NACWA

A Clear Commitment to America's Waters

Nutrients Issue Paper

Technical Discussion

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CRITICAL ISSUES ACTION INITIATIVE

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Introduction

Application of treatment technology standards for nutrients does not ensure that water quality benefits will result but it does mean that treatment costs will increase. The potential water quality benefits from nutrient removal will vary widely and depend largely on site specific circumstances in individual watersheds. Nutrient driven water quality impairment is complex and loadings vary significantly from watershed to watershed across the country. Thresholds for nutrient enrichment vary, as do the magnitude of point and nonpoint source loadings, and waterbody responses. For these reasons, a treatment technology standard appropriate in one location may be overly restrictive in another, or not protective enough in a more sensitive watershed.

Nutrient removal is not considered a part of secondary treatment and existing facilities will incur both capital and operating cost increases to implement nutrient removal. The costs for nutrient removal will vary widely, depending upon the type and condition of existing treatment facilities and how easily they can be retrofit for nitrogen and phosphorus removal.

The paper presents a technical discussion of nutrient removal and provides examples of the challenges associated with establishing appropriate nutrient removal requirements. Considerations beyond the application of uniform nutrient removal requirements for wastewater treatment are necessary for appropriate application of technology and water quality protection. The subjects covered by section are summarized as follows:

- Section 1 is focused on the definition of secondary treatment, regulatory requirements, and the application of this terminology in the wastewater industry.
    - Wastewater treatment facilities required to remove nutrients go beyond secondary treatment.
- Section 2 addresses the wide variability of conditions in the water environment that limit the application of uniform effluent technology limits for nutrients. Site specific conditions in individual watersheds govern whether nitrogen or phosphorus are controlling water quality.
    - In most watersheds, nonpoint sources of nutrients are dominant and point source control through wastewater treatment alone cannot improve water quality.
- Section 3 documents the capital and operations costs associated with advanced wastewater treatment for nutrient removal. A variety of sources of cost data are presented that illustrate the substantial costs for nutrient removal.
    - Costs for advanced wastewater treatment for nutrient vary over a broad range and depend largely upon site specific circumstances.
- Section 4 presents information on nonpoint source best management practices including a summary of nutrient removal effectiveness and costs.
    - Costs for nonpoint source controls range from less than point source nutrient removal, to more, and are variable depending upon site specific applications.

- Section 5 includes a broader discussion of the carbon footprint of advanced wastewater treatment for nutrient removal. Nutrient removal impacts electrical power consumption and generates both direct and indirect greenhouse gas emissions.
    - Section 5 concludes with a comparison between point source and nonpoint source controls with consideration of these broader environmental impacts.

1. Secondary Treatment is Focused on BOD and Suspended Solids

Secondary treatment is defined in terms of BOD, suspended solids, and pH in federal regulations. Only incidental removal of nitrogen and phosphorus occur in secondary treatment in the course of removal of BOD and suspended solids. Federal regulations define secondary treatment performance requirements in terms of BOD, suspended solids, and pH. The following excerpt from the federal regulations describes the minimum level of effluent quality attainable by secondary treatment in terms of BOD5, SS and pH.

Title 40: Protection of Environment PART 133—SECONDARY TREATMENT REGULATION

All requirements for each parameter shall be achieved except as provided for in §§133.103 and 133.105.

(a) BOD_5.

(1) The 30-day average shall not exceed 30 mg/l.
(2) The 7-day average shall not exceed 45 mg/l.
(3) The 30-day average percent removal shall not be less than 85 percent.
(4) At the option of the NPDES permitting authority, in lieu of the parameter BOD_5 and the levels of the effluent quality specified in paragraphs (a)(1), (a)(2) and (a)(3), the parameter $CBOD_5$ may be substituted with the following levels of the $CBOD_5$ effluent quality provided:

(i) The 30-day average shall not exceed 25 mg/l.
(ii) The 7-day average shall not exceed 40 mg/l.
(iii) The 30-day average percent removal shall not be less than 85 percent.

(b) SS.

(1) The 30-day average shall not exceed 30 mg/l.
(2) The 7-day average shall not exceed 45 mg/l.
(3) The 30-day average percent removal shall not be less than 85 percent.

(c) pH.

The effluent values for pH shall be maintained within the limits of 6.0 to 9.0 unless the publicly owned treatment works demonstrates that: (1) Inorganic chemicals are not added to the waste stream as part of the treatment process; and (2) contributions from industrial sources do not cause the pH of the effluent to be less than 6.0 or greater than 9.0.

Primary and secondary treatments are well known and understood in the wastewater industry by utilities, engineering designers, plant operators, and regulators. It is understood that primary and secondary treatment are focused on BOD and suspended solids removal. Common definitions of primary and secondary treatment are as follows:

- **Primary Treatment:** The first stage of wastewater treatment that removes settleable and floating solids. Generally, primary treatment removes approximately 40 to 60 percent of the suspended solids and 30 to 40 percent of BOD.
- **Secondary Treatment:** The second stage of wastewater treatment used to convert dissolved and suspended pollutants into a form that can be removed, producing a highly treated effluent. Secondary treatment normally utilizes biological treatment processes, such as activated sludge or trickling filters, followed by settling in clarifiers to remove approximately 85 percent of the BOD and suspended solids in wastewater.

Only coincidental removal of nitrogen and phosphorus occurs in secondary treatment as a result of bacterial cell synthesis in the biological treatment process. Both nitrogen and phosphorus are needed for cell growth in the biological treatment process for the bacterial culture that is used to remove BOD. It is a common understanding in the wastewater industry that additional levels of treatment beyond secondary treatment are required for ammonia nitrification, and nitrogen and phosphorus removal. Table 1 summarizes various levels of wastewater treatment from a common wastewater technology reference.

Table 1. Levels of Wastewater Treatment from Metcalf and Eddy Table 1-4a

Treatment level	**Description**
Preliminary	Removal of wastewater constituents such as rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems
Primary	Removal of a portion of the suspended solids and organic matter fro the wastewater
Advanced primary	Enhanced removal of suspended solids and organic matter from the wastewater. Typically accomplished by chemical addition or filtration
Secondary	Removal of biodegradable organic matter (in solution or suspension) and suspended solids. Disinfection is also typically included in the definition of conventional secondary treatment
Secondary with nutrient removal	Removal of biodegradable organics, suspended solids, and nutrients (nitrogen, phosphorus, or both nitrogen and phosphorus)
Tertiary	Removal of residual suspended solids (after secondary treatment), usually by granular medium filtration of microscreens. Disinfection is also typically a part of tertiary treatment. Nutrient removal is often included in this definition
Advanced	Removal of dissolved and suspended materials remaining after normal biological treatment when required for various water reuse applications

[a] Source: Metcalf & Eddy Inc, George Tchobanoglous, Franklin L Burton, H David Stensel, "Wastewater Engineering, Treatment and Reuse," Fourth Edition, McGraw-Hill Professional, 2002 (Table 1-4 Adapted, in part, from Crites and Tchobanoglous (1998). (Crites, R., and G. Tchobanoglous (1998) Small and Decentralized Wastewater Management Systems, McGraw-Hill, New York.)

1.1. Nutrient Removal Requires Additional Treatment

Nutrient removal requires additional treatment facilities beyond secondary treatment that are commonly labeled as Advanced Treatment, Nutrient Removal, and Tertiary Treatment. These terms are used to describe the additional unit processes and biological treatment modifications required to accomplish nutrient removal. Secondary treatment processes do

not remove nutrients from wastewater, except for a small fraction of nitrogen and phosphorus required for biological growth. The additional facilities required for phosphorus and nitrogen removal are summarized in the following paragraphs; along with the further need for careful control of internal recycle loadings for effective nutrient removal.

1.1.1. Phosphorus Removal Treatment

Phosphorus removal in wastewater treatment can be accomplished biologically or chemically. Biological phosphorus removal requires an anaerobic zone in the activated sludge process to promote the growth of phosphorus accumulating organisms needed to accomplish a significant reduction in phosphorus. This process requires an easily degradable carbon source in the wastewater, or a supply from either fermentation of primary solids or chemical addition. Biological phosphorus removal facilities requirements include additional anaerobic zones in the activated sludge process, modified sludge return pumping and piping, aeration modifications, and production of a readily degradable carbon source, all of which are not included in secondary treatment plants.

Chemical phosphorus removal involves chemical addition (alum or ferric) to precipitate othro-phosphate and remove the phosphorus precipitants by either settling or filtration. Facilities requirements include chemical feed systems and effluent filters for lower levels of effluent phosphorus that are not included in secondary treatment plants. Additional solids handling capacity is also required since chemical treatment may generate 15 to 25 percent more solids than secondary treatment.

Effluent phosphorus in the range of 0.5 to 1 mg/l can be attained with biological phosphorus removal or chemical precipitation. Lower levels of effluent phosphorus require chemical addition and effluent filtration to reduce effluent phosphorus to the 0.2 to 0.5 mg/l range. Multiple stages of enhanced sedimentation, granular media filters, or membranes, with multiple chemical addition points, are needed to achieve the lowest levels of effluent phosphorus of approximately 0.1 mg/l.

1.1.2. Nitrogen Removal Treatment

Nitrogen removal in wastewater treatment can be accomplished biologically in the activated sludge process by nitrification and denitrification. Nitrification requires substantially larger treatment process tankage and aeration systems that may be 50 to 100 percent larger than that required for secondary treatment alone. Nitrification treatment processes are temperature dependant and cooler winter season wastewater temperatures require larger reactors to compensate for slower reaction kinetics in the biological treatment process.

Denitrification can be accomplished in the activated sludge process in simultaneous nitrification/denitrification reactors, or in subsequent process steps, including separate denitrification filters. In either approach, a supplemental source of readily available carbon is required to drive the biological process since secondary treatment depletes the carbon source available in the wastewater by BOD removal. Common external carbon sources include methanol, an industrial chemical that is fed to the liquid stream treatment

process. In addition to the biological reactor, storage facilities, pumping systems and controls are needed to carefully match process requirements for carbon and maintain effluent quality.

Effluent nitrogen of 6 to 10 mg/l can be attained in activated sludge nitrification/denitrification processes by adding more reactor volume and modifying the secondary treatment process to include multiple stages designed for nitrogen removal. Recycle pumping within the treatment process requires that 2 to 4 times the total plant flow be recirculated through multiple nitrogen removal stages. Facilities requirements for process pumping and piping, and aeration are all beyond those required for secondary treatment. Lower levels of effluent nitrogen in the range of 3 to 6 mg/l require larger reactors and additional treatment process stages to accomplish the reductions, along with a supplemental carbon source for denitrification. Operating costs for nitrogen removal are substantially higher than for secondary treatment due to the additional power costs for aeration and process pumping, and supplemental carbon sources.

1.1.3. Sidestream Recycle Treatment

Nutrient removal treatment results in the concentration of nitrogen and phosphorus in the solids stream where recycle returns from thickening and dewatering can impact overall plant performance. Recycle sidestream treatment facilities are required to mitigate the impact on liquid stream treatment, especially when meeting low effluent nutrient limits. High concentrations of ammonia nitrogen and phosphorus can consume substantial portions of plant capacity and cause process upsets. At a minimum, equalization is required to spread out recycle returns and dampen the impact on liquid stream treatment. Chemical precipitation and prenitrification facilities may be important to add to optimize liquid and solids stream treatment performance. These are facilities not included in secondary treatment plants that add to the capital and operating costs of nutrient removal facilities.

2. Effluent Technology Limits Do Not Assure Water Quality Improvements

Additional costs are always incurred with increased levels of treatment for nutrient removal. However, receiving water quality may not always improve with advanced treatment. Receiving water quality is controlled by a multiplicity of factors with complex interrelationships in the aquatic environment. Point source nutrient load reductions from wastewater treatment plants may, or may not, contribute to water quality improvements depending upon many factors. These factors include the magnitude of point sources compared to other loadings, the limiting nutrient controlling aquatic growth in receiving waters, decomposition of aquatic growth, and many receiving water characteristics related to the processing of nutrients (light penetration, scour, substrate stability, etc).

2.1. Nonpoint Sources Dominate Many Watersheds

In most waterbodies, point source wastewater discharges are only a part of the total nutrient loading to the watershed. According to EPA, most watersheds are impaired by a combination of point sources and nonpoint sources. Figure 1 shows that nationally, only a

small fraction of watersheds are impaired by point source discharges alone. Impairment in most watersheds is caused by a combination of point and nonpoint sources, or is dominated by nonpoint sources. Without nonpoint nutrient controls, technology based nutrient standards for wastewater discharges would have limited benefit for waterbodies nationally.

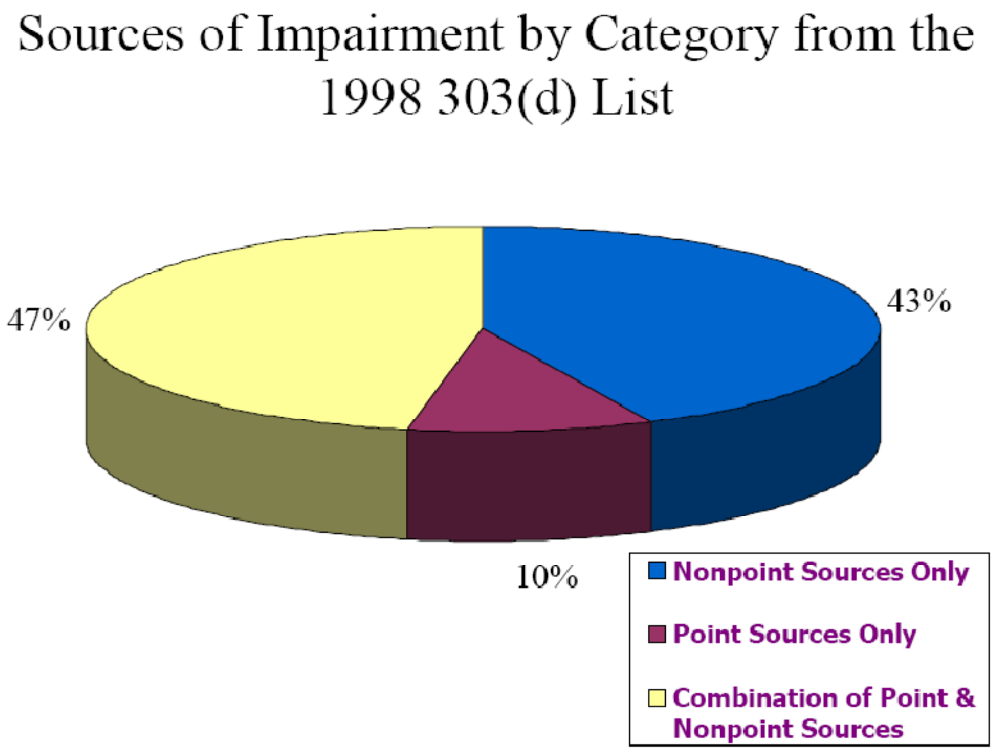

Figure 1. Sources of Water Quality Nationwide from EPA
(Source: Total Maximum Daily Load Program, EPA Region 4, January 2001)

In some watersheds, nonpoint source nutrient loadings outweigh point sources to a degree that advanced treatment for nutrient removal and even complete elimination of point sources by zero discharge would have limited effect on water quality. Nutrient loading summaries for the Gulf of Mexico, Chesapeake Bay, and Flathead Lake, Montana are presented in Figure 2 for phosphorus and Figure 3 for nitrogen. Point source phosphorus loadings in these three key watersheds range from as little as 2 percent in the Flathead Lake watershed, to 22 percent in Chesapeake Bay, and 34 percent in the Gulf of Mexico. Point source nitrogen loadings range from as little as 2 percent in the Flathead Lake watershed, to 20 percent in Chesapeake Bay, and 22 percent in the Gulf of Mexico.

