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Evaluation of Practical Technology-Based Effluent Standards for Phosphorus and Nitrogen in Illinois

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Project No. W111034

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LIST OF ACRONYMS

A/O	anaerobic-oxic
A^2/O	anaerobic-anoxic-oxic
BAF	biological aerated filter
BOD	biochemical oxygen demand
BNR	biological nutrient removal
BPR	biological phosphorus removal
CWQCD	Colorado Water Quality Control Division
gpd	gallons per day
rbCOD	readily biodegradable chemical oxygen demand
IAWA	Illinois Association of Wastewater Agencies
IEPA	Illinois Environmental Protection Agency
IFAS	integrated fixed-film activated sludge
LOT	limit(s) of technology
MBBR	moving bed bioreactor
MBR	membrane bioreactor
MF	microfiltration
MG	million gallons
MGD	million gallons per day
MLE	Modified Ludzack-Ettinger
NPDES	National Pollutant Discharge Elimination System
O&M	operation and maintenance
PAO	phosphate accumulating organism
PID	phased isolation ditch
RAS	return activated sludge
RBC	rotating biological contactor

RO	reverse osmosis
SBR	sequencing batch reactor
SCADA	supervisory control and data acquisition
SRT	solids retention time
TIN	total inorganic nitrogen
TF	trickling filter
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
UCT	University of Cape Town
UF	ultrafiltration
USEPA	United States Environmental Protection Agency
VIP	Virginia Initiative Plant
VFA	volatile fatty acid
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WWTP	wastewater treatment plant

EXECUTIVE SUMMARY

The objective of this report prepared for the Illinois Association Wastewater Agencies (IAWA) was to assess the technologies applicable for nutrient removal upgrades of the municipal wastewater treatment facilities in Illinois. The overall intent of this assessment was to translate the reasonably expected performance of these technologies into the NPDES effluent limits that can reasonably be met by the upgraded facilities. Costs were to be examined when found incidentally to technology evaluations.

A literature review found numerous applicable technologies and combinations of technologies. These technological solutions differ in the average effluent concentrations of nutrients they can produce and in the variability of their performance. The technological solutions also differ in their applicability to various types of existing facilities, footprint requirements, capital and O&M cost expectations, pumping requirements, consumption of chemicals, additional sludge production, additional electrical energy requirements, operator impacts, and overall expected sustainability.

Nutrient removal performance was assessed separately for phosphorus and nitrogen. Three technology performance levels and one sub-level beyond removal incidental to conventional secondary treatment (removal of organics, suspended solids, and possibly ammonia nitrogen) were identified for each nutrient. The average effluent concentrations for the three performance levels were 1 mg/L, 0.5 mg/L, and 0.1 mg/L for total phosphorus (TP) and 10 mg/L, 6 mg/L, and 3 mg/L for total nitrogen (TN). To promote the desirable features of biological nutrient removal (BNR) in non-ideal existing plant contexts, sub-levels were formulated within the first nutrient removal levels for plant upgrades/retrofits (in contrast with new plants) at 1.5 mg/L for TP and 15 mg/L for TN.

The two nutrients are sufficiently independent of each other to allow removal to non-matching levels; on the other hand, technology interferences make simultaneous removal of both nutrients progressively harder with growing stringency of the effluent requirements.

Both nutrients are commonly regulated in treated wastewater discharges as their “total” analytical forms, which may contain recalcitrant chemical species that do not respond to feasible treatment. Typical recalcitrant nutrient concentrations can be accommodated by being built into the effluent standards, but atypical recalcitrant nutrient concentrations (likely due to influent wastewater characteristics) would require special permit allowances. The most direct way of accommodating the recalcitrant nutrient fractions is to exclude them from the permit limits entirely. This appears to be the technology-based regulatory direction currently pursued for nitrogen (but not for phosphorus) in Colorado. The IAWA member agencies may wish to establish their individual refractory nutrient baselines by monitoring.

The plant upgrade costs are heavily dependent on local conditions, including the existing treatment configuration. Retrofits able to reuse/modify existing treatment facilities are significantly less costly than upgrades in which new/replacement treatment processes are constructed. Activated sludge facilities, especially if nitrifying and underloaded, provide an advantageous starting point for nutrient removal upgrades, as also do facilities with effective filtration. Conversely, plants relying on trickling filters or rotating biological contactors are at a disadvantage (as are lagoon plants, which were not included in this study). The economies of scale and the more limited retrofit opportunities combine to impact smaller plants disproportionately more than the larger plants.

Relevant cost information was recently released in Colorado (CDM, 2011) and is partly summarized in an appendix. The draft report is web-accessible as indicated in the references.

Trade-offs exist between technology performance and sustainability, including operating cost, for both nutrients. For phosphorus, most of these trade-offs relate to the degree to which the treatment relies on chemical addition and on tertiary filtration to remove the particulate fraction of TP from the effluent. Chemical phosphorus removal consumes chemicals (which need to be manufactured and delivered) and produces additional quantities of waste solids (which require processing and disposal), but the chemical phosphorus removal for polishing or as a back-up provides performance reliability that is lacking in biological phosphorus removal (BPR). Tertiary filtration reduces the effluent solids, but does so at the cost of hydraulic head which typically is not available in a retrofit and requires intermediate pumping (which consumes extra electricity). Chemical consumption, additional solids, and extra electricity impact both O&M cost and sustainability. BPR is more narrowly applicable than chemical addition and is also less reliable, but it avoids or reduces the consumption of chemical and the extra solids production. Moreover, a BPR upgrade should not require intermediate pumping unless tertiary filtration must be added. BPR without tertiary filtration and with chemical addition serving merely as a back-up is the most sustainable of the phosphorus removal technologies reviewed, but its level and reliability of performance are not accommodated below the long-term effluent TP concentration target of 1 mg/L. In fact, to maximize the extent to which BPR can be relied upon and chemical feed de-emphasized without undue risk of non-compliance, a more generous TP effluent target of 1.5 mg/L was suggested for existing plant retrofits in Colorado and is suggested here as applicable to Illinois as well. The 0.5 mg/L performance level will likely require chemical addition, tertiary filtration, or both, even at new plants. The 0.1 mg/L effluent TP target will require highly efficient tertiary solids separation with a tertiary chemical polishing step, or the use of membrane solids separation in the secondary treatment (membrane bioreactors).

For nitrogen removal, most performance, cost, and sustainability trade-offs relate to the degree to which the treatment requires supplemental carbon addition and to the need to include tertiary denitrification facilities. Unless produced by in-plant fermentation, supplemental carbon (chemical) addition consumes chemicals (which need to be manufactured and delivered and may pose an elevated operator risk) and produces additional quantities of waste solids (which require processing and disposal). Supplemental carbon addition for denitrification is reduced or avoided by maximizing denitrification relying on the carbon present in the influent wastewater or released through endogenous respiration of activated sludge. Tertiary denitrification provides polishing of effluent nitrogen and reduces the effluent solids, but does so at the cost of hydraulic head which frequently is not available in a retrofit and requires new intermediate pumping (which consumes extra electricity). Moreover, tertiary denitrification automatically relies on supplemental carbon addition. Chemical consumption, additional solids, and extra electricity impact both O&M cost and sustainability. Denitrification without supplemental carbon addition is the most sustainable of the nitrogen removal technologies reviewed, but its level and reliability of performance are not sufficiently accommodated below the long-term effluent TN concentration target of 10 mg/L. In fact, mirroring the pattern of the target effluent nitrogen values recently proposed in Colorado, a more generous effluent total inorganic nitrogen (TIN) target of 12 mg/L (approximately equivalent to a TN target of 15 mg/L) is suggested for existing plants and an effluent TIN target of 8 mg/L (intended to be equivalent to 10 mg/L TN) is suggested for new plants. Additionally, to accommodate dischargers with higher influent TN concentrations, annual average relative removal targets of 60 and 70 percent are suggested as optional alternatives to compliance with the 12 mg/L and 8 mg/L TIN concentration targets for existing and new plants, respectively. These relative removal levels are based on the influent TN despite only reflecting TIN in the effluent. If the 15 mg/L and 10 mg/L TN targets are used instead, the corresponding relative removal levels are 50 and 70 percent.

Implementing the technology performance concentration or relative removal targets by specifying them in permits directly as monthly or shorter averages is not consistent with the technology assessments in the main information sources reviewed for this report. Doing so ignores the inherent effluent variability. The simplest method of implementing the technology performance targets in a manner consistent both with the assumptions in the information sources reviewed and with the context of Illinois' effluent limits intended for compliance without fail would be to specify these targets as annual limits, either annual means, or better yet, annual medians. If monthly limits must be specified, statistical considerations of some complexity are required. It is advisable that IAWA advocate for annual median permit limits without any shorter limits.

Section 1.0
INTRODUCTION

1.1 Purpose of the Report

This report was prepared for the Illinois Association Wastewater Agencies (IAWA) in its support of the potential development of achievable technology-based effluent standards for nutrients in Illinois.

IAWA's objective for this effort is to assess the technologies likely to be applicable for phosphorus and/or nitrogen removal upgrades of the range of facilities in Illinois, with an emphasis on those technologies that promote reliability, cost effectiveness, and low operation and maintenance burden, including by avoiding excessive demands on staffing numbers and sophistication. The relevant technologies must accommodate the possibility that phosphorus removal upgrades will be required before any nitrogen removal upgrades. The overall intent of this assessment of the applicable technologies is to relate their expected performance to the NPDES effluent limits that can reliably be met by the upgraded municipal wastewater treatment facilities.

1.2 Organization of the Report

The remainder of the report is organized as follows. Section 2 deals with the speciation of phosphorus and nitrogen to address the relationship between the main forms of the nutrients, wastewater treatment processes, and the removability of the nutrients from municipal wastewater. Section 3 discusses the performance levels of municipal nutrient removal technologies found in recent literature sources and synthesizes those sources into a technology performance hierarchy. Section 4 further summarizes the individual technologies discussed in Section 3 and their interactions. Section 5 reviews the implications of the nutrient removal technologies in the context of upgrading existing plants. Section 6 summarizes the information on capital and operating costs of the nutrient removal technologies found during the literature review for the other sections of the report. Section 7 addresses the conversion of the reported technology performance levels to discharge permit limits respectful of the practical constraints on plant operations, the theoretical behavior of plant effluent statistics, and the absolute compliance regulatory context in Illinois. Finally, Section 8 provides the conclusions of the report, and Section 9 lists the references cited.

Section 2.0
REMOVABLE VS. RECALCITRANT NUTRIENT FRACTIONS

In considering the realistically attainable performance of the technologies applicable to nutrient removal at municipal wastewater treatment plants (WWTPs), it is important to recognize the existence of total phosphorus (TP) and total nitrogen (TN) fractions that do not respond to treatment, i.e., are not removed or may even increase along the treatment train.

For TP, the fraction that may resist treatment is the dissolved non-reactive phosphorus, which essentially is that portion of “dissolved” phosphorus that is not measured in the orthophosphate (soluble reactive phosphorus) test. The significance of TP speciation in wastewater treatment has recently been discussed by Clark et al. (2010) and WEF (2010a), among others. The particulate fraction of TP, including the chemical and biological solids created from dissolved phosphorus through treatment, is removed through clarification and filtration. The chemical reaction in chemical phosphorus removal removes the orthophosphate fraction of TP, but is limited in its effect on the dissolved polyphosphates and on the dissolved organic phosphorus. In biological treatment, the dissolved polyphosphates and dissolved organic phosphorus fractions are partially converted to orthophosphates, which then can be removed by further biological or chemical treatment. However, the portion of the dissolved polyphosphate and dissolved organic phosphorus fractions that does not respond to biological treatment will pass through to the effluent. This is the “recalcitrant” phosphorus.

Normally municipal wastewaters contain only minor quantities of the recalcitrant forms of phosphorus (0.02 mg/L), but atypical concentrations of approximately 0.5 mg/L have been reported as passing to the effluent from advanced phosphorus removal technologies being pilot-tested at a Massachusetts plant (Lancaster and Madden, 2008).

The following discussion is based on the recently prepared WERF compendium on dissolved organic nitrogen (Stensel, 2008). For TN, the “recalcitrant” fraction is a portion of the dissolved organic nitrogen that resists biological treatment. Biological removal is the only municipally viable alternative for TN removal, and this treatment relies on the following biological transformations: ammonification (hydrolysis and deamination) to convert organic nitrogen into ammonia, nitrification to convert ammonia into nitrite and nitrate, and denitrification to convert nitrite/nitrate into molecular nitrogen and nitrogen oxide gases lost to the atmosphere. Some nitrogen becomes incorporated as particulate organic nitrogen into the biosolids and is removed by clarification and filtration, which can also remove particulate organic nitrogen surviving past biological treatment from the influent. However, a portion of the influent dissolved organic nitrogen resists biological transformations and thus cannot be removed biologically. Moreover, additional dissolved organic nitrogen may be produced during biological treatment (including digestion of biosolids) through cell lysis and decay.

The effluent dissolved organic nitrogen typically ranges from 0.5 to 1.5 mg/L at municipal plants, although significant industrial contributions and other local factors may contribute to levels above the typical range (Bott et al., 2007, Clark et al., 2010, and WEF, 2010a). Bott et al. (2007, p. 12) point to dyeing and finishing operations and

WEF (2010a, p. 497) to food and textile manufacturing as the potential industrial sources of recalcitrant dissolved organic nitrogen.

Stensel (2008) reported effluent dissolved organic nitrogen concentrations for three Illinois plants as 1.6 mg/L, 2.0 mg/L, and 3.6 mg/L. The method of selection of these three plants and the relation of their results to those at other plants in Illinois are not indicated, but the results indicate that the concern with recalcitrant nitrogen is justified.

One potential way of avoiding the impact of unknown recalcitrant nutrient fractions on the permittees' ability to comply with their permits would be to regulate only those nutrient forms that respond to available treatment. For example, instead of TP, the permits could regulate the sum of dissolved orthophosphate (dissolved reactive phosphorus) and particulate phosphorus, and instead of TN, total inorganic nitrogen (TIN) or nitrate nitrogen could be regulated. However, such alternative permitting approaches appear to be an exception. USEPA (2008) reported the permit limits of nine nutrient removing facilities used as case studies; not one of those permits regulated the nutrients other than as TP and/or TN (separate limits for ammonia with or without TN limits excepted). Of the 22 facilities reviewed by Bott and Parker (2011), none had limits on other than TP for phosphorus, one had a TIN limit in addition to a TN limit, and three had either TIN or nitrate nitrogen limits without a TN limit. Of those three permits, two involved discharges into groundwater or to a surface potable water source, and the third had a TIN limit of almost 40 mg/L for a large municipal plant without any denitrification capabilities.

Bott and Parker (2011) also report an example in which USEPA chose to increase a TN limit rather than to change the limit to the TIN basis. The reluctance of the regulators to deviate from focusing the limits on TN appears to be explained in Stensel (2008) and Mulholland et al. (2009). Extending that argument also to TP results in the following statement: unless the nutrient forms recalcitrant in treatment also prove biologically inert in the proximate and ultimate receiving waters, the permitting alternatives to TP and TN may not be equivalent to the total nutrient forms for water quality protection.

