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Agency

# Case Studies on Implementing Low-Cost Modifications to Improve Nutrient Reduction at Wastewater Treatment Plants

DRAFT – Version 1.0
August 2015

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# Case Studies on Implementing Low-Cost Modifications to Improve Nutrient Reduction at Wastewater Treatment Plants

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# Acronyms

| | |
|---|---|
| AS | activated sludge |
| A2O | anaerobic/anoxic/oxic process |
| BAT | best available technology |
| BMP | best management practice |
| BNR | biological nitrogen removal |
| BOD | biochemical oxygen demand |
| $BOD_5$ | 5-day biochemical oxygen demand |
| CMAS | Complete Mix-Activated Sludge |
| COD | chemical oxygen demand |
| CSR | continuously sequencing reactor |
| DO | dissolved oxygen |
| EBPR | enhanced biological phosphorus removal |
| EPA | U.S. Environmental Protection Agency |
| F/M ratio | food-to-microorganism (F/M) ratio |
| gpd | gallons per day |
| HLR | hydraulic loading rate |
| HRT | hydraulic retention time |
| IFAS | integrated fixed-film activated sludge |
| IMF | intermittent media filter |
| ISF | intermittent sand filter |
| MLSS | mixed liquor suspended solids |
| MLE | Modified Ludzack-Ettinger |
| $NH_4$ | ammonium |
| $NO_3/NO_2$ | nitrate/nitrite |
| NPDES | National Pollutant Discharge Elimination System |
| O&M | operation and maintenance |
| OLR | organic loading rate |
| ORP | oxidation-reduction potential |
| OWM | EPA Office of Wastewater Management |
| PE | population equivalents |
| RAS | return activated sludge |
| RMF | recirculating media filter |
| RR | recirculation ratio |
| SA | surface area |
| SBR | sequencing batch reactor |

| | |
|---|---|
| SCADA | supervisory control and data acquisition |
| sf | square feet |
| SRT | solids retention time |
| TKN | total Kjeldahl nitrogen |
| TMDL | total maximum daily load |
| TN | total nitrogen |
| TP | total phosphorus |
| TSS | total suspended solids |
| VFA | volatile fatty acid |
| VFD | variable frequency drive |
| WAS | waste activated sludge |
| WWTP | wastewater treatment plant |

# Executive Summary

This technical report supplements a number of recent guidance manuals and reports published by EPA on nutrient removal at wastewater treatment plants (WWTPs) by providing useful information to managers and operators of plants *that may not be specifically designed for nutrient removal* or for those seeking to achieve even better treatment through relatively low-cost modifications. It is intended to help fill gaps in published information about improving nutrient reduction performance at existing WWTPs (generally activated sludge facilities with basic treatment processes), using relatively low-cost techniques.

Although many published reports and papers address the nutrient removal performance of WWTPs, this report is one of the first documented efforts to present empirical data via a compendium of case studies of non-advanced[1] WWTPs that have been optimized to improve nutrient reduction without requiring costly infrastructure upgrades.

The economic implication of regulating nutrients is often perceived as an impediment to progress. The results of this project suggest that opportunities for low-cost nutrient removal optimization are common, particularly at basic activated sludge plants, which are the focus of these case studies.

This report documents optimization techniques through empirical example at specific plants. It does not address site-specific design, engineering or cost factors for other facilities. These case studies are not appropriate for setting permit requirements; such requirements should be established by permit directors in accordance with applicable CWA and state requirements.

## METHODOLOGY

The U.S. Environmental Protection Agency (EPA) focused on identifying relevant case studies to highlight in this report through the following main efforts:

- Internal EPA query to relevant Regional and state staff.
- Broad grey and white literature review.
- Review of existing EPA and other guidance documents.
- Query of selected industry practitioners.
- Supplemental search of Clean Water Needs Survey (CWNS) database.

From a master list of over 80 case studies, a total of 12 have been summarized for the project. The main criteria for selecting case studies included:

- Responsiveness to project objectives: relatively basic (non-advanced) treatment plants improving nitrogen or phosphorus reduction performance using low-cost techniques.
- Availability of monitoring and cost data.
- Representative of a range of scenarios (e.g., system types, geographies) and nutrient optimization approaches.

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[1] For the purposes of this report, "non-advanced" means a WWTP that has not been designed as a nutrient removal plant (e.g., originally no anaerobic selectors for TP removal or anoxic zones for denitrification).

Of the 12 selected case studies, seven fully meet the main criteria. Although the other five do not meet all the specified criteria, they provide useful information that might help target audiences understand nutrient reduction optimization approaches. Most of the other candidate case studies were not selected for one or more of the following reasons:

- Lack of monitoring and/or cost data.
- WWTPs were found to be advanced plants and/or implemented improvements were rebuilds for biological nutrient removal (BNR), requiring significant costs.
- Unable to complete follow-up with WWTP contacts within available time for collecting study data.

EPA anticipated identifying a number of relevant, published case studies through this research. However, despite extensive efforts to identify and develop relevant case studies, relatively few met the aforementioned criteria. EPA concluded that the primary limitation in identifying prospective case studies was that most efforts at improving small or non-advanced plants appear to be unpublished or otherwise under documented. Most published literature focuses instead on optimizing existing BNR systems. Nevertheless, the case studies that were developed show that optimization of non-advanced WWTPs is feasible and cost-effective, and provide useful information to support future efforts at other WWTPs.

As expected, the greatest number of potential case studies were identified for activated sludge systems. EPA also attempted to identify case studies for lagoon and trickling filter systems, but only a few examples of nutrient reduction optimization were uncovered; and most of them included significant infrastructure modifications which disqualified them from the pool of case studies, since they could not be considered “low cost” approaches.

Relevant data on approach, performance, and costs are summarized for the 12 case studies that were developed for this project. These data were then used to develop broader technical information to help treatment plant managers, operators, and others to improve the nutrient reduction performance of their plants.

# RESULTS

A number of modifications can be considered for improving nutrient removal at existing non-advanced WWTPs, including (but not limited to) one or more of the following. Note that many of the optimization activities described below are complimentary to one another and that control system additions or modifications are needed for many applicable optimization activities.

> *Aeration modifications* are changes to physical aeration equipment, controls, operation, and function of equipment and aerated areas. They include installing energy efficient blowers, variable frequency drives (VFDs), diffusers with improved distribution and oxygen transfer efficiency (OTE), airflow meters, airflow control valves, and on/off cycling; and dissolved oxygen (DO), ammonia, or oxidation reduction potential (ORP) control. Aeration modifications are typically used to optimize anoxic conditions that support denitrification for biological nitrogen removal. Creating anaerobic zones before aerated activated sludge treatment can also support enhanced biological phosphorus removal (EBPR).
>
> *Process modifications* include adjustments to process control characteristics, including solids retention time (SRT), mixed liquor suspended solids (MLSS), food-to-microorganism (F/M) ratio, and recycle/return rate. Physical process improvements might include adding VFDs and/or return activated sludge (RAS) pumps for internal recycling; adding online monitoring equipment for process control and optimization; or providing new screens or grit removal equipment at the headworks to improve the performance of the treatment process.

*Configuration modifications* are changes to, or the addition of, flowstreams within the process or changes to the process configuration. They might include changes to channels; manipulating gates; or modifying or adding piping, such as adding internal recycle lines or step-feed provisions; and are frequently employed to create or enhance environments for denitrification (e.g., by returning nitrate rich mixed liquor back to an anoxic zone).

*Chemical modifications* are the addition of, or changes to supplemental alkalinity and organic carbon feed to support biological nitrogen removal.

*Discharge modifications* are made at the end of the treatment system to further reduce nutrients prior to delivery to receiving surface waters. They generally use natural systems and might include soil-based treatment systems or wetland assimilation discharge.

Specific characteristics of the case studies selected for this project are summarized in Table 1 (Summary of Case Studies) and Table 2 (Modifications Featured in Case Studies).

The results of this project illustrate that:

1. No- or low-cost activities can be implemented at existing WWTPs to significantly reduce effluent nutrient discharges with minimal negative impacts on operations. In fact, in most cases, the secondary impacts are overwhelmingly positive and include energy efficiency, lower operational costs, and improved process stability. Although most of the case studies did not specify the capital costs savings associated with their optimization approach over alternative approaches, several did. Modifications at Crewe, Virginia had a capital cost of $6,000, compared with an estimated upgrade cost of $800,000. Victor Valley spent $1.1M instead of $80M for a new treatment train. Two other case study contacts indicated that optimization saved significant money versus more capital intensive alternatives.
2. Low-cost nutrient reduction improvements are most feasible for activated sludge plants, where excess capacity (volumetric and/or aeration) can typically be leveraged to facilitate nitrification and denitrification without requiring physical infrastructure modifications. However, utilizing excess capacity may limit the ability of a WWTP to increase its flow rate in the future without an expansion. For the case studies featured in this project, only one contact indicated that their plant (Victor Valley, CA) needed to be rerated as a result of their optimization efforts. EPA did not specifically ask WWTP contacts about impacts on design capacity.
3. Low-cost nutrient reduction improvements, particularly for relatively basic treatment systems, are underreported in the literature. EPA intends to identify additional case studies and update this document in the future. EPA will also consider additional activities to develop capacity and support nutrient reduction at such facilities.
4. Modestly improved phosphorus reduction often co-occurs as a result of improvements in biological nitrogen removal. To achieve more significant phosphorus reductions, most WWTPs opt for chemical precipitation, which is a well-established technology widely adapted to different plant types and configurations. Enhanced biological phosphorus removal (EBPR) generally requires significant physical infrastructure modifications at existing plants (e.g., creation of anaerobic selector zones). Other opportunities for reducing phosphorus discharges include control or side-stream treatment of return flows and enhancing volatile acid production for driving EBPR in existing anaerobic selectors (only applicable for an existing advanced treatment system). Soil- and plant-based treatment systems are also particularly effective for reducing phosphorus, which is removed from wastewaters by solid-phase sequestration.

