processes. For example, ENR is sometimes referred to as enhanced biological nutrient removal (EBNR). ENR specifically for phosphorus removal may be referred to as enhanced biological phosphorus removal (EBPR). This report generally uses process names and acronyms used in cited publications.

3.2 Nitrogen Removal in Wastewater

Nitrogen in wastewater is generally in the form of ammonia and organic nitrogen (GMB 2004). Nitrogen in municipal wastewater is usually not removed by conventional secondary treatment. BNR for nitrogen is achieved through a series of biochemical reactions that transform nitrogen from one form to another. The key transformations are nitrification and denitrification (USACE 2001). By providing additional biological treatment beyond the secondary stage, nitrifying bacteria present in wastewater treatment can biologically convert ammonia to the non-toxic nitrate through the process known as nitrification. The nitrification process is normally sufficient to remove the toxicity associated with ammonia in the effluent. An additional biological process can be added to the system to convert the nitrate to nitrogen gas. The conversion of nitrate to nitrogen gas is accomplished by bacteria in the process known as denitrification. Effluent with nitrogen in the form of nitrate is placed into a tank devoid of oxygen, where carbon-containing chemicals, such as methanol, are added or a small stream of raw wastewater is mixed in with the nitrified effluent. In this anoxic environment, bacteria use the oxygen attached to the nitrogen in the nitrate form releasing nitrogen gas into the atmosphere (USEPA 2004).

3.3 Phosphorus Removal in Wastewater

Phosphorus removal obtained in a conventional biological wastewater treatment is generally less than 20 percent. Because it is not possible to achieve low phosphorus effluent limits with conventional biological wastewater treatment processes, additional or alternative treatment methods must be employed (Park et al. 1997). Phosphorus can be removed through chemical precipitation, physical processes (using filtration and membrane), or by a process called enhanced biological phosphorus removal (EBPR). Chemical precipitation, which is also commonly referred to as chemical addition or flocculation, can be achieved through addition of alum, lime, or iron salts to the wastewater. With these chemicals, the smaller particles 'floc' or clump together into large masses that settle faster when the effluent reaches the sedimentation tank. This process can reduce the concentration of phosphate by more than 95 percent. The level of phosphorus removal achieved by chemical precipitation can be controlled by manipulating the amount of chemical added. This process produces a chemical sludge, and the cost of disposing this material can be significant (USEPA 2004).

EBPR methods provide a number of advantages over chemical addition including improved treatment, reduced chemical usage, reduced energy consumption, reduced sludge production, and improved sludge settling and dewatering characteristics (Park et al. 1997). EBPR typically involves an activated sludge process modification (alternating aerobic and anaerobic and anoxic conditions) that allows for a high degree of phosphate removal from wastewater, with the potential to achieve very low (<0.1 mg/L) TP (Strom 2006).

Table 1 provides information on select nutrient removal technologies considered representative of the diverse technologies available and that are potentially applicable to municipal wastewater treatment facilities in Montana.

Table 1. Selected Nutrient Removal Processes

Process	Process Description	Nutrient Removed	Sources for Additional Information
Biological			
Suspended Growth (Activated Sludge) ***Bacteria kept in suspension to allow bacteria to grow and consume pollutants from wastewater***			
Ludzack Ettinger	2-step nitrification/denitrification process. Anoxic/aerobic	N	Hatch Mott MacDonald undated;
Modified Ludzack Ettinger (MLE)	2-step nitrification/denitrification process with internal recycle. Anoxic/aerobic	N	Hatch Mott MacDonald undated; GMB 2004
4-Stage Bardenpho	4-step process designed to achieve complete denitrification Anoxic/aerobic/anoxic/aerobic Most commonly used activated sludge process that has consistently demonstrated the ability to meet ENR goals for TN.	N	Hatch Mott MacDonald undated; GMB 2004
5-Stage Bardenpho	Adds an aerobic zone to the 4-stage Bardenpho to achieve P removal Anaerobic/anoxic/aerobic/anoxic/aerobic	N&P	Hatch Mott MacDonald undated; GMB 2004
Oxidation Ditch	Looped channel reactor, with aerobic and anoxic zones created around the channel; for nitrification/denitrification; utilizes long solids retention times to achieve a high degree of nitrification; an anaerobic tank may be added prior to the ditch to enhance biological P removal.	N	USEPA 2000c; Hatch Mott MacDonald undated; GMB 2004
Membrane Bioreactor (MBR)	Consists of suspended growth basins where membranes are employed for suspended solids separation prior to effluent discharge; allows for the establishment of processes with extended residence times; facilitates biodegradation of substances that are facilitated by slow-growing microorganisms; allows clarification, aeration, and sludge digestion in one process step.	N	Hydromantis Inc. 2006; Peterson 2006
Sequencing Batch Reactor (SBR)	For nitrification/denitrification; creates anoxic and aerobic conditions at timed intervals for biological treatment and secondary clarification in a single reactor; cycles within the system can be easily modified for nutrient removal.	N	USEPA 2004; USEPA 1999; Hatch Mott MacDonald undated; GMB 2004; Peterson 2006
Two-stage Activated Sludge (AO)	2-step nitrification/denitrification process with internal recirculation. Good P removal may be achieved if the nitrate concentration is at low enough levels. Anoxic/aerobic	P	Jiang et al. 2004
Three-stage Activated Sludge (A^2O)	Similar to the MLE process, except that an anaerobic zone is included for P removal. Anaerobic/anoxic/aerobic	N&P	GMB 2004; Jiang et al. 2004
Johannesburg	Uses 4 separate process zones to remove N and P; the first anoxic zone is used to remove nitrate and oxygen and set up anaerobic conditions; the remainder of the process is similar to A^2O.	N&P	GMB 2004

Table 1. Selected Nutrient Removal Processes

Process	Process Description	Nutrient Removed	Sources for Additional Information
	Anoxic/anaerobic/anoxic/aerobic		
Attached Growth (Fixed Film) *Utilizes media to provide a surface for biomass to grow and perform nitrification & denitrification*			
Trickling Filter	For nitrification/denitrification; involves a tank, usually filled with a bed of rocks, stones or synthetic media, to support bacterial growth used to treat wastewater.	N	USEPA 2000d; USEPA 2004; USACE 2001
Rotating Biological Contactor	For nitrification/denitrification; series of disks attached to a central axis that rotates and exposes biomass on disks to both air (aerobic conditions) and wastewater (anoxic conditions).	N	GMB 2004; USACE 2001; Peterson 2006
Denitrification Filter	Utilize granular media to remove nitrates after nitrification. May be added to existing treatment systems that use biological processes to convert nitrate-N to N gas; physical/chemical treatment may be added using chemical phosphorus precipitation to achieve TP as low as 0.3 mg/L.	N	Hatch Mott MacDonald undated; Freed 2007
Fluidized Bed Reactor	For nitrification/denitrification; utilizes small media which is kept in suspension by aeration or mixing action; aerobic and anaerobic reactors may be arranged in series for complete BNR OR may be added to an existing BNR process for additional denitrification.	N	GMB 2004
Assimilation (Aquatic) *Utilizes aquatic plants for nutrient assimilation, transfer of oxygen, and improved water quality*			
Constructed Wetland (Surface)	Consist of a series of ponds that contain cultivated plants of some type; remove nutrients such as P and N by plant uptake; suspended solids may be removed by sedimentation and filtration processes. Although available sources (e.g., USEPA 2000a; USEPA 2000f) provide contradictory conclusions about the effectiveness of this method for removing P and N, design and operation modifications (e.g., increased retention times) can produce N and P removal. Because winter weather hinders wetland processes, lagoon wastewater storage may be required during cold months.	N&P	Hydromantis Inc. 2006; USEPA 2000a; USEPA 2000f
Constructed Wetland (Subsurface)	Consist of a porous media (e.g., gravel) through which the wastewater is directed; plants are often grown in the media to facilitate oxygen transfer into the subsurface and promote aerobic conditions; facilitate suspended solids removal through sedimentation and filtration mechanisms. Comments about the effectiveness and limitations surface constricted wetlands (above) also apply to subsurface constructed wetlands.	N&P	Hydromantis Inc. 2006; USEPA 2000b; USEPA 2000f
Wastewater treatment pond/lagoon	Constructed pond that allows sunlight, algae, aerobic and anaerobic bacteria, and oxygen to interact to improve water quality; may be used for secondary treatment or as a supplement to other processes. Removes biodegradable organic material and some of	N	USEPA 2002a; USEPA 2004