Nonetheless, it may be prudent to avoid regulating nitrogen through effluent standards as TN, and instead focus on TIN. In his recent contribution to the Colorado nutrient workgroup's efforts, Lewis (2010) reviewed relevant ecosystems literature and argued against fully including dissolved organic nitrogen in permit limits for nitrogen. In part, his argument was based on the absence of enzymes in algae to utilize organic nitrogen (in contrast to the presence of such enzymes to take up organic phosphorus). While Lewis (2010) suggested counting 50 percent of the effluent dissolved organic nitrogen as bio-available along with TIN against the permit limits, the draft "Nutrients Management Control Regulation" eventually produced and now on the table in Colorado (CWQCD, 2011) proposes to regulate nitrogen as TIN (and phosphorus as TP).

Wastewater treatment agencies may wish to include in their nutrient planning efforts an examination of the levels of the recalcitrant nutrients in their existing effluents, and perhaps in their influents and at intermediate locations along the treatment train. For phosphorus, the key parameter is the difference between the total dissolved phosphorus and the dissolved reactive phosphorus (Lancaster and Madden, 2008). For nitrogen, the key parameter is the difference between the total Kjeldahl nitrogen (TKN) and ammonia nitrogen in a filtered effluent sample (Bott et al., 2007, p. 645). This information may support the agencies in arguing for some allowance in their discharge permits for atypical concentrations of the recalcitrant nutrient fractions. This allowance could accompany the technology based effluent limits in the permits in recognition that not even limit-of-technology treatment processes, let alone the more sustainable basic treatment processes, can remove the recalcitrant nutrient fractions.

For the most part, the remainder of this report follows the widely established precedent by discussing the treatment performance in terms of the total nutrient concentration, TP and TN.

Section 3.0
TECHNOLOGY LEVELS OF NUTRIENT REMOVAL

The following sections are derived from the discussions of nutrient removal performance levels in USEPA's Municipal Nutrient Removal Technologies Reference Document (USEPA, 2008), WEF's Nutrient Removal Manual of Practice (WEF, 2010a), WEF's Technical Submission to EPA (WEF, 2010b), and the first volume of WERF's Nutrient Management reports (Clark et al., 2010). Moreover, the following performance stratification structure largely matches that employed in recent studies into the sustainability trade-offs of municipal nutrient removal, such as that by Falk et al. (2011), although some of the numeric performance targets and technology choices may differ.

The target effluent quality by which the technology performance is expressed in these and similar reports is the typical, long-term effluent concentration referring to averages no shorter than annual. The increasing variability of effluent concentration averages with decreasing averaging period (i.e., with decreasing number of observations used to calculate the average) is a statistical fact that cannot be, and is not, ignored in this report. This issue is discussed after the review of the nutrient removal levels and the applicable upgrade technologies and their costs.

The discussions below address the nutrients separately. This is not intended to suggest that TP and TN cannot be removed at the same level of performance, but rather that they do not necessarily have to be removed at the same level of performance. The TP removal processes and TN removal processes are sufficiently independent of each other in the sense of allowing mixed performance levels for the two nutrients. Even the most aggressive removal of one nutrient can be combined with little more than incidental removal of the other.

On the other hand, the removal processes for the two nutrients are not free of mutual interference. Competing or contradictory design/operation requirements exist that make the combined removal of both nutrients progressively harder with growing stringency of the performance requirements. Interference also exists in the sense that upgrade decisions related to the removal of one nutrient impact the feasibility and economics of simultaneous or subsequent upgrades for the removal of the other. This is discussed in more detail in the nitrogen removal section.

3.1 Phosphorus Removal

Phosphorus removal levels are summarized in Table 1 and further discussed below. The table also contains the approximate raw TP concentrations to facilitate estimates of typical relative removal. Because Table 1 provides the synthesis of the multiple information sources discussed below the table, no single literature source can be cited as its support.

TABLE 1: Comparison of phosphorus concentrations in typical municipal wastewater influents and effluents expected from various levels of phosphorus removal technologies

Nutrient	Typical Raw Municipal Wastewater	Level 0: Secondary Treatment	Level 1P: Basic Municipal Phosphorus Removal		Level 2P: Enhanced P Removal	Level 3P: Limit of Technology P Removal
			Retrofit	New Constr.		
TP, mg/L	4 to 8	4 to 6	1.5	1	0.5	0.1
Relative Removal	0%	20%	70%	80%	90%	98%

Table 1 relates to Table 3-2 in Clark et al. (2010, p. 3-7). Effluent concentration ranges are purposely avoided beyond Level 0 to assure the clarity of the intended meaning. The relative levels of phosphorus removal for Levels 1P through 3P were estimated from their effluent concentrations for a typical raw TP concentration of 5 mg/L (selected close to the bottom of the raw range in recognition of the probable impact of the detergent phosphorus ban).

Level 0: Secondary Treatment (TP 4-6 mg/L)

This level of treatment corresponds to removing carbonaceous biochemical oxygen demand (BOD) and total suspended solids (TSS), with varying extent of nitrification of ammonia, and with only incidental removal of phosphorus by nutrient uptake. The vast majority of municipal WWTPs in Illinois are currently assumed to fit in this category (with lagoon plants forming the notable exception).

As also shown in Table 1, the expected effluent levels of TP for secondary treatment plants are between 4 and 6 mg/L (Clark et al., 2010). It is unclear to what extent the reported TP ranges for raw wastewater and secondary treatment effluents have been rendered obsolete by the recent bans on phosphate in dishwashing detergents. The Illinois Environmental Protection Agency (IEPA) has been including effluent TP monitoring requirements in NPDES permits for several years now, and the collected data could be used to refine the secondary treatment range accordingly. More useful effluent data would include not only the total TP concentrations, but also their speciation into the main chemical forms of which the totals consist.

Level 1P: Basic Municipal Phosphorus Removal (TP 1.5 mg/L Retrofit, 1 mg/L New)

The basic level of TP removal may or may not include chemical addition of metal salts and may or may not include tertiary filtration. The treatment is typically a modification of a secondary treatment process. When labeling this treatment level, literature sources differ in their designations among each other and sometimes within the same report: Clark et al. (2010) use “biological nutrient removal” in Chapter 3 and “conventional municipal nutrient removal” in Chapter 4, while WEF (2010a) terms the processes that can achieve this level as “conventional” or “nominal” nutrient removal.

Whatever label they use, agreement appears to exist among many literature sources on the expected performance of the basic Level 1P technologies at 1 mg/L of effluent TP. This level of TP removal can potentially be accomplished entirely biologically, or a single-point metal salt addition can be used to remove TP in addition to or instead of biological phosphorus removal (BPR). Tertiary filtration, if used, adds robustness to performance, but well-operated secondary clarification may control effluent solids and the TP they contain sufficiently for this TP removal level.

While reliance on BPR is a goal worthwhile from the sustainability standpoint, good engineering practice will typically require that chemical phosphorus removal facilities be installed as part of the TP removal upgrade even for this removal level. For example, the TP removal upgrade projects that were implemented in Illinois in response to the interim TP effluent standard or to third-party negotiated limits of 1.0 mg/L (monthly average) typically relied on chemical phosphorus removal, while only some also incorporated BPR. The explanation for this reliance on chemical in project designs is that BPR alone may not be robust enough to reliably deliver the 1 mg/L TP effluent quality on the monthly average (i.e., maximum month) basis, especially where tertiary filtration is absent. USEPA (2010, p. 8-9) summarizes the operating conditions required by BPR if it is to achieve a 0.5 to 1.0 mg/L effluent TP target as follows: sufficient influent ratio of readily biodegradable chemical oxygen demand (rbCOD) to TP, minimum recycle of oxygen and nitrates to the anaerobic zone, and minimum recycle of phosphorus released in biosolids handling. The need to address the phosphorus in solids processing return streams is also related to the importance of the instantaneous rather than merely the average rbCOD:TP ratio (USEPA, 2010, p. 5-5).

Because effective BPR depends on many variables, in the judgment of the professional engineers responsible for the plant improvement designs chemical removal facilities typically need to be present for standby/polishing and/or solids processing return stream treatment, especially if anaerobic digestion is used. BPR then becomes an optional feature to reduce the chemical consumption and sludge production at the expense of extra capital cost and operational complexity. To encourage BPR-based plant upgrades, the effluent TP standard may have to accommodate the less robust BPR performance expectations by being more generous and/or by not requiring absolute compliance. In Wisconsin, an alternative effluent standard for BPR, NR 217.04(2) 2., corresponds to the effluent TP obtained by removing 90 percent of the TP that would have to be removed to achieve 1 mg/L TP in the effluent, with an upper limit of 2 mg/L on the alternative standard so determined. Thus for 6 mg/L TP in the influent, the alternative BPR effluent standard in Wisconsin would be 1.5 mg/L monthly average TP.

A more generous example of accommodating the basic BPR to reduce reliance on chemical addition is the 1.0 mg/L running annual median TP for plant retrofits in the draft “Nutrients Management Control Regulation” currently on the table in Colorado (CWQCD, 2011); this proposal still fell short of the 1.5 mg/L and 1.0 mg/L annual median TP argued for plant retrofits by the group of wastewater treatment experts participating in the nutrient workgroup (Maxwell, 2011). For new plants, the experts argued for a 1.0 mg/L annual median TP, and the draft regulation proposed a 0.7 mg/L running annual median. CWQCD subsequently explained its proposal not by discounting the experts' justification for different performance expected from retrofitted and new plants, but rather by rethinking its previously expressed goal of avoiding or minimizing the chemical use. The experts' proposal and its premise (minimization of chemical addition) form the basis for the anticipated performance of Level 1P in Table 1.

Level 2P: Enhanced Phosphorus Removal (TP 0.5 mg/L)

The enhanced phosphorus removal level fits within the wide technology performance spectrum between the basic phosphorus removal Level 1P and the current limits of technology (LOT) phosphorus removal Level 3P. Literature sources differ in their decisions as to which effluent concentration targets or target ranges define the enhanced phosphorus removal Level 2P.

WEF (2010a) effectively leaps over this intermediate performance level altogether, because in its report the next level more advanced than Level 1P already corresponds to what most of the reviewed sources reserve for the LOT Level 3P. The statement in the same source that the basic performance (Level 1P for new construction in this report) can typically be accomplished entirely biologically and without tertiary solids separation creates the probably unintended impression that simply adding tertiary filtration to biological treatment could reach Level 3P. This would be an unfortunate impression resulting in unrealistic expectations. This performance and technology leap is avoided in this report, and the intermediate performance technology level is examined.

USEPA (2008) includes the tertiary filtration requirement for TP targets of 0.5 mg/L and below. Neethling (2008, p. 2) states that an effluent of 0.5 to 1.0 mg/L TP can typically be achieved without post-secondary treatment facilities, but tertiary treatment (such as filtration) is needed to reduce effluent TP below 0.5 mg/L. Filtration combined with additional chemical removal can "often" reduce TP to 0.2 to 0.3 mg/L, although "some facilities can do better, others worse, depending on the process arrangements" (Neethling, 2008, p.2). USEPA (2010, p. 8-10) also notes that conventional clarification with BPR and/or chemical phosphorus removal is "not sufficient in many cases" to produce typical effluent TP below 0.5 mg/L, and USEPA (2010, p. 6-3) states that the usual 5 to 10 mg/L TSS in the effluent from traveling-bridge sand filters is not suitable for TP removal below 0.5 mg/L in the effluent. On the other hand, according to USEPA (2007a), BPR in the secondary treatment can "often" reduce TP to 0.3 mg/L or less prior to tertiary filtration.

Insofar as a reasonable synthesis can be derived from the above, it could be that increasing reliance on chemical phosphorus removal and on tertiary solids separation can be expected to achieve the 0.5 mg/L effluent TP target. Further reducing the target to 0.3 mg/L could challenge many plants with conventional tertiary filters and motivate an additional shift away from BPR to reliance on chemical addition.

The plant features to achieve Level 2P performance include:

- increased metal salt use and/or the number of addition points for chemical phosphorus removal, potentially including a tertiary dosing point;

- sludge fermentation or volatile fatty acid (VFA) chemical addition to supplement available VFAs for BPR (if BPR is used to reduce metal salt use);

- removal/recovery of phosphorus from sludge processing return streams (especially if BPR is used with anaerobic digestion); and

- effective tertiary filtration or other tertiary solids separation.

Level 3P: Limit of Technology Phosphorus Removal (TP 0.1 mg/L)

Bott et al. (2007, p. 6) reported that the limit of technology (LOT) for phosphorus removal is typically defined as TP of 0.1 mg/L. USEPA (2007b) reported the same value "at least for larger treatment plants" (p. 5), but stated that the LOT performance has not been demonstrated at plants with capacities below 0.1 million gallons per day (MGD) (p. 6). Clark et al. (2010, p. 3-6) stated that "[t]he most advanced nutrient removal systems operating at the maximum capability of treatment technology with multiple filtration steps or membranes, and larger biological reactors, may reduce effluent phosphorus to approximately 0.05 to 0.07 mg/l". Neethling et al. (2009) observed that performance variability increases as the median effluent TP and TN concentrations decrease, and argued for defining nutrient removal LOT probabilistically, i.e., by coupling numerical values with a designation of the associated performance statistic (such as the 95th percentile monthly average). Using that approach, Bott and Parker (2011) examined the performance of 22 exemplary plants in the U.S. and Canada. They concluded that the 0.1 mg/L effluent TP was largely achievable by plants employing tertiary chemical addition and solids separation as an annual average but not nearly so reliably as a monthly average.

To remove TP to lower residual concentrations than Level 3P, the recalcitrant dissolved phosphorus forms may need to be removed. There is no reliable method for removing these nutrient forms except reverse osmosis (RO) (WEF, 2010a).

Because of the number of the technology components this level of nutrient removal requires, it may not be practically feasible at all existing plant sites, given their existing process, hydraulic, and footprint limitations. The LOT phosphorus removal requires all of the applicable features discussed for Level 2P, with an emphasis on highly effective tertiary solids separation.

The plant features to achieve this level of performance include:

- increased metal salt use and/or number of addition points for chemical phosphorus removal, including a tertiary dosing point;

- sludge fermentation or VFA chemical addition to supplement available VFAs for BPR (if BPR is used to reduce metal salt use);

- removal/recovery of phosphorus from sludge processing return streams (especially if BPR is used with anaerobic digestion); and

- highly effective tertiary filtration or other tertiary solids separation.

3.2 Nitrogen Removal

Nitrogen removal levels are summarized in Table 2 and further discussed below. The table also contains the approximate raw TN concentrations to facilitate estimates of typical relative removal. Because Table 2 provides the synthesis of the multiple information sources discussed below the table, no single literature source can be cited as its support.

TABLE 2: Comparison of nitrogen concentrations in typical municipal wastewater influents and effluents expected from various levels of nitrogen removal technologies

Nutrient	Typical Raw Municipal Wastewater	Level 0: Secondary Treatment	Level 1N: Basic Municipal N Removal		Level 2N: Enhanced N Removal	Level 3N: Limit of Technology N Removal
			Retrofit	New Constr.		
TN, mg/L	25 to 35	20 to 30	15	10	6	3
Relative Removal (TN)	0%	20%	50%	70%	80%	90%
TIN, mg/L			12	8		
Relative Removal (TIN)			60%	70%		

Table 2 relates to Table 3-2 in Clark et al. (2010, p. 3-7). Effluent concentration ranges are purposely avoided beyond Level 0 to assure the clarity of the intended meaning. Relative levels of removal were derived as stated below.

