Impacts on POTWs Transitioning from Secondary to Nutrient Removal Treatment

Nutrient Strategy Development Project

September 22, 2011

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1. INTRODUCTION

This paper was prepared for the Bay Area Clean Water Agencies (BACWA), a joint powers agency whose members collectively provide municipal sanitary services to more than seven million people in the San Francisco Bay Area. BACWA's mission is to provide an effective voice for its members' role as stewards of the San Francisco Bay environment through leadership, science, and advocacy. One of BACWA's goals is to ensure that environmental regulations and policies reflect the best available scientific, technical and economic information and that these regulations and policies balance environmental, social, and economic sustainability.

Long-term water quality monitoring indicates that many portions of San Francisco Bay have experienced marked increases in chlorophyll-a, a pigment found in all green plants including phytoplankton. The exact causes of this change are unknown, but may include changes in light regimes, changes in ecosystem function resulting from invasive species, and coastal influences. Often the availability of nitrogen is the factor that limits phytoplankton growth in estuaries. However, San Francisco Bay ambient nutrient concentrations are relatively high, and have not changed significantly in recent years. While Bay nutrient concentrations are on par with those of other nutrient-impaired estuaries, such as the Chesapeake Bay, the San Francisco Bay has typically been considered resilient to the effects of nutrient loads and has not experienced similar water quality impairment. Concern exists, however, that changes in factors other than nutrient concentrations may lead to nutrient-related impairment.

As sources of nitrogen and phosphorous – the natural end products of wastewater treatment – BACWA member agencies recognize that, should current trends continue, they will play a key role in efforts to reduce nutrient loading. Before undertaking potentially substantial investments to reduce nutrient loading, BACWA agencies have an obligation to their ratepayers to ensure that these investments are necessary to improve water quality, and will not have other unintended environmental impacts. BACWA has engaged consultant assistance to support the development of technical information to determine whether nutrients are impairing the estuary. While this question has not yet been answered, BACWA is also developing a framework for protecting the Bay in an informed way.

BACWA's objective with respect to nutrients is to support the development of scientifically based regulations that will result in water quality improvements while balancing environmental and economic objectives. To this end, BACWA is developing information on the technical aspects of nutrient management as well as potential future regulatory framework. While BACWA's priority is to understand the estuary sufficiently to know whether nutrients are causing impairment, information is also being developed to support regulatory strategy development, should it be needed.

This topic paper is the second in a series of three topic papers. All three topic papers are scheduled to be reviewed and completed in October 2011. Descriptions of the other two topic papers are provided below:

- Modeling: The modeling topic paper presents a conceptual model of the relationships between phytoplankton biomass, nutrients, and physical and biological drivers in the San Francisco Bay (SFB) Estuary. The paper also presents a strawman approach for developing a nutrient based eutrophication model of the SFB Estuary.

- Regulatory Framework: This topic paper will characterize the unique challenges posed by nutrient management regulatory requirements for municipal dischargers and to outline appropriate discharge permitting structures for practical, technically achievable, and affordable compliance.

1.1 Purpose

The purpose of this topic paper is to provide information to BACWA member agencies on the implications of transitioning from secondary to nutrient removal treatment. Furthermore, the topic paper attempts to establish a dialogue with regulators that illustrate the complexity associated with transitioning from secondary to nutrient removal treatment. In particular, this topic paper (1) describes a range of facility requirements and the potential impact on POTW operations, (2) presents a basis for a range of unit costs, and (3) addresses the unintended consequences related to the conversion from secondary to nutrient removal treatment.

1.2 Background

The majority of the BACWA member agency public owned treatment works (POTWs) currently provide secondary treatment. Secondary treatment is a combination of solids and organics removal, followed by disinfection prior to discharge. For some POTWs, a more advanced level of treatment is required for the removal of nutrients, such as nitrogen and in some cases phosphorus. A few BACWA member agencies provide nutrient removal, but most provide secondary treatment to achieve the numerical pollutant limits derived for the San Francisco Bay Basin Plan.

The nutrients of interest include, but are not limited to ammonia, nitrite, nitrate, total nitrogen (TN), phosphate, and total phosphorus (TP). The Regional Monitoring Plan (RMP), Regional Water Quality Control Board (RWQCB), and other stakeholders are focusing on nitrogen species for the San Francisco Bay. The scientific literature suggests that elevated nitrogen loads, not phosphorus, might be negatively impacting the San Francisco Bay. However, phosphorus to nitrogen ratios are a component of algae speciation, so phosphorus is also discussed throughout the paper.

A compilation of typical influent, secondary treatment and various nutrient removal effluent characteristics is provided in Table 1.

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Table 1. Annual Average Treatment Level Objectives *

Treatment Location	Ammonia (mg N/L)	Total Kjedahl Nitrogen (ammonia + Org N) (mg N/L)	Nitrite + Nitrate (mg N/L)	Total N (mg N/L)	Total P (mg P/L)
Influent (Raw Sewage)	20-30	30-40	<1	30-40	4-8
Level 1 (Secondary Treatment Effluent)	20-30	25-35	<1	25-35	4-6
Nutrient Removal					
Ammonia Removal	<1	1-3	20-25	20-30	4-6
Level 2 (Conventional TN/TP Removal)	<1	1-3	8-12	10-15	0.5-1
Level 3 (Advanced TN/TP Removal)	<1	1-3	3-6	4-8	0.1 – 0.3
Level 4 (Limit of Technology (not including RO)) **	<1	1-3	<1	<3	<0.1
Level 5 (RO)	<1	<2	<1	<2	<0.02

Notes:

* Regional Monitoring Plan Workshop on June 29, 2011 at David Brower Center, Berkeley, CA and Falk et al. (2011)

** Limit of Technology values from Bott and Parker (2010)

1.2.1 Nitrogen Removal

The removal of nitrogen during wastewater treatment is primarily achieved by (a) assimilation of nitrogen into biomass and (b) biochemical oxidation/reduction processes that convert organic nitrogen and ammonia to nitrogen gas through a two-step process. The two-step process is commonly referred to as nitrification and denitrification. Besides nitrification and denitrification pathways, the anammox step simultaneously removes ammonia and nitrite to form nitrogen gas. The nitrogen cycle, illustrating several nitrogen removal pathways, is presented in Figure 1.