**Table 1. Summary of Case Studies (basic, non-advanced treatment plants shaded in gray)**

| Case Study | Design Flow (MGD) | WWTP Type | Modification Type | Pre/post TN (mg/l) [1] | Pre/post TP (mg/l) [1] | Capital Costs | Operational Costs/Savings |
|---|---|---|---|---|---|---|---|
| Bay Point, FL | 0.054 | AS (MLE) | Aeration, chemical | 6.33/3.99 | N/A | $170,365 | **Savings** not quantified |
| Bozeman, MT | 5.2 | AS | Aeration, configuration | 17.8/10.5 | 3.7/2.5 | $180,000 | Zero |
| Chinook, MT | 0.5 | AS (Oxidation Ditch) | Aeration | 20.3/5.44 | 4.13/1.72 | $81,000 | Energy **savings** more than offset $1,000/yr in maintenance |
| Crewe, VA | 0.5 | AS (Oxidation Ditch) | Aeration, chemical | 7.85/3.63 | N/A | $6,000 | $17,440/yr **savings** |
| Flagstaff, AZ | 6.0 | AS (IFAS) | Process | 14.0/8.5 | N/A | $10,000 | $1,000/yr |
| Hampden Twp., PA | 5.69 | AS (CSR) | Configuration, process | 4.66/3.64 | N/A | Zero | Zero |
| Layton, FL | 0.066 | AS (SBR) | Aeration, process | 7.88/3.33 | N/A | $53,000 | $13,500/yr **savings** |
| Montrose, CO | 4.32 | AS (Oxidation Ditch) | Aeration | Unk/14.7 | N/A | Zero | $34,000/yr **savings** |
| Tampa, FL | 96 | AS (Separate Stage) | Aeration, configuration | 18.62/13.82 | N/A | Zero | $519,900/yr **savings** |
| Titusville, FL | 6.75 | AS (A2/O) | Discharge, configuration, process | 5.67/0.94 | 0.77/0.04 | $2,240,000 | $45,000/yr |
| Victor Valley, CA | 13.8 | AS | Aeration, process | 8.93/6.83 | N/A | $1,100,000 | 10% **savings** |
| Wolfeboro, NH | 0.6 | AS (Extended Aeration) | Aeration | 6.32/1.97 | N/A | $116,000 | **Savings** not quantified |

*Notes*:
AS = activated sludge; MLE = modified Ludzack Ettinger; IFAS = integrated fixed film activated sludge; SBR = sequencing batch reactor; N/A = not applicable; CSR = continuously sequencing reactor.

[1] Available flow data typically did not allow for quantification of pre- and post- optimization TN and TP loads (mass); therefore, concentration is used as the primary performance metric.

**Table 2. Modifications Featured in Case Studies**

| Modification | | Bay Point | Bozeman | Chinook | Crewe | Flagstaff | Hampden Township | Layton | Montrose | Tampa | Titusville | Victor Valley | Wolfeboro |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aeration** | Aeration cycling | | √ | √ | √ | | √ | √ | √ | | | | √ |
| | Mixer addition | | | √ | | | | | | | | | |
| | Adjustable control aeration | √ | √ | | √ | | √ | | | √ | | √ | √ |
| | Equipment retrofit | | | | | | | | | | | √ | √ |
| **Process** | Flow equalization improvement | √ | | | | | | | | | | | |
| | Recycle rate control | | | | | √ | | | | | | | |
| | Side-stream control | | | | | √ | | | √ | | | | |
| | Batch program modifications | | | | | | | √ | | | | | |
| | Predigestion of primary sludge | | | | | √ | | | | | | | |
| **Configurati** | Plug flow/series operation | | √ | | | | √ | | | | | | |
| | Anoxic zone RAS bleed | √ | | | | | | | | √ | √ | | |
| | Anaerobic zone VFA addition | | | | | | | | | | √ | | |
| **Chemi** | Alkalinity feed improvements | √ | | | √ | | | | | | | | |
| | Carbon product addition | | | | √ | | | | | | | | |
| **Disc** | Soil dispersal | | | | | | | | | | | √ | |
| | Wetland discharge | | | | | | | | | | √ | | |

# 1 Background

## 1.1 SCOPE AND PURPOSE

Impacts to water bodies across the United States from nutrient pollution are well-documented. Various workgroups and workshops have been convened to review the scientific information, evaluate tools to address nutrient pollution, identify barriers to progress, and outline next steps. In a March 2011 memorandum to the states, tribes, and territories, the EPA Acting Assistant Administrator for Water reiterated the need for action by stating:

> "States, EPA, and stakeholders, working in partnership, must make greater progress in accelerating the reduction of nitrogen and phosphorus loadings to our nation's waters" (USEPA 2011a).

One of the primary barriers to reducing nutrients is the cost of upgrading WWTPs to achieve nutrient concentrations necessary to protect designated uses (i.e., recreation, aquatic life). Much of the high cost associated with reducing nutrients to intermediate or low levels results from building significant additional new infrastructure or facility retrofits and additional operation and maintenance costs. The economic implication of regulating nutrients is often an impediment to progress. Often overlooked in the current discussion is the opportunity to improve plant performance largely using existing infrastructure.

This technical report is intended to help fill gaps in published information about improving nutrient reduction performance at existing WWTPs (generally activated sludge facilities with more basic treatment processes and less resources at their disposal), using relatively low-cost techniques. Although many published reports and papers address the nutrient removal performance of WWTPs, this report represents one of the first documented efforts to present empirical data via a compendium of case studies of non-advanced WWTPs that have been optimized to improve nutrient reduction without requiring costly infrastructure upgrades.

"Optimization" as used in this document is defined as an activity that results in an improvement in the nutrient pollutant removal of an existing WWTP without requiring significant infrastructure upgrades.

The availability of sufficient monitoring data has been and continues to be a limiting factor in developing reliable information on low-cost nutrient optimization at non-advanced WWTPs. Accordingly, this report represents an initial effort to collect and compile relevant data. EPA intends to identify additional case studies and update this document in the future.

For the case studies developed for this report, at least two years of pre-optimization and two years of post-optimization TN and/or TP concentration data were targeted. In most cases, discharge monitoring report (DMR) data were used, which typically include one or two TN and/or TP sampling events per month. In some cases, WWTPs provided a larger dataset (more frequent sampling), but in several cases, pre-optimization data were limited (e.g., Montrose, CO; Hampden Twp., PA; Blue Heron, FL). Graphical data presentations in the case studies generally show all datapoints used in the analysis. Data summaries in the case studies and in the report use arithmetic mean and standard deviation of all pre- and post- optimization date data available to EPA. Where WWTPs implemented their optimization strategies slowly over a period of time, optimization date was determined based on recommendations from the WWTP contact and a visual interpretation of the time series data for that WWTP.

A number of optimization options can be considered including (but not limited to) one or more of the following:

- Implementing aeration changes such as cyclical aeration (primarily using existing tanks and mechanical equipment), often supplemented with basic in-line monitoring instrumentation and associated controls.
- Process control changes such as altering SRT, MLSS concentrations, and/or F/M ratios.
- Use of unused and/or existing tankage to create specialized zones (e.g., anoxic zones).
- Installation of baffles to create specialized zones within existing tanks.
- Piping and/or pumping changes to provide internal recycle or alter recycling rates.
- Carbon/volatile fatty acid (VFA) supplementation using existing or new source (e.g., waste or return sludge; septage, respectively) and repurposed fermentation reactors (e.g., conversion of primary clarifiers or equalization basins).
- Nitrification improvements.
- New process modeling, operational training and staffing, and/or sampling.

This report documents optimization techniques through empirical example at specific plants. It does not address site-specific design, engineering or cost factors for other facilities. These case studies are not appropriate for setting permit requirements; such requirements should be established by permit directors in accordance with applicable CWA and state requirements.

### 1.1.1 Methodology

To support the preparation of this report, examples of WWTPs that were successful in reducing effluent nutrient concentrations at low cost were identified and, where appropriate, developed into case studies. A number of sources were used to help identify case studies, including:

- Internal EPA query to relevant Regional and state staff.
- Broad grey and white literature review.
- Review of existing EPA and other guidance documents.
- Query of selected industry practitioners.
- Supplemental search of CWNS database.