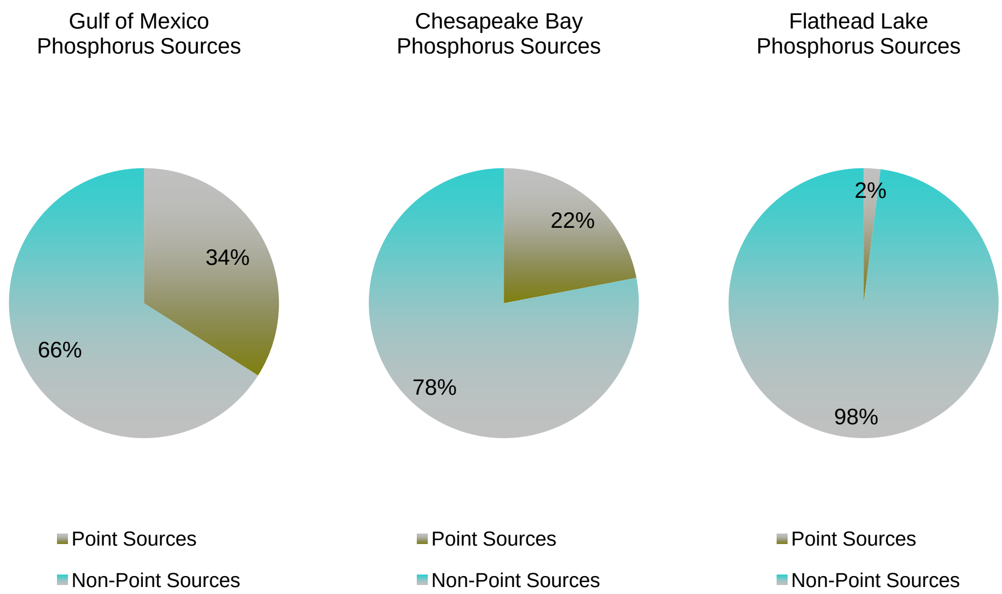

Figure 2. Phosphorus Loading Summaries for Gulf of Mexico, Chesapeake Bay, and Flathead Lake

(Sources: Gulf of Mexico Hypoxia 2008 Action Plan, Chesapeake Bay Program Action Plan, Montana Department of Environmental Quality, Draft Nutrient Management Plan and Total Maximum Daily Load for Flathead Lake, Montana)

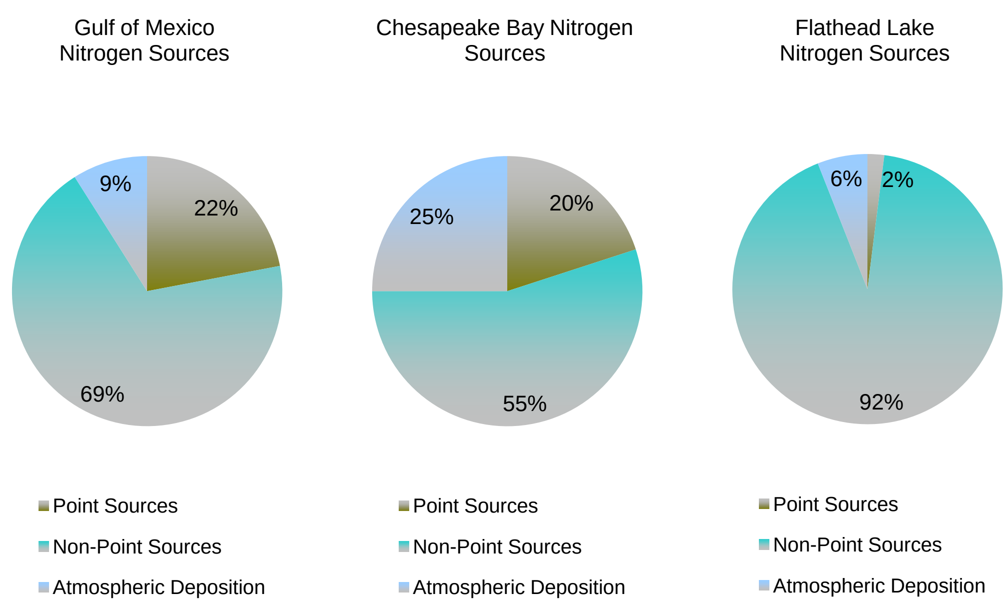

Figure 3. Nitrogen Loading Summaries for Gulf of Mexico, Chesapeake Bay, and Flathead Lake

(Sources: Gulf of Mexico Hypoxia 2008 Action Plan, Chesapeake Bay Program Action Plan, Montana Department of Environmental Quality, Draft Nutrient Management Plan and Total Maximum Daily Load for Flathead Lake, Montana)

Water quality conditions in these watersheds are complex and careful consideration of site specific conditions is required to determine how best to manage nutrient loadings in a manner that is economical and technically feasible. Application of wastewater treatment technology alone will have limited potential to provide water quality benefits if nonpoint sources are not controlled. Nonpoint source control of phosphorus and nitrogen loadings has great potential for substantial reduction of nutrient loadings in these watersheds. Treatment technology standards for nutrients would not necessarily improve water quality and would not reduce nonpoint source loadings.

2.2. Site Specific Considerations are Needed for Appropriate Nutrient Control

Although complex, site specific considerations are required to determine whether limitations on nutrients will provide water quality benefits and to what extent those limits will be associated with water quality improvements. The total maximum daily load (TMDL) process is used to establish water quality based limits for point source discharges through wasteload allocations and load allocations for nonpoint sources. This process provides the opportunity to balance nutrient management considerations and highlights many of the challenges that are involved in doing so.

2.2.1. Variability in In-stream Nutrient Concentrations

Water quality conditions vary widely in watersheds and there are a broad range of nutrient conditions that represent water quality adequate to support beneficial uses. This makes selection of a uniform technology standard for nutrient treatment inappropriate due to the high degree of variability in the water environment. EPA has conducted data analysis of waterbodies in an attempt to provide reference conditions for nutrients. The concept of ecological regions, or ecoregions, is the grouping of areas of similar climate, hydrology, geology, physiography, soils, land use, vegetation, and wildlife. There are four levels of ecoregions with Level I being the coarsest and Level IV the most detailed. Level I has 14 ecoregions in the continental United States while Level III has 104, as shown in Figure 4.

The EPA has established 25th percentile statistics for total phosphorus and total nitrogen for Level I ecoregions for rivers and streams, lakes and reservoirs, and wetlands in these ecoregions. "The nutrient criteria presented by EPA for each ecoregion are generally based on the 25th percentile value of all data from the respective ecoregion. The 25th percentile value corresponds to the concentration at which 25 percent of the measured values are below and 75 percent of the measured values are above" (EPA, 2000). A summary of the rivers and streams criteria are shown in Table 2. Although NACWA does not concur with the direct application ecoregion statistics for water quality standards, these values nevertheless demonstrate the variability in nutrient levels across the country.

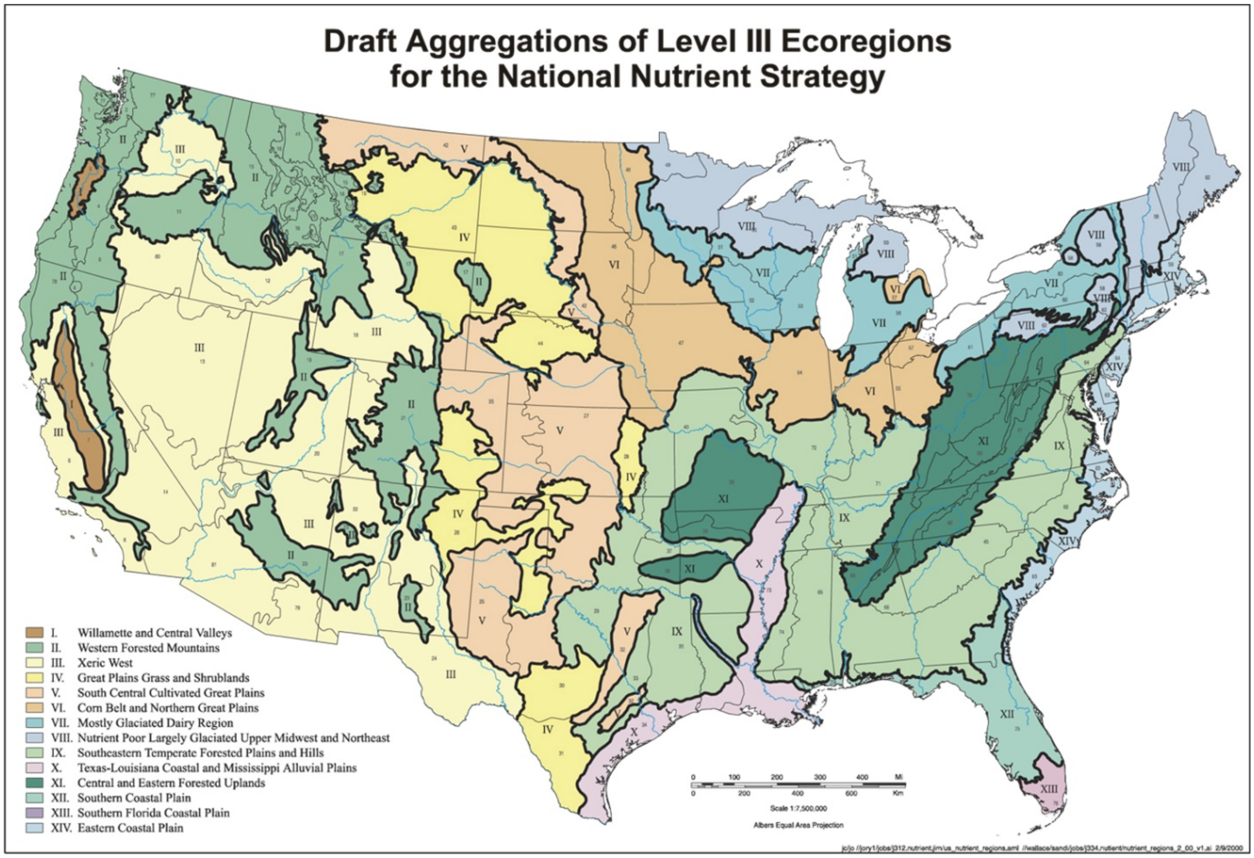

Figure 4. EPA Level III Ecoregions

Table 2. Summary of EPA Ecoregion 25th Percentile Statistics for Rivers and Streams

Ecoregion	*TN (mg/l)*	TP (mg/l)
I: Willamette and Central Valley	0.66	0.055
II: Western Forested Mountains	0.12	0.010
III: Xeric West	0.38	0.022
IV: Great Plains Grass and Shrublands	0.56	0.023
V: South Central Cultivated Great Plains	0.88	0.067
VI: Corn Belt and Northern Great Plains	2.18	0.076
VII: Mostly Glaciated Dairy Region	0.54	0.033
VIII: Nutrient-Poor, Largely Glaciated Upper Midwest and Northeast	0.38	0.010
IX: Southeastern Temperature Forested Plains and Hills	0.69	0.037

Ecoregion	*TN (mg/l)*	TP (mg/l)
XI: The Central and Eastern Forested Uplands	0.31	0.010
XII: Southeastern Coastal Plain	0.90	0.040
XIII: Southern Florida Coastal Plain	1.14	0.015
XIV: Eastern Coastal Plain	0.71	0.031

The ecoregion nitrogen and phosphorus concentrations presented in Table 2 illustrate the high degree of variability in nutrient conditions for in-stream water quality. Depending upon the location of the watershed, ecoregion statistics for nitrogen could vary by a factor of 18 times and range from a low of 0.12 mg/l to a high of 2.18 mg/l. Similarly, phosphorus conditions could vary by a factor of more than 7 times and range from a low of 0.010 mg/l to a high of 0.076 mg/l.

Ecoregion statistics represent in-stream conditions and are not effluent limits. Developing effluent limits requires consideration of ambient water quality conditions in the receiving water and the relative loading from all sources impacting the watershed. For these reasons, effluent limits may vary even within the same ecoregion with the same in-stream values. Selection of a uniform treatment technology standard for nutrients is inappropriate for water quality management across the country. Selection of a very restrictive low concentration treatment technology standard appropriate for the most sensitive watersheds would overly restrict surface water discharges in much other area and be inordinately expensive without commensurate water quality benefits.   Further, overly restrictive standards may have detrimental consequences in terms of secondary environmental impacts (energy use, chemical use, green house gas emissions) and may skew development patterns in a way that increases nonpoint source loadings.

2.2.2. Watershed Variability Defies Uniformity in Technology Limits

Beyond the variability in targeted water quality conditions across the nation, the nutrient limiting aquatic grow varies from watershed to watershed. Not all water bodies require control of both nitrogen and phosphorus to prevent adverse water quality impacts. In fact, some waterbodies are impaired only by nitrogen, or only by phosphorus. This makes selection of a uniform treatment technology standard for nitrogen and phosphorus treatment impractical since it may be unnecessary to control one, or the other, depending upon the site specific watershed conditions.