Table 1. Selected Nutrient Removal Processes

Process	Process Description	Nutrient Removed	Sources for Additional Information
	the N from wastewater, but only in moderate amounts. Lagoon operation is significantly impacted by winter weather.		
Physical			
Reverse Osmosis	Performs micro-filtration processes using membrane; will remove nearly all particulate P and 95-99% soluble P; membrane treatments may be expensive.	P	USACE 2001
Sand Filtration	Traps some solids remaining in the wastewater after secondary treatment. Can reduce P adsorbed to solid particles, such as particles remaining in suspension after chemical addition (see below). In some cases, biological nitrification/denitrification is also achieved with sand filters. Performance may be adversely affected by cold weather.	P	Hydromantis Inc. 2006
Chemical			
Chemical Addition	Also commonly referred to as chemical precipitation or flocculation. Metal salts (e.g. alum, iron) or other chemicals may be used as coagulants and precipitating agents to enhance the formation and separation of solids that can removed from wastewater stream. Chemicals are added to either a conventional secondary treatment process (e.g., activated sludge) or may be incorporated as part of a tertiary treatment technology (e.g., sand filtration); the effectiveness of the agent will be a function of the solids separation efficiency and its effectiveness in forming a solid-associated contaminant.	P	USEPA 2000e; Hydromantis Inc. 2006

4.0 Summary of Key References

This section summarizes the most relevant and potentially useful sources of cost and performance data identified from literature searches and other information gathering. The following factors were considered in choosing the most relevant and potentially useful sources:

- Year of publication – Recent publications are more likely than older publications to present current cost information and state-of-the-art processes and performance.

- Accepted or demonstrated technologies – Publications about experimental treatment processes were considered less relevant than case studies and other publications about accepted treatment methods.

- Comparative analysis – Many variables (e.g., year, waste stream characteristics) affect the cost and performance of wastewater treatment processes. Comparative analyses, in which the outcomes of alternative treatment scenarios or effluent limitations are compared, provide insights about the relative advantages and disadvantages of technologies.

- Cost curves or scaling information – Some sources present cost curves or other information describing the relationships between design capacity and cost. These relationships may be based on data from a sample of facilities with similar configurations or from detailed engineering and cost calculations for a various design capacities.

- Case studies – Case studies generally include important details about the advantages and disadvantages of the available technologies. In addition, case studies are more likely than guidance documents, cost estimation studies, and other types of references to provide actual, post-construction cost and performance information.

4.1 Advanced Wastewater Treatment to Achieve Low Concentrations of Phosphorus (USEPA 2007)

USEPA Region 10 compiled performance and cost data from 23 municipal WWTPs with advanced phosphorus reduction technologies. This report (i.e., USEPA 2007) documents the levels of phosphorus control attainable by current technologies and certain combinations of technologies. The report presents total residential sewer rates, but no cost data specific to phosphorus reduction.

Phosphorus reduction technologies used at the WWTPs studied by USEPA included chemical addition, ENR, and various filtration technologies. All but one of the WWTPs employs tertiary filtration aided by chemical addition. Monitoring data from these WWTPs shows that this combination of technologies can consistently achieve an effluent phosphorus concentration of 0.01 mg/L.

All of the WWTPs studied by USEPA used some form of filtration (e.g., traveling sand bed filtration, mixed-media gravity filtration, Dynasand® filtration). Facilities with the lowest reported phosphorus concentrations (i.e., 0.01 mg/L) used two-stage filtration in addition to other technologies (e.g., chemical addition).

Some WWTPs studied by USEPA used ENR in secondary treatment to reduce phosphorus concentrations, to 0.3 mg/L or less, before tertiary treatment.[2] BNR enhances the performance of tertiary treatment and can reduce tertiary treatment costs (e.g., by reducing the amount of chemical addition required to meet treatment goals).

Four of the WWTPs studied by USEPA used anaerobic digesters to remove phosphorus from the waste stream. A disadvantage of this technology discussed by USEPA is that phosphorus may be released from treatment sludge. USEPA provides limited information to suggest that alum addition can be used to reduce phosphorus resolubilization from treatment residuals.

USEPA was unable to compile cost information for phosphorous treatment at these WWTPs. However, total monthly residential sewer rates for the 23 municipalities were presented as an

[2] According to USEPA (2007), typical TP concentrations in raw sewage are 6 to 8 mg/L, and secondary treatment without BNR are able to reduce phosphorus concentrations to 3 to 4 mg/L.

indication that advanced phosphorous treatment is affordable. Total monthly residential sewer rates ranged from $18 (for a 2 million gallons per day [MGD] facility in Colorado equipped with biological nutrient removal, chemical addition (alum or iron), and two-stage filtration) to $46 (for a 5.6 MGD facility in Oregon equipped with biological nutrient removal, chemical addition, and multimedia traveling bed filtration).

4.2 Nutrient Reduction Technology Cost Estimations for Point Sources in the Chesapeake Bay Watershed (CBP 2002)

The Chesapeake Bay Program is a partnership of state governments and various federal, academic, local, and nongovernmental parties with a shared goal to study and restore the Chesapeake Bay. Because nitrogen and phosphorus pollution are important issues affecting the Chesapeake Bay ecosystem, the Chesapeake Bay Program convened a task force to provide cost estimates for treatment technologies associated with varying levels of nitrogen and phosphorus removal from municipal and other wastewater sources in the watershed. The result of this effort was the November 2002 report, *Nutrient Reduction Technology Cost Estimations for Point Sources in the Chesapeake Bay Watershed* (CBP 2002). This report is hereafter referred to as the Chesapeake Bay Cost Study.

The Chesapeake Bay Cost Study used actual cost data, engineering information, and statistical information to estimate costs for individual point source facilities in the Chesapeake Bay watershed. Costs were estimated for four levels of treatment (i.e., scenarios for total nitrogen and total phosphorus control) based on 2000 dollars and projected 2010 flows. Cost estimates were prepared separately for "significant" municipal sources (discharges greater than 0.5 MGD), "non-significant" municipal sources (discharges less than 0.5 MGD), significant industrial sources, and combined sewer overflow. The four treatment tiers for municipal sources are characterized in Tables 2 and 3. Methods and cost estimates for the significant municipal sources are presented below for each Tier.

Table 2. Nutrient Control Scenarios Used for the Chesapeake Bay Cost Study

Point Source Category	Tier 1	Tier 2	Tier 3	Tier 4
"Significant" Municipal Sources (discharge > 0.5 MGD)	POTWs with operating or planned nutrient removal technology: TN = 8 mg/L TP = 1.5 mg/L. All other POTWs: TN and TP concentrations in 2000	TN = 8 mg/L TP = 1 mg/L or permit level if less	TN = 5 mg/L TP = 0.5 mg/L or permit level if less	TN = 3 mg/L TP = 0.1 mg/L or permit level if less
"Non-significant" Municipal Sources (discharge < 0.5 MGD)	TN and TP = concentrations in 2000	TN and TP = concentrations in 2000	TN and TP = concentrations in 2000	TN = 8 mg/L TP = 2 mg/L or concentrations in 2000 if less

Source: CBP (2000)

Table 3. Nutrient Reduction Technologies Assumed for Cost Estimation for the Chesapeake Bay Study – Significant Municipal Sources

Nutrient	Tier 1	Tier 2	Tier 3	Tier 4
Nitrogen	Existing technologies	Extended aeration processes and denitrification zones	Additional aeration, a secondary anoxic zone, methanol addition, and additional clarification tankage	Deep bed denitrification filters
Phosphorus	Existing technologies	Chemical precipitation (alum addition)	Increased chemical precipitation	Microfiltration

4.2.1 Tier 1 Cost Estimation

No incremental costs were required for most facilities, because Tier 1 is based on technologies already in use. However, additional operating costs were required for some facilities because flows were projected to 2010 levels.