The literature review identified the majority of the WWTP examples having sufficient data and documentation to support a case study. However, many of the examples reported in the literature featured WWTPs with a relatively high level of technical sophistication or consultant support for nutrient reduction improvements. The CWNS database search was least effective, given its relatively low-resolution data, which made it difficult to identify WWTPs that had undergone low-cost optimization.

Case study information was tracked and characterized using a Microsoft Excel spreadsheet. From a master list of over 80 case studies, a total of 12 have been summarized for the project. The evaluation criteria used to select these 12 case studies included:

- Responsiveness to project objectives: relatively basic (non-advanced) treatment plants improving nitrogen or phosphorus reduction performance using low-cost techniques.
- Availability of monitoring and cost data.
- Representative of a range of scenarios (e.g., system types, geographies) and nutrient optimization approaches.

Of the 12 selected case studies, seven fully meet the evaluation criteria. Although the other five do not meet all of the specified criteria, they provide useful information that might help target audiences understand nutrient reduction optimization approaches. Most of the other candidate case studies that were not selected were disqualified early in the project for one or more of the following reasons:

- Lack of monitoring and/or cost data.
- WWTPs were found to be advanced plants and/or implemented improvements were rebuilds for biological nutrient removal (BNR), requiring significant costs.
- Incomplete follow-up with WWTP contacts.

EPA anticipated identifying a number of relevant, published case studies through this research. However, despite extensive efforts to identify and develop relevant case studies, relatively few met the aforementioned criteria. EPA concluded that the primary limitation in identifying prospective case studies was that most efforts at improving small or non-advanced plants appear to be unpublished or otherwise under documented. Most published literature focuses instead on optimizing existing BNR systems. Nevertheless, these case studies show that optimization of non-advanced WWTPs is feasible and cost-effective, and provide useful information to support future efforts at other WWTPs.

As expected, the greatest number of potential case studies were identified for activated sludge systems. EPA also attempted to identify case studies for lagoon and trickling filter systems, but only a few examples of nutrient reduction optimization were uncovered and most of them included significant infrastructure modifications which disqualified them from the pool of case studies since they could not be considered “low cost” approaches.

### 1.1.2 Case Studies

Relevant data on approach, performance, and costs are summarized for the 12 case studies. These data were then used to develop technical information to help treatment plant managers, operators, and others to improve the nutrient reduction performance of their plants.

Table 1-1 lists the case studies and their corresponding pre- and post-optimization TN treatment levels. All of the case studies listed are suspended growth (i.e., activated sludge) systems and, although some were optimized for both TN and TP, all were optimized to improve nitrogen reduction.

**Table 1-1. Summary of TN Treatment Levels for Case Studies**

| Case Study | Pre-/Post-Optimization | Level 1[1] | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|---|
| | | >15 mg/l | 8–15 mg/l | 4–8 mg/l | 2–4 mg/l | <2 mg/l |
| Bay Point, FL | Pre-Optimization | | | **6.33** | | |
| | Post-Optimization | | | | **3.99** | |
| Bozeman, MT | Pre-Optimization | **17.8** | | | | |
| | Post-Optimization | | **10.5** | | | |
| Chinook, MT | Pre-Optimization | **20.3** | | | | |
| | Post-Optimization | | | **5.44** | | |
| Crewe, VA | Pre-Optimization | | | **7.85** | | |
| | Post-Optimization | | | | **3.63** | |
| Flagstaff, AZ | Pre-Optimization | | **14.0** | | | |
| | Post-Optimization | | **8.50** | | | |
| Hampden Twp., PA | Pre-Optimization | | | **4.66** | | |
| | Post-Optimization | | | | **3.64** | |
| Layton, FL | Pre-Optimization | | | **7.88** | | |
| | Post-Optimization | | | | **3.33** | |
| Montrose, CO | Pre-Optimization | **unknown** | | | | |
| | Post-Optimization | | **14.7** | | | |
| Tampa, FL | Pre-Optimization | **18.62** | | | | |
| | Post-Optimization | | **13.82** | | | |
| Titusville, FL | Pre-Optimization | | | **5.67** | | |
| | Post-Optimization | | | | | **0.94** |
| Victor Valley, CA | Pre-Optimization | | **8.93** | | | |
| | Post-Optimization | | | **6.83** | | |
| Wolfeboro, NH | Pre-Optimization | | | **6.32** | | |
| | Post-Optimization | | | | | **1.97** |

[1] The treatment levels represent generally accepted ranges of effluent nutrient targets for wastewater treatment. Generally, most resources refer to Level 1 as 'no nutrient treatment' or often 'basic secondary treatment.' The Agency used these as general categories based on effluent data, where nutrient removal targets graduated for Level 2 at 8-15 mg N/L to the most stringent Level 5 from at <2 mg N/L.

The case studies are summarized and described further in Section 3 and provided as stand-alone write-ups in Appendix B. Additionally, case study information is incorporated throughout the document to illustrate and emphasize key points. Other case studies identified during the literature review but not developed further for this project are identified as additional resources where appropriate.

## 1.2 RELATED / PREDECESSOR GUIDANCE AND REPORTS

This report supplements a number of recent guidance manuals and reports published by EPA on nutrient removal at WWTPs by providing useful information to managers and operators of plants *that may not be specifically designed for nutrient removal* or for those seeking to achieve even better treatment through relatively low-cost modifications.

Table 1-2 provides a summary of EPA's recent documents and reports to help provide more background information on wastewater treatment processes, design principles, and nutrient removal technologies. Older EPA documents are cited where warranted throughout this report. Additional nutrient reduction resources are listed in Appendix A.

**Table 1-2. List of Related EPA Guidance and Reports**

| Document | Pub. Year | Document ID | Brief Synopsis |
|---|---|---|---|
| Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers | 2011 | EPA/600/R-11/088 | This manual provides an overview of wastewater treatment pond systems and discusses factors affecting treatment, process design principles and applications, aspects of physical design and construction, effluent total suspended solids (TSS), algae, nutrient removal alternatives, and cost and energy requirements. |
| Nutrient Control Design Manual | 2010 | EPA/600/R-10/100 | This EPA design manual provides updated, state-of-the-technology design guidance on nitrogen and phosphorus control at municipal WWTPs. |
| Nutrient Control Design Manual State of Technology Review Report | 2009 | EPA/600/R-09/012 | This document presents an extensive state-of-the-technology review of nitrogen and phosphorus control technologies and techniques currently applied and emerging at municipal WWTPs, including a description of technologies and key design and operational issues. |
| Municipal Nutrient Removal Technologies Reference Document, Volume 1—Technical Report | 2008 | EPA 832-R-08-006 | This reference document includes technical information (performance and costs) to assist municipal decision makers and regional and state regulators in planning for nutrient removal from municipal wastewater. |
| Municipal Nutrient Removal Technologies Reference Document, Volume 2—Appendices | 2008 | EPA 832-R-08-006 | Appendices for Volume 1. Mostly includes case study write-ups for WWTPs used to inform document. |
| Biological Nutrient Removal Processes and Costs | 2007 | EPA-823-R-07-002 | 15-page fact sheet summarizing studies of BNR performance and costs. |
| Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus | 2007 | EPA 910-R-07-002 | EPA Region 10 presents observations of advanced wastewater treatment installed at 23 municipalities in the U.S., achieving very low phosphorus concentrations. |

During the literature review, a number of documents were identified that included hypothetical case studies; that is, the authors used modeling or engineering judgment to identify potentially feasible nutrient reduction improvements that could be applied to existing plants and, in many cases, estimated costs associated with the identified improvements. Although those "case studies" did not meet the objectives of this project—which focused on empirical data based on implemented improvements at actual treatment plants—information pertaining to the hypothetical studies can be valuable and the references are summarized in Table 1-3 (see Section 8, References for full complete listings).

**Table 1-3. Summary of Studies of Hypothetical Nutrient Removal Case Studies**

| Citation Data | | System Types | | | Nutrient | | |
|---|---|---|---|---|---|---|---|
| **Author** | **Year** | **AS** | **Lag** | **TF** | **TN** | **TP** | **Scope** |
| Camacho | 1992 | x | | x | x | x | Chesapeake Bay Program compliance, with concept designs and cost estimates for both specific and generalized plants. |
| CH2M Hill | 2010 | x | x | x | x | x | Concept designs and cost estimates for upgrading specific and generalized plants in Utah to different nutrient removal levels. |
| Colorado | 2010 | x | | x | x | x | Concept designs and cost estimates for upgrading generalized plants in Colorado to different nutrient removal levels. |
| Foess | 1998 | x | | | x | x | Cost comparison of advanced very small flow generalized systems for Florida applications. |
| Jiang et al | 2004 | x | | | | x | Concept designs and cost estimates for upgrading generalized plants in Georgia to different nutrient removal levels. |
| JJ Environmental | 2015 | x | | | x | | Concept designs and cost estimates for low-cost upgrades to MLE processes for 20 specific facilities in New England. |
| Keplinger | 2004 | | | | | x | Concept designs and cost estimates for chemical phosphorus precipitation for several small Texas facilities. |
| Randall, et al | 1999 | x | x | x | x | | Concept designs and cost estimates for low-cost upgrades for 8 mg/l TN target for WWTPs in Chesapeake Bay watershed. |
| Tetra Tech | 2011 | x | x | x | x | x | Concept designs and cost estimates for upgrading generalized plants in the state of Washington to different nutrient removal levels. |
| Tetra Tech | 2013 | x | | x | | x | Concept designs and cost estimates for upgrading generalized plants in Ohio to different phosphorus removal levels. |
| Tetra Tech | 2014 | x | x | x | | x | Concept designs and cost estimates for upgrading specific plants in Lake Champlain watershed to different phosphorus removal levels. |
| USEPA | 1987 | x | x | x | | x | Concept designs for upgrading generalized plants in Chesapeake Bay watershed to different phosphorus removal levels. |
| USEPA | 2008 | x | | x | x | x | Concept designs and cost estimates for upgrading generalized plants in U.S. to different nutrient removal levels; also includes nine actual activated sludge BNR case studies. |

*Notes*:
TN = total nitrogen; TP = total phosphorus; AS = activated sludge; Lag = lagoon; TF = trickling filter.