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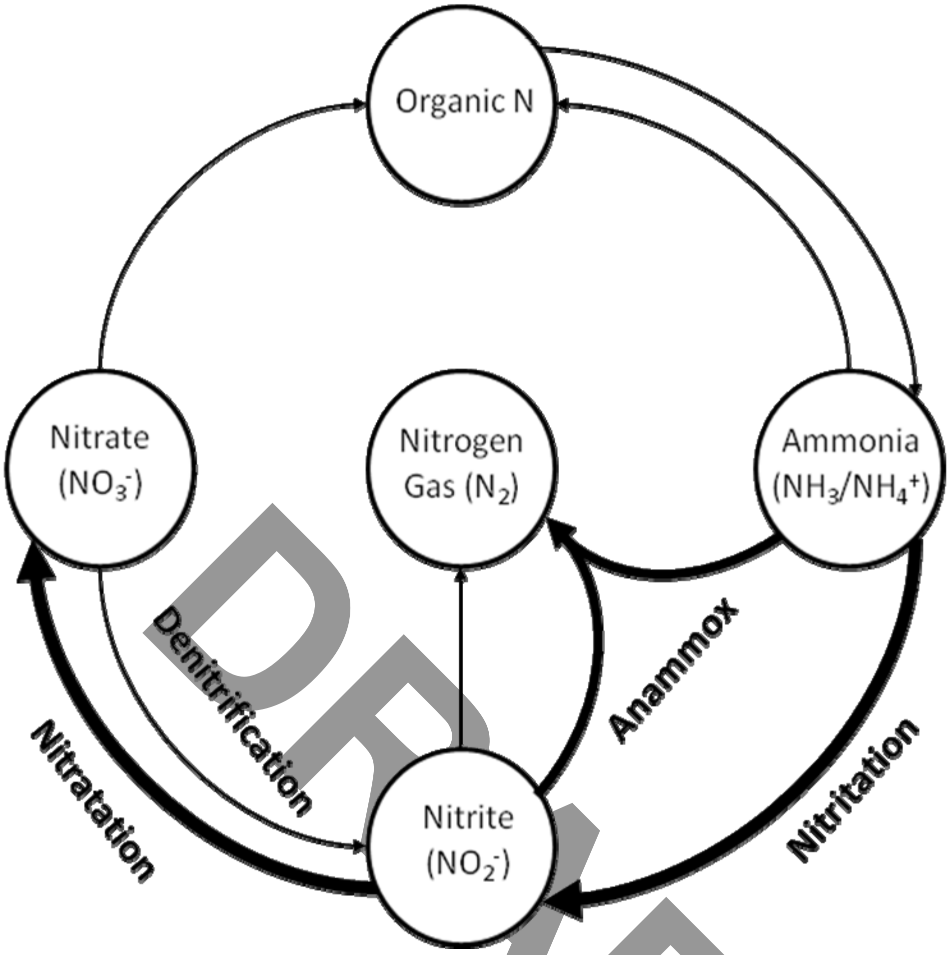

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Figure 1. Primary Biological Nitrogen Transformations.

1.2.1.1 Nitrification/Denitrification

Nitrification is a two-step process where ammonia (NH_3/NH_4^+) is first oxidized to nitrite (NO_2^-) (nitritation), followed by nitrite oxidation to nitrate (NO_3^-)(nitratation). The two-step process is carried out by nitrifying organisms and is commonly referred to as nitrification. The overall process stoichiometry is as follows:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ \quad (1)$$

The nitrate end-point of nitrification can be followed by denitrification if the treatment objective is to remove nitrogen. Denitrification is a biological process where denitrifying bacteria reduce nitrate first to nitrite, followed by subsequent reduction to nitrogen gas. Denitrification requires a carbon source (such as biochemical oxygen demand (BOD)). Overall, the process stoichiometry with methanol as the carbon source is as follows:

$$6NO_3^- + 5CH_3OH + CO_2 \rightarrow 3N_{2(g)} + 6HCO_3^- + 7H_2O \quad (2)$$

Combined nitrification and denitrification configurations are used in activated sludge wastewater treatment plants to remove nitrogen. A more detailed discussion on nitrification/denitrification, as well as the various treatment configurations can be found in the Water Environment Federation (WEF) Nutrient Removal Manual (2010).

1.2.1.2 Anammox

Although effective at nitrogen removal, the inherent disadvantage in the conventional nitrification/denitrification approach is that each step requires energy. A more energy efficient emerging approach is anaerobic ammonia oxidation (anammox). Anammox is a two-step process that initially requires nitritation where the ammonia is oxidized to nitrite (nitritation):

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \qquad (3)$$

The nitritation step typically stops at equal parts ammonia-N:nitrite-N. The subsequent second step simultaneously removes the ammonia and nitrite to form nitrogen gas (anammox step relying on the special anammox bacteria) as follows:

$$NH_4^+ + NO_2^- \rightarrow N_{2(g)} + 2H_2O \qquad (4)$$

The primary benefits of the anammox processes compared to conventional activated sludge for nitrogen removal is reduced power consumption (about 60% less per pound N removed), little or no required external carbon source, low yield (<0.15 lb TSS/lb N), and greatly reduced CO_2 emissions.

Although promising, the anammox technology is currently limited to the return stream from the dewatering facility (i.e., centrate/filtrate). Within a POTW, the return stream constitutes about 15 to 25 percent of the nitrogen load fed into the activated sludge process. Anammox is limited to the return stream as it requires relatively warm waters (≥30 C) to ensure that Equation 3 stops at nitrite. At relatively cooler water temperatures (about 20 C), Equation 3 proceeds all the way to nitrate (Equation 1) and subsequently must go through the denitrification pathway to remove N (Equation 2).

1.2.2 Treatment Levels for BACWA Member Agencies

An illustration of the current treatment levels provided by BACWA member agencies is provided in Figure 2.