2.2.2.1. Nitrogen and Phosphorus Limitation

A limiting nutrient is a chemical necessary for plant growth, but it is available in lesser quantities than needed for cellular growth. Once a limiting nutrient in a waterbody is exhausted, the population of the organism dependent on availability of the nutrient stops growing. If more of the limiting nutrient is added, greater populations will result until their growth is again limited by nutrients or by other limiting environmental factors, such as temperature or lack of sunlight.

Elevated nutrient concentrations can contribute to eutrophication. Either nitrogen or phosphorus may be the limiting factor for algal growth, depending on algal species. Which nutrient limits the growth of phytoplankton is not necessarily specific to the element in least abundance. Aquatic organisms require nutrients to be present in certain relative quantities or ratios. A high availability of phosphorus does not always indicate continued production because the system may become nitrogen limited. Estuarine systems tend to be nitrogen limited and fresh waters are phosphorus limited. Recently some researchers report that freshwater systems can be co-limited.

2.2.2.2. Redfield Ratio

In 1958 Alfred Redfield published his research that marine plankton consist of carbon (C), nitrogen (N), and phosphorus (P) in a characteristic molar ratio and that the occurrence of C, N, and P is influenced by the corresponding interactions between marine organisms and the ocean environment. Redfield stated, "The environment not only determines the conditions under which life exists, but the organisms influence the conditions prevailing in the environment." The unchanging stoichiometry of C, N, and P in the ocean led to understanding of nutrient limitation of marine net primary production and ocean carbon cycling.

Refuting the ratio theory, Wang et al argue that the TN:TP ratio is inappropriate as an index to identify limiting nutrients and contend that it is almost impossible to specify a 'cut-off' TN:TP ratio to identify a limiting nutrient for a multi-species community because optimal N:P ratios vary greatly among phytoplankton species.

Early stoichiometric analysis of nutrient limitation compared relative availability of elements in world rivers against nutrient ratios found in algal biomass (16:1 being the Redfield ratio) and found that P is likely to be the limiting nutrient. Lewis and Wurtsbaugh make the argument that that analysis is not appropriate because it does not take into account 'assimilable' (readily available for uptake) fractions of the nutrients. This point is illustrated with the example of iron, which is abundant and in more favorable ratios than P, but since it is relatively insoluble in water, it has been shown to be a limiting nutrient in marine waters. Lewis and Wurtsbaugh proposed that the P limitation paradigm would show a tighter correlation between P and Chlorophyll a (Chla) than between N and Chla. However, after studying previously published datasets and performing statistical analysis, Lewis and Wurtsbaugh found that when nutrient assimilability is taken into account N and P are shown to have an equal degree of control on algal biomass, even when the required nutrient ratio of the biomass is set to 16:1.

2.2.2.3. Phosphorus Limitation

Phosphorus is an essential mineral nutrient for all life forms and is generally the limiting nutrient in freshwater systems. Lakes and reservoir sediments serve as phosphorus sinks. Phosphorus-containing particles settle and are covered by sediment. Continuous accumulation of sediment will leave some phosphorus too deep within the substrate to be reintroduced into the water column.

A fraction of the phosphorus in the bottom sediment may be reintroduced to the water column. Phosphorus stored in the uppermost layers of the bottom sediments of lakes and reservoirs is subject to bioturbation by benthic invertebrates and chemical transformations by water chemistry changes. For example, the reducing conditions of a hypolimnion often experienced during the summer months may stimulate the release of phosphorus from the benthos. Recycling of phosphorus often stimulates blooms of phytoplankton. As a result of this phenomenon, a reduction in phosphorus loading may not be effective in reducing algal blooms for a number of years.

As Correll states, phosphorus plays a unique and important role in the eutrophication of receiving waters, especially lakes, reservoirs, streams, and the upper reaches of estuaries. Although N and C can be obtained from the atmosphere, P is transported primarily by surface waters. In most aquatic ecosystems, P is naturally present in more limiting amounts than the other essential elements. Human activities often result in large fluxes of P to receiving waters. Because P tends to be retained efficiently in these aquatic systems, this leads to higher primary production, especially in the summer and fall. High primary production, in turn, leads to high rates of decomposition and depletion of dissolved oxygen in bottom waters and in surface waters at night in calm weather. These eutrophic conditions can result in fish kills and major shifts in the species composition at all trophic levels. Lake primary production can be accurately predicted from data on input fluxes of P, but research and data synthesis are needed to establish reasonable standards for total P concentration in various types of receiving waters.

Correll contends that when receiving waters have limiting amounts of P, the phytoplankton biomass has N:P atomic ratios significantly above the Redfield ratio of 15 to 16. When N is limiting, the Redfield ratio is much lower. If one needs to assess the P status of receiving water based only on P concentrations in the water column, it is better to measure the sum of dissolved and particulate total P than to rely on dissolved orthophosphate concentrations.

2.2.2.4. Nitrogen Limitation

Howarth and Marino describe the turn in thinking that all waterbodies are phosphorus limited and that many marine ecosystems are N limited. They report that the first special volume of Limnology and Oceanography, published in 1972, focused on whether phosphorus or carbon was the major agent causing eutrophication in aquatic ecosystems. Only slight mention was made that estuaries may behave differently from lakes and that nitrogen may cause eutrophication in estuaries.

Howarth and Marino continue that an understanding of eutrophication in estuaries proceeded in relative isolation from the community of scientists studying lakes. National water quality policy in the United States was directed almost solely toward P control for both lakes and estuaries, and similarly, European nations tended to focus on P control in lakes. Although bioassay data indicated N control of eutrophication in estuaries as early as the 1970s, this body of knowledge was treated with skepticism by many freshwater scientists and water-quality managers, because bioassay data in lakes often did not properly indicate the importance of P relative to C in those ecosystems. Hence, the

bioassay data in estuaries had little influence on water-quality management. Over the past two decades, a strong consensus has evolved among the scientific community that N is the primary cause of eutrophication in many coastal ecosystems. The development of this consensus was based in part on data from whole-ecosystem studies and on a growing body of evidence that presented convincing mechanistic reasons why the controls of eutrophication in lakes and coastal marine ecosystems may differ. Even though N is probably the major cause of eutrophication in most coastal systems in the temperate zone, optimal management of coastal eutrophication suggests controlling both N and P, in part because P can limit primary production in some systems.

Maberly et al., 2002 found that contrary to the assumption that upland lakes tend to be phosphorus limited, the phytoplankton and epilithon of many sites show a growth response to N additions as well as P additions in bioassays. Of the 30 lakes studies, about one-third were N limited and one third we co-limited by N and P. Further researched showed evidence of N limitation or co-limitation in upland sites in the United Kingdom.

2.2.2.5. Phosphorus and Nitrogen Co-Limitation

Sterner reports that often lakes are said to be primarily phosphorus limited, but this paradigm has been described in numerous ways and there is considerable evidence that algae in lakes are often limited by other elements. Crucial whole-ecosystem experiments that support the paradigm of the primacy of P limitation are few in number and have been limited to naturally oligotrophic lakes.

A large amount of observational and experimental data seems to contradict the phosphorus limitation paradigm and instead indicates that most lakes are co-limited by N and P as well as, perhaps, by iron (Fe) and other nutrients. The biogeochemical theory behind the phosphorus limitation paradigm is that mechanisms can supplement cycles of C and N (and, discussed here, perhaps Fe) so that ultimately it is P that limits production and biomass. However, no mechanism has been proposed for ecosystems to overshoot this endpoint. So, the occurrence of co-limitation by P, N and other nutrients over short, but still ecologically meaningful time scales that influence, might occur in lakes. One point of view has been that small-scale experimentation is simply misleading. However, an alternative is that even if P is ultimately limiting over multi-annual time scales, over shorter but still meaningful time scales, co-limitation of multiple nutrients is expected, and indeed is very common.

In another study, Maberly et al. reported that lake water chemistry is strongly affected by the land cover in the watershed. Vegetation is well known to alter soil properties and this in turn may influence stream and ultimately lake chemistry. Maberly et al. found relationships between watershed characteristics and lake water chemistry, phytoplankton and periphyton biomass, and phytoplankton and periphyton nutrient limitation for 30 upland lakes in the United Kingdom. These watershed characteristics included the proportion of different land cover categories in the watershed and some hydrological information. Multiple regression models could predict alkalinity, pH, total dissolved phosphorus, dissolved inorganic nitrogen, dissolved organic nitrogen, dissolved organic carbon and phytoplankton chlorophyll a from the proportional contribution of between

two and six land cover categories within the watershed and explain between 42 and 73 percent of the variance. Phosphorus limitation was positively linked to the proportion of shrub-heath and bracken in the watershed, and negatively linked to the proportion of pasture. Nitrogen limitation was positively linked to the proportion of marsh and rough grass, deciduous and mixed woodland, and negatively linked to the proportion of rough pasture, shrub heath and bare ground in the watershed. Nitrogen limitation decreased and phosphorus limitation increased with watershed slope, although the correlation between land cover classes and slope was not significant. The results suggest that map-based data can be used to predict water chemistry and nutrient limitation in upland lakes.

2.2.2.6. Co-limitation in Lakes

Lewis and Wurtsbaugh investigated the conventional wisdom that lakes are generally naturally phosphorus limited and proposed a new paradigm in which lakes are generally considered to be either N and P co-limited, or reciprocally limited (growth stimulated by the addition of either N or P). According to Lewis and Wurtsbaugh: "Control of phytoplankton in lakes by phosphorus is one of the oldest and most stable paradigms in modern limnology." However, through this lens, Lewis and Wurtsbaugh assert that that data that would contradict this paradigm may have been ignored or downplayed. This attitude and the weight of accumulated studies, has led to a belief in the P paradigm that is much stronger than the data actually support.

Lewis and Wurtsbaugh concluded that phytoplankton biomass growth is as likely to be limited by N as P, even in oligotrophic lakes, and despite a possible community dominance of N-fixers. Therefore Lewis and Wurtsbaugh assert that the paradigm should shift from P limitation to a co-limitation control paradigm of P and N for nutrient limitation.

Lewis and Wurtsbaugh acknowledge that anthropogenically enriched lakes receiving N:P biased discharges can push the algal community to either an N limited state, or a P limited state. Since domestic waterwater and animal waste usually have a low N:P ratio, lakes may be unnaturally pushed into P limitation. In terms of lake management, the Lewis and Wurtsbaugh conclude with this statement:

> *"Even so, the key management principle for control of eutrophication in individual lakes remains the same as it was under the phosphorus paradigm: the most promising management tool for control of phytoplankton growth in most situations is restriction of phosphorus supply"*

2.2.3. Limiting Nutrients in Reference Watersheds

In Table 3 and the discussion that follows, nitrogen and phosphorus limitations are identified for some key waterbodies across the country for which detailed studies, watershed management plans, or total maximum daily loads have been prepared. The list of reference waterbodies presented is not comprehensive, but does illustrate the complexity of watersheds and provide some representation geographically of both marine waters and freshwater. There is great variation between the estuaries and rivers presented here, with some marine waters being nitrogen limited, while others are limited by both nitrogen and

phosphorus. Some of the rivers are phosphorus limited, but others have been found to be limited by both nitrogen and phosphorus.

The lack of uniformity in waterbodies highlights the need for careful consideration of site specific water quality conditions and the selection of management efforts to protect water quality, including the appropriate wastewater treatment requirements. A uniform technology based wastewater treatment standard would not be generally applicable to all waterbodies, nor would it necessarily be set at a level that would be protective. It may be unnecessary to control nitrogen or phosphorus discharges in some waterbodies.

2.2.3.1. Chesapeake Bay

Chesapeake Bay has long been recognized as limited by both nitrogen and phosphorus. Figure 5 illustrates the complex relationships between nutrient limitations, season, light availability, and location in the estuary. Upstream freshwater segments of Chesapeake Bay tend to be phosphorus limited during spring runoff conditions (March through June). More saline waters, closer to the Atlantic Ocean, tend to be nitrogen limited. The more turbid upstream freshwater component tends to be light-limited for longer periods of time than the waters closer to the ocean. (Fisher et al., 1992; Harding et al., 2002). Further downstream, light limitation plays a less important role.

Table 3. Variations in Waterbody Nutrient Limitations

Waterbody	*Limiting Nutrient*	Watershed Characteristics
Estuaries		
Chesapeake Bay	Nitrogen and Phosphorus	Marine waters
Gulf Mexico	Nitrogen (with Phosphorus limiting in Mississippi Delta)	Marine waters
Long Island Sound	Nitrogen	Marine waters
Neuse River Estuary	Nitrogen (with Phosphorus limiting upstream)	Marine waters
Puget Sound	Nitrogen	Marine waters
Rivers		
Clark Fork River	Nitrogen and Phosphorus	Freshwater Ecoregion II Western Forested Mountains (snowmelt dominated, regulated, ~1,000 cfs+, high elevations, mostly forested land use)
Snake River – Hells Canyon	Phosphorus	Freshwater Ecoregion III Xeric West (arid, snowmelt dominated, regulated, ~5,000 cfs+, agriculture, forest, mining, and urban land uses)
Spokane River	Phosphorus	Freshwater Ecoregion II Western Forested Mountains (~400 cfs+, regulated, forest, urban, and agriculture land use)
Truckee River	Nitrogen and Phosphorus	Freshwater Ecoregion III Xeric West
Wenatchee River	Phosphorus	Freshwater Ecoregion II Western Forested Mountains (~400 cfs+, snowmelt dominated, mostly forested land use)