4.2.2 Tier 2 Cost Estimation

Nitrogen reduction costs were based on actual cost information collected for facilities in the Chesapeake Bay watershed that already meet the Tier 2 goals. A regression model was used to estimate capital costs from designed flow rates, as follows. These regression models and associated cost curves are included in the Chesapeake Bay Cost Study.

Phosphorus reduction costs were based on engineering reference data updated to 2000 dollars. Although all sources were assumed to use chemical precipitation with alum addition, the authors acknowledged that biological phosphorus removal is often preferred to chemical precipitation. The chosen methodology produced cost curves that are available in the Chesapeake Bay Cost Study.

Operation and maintenance (O&M) costs for Tier 2 included costs of alum and sludge disposal. Assumptions and functions for estimating these costs based on initial and target nutrient concentrations are provided in the report.

4.2.3 Tier 3 Cost Estimation

Tier 3 nutrient reduction costs were not estimated from actual facility data because data were available for too few facilities in the Chesapeake Bay watershed. Therefore, generic estimates of capital and O&M costs related to plant average flow were developed from engineering information and assumptions. Costs estimates were prepared for four plant sizes: 0.1 MGD, 1.0 MGD, 10 MGD, and 30 MGD. These point estimates defined cost curves that were used to estimate costs for individual facilities in the Chesapeake Bay watershed.

The technologies assumed for Tier 3 nitrogen reduction include increased nitrification using a secondary anoxic reactor with methanol addition, and increased clarification capacity. Detailed assumptions and cost inputs are available in Appendix G to the Chesapeake Bay Cost Study. Resulting cost information is summarized in Table 4. Based on these estimates, capital costs for Tier 3 nitrogen reduction range from $0.41 to $2.41 per gallon of design flow. Cost curves developed from these point estimates are available in the Chesapeake Bay Cost Report.

Table 4. Estimated Costs to Reduce TN to 5.0 mg/L[a]

Cost Type	Annual Average Flow			
	0.1 MGD	**1.0 MGD**	**10 MGD**	**30 MGD**
Capital Cost	$241,000	$1,112,000	$4,927,000	$12,383,000
O&M Cost	$7,046	$29,218	$157,469	$293,938

Source: CBP (2002)

[a] Costs were estimated assuming that TN is reduced from 8 mg/L to 5mg/L using a secondary anoxic reactor and increased clarification.

Phosphorus reduction for the Tier 3 scenario was assumed to be achieved by increased chemical precipitation using capital improvements enacted to achieve Tier 2. Therefore, Tier 3 involved only additional O&M costs. Specifically, the amount of alum added per mg/L phosphorus removed increased from 14.4 mg/L (Tier 2) to 19.2 mg/L (Tier 3).

4.2.4 Tier 4 Cost Estimation

The cost estimation methodology for Tier 4 assumed that TN of 3 mg/L would be achieved by adding deep bed denitrification filters, and TP of 0.1 mg/L would be achieved by metal salt addition with microfiltration. The resulting cost estimates, which are presented in Tables 5 and 6, involve numerous design and unit cost assumptions documented in the Chesapeake Bay Cost Report. The report also presents cost curves derived from the point estimates in Tables 5 and 6.

Table 5. Estimated Costs to Reduce TN to 3.0 mg/L[a]

Cost Type	Annual Average Flow			
	0.1 MGD	**1.0 MGD**	**10 MGD**	**30 MGD**
Capital Cost	$312,000	$1,268,000	$9,620,000	$26,520,000
O&M Cost	$22,993	$69,925	$311,634	$841,120

Source: CBP (2002)

[a] Costs were estimated assuming that TN is reduced using deep bed denitrification filters. Facilities are assumed not have filtration and pumping stations before Tier 4 upgrades are installed.

Table 6. Estimated Costs to Reduce TP to 0.1 mg/L[a]

Cost Type	Annual Average Flow			
	0.1 MGD	1.0 MGD	10 MGD	30 MGD
Capital Cost	$388,000	$1,315,000	$6,969,000	$18,330,000
O&M Cost	$54,385	$189,800	$1,095,000	$3,066,000

Source: CBP (2002)

[a] Costs were estimated assuming that TP is reduced using metal salt addition and microfiltration.[3] Facilities are assumed not have filtration and pumping stations before Tier 4 upgrades are installed.

For "non-significant" municipal sources (i.e., sources with discharges less than 0.5 MGD), no action and no costs were assumed for Tiers 1 through 3. Costs for attaining Tier 4 TN and TP goals were estimated using cost curves developed from: (1) limited facility data from Virginia and Maryland, and (2) the cost estimation methodology developed for significant municipal sources under Tier 2.

4.3 Wastewater Phosphorus Control and Reduction Initiative (MESERB 2005)

The Minnesota Environmental Science and Economic Review Board (MESERB) sponsored a comparative evaluation of the cost-effectiveness and performance of municipal wastewater treatment phosphorus control technologies. The authors compiled detailed information on existing processes and wastewater characteristics for 17 WWTP in Minnesota. They then performed engineering and cost evaluations for each facility to identify the most cost-effective means of retrofitting the facilities to attain an effluent concentration goal of 1.0 mg/L phosphorus. Because of the detailed, facility-specific approach used, MESERB (2005), more than other available references, explores how technology selection is affected by facility-specific considerations, including wastewater characteristics, design/operating parameters (e.g., compatibility with existing processes), and environmental factors (e.g., temperature, pH).

MESERB (2005) focused on two phosphorus removal technologies: chemical addition and enhanced biological phosphorus removal (EBPR). Filtration technologies commonly used to reduce phosphorus further following chemical addition or EBPR are not included in the report's cost and performance evaluation, because the effluent concentration goal (1.0 mg/L) can be attained at most plants without filtration. According to the report, filtration used after other treatment processes can reduce effluent discharge concentrations to less than 0.5 mg/L TP. Although the report focused on chemical addition and EBPR, several other wastewater treatment technologies (e.g., lagoons, trickling filters) are discussed in detail in the conceptual design evaluations for the 17 WWTPs.

Cost estimates were facility-specific and drew on information from several sources, including USEPA reports, trade journals, vendor quotes, and internal project data. The cost estimates for each facility are presented in great detail, and cost curves (i.e., relating cost to the system design flow) are presented for EBPR and chemical addition. When dated cost information was in the

[3] Microfiltration is also referred to as low pressure membrane filtration or ultrafiltration.

cost evaluation, the Engineering News Record (ENR) Construction Cost Index was used to scale costs to 2005.

The report draws general conclusions about the compatibility, cost, and performance of potential EBPR and chemical addition. The most relevant general conclusions are listed below:

- Chemical addition is the recommended phosphorus reduction process at plants without suspended-growth activated sludge systems to which EBPR may be retrofitted. Examples of such facilities are those with trickling filters, rotating biological contactors, or lagoons for secondary treatment.

- For WWTPs with activated sludge systems, the cost-effectiveness of EBPR, EBPR plus chemical addition, or chemical addition only is affected by many site-specific factors.

- Wastewater characteristics have a major impact on the feasibility, performance, and economics of an EBPR. For example,

  - Wastewaters exhibiting biological oxygen demand (BOD)/P ratios of greater than 40 may be able to consistently achieve an effluent phosphorus of less than 1 mg/L;

  - Wastewaters with BOD/P ratios between 25 and 35 will require chemical addition for effluent polishing; and

  - Chemical addition usually is the most cost-effective choice when the BOD/P ratio is less than 25.