Level 0: Secondary Treatment (TN 20-30 mg/L)

This level of treatment corresponds to removing carbonaceous BOD and TSS, with varying extent of nitrification of ammonia, and with only incidental removal of TN by nutrient uptake and by incidental denitrification (potentially simultaneous with nitrification). The vast majority of municipal WWTPs in Illinois are currently assumed to fit in this category (with lagoon plants forming the notable exception).

As also shown in Table 2, the expected effluent levels of TN from secondary treatment are between 20 and 30 mg/L (Clark et al., 2010). The IEPA has been including effluent TN monitoring requirements in NPDES permits for several years now, and the collected data could be used to refine the secondary treatment range accordingly. More useful effluent data would include not only the total TN concentrations, but also their speciation into the main chemical forms of which the totals consist.

Level 1N: Basic Municipal Nitrogen Removal (TN 15 mg/L Retrofit, 10 mg/L New)

The basic level of nitrogen removal may or may not include addition of supplemental carbon for TN removal and generally does not need to include tertiary filtration or other tertiary treatment. The treatment is typically a modification of a secondary treatment process or series of secondary treatment processes.

In addition to the varying labels for this nitrogen removal level (similar to the basic phosphorus removal level discussed above), much variability is also evident among the literature reports on the expected performance of the basic technologies for TN removal. Clark et al. (2010) expect "~10" mg/L TN in Chapter 3 and 8 mg/L TN in Chapter 4, in each case remarking in matching footnotes that the "effluent concentrations vary widely according to the averaging period and/or performance statistic employed" (pp. 3-7 and 4-13). WEF (2010a) expects 8 mg/L TN (presumably as the "typical monthly performance achievable", p. 86). USEPA (2008) expects "8 mg/L or higher" (Table 5-2, p. 5-4), and bases its technology performance discussions on annual average target concentrations throughout the report. USEPA (2009, p. 44) expects the Modified Ludzack-Ettinger (MLE) process to be "often sufficient" for a TN effluent goal of 10 mg/L, as long as this does not require the removal of more than 80 to 85 percent of the influent TN. On the other hand, USEPA (2010) suggests the Level 1N technologies for up to 70-percent TN removal and states that they are "often" (p. 8-9) sufficient to produce effluents with TN "typically" between 5 and 8 mg/L, although achieving this year-round in very cold climates presumes that the internal recycle rates can be sufficiently increased. WEF (2010b) examined the applicable internal recycle rates and puts the achievable range of the Level 1N technologies at 6 to 10 mg/L TN.

The main area of agreement of the literature sources reviewed with respect to TN removal at Level 1N appears to be the expectation that this treatment level typically does not require supplemental carbon addition and can rely on a single pre-anoxic zone in a combined-stage activated sludge system. In fact, the applicability of this particular treatment technology appears to constitute the approach in the cited sources to defining the basic TN removal that this report designates as Level 1N. Recognizing the U.S.-wide or even sub-continental scope of the USEPA, WEF, and WERF sources cited and allowing for the lower winter temperatures in Illinois relative to much of the U.S., the synthesis of the performance expectations for Level 1N removal suggests an effluent concentration target of 10 mg/L TN.

However, it is acknowledged that a group of wastewater treatment experts in Colorado recently suggested a more generous set of performance expectations to better accommodate the anticipated variability of the effluents from Level 1N technologies, especially in the more challenging retrofit contexts (Maxwell, 2011). As already stated, the Colorado technology limits for nitrogen target TIN instead of TN. The numerical values are 15 mg/L for retrofits and 10 mg/L for new plants as suggested by the experts, and 10 mg/L for retrofits and 7 mg/L for new plants as proposed in the draft regulation (Maxwell, 2011). Because all of these values are annual median effluent TIN concentrations, they are more generous than the 10 mg/L annual average effluent TN target.

Furthermore, to accommodate the Level 1N technologies for atypical wastewaters in which the concentration target would be unattainable due to industrial sources or tighter sewer systems, a required relative removal of 70 percent of the raw influent TN would be useful as an alternative means of complying with the 10 mg/L TN concentration limit. This relative removal matches one of the USEPA values cited above and comes close to the center of the removal range corresponding to the “typical raw municipal wastewater” shown in Table 2.

Due to rounding, the approximately 70-percent relative removal shown in Table 2 for Level 1N applies reasonably well both to the 10 mg/L TN target and to the 8 mg/L TIN target suggested for new plants. The 12 mg/L TIN target suggested for plant retrofits corresponds to approximately 60-percent removal of the influent TN, while the 15 mg/L TN target for retrofits corresponds to 50-percent TN removal. The relative removal levels for TIN effluent concentrations use the full influent TN as the removal basis despite disregarding organic nitrogen in the effluent. Influent TIN is not satisfactory as the basis for relative TIN removal because it ignores the likely significant organic component of the influent TN which is only converted to inorganic nitrogen during wastewater treatment.

By definition, TN removal at Level 1N is typically within the abilities of all the mainstream biological denitrification flow sheets, with or without anaerobic zones for BPR. Thus even processes that include only a single anoxic zone upstream of the aerobic zone for denitrification utilizing carbon present in the wastewater (without supplemental carbon addition) can typically be designed and operated for TN removal at this level. The reactor and recycle configurations of biological wastewater treatment systems for nutrient removal mentioned in this report have all been described elsewhere, including in the manuals by USEPA (2009) and USEPA (2010) that are accessible free of charge as shown in the references. Note that the older manual (USEPA, 2009) was an interim product that depicted a wider assortment of reactor configurations than was carried through to the final report by USEPA (2010).

Because they lack an anoxic zone in the wastewater flow path, the A/O and modified A/O (i.e., A/O with a return activated sludge [RAS] denitrification zone) process configurations only accomplish denitrification incidentally to BPR and thus should not be considered TN removal processes or expected to meet this level of TN removal. On the other hand, the well-known MLE, A^2/O, UCT/VIP, 4- and 5-stage Bardenpho, Johannesburg, Westbank, and step-feed configurations of activated sludge are typically applicable, as are oxidation ditches promoting nitrification/denitrification, including the multi-channel or phased isolation ditch (PID) designs. Membrane bioreactors (MBRs) with ultrafiltration (UF) or microfiltration (MF) membranes instead of secondary clarifiers, as well as sequencing batch reactors (SBRs) with unaerated cycle components, are also included at this level.

Because tertiary denitrification processes used as add-ons downstream of the secondary treatment facilities can be configured for the more stringent TN removal levels, they can also be used for TN removal at Level 1N. This, however, requires supplemental carbon addition for denitrification and potentially additional pumping already at Level 1N. The add-ons can consist of biofilm-based processes (denitrifying biological aerated filter [BAF], denitrification filters) or suspended-growth activated sludge with its own set of clarifiers. Depending on whether the upstream secondary treatment is sufficiently nitrifying, the tertiary TN polishing process may also need to provide or complete nitrification before the tertiary denitrification. Because of the extra capital and operating expense, tertiary TN removal should be used to achieve the Level 1N performance level only as a last resort, such as when the upstream process is non-nitrifying and does not lend itself to the creation or integration of anoxic zones for denitrification within secondary treatment, such as trickling filters (TFs) and rotating biological contactors (RBCs). When the secondary treatment cannot readily be upgraded to Level 1N TN removal, an alternative to the costly tertiary TN removal is the likewise costly upgrade of the secondary treatment to MBRs.

Level 2N: Enhanced Nitrogen Removal (TN 6 mg/L)

The enhanced nitrogen removal level fits within the wide technology performance spectrum between the basic nitrogen removal Level 1N and the current LOT nitrogen removal Level 3N. Literature sources differ in their decisions as to which effluent concentration targets or target ranges define the enhanced nitrogen removal Level 2N. The decision in this report was to set this TN removal level at the estimated margin of applicability of denitrification relying on wastewater and endogenous respiration carbon sources without supplemental carbon addition in a colder climate.

USEPA (2010, p. 8-9) expects the performance of dual anoxic zone systems to allow 70 to 90-percent TN removal, or typically 3 to 5 mg/L TN in the effluent. WEF (2010b) adds the second anoxic stage with supplemental carbon for effluent TN targets of 6 mg/L and below (compared with the single anoxic zone systems for effluent TN targets between 6 mg/L and 10 mg/L).

In some cases, supplemental carbon addition and/or tertiary denitrification will be inevitable or economically preferable to avoiding carbon addition by oversizing the post-anoxic zone of a combined-stage system at this performance level. For example, USEPA (2009, p. 44) states that for TN goals of 3 to 5 mg/L post-anoxic treatment is generally needed and, although endogenous respiration can be used to remove nitrate in post-anoxic tanks, it is “often necessary” to add supplemental carbon to those tanks. USEPA (2010, p. 6-36) states that post-anoxic zone denitrification often requires supplemental carbon, especially in colder regions due to low endogenous denitrification rates.

Thus an effluent target of 6 mg/L provides a reasonable synthesis of the expectations in the cited sources with respect to the effect of adding post-anoxic zones to single-sludge activated sludge systems, possibly without forcing the addition of supplemental carbon.

According to WEF (2010b), oxidation ditches and SBRs can also be configured and operated for TN removal to Level 2N. On the other hand, the ability of the step feed activated sludge systems to deliver the Level 2N performance is questionable because of the nitrogen present in the feed to the last pass (WEF, 2010b).

Tertiary denitrification technologies applicable to Level 3N removal can also be used to meet Level 2N performance requirements.

To accommodate the Level 2N technologies for atypical wastewaters in which the 6 mg/L TN target would be unattainable for these technologies, a required relative removal of 80 percent of the raw influent TN could be specified as an alternative means of complying with the permit. This relative removal matches the center of the USEPA relative range cited above and also the reduction of the mid-range “typical raw municipal wastewater” shown in Table 2 to the 6 mg/L target.

The plant features to achieve Level 2N performance include:

- multiple anoxic zones in combined or separate stages;
- tank volume sufficient for endogenous respiration as a carbon source or supplemental carbon addition to sustain denitrification in post-anoxic zones of a combined-stage activated sludge system; or the addition of tertiary denitrification filters/activated sludge with supplemental carbon feed;
- removal/recovery of nitrogen from sludge processing return streams or equalization of those streams.

Level 3N: Limit of Technology Nitrogen Removal (TN 3 mg/L)

Bott et al. (2007, p. 6) reported that the LOT for nitrogen removal is typically defined as TN of 3.0 mg/L. USEPA (2007b) reported the same value “at least for larger treatment plants” (p. 5), but stated that the LOT performance has not been demonstrated at plants with capacities below 0.1 MGD (p. 6). Clark et al. (2010, p. 3-6) stated that “[t]he most advanced nutrient removal systems operating at the maximum capability of treatment technology with multiple filtration steps or membranes, and larger biological reactors, may reduce effluent phosphorus to approximately 0.05 to 0.07 mg/l and effluent nitrogen to 3 to 4 mg/l”. Neethling et al. (2009) observed that performance variability increases as the median effluent nutrient concentrations decrease, and argued for defining nutrient removal LOT probabilistically, i.e., by coupling numerical values with a designation of the associated performance statistic (such as the 95th percentile monthly average). Using that approach, Bott and Parker (2011) examined the performance of 22 exemplary plants in the U.S. and Canada. They concluded that the 3.0 mg/L effluent TN was achievable as an annual average by plants incorporating separate denitrification (with supplemental carbon addition) downstream of secondary clarifiers, but not otherwise.

To remove TN to lower residual concentrations than Level 3N, the recalcitrant dissolved nitrogen may need to be removed. There is no reliable method for removing the recalcitrant nutrient forms other than RO (WEF, 2010a).

Because of the number of the technology components this level of nutrient removal requires, it may not be practically feasible at all existing plant sites, given their existing process, hydraulic, and footprint limitations. This TN removal level is expected to require a tertiary denitrification step with supplemental carbon addition. USEPA (2010, p. 8-9) equates performance at this level (effluent TN of 3 mg/L or less) to removing 90 percent of TN, emphasizes the need for process optimization and effective automation, and observes that effluent dissolved organic nitrogen may limit the ability to perform at this level. Stensel (2008, p. 2) also states that in many cases 3 mg/L TN in the effluent represents the LOT for biological nitrogen removal, and that most LOT plants employ effluent filtration or membrane separation.

USEPA (2009, p. 62) also mentions the role of effluent filtration in removing a portion of the effluent organic nitrogen surviving biological treatment and secondary clarification.

The plant features to achieve this level of performance include:

- tertiary denitrification stage with supplemental carbon addition;
- removal/recovery of nitrogen from sludge processing return streams or equalization of those streams; and
- effective tertiary filtration or other tertiary solids separation (tertiary denitrification filters may serve this function).

Section 4.0
APPLICABLE UPGRADE TECHNOLOGIES

4.1 Chemical Phosphorus Removal

Metal salt addition to primary clarifiers, activated sludge tanks, secondary clarifiers, tertiary treatment, or sludge processing return streams to precipitate/adsorb phosphorus into chemical sludge is essentially universally applicable to the range of Illinois facilities. Any facility that employs primary or secondary clarification is expected to be amenable to a chemical phosphorus removal upgrade. For the pH range typical for municipal plants, salts of two cations are applicable: iron and aluminum.

The technology is mature and well known in Illinois, where its use has been growing as a primary or back-up means of compliance with the interim phosphorus effluent standard of 1.0 mg/L as a monthly average. Its advantages include generally low capital cost and low footprint requirements (especially if suitable building space to house the chemical storage and feed equipment is already available), and relative simplicity and high reliability of operation. The technology is flexible in that increasing the chemical dose and/or the number of addition points tends to improve the effluent performance. Other than the alkalinity reduction by the addition of aluminum/iron salts of strong acids (sulfates, chlorides) in low alkalinity wastewaters (which may limit nitrification and may require alkalinity preservation or addition, separately or integrally, such as through polyaluminum chloride or sodium aluminate in lieu of alum) and the reduction of secondary influent organics by chemical addition to primary clarification, chemical phosphorus removal is not expected to interfere with TN removal and can be implemented jointly with or separately from the TN upgrade. The main disadvantages of chemical phosphorus removal include the high O&M cost for the chemical, and the increased sludge production due to the chemical sludge (generally a 15 to 30 percent increase) that requires processing. The increased sludge production may necessitate solids processing and storage improvements for plants close enough to their solids processing capacity.

Where applicable, BPR may be used instead of, or in conjunction with, chemical phosphorus removal to reduce the required chemical dose and resulting sludge production.

Rather than aluminum or iron salts, lime can potentially also be applied to remove phosphorus chemically. However, the quantity of lime sludge produced and the high capital expense and O&M issues related to storage, handling, and feeding of lime make lime addition impractical, including for the purposes of this report.