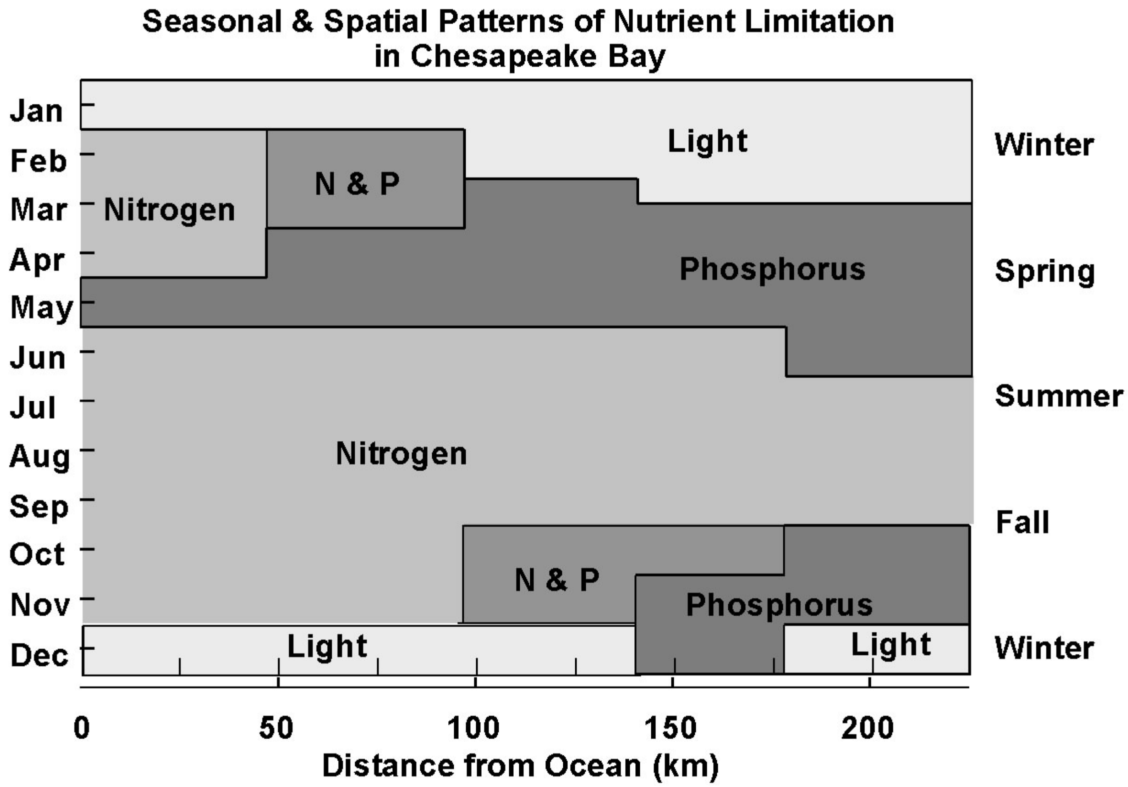

Figure 5. Nutrient Limitations in Chesapeake Bay
(Source: Presentation by Hans Pearl)

2.2.3.2. Gulf of Mexico

Nitrogen loadings are primarily responsible for the areal extent of hypoxia and a dead zone in the Gulf of Mexico (NRC, 2008). However, under high discharge conditions, the nitrogen loading is much higher than the phosphorus loading from the watershed and phosphorus may limit phytoplankton production close to the Mississippi delta. Work by Dr. R. Eugene Turner and Dr. Nancy Rabalais and peers based on collecting large amounts of data to determine nutrient loadings from the watershed, nutrient recycling from the sediment, and the associated growth of phytoplankton and the size of the hypoxic dead zone have provided a greater understanding of water quality in the Gulf of Mexico (Turner et. al., 2005a, 2005b, 2008. and Rabalais et. al. 2001). Key points are as follows:

- *"Phosphorus limitation is now occurring because over the past 50 years excessive N loadings have dramatically altered nitrogen to phosphorus ratios. Taken together, N and P both contribute to excess phytoplankton production and the hypoxia associated with such production, and they will need to be reduced concurrently to make progress in reducing the size of the hypoxic zone."*

- *"While it is likely that N limitation characterizes coastal shelf and offshore waters, more recent nutrient addition bioassays and examinations of nutrient stoichiometric ratios have shown that river plume influenced inshore productivity appears to be more P limited, especially during periods of highest productivity and phytoplankton biomass formation (Feb-May) (EPA, 2007)"*

2.2.3.3. Long Island Sound, Connecticut and New York

Long Island Sound is nitrogen limited with low dissolved oxygen concentrations in the western portion of Long Island Sound during the summer. Research conducted for the Long Island Sound Study (LISS) suggest that phytoplankton in Long Island Sound are nitrogen limited (NYSDEC and CTDEP 2000). The entire State of Connecticut is within the Long Island Sound watershed (USEPA, 2003) and wastewater facilities in Connecticut and New York are a dominant source of nitrogen. Connecticut and New York have formalized a nitrogen reduction program in a TMDL approved by EPA in April 2001. Through the Long Island Sound Study, a 2014 goal of 58.5 percent nitrogen reduction from baseline has been established for Connecticut and New York.

2.2.3.4. Neuse River Estuary, North Carolina

Eutrophication of the Neuse River Estuary from point and non-point source nutrient (specifically nitrogen) loading (Stanley et al. 1999) has stimulated phytoplankton productivity and impaired water quality. In response, the State of North Carolina established the goal of reducing total nitrogen (N) loads to the Estuary by 30 percent. Although now there is evidence that the Neuse River Estuary is co-limited in some locations along its length (Arhonditsis et. al., 2007) with phosphorus limited upstream and nitrogen limited downstream.

2.2.3.5. Puget Sound, Washington

Puget Sound marine waters are considered to be nitrogen limited (Environ, 2008). The Hood Canal Dissolved Oxygen Program Integrated Assessment and Modeling Study included the following, "Curl and Paulson (1991) noted that low oxygen concentrations in Lynch Cove appeared to be getting worse and posited that anthropogenic sources of nitrogen may be a factor. Newton et al. (1995) established that nitrogen limited phytoplankton growth" (Ecology, 2005). A Washington Department of Transportation study concluded that "Sound waters tend to be nitrogen limited; the N:P ratio of dissolved inorganic nitrogen (NO3+NO2+NH4) to PO4 has been repeatedly identified to be 16:1. This indicates that the addition of available nitrogen forms, particularly NO3 and NH4, would likely increase algal growth until another factor, such as phosphorous, light, or oxygen, became limiting" (WSDOT, 1999).

2.2.3.6. Clark Fork River, Montana

Nitrogen and phosphorus are considered co-limiting on the Clark Fork River in western Montana where excess algal growth impairs beneficial uses. A voluntary nutrient management plan was developed in the late 1990's as the functional equivalent of a TMDL to reduce nitrogen and phosphorus loadings. The Clark Fork River Voluntary Nutrient Reduction Program (Tri-State, 1998) referred to "using three approaches (regression, probabilistic and reference reaches) to predict in-stream concentrations for improved water quality, Dodds and Smith evaluated a range of targets for total nitrogen and phosphorus" (p.11). The Clark Fork/Pend Oreille Sub-basin Assessment and TMDL (DEQ, 2001) includes "According to Falter's review of data and literature, the fact that the Clark Fork River is often nitrogen limited…" (Appendix D).

2.2.3.7. Snake River, Idaho and Oregon

The Snake River eastern Oregon/western Idaho is phosphorus limited and a TMDL has been prepared to reduce phosphorus loadings. The Snake River – Hells Canyon TMDL (IDEQ, 2004) indicated that "the N:P ratios are substantially above the threshold value of ten, and are also above the range (7 to 15) where nitrogen and phosphorus have been observed to act as co-limiting agents" (p.284). Impairments include bacteria, dissolved oxygen, nutrients, pH, and sediment.

2.2.3.8. Spokane River, Washington and Idaho

The mainstem of the Spokane River in eastern Washington is phosphorus limited and management plans are focused on phosphorus removal, at or beyond the limits of treatment technology. The draft Spokane River and Lake Spokane Dissolved Oxygen TMDL (Ecology, 2008) indicates that dissolved oxygen is affected by nutrients and limits for ammonia, total phosphorus and CBOD are necessary, with phosphorus having the greatest effect on dissolved oxygen levels (p. v).

Upper reaches of the river may be nitrogen limited but are relevant to the consideration of wastewater treatment requirements since there are no discharges into these areas. Welch stated the following "Nitrogen was clearly the limiting nutrient in the upper Spokane River, Washington" (Welch et al. 1989). Falter stated "the Spokane River is basically a P-limited system in the spring and fall. In August, however, the Spokane appears to be N-limited upstream from RM 108 to lake outlet" (IDHW, 1982).

2.2.3.9. Truckee River, Nevada

The Truckee River may appear to be nitrogen limited, but phosphorus control may be most important to protecting water quality. "The values observed in the Truckee River itself are therefore indicative of nitrogen limitation, except in a very few instances" (TMWRF, 2007). While the Truckee River is nitrogen limited as determined by the N:P ratio, geologic conditions, and olgiotrophic source waters (Lake Tahoe), water quality conditions may still be driven by phosphorus. "The inorganic N:P rations in summer are suggestive of strong nitrogen limitation for plant growth or biomass in the study area and especially downstream. But because nitrogen-fixing periphytic organisms can utilize atmospheric nitrogen, a more certain way to limit periphyton and other plant metabolism downstream is to limit the phosphorus supply" (TMWRF, 2007).

2.2.3.10. Wenatchee River, Washington

The Wenatchee River in eastern Washington is phosphorus limited and a TMDL has been prepared to reduce phosphorus loadings. The Wenatchee River Basin Dissolved Oxygen, pH, and Phosphorus TMDL states "In general, the N:P ratio is above 7 in the river at all times, indicating phosphorus limitation" (Ecology, 2006. p.43). The Wenatchee River and Icicle Creek are identified as impaired because of low dissolved oxygen and high pH.

3. Significant Costs of Nutrient Removal

Nutrient removal requires additional treatment facilities beyond secondary treatment, which results in increases in both capital and operating costs. Costs for treatment plant retrofits for nutrient removal are highly dependent upon existing infrastructure and the extent to which facilities modifications are required to meet effluent nitrogen and phosphorus limits. For these reasons, it is difficult to generalize about the costs for modifications required for nutrient removal in a manner applicable across the country. Review of the cost data in this section shows a wide range of costs for both retrofit facilities and new plants.

Nutrient removal also requires additional energy, chemicals, maintenance materials, and labor which increase operations and maintenance costs. When chemicals are added for nutrient removal, additional solids must be processed in the treatment plant and managed in biosolids utilization or disposal programs. Increases in solids loadings also increase capital, operating, and disposal costs for wastewater treatment.

EPA has recently undertaken a study of nutrient removal treatment plants and presented a detailed cost study of those facilities. This provides a broad survey of relatively recent nutrient removal costs at various effluent levels. The discussion that follows provides a brief summary of the EPA findings and a comparison with actual costs at a few reference facilities. The discussion of costs in this section closes with a summary of the range of unit costs for advanced treatment in dollars per pound of nitrogen or phosphorus removed for comparison with nonpoint source best management practice costs.

3.1. EPA Municipal Nutrient Removal Technologies Reference Document

EPA has recently published a Municipal Nutrient Removal Technologies Reference Document (September 2008) evaluating the performance and costs of facilities removing nitrogen and phosphorus. EPA examined effluent nitrogen and phosphorus performance at 29 full scale treatment plants in the United States and one in Canada. Detailed process information and costs were analyzed for more than 40 different treatment technologies for removing nitrogen and phosphorus from municipal wastewater. Nine facilities were studied in depth with case studies presented in an appendix. The case studies used performance data from a one year period to identify the factors influencing performance, reliability, and costs.

Table 4 provides a summary of the EPA Reference Document findings for the costs of treatment facility retrofits for nutrient removal. The EPA study cites capital costs of $0.20 to $5.20 for retrofit technologies for effluent nitrogen in a range from 5.1 mg/l down to approximately 1 mg/l. Retrofit costs cited for phosphorus ranged from 0.18 to $0.47 for effluent phosphorus in a range from 0.5 mg/l down to approximately 0.1 mg/l. Costs of $0.75 to $3.25 per gpd are cited for plants removing nitrogen and phosphorus with nitrogen down to 3 mg/l and phosphorus of 0.1 mg/l.

Table 4. EPA Reference Document Cost Estimates for Retrofit Technologies for 10 mgd[a]

Target concentration (annual average)	*Initial concentration (annual average)*	*Technologies (conversion or add-on indicated by footnote)*	*Location*	*Flow rate (MGD)*	*Capital $/gpd capacity*	*O&M $/MG treated*	Life-cycle $/MG treated
Total N target only							
TN, 5.1 mg/L	9.6 mg/L TN	Cyclic on/off aeration[a]	Ridgefield, CT	1	$0.20	$111	---
TN, 5.0 mg/L	7 mg/L TN	Denitrification filter[b]	Cheshire, CT	3.5	$1.65	$136	---
TN, 3 mg/L or less	8 mg/L TN	MLE-)4-stage Bardenpho[a]	Seneca, MD	20	$0.21	$63	---
	8 mg/L TN	MLE-)4-stage Bardenpho[a]	Freedom, MD	3.5	$0.99	---	---
	8 mg/L TN	MLE-)4-stage Bardenpho[a]	Cumber- land, MD	15	$1.10	$122	---
	15 mg/L TN	Lagoon-)4- stage Bardenpho[a]	Hurlock, MD	1.5	$4.12	---	---
	8 mg/L TN	Denitrification filter[b]	Baltimore, MD	180	$1.39	---	---
	8 mg/L TN	Denitrification filter[b]	Cox Creek, MD	15	$1.74	$104	---
	6.5 mg/L TN	5-stage Bardenpho + denitrification filter[b]	Frederick, MD	7	$1.41	---	---
	40 mg/L TN[d]	Phased oxidation ditch[a]	CW	10	$0.47	$44	$157
	40 mg/L TN[d]	MLE retrofit[a]	CW	10	$0.71	$82	$164
	40 mg/L TN[d]	Step-feed retrofit[a]	CW	10	$0.65	$91	$245
	40 mg/L TN[d]	Denitrification filter[b]	CW	10	$0.71	$156	$324
TN, 1 mg/L	42 mg/L TN[e]	5-stage Bardenpho with MBR and reverse osmosis[b]	Las Virgenes, Calabasas, CA	16	$5.20	---	---
Total P Target Only							