- For chemical treatment, the capacity of the sludge processing and handling operations should be evaluated during the design of the phosphorus removal treatment system. In addition, sludge processing residuals and other plant returns must be characterized to assess their impact on phosphorus loads when evaluating phosphorus removal systems, especially EBPR (MESERB 2005).

4.4 Refinement of Nitrogen Removal from Municipal Wastewater Treatment Plants, Maryland (GMB 2004)

Researchers investigated 20 POTWs selected by the Maryland Department of the Environment as candidates for biological nitrogen removal. Information for each POTW was used to determine appropriate alternatives for meeting proposed goals. ENR alternatives were grouped into three categories: reconfiguration to the Bardenpho process with existing reactors; reconfiguration to the Bardenpho process with construction of additional reactor volume, and addition of denitrification filters. Costs were estimated for alternatives identified for nitrogen reduction for each plant. For each of the 20 POTWs, computer modeling was performed to determine the reactor size and configuration required to achieve the ENR goal of 3 mg/L TN.

Cost estimates were prepared for each selected alternative giving consideration to needed capital improvements, equipment modifications, process changes, and O&M costs. Process improvements included pumps, blowers, clarifier equipment, diffusers, mixers, denitrification filters, piping, chemical dosing systems, and other equipment. Materials and labor were also included in this estimated cost. Process improvements were estimated in detail, and associated work of other disciplines (electrical, mechanical, architectural, and site work) was accounted for as a multiplier of the estimated cost of process improvements. Cost estimates also included taxes, overhead, and profit. A construction contingency factor of 25 percent was added to all cost estimates. The total costs were indexed using the September 2004 Engineering News Record cost index. Ranges of costs for each of the three ENR categories are provided in Table 7.

Table 7. Ranges of Estimated Costs for Nitrogen Removal to 3 mg/L TN for 20 POTWs in Maryland [a]

ENR Category	Number POTWs in Category	Estimated ENR Costs [e]	Costs per Gallon Treated of ENR Improvements [e]
Reconfiguration to the Bardenpho process with existing reactors [b]	7	\$1.0M – \$11M	\$0.22 – \$0.91
Reconfiguration to the Bardenpho process with construction of additional reactor volume [c]	4	\$5M – \$30M	\$0.39 – \$5.50 [f]
Addition of denitrification filters [d]	9	\$9M – \$250M	\$1.11 – \$1.92

Source: GMB (2004)
ENR = enhanced nitrogen removal
[a] Only ranges of estimated costs for the three groups of ENR alternatives are provided here. Detailed cost information is provided in GMB (2004) for each of the 20 POTWs investigated, including estimated ENR cost, cost per pound of TN removed, and cost per gallon per day treated.
[b] Includes the following plants: Parkway, Seneca, Ballenger, Cambridge, Piscataway, Freedom, Pine Hill
[c] Includes the following plants: Annapolis, Hurlock, Salisbury, Cumberland
[d] Includes the following plants: L. Patuxent, Sod Run, Hagerstown, Westminster, Conococheague, Frederick, Bowie, Back River, Cox Creek
[e] Obtained from Table 2 and Figure 11 of GMB (2004).
[f] Of the four plants, two (associated with the highest cost per gallon) were considered anomalies (see GMB [2004] for details). The construction of additional reactor volume for ENR is estimated at \$0.73 per gallon treated, which is considered to be more representative of the category.

4.5 Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities (Jiang et al. 2004 & 2005)

4.5.1 Construction De Novo (Jiang et al. 2004)

The authors described eight designs of wastewater treatment facilities covering a wide range of phosphorus removal and estimated costs of phosphorus removal through entirely new facilities, constructed *de novo*, essentially on “greenfield sites.” The range of plant designs that would meet limits of between 0.05 and 2.0 mg/L of TP in their effluents were considered. Capital, O&M, and total costs for the construction and operation of plants with capacities ranging between 1 and 100 MGD were developed.

Capital costs consisted of construction costs (equipment, installation, piping, and instrumentation and controls) and indirect costs (engineering and contingency). The indirect engineering and contingency costs were each estimated as 15 percent of the total construction cost. O&M costs consisted of maintenance costs (assumed to be 4 percent of total capital cost), taxes and insurance (assumed to be 2 percent of total capital cost), labor, electricity, chemicals, and residuals management. The authors assumed a 20-year lifespan for the WWTP. As appropriate, costs were updated for inflation according to the Engineering News Record construction cost index for 2004. The total annual economic cost (TAEC) was calculated as construction cost multiplied by a capital recovery factor (8.72 percent assuming a 20-year lifespan for the plant) plus the annual O&M cost. Land cost was not factored into the total cost because land prices vary considerably by location. Detailed capital and O&M costs are presented in Jiang et al. (2004) for each of the eight processes by flow (1 MGD to 100 MGD), but are not provided here.

4.5.2 Adaptation of Existing Facilities (Jiang et al. 2005)

In the Jiang et al. (2004) report described above, cost of removing phosphorus from municipal wastewater were estimated for treatment facilities that would be constructed *de novo*. A follow-up report (Jiang et al. 2005) evaluates costs for adapting existing facilities to a higher level of phosphorus removal. The alternatives selected simulate both biological phosphorus removal and the removal of phosphorus by means of precipitation through chemical addition.

A basic activated sludge (AS) system was used as the reference plant for current operations under dry weather conditions. Three treatment system upgrades were simulated: (1) the basic activated sludge process with chemical addition (AS + alum); (2) the anoxic/oxic (A/O) arrangement of the activated sludge process; and (3) the anaerobic/aerobic/oxic (A/A/O) arrangement of the activated sludge process. Each of these process modifications are described in detail in the report. The range of plant upgrades that would meet limits of between 0.05 and 2.0 mg/L of TP in their effluents were simulated and the costs of the upgrades were estimated. Five capacities of plants were considered, from 1 MGD to 100 MGD. Characterization of the nutrients in influent wastewater at the WWTP was described as: 6.34 mgP/L TP and 16.1 mgN/L ammonium (NH_4^+). Other assumptions regarding the influent, key design choices, physical and economical modeling parameters, operational practices, etc. are discussed in Jiang et al. (2005).

Estimated of facility upgrades include both a capital cost and O&M cost. O&M costs were estimated to include costs for energy (specifically aeration energy, pumping energy, and mixing energy), chemicals (alum added to the aeration basin and polymers added to the clarifier), biological and chemical sludge disposal, labor, maintenance, and insurance. The costs estimated in the report exclude all costs of the basic activated sludge system, and focus on the adaptation of the basic activated sludge system to the alternative designs listed above. *De novo* costs of an activated sludge system were described in the previous report (Jiang et al. 2004). Incremental costs of the upgrades are presented and compared through the Total Annual Economic Cost (in $) and the marginal unit cost of phosphorus removal (i.e., the cost of the additional phosphorus removed as a result of the upgrade) (in $/kg). The TAEC was calculated as the annualized capital cost multiplied by a capital recovery factor (8.72 percent assuming a 20-year lifespan for the plant) plus the annualized O&M costs. The TAECs are presented in Table 8 for each of the three designs (AS + alum, A/O, and A/A/O) by TP limit and flow. The Bureau of Labor Statistics and Engineering News Record indexes were used for cost updating to year 2004 values.

Under TP limits of 0.05 to 2.0 mg/L, the AS + alum was the most economical, perhaps demonstrating (according to the authors) that the unit costs of phosphorus removal are lower in plants with chemical precipitation due mainly to the higher capital costs of installing the anaerobic tank volume necessary for upgrading the biological processes of phosphorus removal.