A recently released United States Environmental Protection Agency (USEPA) report signals that nutrient over-enrichment may be a serious threat to estuaries nationwide (USEPA, 2010). Given that the impacts of nutrient over-enrichment are a case specific phenomena, there is an on-going effort to determine whether over-enrichment is a threat to the San Francisco Bay, and in turn whether BACWA member agencies currently performing secondary treatment should convert to nutrient removal treatment. If nutrient removal is ultimately required, there are various nutrient removal treatment levels that could be selected. A more detailed discussion of the impacts of treatment level selection is provided in Section 3.1.

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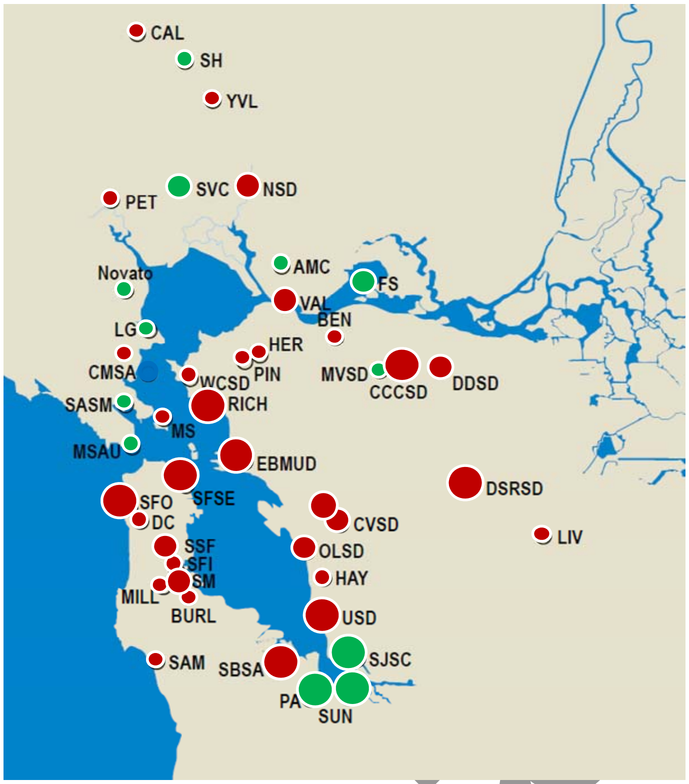

Flow (mgd)	Ammonia Removal	Secondary Treatment
>20	🟢	🔴
10-20	🟢	🔴
<10	🟢	🔴

Figure 2. Current POTW Treatment Levels of BACWA Member Agencies

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1.2.3 Facility Needs to Convert from Secondary to Nutrient Removal

The conversion from secondary to nutrient removal treatment will most likely require additional treatment facilities. The extent of additional treatment facilities is POTW specific. For example, a POTW that is constrained by footprint (space limitations) might implement different technologies than those with available space. The additional treatment facilities that might be required for a POTW to convert from secondary to nutrient removal treatment include:

- Expansion of secondary treatment facilities
  - Aeration basin volume (to meet nitrification oxygen demand and increase sludge age to grow nitrifiers)
  - Additional blower capacity (to meet nitrification oxygen demand)
  - Additional secondary clarifiers (to accommodate increased solids loading)
  - New pumps for internal recirculation to denitrify
- Chemical feed
  - Alkalinity feed for stable nitrification
  - External carbon source for denitrification
- New unit processes (dependent on permit structure)

2. Basis for Development of Unit Cost Estimates

The cost associated with retrofitting a particular POTW from secondary to nutrient removal treatment is case specific, as previously described, which makes it difficult to estimate general retrofit costs for a wide range of facilities. Therefore, several case studies were used as points of reference to develop a potential range of unit costs, including:

- Sacramento Regional County Sanitation District (High Purity Oxygen) (HDR, 2011c)
- Master Plans (Napa Sanitation District (Brown and Caldwell/Carollo, 2011); Delta Diablo Sanitation District (HDR, 2011a); Hampton Roads Sanitation District (HRSD) (HDR, 2011b))
- Water Environment Research Foundation (WERF) Sustainability Report (Falk et al., 2011)
- Florida Nutrient Numeric Criteria (NNC)(Reardon, 2010)

In addition to cost, permit limits can also span a wide range. The WERF Sustainability Report (Falk et al., 2011) discharge limits, as shown in Table 1, were used to discuss the impact of permit limits on both unit and operation costs. Level 1 treatment represents secondary treatment. Levels 2 through 4 are representative of nutrient removal permits being issued nationwide. Additionally, Levels 2 through 4 reflect the November, 2007 petition for rulemaking submitted by the National Research Defense Council (NRDC) to the USEPA. The NRDC petition claims that Levels 2-4 are achievable using current technology (barring reverse osmosis). Level 5, the most stringent nutrient level objective, would require an advanced membrane technology, such as reverse osmosis (RO) for treating 50% of the flow. Level 5 treatment objective is based on the recently released WERF report by Bott and Parker (2010), whereby they performed treatment performance statistics on 22 different POTWs doing nutrient removal treatment. Their results suggest that a nutrient removal POTW cannot reliably meet Level 4 objectives.

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3. Results and Discussion

This section will explain the basis for the wide range in unit costs, the impact on operations and maintenance, ancillary benefits associated with nutrient removal, convergence of technology, and the potential for sidestream treatment for POTWs that transition from secondary to nutrient removal treatment.

3.1 Factors Impacting Unit Cost

The following factors result in a wide range of unit cost:

- Averaging period for permit compliance
- POTW specific variables
  - Economy of scale
  - Existing plant capacity
  - Existing secondary treatment process technology
  - Land availability and constraints
  - Existing solids management

The permit compliance averaging period impacts the extent of treatment facility requirements. California permits are based on maximum day effluent limits for toxic compounds, such as ammonia (see Sacramento Regional County Sanitation District 2010 Discharge Permit). The POTW must be designed to meet this worst-case scenario over a calendar year. In the case of Sacramento Regional County Sanitation District (SRCSD), their recently issued permit will result in a facility sized to address the 2.2 mg N/L ammonia maximum day limitation. This type of limit results in an inefficient POTW with respect to energy consumption because all the pumps/blowers are designed for the worst-case scenario (e.g. maximum day conditions). This condition varies significantly from what pumps/blowers experience on an average day-to-day basis. Additionally, the maximum day condition eliminated some options from consideration. Had the permit been structured for maximum month (such as 2.2 mg N/L ammonia on a calendar month), the increase in air activated sludge basins and pumps could have been less.