In the Scope column, "generalized plants" refers to plants with characteristics that were made up by the author (typically based on representative characteristics of a set of plants in the study area), and "specific plants" use the characteristics of actual, identified treatment plants in the associated conceptual design and costing exercises.

In addition to these published efforts, several EPA Regions have pursued WWTP optimization as important outreach elements of their National Pollutant Discharge Elimination System (NPDES) and water infrastructure programs. For example, Region 1 has a master list of WWTPs that are candidates for nutrient optimization. Region 4 has been assisting WWTPs in optimizing for energy reduction for several years, noting nitrogen removal as a collateral benefit. The Sustainable Infrastructure program of Region 9 sponsored a number of energy efficiency evaluations at WWTPs, many of which included recommended process improvements that also reduce nitrogen. State government agencies have also developed tools to help utilities optimize nutrient removal at WWTPs (e.g., Wisconsin Pollutant Discharge Elimination System Program's Phosphorus Operational Evaluation and Optimization Report Worksheet).

## 1.3 HOW TO USE THIS DOCUMENT

Although the primary focus of this report is on transferring technical information to WWTP managers and operators, it is organized in a way that allows multiple audiences, including regulators, policy makers, and nontechnical persons, to access information of interest.

Section 2 provides an introduction to nutrient removal in wastewater treatment, along with descriptions of the nutrient reduction attributes of various common types of wastewater systems. In addition to providing the technical background that supports the rest of the report, that section also provides preliminary information about potential optimization techniques for those readers seeking an overview rather than detailed technical information.

Sections 3 through 5 focus on the details of improving nutrient reduction for the three main types of treatment systems considered: activated sludge, treatment lagoons, and trickling filters. Section 3, the section about activated sludge, in particular, uses case studies to provide data for, and examples of, nutrient reduction optimization efforts across the United States. These sections are targeted to readers interested in the technical details associated with nutrient reduction optimization, including WWTP technical managers and operators, technical outreach specialists, and consultants.

Section 6 provides a brief introduction to other potential nutrient reduction strategies that are not the main focus of this document, and Section 7 provides conclusions and recommendations for practitioners and others.

# 2 Introduction

## 2.1 NITROGEN REMOVAL

### 2.1.1 Nitrogen Removal Fundamentals

A thorough understanding of nitrogen removal during wastewater treatment is necessary to recognize potential optimization opportunities. Those opportunities are introduced in Section 2.1.2 as a precursor to more detailed information and summaries of optimization case studies in sections 3 through 5.

Nitrogen in municipal wastewater can come from multiple sources. Urine contains about 90 percent of the nitrogen excreted by humans, mostly from the breakdown of amino acids from food. Food wastes and some industrial processes can also contribute significant amounts of nitrogen to municipal wastewater influents. Nitrogen in food comes from amino acids in protein and from purines, pyrimidines, free amino acids, vitamins, creatine, creatinine, and amino sugars (Minnis 2006). Urea and organic nitrogen in wastewater influents are typically quickly converted to ammonia under anaerobic conditions within sewer collection systems via a process called “ammonification”.

Removal of nitrogen during wastewater treatment is typically the result of natural biological processes including uptake, biological nitrification and denitrification (generically termed “biological nitrogen removal”), and anaerobic ammonia oxidation.

**Biological (Cell) Uptake**

Nitrogen is an essential component of all proteins. Therefore, all biological organisms require nitrogen to grow.

Nitrogen comprises approximately 12 percent, by dry weight, of the cell mass of microbes during wastewater treatment. Therefore, even in wastewater treatment systems not specifically engineered for nitrogen reduction, a certain amount is removed by wasting biological solids, as is typical in a biological wastewater treatment process. Those reductions are generally modest.

Nitrogen is also a primary macronutrient for plants, present in plant tissue in quantities from 1–6 percent, on a dry mass basis. Relatively few plants fix atmospheric nitrogen, so most rely on nitrogen compounds in the soil (chemical fertilizer, manure, or wastewater or reclaimed effluent dispersed into the soil near their root zone) to support their growth. Both oxidized and reduced species of nitrogen can be taken up by plants, although amino acids and proteins can be built only from ammonium ($NH_4$), so oxidized species must first be reduced.

**Biological Nitrogen Removal**

“Biological nitrogen removal” (BNR) is the general term used to describe the 2-step nitrification-denitrification process, which is the primary approach used to deliberately remove nitrogen during municipal wastewater treatment.

Nitrification is the biological oxidation of ammonia to nitrate. Influent ammonia is first oxidized to nitrite ($NO_2$) by ammonia-oxidizing bacteria (AOB), then nitrite is oxidized further to nitrate ($NO_3$) by nitrite-oxidizing bacteria (NOB). Nitrification requires both oxygen and alkalinity to buffer against a pH drop that can inhibit nitrifying bacteria. A portion of this lost alkalinity is recovered in the subsequent denitrification process.

Since AOB and NOB use inorganic carbon for cellular growth and synthesis rather than organic carbon sources, they are classified as autotrophic organisms, and grow relatively slowly and with a lower yield than the heterotrophic organisms responsible for biological oxygen demand (BOD) removal. Temperature has a significant impact on the process kinetics and performance of the nitrifying organisms; the rate and amount of nitrification generally decrease with a lower temperature. Growing and maintaining a nitrifying biomass, therefore, requires a relatively long aerobic solids retention time (SRT, or sludge age). The minimum SRT required for nitrification increases with cooler temperatures to compensate for slower growth rates.

“Denitrification”, the biochemical reduction of oxidized nitrogen—nitrate—to dinitrogen gas, is much less sensitive to temperature, although it is still affected, and requires a relatively short anoxic SRT. Denitrification is performed by heterotrophic bacteria and requires an organic carbon source. Available carbon sources already present in wastewater or provided within the treatment process include biodegradable soluble chemical oxygen demand (COD) in the influent wastewater, biodegradable soluble COD from biological hydrolysis of particulates and colloids, and the biodegradable soluble COD produced during endogenous decay of microbial cells. Supplemental sources of carbon can also be added to the system if carbon is lacking or to achieve higher levels of denitrification.

A generalized liquid-phase schematic diagram of a traditional secondary suspended growth (i.e., activated sludge) treatment process is shown in Figure 2-1. There are three main types of denitrification processes: 1) pre-anoxic denitrification (Figure 2-2), 2) post-anoxic denitrification (Figure 2-3), and 3) single-reactor nitrification/denitrification (Figure 2-4). One or two of the processes can be used within a secondary (i.e., biological) treatment process. The first two involve the creation of dedicated unaerated or anoxic zones for denitrification. Single-reactor nitrification and denitrification provide nitrification and denitrification in the same space. This includes simultaneous nitrification/denitrification, which is promoted under low dissolved oxygen (DO) conditions; cyclic processes where aeration is switched on and off; step-feed processes; and others.