Table 8. Estimated Costs for Phosphorus Removal to TP Limits Ranging from 2 mg/L to 0.05 mg/L for Three Technology Upgrades to the Basic AS System [a]

Total Annual Economic Cost by TP Limit [b]	Plant Capacity				
	1 MGD	10 MGD	20 MGD	50 MGD	100 MGD
AS + alum					
2 mg/L	$45,100	$150,000	$263,000	$602,000	$1,160,000
1 mg/L	$64,800	$340,000	$642,000	$1,540,000	$3,020,000
0.5 mg/L	$465,000	$1,710,000	$2,930,000	$6,650,000	$13,000,000
0.13 mg/L	$671,000	$3,710,000	$6,930,000	$16,720,000	$33,120,000
0.05 mg/L	$1,070,000	$5,550,000	$10,160,000	$23,140,000	$44,930,000
A/O					
2 mg/L	$113,000	$501,000	$863,000	$1,860,000	$3,450,000
1 mg/L	$149,000	$778,000	$1,380,000	$3,110,000	$5,920,000
0.5 mg/L	$568,000	$2,090,000	$3,580,000	$7,990,000	$15,420,000
0.13 mg/L	$728,000	$3,530,000	$6,430,000	$15,090,000	$29,640,000
0.05 mg/L	$1,160,000	$5,750,000	$10,410,000	$23,530,000	$45,430,000
A/A/O					
2 mg/L	$140,000	$558,000	$942,000	$1,980,000	$3,750,000
1 mg/L	$192,000	$830,000	$1,450,000	$3,210,000	$6,090,000
0.5 mg/L	$648,000	$2,140,000	$3,650,000	$8,080,000	$15,650,000
0.13 mg/L	$753,000	$3,570,000	$6,480,000	$15,140,000	$29,780,000
0.05 mg/L	$1,180,000	$5,750,000	$10,380,000	$23,350,000	$45,160,000

[a] Source: Jiang et al. (2005). In this report, detailed estimates of costs are provided for each of the scenarios in the table, including capital costs, O&M costs (for energy, labor, chemical, sludge disposal, and maintenance & insurance), and unit cost of TP removal (expressed as $/kg TP removed). Estimates of TP removed per year (in million tons) associated with each of the adaptation configurations are also provided in the report.
[b] See the report for details regarding the adaptation configuration required to meet the TP limits.

4.6 Cost and Affordability of Phosphorus Removal at Small Wastewater Treatment Plants (Keplinger et al. 2004)

Keplinger et al. (2004) documented a phosphorus control analysis for six small Texas communities along the North Bosque River ranging in size from 360 – 14,900 people. The analysis was initiated to evaluate the potential impact of a 1 mg/L TP effluent standard that had been considered in the course of Total Maximum Daily Load (TMDL) development. Four treatment systems were initially considered for the analysis, including chemical precipitation, biological treatment with chemical polishing, wetlands treatment, and land treatment. Wetlands treatment was considered not to be cost-effective because of the large land areas that would be required, and land treatment was eliminated from the analysis due to the need for detailed site-specific investigations. Site-specific cost evaluations determined that chemical precipitation would be less costly than biological treatment for all of the WWTPs. Therefore, Keplinger et al.

(2004) confined its analysis to phosphorus removal utilizing aluminum sulfate (alum) addition as the primary supplemental removal mechanism. Use of alum creates greater amounts of sludge, which would require disposal.

Costs were divided into two major categories: capital costs and O&M costs. One-time capital costs consisted of expenses associated with physical plant upgrades (e.g., alum storage tanks, feed lines, feed pumps). Capital service costs (annual loan payments) were also estimated. O&M costs for phosphorus removal consisted of alum cost, additional sludge disposal cost, and additional expenses that would be incurred on an ongoing basis, including materials, supplies, utilities, maintenance, and labor. Costs were presented in 2001 dollars and were based on a 25-year assumed life of the capital improvements (see Table 9). In addition to total capital and O&M costs, efficiency (cost per pound) and affordability measures (costs per person and per household) were developed.

Table 9 shows the estimated costs of adding chemical precipitation at each of the six WWTPs and the impact of the cost on residential sewer bills. Differences among the estimated costs resulted from facility-specific design differences and system capacities. All capital cost estimates were scaled up 78 percent higher than site-specific estimates, because an actual capital cost incurred by one of the facilities was 78 percent higher than had been estimated. Thus, Keplinger et al. (2004) considered the cost estimates to be conservative overall.

In general, capital costs were similar for five of the six facilities and were not greatly affected by difference in system flow rates. Site-specific factors, which were not identified by Keplinger et al. (2004), caused much higher capital costs for the Meridian WWTP. System flow rates affected the magnitude of O&M costs more than they affected capital.

Although similar treatments processes were evaluated for the six communities, large differences were found in affordability measured as the additional monthly cost per residence and annual cost per person. These differences are explained partially by site-specific differences in treatment costs, but are driven primarily by differences in community size (i.e., the number of households among which the costs are divided). Therefore, the case study documented by Keplinger et al. (2004) indicates that particular technologies cannot be generalized as affordable or unaffordable without consideration of community size and site-specific factors affecting implementation cost.

Table 9. Estimated Cost of Phosphorus Reduction at Six WWTPs Discharging to the North Bosque River, Texas

Community	Permitted Discharge (MGD)	Effluent TP (mg/L)	Capital Cost [a,b] ($)	O&M Cost[a] ($/yr)	Base Residential Bill (2002) ($/mo)	Monthly Additional Treatment Cost ($/mo)	Cost per Person ($/yr)
Stephenville	3.00	2.69	$786,288	$64,413	$20.69	$1.19	$5.18
Clifton	0.65	2.40	$979,000	$14,775	$22.00	$3.77	$15.80
Meridian	0.45	3.36	$2,290,860	$31,191	$18.64	$14.73	$69.10
Hico	0.20	3.52	$825,920	$9,215	$12.00	$7.77	$33.23
Valley Mills	0.36	3.14	$957,640	$20,154	$8.00	$12.02	$58.19
Iredell	0.05	2.96	$792,100	$7,518	$15.14	$25.43	$151.75

Source: Keplinger et al. (2004)

[a] Capital and O&M estimates for all facilities assumed the use of chemical precipitation with alum addition to achieve an effluent concentration of 1 mg/L TP.

[b] All capital cost estimates were scaled up 78 percent higher than site-specific estimates because an actual capital cost incurred by one of the facilities was 78 percent higher than had been estimated.

4.7 Enhanced Nutrient Removal Strategies: Approaches and Case Studies Demonstrating Nutrient Removal Success (Sadler and Stroud 2007)

Sadler and Stroud (2007) presented case studies of advanced nutrient removal upgrades at four moderately sized community wastewater treatment systems in North Carolina. The case studies include descriptions of the existing systems, advanced nutrient removal upgrades, and cost and performance results. Upgrades at the four WWTPs are summarized briefly below.

- **Goldsboro, NC** -- conversion of existing oxidation ditch tankage to enhanced biological nutrient removal cells with piping modifications for process flexibility.

- **South Cary, NC** -- conversion of existing complete mixed aeration to enhanced biological nutrient removal cells with piping modifications for process flexibility.

- **Wilson, NC** -- conversion from a trickling filter to a sidestream enhanced biological phosphorus removal basin.

- **Gastonia, NC** -- piping and equipment modifications for nutrient removal and process optimization.

In addition, effluent filtration was used at the Goldsboro, South Cary, and Wilson facilities.

Performance and cost results for the case studies are summarized in Table 10. These case studies show that advanced nutrient removal can be affordable for moderately sized WWTPs.