A seasonality based permit compliance averaging period typically separates wet and dry weather periods. This approach is attractive as it excludes sizing treatment facilities for peak wet weather events. During a significant precipitation event, the POTW is subjected to peak flows with subsequently less hydraulic residence time within the POTW. Less time for treatment that can in turn negatively impact discharge levels. Additionally, the receiving water body is typically less sensitive to nutrient loads during the wet weather period. The treatment objectives can in turn be less stringent than the dry weather period when the receiving water is more sensitive to nutrient loads.

The POTW specific sub-variables from the bullet list above highlights the discrepancies amongst POTWs and how they might influence the amount of equipment, concrete, and/or pumps required as POTWs transition from secondary to nutrient removal treatment. The economy of scale relates to the size of the POTW in terms of flow. The unit cost for an upgrade with identical facility requirements is indirectly related to POTW size. As for plant capacity, this relates to how close influent flows and loads are to the design capacity. For example, a plant operating at 50 percent design capacity will likely require minimal or no basin expansion, whereas a plant operating at or near design capacity will require basin expansion (nearly double) of the activated sludge process.

The existing secondary treatment technology will play a significant role in cost as some technologies are not easily upgraded to nutrient removal. For example, a high purity oxygen (HPO) process will most likely require conversion to air activated sludge (AAS). Although some basins/tanks may be salvaged, the footprint requirements increase to levels such that space might not be available on-site. The increase in footprint for AAS at SRCSD is anticipated to be about 3.5 times greater than HPO. For landlocked POTWs, a technology with a more compact footprint than AAS might be required or, in extreme cases, additional land may need to be acquired. One such compact technology is a membrane bioreactor (MBR), which requires more cost and requires more energy than AAS. A database compiled by Dave Reardon (HDR) suggests that AAS meeting a Level 2 treatment objective (Table 2) requires between 2,500 to 3,750 KiloWatt-hour/million gallons (kWh/MG) treated, whereas a MBR meeting comparable treatment objectives requires between 3,500 to 6,000 kWh/MG treated.

3.2 Unit Cost for Conversion from Secondary Treatment to Nutrient Removal

The unit cost associated with transitioning from secondary to nutrient removal treatment is broken up into a Greenfield[1] POTW and a compilation of case studies for POTW retrofits. For a Greenfield plant, the WERF Sustainability Report by Falk et al. (2011) was used as it provides both total project capital cost and operations for a nominal 10 mgd flow POTW as shown in Table 2. The increase in total project capital costs with increased treatment is due to the fact that additional unit processes

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[1] A Greenfield plant refers to an undeveloped tract of land for constructing a POTW.

are required to meet the more stringent treatment levels. As for operations cost, the increase relates to the fact that additional energy (i.e., for aeration, chemicals, pumping, and mixing) and chemicals are required to meet treatment objectives. The removal of ammonia over total nitrogen requires more energy. The oxygen transfer rates improve the transition from ammonia removal to total nitrogen removal (about 10 percent). Additionally, a portion of the aeration is recovered under total nitrogen removal which translates to roughly 10-20 percent savings in aeration. However, a larger footprint is required for total nitrogen removal over solely ammonia removal. The chemicals are necessary to compliment the biological treatment limitations from Level 3 onwards.

Table 2. Total Project Capital and Operations Costs for a 10 mgd WWTP (Falk et al., 2011)[i]

Level (Treatment Performance)	Total Project Capital Cost ($/gpd) [ii]	Total Project Capital Cost (Million $) [ii]	Operations Cost ($/MG Treated) [iii]	Operations Cost ($1,000/yr) [iii]	Total Present Worth Project Costs (Million $) [iv]
1 (Secondary Treatment)	9.3	93	250	910	110
2 (8 mg N/L; 1 mg P/L)	12.7	127	350	1,260	150
3 (4-8 mg N/L; 0.1-0.3 mg P/L)	14.4	144	640	2,350	180
4 (3 mg N/L; <0.1 mg P/L)	15.3	153	880	3,200	210
5 (1 mg N/L; <0.02 mg P/L)	21.8	218	1,370	4,990 **	300

Notes:

i The total project capital cost is for a Greenfield plant.

ii The total project capital cost are the equipment cost, construction, and administration “soft” costs

iii Operations cost = energy and chemical cost. Labor and maintenance costs are excluded

iv The assumed discount rate was 5 percent at an escalation rate of 3.5 percent (capital, energy, non-energy)

Information gathered from the case study reports listed in Section 2 provides a wide range of unit cost for upgrading treatment plants to nutrient removal. Table 3 presents the range of conversion unit cost for upgrading three types of treatment configurations. Specific examples from treatment plants in the case study reports are listed for reference along with challenges and designs unique to each cost range. The width in unit cost variability is largely due to the case specific nature of each conversion as discussed in Section 4.1.

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Table 3. Unit Cost Conversion from Secondary Treatment to Nutrient Removal