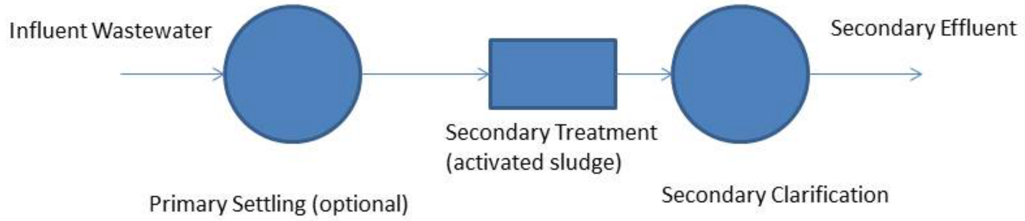


**Figure 2-1. Generalized secondary (activated sludge) liquid-phase treatment schematic**

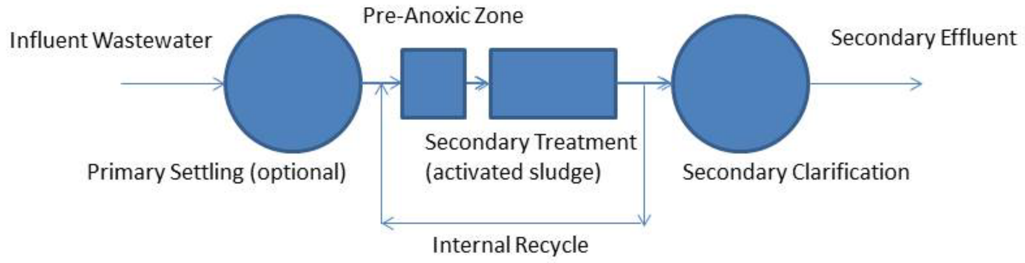


**Figure 2-2. Generalized pre-anoxic zone nitrification/denitrification liquid-phase treatment schematic**

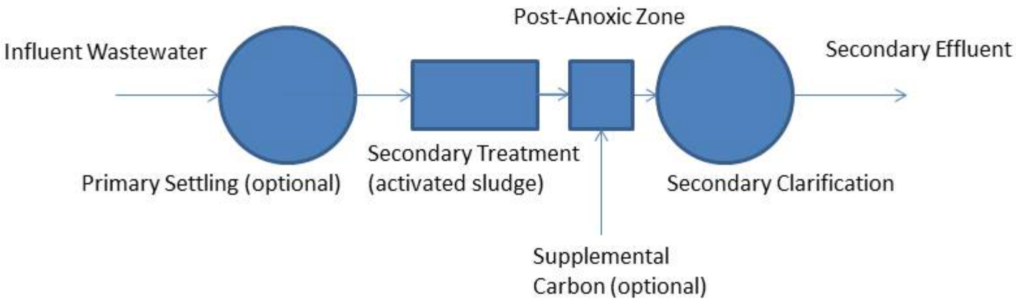


**Figure 2-3. Generalized post-anoxic zone nitrification/denitrification liquid-phase treatment schematic**

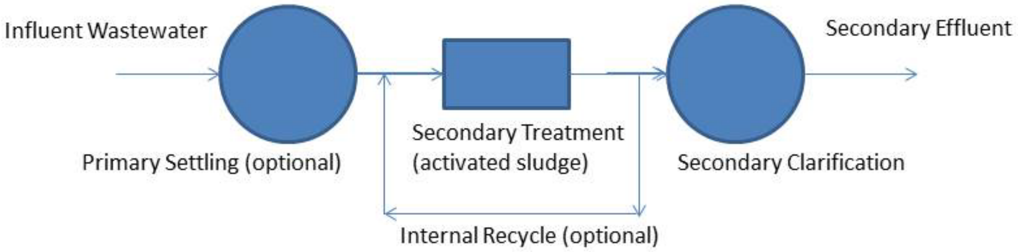


**Figure 2-4. Generalized single-reactor nitrification/denitrification liquid-phase treatment schematic**

Pre-anoxic denitrification typically relies on the carbon in the influent or primary clarifier effluent to feed the denitrifying organisms that reduce nitrate, which is produced in the downstream aerobic zone. It must, therefore, be returned to the pre-anoxic zone in the return activated sludge (RAS) and/or internal recycle streams. In comparison, the post-anoxic zone follows the aerobic zone and the carbon from endogenous decay is used for denitrification, which results in a much lower nitrate/nitrite reduction rate than in the pre-anoxic zone. Carbon from external sources can also be added to this zone to increase the denitrification rate.

Simultaneous and/or cyclic nitrification/denitrification are commonly used in systems with long SRTs (20 days or more) and hydraulic retention times (HRT), such as oxidation ditches and lagoons. Nitrification and denitrification rates are relatively slow, which is why longer SRTs are required to achieve complete nitrification.

## Anaerobic Ammonium Oxidation

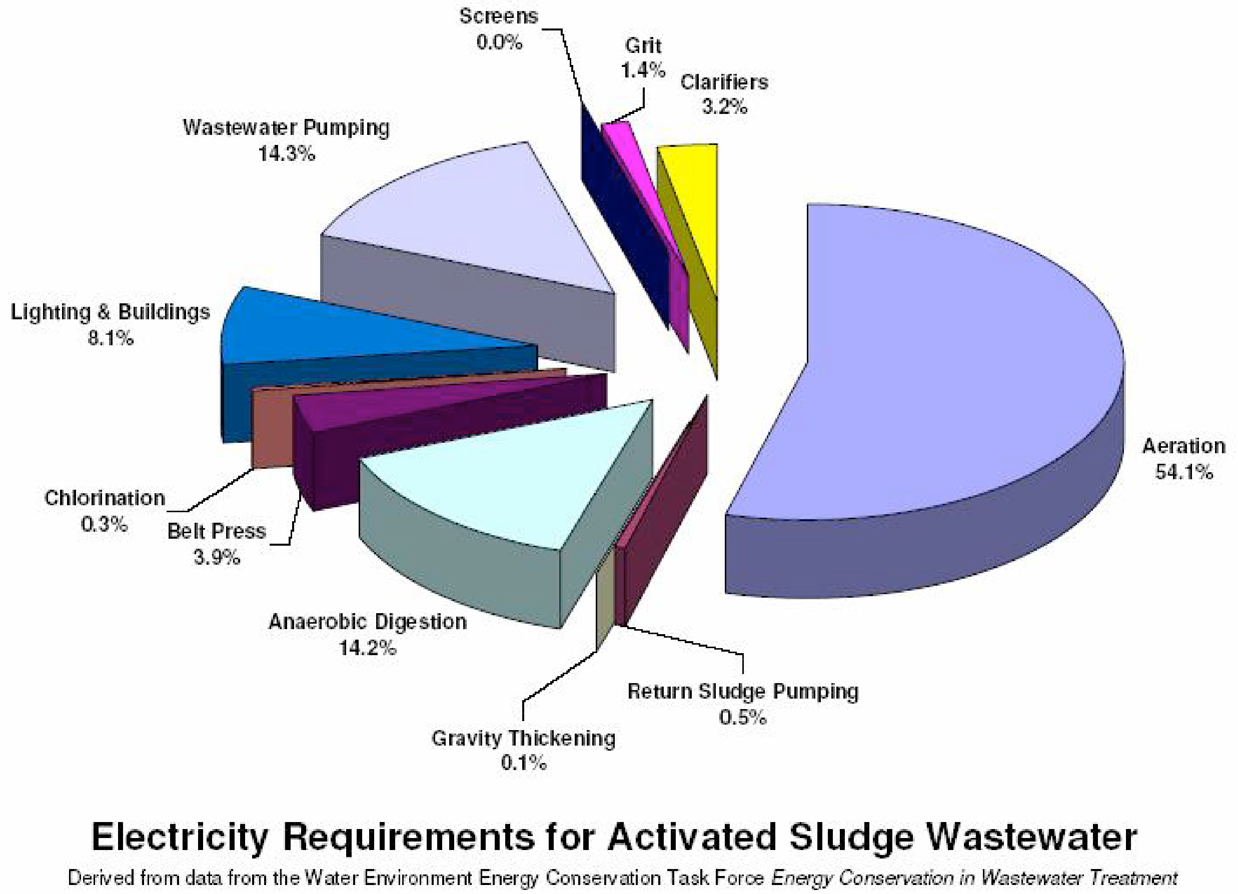
Anaerobic Ammonium Oxidation (Sometimes called AnAmmOx, which is also a trademarked process name, and is a type of deammonification process) is a natural biological process that uses nitrite as the electron acceptor in the anaerobic oxidation of ammonium, producing $N_2$ gas. The first step in the process is the aerobic nitrification of part of the ammonia to nitrite. This process has recently received considerable interest because it has the benefit of not requiring an organic carbon source and using less air (and thus energy) than the traditional aerobic nitrification followed by anoxic denitrification process described above, since only part of the ammonium has to be oxidized to $NO_2$. Thus far in practice, however, this process has primarily been engineered for the treatment of high temperature and high ammonia sidestreams, such as anaerobic digester dewatering recycle streams.

## 2.1.2 Nitrogen Removal Optimization Opportunities

There are a variety of physical and operational modifications that can be made to a wastewater treatment system to improve nitrogen removal. This document mainly focuses on operational modifications and physical modifications that are relatively minor; significant infrastructure modifications, like adding new reactors, are generally outside its scope. Some operational changes might require equipment upgrades or modifications, but they are generally low-cost compared with the more substantial upgrades associated with building new structures. Although it is recognized that there is often overlap of and interdependency between categories of potential modifications, optimization activities have been grouped into the following main categories: 1) aeration, 2) process, 3) configuration, 4) chemical, and 5) discharge.

### Aeration

As implied in Section 2.1.1, the oxidation-reduction (or redox) state of the treatment environment is a major controlling factor for nitrogen removal processes with aerobic (or oxic) conditions required for nitrification, and anoxic conditions required for denitrification. Considering that many treatment plants that have never optimized their aeration systems over-aerate, improving the control of aeration is often the lowest hanging fruit for a plant endeavoring to improve nitrogen reduction. Reducing overall aeration has the added bonus of reducing energy costs, often quite significantly, as aeration equipment typically has the single largest energy demand of internal plant processes (see Figure 2-5). A number of utilities have stumbled upon significantly improved nitrogen removal as a by-product of energy-efficiency efforts.



*Source:* WERF 2011.