Table 10. Summary of Enhanced Nutrient Removal Case Studies

Measure	Community			
	Goldsboro	South Cary	Wilson	Gastonia
Design Capacity	14.2 MGD	12.8 MGD	14 MGD	6 MGD
TP Before and After Upgrade	Before: 2 mg/L After: ND	Before: 2 mg/L After: 0.5 mg/L	Before: 2.6 mg/L After: 0.35 mg/L	Before: <2 mg/L After: 0.5 mg/L
TN Before and After Upgrade	Before: 14 mg/L After: 3.3 mg/L	Before: 26 mg/L After: 2.2 mg/L	Before: NA After: NA	Before: 22 mg/L After: 5.5 mg/L
Capital Cost of Upgrade	$4 million	$14.1 million	$3 million	$1.4 million
Capital Cost per Gallon of Capacity (2006$)	$0.76/gal	$1.43/gal	$0.90/gal	$0.27/gal

Source: Sadler and Stroud (2007)
ND = Non-detect
NA = Not applicable

4.8 Cost and Performance Evaluation of BNR Processes (Foess et al. 1998)

Foess et al. (1998) compiled cost and performance data for BNR processes used at WWTPs with small design capacities (defined for the study as 2,000 to 100,000 gallons per day [GPD]). The purpose of this analysis was to provide information on which to base Best Available Technology (BAT) limitations for Monroe County, Florida. The authors gathered information on approximately 25 commercially available treatment systems and performed 17 site visits to operating facilities. For the range of design capacities of interest, almost all treatment systems in operation were found to be pre-engineered package systems. Based on their research, the authors selected eight representative systems for comparative analysis. Only BNR processes were included in the analysis. Table 11 summarizes the cost and performance data for eight treatment systems scaled to five design capacities between 4,000 and 100,000 GPD. Nutrient concentrations attainable by the treatment systems are the same for all design capacities. Based on the cost analysis, Foess et al. (1998) concluded that conventional suspended-growth nutrient removal technologies generally are the least expensive processes for systems with design capacities above 10,000 GPD.

The information presented in Table 11 is for newly constructed treatment systems. Foess et al. (1998) also examined the costs of retrofitting two nitrogen reduction processes (i.e., anoxic tank for MLE upgrade, deep-bed denitrification filters) to existing WWTPs. The deep-bed denitrification filter was found to provide better nitrogen removal than MLE, but at a cost two to four times higher, depending on design capacity.

In addition to the performance and cost analysis, Foess et al. (1998) ranked the eight BRN processes with a weighted scoring system that considered unit cost, nitrogen removal performance, process control flexibility, ease of operation, and land requirements. Each process was scored for each criterion on a scale from 1 (lowest) to 5 (highest). Weighted total scores were then used to rank the processes overall, with 1 being the highest ranking. This ranking analysis, which is summarized in Table 12, assigned the highest rank to the three-stage process, followed by the MLE process, and the MLE process plus deep-bed filtration. The SBR and intermittent cycle systems (Systems 4 and 5, respectively) tied for the fourth rank. The four-stage system ranked fifth and the attached-growth systems (Systems 7 and 8) were ranked tied for the sixth rank. A similar scoring analysis was performed for the two retrofit processes discussed above.

Table 11. Cost and Performance of Package BNR Treatment Processes Available for WWTPs with Design Flows of 0.1 MGD or Less

Treatment Process	Achievable Effluent Quality (mg/L)		Construction Costs of Treatment Processes by Design Flow (GPD) [b]				
	TN	P [a]	4K GPD	10K GPD	25K GPD	50K GPD	100K GPD
Construction Costs							
1. MLE Process	10	2	$261,000	$311,000	$422,000	$601,000	$874,000
2. Four-Stage	6	2	$336,000	$368,000	$475,000	$666,000	$968,000
3. Three-Stage	6	2	$291,000	$333,000	$441,000	$627,000	$913,000
4. SBR	8	2	$336,000	$381,000	$482,000	$697,000	$966,000
5. Intermittent Cycle	8	2	$229,000	$374,000	$584,000	$861,000	$1,026,000
6. MLE + Deep Bed Filtration	6	1	$308,000	$368,000	$486,000	$664,000	$958,000
7. Submerged Biofilters	12	2	$247,000	$296,000	$450,000	$847,000	(c)
8. RBCs	12	2	$263,000	$342,000	$527,000	$868,000	$1,092,000
O&M Costs ($/year)							
1. MLE Process	10	2	$30,400	$35,500	$49,400	$66,600	$100,100
2. Four-Stage	6	2	$52,500	$57,600	$73,800	$95,900	$132,300
3. Three-Stage	6	2	$35,900	$41,900	$56,400	$76,200	$115,900
4. SBR	8	2	$28,000	$34,100	$49,100	$67,600	$100,000
5. Intermittent Cycle	8	2	$28000	$34100	$49100	$67600	$100,000
6. MLE + Deep Bed Filtration	6	1	$36,900	$42,700	$58,100	$75,900	$111,400
7. Submerged Biofilters	12	2	$19,500	$24,400	$41,100	$60,400	(c)
8. RBCs	12	2	$22,000	$26,500	$39,200	$52,100	$78,000

Source: Foess et al. (1998)

1. Modified Ludack-Ettinger (MLE) Process – continuous-flow suspended-growth process with an initial anoxic stage followed by an aerobic stage
2. Four-Stage Process – continuous- flow suspended-growth process with alternating anoxic/aerobic/anoxic/aerobic stages
3. Three-Stage Process – continuous-flow suspended-growth process with alternating aerobic/anoxic/aerobic stages
4. SBR – Suspended-Growth Process batch process sequenced to simulate the four-stage process
5. Intermittent-Cycle Process – modified SBR process with continuous influent flow but batch, four-stage, treatment process
6. MLE and Deep-Bed Filtration Process – Alternate 1 followed by attached-growth denitrification filter
7. Submerged Biofilter Process – continuous-flow or intermittent-cycle process using one or more submerged media biofilters with sequential anoxic/aerobic stages
8. RBC Process – continuous-flow process using rotating biological contactors (RBCs) with sequential anoxic/aerobic stages
[a] Achievable phosphorus concentrations may be reduced to 1 mg/L by the addition of filtration to all processes except submerged biofilters, which already includes filtration.
[b] Although Foess et al. do not report the years of the cost data, the year of publication (i.e., 1998) can be assumed.
[c] Design capacity is greater than capacity offered by vendor.

Table 12. Weighted Ranking of Package BNR Treatment Processes Available for WWTPs with Design Flows of 0.1 MGD or Less

Treatment Process	Scoring Criteria (weighting factor)					Weighted Score	Ranking
	Unit Cost (30%)	Nitrogen Removal (30%)	Control/ Flexibility (15%)	Ease of Operation (15%)	Land Required (10%)		
1. MLE Process	4	4	3	3	3	3.6	2
2. Four-Stage	1	5	5	2	3	3.2	5
3. Three-Stage	3	5	4	3	3	3.8	1
4. SBR	3	4	3	3	4	3.4	4 (tie)
5. Intermittent Cycle	3	4	3	3	4	3.4	4 (tie)
6. MLE + Deep Bed Filtration	2	5	5	2	3	3.5	3
7. Submerged Biofilters	3	2	2	4	5	2.9	6 (tie)
8. RBCs	3	2	2	4	5	2.9	6 (tie)

Source: Foess et al. (1998)

4.9 Other Relevant References

This section describes selected references that do not contain directly applicable or sufficiently detailed cost and performance data, but that may contain background information useful for the affordability analysis.

Detailed Costing Document for the Centralized Waste Treatment Industry (USEPA 1998). This document was prepared to support implementation of the effluent guidelines for the centralized waste treatment (CWT) industry, which processes wastewater and residuals from other manufacturing facilities (USEPA 1998). The report provides very detailed cost information, including flow-based cost curves, for a number of conventional wastewater treatment processes. The CWT effluent guidelines address metal-bearing, oily, and organic wastewaters, not nutrients, and most of the technologies described are not directly relevant to nutrient reduction. However, the report does provide cost information for certain processes and equipment (e.g., sequencing batch reactors, tanks, sludge dewatering systems) that may be helpful for estimating costs for nutrient reductions systems. Although this document was published in 1998, all cost estimates were scaled to 1989 using the Engineering News Record Construction Cost Estimate (USEPA 1998).

Onsite Wastewater Treatment Manual (USEPA 2002b). This document discusses many treatment processes potentially relevant to estimating nutrient reduction cost. For example, it includes fact sheets with process descriptions and performance and cost information for secondary treatment technologies and advance phosphorus and nitrogen reduction. However, the document is written to provide guidance to operators of small onsite treatment systems (i.e., generally serving fewer than 20 people) rather than publicly-owned treatment works.