Technology	Plant Name	Conversion Unit Cost ($/gpd)	Comment
Trickling Filter/ Activated Sludge	Summary	3.2 – 4.7	Only 1 available data set
	Delta Diablo Sanitation District	3.2 – 4.7	HDR Master Plan (2011a) to leverage existing tankage and add membranes for a membrane bioreactor
High Purity Oxygen	Summary	0.3 - 12 [i]	Lower range for 10-20% NH3 load reduction; upper range for 2010 Adopted NPDES Permit
	Sacramento Regional County Sanitation District (SRCSD)	0.3 - 3.2	10-20% NH3 load reduction (HDR, 2011c)
	SRCSD	1.8 - 5.7	50-60% NH3 load reduction (HDR, 2011c)
	SRCSD	2.7 – 3.4	80-95% NH3 load reduction (HDR, 2011c)
	SRCSD	6.9 – 12	2.2 mg N/L ammonia Maximum Day; 10 mg N/L nitrate Monthly Average (HDR, 2011d)
Activated Sludge	Summary	2.1 – 16	Lower range for POTW with ponds storage; upper range for RO
Activated Sludge	Napa Sanitation District	2.1 – 4.1	Brown and Caldwell/Carollo Master Plan (2010).
Activated Sludge	Atlantic Treatment Plant [ii]	2.7	Includes methanol feed and enhancement facility (NEF), construction space (HDR, 2011b)
Activated Sludge	Boat Harbor Treatment Plant [ii]	6.6	Significant site constraints includes methanol feed and NEF (HDR, 2011b)
IFAS	James River Treatment Plant [ii]	7.4	Includes methanol feed and NEF (HDR, 2011b)
Activated Sludge; no primaries	Chesapeake Elizabeth Treatment Plant [ii]	5.4	NEF used existing gravity thickener structure (HDR, 2011b)
Modified Ludzack-Ettinger Process	Williamsburg Treatment Plant [ii]	3.8	Plant receives high strength brewery waste, includes methanol feed and NEF (HDR, 2011b)
Modified Ludzack-Ettinger Process	Bench-top Study	3.4	Falk et al. (2011) – Level 1→Level 2 (Garden Variety TN/TP removal)
5-Stage Bardenpho/Filtration	Bench-top Study	5.1	Falk et al. (2011) – Level 1→Level 3 (Advanced TN/TP removal)
5-Stage Bardenpho/ Tertiary Denit Filter	Bench-top Study	6.0	Falk et al. (2011) – Level 1→Level 4 (Advanced TN/TP removal)
5-Stage Bardenpho/RO	Bench-top Study	13	Falk et al. (2011) – Level 1→Level 5 (Advanced TN/TP removal)
Modified Ludzack-Ettinger Process	Florida Nutrient Numeric Criteria	8.2	Reardon et al. (2010) – For plants making changes to meet Florida NNC
5-Stage Bardenpho/RO	Florida Nutrient Numeric Criteria	165	Reardon et al. (2010) – For plants implementing Reverse Osmosis to meet Florida NNC

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Notes:

[i] Lower range only accounts for 10-20 percent NH3-N load reduction

[ii] Hampton Roads Sanitation District (HRSD) Plant Upgraded to 5-stage Bardenpho process with nitrification enhancement facility (NEF), construction cost only.

3.3 Impact of Conversion from Secondary to Nutrient Removal Treatment on Operations and Maintenance

Various areas of operations and maintenance are impacted with the transition from secondary to nutrient removal treatment. A few of these areas are discussed below.

3.3.1 Solids Production

The removal of ammonia by nitrification requires a longer solids retention time (SRT) than required for secondary treatment (on the order of 10 days versus 2 days). By increasing the sludge age, the solids yield (i.e., lb TSS/lb BOD) is reduced, and in turn, less waste activated sludge is sent to solids processing. The extent of solids reduction is shown in Figure 3. This results in a reduction in chemical demand and energy associated with treating the solids waste.

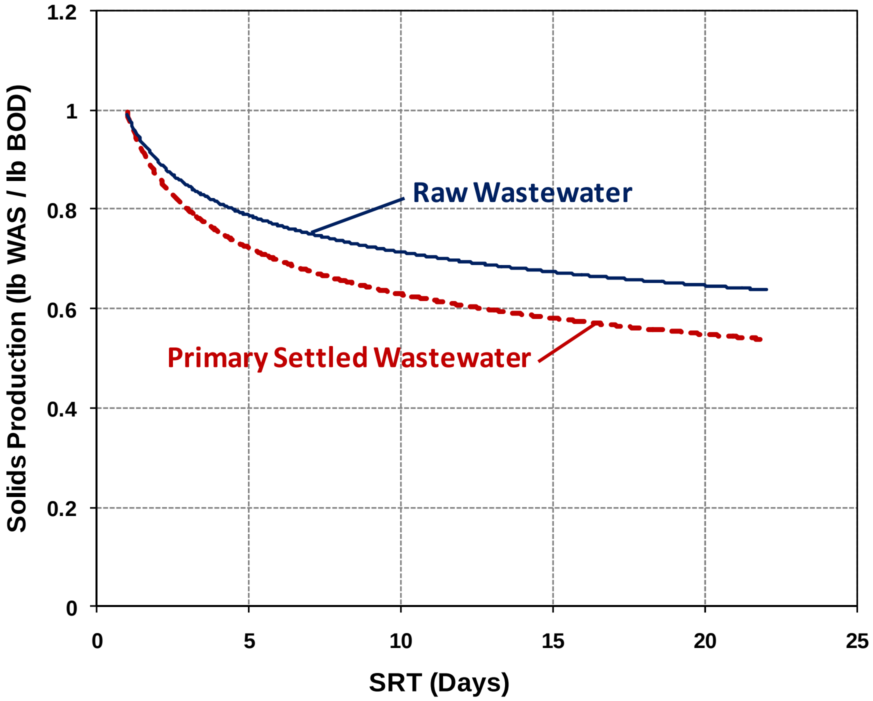

Figure 3. Effect of Sludge on Solids Residence Time (Adapted from Benjes, 1980).

3.3.2 Foaming

An increase in SRT required for nitrification can also promote the growth of floating bacteria. These bacteria have a tendency to induce foam and can accumulate on the reactor's surface. The use of anaerobic/anoxic selectors for biological P removal and denitrification can assist in suppressing foam inducing organisms as they are typically obligate aerobes.

There are several foam control strategies that have results ranging from marginal to complete control. One such foaming control approach is to implement surface wasting using a weir instead of the typical mechanical wasting approach. The collected foam can be thickened and stabilized (e.g., using a dissolved air flotation and lime stabilization) and eliminated from the process train without negatively impacting the anaerobic digesters. Converting a basin from mechanical wasting requires the construction of break walls, which incurs an additional expense. A less intrusive approach is the addition of floc settling chemicals (e.g., polymer) in the clarifier clearwell. The polymer can overcome the effects of filaments on sludge settling. Although effective, this strategy is costly from an operations standpoint and would require detailed analysis on polymer selection. Another approach is the use of a SRT controller that can reduce the sludge age so that it is sufficient for nitrifiers but too short for foam inducing organisms to thrive.