**Figure 2-5. Average WWTP energy use breakdown.**

*Aeration modifications* are changes to physical aeration equipment, controls, operation, and function of equipment and aerated areas. They include installation of energy-efficient blowers, variable frequency drives (VFDs) to provide adjustable control to air blowers or surface aerators, diffusers with improved distribution and oxygen transfer efficiency (OTE), airflow meters, airflow control valves, on/off cycling, the installation of DO, and ammonia or oxidation-reduction potential (ORP) control.

Nitrification is a prerequisite for BNR, so if a WWTP is not fully nitrifying, optimization efforts are probably limited. As previously indicated, nitrification requires a sufficient SRT (which translates into a sufficient reactor volume) and sufficient aeration capacity to convert ammonia to nitrate. Many existing WWTPs, particularly those featuring mechanically aerated aerobic processes like activated sludge, already achieve significant nitrification for the following reasons:

1. Ammonia can be toxic to aquatic organisms; therefore, effluent ammonia limits have been common for some time, and simple conversion of ammonia to nitrate generally alleviates toxicity concerns.
2. Historically, WWTPs were not designed with energy efficiency as a top priority; therefore, oversizing of aeration systems has generally been standard practice. Likewise, aeration controls might not have been prioritized either in capital programs or in ongoing performance evaluation.
3. Many conventional (i.e., non-advanced) and relatively small treatment plants use activated sludge processes with relatively long SRTs and HRTs (long enough to affect nitrification), since the increased volumetric capacity required generally only has minor effects on the system footprint and because the increased volumetric and aeration capacity provide internal buffering capability that might be important for plants that are not staffed around the clock.

Many WWTPs nitrify and most that do have at least some excess aeration capacity under most conditions. However, for those WWTPs, denitrification is often limited because of a lack of proper conditions (i.e., nitrate, organic carbon, and anoxia).

The anoxic conditions required for denitrification can be created in several different ways in an activated sludge system, provided that the system has some excess treatment capacity (even a small amount). These include on/off cycling or throttling of aeration (for enhancing simultaneous or phased denitrification within a single reactor), or the creation of dedicated anoxic and aerobic zones by turning off the air to a portion of the aerated volume—typically at the front end of the basin (to create a dedicated anoxic zone). Frequently, mixers are added to keep solids in suspension or provide mixing in dedicated anoxic zones, or when air is turned down or cycled off. Other modifications that improve the ability to modulate aeration include adjusting the pitch angle of centrifugal blower blades and the use of synchronous blower motors.

Equipment upgrades that allow for adjustable aeration control include the use of VFDs on positive displacement blowers to control aerator output and/or use of online monitoring tools to inform aerator operational mode. Equipment replacement might also be beneficial in increasing the efficiency and performance of the aeration system, as is the case with replacing aged blowers and diffusers.

Some type of improved aeration control is the most common nitrogen removal optimization technique at existing WWTPs, although it can often be supplemented with process, piping, and/or chemical activities for enhanced effectiveness.

## Process

*Process modifications* include adjustments to process control characteristics. As previously indicated, SRT is a particularly important process parameter for nitrification. Mixed liquor suspended solids (MLSS) and food-to-microorganism (F/M) ratio are related parameters. Internal recycle and RAS return rate can be particularly important for denitrification. Physical process improvements can include the addition of VFDs and/or RAS pumps for improved control of internal recycling; the addition of online monitoring equipment for process control and optimization; or providing new screens or grit removal equipment at the headworks to improve the reliability of the treatment process. Other examples of process modifications include flow equalization improvements, optimizing internal mixed liquor recycle rates, modifying plant recycle flow patterns, controlling sidestream flows, and adding the capability to ferment primary sludge.

As previously indicated, denitrification is often limited because of a lack of proper conditions (i.e., nitrate, organic carbon, anoxia). As highlighted above, providing anoxic conditions is largely a function of aeration control. Although a WWTP might be nitrifying, it is critical to get the nitrate into the anoxic environment, along with organic carbon, for denitrification. For this reason, establishing anoxic conditions at the influent end of the process, where influent organic carbon should be readily available, is generally preferred. With anoxic conditions and organic carbon, treatment effectiveness depends largely on exposing nitrified mixed liquor to these conditions, typically by internally recycling mixed liquor to the denitrification reactor. Adding or improving the control of internal mixed liquor recycle systems is, therefore, an important process control parameter for nitrogen removal. Likewise, it is important to minimize aeration occurring within other unit processes and structures (e.g., influent and return channels) that may increase DO carry-over into existing or new anoxic zones.

For systems that recycle mixed liquor for denitrification, the recycle rate can be optimized by monitoring the nitrite and/or nitrate leaving the primary anoxic zones either by manually sampling or using online monitoring to set the internal recycle (IR) rate. Only the amount of $NO_x$ that can be denitrified needs to be returned to the primary anoxic zones. This can be an automated process involving a feedback loop or use a manually set rate. The IR pumps will need to be equipped with VFDs or multiple small pumps will need to be used to effectively control the IR rate.

Note that increasing recycle rates, whether of mixed liquor or activated sludge, *might* add DO to the anoxic zone. Tradeoffs, or unanticipated consequences, of activities like these are, therefore, essential to consider when evaluating nitrogen optimization alternatives.

The availability of organic carbon in the anoxic zone can sometimes be a limitation for denitrification, especially for single sludge and post-denitrification systems. Various options for providing organic carbon are available, including some options internal to the plant that can be enhanced through process modifications.

Primary sludge can be fermented to produce volatile fatty acids (VFAs) or available soluble carbon for use in biological nutrient removal. Primary sludge fermentation can be accomplished in the primary clarifier sludge blanket by modifying the primary sludge wasting rate to provide a deeper blanket and longer residence time to allow fermentation, adding available soluble BOD to the secondary treatment process influent. A portion of the primary sludge should be returned to the influent of the primary clarifier to elutriate the VFAs in the sludge. Primary sludge can also be fermented in a separate tank, typically a gravity thickener fermenter. Fermenting in a separate reactor will involve a higher capital cost, but will also provide more carbon to the process and more flexibility over where the carbon-rich stream is returned.

Other process modifications may be important as well. For example, treatment processes generally perform better, producing more consistent effluent, when the influent flow and load are consistent or when the system is operated to minimize the impacts of the variations in the flows and loads. Optimization could, therefore, include adding or improving influent flow equalization or controlling or equalizing the plant return flows, such as the sludge dewatering return to avoid spikes in nitrogen load and flow.

## Configuration

*Configuration modifications* are changes to, or the addition of, flowstreams within the process or changes to the process configuration. They might include changes to channels, manipulation of gates or baffles, or modifying or adding piping, such as adding internal recycle lines or step-feed provisions. Configuration modifications are distinguished from process modifications in that they will require some (although usually minimal) new infrastructure. Process modifications use existing infrastructure but might require new monitoring or control equipment.

Converting a complete mix reactor to a plug flow reactor can allow for the creation of aerobic and anoxic zones to provide nitrification and denitrification. In some systems, a portion of the RAS can be directed to the post-anoxic zone (sometimes called a “RAS bleed-off”) to provide carbon, improve denitrification, and lower the effluent TN. Step-feeding of influent can also be implemented to provide a higher SRT by allowing higher MLSS in the front zones.

Modifications under this category could also include repurposing existing tankage, which can include physical modifications, such as adding baffle walls and the like.

## Chemical

*Chemical modifications* include the addition of alkalinity and supplemental carbon to improve nitrification and denitrification, respectively. If low alkalinity is limiting nitrification, then alkalinity can be added to the process (e.g., using lime) to improve nitrification. Performance can also be improved by using inline monitoring and controls to maintain an optimum feed rate. Supplemental carbon can be added, usually to a post-anoxic zone, to improve or speed up denitrification. Supplemental carbon feed systems can be improved by selecting a more effective carbon source or adding controls and monitoring to optimize the feed rate. As indicated above and in the context of this technical document, nitrogen removal optimization using chemical addition is supplemental to other aeration, process, and/or piping modifications.

## Discharge

*Discharge modifications* are made at the end of the treatment system to further reduce nutrients prior to delivery to receiving surface waters. They generally use natural systems and might include land application or wetland assimilation discharge. This category of nitrogen removal enhancement is typically independent of the other four approaches.

Modifying a WWTP discharge can be an effective way to reduce nitrogen delivery to surface waters, although it might not be widely practical or affordable. Managers of plants having some kind of alternative to a direct surface water discharge might have already considered alternatives that could have lower impacts and help meet water quality objectives.

Two alternatives to direct discharge are addressed in this document, including land application of effluent, which in most cases, uses the soil as a treatment process; and wetland assimilation in which effluent is discharged into natural or man-made wetlands for further attenuation of nutrients prior to receiving water delivery.

Nitrogen removal in both types of discharge is primarily through biologically mediated nitrification and denitrification. Although, vegetative uptake can be a significant removal mechanism provided that biomass is harvested as needed to ensure that sequestered nitrogen is permanently removed from the system.

## 2.2 PHOSPHORUS REMOVAL

### 2.2.1 Phosphorus Removal Fundamentals

A thorough understanding of phosphorus removal during wastewater treatment is necessary to be able to recognize potential optimization opportunities. Those opportunities are introduced in Section 2.2.2 as a precursor to more detailed information and summaries of case studies in sections 3 through 5.