The expected performance of chemical phosphorus removal is a matter of influent phosphorus speciation, dosing point number and location, chemical dose, and plant context. Without tertiary filtration, chemical phosphorus removal (alone or in combination with biological phosphorus and/or nitrogen removal) should not be expected to perform much beyond Level 1P. It is noted that the existing record of compliance of Illinois plants without filters with the interim phosphorus effluent standard (which numerically matches the Level 1P target but is harder to meet because it is implemented as a monthly average) indicates performance towards Level 2P. Indeed, USEPA (2008) places the typical (long-term average) performance of chemical phosphorus removal at 0.5 to 1.0 mg/L. With filtration, the expected performance reaches the enhanced removal Level 2P (i.e., 0.5 mg/L TP target). Combined with highly efficient tertiary solids removal through filtration or similar tertiary methods, chemical phosphorus removal including a tertiary dosing point constitutes an essential part of the LOT portfolio for Level 3P phosphorus removal.

Some of the tertiary phosphorus removal methods are not yet widespread enough to allow conclusions on the TP removal LOT, although they appear to promising. These technologies have been discussed by USEPA (2007a).

4.2 Biological Phosphorus Removal

BPR is also a firmly established, if still evolving, wastewater treatment technology. Freely accessible reports by USEPA (2009) and USEPA (2010) provide descriptions of the biological process configurations for BPR and TN removal, including those discussed in this report.

BPR relies on encouraging the growth of the assemblage of phosphate accumulating organisms (PAOs) by alternating exposure to anaerobic and oxic (aerobic) conditions. The PAOs with the accumulated phosphorus are removed with waste activated sludge. The simplest BPR activated sludge process configuration is known as A/O (originally Phoredox). The A/O configuration is not directly applicable for the purposes of this report because it does not address TN removal and, unless modified by adding RAS denitrification, cannot be implemented in a nitrifying activated sludge process (where the attempted A/O simply becomes the anoxic selector [or Ludzack-Ettinger] activated sludge configuration). IAWA must consider the possibility that TN will also be regulated in municipal effluents in Illinois, and fully nitrifying plants are the norm rather than the exception in the State.

Many activated sludge configurations building on the A/O concept are available that remove TN in addition to removing TP biologically. All of them include at least one zone of each of the following types: anaerobic zone ideally devoid of dissolved oxygen and nitrate nitrogen with volatile fatty acids (VFAs) present, anoxic zone ideally devoid of dissolved oxygen with nitrate nitrogen and organic carbon present, and oxic zone with sufficient dissolved oxygen. The various configurations represent different combinations of the reactor and recycle arrangement solutions to the various process challenges, such the need to avoid recycling nitrates and dissolved oxygen to the anaerobic zone with RAS, the need to have both organic carbon and nitrate nitrogen available in the anoxic zone(s), and the fact that nitrates are not appreciably produced by nitrification until most of the organic carbon has been removed. Which particular process configuration may be the most advantageous for the upgrade of a particular facility for BPR depends on site-specific factors, but such level of detail is not necessary for the purposes of this report, and especially not when it comes to BPR performance.

Activated sludge plants, including oxidation ditches and SBRs, can generally be configured for BPR with TN removal, although local conditions may make BPR within existing tanks less practical at some of the plants. For example, a facility with multiple activated sludge tanks that cannot be operated in series will require the addition of a baffle wall, mixer, and any internal recycle piping and pumping facilities within each activated sludge tank; also any RAS entry modifications will need to be done for each tank. This is in contrast with those activated facilities that operate tanks in series, such that an entire tank may be converted to an appropriately sized non-aerated zone. The alternative to converting each of the multiple parallel activated sludge tanks to BPR removal is to construct the upstream non-aerated zone(s) as new tank volume.

Additionally, because BPR relies on the exposure of suspended-growth PAOs in the mixed liquor to various environmental conditions, it is not readily applicable to upgrading plants that rely on attached-growth secondary treatment, such as TF and RBC plants. For these facilities, the BPR upgrade would likely involve a costly switch to activated sludge treatment and likely either additional secondary clarifier capacity or membranes (MBR). A TF hybrid with activated sludge successfully applied to BPR with TN removal was reported (Kelly et al., 2006); in this configuration, the TFs provided the nitrification function, and all of the anaerobic and anoxic zones were implemented in activated sludge tanks. Thus activated sludge hybrids employing TFs or RBCs in place of the aerated zones of the nutrient removal flow sheets are possible; however, the feasibility and cost-effectiveness of such hybrid arrangements will vary from plant to plant.

As already stated above, a major disadvantage of BPR is its lower reliability of performance. As a biological treatment method, BPR is susceptible to biological upsets and is less controllable than chemical phosphorus removal. On the other hand, the highly desirable feature of BPR is its avoidance or reduction of metal salt addition and lower sludge production. Where BPR is feasible, it potentially offers a cost-effective and more environmentally sustainable addition to chemical phosphorus removal. The outcome of the economic comparison between BPR and chemical removal of phosphorus will reflect the influent BOD to TP ratio as well as the concentration of TP to be removed (Reardon, 1994; WEF, 2010b).

The Kelowna plant example discussed in Section 7.1 shows that the inclusion of standby chemical phosphorus removal facilities in BPR upgrades is a prudent precaution, unless the discharge permit can be structured in a way accommodating the occasional performance fluctuations of the BPR systems.

The expected performance of BPR mirrors that described for chemical phosphorus removal, except that BPR’s biological temperament must be acknowledged. Without tertiary filtration and not supplemented by chemical phosphorus removal, BPR <u>may</u> suffice at Level 1P, but not far beyond. Even at Level 1P, a chemical back-up is a reasonable precaution for the event of a biological upset. USEPA (2010, p. 8-9) recommends that a chemical back-up be considered for consistent compliance of BPR at 80 to 90 percent TP removal and a performance target of 0.5 to 1.0 mg/L. USEPA (1987, p. 31) stated that excellent secondary clarifier performance or effluent soluble phosphorus uncommonly low for BPR would be needed to meet an effluent TP of 1.0 mg/L while relying on BPR without polishing filters. To accommodate BPR without chemical addition and without filtration, a group of wastewater treatment experts participating in the Colorado nutrient workgroup recommended 1.5 mg/L and 1.0 mg/L annual median TP effluent limits for plant retrofits and for new construction, respectively (Maxwell, 2011).

Moving into Level 2P (defined as the 0.5 mg/L TP performance target) requires both a chemical back-up or polishing and efficient tertiary solids separation. Combined with highly efficient tertiary solids removal through filtration or other tertiary methods and with chemical phosphorus removal at multiple points of addition including a tertiary dosing point, BPR may constitute a desirable component of the LOT portfolio for Level 3P phosphorus removal.

4.3 Biological Nitrogen Removal

Unlike with TP removal, municipally applicable TN removal must rely on biological treatment that goes beyond mere nitrogen uptake for biological growth, without any feasible recourse to a purely chemical polishing or back-up method. Consequently, the need to accommodate the potential TN upgrade in the future constrains the biological treatment considerations even for BPR.

TN removal relies on biological denitrification in which an assemblage of heterotrophic bacteria oxidizes organic matter in the absence of dissolved oxygen by utilizing nitrate (or nitrite) nitrogen for “respiration” instead (reducing it in the process to nitrogen gas and nitrous oxide, both lost to the atmosphere). By definition, this removal mechanism presumes that organic nitrogen has been converted to ammonia (during the destruction of the organic compounds in the wastewater) and that the remaining original and additional ammonia has been converted to nitrate nitrogen by biological nitrification. Many Illinois plants are already required to nitrify to comply with ammonia effluent limits; others nitrify at least to some extent or seasonally without an explicit NPDES requirement to do so.

For plants that need to complete their nitrification (either because of new/stricter ammonia limits or because of having to upgrade to TN removal), the upgrade solution may involve the addition of more activated sludge tank volume upstream of the secondary clarifiers, or the addition of attached-growth media to the existing activated sludge tanks (integrated fixed-film activated sludge [IFAS] or moving bed bioreactor [MBBR]) or as tertiary nitrification filters (BAFs) downstream of the secondary clarifiers. The addition of tertiary nitrification as a separate activated sludge stage with its own set of clarifiers and RAS facilities is also a possibility, although the footprint requirements make it less competitive. The IEPA has historically been reluctant to accept proposals for IFAS-based nitrification upgrades not providing compliant volumetric organic bulk tank loading for single-stage nitrification. If possible, the secondary nitrification upgrade is preferred because it avoids intermediate pumping to the tertiary filters and maximizes the probability that wastewater or endogenous respiration carbon can be utilized for denitrification instead of supplemental carbon for the TN upgrade.

Denitrification can be implemented in suspended-growth (activated sludge) or attached-growth (fixed-film) systems, and with or without supplemental carbon addition (if within secondary treatment). The purely attached-growth implementations (denitrification filters) generally fit in the tertiary position where denitrification does require supplemental carbon. This offers a greater degree of denitrification control but involves extra footprint, probable need for intermediate pumping, and significant O&M expense for the supplemental carbon chemical. Hybrid implementations for denitrification are available that combine attached growth with suspended growth (IFAS and MBBR) and can be implemented upstream of the secondary clarifiers. Denitrification systems that are implemented as activated sludge configurations upstream of the secondary clarifiers reduce or avoid the need to add supplemental carbon and typically eliminate the necessity to add intermediate pumping.

Suspended growth denitrification relying on supplemental carbon can also be implemented in a separate suspended growth stage downstream from the secondary clarifiers of the nitrifying activated sludge (USEPA, 2010). This typically requires the expense of adding an extra set of clarifiers and RAS pumping facilities, and might also involve intermediate pumping. USEPA (2008) provides an example of an activated sludge plant with three separate activated sludge stages: carbonaceous removal stage, nitrification stage, and denitrification stage.

Activated sludge plants, including oxidation ditches and SBRs, can generally be configured for TN removal (possibly with BPR), although local conditions may make the upgrade more challenging to implement in the existing tank volume at some of the plants. As with BPR, the TN removal upgrade within existing tanks is a more promising alternative for plants using activated sludge tanks in series than it is for facilities relying on multiple parallel tanks, where duplication of baffles, mixers, internal recycles, and RAS entry modifications would be expected. Additionally, the plants whose existing secondary treatment is based on attached growth (TFs or RBCs) present special challenges for upgrades to TN removal in that they are not readily integrated into treatment schemes avoiding the expense of supplemental carbon addition and intermediate pumping for denitrification.

In the interest of cost-effectiveness, denitrification in the single activated sludge stage with carbonaceous removal and nitrification is the preferred approach (to minimize pumping and supplemental carbon needs). Many process configurations are available that differ in their reactor and recycle arrangements, but essentially address the same process challenges. Some of these configurations only remove TN, while most also remove TP biologically. The freely accessible reports by USEPA (2009) and USEPA (2010) describe the various process configurations, including those discussed below.

For the purposes of this report, the most important considerations relating to these combined-stage processes are the number of anoxic zones present and the reliance on supplemental carbon addition in the downstream anoxic zones.

The simplest combined stage denitrification process configurations only include one anoxic zone in the mixed liquor flow path and do not include supplemental carbon addition. The representative configurations include MLE, A^2/O, UCT/VIP, Westbank, and step feed. (MLE does not include BPR; step feed can be configured to include BPR.) USEPA (2008) includes several examples of such systems, some performing into Level 2N, others remaining in Level 1N. Consequently, the single anoxic zone configurations without filtration should not be expected to perform better than at Level 1N. See also the Nitrogen Control Manual (USEPA 1993, p. 284). SBRs and oxidation ditches can also generally be configured to denitrify at Level 1N (USEPA, 2008).

Applications of step-feed systems to BPR with TN removal are described much less widely than the other activated sludge process configurations for nutrient removal, including the TN-only step feed. Because of its potential significance for cost-effective

TN/BPR retrofits within existing tank volume, this configuration is addressed in some detail here. Step-feed systems for TN removal alone or in combination with BPR were discussed by Johnson et al. (2005). The step-feed arrangement avoids the internal recycle of nitrified mixed liquor by feeding portions of the secondary influent to the unaerated upstream zone of each pass and relies on the forward flow of nitrates from the aerobic zone of one pass to the anoxic zone of the next pass.

As also described by USEPA (2009) and USEPA (2010), in step feed for TN-only removal, two zones per pass (anoxic followed by aerobic) are used; the anoxic zone in each pass receives a portion of the wastewater feed. The RAS enters the anoxic zone of the most upstream pass, and the most downstream pass may receive no wastewater feed.

A more complex step-feed arrangement is needed to simultaneously maximize BPR. The BPR step feed was described by Crawford et al. (2000) and Johnson et al. (2003). Each pass consists of three zones (anaerobic, anoxic, and aerobic) essentially replicating a UCT scheme in each pass. A portion of the secondary influent is fed to the anaerobic zone of each pass, which also receives an internal recycle from the immediately downstream anoxic zone. Mixed liquor flows from the anaerobic zone to the anoxic zone and then to the aerobic zone of the pass, and then is routed to the anoxic (not anaerobic) zone of the next pass. RAS enters the anoxic (not anaerobic) zone of the most upstream pass. The most downstream pass may receive no wastewater feed and may lack the anaerobic zone.

To accommodate the Level 1N treatment processes without chemical addition and without filtration, a group of wastewater treatment experts participating in the Colorado nutrient workgroup recommended 15 mg/L and 10 mg/L annual median TIN effluent limits for plant retrofits and for new construction, respectively (Maxwell, 2011).

Improving the TN removal performance of combined-stage activated sludge processes to Level 2N will generally require a second anoxic zone in the main wastewater path downstream of the nitrification zone, with 4- and 5-stage Bardenpho as representative configurations. (Note that 4-stage Bardenpho does not include BPR.) However, without supplemental carbon addition to the downstream anoxic zone of these systems, the denitrification rate in that zone will be low in cold climates. The overall performance in Illinois should not be expected to match the Florida experience (at less than 3 mg/L TN). WEF (2010b, pp. 32 and 50) estimates that achieving effluents below 6 mg/L will require supplemental carbon addition to the downstream anoxic zone. A reasonable TN target for dual anoxic zone systems in Illinois is 6 mg/L, towards the top of the 3-6 mg/L range considered by USEPA (1993), but in some systems even this level will require supplemental carbon. WEF (2010b) includes oxidation ditches and SBRs in technologies able to meet Level 2N performance.

Achieving Level 3N performance in Illinois will typically require supplemental carbon feed to a separate, tertiary denitrification stage, even if a denitrifying system (such as a combined-stage denitrifying activated sludge) is also employed upstream. The tertiary denitrification step, such as a denitrifying filter, will provide the polishing required for the LOT removal of TN. Some recently developed technologies based on continuous back-wash sand filtration appear to offer the opportunity to combine chemical phosphorus removal, denitrification, and effluent solids polishing in one tertiary treatment step. The treatment is not yet widespread enough to allow conclusions with respect to its impact on the nutrient removal LOT.

While the nutrient removal levels discussed in this report deal with the two nutrients separately and do not clearly distinguish between removing one nutrient or both, it has been recognized (e.g., Bott and Parker, 2011) that removing both TP and TN is a harder task than removing either TP or TN, especially the closer the required performance comes to the LOT Level 3. This is not only because the simultaneous removal of both nutrients is a more complex enterprise than the removal of one, but also because the optimum design and operating conditions differ for the two nutrients, and because some issues of conflict exist. These conflict issues include the optimum solids retention time (SRT), competition for influent organics, nutrient needs, and desirability of high secondary clarifier blankets. Furthermore, as the required performance approaches the LOT level, even the typical municipal concentrations of the recalcitrant nutrient fractions may begin to interfere with compliance.