3.3.3 Disinfection

Chlorine added for disinfection rapidly reacts with ammonia (chloramination) to produce monochloramine (NH_2Cl) as follows:

$$NH_4^+ + HOCl \rightarrow NH_2Cl + H_2O + 2H^+ \qquad (5)$$

The removal of ammonia in a nutrient removal plant will result in free chlorine being present over monochloramine as the disinfectant. Although free chlorine is a more effective disinfectant than monochloramine, it produces more undesirable disinfection by-products (DBPs). Examples of DBPs include nitrosodimethylamine (NDMA), trihalomethanes (THMs), and haloacetic acids (HAAs).

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Rather than converting from chlorine to a different disinfectant (e.g., UV), several variations of chlorine disinfection can be considered. For example, controlled chloramination and sequential chlorination, can be used to disinfect and reduce DBP formation potential. Controlled chloramination entails adding external ammonia to meet the demands associated with Equation 5. Sequential chlorination is a variation on chlorine disinfection that is a two-step process for POTWs with filtration. The first step is free chlorine addition before filtration, followed by ammonia addition after filtration to form monochloramines (Maguin et al., 2009). The rationale for the two step process is to minimize NDMA and the formation of THMs/HAAs by limiting the amount and reaction time of free chlorine. This process was created and first used at the Sanitation Districts of Los Angeles County.

An additional free chlorine demand concern with converting to ammonia removal and/or total nitrogen removal is nitrite breakthrough. Rather than oxidizing the ammonia all the way to nitrate (Figure 1), incomplete nitrification can lead to nitrite production. The presence of nitrite is a concern as the free chlorine demand is 5 pounds free chlorine per lb nitrite (Cowman and Singer, 1994). The increased demand relates to the fact that nitrite rapidly reduces free chlorine and it accelerates chloramines decomposition (Skadsen, 1993). This unintended consequence associated with transitioning from secondary nutrient removal treatment can prove costly in operations. The extent of increased free chlorine demand will be plant specific as it is a function of nitrite breakthrough.

3.3.4 Labor

The conversion to nutrient removal treatment increases complexity and in turn requires more operators. The longer sludge age associated with activated sludge under nutrient removal lends itself to a more robust process than the shorter sludge ages of conventional activated sludge secondary treatment. However, the nitrifying microorganisms that govern the sludge are more sensitive to process upsets than the microorganisms that perform secondary treatment. As a result, the operators must be more experienced and skilled in dealing with the nitrifying populations associated with activated sludge under nutrient removal.

A nutrient removal plant requires more labor to operate and maintain the supplementary equipment associated with nutrient removal (e.g., pumps, mixers, chemical feed, etc.). The extent of increased labor is heavily dependent on the level of treatment. For example, the amount of labor required to meet the Level 2 and Level 4 objectives in Table 1 is significantly different. In the case of Level 2, the only change from secondary treatment is converting the conventional activated sludge process to one that performs nutrient removal. In contrast, Level 4 requires conversion from conventional activated sludge to a more sophisticated and complex activated sludge process than Level 2, a high-rate clarifier, denitrifying filters, and an external carbon source to meet low level nitrate levels.

The external carbon source (e.g., methanol) required of the more advanced treatment levels (e.g., TN < 6 mg N/L) is not only a chemical burden, but also a safety concern. Methanol is commonly used as the external carbon source which is explosive. As a result, the operators must be trained in handling methanol as the regulations are in-line with an automobile gas station.

3.3.5 Sustainability

The WERF Sustainability Report (Falk et al., 2011) investigated where a point of "diminishing returns" is reached where the sustainability impacts of increased levels of nutrient removal outweigh the benefits of improved water quality. Within the report, greenhouse gas (GHG) emissions were measured along with potential algal production as a water quality surrogate. The distribution of GHG emissions for pumping/mixing, aeration, cogeneration, N_2O emissions, chemical manufacturing/delivery/use, deep well injection (Level 5), and sum of CH_4 emissions and biosolids hauling is provided in Figure 4.