Phosphorus in municipal wastewater can come from multiple sources. Urine contains over 90 percent of the phosphorus excreted by humans. Dietary phosphorus is readily absorbed in the small intestine and any excess is excreted into urine by the kidneys (Minnis 2006). Like nitrogen, food wastes and some industrial processes can also contribute significant amounts of phosphorus to municipal wastewater influents. Soluble phosphorus in wastewater is typically in the form of orthophosphate ($PO_4^{-3}$).

Removal of phosphorus during wastewater treatment is typically the result of natural biological processes, including uptake and enhanced biological phosphorus removal (EPBR), although many WWTPs will use metal salts to precipitate phosphorus to the solids (sludge) fraction. In either case (biological or chemical treatment), phosphorus is removed by converting it to a solid, so it partitions to the sludge.

**Biological Uptake**

Phosphorus is a constituent of nucleic acids, nucleotides, phospholipids, low phosphorus starches (LPS), and teichoic acids in microbial cells. Phosphorus makes up approximately 2 percent, by dry weight, of the cell mass of microbes during wastewater treatment (not designed for EBPR). Therefore, even in wastewater treatment systems not specifically engineered for phosphorus reduction, a certain amount is removed (usually about 2 mg/l). These reductions are generally modest, however, and rarely sufficient to meet water quality objectives or effluent permit limits.

Phosphorus is also a primary macronutrient for plants, present in plant tissue, typically at approximately 0.2 percent, on a dry mass basis. Phosphorus is especially important for plant bioenergetics, for the conversion of light energy to chemical energy during photosynthesis. It is also important in the activation of proteins and regulation of metabolic process. Phosphorus is commonly a limiting factor for plant growth in many soils under most environmental conditions.

**Enhanced Biological Phosphorus Removal**

Specialized bacteria in activated sludge mixed liquors called “polyphosphate accumulating organisms” (PAOs) can be used to biologically remove phosphorus from wastewater to levels that might meet water quality objectives. PAOs require two stages for phosphorus removal. The first stage is anaerobic, in which PAOs uptake VFAs from the organic carbon in the influent (or added as a sidestream flow) and store it as polyhydroxyalkanoate (PHA) for later oxidation in an aerobic zone. During this process, the PAOs also release phosphorus in the form of orthophosphate under anaerobic conditions, which provides the energy required for the uptake and storage of the VFAs. This first anaerobic stage is sometimes called an “anaerobic selector” because it preferentially selects for the proliferation of PAOs.

The second stage takes place under aerobic (or oxic) conditions. In the aerobic stage, the stored PHA is metabolized, providing energy for cell growth and the luxury uptake of soluble orthophosphate, which is stored as polyphosphates. The PAOs uptake and store more phosphorus under aerobic conditions than is released under anaerobic conditions, providing a net uptake and storage of phosphorus. This also provides the PAOs with a competitive advantage over other organisms, allowing them to thrive under these conditions. The stored phosphorus is then removed from the system with the waste sludge. If secondary clarifiers are allowed to become anaerobic or the waste activated sludge (WAS) is treated in an anaerobic digester, the PAOs can release stored phosphorus back into the process stream. Up to four times as much phosphorus can be removed biologically using EBPR than conventional activated sludge treatment.

#### Chemical Precipitation

Phosphorus can also be removed using chemical precipitation. The most common chemicals used for the precipitation of phosphate are aluminum sulfate, ferric chloride, and ferrous chloride. The precipitated phosphates must be removed by sedimentation and/or filtration. Note that the use of metal salts for the precipitation of phosphorus will add to the sludge production of the plant (EBPR generally does not increase sludge production appreciably). If the secondary clarifiers are used for the removal of precipitants, inert solids will also be added to the activated sludge process, decreasing the capacity for volatile solids or active biomass.

### 2.2.2 Phosphorus Removal Optimization Opportunities

EBPR can be added to an activated sludge treatment system by creating an anaerobic selector zone at the front of the secondary treatment process. The anaerobic selector must be upstream of the internal (nitrified) recycle if used in conjunction with a nitrification/denitrification process. Soluble VFAs can be provided for EBPR through primary sludge fermentation, as described in Section 2.1.2. Supplemental carbon can also be added to provide the VFAs needed for EBPR. Unlike BNR, EBPR generally requires a dedicated anaerobic reactor, so some type of partitioning and strict anaerobic conditions are required, which makes low-cost upgrades less feasible for plants not originally designed with EBPR in mind.

For activated sludge and most other types of WWTPs, metal salts can be added to chemically precipitate orthophosphate, which can then be removed with solids, during primary or secondary clarification and/or tertiary filtration. Metal salts can be added upstream of the primary and/or secondary clarifiers as well as at other points within the treatment system. Chemical precipitation, however, can limit EBPR. To optimize EBPR, chemical precipitation of phosphorus should be used as part of a tertiary treatment process. Chemical precipitation is the most common technique to achieve higher levels of phosphorus removal in plants not designed for EBPR. However, this technique is well-established and fully documented and described in various references, so it is not a focus of this document.

As with nitrogen removal, modifying a WWTP discharge through land application or wetland assimilation can be an especially effective way to reduce phosphorus delivery to surface waters, although it may not be widely practical. Phosphorus removal in “natural” systems such as these is typically the result of physiochemical immobilization reactions either in the soil matrix or in solution in free surface wetlands (e.g., precipitation).

## 2.3 NUTRIENT REMOVAL ATTRIBUTES OF TYPICAL WASTEWATER TREATMENT FACILITIES AND OPPORTUNITIES FOR IMPROVEMENT

Effluent nutrient characteristics vary considerably between different system types, different geographical areas (e.g., temperature can play a significant role in biological nutrient removal processes), and different influent wastewater, among other variables. Accordingly, average effluent nutrient concentrations should only be considered ballpark values. Average effluent nutrient concentrations for wastewater treatment systems are provided in Table 2-1.

**Table 2-1. Nutrient removal performance (effluent concentration) for wastewater treatment plants.**

| Treatment System | Total Nitrogen (mg/l) | Total Phosphorus (mg/l) |
|---|---|---|
| Raw Wastewater[1] | 40 | 7.0 |
| Primary Treatment[2] | 37 | 6.2 |
| Activated Sludge (with no nutrient removal)[1] | 25 | 5.6 |
| Facultative Lagoon[3] | 16 | 4.2 |
| Trickling Filter[2] | 25 | 5.8 |

Sources:
[1] Metcalf and Eddy 2004
[2] Metcalf and Eddy 1991
[3] Metcalf and Eddy 1991; WEF 2003; USEPA 2011b

### 2.3.1 Activated Sludge

Activated sludge is a suspended growth biological treatment process in which a large mass of aerobic floc-forming microorganisms convert organic material and other constituents to gases or assimilate them into cell tissue. Although activated sludge is conventionally defined to include only aerobic process, the term can be used to describe systems that include anaerobic and anoxic processes in addition to aerobic ones. The three basic elements of an activated sludge process are the biological reactor(s), liquids-solids separation unit (secondary clarifier for conventional process or membranes in the case of membrane bioreactors), and a return stream of the solids back to the reactor (Figure 2-6).

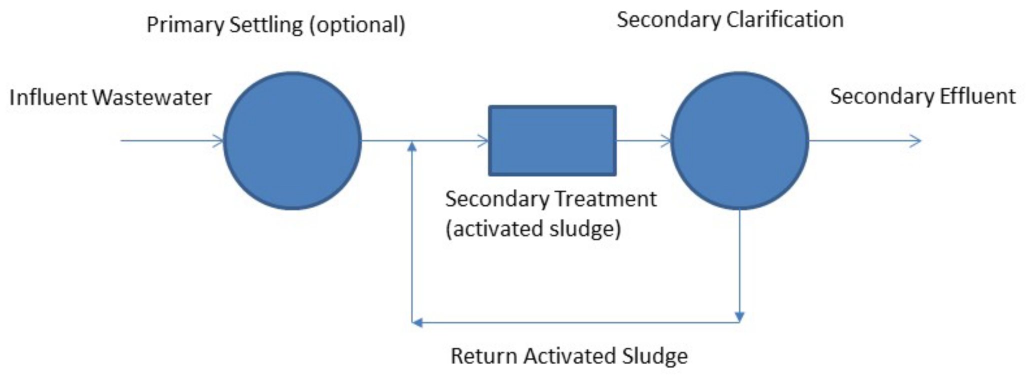


**Figure 2-6. Basic (non-advanced) Activated Sludge WWTP process schematic**

A portion of the solids is removed from the process or wasted in order to maintain an active, growing biomass population, and to remove solids-associated constituents (like phosphorus). Activated sludge processes that have been developed to include biological nitrogen and/or phosphorus removal are commonly called “biological nutrient removal processes”.

Biological nutrient removal is a well-documented set of processes for enhancing nitrogen and phosphorus removal. As described in Section 2.1.1, BNR is a 2-step process, sequentially requiring nitrification of ammonia to nitrate under aerobic (oxic) conditions, followed by the anoxic (no free oxygen) denitrification of nitrate to dinitrogen gas, which is harmlessly released to the atmosphere. A number of different process configurations have been used to affect nitrification/denitrification in WWTPs. Upgrades of existing WWTPs for BNR is often practical, although the extent to which TN can be reduced in WWTP effluents is a function of both pre-upgrade process configuration and upgrade cost.