4.4 Return Stream Processing

As discussed above, BNR processes are highly dependent on influent wastewater characteristics. The needed amount of chemical, such as metal salt for TP removal and supplemental carbon for denitrification, also depends on the influent to the process. In this context, “influent” refers to the influent to the biological or chemical nutrient removal process rather than to the raw influent to the WWTP, and thus reflects the net effect of any upstream treatment processes (primary clarification) and any upstream introduction of plant return streams (digestion supernatant, dewatering filtrate/centrate, etc.). The effects of the plant return streams are especially significant when they are related to anaerobic digestion of biosolids; in that case the return streams from solids processing can contain 50 to 500 mg/L of TP and 500 to 1,500 mg/L of ammonia nitrogen (WEF, 2010a). The high nutrient concentrations in the return streams can lower the influent ratio of available organics to nutrient content, which impacts both BPR and denitrification. Additionally, the return streams are often intermittent rather than constant, resulting in dynamic peaks in the influent nutrient concentrations and in the shortage of organics relative to the nutrient loading.

The return stream attenuation may be critical for compliance with TP or TN effluent limits (WEF, 2010a). The attenuation can consist of return stream equalization (through storage or operating practices) for peak nutrient loading reduction, separate treatment of the return streams (by nutrient removal or recovery using stand-alone chemical or biological processes), and (for nitrogen) return stream treatment integrated into the mainstream treatment process (such as by introducing the return streams into a reactor on the RAS line).

4.5 Tertiary Filtration

Because effluent TSS contain nutrients, effluent TSS reduction by tertiary filtration may be essential for compliance with TP or TN effluent limits. Tertiary filters can be of the traditional granular-media down-flow type, using single- or multiple-media shallow (conventional) beds, or of the deep-bed type. Continuous backwash upflow sand filters, cloth filters, and low-pressure membrane filters are also applicable for tertiary filtration. Membrane filtration could also serve as a solids separation technology in lieu of secondary clarifiers in the MBR arrangement of activated sludge. (However, the approvability of MBR designs without secondary clarifiers and at higher volumetric BOD loading rates than the traditional single-stage nitrification activated sludge systems in Illinois could not be verified for this report.)

The impact of effluent filtration on final concentrations of TP and TN depends on the nutrient content of the effluent TSS and on the capability of filtration to reduce effluent TSS to very low levels. According to USEPA (2010, p. 11-2), most properly operated granular media filters can achieve less than 0.1 mg/L TP and 5 mg/L TSS in the effluent. However, the 0.1 mg/L effluent TP performance appears inconsistent with the 5 mg/L effluent TSS performance unless all dissolved phosphorus was removed and the TSS contain no more than 2 percent phosphorus. If BPR or chemical phosphorus removal is used, the effluent TSS may contain approximately 5 percent of TP, which means that about 0.25 mg/L of effluent TP would be contained in the remaining 5 mg/L of TSS. Tertiary filtration with upstream BPR and/or chemical phosphorus removal is expected to reduce TP to 0.5 mg/L in the effluent, as discussed above for Level 2P performance. The ability to achieve this level of performance will rely on reducing the dissolved TP to low levels by chemical treatment or BPR and on reducing the effluent TSS below 5 mg/L by tertiary filtration.

Achieving Level 3P phosphorus removal with conventional tertiary filters requires high chemical doses and additional tertiary treatment processes with chemical addition, such as rapid mix, flocculation, and tertiary clarification upstream of the filtration (Bott et al., 2007). Ballasted sedimentation using fine sand particles to increase the settling velocity of chemical solids is used by one manufacturer to reduce the footprint.

Dual-stage filtration based on two stages of continuous backwash upflow sand filtration steps in series is another tertiary treatment technology consistent with Level 3P performance (Bott et al., 2007; USEPA, 2010). One manufacturer’s approach to this technology consists of maximizing the adsorption of phosphorus to freshly formed hydrated ferric oxide coating on sand particles. Routing the backwash from this manufacturer’s filters back to the biological process for additional upstream adsorption of phosphorus has been shown to reduce the whole-plant dose of chemical for phosphorus removal.

Membrane filtration is also a technology consistent with Level 3P performance (Bott et al., 2007), both in the tertiary filtration position, and replacing secondary clarifiers in MBRs.

The importance of TSS removal by tertiary filtration for TN compliance is not as pronounced as that for TP compliance. While TSS could contain 5 percent of TN and thus filtration could be helpful for compliance with low TN limits (USEPA, 2008, p. 4-14), TN limits low enough for the nitrogen content of well clarified TSS to matter will likely necessitate the addition of tertiary denitrification filters, which provide the TSS polishing as a side effect to their main purpose, nitrate removal.

Section 5.0
PLANT UPGRADE CONSIDERATIONS

When it comes to selecting from the applicable BNR process configurations, new plants are less constrained than plant upgrades by the already existing treatment units, sludge handling processes, and other factors (USEPA, 2007b):

- Existing aeration tank size and configuration impact the feasibility and economy of BNR configurations for plant retrofits.
- Existing footprint or available land may impact the ability to add new tanks (or buildings, although this reference focused on BNR and thus did not consider buildings).
- More or less extensive aeration system modifications may be required, depending on the existing aeration system type and configuration.
- Biosolids processing may need to be modified when upgrading the plant to achieve required TP and/or TN removal.

Nutrient removal upgrade technologies differ not only in the effluent performance they offer, but also in the scope of applicability to various existing WWTPs, in the capital and O&M resources they consume, and in the sustainability impacts they present to the environment.

The following technology aspects are assessed in this report:

- Performance Level: Criterion describes the nutrient removal level expected from the technology, as discussed in other sections of this report.
- Reliability/Controllability: Criterion describes the extent to which the performance can be reliably controlled, as discussed in other sections of this report.
- Applicability: Criterion assesses how widely applicable the technology is to upgrading existing facilities. This relates to the requirements the technology has for the existing treatment facilities.
- Capital Cost: Criterion assesses the magnitude of the probable capital cost of implementing the technology.
- O&M Cost: Criterion assesses the magnitude of the probable increase in the O&M costs due to implementing the technology. Upgrades relying on chemical addition or requiring intermediate pumping will tend to have high O&M costs.
- Footprint: Criterion assesses the site footprint a plant upgrade relying on the technology is expected to require. This also has implications for applicability and capital cost. The potential footprint advantages of some technologies (IFAS/MBBR and MBR) can only be realized if their approvability for designs in Illinois evolves favorably.

- Pumping: This criterion assesses the expectation that intermediate pumping of the entire plant flow is needed to allow the use of the technology in an upgrade (such as for MBRs and for tertiary filters, including denitrification filters). A minor pumping impact is assessed for internal recycles because they could be implemented as low-head pumping applications. Pumping impacts may also be reflected in applicability, footprint, capital cost, O&M cost, and sustainability impacts.

- Chemical Needs: Chemical removal of phosphorus and supplemental carbon addition for denitrification require chemical storage and feed facilities and ongoing periodic delivery of the respective chemicals to the plant site. This results in some capital expense, ongoing O&M expense, and sustainability impacts. Fermentation may provide an in-plant source of VFAs for BNR upstream from clarifier units, but not for tertiary denitrification filters (USEPA 2008, pp. 5-11 and 5-14). A potential beneficial impact of pre-denitrification on chemical use exists if alkalinity otherwise would have to be added for nitrification (Reardon, 1994); however, municipal plants adding alkalinity for nitrification in Illinois are expected to be an exception.

- Additional Sludge: Chemical addition for phosphorus removal and supplemental carbon addition for denitrification produce additional sludge (unless the carbon source is in-plant fermentation). This presents an ongoing extra O&M expense and sustainability impact, and may expose the marginality of existing solids treatment (potential additional capital expense). USEPA (2008, p. 5-17) expects significant sludge generation impacts with chemical phosphorus removal if effluent TP below 0.5 mg/L, and especially below 0.2 mg/L, is required.

- Additional Electricity: Criterion assesses the expectation that the technology will increase the electrical energy use. Anaerobic zone mixers and fermenters present a minor impact because of the relatively small volume of these tanks (USEPA, 2008, p. 5-17). Pre-anoxic tank mixers and low-head internal recycles approximately offset the aeration savings from pre-denitrification; post-anoxic tanks do not contribute to electrical energy savings due to their placement (Reardon, 1994). However, post-anoxic tanks do require mixing, and their additional electricity use depends on the size of any additional tank volume (USEPA, 2008, p. 5-11). Major additional electricity impact is assessed in this report for technologies needing additional forward flow lift (all tertiary filters).

- Operator Impact: This criterion assesses the requirements of the technology on plant operator quantity and quality and thus also its impacts on the ongoing O&M costs. For this report, high operator impact is assessed for multiple technologies and for technologies requiring simultaneous control of multiple parameters, especially if they relate to BNR rather than to a physical or chemical process. It is recognized that some operator impact may be shifted onto expanded SCADA systems.

- Sustainability Impact: Criterion combines several other criteria into an overall sustainability impact expectation. According to USEPA (2008, p. 5-6), factors promoting technology sustainability are lower energy use, lower sludge production, and lower chemical use.

The summary of the technology evaluation presented in Appendix A suggests the following:

- For TP removal, sustainability impacts are limited to less than “medium” only if BPR is the basis of the technological solution. Tertiary filtration and chemical addition both improve performance and reliability of BPR but also increase the sustainability impacts. Consequently, sustainability benefits when the level of the technology standard allows the reliance on BPR to be maximized, which occurs when the required performance is no more stringent than Level 1P, or perhaps into Level 2P with either less reliability or with higher chemical and electricity (filtration and intermediate pumping) use. Even Level 1P may need to be relaxed to accommodate BPR without forcing chemical use, especially for existing plant retrofits, as proposed in Table 1. Effluent requirements at Level 2P increase the chemical use, electricity use, sludge production, and sustainability impacts. Level 3P is only achieved with medium to high sustainability impacts.

- For TN removal, the key to preserving sustainability is to avoid the addition of intermediate pumping (extra electricity) and the addition of supplemental carbon from external sources (additional chemical and sludge production). Consequently, only single-sludge activated sludge systems without supplemental carbon feed (unless generated using in-plant fermentation) show “low” sustainability impacts. Such systems are expected to perform reliably at Level 1N, or with compromised reliability or increasing supplemental carbon use at Level 2N. Even Level 1N may need to be relaxed to accommodate existing plant retrofits without forcing chemical use, as proposed in Table 2. Level 2N may be achievable with low sustainability impacts, but Level 3N is only achieved with high sustainability impacts.

Section 6.0
UPGRADE COSTS

The target performance is an obvious factor impacting the capital cost of both new plants and plant upgrades designed for nutrient removal. However, the existing treatment system and space constraints are some of the factors that may produce large variations in the capital cost of retrofitting essentially the same configuration at various existing plants, even if they have similar capacities (USEPA, 2007b). For example, upgrades of two 1-MGD plants to the MLE process configuration in Maryland cost $3.12 and $4.95 per gpd of plant capacity, 2006 currency. Despite this considerable variability in response to site-specific factors, USEPA (2007b) also observed that plant upgrade costs per unit of capacity displayed a general trend of decreasing with the increasing plant capacity as approximately as follows: $6.97/gpd average for plants up to 1 MGD, $1.74/gpd average for larger plants up to 10 MGD, and $0.59/gpd average for plants above 10 MGD. A similar trend of increasing capital and O&M unit costs with decreasing plant size was evident for new plants smaller than 1 MGD (USEPA, 2007b, p. 11).

USEPA (2008) included capital and O&M cost information from various published sources and from additional cost modeling performed. The most significant findings for the purposes of the present report were that both capital and O&M costs vary substantially for all technologies in response to local conditions, and that the size of the plant is a significant cost factor in that higher unit costs (both capital and O&M) are associated with smaller facilities due to the economies of scale.

While the cost data compiled and modeled by USEPA (2008) appears to be the most extensive such compilation available, the application of the data for the purposes of the present report beyond the general findings as to cost variability, economies of scale, and capital vs. O&M trade-offs is hindered because of unclear technology performance assumptions and capital and O&M cost scope.

The simulated cost scenarios in USEPA (2008) do not always follow the technology performance abilities discussed elsewhere in the same report. A step-feed or MLE retrofit without supplemental carbon and without tertiary denitrification is assumed to deliver an effluent TN target of 3 mg/L in the cost model (pp. 4-12 to 4-14), although that is not a performance expectation supported by the bulk of the report.

The simulated project costs in USEPA (2008) make a distinction between “retrofits” and “expansions” that appears to be based on whether the upgrade project merely modifies the existing biological treatment (such as by baffle wall additions and piping arrangements) or replaces it with entirely new tanks and equipment. The former constitutes a retrofit, while the latter is an expansion. (Increase in plant capacity does not feature in the “expansions”.) However, the fate of the pre-existing tanks does not explain why the O&M costs, which were not stated to include any debt service or other annualized capital costs, for the same final system configuration should be significantly higher for expansion projects than they are for retrofits. For example, the upgrade to A/O with a new fermenter and a new sand filter to achieve the same 0.5 mg/L effluent TP target is shown to cost $25/MG to $55/MG to operate as a retrofit (Figure 4-1 on p. 4-11) but $310/MG to $540/MG as an expansion (Figure 4-10 on p. 4-22). Capital costs for the same upgrade project are shown as $0.43/gpd to $0.60/gpd for a retrofit and $1.50/gpd to $2.50/gpd for an expansion. (The low end of each range applies to a 10-MGD plant, and the high end to a 1-MGD plant.)

Only the purely chemical phosphorus removal upgrades are presented by USEPA (2008) to have the same O&M (as well as capital) costs regardless of whether the upgrade is a retrofit or an expansion. In particular, the following 2007-based simulated costs are presented for TP-only upgrades with the 5 mg/L initial annual average effluent TP. For chemical phosphorus removal upgrades the capital cost ranged from $0.03/gpd to $0.29/gpd for a single point chemical (alum) addition without filters and from $0.29/gpd to $0.74/gpd for a dual point alum addition with sand filters. For those same projects, the O&M cost ranged from $91/MG to $130/MG and from $215/MG to $270/MG. The annual average target effluent TP was 0.5 mg/L for the single-point chemical addition without filters, and 0.1 mg/L for the dual-point chemical addition with sand filters.

USEPA (2008) also reported the actual 2007-based retrofit costs at some of the plants selected for case studies in that report, including the costs at the 3-MGD Kalispell BPR/nitrification upgrade to a modified UCT with fermenter and tertiary filter to meet a 1 mg/L TP effluent target. The Kalispell costs were $3.03/gpd and $108/MG (excluding labor, p. 4-3). The Kalispell upgrade appears to have started from a non-nitrifying facility, which would suggest it was an expansion rather than a retrofit. Interpolating to the 3-MGD Kalispell capacity from the expansion cost model results for 1 MGD and 5 MGD for modified UCT with fermenter and filter produces about $3.30/gpd capital and $650/MG O&M (including labor). The simulated expansion capital cost comes close to matching the actual $3.03/gpd, but the simulated O&M cost exceeds the Kalispell value ($108/MG) far more than would be expected simply from adding labor costs, even considering that the cost model overestimated the actual Kalispell O&M by 29 percent in model validation (p. 4-7).