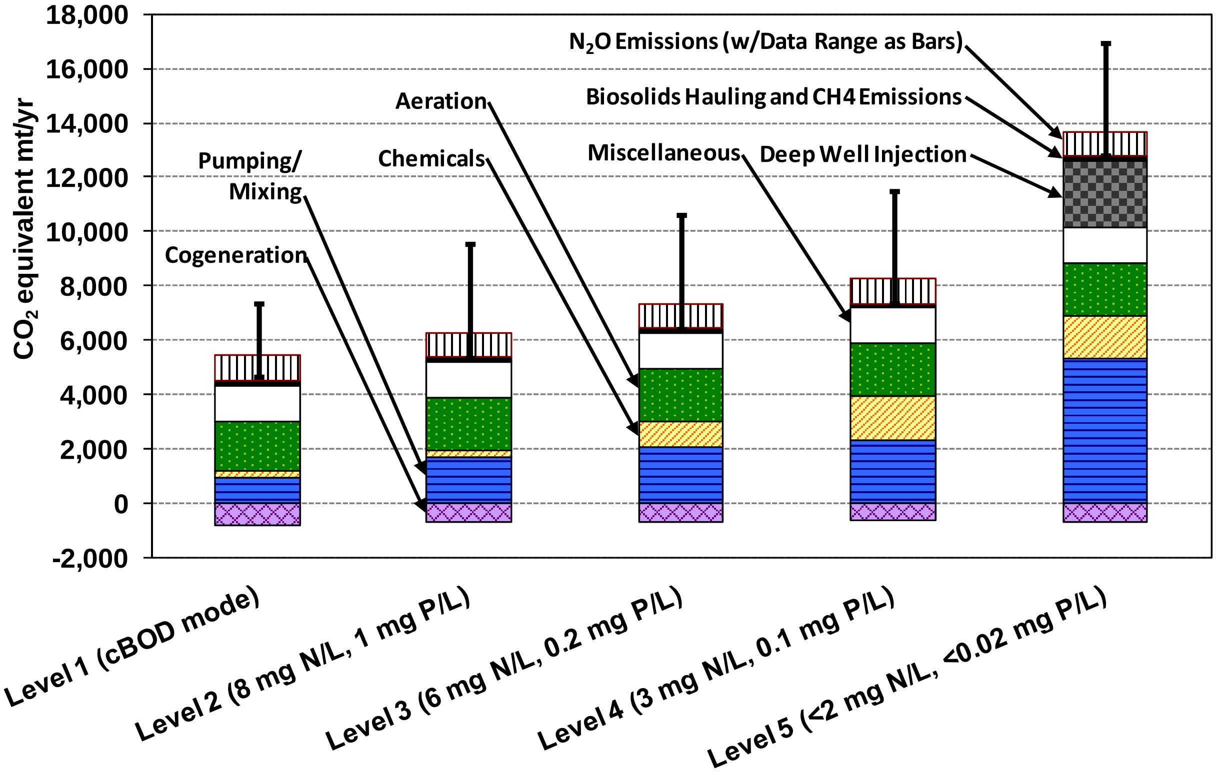

Figure 4. GHG Emissions Distribution per Treatment Level

The three largest contributors to GHG emissions are all energy related: aeration, pumping/mixing, and deep well injection (Level 5). The steady increase in emissions from Levels 2 to 4 is due to chemical demand for methanol to fuel denitrification, alum, and polymer. More chemicals are required for tertiary add-on solids separation processes with more advanced treatment. For example, the use of high rate clarification (assume dose of 50 mg/L alum; 2 mg/L polymer) increases chemical demand from Level 3 to Level 4 or 5. The least significant variables were methane and biosolids hauling.

Besides GHG emissions, the impact on the receiving water body using the water quality surrogate is potential algal production. The algae production results in Figure 5 are on the primary y-axis (left-hand side) along with the GHG emission equivalents on the secondary y-axis (right-hand side). The algal savings are 95% from Level 1 to 3. Both Levels 4 and 5 remove an additional 4 percent (99 percent total removal with respect to Level 1) with a corresponding doubling of GHG emissions from Level 3 to 5.

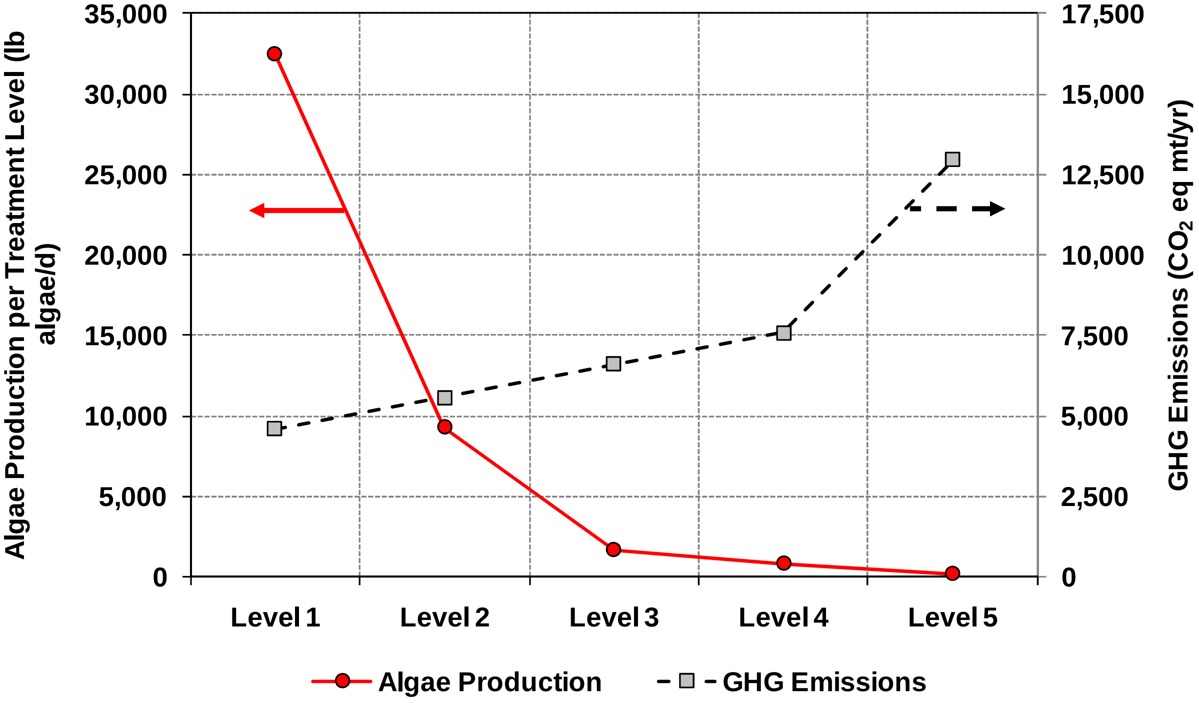

Figure 5. GHG Emissions and Algae Production per Treatment Level

The overall message from the WERF Sustainability Report is that a combination of Level 3 treatment complimented with best management practices on non-point sources might be a more sustainable approach than solely regulating point source discharges for achieving comparable water qualities.

3.4 Ancillary Benefits of Nitrogen Removal

The longer sludge age associated with the conversion of secondary to nutrient removal treatment will provide ancillary benefits as follows:

- Reduced effluent biochemical oxygen demand (BOD) and total suspended solids (TSS) loads
- Lower biomass yield (lb TSS produced per lb BOD feed) as sludge age is inversely related to yield (Figure 3)
- Improved removal of trace organic compounds (TrOCs) (Horz et al., 2004)
- Improved removal of heavy metals (Stasinakis et al., 2003)
- Improved secondary clarifier effluent filterability (Leu et al., In press; Chan et al.; In press) and lower levels of particulate-associated Coliform (Emerick et al., 2000)

- Improved process stability from the anaerobic/anoxic zones serving as a selectors (Jenkins et al., 2004)

3.5 Convergence of Technology – Reclaim or Discharge

As National Pollution Discharge Elimination System (NPDES) permits continue to be more stringent with respect to numerical limits as well as the averaging period for permit compliance (e.g., maximum day ammonia limits), a situation can arise where the treatment requirements for reuse are less stringent than discharging to the receiving water body. This is a common issue nationwide for POTWs. In many cases, the NPDES permit would require a complex activated sludge process with an external carbon source, denitrifying filters, and other unit processes to meet the discharge objectives. In contrast, the treatment requirements for unrestricted Title 22 reuse in California require secondary treatment, followed by filtration and disinfection (albeit more stringent disinfection).