Target concentration (annual average)	*Initial concentration (annual average)*	*Technologies (conversion or add-on indicated by footnote)*	*Location*	*Flow rate (MGD)*	*Capital $/gpd capacity*	*O&M $/MG treated*	Life-cycle $/MG treated
TP, 0.5 mg/L	5 mg/L TP	Fermenter retrofit, no filter[b]	CW	10	$0.18	$7	$50
	5 mg/L TP	1-point chemical addition, no filter[b]	CW	10	$0.03	$91	$98
	5 mg/L TP	Fermenter + sand filter retrofit[b]	CW	10	$0.44	$25	$130
TP,	5 mg/L TP	Fermenter + sand filter + 1-point chemical addition[b]	CW	10	$0.47	$106	$218
0.1 mg/L	5 mg/L TP	2-point chemical addition + filter[b]	CW	10	$0.29	$215	$283
			Ammonia-N + TP limits				
Ammonia- N+TP, 1.5 mg/L & 1 mg/L	37 mg/L Ammonia-N, 10 mg/L TP	Cyclic on/off aeration[a] for ammonia-N	Broomfield , CO	8	$1.00	---	---
Ammonia- N+TP, 1.5 mg/L & 1 mg/L	37 mg/L Ammonia-N, 10 mg/L TP	IFAS[a] for ammonia-N	Broomfield , CO	8	$0.85	---	---
Ammonia- N+TP, 1.5 mg/L & 1 mg/L	37 mg/L Ammonia-N, 10 mg/L TP	MBBR[b] for nitrification/ den itrification	Broomfield , CO	8	$1.70	---	---
Ammonia- N+TP, 1.4 mg/L & 1 mg/L	24 mg/L Ammonia-N, 4 mg/L TP	Modified UCT with fermenter and sand filter[c]	Kalispell, MT, case study	3	$3.03	$108	---
Ammonia- N+TP, 1 mg/L & 0.18 mg/L	18.9 mg/L Ammonia-N, 6.4 mg/L TP	Step-feed AS with dual-media and deep-bed filter ~ 1-point chemical	Fairfax, VA, case study	67	$1.07	$106	---
Ammonia- N+TP, 0.6 mg/L & 0.2 mg/L	27 mg/L Ammonia-N, 5.8 mg/L TP	A/O with VFA and dual media filters and chemi- cal addition[a]	Clark Co., NV, case study	100	$2.01	$183	---
			TN+TP limits				
TN+TP, 6 mg/L & 0.25 mg/L	28.8 mg/L TN, 6 mg/L TP	3-stage Westbank with fermenters[a]	Kelowna, BC, case study	10.5	$3.25	$77	---
TN+TP, 3.9 mg/L & 2 mg/L	56 mg/L TN, 7.7 mg/L TP	Oxidation ditch with sand filtera	North Cary, NC, case study	12	$2.84	$60	---
TN+TP, 3.7 mg/L & 1 mg/L	31.2 mg/L TN, 5.8 mg/L TP	Plug flow AS with denitrification filterc	Central Johnston Co., NC case study	7	$0.58	$221	---
TN+TP, 3 mg/L & 1 mg/L	24 mg/L TN, 3.7 mg/L TP	3-stage activated sludge with chemical additionb	Western Branch, MD, case study	30	$1.73	$165	---

Target concentration (annual average)	*Initial concentration (annual average)*	*Technologies (conversion or add-on indicated by footnote)*	*Location*	*Flow rate (MGD)*	*Capital $/gpd capacity*	*O&M $/MG treated*	Life-cycle $/MG treated
TN+TP, 3 mg/L & 1 mg/L	28 mg/L TN, 5 mg/L TP	5-stage Bardenpho with sand filter + chemical additiona	Clearwater , FL (Marshall Street) case study	10	$2.95	$242	---
TN+TP, 3 mg/L & 0.5 mg/L	33.2 mg/L TN, 3.8 mg/L TP	Denitrification filter + chemical additionb	Lee Co., FL (Fiesta Village) case study	5	$2.79	$265	---
TN+TP, 3 mg/L & 0.1 mg/L	40 mg/L TN, 5 mg/L TP	PID retrofit with 1-point chemical addition, clarifier, and filtera	CW	10	$0.89	$199	$411
	40 mg/L TN, 5 mg/L TP	5-stage Bardenpho retrofit with chemical additiona	CW	10	$1.30	$256	$566
	40 mg/L TN, 5 mg/L TP	Nitrification/ chemical addition/ denitrification filter retrofit[b]	CW	10	$0.75	$448	$626

[a] Source: Table ES-1, EPA. 2008. Municipal Nutrient Removal Technologies Reference Document, Volume 1 – Technical Report. EPA 832-R-08-006. Washington, DC.

Notes:
CW = EPA cost estimate from CAPDETWorks
A/O with VFA = anoxic/oxic enriched with volatile fatty acids
AS = activated sludge
CT = Connecticut Study. CT-1 plant included labor in the O&M cost; CT-2 did not.
IFAS = integrated fixed-film activated sludge
MD = Maryland Study. Incremental cost for retrofitting from 8 mg/L TN to 3 mg/L TN does not include labor in O&M. MLE = modified Ludzack-Ettinger process
MBBR = moving-bed biofilm reactor
MBR = membrane bioreactor
PID = phased isolation ditch
Other = other literature sources
TN = total nitrogen as N
TP = total phosphorus as P

EPA also prepared cost estimates for 12 retrofit and 20 expansion alternatives using CAPDETWorks estimating software to investigate facility costs at the 1, 5, and 10 mgd capacities. Table 5 presents the EPA estimated costs for a 10 mgd facility at various levels of effluent nitrogen and phosphorus.

Table 5. EPA Reference Document Cost Estimates for Expansion Technologies for 10 mgd[a]

Nutrient/ target concentration	*Initial concentration*	*Technology*	*Capital $/gpd capacity*	*O&M $/MG treated*	Life-cycle $/MG treated
TN, 5 mg/L	40 mg/L TN	PID	$0.63	$122	$273
	40 mg/L TN	MLE	$1.61	$309	$695
	40 mg/L TN	4-stage Bardenpho	$2.17	$453	$971
	40 mg/L TN	Denitrification filter	$0.71	$156	$324
TP, 1 mg/L	5 mg/L TP	A/O, no additional equipment	$1.21	$280	$568
TP, 0.5 mg/L	5 mg/L TP	1-point chemical addition	$0.03	$91	$98
	5 mg/L TP	A/O with fermenter	$1.26	$290	$590
	5 mg/L TP	A/O with fermenter and sand filter	$1.52	$308	$670
TP, 0.1 mg/L	5 mg/L TP	2-point chemical addition with filter	$0.29	$215	$283
	5 mg/L TP	A/O with fermenter, filter, and chemical addition	$1.55	$389	$758
TN+TP, 5 mg/L & 1 mg/L	40 mg/L TN, 5 mg/L TP	Step-feed	$1.36	$299	$625
	40 mg/L TN, 5 mg/L TP	SBR	$1.94	$302	$766
	40 mg/L TN, 5 mg/L TP	3-stage processes (e.g., UCT, VIP)	$2.05	$436	$925
TN+TP, 5 mg/L & 0.5 mg/L	40 mg/L TN, 5 mg/L TP	5-stage Bardenpho, no filter	$2.19	$452	$975
	40 mg/L TN, 5 mg/L TP	Modified UCT with fermenter and filter	$2.33	$456	$1014
	40 mg/L TN, 5 mg/L TP	5-stage Bardenpho with filter	$2.45	$455	$1040
TN+TP, 5 mg/L & 0.1 mg/L	40 mg/L TN, 5 mg/L TP	PID with chemical addition, clarifier, and filter	$0.83	$259	$456
	40 mg/L TN, 5 mg/L TP	SBR with chemical addition and filter	$1.87	$387	$834
TN+TP, 3 mg/L & 0.1 mg/L	40 mg/L TN, 5 mg/L TP	Nitrification with 1-point chemical addition and denitrificiation filter	$0.75	$448	$626
	40 mg/L TN, 5 mg/L TP	5-stage Bardenpho with chemical addition and filter	$2.48	$477	$1070

[a] Source: Table ES-2, EPA. 2008. Municipal Nutrient Removal Technologies Reference Document, Volume 1 – Technical Report. EPA 832-R-08-006. Washington, DC.

Notes:
A/O = anoxic/oxic
PID = phased isolation ditch
SBR = sequencing batch reactor
TN = total nitrogen as N
TP = total phosphorus as P
UCT = University of Cape Town process
VIP = Virginia Initiative process
For combined TN and TP technologies (TN+TP), first target number is for TN, second for TP.

3.2. Nutrient Removal Costs at Reference Facilities

Generalization about the costs for nutrient removal is difficult due to the wide variability in existing facilities, effluent requirements, and many other site specific factors. These factors include characteristics of the sewer service area and variability in the chemical composition of the wastewater, which may limit the ability to removal some nutrient constituents. Other site specific conditions of importance are the type and condition of existing treatment processes, and their compatibility with nutrient removal process needs. The layout and configuration of treatment facilities, and the overall availability of physical site space, often control the potential application of advanced treatment processes and are a large influence on costs.

Some reference facility costs are presented in the following discussion as a comparison to the EPA Reference Document. These costs are presented as a reference point for comparison with the cost per gallon data from the EPA 2008 Reference Document.

3.2.1. Coeur d'Alene, Idaho

The City of Coeur d'Alene, Idaho is currently in the process of evaluating treatment process alternatives to upgrade to advanced levels of phosphorus removal. The existing 6 mgd trickling filter/solids contact (TF/SC) facility uses chemical precipitation with alum for seasonal 85 percent seasonal phosphorus removal (~1 mg/l) and controls effluent ammonia nitrogen to approximately 10 mg/l. Future effluent requirements will approach the limits of treatment technology at 0.050 mg/l total phosphorus. Future requirements will also include effluent ammonia nitrogen of 7.4 mg/l and CBOD of 15 mg/l.

Treatment alternatives under consideration for extremely low effluent phosphorus include chemical addition (alum or ferric) and series granular media filtration or membrane filtration. The estimated capital costs for upgrading the facility for extremely low effluent phosphorus and moderate levels of ammonia nitrogen range from $3.40 to $5.20 per gpd of capacity. This includes liquid stream treatment costs for phosphorus and ammonia, as well as an allocation of solid processing facilities costs. Total estimated retrofit costs for the improvement program, which includes some unit process capacity additions and miscellaneous plant improvements, range from approximately $8.50 to $9.50 per gpd.

There are no direct parallels in the EPA Municipal Nutrient Removal Technologies Reference Document with the existing Coeur d'Alene facility effluent requirements. Coeur d'Alene effluent phosphorus limits at 0.050 mg/l or less are lower and than any of the facilities that EPA reviewed at 0.100 mg/l. The Coeur d'Alene ammonia limits at 7.5 mg/l are higher than most of the nitrogen removal facilities EPA reviewed that were in the range of 3 to 5 mg/l total nitrogen (total nitrogen includes ammonia, nitrate, nitrite and organic nitrogen). The EPA study cites capital costs of $1.07 to $2.01 for retrofit technologies for effluent ammonia of approximately 1 mg/l and phosphorus of 0.2 mg/l. The EPA study does not appear to include the cost impact on solids processing facilities from enhanced levels of liquid stream treatment. Estimated costs for the Coeur d'Alene nutrient removal upgrades appear to be significantly higher than the EPA Reference Document.

3.2.2. Bozeman, Montana

The City of Bozeman has recently made treatment process modifications to remove nitrogen and has begun construction on a phased improvement program to achieve lower levels of effluent nutrients. The existing 5 mgd activated sludge facility is in good condition and is well run, which enhances the potential for economical modifications for nutrient removal. The first phase of plant improvements targeted approximately 50 percent nitrogen removal through a limited capital improvement project to implement phased nitrification/denitrification within the existing activated sludge system. The modifications were successfully implemented at a very modest cost of approximately $0.03 per gpd capacity for effluent quality of approximately 9 mg/l total nitrogen and 5 mg/l total phosphorus. These costs are lower than the EPA Reference Document costs, but the Phase 1 effluent nitrogen in Bozeman at 9 mg/l is higher than the targets summarized by EPA at 5 mg/l and less.

Phase 2 of the improvement program is now under construction for targeted effluent quality of 7.5 mg/l total nitrogen and 1 mg/l total phosphorus with capacity expansion to 8.5 mgd. These improvements include biological nitrogen and phosphorus removal in a 5-stage Bardenpho activated sludge process. Total construction costs for this phase of improvements, which include solids processing facilities, disinfection, and an administration/laboratory building are approximately $6.10 per gpd. The costs for nitrogen and phosphorus control facilities are approximately $1.60 per gpd. These costs are comparable to the EPA Reference Document costs for facilities targeting nitrogen of 5 mg/l and phosphorus of 1 mg/l (range of $1.36 to $2.05 per gpd).

A subsequent Phase 3 program of improvements are planned to add effluent filtration and chemical feed facilities for low effluent phosphorus. Effluent phosphorus is targeted for 0.2 mg/l.

3.2.3. Spokane County, Washington

Spokane County, Washington is currently in the process of constructing an 8 mgd state-of-the-art advanced membrane treatment facility with effluent target of 0.050 mg/l total phosphorus, ammonia nitrogen of 0.25 mg/l, total nitrogen of 10 mg/l, and CBOD of 1.1 mg/l. This new Greenfield facility provides a cost reference for advanced nutrient removal for phosphorus at the limits of technology, as well as low levels of nitrogen and CBOD. On a unit cost basis, the Spokane County facility is approximately $18 per gallon per day of capacity.

Reference cost studies conducted as part of the Spokane County program found that costs for new advanced wastewater treatment facilities with membranes ranged from $15 to $33 per gallon per day of capacity over a range of plant sizes from 0.25 to 31 mgd. Facilities in this survey varied widely in not only in size, but also in effluent requirements and solids processing facilities. The larger facilities included anaerobic digestion for solids stabilization and dewatering facilities. The smaller facilities (less than 2 mgd) had aerobic digestion or solids minimization processes. The smaller facilities (less than 2 mgd) also had the highest unit costs ($25 per gpd) and least economy of scale.

3.3. Cost Estimates for New Phosphorus Removal Facilities

Jiang, et al investigated the costs of new phosphorus removal facilities in a 2004 study titled Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Construction De Novo. The study explored cost estimates for eight example designs representing new facilities over a range of capacities from 1 to 100 mgd. The treatment process trains investigated include biological phosphorus removal, chemical precipitation, effluent filtration, activated aluminum adsorption, and membrane filtration.

The baseline treatment process train in the study was a one stage activated sludge process capable of approximately 90 percent BOD removal. The authors noted that the activated sludge system would remove 10 to 25 percent of the wastewater phosphorus through normal growth of cell material. Assuming influent wastewater BOD of about 250 mg/l and influent phosphorus of between 5 and 20 mg/l, cell growth in the activated sludge process would remove about 237 mg/l of BOD and 2.37 mg/l of phosphorus, or about one-hundredth of the amount of BOD removed.

Effluent phosphorus for the treatment process trains ranged from 5.86 mg/l for the baseline process down to 1 mg/l (86.7 percent removal) for an activated sludge process with chemical addition. Lower effluent phosphorus levels coupled the activated sludge process with chemical addition and tertiary clarification for effluent phosphorus of 0.325 mg/l (95.7 percent removal) and with an effluent filter for 0.145 mg/l effluent phosphorus (98.1 percent removal). The lowest effluent phosphorus in the study was 0.05 mg/l (99.3 percent removal) for a process with activated sludge with chemical addition followed by an ultra filtration membrane.