The following illustrates the costs for TN removal upgrades reported in USEPA (2008): The addition of a denitrifying filter with methanol feed to achieve 3 mg/L TN was shown to cost $0.70/gpd to $1.35/gpd to build and $155/MG to $440/MG to operate (both as a retrofit and as an expansion). It appears that these costs did not include the intermediate lift station that would likely be needed when adding a tertiary denitrification filter to an existing plant. The MLE retrofit (without carbon addition) to meet 3 mg/L effluent TN (not a reasonable performance target) was shown to cost $0.70/gpd to $1.13/gpd to build and $80/MG to $100/MG to operate. When built as a plant expansion, the MLE upgrade to meet 5 mg/L effluent TN (still not a reasonable target for this technology based on other sources cited in this report) was shown to cost $1.60/gpd to $2.50/gpd to build and $305/MG to $550/MG to operate. Thus an MLE upgrade implemented as a plant expansion appears to be more costly both to build and to operate than a tertiary denitrification filter addition regardless of the plant size. Again, the unclear reason for the difference in the operating costs of the same (MLE) plant upgrade between retrofit and expansion prevents useful conclusions from being reached.

WEF (2010b) also discussed costs of plant upgrades to nutrient removal and further highlighted the impact of the existing plant configuration on the upgrade cost. For example, underloaded activated sludge plants that are fully nitrifying may provide an advantageous starting point for nutrient removal upgrades in that a portion of the activated sludge tanks can be converted to the non-aerated zones required for BPR or TN removal.

To the authors' knowledge, several recent capacity expansion projects in Illinois included anaerobic or anoxic zones within the overall tank volume, compliant with the volumetric design organic loading recommended for single-stage nitrification using the overall tank volume. The same approach could presumably be considered for existing facilities designed for the compliant volumetric organic loading, in that a portion of the existing tank volume could be converted to anaerobic or anoxic zones. Conversely, activated sludge plants designed for higher volumetric loadings (and shorter SRTs) that are nitrifying seasonally at best, as well as plants based on attached-growth biological treatment, such as trickling filters (TFs) and rotating biological contactors (RBCs), can only be upgraded at a much greater cost. This is because costs and footprint requirements escalate if activated sludge tank volume must be added, and technological alternatives to extra tank volume tend to be costlier still. As a practical matter, because of the requirement to maintain operation under construction, the existing or available plant footprint may constrain the feasibility of the plant upgrade project at the existing site even if the upgraded facility could well fit within the footprint.

WEF (2010b) reported capital costs of upgrading existing facilities within the same sanitary district to achieve Level 2N removal depending on the starting point as follows: $1.35/gpd for a plant that already was removing TN to 8 mg/L before the upgrade, and $7.50/gpd for a plant that did not nitrify before the upgrade.

Falk et al. (2011) presented the following estimated costs based on a 10-MGD facility required to meet nutrient removal levels for both nutrients from Level 0 to Level 3 in this report as follows: Capital costs (including construction, engineering, and administration) $7.9, $13.3, $14.4, and $16.4 per gpd of capacity, and operating costs (excluding labor and maintenance) $222, $347, $643, and $876 per MG treated, respectively. Capital costs in Falk et al. (2011) referred to new construction rather than to retrofits. The technology levels were similar to those described in this report and built on each other as follows: Level 0 was based on a non-nitrifying plant; Level 1 relied on an A^2/O biological treatment with optional chemical addition for phosphorus removal; Level 2 applied 5-stage Bardenpho with optional methanol addition to the second anoxic zone and added tertiary filtration with chemical addition for phosphorus removal; Level 3 added primary sludge fermentation and required methanol addition to the second anoxic zone, inserted flocculation and high-rate clarification with chemical and polymer addition between secondary clarifiers and tertiary filters, and upgraded the tertiary filters to tertiary denitrification with methanol addition.

The most stringent treatment level studied by Falk et al. (2011), which included RO with deep well injection of the RO reject to reduce effluent TP to less than 0.02 mg/L and effluent TN to 2 mg/L, was not included in this report because it was deemed impractical. The estimated new plant capital cost for this final level was $21.6/gpd and the partial operating cost (excluding labor, maintenance, and membrane replacement) $1,365/MG.

It is evident that the numerous factors impacting reported actual and modeled costs prevent fully useful cost conclusions from being reached for this report. Similar to the ongoing effort in Colorado (CWQCD, 2010, p. 22), if plant upgrade costs more closely applicable to the probable upgrade projects in Illinois are needed for the continued development of the technology-based nutrient standards, a limited set of representative upgrade projects may need to be defined for the desired sampling of existing facility types and sizes and upgraded plant performance, and representative costs developed for those defined projects. The tentative outcome of the cost modeling for Colorado was very recently released in a draft report for CWQCD (CDM, 2011). Several charts were prepared from the 2010-based costs presented in Table 3-19 on p. 3-40 and in appendices of that draft report, including a comparison overlay with the 2010-based costs for several comparable nutrient upgrade scopes presented by USEPA (2008). These charts do not exist in the CDM report, but rather were prepared for the present report and are included in Appendix B.

The main finding of this section is that the economies of scale make the implementation of nutrient removal at smaller plants disproportionately more costly per unit of capacity than at larger plants. Additionally, to the extent that small facilities rely on systems not readily upgraded to utilize other than downstream add-ons (USEPA, 2007b), also the retrofit opportunities at smaller plants tend to be more restricted and biased towards the costlier and less sustainable add-on options. The smaller tributary sewer systems deliver more variable influent flows, and thus further exacerbate the small-plant handicap by challenging biological treatment performance. Finally, the staffing levels at the smaller facilities may not be consistent with the added complexity of nutrient removal.

Section 7.0
STATISTICAL AND PERMITTING ISSUES

While most of this section examines the plant compliance with effluent limits for nutrients from the standpoint of statistics and sample variance, it is acknowledged that real-world reasons exist for the expected (as well as unexpected) statistical behavior of the effluent concentrations. Municipal WWTPs receive influents that typically vary widely over time in terms of quantity and characteristics, daily, weekly, and seasonally. This variability in the influent necessarily produces some variability in the effluent that cannot be controlled, since much of the treatment that produces the effluent is provided by a biological system.

7.1 The Kelowna Example

WEF (2010a) states that biological processes can typically be designed to meet Level 1 performance for both nutrients without filtration (and by definition without chemical addition). USEPA (2008) agrees (for example, p. 5-3 and 5-4) by only including the recommendation or preference for filtration for nutrient removal beyond Level 1. One of the BPR examples USEPA (2008) provides that is supported by twelve months of effluent data is that of the Kelowna plant in British Columbia (which site has been seminal in developing the fermenter technology). This example also proves useful for the present report.

The Kelowna plant uses primary sludge fermentation to supplement the VFAs for BPR in the Westbank configuration. The plant has a primary effluent equalization basin. No sludge digestion is included, and the biosolids are dewatered for off-site composting. The twelve months of data used by USEPA (2008) show an annual average effluent TP of 0.139 mg/L (with average TN of 4.38 mg/L) and the maximum monthly average TP of 0.20 mg/L (with the maximum monthly TN of 4.9 mg/L).

The Kelowna plant also attracted the attention of a WERF study (Bott and Parker, 2011). Reflecting the more rigorous requirements of WERF for data quantity and resolution, Bott and Parker (2011) relied on three years of daily effluent data for this and other facilities. The overall average TP did not change much from the value reported by USEPA (2008), being approximately 0.15 mg/L. However, the maximum running 30-day effluent TP average for the three-year period was 1.2 mg/L, which is appreciably higher than the maximum of the twelve calendar month averages reported by USEPA (2008) at 0.20 mg/L. Only when certain atypical effluent TP concentrations (mostly related to a biological upset from a three-day heavy metal slug in the plant influent) were removed from the data did the maximum 30-day average drop to 0.26 mg/L. The daily maximum effluent TP experienced during the biological plant upset was 4.1 mg/L, within the typical raw TP range shown in Table 2.

The Kelowna example illustrates that even the most exemplary plants are subject to the vagaries of influent and other conditions beyond anyone's control, and also that performance extrapolation from seemingly sufficiently long records of effluent quality (such as monthly averages recorded for 12 months) to effluent quality "expected" to be met at the same plant or even other plants in the future is ill-advised, as further discussed below.

It is recognized that this report deviates from the reasoning in USEPA (2008, p. 2-57) that because the observed performance results reflect operating philosophy, permit limits, temperature, influent, flow, and relative loading specific to the given plant, the observed results "do not necessarily represent optimum operation of the technologies presented". For this report, it appears more relevant that the performance observed during the selected period of time at the plants selected as the nutrient removal examples does not necessarily represent a reliably repeatable performance of those technologies even at those same plants, let alone at other plants. As aptly observed by Maxwell (2011), setting the effluent standards at the "best in class" performance would mean that most dischargers will soon fail to comply.

7.2 Averaging Basis

Similar to the approach in USEPA (2008), the nutrient removal performance levels discussed in this report are intended to refer to typical long-term performance, as would reasonably be approximated by annual averages or medians. WEF (2010a) described the basis of its performance levels simply as "typical monthly performance achievable" (p. 86), but because this reference did not further discuss its statistical basis, it would appear misleading to interpret the quoted phrase as the maximum monthly average that can be reliably met.

Conversion from long-term average effluent quality to short-term averages depends on the statistical behavior of the actual effluent concentration time series. Two approaches can generally be used for this conversion: the empirical percentile chart prepared for the desired averaging period from long-term data collected from the effluent in question, and the formulas applicable to the theoretical statistical distributions assumed to describe the effluent. Whichever method is used, it quickly reveals that the shorter the averaging period, the greater the variability of the average for the same underlying data series. This basic fact has to be recognized in permit writing.

Effluent limits in Illinois are intended for absolute compliance: a numerical value is stated for a given season (if limits are seasonal) and averaging period, and the actual average concentration or mass loading reported for the effluent is compared against the applicable limit. There is no built-in allowance for any excursion above the limit, and any such excursion constitutes a violation subject to enforcement action.

Consequently, if a monthly average TP limit in an Illinois NPDES permit were set at 1 mg/L because this performance is expected to be achievable by "all" technologies (USEPA, 2008, p. 5-3), then that expectation is not being implemented as implied in the expectation. Instead, the actually implemented permit limit is stricter than the expectation, to the same extent that a monthly average permit limit is stricter than an annual average permit limit set at the same numeric value. This difference in stringency grows with the variance of the effluent concentrations and depends on the number of the compliance monitoring samples per month.

The well-known fact that the variability (variance) of sample averages grows with the decreasing sample size (i.e., with the decreasing averaging period) has an important corollary. When performing any percentile comparisons, one must always keep the averaging basis (in other words, the definition of the variable whose distribution is being studied) in mind: either keep the averaging basis constant, or properly compensate for changing it. For example, USEPA (2008, p. 3-4) compares the stringency of U.S. weekly and monthly average limits with that of corresponding Canadian probabilistic limits which apply to certain percentiles of individual observations. This comparison appears to suggest that the monthly average limit is as stringent as the limit applicable to the 92.3 percentile (probably derived as 1-28/365) of daily observations. However, without converting the variance from daily samples to their monthly averages, the comparison lacks the intended meaning.

What is even more important, the implication that (even correctly converted) percentiles are on an equal footing between the U.S. system based on absolute compliance and a probabilistic compliance system that actually allows a certain percentage of samples above the limit is misleading. The fact remains that the monthly average limit must never be exceeded, no matter at what percentile of which averaging period it was derived. Thus, for example, the suggestion in Kang et al. (2008) that those facilities whose monthly average percentile curves cross the 92-percent line below the given concentration would readily comply with the monthly average limit at that concentration is not supported by their evidence. The 92nd percentile of monthly averages simply corresponds to the value expected to be exceeded by one out of twelve monthly averages on the average, and one expected violation every year does not constitute ready compliance. Extrapolating the lognormal probability line beyond the highest of the 12 monthly averages to any particular higher percentile in an attempt to estimate the weekly or daily average as hard to meet as the 92nd percentile monthly average would also ignore the fact that the lognormal probability line established from monthly averages only applies to monthly averages.

To deal with the challenge of absolute compliance in the context of technology-based effluent limits for nutrients, the simplest approach would be to implement the typical long-term average technology performance expectations as annual average limits in NPDES permits, and to refrain from imposing permit limits on shorter averages. This would offer the advantage of avoiding the need to tackle the statistical issues related to the impact of averaging period and sample size on sample variance for the assumed shape of the distribution. A further improvement on the annual average is the annual median; the median statistics better accommodate the inevitable performance fluctuations of the biological treatment processes (Clark et al., 2010; Maxwell, 2011).

A more complex approach would be to attempt a conversion from an annual average limit to an equally stringent monthly average limit, the latter being numerically more generous to allow for the expected variability in the monthly averages. The conversions have been described in the technical support document by USEPA (1991) for the ideal case of lognormally distributed individual effluent observations without any serial correlations and further extended by Hajda (2008) to less constrained cases. However, these conversions inevitably raise the rather intractable question of which percentile of the monthly averages the monthly limit should match. For example, selecting the 95th monthly average percentile as the monthly average limit would mean that the permittee is being set up to fail in five percent of months, or three times in each five-year permit cycle, hardly a satisfactory outcome. Conversely, selecting a percentile that would be high enough to look sufficiently “safe” to the plant operator may result in a permit limit numerically so generous that it would appear unrelated to the original technology-based performance level. In Wisconsin’s recently adopted phosphorus regulations, if a TP limit is implemented as an annual average, the accompanying monthly average limit is imposed at three times the annual average.

Selecting the percentile from a distribution, of course, assumes that the future statistical behavior of the actual effluent can be anticipated in the first place. The Kelowna example above should suffice as a reminder that no one can anticipate all issues that will impact the plant performance in the future. Assuming such powers of anticipation from the permit writer or mandating them through the permit from the plant operator would be unproductive.

The long-term statistical behavior (average, variance, and the shape of the upper tail of the distribution) of any given plant, let alone all plants of a given configuration, will only be known in the long term and only in retrospect. It is clear that one year of operating data does not provide the required level of insight even for the facility where the data was collected. Bott and Parker (2011) recognized that even three years of performance data will only lessen the degree of uncertainty, but will not address the fundamental issue of effluent performance of nutrient removing plants near the limits of technology. Weather, chemical suppliers, human operators, equipment reliability, and wastewater characteristics are all examples of factors that can wreak havoc with the plant’s ability to match performance expectations.

Other than avoiding short-term average limits for nutrients, a permit implementation of technology-based performance expectations accommodating real-world statistical variability in the effluent could take the form of a stated number of excursions above the limit per time (such as three excursions per five years for the 95-percent monthly average level when reported once per calendar month). Alternatively, the permit could require not that every monthly average comply with a stated limit, but instead that a stated percentile value calculated from the individual observations (not from their monthly averages) so comply. Such probabilistic limits on individual observations can be used in conjunction with long-term medians to assure continuous treatment.