Although meeting the unrestricted Title 22 reuse requirements might be easier than meeting the NPDES permit, there are additional costs associated with identifying potential reclaimed water users, building a reclaimed water distribution system, and managing treated effluent during the wet season when recycled water demands are typically at their lowest. The incorporation of these costs will provide a normalized comparison to assist in decision making.

Under such situations, the utility will need to determine which option provides the most value to their rate payers.

3.6 Emerging Sidestream Nutrient Removal Technologies

The removal of nitrogen within the main plant flow is proven, well understood, and documented. The advent of more stringent permits has led researchers to consider various locations in the plant for nutrient load reduction. In particular, the dewatering centrate/filtrate return stream (referred to as the sidestream) for plants with digesters constitutes between 15-25 percent of the N load and the majority of the P load.

There are several technologies that can remove either N or P from the sidestream. For nitrogen removal, the technologies are either biologically or chemical/physical. The biologically based technologies include, but are not limited to the following:

- Activated sludge technology to treat the sidestream (e.g., sequencing batch reactor)
- SHARON (partial nitritation followed by denitrification using an external carbon source)
- Anammox (partial nitritation followed by anammox bacteria using ammonium/nitrite simultaneously to form nitrogen gas)

Of the listed options, the topic paper will focus on anammox as it requires the least amount of energy, has the smallest footprint, and does not require an external carbon source. Although there are currently no full-scale anammox installations in the United States, the technology is established in Europe and Asia with more than a dozen installations. An image of the Rotterdam, Netherlands anammox reactor is provided in Figure 6.

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Figure 6. Anammox Reactor at Rotterdam WWTO, NL

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For chemical/physical removal of N, ammonia stripping is an older/proven technology. Ammonia stripping is rarely applied to POTWs anymore due to the amount of chemicals and the required stripping tower. A novel technology (Ammonia Recovery Process (ARP) by ThermoEnergy®) is emerging that uses the chemistry associated with ammonia stripping and increases the pH to greater than 10 standard units (su) to volatilize the ammonium. Rather than strip out ammonia gas in a stripping tower, the ARP technology mists the stream to increase surface area and applies a vacuum pressure all within an enclosed vessel to draw out the ammonia gas. An image of an ARP reactor is shown in Figure 7. Once separated, the ammonia gas is condensed back to the liquid form using sulfuric acid to form reagent grade ammonium sulfate. The ammonium sulfate is then sold as a fertilizer (40% ammonium sulfate) and in turn creates a revenue source.

Figure 7. Image of an ARP Reactor by ThermoEnergy®

For POTWs performing biological P removal, the presence of P in the sidestream constitutes the majority of the P load within the main plant flow. Historically, the P leaving the digesters has a tendency to form struvite crystals that can deposit on piping/pumping and be problematic for operations. Rather than consider struvite crystals as a nuisance, manipulation of water chemistry can facilitate the formation of struvite crystals within a unit process to separate the crystals. Struvite crystals are a formation of ammonia magnesium phosphate (MAP). An image of a MAP reactor provided by Ostara® and the corresponding crystals are provided in Figure 8. Like the ARP technology, the MAP crystals create a revenue source.

Figure 8. Image of a MAP Reactor from Ostara ® (Left) and the MAP Crystal from Ostara ® (Right)

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A summary table of the three discussed sidestream technologies is provided in Table 4. The strength in all three technologies is that they provide BACWA member agencies an opportunity to proactively remove a portion of nutrient load with minimal investment compared to the main plant flow. However, the unit cost on a per gallon basis is more expensive than the main plant flow. For example, the range of values in Table 3 is $2.1-16/gpd for AAS, whereas the Anammox/ARP are both between $20-50/gpd. Despite the expensive start-up costs, there is a subsequent operations savings benefit. A planning level cost-benefit analysis is recommended for any POTW considering sidestream treatment.

Table 4. Sidestream Emerging Technologies Unit Cost

Technology	Unit Cost	Revenue Stream Potential	Comment
Anammox	$20 - 50 / gpd treated [i] ($ 0.3 – 1.6/lb N) [ii]	-	Reduces aeration demands in main plant flow; reduces overall plant wide greenhouse gas emissions
ARP by ThermoEnergy ®	$20 - 50 / gpd treated [i] ($ 0.3 – 1.6/lb N) [ii]	$1-2/gal	Operations cost dependent on water chemistry (ability to raise/drop pH), not N load. Reduces aeration demands in main plant flow.
Struvite Reactor (e.g., Ostara ®) [iii]	$0.7-1.4/lb P Removed	$100-250/ton for POTW in revenue	Suffers from economy scale. Currently limited to plants >40 mgd practicing biological phosphorus removal.

Notes:
i The gpd treated is based on the sidestream average annual flow
ii Assumes a 20-yr period and a sidestream concentration of 500 – 1,000 mg N/L
iii A struvite reactor is only applicable for facilities that both perform biological P removal and have anaerobic digestion with dewatering.

4. Summary and Conclusions

As BACWA and its member agencies start to prepare for the potential for more stringent nutrient discharge requirements, it is critical that they understand their implications. This topic paper attempts to inform BACWA and its member agencies about the following implications associated with transitioning from secondary to nutrient removal levels of treatment:

- Factors that govern unit cost
    - Nutrient permit limits/structure
    - POTW specific variables
- Impact of conversion on operations and maintenance
- Ancillary benefits of transitioning from secondary to nutrient removal treatment
- Convergence of technology where reclaimed water is more viable than meeting discharge permit limits
- Emerging sidestream technologies as a tool to proactively remove a portion of the nutrient load at a minimal cost relative to the main plant flow.

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