Constructed Wetlands Treatment of Municipal Wastewaters (USEPA 2000f). Constructed wetlands are shallow vegetated ponds (usually less than one meter deep) in which wastewater is treated by natural processes. The use of constructed wetlands to treat domestic wastewater is a viable alternative in many communities the United States, particularly where inexpensive land is available. This USEPA manual (USEPA 2000f) discusses the appropriate use, design, and performance of constructed wetlands. According to the manual, constructed wetlands are often mistakenly believed to be capable of removing significant nitrogen and phosphorus from wastewater streams. Other sources (e.g., USEPA 2000a; USEPA 200b) indicate that constructed wetlands can achieve nitrogen and phosphorus reduction. However, significant engineering and operational modifications (e.g., creating aerobic zones, removing senescent vegetation, increasing retention times) may be necessary to obtain these benefits.

Saving the Chesapeake Bay - Planning for Less than 3 mg/l Total N and 0.1 mg/l Total P - the Lynchburg Regional WWTP Story (Bratby et al. 2007). Bratby et al. (2007) developed a model to evaluate four innovative nutrient reduction systems designed for an ultimate goal of achieving concentrations of 3 mg/L nitrogen and 0.1 mg/L phosphorus at the 22 MGD Lynchburg, Virginia WWTP. The systems evaluated included:

- Two-stage step feed activated sludge;
- Three-stage step feed activated sludge;
- A five-stage Bardenpho-based activated sludge process; and
- An integrated fixed-film - activated sludge (IFAS) process.

The two-stage step feed activated sludge process was found to be the most beneficial for long-term objectives. Cost estimates were presented in terms of total 20-year net present values, and ranged from $150 million to $159 million for the four systems evaluated. The publication does not provide details on the capital and O&M costs of each of the options or information on to scale costs to WWTPs with smaller design capacities.

Engineering News Record Construction Cost Index (ENR 2007). Several of the studies summarized in Section 4 present treatment system cost estimates based in part on previously published information. When cost estimation methodologies require cost information form various sources to be indexed to the same year or updated to the current year, the Engineering News Record (ENR) Construction Cost Index is commonly used. Since 1908 ENR has calculated the index using a data on labor and construction materials costs in 20 cities. The index is currently updated monthly and published along with the annual index history in the ENR, a weekly subscription periodical.

5.0 Summary and Recommendations

Information sources summarized in this report show that advanced nitrogen and phosphorus removal from municipal waste streams may be achieved by various currently available biological, chemical, and physical treatment processes. USEPA (2007) and Sadler and Stroud (2007) published case studies including cost and performance results for multiple facilities that have already applied advance nutrient reduction technologies. Both of these sources concluded that advanced nutrient reduction can be affordable for POTWs. Several other studies summarized in Section 4 (e.g., CBP 2000; MESERB 2005; Keplinger et al. 2004; GMB 2004) gathered detailed facility-specific data for engineering and cost analyses to identify cost-effective nutrient reduction upgrades for POTWs of various sizes. Keplinger et al. (2004) and Foess et al.

(1998) performed analyses of this type specifically focusing on small communities. Detailed engineering information and assumptions, cost curves (i.e., that relate treatment costs to process design capacity), and comparative analyses in CBP (2000), MESERB (2005), GMB (2004), and other sources summarized in Section 4 may provide useful background information for developing a detailed methodology for the MT DEQ affordability analysis.

The predominant advanced reduction technologies for nitrogen are enhancements to secondary biological treatment. In general, BNR processes are able to reduce average TN in effluent to 8 to 10 mg/L, and ENR processes refine the BNR to achieve TN concentrations to as low as 3 mg/L (Freed 2007).

The primary forms of advanced phosphorus removal include refined biological treatment, chemical addition, and filtration. BNR can achieve average TP concentrations in the range of 1 to 3 mg/L, and enhanced biological phosphorus removal can achieve 0.3 mg/L TP (Freed 2007) with the potential to achieve very low (<0.1 mg/L) TP (Strom 2006). As upgrades to existing systems, BNR and ENR methods are most suitable for suspended growth secondary treatment systems. For systems without suspended growth systems, chemical addition is the recommended phosphorus reduction process (e.g., MESERB 2005). Biological, chemical, and physical processes may be combined to achieve very low TP concentrations. For example, monitoring data reported by USEPA (2007) showed that chemical addition followed by tertiary filtration can consistently achieve TP concentrations of 0.01 mg/L.

Although the body of available literature provides fairly consistent estimates of achievable TN and TP concentrations, actual performance is affected by site specific factors, including wastewater characteristics, preexisting treatment processes, and the facility design capacity (e.g., MESERB 2005). These factors have an even greater effect on facility-specific costs. Several of the studies summarized in Section 4 present cost information (e.g., capital costs, incremental annual treatment costs per household) for case-study POTWs. However, the unit costs and affordability for particular technologies are difficult to generalize (Keplinger et al. 2004).

Some studies (e.g., CPB 2002, MESERB 2005) include cost curves that can be used to estimate costs of certain treatments scaled to design capacity. In addition, comparative costing analyses include conclusions about the relative cost of alternative treatment configurations. For example, Foess et al. (1998) concluded that conventional suspended-growth nutrient removal technologies generally are less expensive than attached growth processes for systems with design capacities above 10,000 GPD. Cost comparisons for six small WWTPs in Texas showed chemical precipitation to be less costly than biological treatment (Keplinger et al., 2004). In the same study, affordability was found to be driven by differences in community size (i.e., the number of households among which the treatment costs would be divided).[4]

A potential next step in developing the MT DEQ affordability analysis would be to use the information sources described in this report to estimate costs for Montana POTWs that may be

[4] The available studies evaluate treatment system size in terms of design flow or population served. For the MT DEQ affordability analysis, it may be necessary to assume a relationship between design flow and community population. For residential customers, USACE (1988) and others assume 100 gallons influent per person per day. Adjustments for industries and institutions may be available in the literature.

affected by potential nutrient criteria. Two possible approaches to use the information summarized in this report include (1) estimating compliance costs for individual Montana POTWs based on facility-specific information (e.g., existing treatment processes, populations served), and (2) developing cost estimates for a number of model POTW scenarios that consist of hypothetical treatment systems, sizes, and effluent targets.

6.0 References

Sources Cited in this Report:

Bratby, J., P. Schuler, A. Rucker, J. Jimenez, D. Parker, 2007. "Saving the Chesapeake Bay - Planning for Less than 3 mg/l Total N and 0.1 mg/l Total P - the Lynchburg Regional WWTP Story." In *Nutrient Removal 2007; the State of the Art.* Conference conducted by the Water Environment Federation, March 2007.

Chesapeake Bay Program (CBP) 2002. *Nutrient Reduction Technology Cost Estimations for Point Sources in the Chesapeake Bay Watershed.* Prepared by the Nutrient Reduction Technology Cost Task Force, A Stakeholder Group of the Chesapeake Bay Program. November 2002.

Enginering News Record (ENR) 2007. "Building Cost Index History." *Engineering News Record*. March 19, 2007.

Foess, G.W., P. Steinbrecher, K. Williams, and G.S. Garrett 1998. *Cost and Performance Evaluation of BNR Processes*. Florida Water Resources Journal. December 1998, 11-13. Available at: http://www.fwrj.com/articles/9812.pdf.

Freed, T 2007. "Wastewater Industry Moving Toward Enhanced Nutrient Removal Standards." *WaterWorld*, March 2007. Available at: http://ww.pennnet.com/articles/article_display.cfm?article_id=286210.

Gannett Flemming, Inc./Miles & Buhr (GMB) 2004. *Enhancement of Nitrogen Removal From Municipal Wastewater Treatment Plants*; *Final Draft.* October 2004.

Hatch Mott MacDonald undated. *Biological Nutrient Removal – Technology Update*. Available at: http://www.hatchmott.com/documents/adobe/bnr%20tech%20update_w.pdf.