The annual median or average basis of compliance would appear to offer the most direct and simplest method of implementing the technology-based performance expectations consistent with the available data. All other methods need to address the underlying statistical behavior more explicitly, a non-trivial exercise both in selecting the parameters and in implementing the needed conversions.

Section 8.0
CONCLUSIONS

Literature review shows that numerous technologies are available to upgrade municipal wastewater treatment plants in Illinois to remove phosphorus, nitrogen, or both. The technologies with the widest applicability to plant upgrades regardless of the existing treatment type are the expensive add-on processes that have the highest expected O&M costs and sustainability impacts. In this report, sustainability combines chemical addition, solids production, and electricity consumption; O&M cost expectations additionally incorporate expected operator impacts.

The most desirable plant upgrades from the sustainability perspective are retrofits that rely on biological treatment without external chemical addition and that do not require the addition of intermediate pumping for tertiary filtration or membrane processes. Not all existing plants will be amenable to these sustainable upgrades; for example, trickling filters and rotating biological contactors are hard to integrate into sustainable BNR. Moreover, the avoidance of chemical addition and absence of tertiary filtration make the expected performance of the biological process less reliable than the less sustainable alternatives.

The worthwhile effort to preserve the applicability of the most sustainable technologies will involve the call for permit requirements generous enough to properly accommodate the temperament of the biological processes. The practically desirable discharge permit requirements will avoid nutrient limits for averaging periods shorter than annual because shorter averages do not accommodate the higher variability of the biological process effluent (and because technologies are typically stratified on their average rather than extreme performance in the literature). A further improvement in accommodating the variability in the effluent is produced by applying the annual limit to the median rather than to the mean of the effluent concentrations.

For phosphorus removal, the practically desirable permitting approach means relaxing the monthly averaging precedent of the existing interim effluent standard to the annual basis of the numerically identical Level 1P performance target of this report. Furthermore, to allow the plant retrofits the option to rely on BPR without forcing the choice between the risk of non-compliance and the environmentally inferior use of extra chemicals and/or additional pumping, the practically desirable permitting approach would use the 1 mg/L target as an annual median for new construction, and allow a more generous 1.5 mg/L annual median effluent TP for existing plants, as recently proposed by treatment experts in Colorado.

For nitrogen removal, the most practically desirable permitting approach would combine the annual time basis, median statistics, and TIN rather than TN expression of the limits. The Level 1N 10 mg/L TN target in Table 2 would translate to an 8 mg/L TIN annual median limit for new plants. A more generous annual median TIN limit of 12 mg/L, corresponding to the 15 mg/L TN target in Table 2, would promote the applicability of Level 1N technologies to retrofit existing plants for nitrogen removal.

To accommodate influent nutrient concentrations above the typical municipal ranges for which the technology performance was stated in the literature sources, permits should allow the option to comply on the relative removal rather than absolute effluent concentration basis. This is especially useful for nitrogen, because the Level 1N technologies rely on an internal recycle such that the achievable nitrogen removal is a function of the recycle ratio, and the achievable effluent concentration is largely proportional to the influent concentration. Due to rounding, the approximately 70-percent relative removal shown in Table 2 for Level 1N applies reasonably well both to the 10 mg/L TN target and to the 8 mg/L TIN target suggested for new plants. The 12 mg/L TIN target suggested for plant retrofits corresponds to approximately 60-percent removal of the influent TN, while the 15 mg/L TN target for retrofits corresponds to 50-percent TN removal. The relative removal levels for TIN effluent concentrations use the full influent TN as the removal basis despite disregarding organic nitrogen in the effluent.

Small plants suffer from multiple handicaps. They are impacted by the economies of scale and more likely to employ processes that are not readily amenable to the most sustainable and least costly retrofits. The smaller sewer systems tributary to the smaller plants are also expected to deliver more variable flows and loadings, which may challenge nutrient removal performance. Finally, the smaller plants may not be equipped with the operating staff consistent with the more complex treatment processes for nutrient removal. These small-plant handicaps could be reflected by continuing the exemption of the interim effluent phosphorus standard for minor plants in the technology-based nutrient regulations.

Finally, while capital and O&M costs were not the main focus of this study, the information that was reviewed made it clear that a literature review has a limited use in this regard. Multiple project- and site-specific factors confound the reported costs, and assumptions for which the costs are reported are not clear.

Section 9.0
REFERENCES

Bott, C.B., S.N. Murthy, T.T. Spano, and C.W. Randall (2007). WERF Workshop on Nutrient Removal: How Low Can We Go & What Is Stopping Us From Going Lower? Water Environment Research Foundation, 05-CTS-1W, available at https://www.werf.org/AM/Template.cfm?Section=Search&Template=/CustomSource/Research/PublicationProfile.cfm&id=05-CTS-1W (accessed July 15, 2011).

Bott, C.B., and D.S. Parker (2011). Nutrient Management Volume II: Removal Technology Performance & Reliability. Water Environment Research Foundation and IWA Publishing, NUTR1R06k.

CDM (2011). Cost/Benefit Study of the Impacts of Potential Nutrient Controls for Colorado Point Source Discharges. Draft report for CWQCD, September 2011, http://projects.ch2m.com/CWQFwebsite/Workgroups/Content/nutrient_criteria/Meetings/CostBenefitStudy/Draft%20Report/DRAFT%20Cost%20Benefit%20Study.pdf (accessed September 14, 2011).

Clark, D.L., G. Hunt, M.S. Kasch, P.J. Lemonds, G.M. Moen, and J.B. Neethling (2010). Nutrient Management: Regulatory Approaches to Protect Water Quality, Volume 1, Review of Existing Practices. Water Environment Research Foundation and IWA Publishing, NUTR1R06i.

Crawford, G., S. Black, M. Elliot, C. Filipe, G.T. Daigger, and D. Stafford (2000). "The Step Bio-P Process at Lethbridge – over one full year of operation", Proceedings of the 73rd WEF Conference and Exhibition, Anaheim, CA, October 14-18, 2000, pp. 872-887.

CWQCD (2010). Technologies, Performance and Costs for Wastewater Nutrient Removal and Implementation Recommendations, Colorado Water Quality Control Division (CWQCD), November 2010, http://projects.ch2m.com/CWQFwebsite/Workgroups/Content/nutrient_criteria/Meetings/2010/12%202010%20December/Water%20Quality%20Control%20Division%20Nutrient%20Paper%20V2%20FINAL%2012-6-10.pdf (accessed July 20, 2011).

CWQCD (2011). Colorado Department of Public Health and Environment, Water Quality Control Commission, 5 CCR 1002-85, Regulation #85, Draft: July 5, 2011, http://projects.ch2m.com/CWQFwebsite/Workgroups/Content/nutrient_criteria/Meetings/Regulations%2031%20and%2085/WQCD%2020110705%20Reg%2085%20CLEAN.pdf (accessed September 20, 2011).

Falk, M.W., D.J. Reardon, and J.B. Neethling (2011). "Wastewater treatment nutrient removal and energy/GHG nexus", Presented at WEF Energy and Water 2011, Chicago, IL, July 31-August 3, 2011.

Hajda, P. (2008). "Betting against stringency mismatches in standards and limits: Monte Carlo validation of lognormally based quantile conversions between sample sizes". Presented at WEFTEC.08, 81st Annual Water Environment Federation Technical Exhibition and Conference, Chicago, IL, October 18-22, 2008.

Johnson, B.R., G.T. Daigger, G. Crawford, M.V. Wable, and S. Goodwin (2003). "Full-scale step-feed nutrient removal systems: a comparison between theory and reality", Proceedings of the Water Environment Federation, WEFTEC 2003, Los Angeles, CA, October 12-15, 2003, pp. 334-351.

Johnson, B.R., S. Goodwin, G.T. Daigger, and G.V. Crawford (2005). A comparison between the theory and reality of full-scale step-feed nutrient removal systems, Water Science and Technology, **52**(10-11):587-596.

Kang, S.J., K. Olmstead, K.M. Takacs, J.H. Collins, J. Wheeler, and P. Zahreddine (2008). "Capabilities, reliabilities, and costs of full-scale nutrient removal technologies". Presented at WEFTEC.08, 81st Annual Water Environment Federation Technical Exhibition and Conference, Chicago, IL, October 18-22, 2008.

Kelly, H., H. Frese, and A. Gibb (2006). "Biological nutrient removal operating experience for Trickling Filter – Activated Sludge combination", PNCWA Coeur d' Alene, ID, October 1, 2006, http://www.dayton-knight.com/publications/staff%20papers/TF-SC%20No%202%20PNCWA-2006%20Oct.pdf (accessed July 27, 2010).

Lancaster, C.D., and J.E. Madden (2008). "Not so fast! The impact of recalcitrant phosphorus on the ability to meet low phosphorus limits". Presented at WEFTEC.08, 81st Annual Water Environment Federation Technical Exhibition and Conference, Chicago, IL, October 18-22, 2008.

Lewis, W.M., Jr. (2010). Advantages of Regulating Bioavailable Nitrogen Rather Than Total Nitrogen for Protection of Water Quality in Colorado, April 14, 2010, http://projects.ch2m.com/CWQFwebsite/Workgroups/Content/nutrient_criteria/Meetings/2010/10%202010%20October/PAR%201131%20-%20Nutrient%20Regulatory%20ApproachesRpt302.pdf (accessed September 20, 2011).

Maxwell, M. (2011). "Tetra Tech 20110808 Reg 85 Comments on July 5, 2011 Draft Control Regulation", Memorandum to Dave Akers, CDPHE, August 8, 2011, http://projects.ch2m.com/CWQFwebsite/Workgroups/Content/nutrient_criteria/Meetings/08%202011%20August%20Reg%203185%20Comments/Tetra%20Tech%2020110808%20Reg%2085%20Comments.pdf (accessed September 20, 2011).

Mulholland, M.R., N.G. Love, D.A. Bronk, V. Pattarkine, A. Pramanik, and H.D. Stensel (2009). Establishing a Research Agenda for Assessing the Bioavailability of Wastewater Treatment Plant-Derived Effluent Organic Nitrogen in Treatment Systems and Receiving Waters. Water Environment Research Foundation, STAC Report 09-002, February 27, 2009, http://www.chesapeake.org/stac/Pubs/eonreport.pdf (accessed July 20, 2011).

Neethling, J.B., lead editor (2008). Tertiary Phosphorus Removal, Water Environment Research Foundation, last updated November 4, 2008, http://www.werf.org/AM/Template.cfm?Section=Nutrients&TEMPLATE=/CM/ContentDisplay.cfm&CONTENTID=8724 (accessed July 25, 2011).

Neethling, J.B., D. Stensel, D. Parker, C. Bott, S. Murthy, A. Pramanik, and D. Clark (2009). "What is the Limit of Technology (LOT)? A rational and quantitative approach". Presented at WEFTEC 2009, Orlando, FL, October 10-14, 2009.

Reardon, R. (1994). Cost Implication of Design for Nutrient Removal. Paper presented at the 67th Annual Conference & Exposition, Water Environment Federation, Chicago, IL, October 18-22, 1994.

Stensel, H.D., lead editor (2008). Dissolved Organic Nitrogen (DON) in Biological Nutrient Removal Wastewater Treatment Processes, Water Environment Research Foundation, November 2008, http://www.werf.org/nutrients/LOTDissolvedOrganicNitrogen (accessed July 20, 2011).

USEPA (1987). Design Manual: Phosphorus Removal, Office of Research and Development, Center for Environmental Research Information, Water Engineering Research Laboratory, Cincinnati, OH, EPA/625/1-87/010, September 1987, available at http://nepis.epa.gov/Simple.html by searching for "625187010" (accessed July 28, 2011).

USEPA (1991). Technical Support Document for Water Quality-based Toxics Control, Office of Water, Washington, DC, EPA/505/2-90-001, March 1991, http://www.epa.gov/npdes/pubs/owm0264.pdf (accessed October 17, 2011).

USEPA (1993). Manual: Nitrogen Control, Office of Research and Development, Center for Environmental Research Information, Risk Reduction Engineering Laboratory, Cincinnati, OH, and Office of Water, Office of Wastewater Enforcement and Compliance, Washington, DC, EPA/625/R-93/010, September 1993, available at http://nepis.epa.gov/Simple.html by searching for "625R93010" (accessed July 20, 2011).

USEPA (2007a). Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus, Office of Water and Watersheds, United States Environmental Protection Agency, Region 10, Seattle, WA, EPA 910-R-07-002, April 2007, http://yosemite.epa.gov/r10/water.nsf/Water+Quality+Standards/AWT-Phosphorus/$FILE/AWT+Report.pdf (accessed July 28, 2011).

USEPA (2007b). Biological Nutrient Removal Processes and Costs, Office of Water, United States Environmental Protection Agency, Washington, DC, EPA-823-R-07-002, June 2007, http://www.nj.gov/dep/wms/bwqsa/EPA%20-Biologicl%20nutrient%20removal%20processes&costs.pdf (accessed August 9, 2011).

USEPA (2008). Municipal Nutrient Removal Technologies Reference Document, Volume 1 – Technical Report, and Volume 2 – Appendices. U.S. Environmental

Protection Agency, Office of Wastewater Management, Municipal Support Division, Municipal Technology Branch, EPA 832-R-08-006, September 2008, http://water.epa.gov/scitech/wastetech/upload/mnrt-volume1.pdf and http://water.epa.gov/scitech/wastetech/upload/2008_10_06_mtb_mnrt-volume2.pdf (accessed July 20, 2011).

USEPA (2009). Nutrient Control Design Manual – State of Technology Review Report, Office of Research and Development/National Risk Management Research Laboratory-Water Supply and Water Resources Division, EPA/600/R-09/012, January 2009, http://www.epa.gov/nrmrl/pubs/600r09012/600r09012.pdf (accessed July 20, 2011).

USEPA (2010). Nutrient Control Design Manual, Office of Research and Development/ National Risk Management Research Laboratory-Water Supply and Water Resources Division, EPA/600/R-10/100, August 2010, http://www.epa.gov/nrmrl/pubs/600r10100/600r10100.pdf (accessed July 20, 2011).

WEF (2010a). Nutrient Removal, WEF Manual of Practice No. 34, WEF Press, Water Environment Federation, Alexandria, VA.