Cost estimates in the study were based upon USEPA cost information for wastewater treatment facilities published in 1978 and water treatment facilities published in 1979. Cost estimates were updated to a year 2004 basis. The authors note that “total capital costs increase with the target P removal efficiency” and that “when the required removal efficiency exceeds 90 percent, these costs rise quickly as a consequence of the extra unit processes needed for removal of the phosphorus still remaining after biological treatment.”

At 10 mgd capacity, the estimated capital cost of the baseline activated sludge process was $3.95 per gallon per day (gpd) in year 2004 dollars. The activated sludge process with chemical addition for 1 mg/l effluent phosphorus was estimated to cost $5.47 per gpd. The activated sludge process with chemical addition and tertiary clarification for effluent phosphorus of 0.325 mg/l was estimated to cost $5.60 per gpd. Adding an effluent filter for effluent phosphorus of 0.145 mg/l was estimated to cost $5.87 per gpd. The lowest effluent phosphorus of 0.05 mg/l with an ultra filtration membrane was estimated to cost $7.28 per gpd. This limit of technology effluent phosphorus level is more than 80 percent higher in estimated cost compared to the baseline facility.
Table 6 summarizes the phosphorus removal costs at the 10 mgd capacity level.

Table 6. Estimated Capital Costs for New Phosphorus Removal Facilities at 10 mgd Capacity[a]

Treatment Process	Effluent Phosphorus, mg/l	Capital Cost[b], $/year	Unit Capital Cost[b], $/gpd
Activated Sludge	5.86	$39,530,000	$3.95
Activated Sludge + Chemical	1.0	$54,650,000	$5.47
Activated Sludge + Chemical + Tertiary Clarification	0.325	$56,030,000	$5.60
Activated Sludge + Chemical + Tertiary Clarification + Filter	0.145	$58,720,000	$5.87
Activated Sludge + Chemical + Filter + Membrane	0.050	$72,790,000	$7.28

[a]Jiang, F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell, "Estimation of Costs of Phosphorus Removal In Wastewater Treatment Facilities: Construction De Novo," Water Policy Working Paper #2004-010, June 2004.
[b] Costs are May 2004 ENR CCI 6,672.

3.3.1. Operations and Maintenance Estimates for New Phosphorus Removal Facilities

The 2004 study of new phosphorus removal facilities (Jiang, 2004) included operations and maintenance cost estimates for a variety of treatment processes. Table 7 summarizes the annual operating costs and electrical energy costs. Estimated operating costs, and electrical energy costs, approximately double for effluent phosphorus at the limits of technology of 0.05 mg/l, as compared to conventional secondary treatment with activated sludge.

Table 7. Estimated Operations and Maintenance Costs and Electrical Costs for New Phosphorus Removal Facilities at 10 mgd Capacity[a]

Treatment Process	Effluent Phosphorus, mg/l	O&M Cost[b], $/year	Energy Cost[b, c], $/year
Activated Sludge	5.86	$4,130,000	$320,000
Activated Sludge + Chemical	1.0	$7,100,000	$450,000
Activated Sludge + Chemical + Tertiary Clarification	0.325	$7,500,000	$460,000
Activated Sludge + Chemical + Tertiary Clarification + Filter	0.145	$7,820,000	$480,000
Activated Sludge + Chemical + Filter + Membrane	0.050	$9,180,000	$620,000

[a]Jiang, F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell, "Estimation of Costs of Phosphorus Removal In Wastewater Treatment Facilities: Construction De Novo," Water Policy Working Paper #2004-010, June 2004.
[b] Costs are May 2004 ENR CCI 6,672.
[c] Electricity at $0.0499 per kWh.

3.3.2. Cost Estimates for Retrofit Phosphorus Removal Facilities

Jiang, et al conducted a subsequent investigation of phosphorus removal retrofit costs in a 2005 study titled Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Adaption of Existing Facilities. The study explored cost estimates for five example retrofit designs for a range of capacities from 1 to 100 mgd. The treatment process trains investigated include biological phosphorus removal, chemical precipitation, effluent filtration, activated aluminum adsorption, and membrane filtration.

Five capacities of plant were considered, from 1 MGD to 100 MGD. Five levels of effluent phosphorus were considered and a treatment process model was used to simulate results: 2 mg/l, 1 mg/l, 0.5 mg/l, 0.13 mg/l, and 0.05 mg/l. Three alternative designs for the facility are considered: the basic activated sludge (AS) process with chemical addition, the Anoxic/Oxic (A/O) arrangement of the activated sludge process, and the Anaerobic/Aerobic/Oxic (A/A/O) arrangement of the activated sludge process. To estimate costs for phosphorus removal, additions to the three basic activated sludge configurations were considered: chemical addition (alum), sand media filtration, or ultra filtration membrane.

Table 8 presents a summary of the estimated capital costs, operations and maintenance costs, and total annual costs for the treatment process options and various effluent phosphorus levels at the 10 mgd plant size. Chemical precipitation in the conventional activated sludge process appears to be the most cost effective retrofit option down to an effluent phosphorus level of 0.50 mg/l. At the effluent phosphorus levels of 0.13 mg/l and 0.05 mg/l the total annual costs are similar for all three activated sludge process options. Operating costs increase substantially moving beyond effluent phosphorus levels of 0.50 mg/l down to 0.13 mg/l and 0.05 mg/l. Capital costs become much higher when moving down to the effluent phosphorus level of 0.05 mg/l.

Table 8. Estimated Phosphorus Removal Retrofit Costs for 10 mgd Capacity[a]

Retrofit Process	*Capital Cost[b], $*	*O&M Cost[b], $/year*	Total Annual Economic Cost[c], $/year
Effluent Total Phosphorus 2 mg/l			
Activated Sludge + Chemical	$221,000	$130,200	$150,000
Anoxic/Aerobic	$1,890,000	$335,800	$501,000
Anaerobic/Anoxic/Aerobic	$2,080,000	$376,900	$558,000
Effluent Total Phosphorus 1 mg/l			
Activated Sludge + Chemical	$267,000	$316,200	$340,000
Anoxic/Aerobic + Chemical	$2,090,000	$596,000	$778,000
Anaerobic/Anoxic/Aerobic + Chemical	$2,280,000	$632,800	$830,000
Effluent Total Phosphorus 0.5 mg/l			
Activated Sludge + Chemical + Filter	$6,110,000	$1,175,800	$1,710,000
Anoxic/Aerobic + Chemical + Filter	$7,890,000	$1,404,000	$2,090,000
Anaerobic/Anoxic/Aerobic + Chemical + Filter	$8,080,000	$1,439,000	$2,140,000
Effluent Total Phosphorus 0.13 mg/l			
Activated Sludge + Chemical + Filter	$6,420,000	$3,152,000	$3,710,000
Anoxic/Aerobic + Chemical + Filter	$8,200,000	$2,813,000	$3,530,000
Anaerobic/Anoxic/Aerobic + Chemical + Filter	$8,390,000	$2,837,000	$3,570,000
Effluent Total Phosphorus 0.05 mg/l			
Activated Sludge + Chemical + Filter + Membrane	$13,750,000	$4,350,000	$5,550,000
Anoxic/Aerobic + Chemical + Filter + Membrane	$15,600,000	$4,390,000	$5,750,000
Anaerobic/Anoxic/Aerobic + Chemical + Filter + Membrane	$15,790,000	$4,377,000	$5,750,000

[a] Source: Jiang, F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell, "Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Adaption of Existing Facilities. Water," Water Policy Working Paper #2005-011, February 2005.
[b] Costs are May 2004 ENR CCI 6,672.
[c] Total annual costs are based on a 20 year analysis with an Opportunity Cost of Capital (OCC) of 6%.

Table 9 highlights the energy costs for each of the phosphorus removal retrofit options. Total operations and maintenance costs in the study were based on an EPA algorithm that includes component costs for energy, chemicals, sludge disposal, labor, maintenance, and insurance. The study modeled energy consumption based on aeration energy, pumping energy, and mixing energy.

This study shows that the estimated energy costs increase by approximately 40 percent or more when effluent phosphorus drops from 1 mg/l to the 0.13 to 0.5 mg/l range for the biological phosphorus removal options. Energy costs increase by a factor of 30 times to drop to 0.13 to 0.5 mg/l from the base activated sludge with chemical addition. Estimated

energy costs for effluent phosphorus at the limits of treatment technology at 0.05 mg/l are nearly 200 percent higher than at the 1 mg/l level.

Table 9. Estimated Energy Costs for Phosphorus Removal Retrofit at 10 mgd Capacity[a]

Retrofit Process	O&M Cost[b], $/year	Energy Cost[b], $/year
Effluent Total Phosphorus 2 mg/l		
Activated Sludge + Chemical	$130,200	$1,300
Anoxic/Aerobic	$335,800	$138,000
Anaerobic/Anoxic/Aerobic	$376,900	$156,000
Effluent Total Phosphorus 1 mg/l		
Activated Sludge + Chemical	$316,200	$2,400
Anoxic/Aerobic + Chemical	$596,000	$140,000
Anaerobic/Anoxic/Aerobic + Chemical	$632,800	$159,000
Effluent Total Phosphorus 0.5 mg/l		
Activated Sludge + Chemical + Filter	$1,175,800	$70,800
Anoxic/Aerobic + Chemical + Filter	$1,404,000	$209,000
Anaerobic/Anoxic/Aerobic + Chemical + Filter	$1,439,000	$227,000
Effluent Total Phosphorus 0.13 mg/l		
Activated Sludge + Chemical + Filter	$3,152,000	$68,700
Anoxic/Aerobic + Chemical + Filter	$2,813,000	$207,000
Anaerobic/Anoxic/Aerobic + Chemical + Filter	$2,837,000	$225,000
Effluent Total Phosphorus 0.05 mg/l		
Activated Sludge + Chemical + Filter + Membrane	$4,350,000	$342,000
Anoxic/Aerobic + Chemical + Filter + Membrane	$4,390,000	$481,000
Anaerobic/Anoxic/Aerobic + Chemical + Filter + Membrane	$4,377,000	$499,000

[a] Source: Jiang, F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell, "Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Adaption of Existing Facilities. Water," Water Policy Working Paper #2005-011, February 2005.
[b] Costs are May 2004 ENR CCI 6,672.

3.3.3. Chesapeake Bay Nutrient Reduction Cost Study

Nutrient removal costs were estimated as part of the Chesapeake Bay program based on a variety of sources for four levels of nitrogen and phosphorus treatment. Cost estimates were based on year 2000 dollars and projected 2010 wastewater flows. Facilities larger than 0.5 mgd are considered "significant" municipal sources and facilities less than 0.5 mgd are designated "non-significant" municipal sources. Table 10summarizes the treatment technologies and tier designations.

Table 10. Chesapeake Bay Study Nutrient Reduction Technologies for Significant Municipal Sources[a]

Nutrient	Tier 1	Tier 2	Tier 3	Tier 4
Nitrogen	Existing Technologies	Extended aeration process 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)	Increased chemical precipitation	Microfiltration

[a]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.

Table 11 summarizes the nitrogen and phosphorus removal costs for Tier 3 and 4 treatment levels for 10 mgd capacity.

Table 11. Chesapeake Bay Study Tier 3 and Tier 4 Cost Estimates at 10 mgd Capacity[a]

Tier/Nutrient	Capital Cost[b], $	O&M Cost[b], $/year	Comment
Tier 3 TN 5 mg/l	$4,927,000	$158,000	Additional aeration, a secondary anoxic zone, methanol addition, and additional clarification tankage. Costs estimated based on reducing TN from 8 mg/l to 5 mg/l.
Tier 4 TN 3 mg/l	$9,620,000	$312,000	Deep bed denitrification filters
Tier 4 TP 0.1 mg/l	$6,969,000	$1,095,000	Costs estimated assuming chemical addition and microfiltration

[a]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.
[b] Costs are year 2000.

3.4. Wastewater Treatment Unit Reduction Costs

Table 12 summarizes the point source reduction costs for nitrogen and phosphorus removal in wastewater treatment facilities using the information provided in two studies discussed previously (EPA's 2008 reference document and Jiang et al). Cost data has been combined with the targeted effluent concentrations to estimate the unit cost per pound of nitrogen or phosphorus removed. The costs presented in Table 12 are limited to the information available for retrofit facilities in the EPA study and the hypothetical estimate of the cost of new treatment facilities with nutrient removal from EPA and Jiang et al. Individual treatment plant conditions vary widely and the unit costs for nutrient removal should also be expected to vary widely.

Table 12. Estimated Wastewater Treatment Unit Costs for Nitrogen and Phosphorus[a, b]

Effluent Target	Nitrogen Reduction Cost, $/lb Removed[c]	Phosphorus Reduction Cost, $/lb Removed[d]
EPA Reference Document Retrofit Technologies for 10 mgd Capacity[e]		
Total Nitrogen 3 mg/l	0.50 – 1.10	
Total Phosphorus 0.5 mg/l		2.60
Total Phosphorus 0.1 mg/l		5.00 - 7.00
EPA Reference Document Expansion Technologies for 10 mgd Capacity[f]		
Total Nitrogen 5 mg/l	1.00 – 3.30	
Total Phosphorus 0.5 mg/l		3.00 – 18.00
Total Phosphorus 0.1 mg/l		7.00 to 19.00
Jiang et al Phosphorus Cost Study for Retrofit Technologies for 10 mgd Capacity[g]		
Total Phosphorus 1 mg/l		2.80
Total Phosphorus 0.5 mg/l		12.50
Total Phosphorus 0.13 mg/l		25.00
Total Phosphorus 0.05 mg/l		37.00

[a] Source: EPA. 2008. Municipal Nutrient Removal Technologies Reference Document, Volume 1 – Technical Report. EPA 832-R-08-006. Washington, DC.
2009
[b] Source: Jiang, F., M.B. Beck, R.G. Cummings, K. Rowles, and D. Russell, "Estimation of Costs of Phosphorus Removal in Wastewater Treatment Facilities: Adaption of Existing Facilities. Water," Water Policy Working Paper #2005-011, February 2005.
[c] Nitrogen reduction unit costs are based on EPA life cycle costs per million gallons treated and a reduction from total nitrogen of 40 mg/l.
[d] Phosphorus reduction unit costs are based on EPA life cycle costs per million gallons treated and a reduction from total phosphorus of 5 mg/l.
[e] Retrofit technologies costs from the EPA Nutrient Removal Technologies Reference Document are based on cost studies from actual facilities (see Table 4).
[f] Expansion technologies costs from the EPA Nutrient Removal Technologies Reference Document are based on hypothetical process trains and cost estimating tools (see Table 5).
[g] Phosphorus retrofit technologies costs from the Jiang et al are based on hypothetical process trains and cost estimating tools (see Table 8)

Figure 6 illustrates the dramatic change in the wastewater treatment unit costs for nutrient removal as effluent target concentrations are reduced from base nutrient removal levels to the limits of treatment technology. Costs for wastewater treatment at the boundaries of what can be accomplished with treatment technology is very expensive. The unit cost data for Figure 6 is for phosphorus removal from the estimated costs for retrofit of a 10 mgd facility from Jiang et al. Costs per pound of phosphorus removal are modest for the base level of nutrient removal with chemical addition for effluent phosphorus of 1 mg/l (<3 $/lb). As effluent target concentrations are reduced, the unit costs per pound of phosphorus removed increases substantially. Costs for enhanced levels of phosphorus removal with chemical addition and filtration for effluent phosphorus of approximately 0.5 mg/l quadruple (~13 $/lb). As effluent limits approach the limits of treatment technology in the range of 0.05 to 0.10 mg/l, additional filtration steps and/or membranes

are required. The unit costs per pound of phosphorus removed increases from base nutrient removal levels by an order of magnitude (~25 to 37 $/lb).