Hydromantis Inc. 2006. *Review of the State of Knowledge of Municipal Effluent Science and Research: Review of Existing and Emerging Technologies; Review of Wastewater Treatment Best Management Practices*. Prepared for Canadian Council of Ministers of the Environment. January 2006. Available at: http://www.ccme.ca/assets/pdf/csr_rev_emerge_tech_bmp.pdf.

ICF 2006. *Scoping Evaluation of Economic Impact Assessment Methodologies For Water Quality Standards*. Prepared for Michael Suplee, Ph.D., Montana Department of Environmental Quality, Helena, Montana. Prepared By: Arun Varghese and Josh Cleland, ICF International, Lexington, Massachusetts. June 30, 2006.

Jiang F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell 2005. *Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Adaption of Existing Facilities.* Water Policy Working Paper #2005-011. Available at: http://www.h2opolicycenter.org/pdf_documents/W2005011.pdf.

Jiang F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell 2004. *Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Construction De Novo.* Water Policy Working Paper #2004-010. June 2004. Available at: http://www.h2opolicycenter.org/pdf_documents/water_workingpapers/2004-010.pdf

Keplinger, K.O., J.B. Houser, A.M. Tanter, L.M. Hauck, and L. Beran 2004. "Cost and Affordability of Phosphorus Removal at Small Wastewater Treatment Plants." *Small Flows Quarterly* 5(4):36-49. Fall 2004. Available at: http://www.nesc.wvu.edu/NSFC/Articles/SFQ/SFQ_f04_PDF/Juried_f04.pdf.

MESERB, 2005. *Wastewater Phosphorus Control and Reduction Initiative*. Prepared for the Minnesota Environmental Science and Economic Review Board. Prepared by HydroQual, Inc., Mahwah, NJ, in association with H. David Stensel, Ph.D., P.E., University of Washington, Seattle, WA. Project Number MESE0001. April 2005. Available at: http://www.meserb.org/phosphorus.htm.

Opus International Consultants Limited 2005. *Eastern Seaboard Wastewater Treatment Plant Projects; Treatment Options Evaluation; Draft Report*. Thames Coromandel District Council, Wellington, New Zealand. November 2005. Available at: http://www.tcdc.govt.nz/ApplicationResources/MCMSResources/es/App%20E%20-%20Opus%20Treatment%20Process%20Options%20Report.pdf.

Park, J.K., J. Wang, and G. Novotny 1997. *Wastewater Characterization for Evaluation of Biological Phosphorus Removal*. Research Report 174. August 1997. Available at: http://www.dnr.state.wi.us/org/water/wm/ww/biophos/1intro.htm.

Peterson, S. 2006. "Nitrogen Removals in Small Flows Wastewater Facilities in Massachusetts." *Small Flows Quarterly* 7(3):29-35. Summer 2006. Available at: http://www.nesc.wvu.edu/nsfc/Articles/SFQ/SFQ_su06/Juried.pdf.

Sadler, M.E. and F.R. Stroud 2007. "Enhanced Nutrient Removal Strategies: Approaches and Case Studies Demonstrating Nutrient Removal Success." In *Nutrient Removal 2007; the State of the Art.* Conference conducted by the Water Environment Federation, March 2007.

Strom, P.F. 2006. *Technologies to Remove Phosphorus from Wastewater*. Rutgers University. August 2006. Available at: http://www.water.rutgers.edu/Projects/trading/p-trt-lit-rev-2a.pdf.

U.S. Army Corps of Engineers (USACE) 2001. *Facilities Engineering Utilities; Biological Nutrient Removal*; Public Works Technical Bulletin, No. 420-49-39. September 2001. Available at: ftp://ftp.tjcog.org/pub/tjcog/regplan/jorlk/bnr.pdf.

U.S. Army Corps of Engineers (USACE) 1998. *Domestic Wastewater Treatment*; Technical Manual No. 5-814-3. Air Force Technical Manual No. AFM 88-11, Volume 3. Headquarters, Department of the Army and the Air Force, Washington, DC. August 1998. Available at: http://www.usace.army.mil/publications/armytm/tm5-814-3/toc.pdf.

USEPA 2007. *Advanced Wastewater Treatment to Achieve Low Concentrations of Phosphorus*. U.S. Environmental Protection Agency, Region 10, Seattle, WA. EPA 910-R-07-002. April 2007.

USEPA 2004. *Primer for Municipal Wastewater Treatment Systems.* Office of Water and Office of Wastewater Management, U.S. Environmental Protection Agency. EPA/832/R-04/001. September 2004. Available at: http://www.epa.gov/OWM/primer.pdf.

USEPA 2002a. *Wastewater Technology Fact Sheet; Facultative Lagoons.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-02/014. September 2002. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 2002b. *Onsite Wastewater Treatment Manual.* Office of Water and Office of Research and Development, U.S. Environmental Protection Agency. EPA/625/R-00/008. February 2002. Available at: http://www.epa.gov/ORD/NRMRL/Pubs/625R00008/625R00008.htm.

USEPA 2000a. *Wastewater Technology Fact Sheet; Free Water Surface Wetlands.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-00/024. September 2000. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 2000b. *Wastewater Technology Fact Sheet; Wetlands: Subsurface Flow.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-00/023. September 2000. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 2000c. *Wastewater Technology Fact Sheet; Oxidation Ditches.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-00/013. September 2000. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 2000d. *Wastewater Technology Fact Sheet; Trickling Filter Nitrification.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-00/015. September 2000. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 2000e. *Wastewater Technology Fact Sheet; Chemical Precipitation.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-00/018. September 2000. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 2000f. *Constructed Wetlands Treatment of Municipal Wastewaters*. National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH. EPA/625/R-99/010. September 2000. Available at: http://www.epa.gov/owow/wetlands/pdf/Design_Manual2000.pdf.

USEPA 1999. *Wastewater Technology Fact Sheet; Sequencing Batch Reactors.* Office of Water, U.S. Environmental Protection Agency. EPA/832/F-99/073. September 1999. Available at: http://www.epa.gov/owm/mtb/mtbfact.htm.

USEPA 1998. *Detailed Costing Document for the Centralized Waste Treatment Industry.* Office of Water, U.S. Environmental Protection Agency, Washington, DC. EPA-821-R-98-016. December 1998. Available at: http://www.epa.gov/waterscience/guide/cwt/proposal/econ/cwtdcs.html.

USEPA 1995. *Interim Economic Guidance for Water Quality Standards*. U.S. Environmental Protection Agency, Washington, DC. EPA 823-R-95-002. March 1995. Available at: http://www.epa.gov/waterscience/econ/.

Additional Site-specific Sources That May Be Useful:

Black and Veatch 2006. *Long-Term Wastewater Management Plan*. Prepared for the City of Soledad, CA. March 2006. Available at: http://www.cityofsoledad.com/assets/pdf_files/pubWorksProjects/projectLTWMP.pdf.

CDM 2005. *Water Facilities Plan*. Prepared for Town of Stonington, CT. Available at: http://stoningtonct.virtualtownhall.net/Pages/StoningtonCT_WPCA/wpca_plan/plan.

Hazen and Sawyer 2007. *Moores Creek WWTP; Nutrient Removal Preliminary Engineering Report*; Rivanna Water and Sewer Authority, Charlottesville, VA. February 2007. Available at: http://www.rivanna.org/documents/report_nutrient.pdf.

HDR Engineering. Inc. 2003. *Spokane County Wastewater Facilities Plan Amendment, Volume I*. Prepared for Spokane County Public Works, Spokane, WA. February 2003. Available at: http://www.spokanecounty.org/utilities/.

RMC Water and Environment 2006. *Wastewater Treatment Plan; Master Plan; Final Report;* prepared for the City of Waterford, CA. March 2006. Available at: http://www.cityofwaterford.org/Waterford%20WWTP%20Report_Mar2006%5B1%5D.pdf.