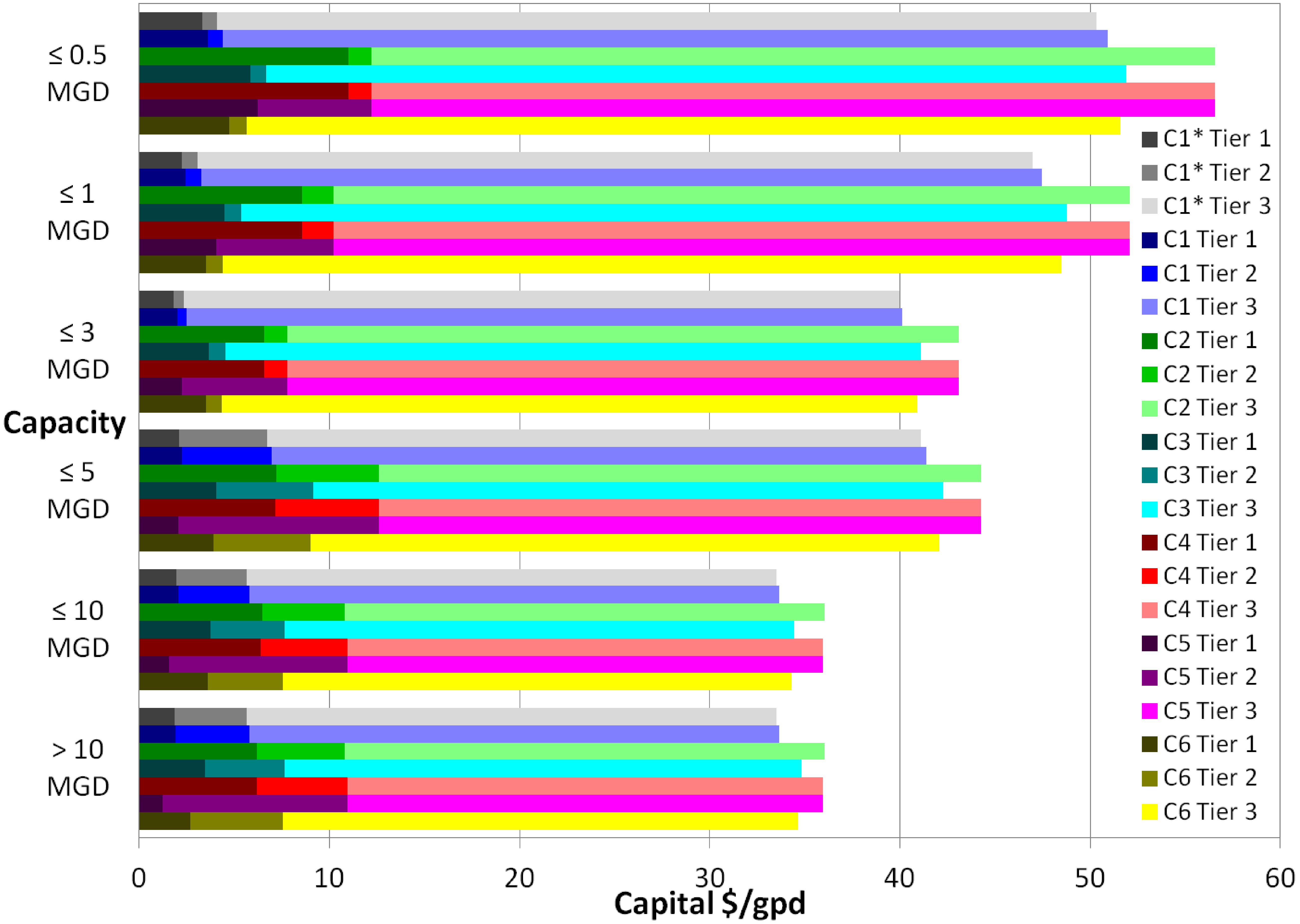
WEF (2010b). Technical Submission to EPA: Removal of Nutrients with Currently Available Secondary Treatment Technologies, Special Publication, Water Environment Federation, Alexandria, VA.

Appendix A
TECHNOLOGY SUMMARY

APPENDIX: TECHNOLOGY SUMMARY

Upgrade Technology	**Performance Level**	**Reliability/ Controllability**	**Applicability**	**Capital Cost**	**O&M Cost**	**Footprint**	**Pumping**	**Chemical Needs**	**Additional Sludge**	**Additional Electricity**	**Operator Impact**	**Sustainability Impact**
metal salt addition	1P	High	High	Low	Low-Medium	Low	None	Medium	Medium	Low	Low	Medium
	2P	Medium	High	Low	Medium	Low	None	High	High	Low	Low	Medium-High
metal salt addition with tertiary filtration	2P	High	Medium-High	Medium	Medium-High	Medium	High	High	High	Medium-High	Low-Medium	High
BPR	1P	Medium	Medium	Medium	Low	Low-Medium	None	Low	Low	Low	Low-Medium	Low
BPR with tertiary filtration	2P	Medium	Medium	Medium-High	Low-Medium	Medium	High	Low	Low	High	Medium	Low-Medium
BPR with metal salt addition	2P	Medium	Medium	Medium	Medium	Low-Medium	None	Medium	Medium	Low	Medium	Medium
BPR with metal salt addition and tertiary filtration	2P	High	Medium	Medium-High	Medium	Medium	High	Medium	Medium	High	Medium-High	Medium-High
BPR with metal salt addition and MBR	2P/3P	High	Medium-High	High	Medium-High	Low-Medium	High	Medium-High	Medium-High	High	Medium-High	Medium-High
advanced tertiary phosphorus removal	3P	High	High	High	Medium-High	Medium	High	Medium-High	Medium-High	High	Medium-High	Medium-High
single-sludge BNR, single anoxic	1N	Medium	Medium-High	Medium	Low-Medium	Medium	Low	None	None	Low-Medium	Medium	Low
single-sludge BNR, dual anoxic	1N	High	Medium	Medium-High	Low-Medium	Medium-High	Low	None	None	Medium	Medium	Low
	2N	Medium										
single-sludge BNR, dual anoxic w/ carbon addition	2N	High	Medium	Medium-High	Medium-High	Medium-High	Low	Medium-High	Medium	Medium	Medium-High	Medium
separate-stage denitrifying activated sludge	2N	High	Low	High	Medium	High	Medium	High	Medium-High	Medium	Medium	Medium-High
tertiary denitrification filter	3N	High	Medium-High	Medium-High	High	Medium	High	High	Medium-High	High	Medium	High

Appendix B
COLORADO COSTS


≤ 0.5 MGD
≤ 1 MGD
≤ 3 MGD
Capacity
≤ 5 MGD
≤ 10 MGD
> 10 MGD
0
10
20
30
40
50
60
Capital $/gpd
C1* Tier 1
C1* Tier 2
C1* Tier 3
C1 Tier 1
C1 Tier 2
C1 Tier 3
C2 Tier 1
C2 Tier 2
C2 Tier 3
C3 Tier 1
C3 Tier 2
C3 Tier 3
C4 Tier 1
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C5 Tier 3
C6 Tier 1
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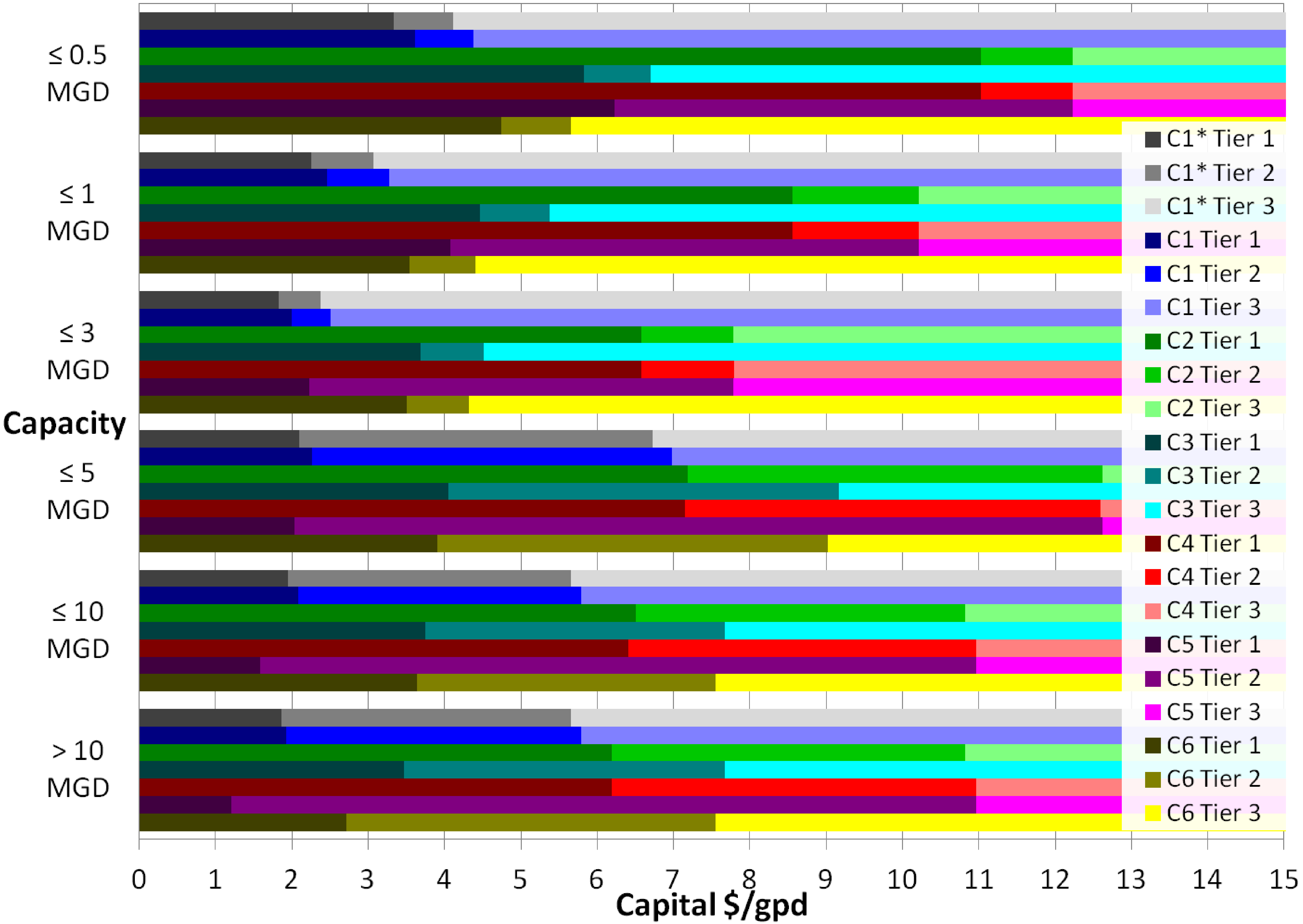
C6 Tier 3



≤ 0.5 MGD
≤ 1 MGD
≤ 3 MGD
Capacity
≤ 5 MGD
≤ 10 MGD
> 10 MGD
C1* Tier 1
C1* Tier 2
C1* Tier 3
C1 Tier 1
C1 Tier 2
C1 Tier 3
C2 Tier 1
C2 Tier 2
C2 Tier 3
C3 Tier 1
C3 Tier 2
C3 Tier 3
C4 Tier 1
C4 Tier 2
C4 Tier 3
C5 Tier 1
C5 Tier 2
C5 Tier 3
C6 Tier 1
C6 Tier 2
C6 Tier 3
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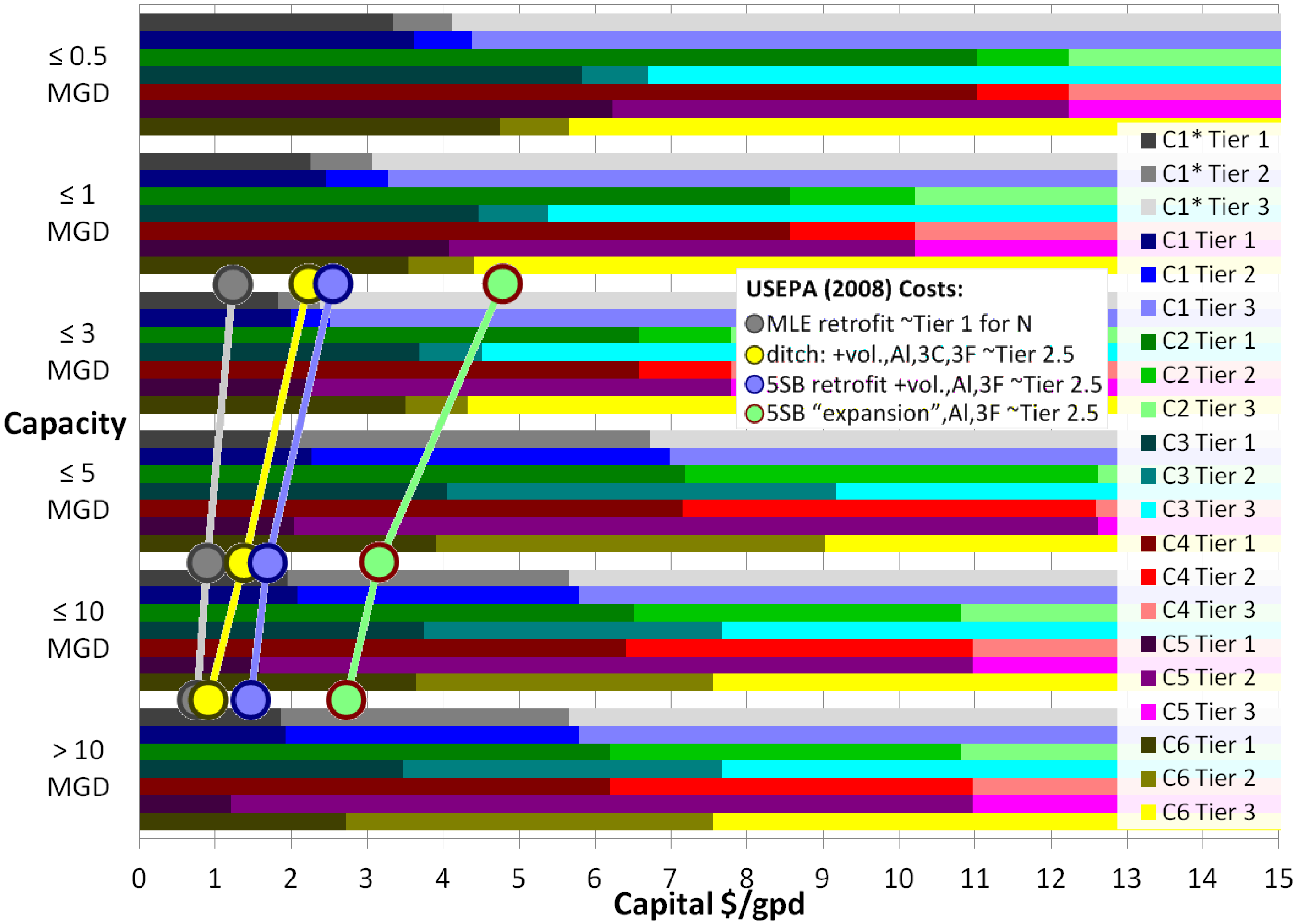
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Capital $/gpd


≤ 0.5 MGD
≤ 1 MGD
≤ 3 MGD
≤ 5 MGD
≤ 10 MGD
> 10 MGD
Capacity
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Capital $/gpd
C1* Tier 1
C1* Tier 2
C1* Tier 3
C1 Tier 1
C1 Tier 2
C1 Tier 3
C2 Tier 1
C2 Tier 2
C2 Tier 3
C3 Tier 1
C3 Tier 2
C3 Tier 3
C4 Tier 1
C4 Tier 2
C4 Tier 3
C5 Tier 1
C5 Tier 2
C5 Tier 3
C6 Tier 1
C6 Tier 2
C6 Tier 3
USEPA (2008) Costs:
MLE retrofit ~Tier 1 for N
ditch: +vol.,Al,3C,3F ~Tier 2.5
5SB retrofit +vol.,Al,3F ~Tier 2.5
5SB “expansion”,Al,3F ~Tier 2.5