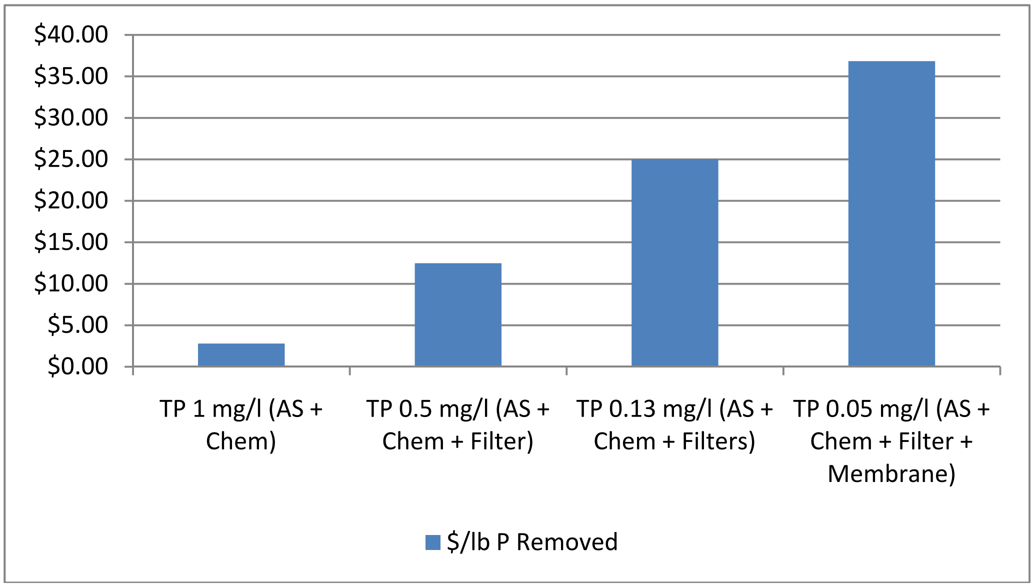

Figure 6. Estimated Wastewater Treatment Unit Costs for Phosphorus Removal from Base Nutrient Removal to Limit of Technology

(Source: Phosphorus retrofit technologies costs from the Jiang et al at 10 mgd capacity based on hypothetical process trains and cost estimating tools (see Tables 8 and 12))

4. Nonpoint Source Nutrient Reduction

Nonpoint source management practices may represent the best way to achieve overall environmental benefits in a watershed for a number of reasons. In many watersheds, nonpoint sources are the dominant source of nutrient loadings. Many nonpoint source controls can address nutrient impairments more cost effectively than point source reductions, especially as wastewater treatment requirements approach the limits of technology. Further, nonpoint source management practices can achieve suspended sediment reductions which point sources cannot. Siltation, sedimentation, and bacterial impairments tend to occur concurrently with nutrient impairment and nonpoint source controls can address multiple water quality impairments simultaneously. Nonpoint source controls can also improve habitat quality for biological resources by reducing peak stream flow velocity (scouring) and providing greater riparian shading of streams (reduces temperature, improves dissolved oxygen). Nonpoint source controls can sequester carbon from the watershed (e.g. riparian buffers assimilate carbon) and use less energy than wastewater treatment plants, which reduces greenhouse gas emissions.

4.1. Nonpoint Source Nutrient Reduction Costs

Nonpoint source reduction of nutrients may be cost effective when compared to the cost of wastewater treatment. This section discusses the costs of nonpoint source nutrient reductions from a variety of best management practices (BMPs) ranging from urban/ suburban stormwater, to agriculture, and a few forestry land management practices.

Just as existing conditions at wastewater treatment plants vary widely from plant to plant, land management activities and existing conditions vary widely throughout watersheds. This results in a great variety of nonpoint source best and a high degree of variability in their performance in reducing nitrogen and phosphorus loadings. Table 13 highlights the variability in nutrient removal effectiveness for various best management practices. Variability in nonpoint source nutrient reduction is much higher than in wastewater treatment facilities. The costs to reduce nonpoint source nitrogen and phosphorus loadings also varies widely as the discussion and nonpoint source cost summary tables that follow illustrate.

Table 13. Nonpoint Source Best Management Practice Nutrient Removal Efficiency[a]

Best Management Practice	Typical Pollutant Removal (percent)	
	Nitrogen	Phosphorus
Drying Detention Basins	15 - 45	15 - 45
Retention Basins	30 - 65	30 - 65
Constructed Wetlands	<30	15 - 45
Infiltration Basins	50 - 80	50 - 80
Infiltration Trenches/Dry Wells	50 - 80	15 - 45
Porous Pavement	65 - 100	30 - 65
Grassed Swales	15 - 45	15 -45
Vegetated Filter Strips	50 - 80	50 - 80
Surface Sand Filters	<30	50 - 80
Other Media Filters	15 - 45	<30

[a]USEPA. Preliminary Data Summary of Urban Storm Water Best Management Practices, EPA-821-R-99-012

There are many publications regarding nonpoint source nutrient reduction and best management practices. The following section summarizes nonpoint source nutrient reduction costs for comparison with wastewater treatment point source reduction costs. The nonpoint source nutrient reduction costs presented can be compared with the costs for wastewater treatment nitrogen and phosphorus removal that were discussed in the previous section. It appears that the cost of nonpoint source best management practices for future production from agriculture are less than for point source reductions at wastewater treatment plants. This indicates the potential for water quality offsets or treating from nonpoint source reduction when treatment plant costs per unit reduction are higher. On the other hand, it appears that the urban storm water nonpoint source reductions are more expensive than wastewater treatment nutrient removal. Agricultural best management practice costs for nitrogen and phosphorus reduction are summarized from studies from Pennsylvania, Maryland, and Utah in Table 14, Table 15, and Table 16. Costs for a variety of farm management practices in Pennsylvania are summarized in Table 14 where costs appear very moderate for BMPs such as conservation tillage and grass buffers, in comparison to the urban/suburban BMPs discussed above.

Table 14. Summary of Select Nonpoint Source Best Management Practice (BMP) Cost per Unit Phosphorus and Nitrogen Reduction[a]

Nonpoint Source BMP	Nitrogen Unit Cost, $/lb TN Load Reduced	Phosphorus Unit Cost, $/lb TP Load Reduced
Conservation Tillage	0.50	2.57
Grass Buffers	0.61	11.06
Early Planting Cover Crops	2.31	72.32
Forest Buffers	2.16	85.66
Off Stream Watering with Fencing		121.12
Wetland Restoration	2.16	43.22
Urban Nutrient Management (Pervious Urban)	1.01	2,199

[a] Source: Sweeney, "Pennsylvania Nonpoint Source BMP Effectiveness, Cost Effectiveness and Potential for Reducing Loads," 2004

Cost for a variety of nonpoint source management practices in Maryland are summarized in Table 15 from the Assawoman Bay watershed project. As in the Pennsylvania study, costs appear modest for BMPs such as conservation tillage, riparian fencing, and grass buffers.

Table 145. Summary of Select Nonpoint Source Best Management Practice (BMP) Cost per Unit Nitrogen Reduction[a]

Agricultural Best Management Practices	Nitrogen Present Value Expense, $/lb
Agricultural nutrient management planning	0.92
Conservation tillage	3.27
Out of stream watering and stream fence	3.86
Tree planting -- agriculture	7.03
Riparian grass buffers	17.10
Barnyard runoff control	26.05
Riparian forest buffers	29.54
Wetland restoration	51.69

[2]Assawoman Bay Watershed Restoration Action Strategy (WRAS), 2008.

Utah State University investigated nonpoint source phosphorus reduction as part of a study of the potential effectiveness of water quality trading programs for reducing total phosphorus in impaired streams, such as those river systems in the Bear River watershed in Idaho and Utah. A summary of agricultural phosphorus reduction unit costs is presented in Table 16. This study found that there are significant differences in point source costs relative to nonpoint costs that would provide an incentive for point source-to-nonpoint source trading. Several of the best management practices, such as sprinkler irrigation, agricultural nutrient management, and stream bank stabilization appear to be very economical.

Table 16. Estimated Agricultural Best Management Practice Costs for Phosphorus and Nitrogen Reduction in Utah[a]

Nonpoint Source BMP	Phosphorus Unit Cost, $/lb TP Load Reduced
Land retirement	3,342
Grazing land protection	108
Stream fencing	623
Stream bank stabilization	7
Cover crops	306
Grass filter strips	187
Animal waste facility	331
Conservation tillage	153
Agricultural nutrient management	76
Sprinkler irrigation	58

[a] Source: Glover, Terry. Appendix 8.5 Estimates of Phosphorus Abatement Costs. EPA Targeted Watersheds Grant Final Report - Bear River Watershed DRAFT. 2008.

An evaluation by the Minnesota Public Works Association (MPWA), Environmental Committee considered the unit cost of phosphorus and total suspended solids reductions in a recent study (MPWA, 2009). The typical phosphorus, suspended solids, and runoff volume removal costs for different BMPs based on analyses completed by the MPWA are shown in Table 17 MPWA noted that the costs are variable and dependent on a wide range of design considerations.

Table 17. Stormwater Best Management Practice Costs from the Minnesota Public Works Association[a]

Best Management Practice	Estimated Capital Cost	Estimated Life Cycle Cost	Phosphorus Removal Cost/lb	TSS Removal Cost/lb	Runoff Volume Removal Cost/ac-ft
National urban runoff program (NURP) Basin	$336,000	$33,840	$1,554	$25	$6,936
Rain Garden	$210,000	$15,250	$8,715	$15	$5,259
Rain Garden No.2	$100,000	$8,000	$2,460	$67	$2,000
Water Reuse / Stormwater Irrigation System	$10,000	$3,150	$533	$1.2	$450
Wastewater Treatment Plant	*	$10,430	$220	$5.70	No Benefit
On-Site Flocculation	$310,000	$58,750	$280	$0.60	No Benefit
Underground Treatment Devices	$1,200,00	$83,000	$830	$13	No Benefit

[a]Source: MPWA, "The Cost Versus Benefit of a Specific Stormwater Best Management Practice," Minnesota Public Works Association, 2009.

There are a variety of urban stormwater BMPs including rain gardens, vegetated swales, stream buffers, wet detention, bioretention cells, native vegetation, and ponds. Wet and dry ponds are fairly common because they also retain or detain the stormwater flow. A study from four creeks in the Kalamazoo River watershed in southern Michigan focused

on wet retention ponds and dry detention ponds. These were selected because of their wide use, general applicability, and available data including construction costs and pollutant load reduction efficiencies. The results of this evaluation are summarized in Table 18 (Kieser, 2009). The evaluation was based on designing for a 2.75-inch rainfall event with the construction and maintenance costs based on literature values. The load reduction efficiencies used were from the Michigan Water Quality Trading Rule.

The unit costs in the Michigan study are generally lower for wet ponds than for dry ponds, with the exception of some anomalies (Arcadia Creek). The unit costs for dry ponds were similar to the costs in the Minnesota study presented above. Wet ponds in Michigan appeared to have lower unit costs compared to the unit costs for urban BMPs in the Minnesota study. However, wet ponds may not be appropriate for many situations, such as in arid climates and situations with high groundwater and where there are vector control problems (mosquitoes).

Table 18. Kalamazoo River Watershed Urban Best Management Practice Cost Analysis[a]

Kalamazoo River Location	Wet pond 30-year cost including O&M ($)	Dry pond 30-year cost including O&M ($)	Wet pond TSS load reduction with 50% area treated (tons/yr)	Dry pond TSS load reduction with 50% area treated (tons/yr)	Wet pond TP load reduction with 50% area treated (lbs/yr)	Wet pond 30-year cost per pound TP including O&M ($/lb/yr)	Dry pond TP load reduction with 50% area treated (lbs/yr)	Dry pond 30-year cost per pound TP including O&M ($/lb/yr)	Pond volume with 50% area treated (cf)	Area (5-ft depth) (acres)
Arcadia Creek	207,520	175,608	97	54	660	4,229	220	10,736	2,515,762	12
Axtell Creek	62,401	52,805	27	15.19	186.2	334	62.1	847	756,488.5	3.5
Portage Creek	281,108	237.879	122	67.9	860.9	324	287	823	3,407,873	15.6
West Fork	22,385	18,943	10.1	5.62	64.0	369	21.3	936	271,379	1.2

[a]Source: Kieser, "Urban Pollutant Loads and General BMP Cost Analysis," Kalamazoo River Watershed Association, 2009.

Stormwater BMP costs for nitrogen and phosphorus reduction were evaluated for the Christina River Basin in northern Delaware (Corrozi, 2009) based on reference cost data from EPA (EPA, 1999). "The Christina Basin is a diverse, suburbanizing watershed situated in the Delaware River Basin. Most of the Christina Basin is occupied by 3 land uses of similar proportions – Urban/Suburban (34%), Agricultural (31%), and Open Space/Forested Lands (35%)" (University of Delaware, 2009). The unit costs for nitrogen and phosphorus reduction presented in Table 19 were calculated based on construction costs, inflation adjustments, and operation and maintenance costs combined with nutrient reduction estimates. The unit costs for phosphorus unit costs for wet and dry ponds are similar to those presented in the Michigan study above.

Table 19. Christina Basin Stormwater Nitrogen and Phosphorus BMP Costs[a]

Best Management Practice	TN Reduction Cost, $/lb	TP Reduction Cost, $/lb
Wet Pond	112	698
Dry Pond	90	1,535
Infiltration Structures	100	2,643
Sand Filters	277	9,067

[a]Corrozi, "Stormwater BMP Cost Calculations, Christina Basin Tributary Action Team," 2009

An "Economic Evaluation of Stream Bank Stability for Phosphorus Reduction" evaluation from the Ozarks included consideration of how best to invest in phosphorus reductions (Dove, 2008). The Ozarks are a region mostly in southern Missouri with high and deeply dissected plateaus making the area the most mountainous topography between the Appalachians and Rocky Mountains in the Midwest. The options considered include point source reductions, urban stormwater BMPs, stream restoration, and stream buffers.

Using the cost of construction, along with the nutrient reduction, an estimate of the cost per unit mass of phosphorus removed was calculated. Both the costs and efficiencies at removing nutrients varies greatly, not only because there are potentially many different types of BMPs which can be applied, but also because of the location, design, materials used, climate and other factors which influenced individual BMPs. Since both the costs and efficiencies vary greatly, the unit costs for phosphorus reduction also varied greatly.

The conclusions of the Ozarks study are summarized in Table 20. While the summary indicates that point source reduction was the best value, this was based only on upgrading the Springfield, MO wastewater treatment plant with alum precipitation of phosphorus. The unit cost per pound of phosphorus removed is comparable to the base level of nutrient removal illustrated in Figure 6. The next options were stream restoration and buffers, which were noted as having additional non-economic benefits to the watershed and property value enhancements. While urban BMPs had the highest cost, this cost does not reflect all of the watershed benefits. Noted in the evaluation was that the costs were only for considering phosphorus and that the costs are more comparable when all contaminants reduced by urban BMPs are considered. Further, urban BMPs provide benefits by reducing non-point source pollutants closer to the source, before the water moves downstream, and reduces peak flows which can impact bank stability and create the need for stream restoration.

Table 20. Economic Evaluation of Phosphorus Reduction for Ozark Streams[a]

Phosphorus Removal Method	Data Source	Cost per Pound Phosphorus Removed Annually
Wastewater Treatment Plant	Springfield WWTP Upgrades, EPA Guidance documents	$4.60/lb
Stormwater BMP's	EPA 1999 Study	$698/lb to $1,535/lb
	Olsson 2006 Study	$466/lb
Stream Restoration	Ward Branch and Other Restoration Plans in NE, KS, and MO	$188/lb
Stream Buffers	Jordan Creek, Springfield Christian County, MO	$278/lb

[a]Source: Dove, "Economic Evaluation of Stream Bank Stability for Phosphorus Reduction, Can We Afford Not to Protect our Ozark Streams?" Watershed Center, 2008.

5. Nutrient Removal Carbon Footprint

Nutrient removal treatment facilities have a larger environmental impact than secondary treatment as a result of the additional energy consumption and greenhouse gas emissions (GHG) from advanced wastewater treatment processes. Carbon footprint is used to describe the greenhouse gas emissions associated with an activity such as wastewater treatment. Greenhouse gas emissions occur directly from the wastewater treatment plant processes and indirect emissions occur from the consumption of electrical power. Advanced wastewater treatment facilities for nutrient removal both emit more greenhouse gases directly and consume more electrical power.

Decisions to require advanced treatment for nutrient removal should be considered carefully in order to avoid unnecessarily increasing greenhouse gas emissions with marginal water quality benefits. Since advanced treatment will consume more electrical power and generate more greenhouse gas emissions, care should be taken to avoid unnecessarily restrictive effluent nutrient requirements that will adversely affect other parts of the environment and public health.

5.1. Green House Gas Public Health Risk

EPA has recently concluded that carbon dioxide and five other greenhouse gases are a danger to public health and welfare. EPA's proposed endangerment finding is based on an analysis of six gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. This is potentially the first step in regulation of green house gases under the Clean Air Act.

5.2. Wastewater Treatment Green House Gas Emissions

There are interesting implications for wastewater facilities, since treatment plants are a quantifiable source of green house gas emissions. The greenhouse gases associated with wastewater treatment are primarily carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O).

Emissions include carbon dioxide related to power consumption at treatment plants and production of chemicals used in treatment (energy used to power plants is an indirect source of GHG). Carbon dioxide emissions resulting from the conversion of organic matter in the wastewater treatment process not originating from fossil fuel combustion are not considered to contribute to the greenhouse effect. Methane gas emissions result from raw sewage conveyance and solids processing such as thickening, digestion, dewatering, and solids storage.

Nitrous oxide is emitted from nitrogen removal processes (nitrification/denitrification) and has nearly 300 times the greenhouse gas effect of carbon dioxide. Nitrous oxide measurements have demonstrated substantial emissions from wastewater treatment, although there are large variations reported. Identification and analysis of the factors resulting in nitrous oxide emissions is an area of current research.

The EPA inventory of greenhouse gas emissions (EPA 2009) indicates that secondary treatment plants without intentional nitrification/denitrification are assumed to generate 3.2 grams N2O per capita per year. Nutrient removal treatment plants with intentional nitrification and denitrification generate approximately 7 grams N2O is generated per capita per year, or approximately 120 percent more of this greenhouse gas.

5.3. Nutrient Removal Power Consumption

Power consumption in nutrient removal treatment facilities is substantially higher than in secondary treatment. Additional power is required for pumping and mixing the biological treatment process to removal nitrogen and phosphorus, and for chemical feed systems and filters. EPA's Municipal Nutrient Removal Technologies Reference Document (September 2008) provides electrical power consumption information from nine facilities removing nitrogen and phosphorus that were studied in depth. Table 21 summarizes the electrical power required for phosphorus and nitrogen removal per million gallons of treated wastewater and as a percentage of total plant power use. From these treatment plants, power required for phosphorus removal accounted for between 2 and 28 percent of total plant power consumption. Nitrogen removal accounted for between 35 and 69 percent of total plant power consumption.

The electrical power required for phosphorus varied widely between the plants in Table 21, ranging from 24 to 721 kWh per million gallons treated. This is likely a reflection the variety of methods applied to remove phosphorus and the allocation of power usage in accounting for power associated with phosphorus.. Nitrogen removal power use was more consistent and ranged from 584 to 1,632 kWh per million gallons treated.

Table 21. Electrical Power Consumption for Nitrogen and Phosphorus Removal at Wastewater Treatment Facilities[a]

Facility	Design Flow, mgd	Effluent P, mg/l and N, mg/l	Phosphorus Removal Electrical Power		Nitrogen Removal Electrical Power	
			kWh/mgal Treated	Percentage of Total Plant Power, %	kWh/mgal Treated	Percentage of Total Plant Power, %
Kalispell, MT	3	TP 0.121, (NH_3N 0.070)	355	15%	984	43%
Lee County, FL	5	TP 0.102, TN 1.57	34	2%	1,047	46%
Central Johnston, NC	7	TP 0.26, TN 2.14	721	28%	1,632	63%
Clearwater, FL	10	TP 0.132, TN 2.32	255	12%	1,267	61%
Kelowna, BC	10.5	TP 0.139, TN 4.38	231	15%	1,070	69%
North Cary, NC	12	TP 0.38, TN 3.7	86	ND[b]	584	ND[b]
Western Branch, MD	30	TP 0.47, TN 1.70	24	1%	810	35%
Fairfax, VA	67	TP 0.090, TN 5.25	137	ND[b]	738	ND[b]

[a] Source: EPA. 2008. Municipal Nutrient Removal Technologies Reference Document, Volume 1 – Technical Report. EPA 832-R-08-006. Washington, DC.
[b] No data was available for total plant power consumption to assess phosphorus and nitrogen power use as a percentage of total.

5.4. Illinois Study

The Illinois Association of Wastewater Agencies (IAWA) conducted a study of 22 wastewater treatment facilities to analyze the impact of nutrient removal on direct atmospheric emissions of greenhouse gases and indirect emissions resulting from electrical power consumption. The report found that the largest emission source would be from electrical power consumption increases for nutrient treatment. Increased emissions would also come from the nutrient removal biological treatment process, as well as emissions associated with truck transportation of biosolids and chemicals used in treatment.

The Illinois study found that a secondary treatment plant would increase emissions by 1,045 lbs of carbon dioxide equivalents for nutrient removal for every million gallons per day of flow. The increase in annual greenhouse gas emissions for nutrient removal at a nominal plant flow of 10 MGD would be equivalent to the emissions from about 300 automobiles. The increase in greenhouse gas emissions from nutrient removal at all treatment plants in Illinois would be more than 470,000 tons of carbon dioxide equivalents per year.

5.5. Upper Blackstone Study

The Upper Blackstone Water Pollution Abatement District in Worcester, Massachusetts conducted the study of greenhouse gas emissions related to effluent nutrient discharge limits. The District operates a 56 mgd secondary treatment facility designed to treat peaks of 120 mgd. Effluent phosphorus limits were reduced from 0.75 to 0.1 mg/l and total nitrogen limits of 5 mg/l were added. Questions were raised about the water quality benefit that would result from the revised effluent limits and whether excessive eutrophication or dissolved oxygen variations would be improved.

The study found that meeting the new discharge permit would require an additional 3,000,000 kWH annually, an approximately 18 percent increase in electrical power over existing secondary treatment requirements of about 16,500,000 kWH in power each year. Additional electrical power is required for process pumping, internal recycle pumping and mixing for the biological treatment process, a new high rate clarification process, and chemical feed systems. Assuming 1.55 pounds of CO2 generated per kWH consumed (U.S. EPA, 2007) 4,650,000 pounds annually of carbon dioxide would be generated, which is approximately equivalent to over 400 automobiles.

The Upper Blackstone study identified over 10,000,000 gallons of additional chemicals that would have to be delivered to the site, equivalent to about 1,360 trucks annually. Phosphorus removal processes will require multi-point addition of ferric chloride, along with sodium hydroxide for alkalinity control. To meet nitrogen removal requirements, methanol will be required as a carbon source to support the biological treatment process.

The addition of a chemical coagulant for phosphorus removal is projected to increase sludge production by approximately 50 percent during the phosphorus removal system and decrease dewatering performance. The projected increase in power for dewatering is 100,000 kWH annually. Changes in sludge composition are expected to impact multiple hearth incinerator efficiency and increase natural gas consumption, resulting in an increase of approximately 14 percent in atmospheric NOx emissions.

The indirect impacts achieving the reduced effluent nutrient limits in Upper Blackstone include:

- 20 percent increase in power consumption
- Five additional 8,000 gallon tanker trucks per day for chemical deliveries
- Consumption of nearly 150,000 gallons of methanol annually
- 50 percent increase in sludge production and a four fold increase in ash production
- 20.6 million cubic feet increase annually in natural gas use
- 14 percent increase in NOx emissions from multiple hearth furnaces

5.6. Point and Nonpoint Source Nutrient Management Comparison

Table 22 presents a summary comparison of point source nutrient reduction using advanced wastewater treatment and nonpoint source nutrient reduction with best management practices. Advanced wastewater treatment is very effective in removal of nitrogen and phosphorus. Costs for advanced treatment have been summarized from the previous discussion of cost studies and presented in a range of values in Table 22. Advanced wastewater treatment for nutrient removal costs substantially more than secondary treatment and also uses much larger amounts of electrical power and chemicals. Electrical power consumption and chemical use produce indirect emissions of greenhouse gases, and advanced treatment generates direct greenhouse gas emissions (nitrous oxide).

Nonpoint source best management practices provide nutrient reduction and a broader array of watershed benefits by enhancing habitat, aesthetics, and reducing sediment loadings. The effectiveness of nonpoint source BMPs in removing nutrients is more variable than point source treatment. However, most nutrient reduction BMPs also remove sediment that is commonly associated with water quality impairment. Nonpoint source BMP costs also vary over a large range, some less than point source reduction and some higher. This highlights the potential for balanced watershed management approaches that combine the most cost effective point and nonpoint source activities and avoid the high marginal costs of treatment that result in little additional nutrient reduction in the watershed. Nonpoint source BMPs do not consume electrical power or chemicals and provide the opportunity to sequester carbon in soils and vegetation.

Table 22. Summary Comparison of Point and Nonpoint Source Nutrient Management

Management Approach	Performance, % Reduction		Cost Effectiveness, $/lb Removed		Electrical Power Consumption	Chemical Use	Greenhouse Gas Emissions	Watershed Enhancements (Habitat, Aesthetics, Sediment Reduction)
	Nitrogen	Phosphorus	Nitrogen	Phosphorus				
Point Source Nutrient Reduction								
Advanced Wastewater Treatment	80 – 90[a]	90 – 99[a]	$0.50 - $3.30[b]	$2.60 – $37.00[b]	50% - 250% increase over Secondary Treatment[c]	Alum, Ferric, Methanol, other carbon sources	120% increase over Secondary Treatment[d]	None
Nonpoint Source Best Management Practices (BMPs)[e]								
Conservation Tillage[f]	15	66	$0.05 – $3.30	$2.60 – $150	None	None	Sequesters Carbon	Moderate
Grass Buffers[g]	50 - 80	50 - 80	$0.60 – $17.00	$11.00 – $190	None	None	Sequesters Carbon	Moderate
Detention Basins[h]	30 - 65	30 - 65	$110	$320 – $700	None	None	Sequesters Carbon	High
Wetlands[i]	<30	15 - 45	$2.20	$43.00 – $52.00	None	None	Sequesters Carbon	High

[a] Assumes nitrogen reduction from 40 mg/l to 8 and 3 mg/l, and phosphorus reduction from 5 mg/l to 0.5 and 0.05 mg/l.
[b] See Table 12. Range of treatment costs from EPA.2008 Municipal Nutrient Removal Technologies Reference Document and Jiang et al converted to unit rates in $/lb.
[c] See Table 21. Range of electrical power consumption selected from the data for operating plants presented in the EPA (2008) Reference Document
[d] EPA 2009 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2007.
[e] See Table 13. Nonpoint source BMP effectiveness rates from EPA 1999. Conservation tillage nitrogen removal from North Carolina Cooperative Extension Service (2001) and phosphorus removal effectiveness from Glover (2008).
[f] Costs from Tables 14, 15, and 16, rounded to two significant digits.
[g] Costs from Tables 14, 15, and 16, rounded to two significant digits.
[h] Costs from Tables 18 and 19, rounded to two significant digits.
[i] Costs from Tables 14 and 15, rounded to two significant digits.

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