Phosphorus is removed biologically from wastewater by uptake into cell mass, which is then wasted and disposed (or reused) as biosolids. EBPR is a process whereby bacterial cells are triggered to uptake much larger amounts of orthophosphate than they would under normal conditions (in very simple terms, EBPR is stimulated by anaerobic preconditioning followed by aerobic conditions). Although EBPR can be retrofit into existing WWTPs, in many cases, retrofits use chemical precipitation of phosphorus, which generally features lower capital costs (but more expensive recurring costs for chemicals and for sludge disposal) and oftentimes easier incorporation into existing WWTP process configurations.

Optimization opportunities for activated sludge processes are described in more detail in Section 3.

Conventional (non-advanced) activated sludge treatment processes are typically designed and operated with a focus on BOD and TSS removal, and sometimes nitrification. Nitrogen and phosphorus removal in those processes predominantly occurs from the nutrients being assimilated into the cell biomass during microbial (net) growth. Approximately 1 mg of phosphorus removal and 5 mg of nitrogen removal can be expected per 100 mg of BOD reduced in the system, although the ratio can vary depending on system characteristics and other factors. In addition, solids handling and treatment processes, such as aerobic or anaerobic digestion, often release some of these nutrients back into the solution during the reduction of the biomass, which is then returned back to the treatment process via the solids-handling sidestreams. As a result, overall nutrient removal in conventional activated sludge treatment processes is typically relatively low (see Table 2-1). To address this limitation when nutrient removal is required, conventional processes have been modified and new processes developed for targeted biological removal of nitrogen and phosphorus from wastewater.

Phosphorus removal will depend in part on the carbon (typically reported as BOD) available and its ratio to the phosphorus concentration in the influent. Similarly, nitrogen removal, which typically involves both nitrification and denitrification, will also depend on the carbon available (only the denitrification stage is carbon-dependent) and its ratio to the influent nitrogen (TKN) concentration, as well as the concentration of recalcitrant organic nitrogen. Therefore, nutrient removal performance will be a function of the influent wastewater characteristics and nutrient concentrations. For the purposes of this discussion, the following “typical” average wastewater influent concentrations have been assumed (Metcalf and Eddy 2014):

- BOD = 133–400 mg/L
- TKN = 23–69 mg/L
- Nonbiodegradable Soluble TKN = 1–2 mg/L
- TP = 3.7–11 mg/L

Table 2-2 shows several commonly used activated sludge treatment processes and the effluent nitrogen and phosphorus concentrations that can typically be achieved with each process. Note that it might not be possible to achieve the same effluent concentrations using some of the processes under higher TKN loadings (partly due to the higher nonbiodegradable soluble TKN concentration, as well as limitations of individual configurations), in which case the achievable effluent nitrogen concentration may exceed the upper end of the range reported in Table 2-2.

**Table 2-2. Average effluent TN and TP for various activated sludge process configurations**

| Process Configuration | Application | Achievable Effluent TN | Achievable Effluent TP |
|---|---|---|---|
| Conventional Treatment Processes (Complete-Mix, Extended Aeration, Plug Flow) | BOD Removal, TSS Removal, and Nitrification | 15 – 35 mg/L | 4 – 10 mg/L |
| Sequencing Batch Reactor | Can be used for nitrogen removal and phosphorus removal or both simultaneously depending on volume | 5 – 8 mg/L | 0.5 – 2.0 mg/L |
| Oxidation Ditch | Cyclic Nitrification/Denitrification | 5 mg/L | 4 – 10 mg/L |
| dNOx$^{TM}$ Oxidation Ditch | Cyclic Nitrification/Denitrification | 10 mg/L | 4 – 10 mg/L |
| Low DO Oxidation Ditch | Simultaneous Nitrification/Denitrification | 3 mg/L | 4 – 10 mg/L |
| Orbal$^{TM}$ | Simultaneous Nitrification/Denitrification | 3 mg/L | 4 – 10 mg/L |
| MLE | Pre-anoxic Denitrification | 6 – 10 mg/L | 4 – 10 mg/L |
| Step-feed BNR | Nitrification/Denitrification | 5 mg/L | 4 – 10 mg/L |
| 4-Stage Bardenpho | Nitrification/Denitrification | 3 mg/L | 4 – 10 mg/L |
| Post-Anoxic Zone with Carbon Addition | Applicable for various nitrogen removal and combined nitrogen and phosphorus removal process configurations | 3 mg/L | NA (Dependent on whether or not EBPR is included) |
| Modified Bardenpho (5-Stage) | Can include supplemental carbon feed to post-anoxic zone | 3 to 5 mg/L | 0.5 – 2.0 mg/L |
| A/O | EBPR only, no nitrification | 15 – 35 mg/L | 0.5 – 2.0 mg/L |
| $A^2O$ | EBPR, denitrification (high influent BOD/P ratio) | 6 – 10 mg/L | 1.0 – 2.0 mg/L |
| UCT | EBPR, denitrification (low influent BOD/P ratio) | 6 – 10 mg/L | 0.5 – 2.0 mg/L |

| Process Configuration | Application | Achievable Effluent TN | Achievable Effluent TP |
|---|---|---|---|
| Johannesburg | EBPR, denitrification (see Notes) | 5 mg/L | 0.1 – 0.5 mg/L |
| EBPR with VFA addition | Used with multiple configurations (see Notes) | NA (Supplement to various processes, TN will depend on configuration used) | 0.1 – 0.2 mg/L (soluble) |
| Chemical Phosphorus Removal | Metal salts may be added to secondary clarifiers or to basins (see Notes) | NA (Supplement to various processes, TN will depend on configuration used) | <0.1 mg/L |

Source: Metcalf and Eddy/AECOM 2014.

Notes: These processes must typically also be combined with tertiary filters or membranes to achieve phosphorus concentrations less than 0.5 mg/L, because of the effluent TP associated with effluent TSS.

TN = total nitrogen; TP = total phosphorus; MLE = Modified Lutzack Ettinger process; EBPR = enhanced biological phosphorus removal; VFA = volatile fatty acids.

## 2.3.2 Lagoons

Lagoons have been used as low-cost wastewater treatment systems for many years, particularly in relatively small and/or rural communities where sufficient land is available to site a lagoon that generally has a larger footprint than more mechanically based treatment systems (e.g., activated sludge).

Facultative lagoons are the most common type of lagoon used for WWTPs in the United States. They typically feature aerobic conditions in the upper layer and anoxic or anaerobic conditions toward the bottom, with the transition depth depending on the influence of wind-driven mixing.

Lagoon systems have not traditionally been designed to specifically remove nutrients, but primarily owing to their long HRT and SRT and co-occurring aerobic and anoxic conditions, often remove significant amounts of nitrogen with reductions of 40 percent common and reductions of 90 percent or greater achievable in some facultative systems during warm weather when biological reaction rates and other reduction processes (e.g., ammonia volatilization) are highest.

Because of the relatively long residence time of facultative lagoons, it may be possible to operate them to store wastewater in the winter (when nitrogen reduction is lowest) and discharge in the summer (when nitrogen reduction is highest) in order to maximize TN reductions. This type of operation is called a “controlled discharge” lagoon.

Various operating strategies can also be employed to optimize BNR in aerated lagoons, particularly those with mechanical aeration, similar to the optimization strategies available for activated sludge processes.

Phosphorus reductions are also widely variable, reported to range from 30–95 percent (Assenzo and Reid 1966; Pearson 2005; Crites et al. 2006). The long residence times in lagoons afford considerable capacity for storing phosphorus-rich sludge, much of which is generated via physiochemical mechanisms such as adsorption, coagulation, and precipitation, although biological uptake into algal and bacterial biomass is also important. Chemical precipitation has been used to reliably meet effluent phosphorus concentrations of 1.0 mg/l, using ferric or aluminum salts applied in batch or continuous modes.

Because lagoon systems are often sited in areas with available land, land application or some other type of modified discharge (e.g., wetland assimilation) might be a viable way to decrease nutrient load delivery to surface waters.

### 2.3.3 Trickling filter

A “trickling filter” is a nonsubmerged, attached growth, aerobic, biological secondary treatment process, in which wastewater is continuously or periodically distributed over rock or plastic packing. A biofilm grows on the filter media that treats the wastewater as it flows over it. Air moves through the media voids to provide oxygen for the treatment process either by natural draft aeration or forced draft aeration.

Trickling filters are commonly used for BOD removal and sometimes for nitrification when organic loading rates are low.

Nutrient reduction in WWTPs using trickling filters is typically modest, with average reductions of 10–30 percent TN and 8–12 percent TP (Metcalf and Eddy 1991). Nutrient reduction optimization options for trickling filters are likewise limited. Process variables can be modified in an effort to improve nitrogen removal, particularly if the trickling filters are designed to nitrify and are equipped with internal recycle, the rate of which can be adjusted (generally increased, but operational problems may occur if recycle rates are too high) to optimize denitrification.

A denitrification filter can be added after a nitrifying trickling filter to provide more significant total nitrogen reductions, although supplemental carbon will often be needed and overall costs will be significant. Chemical precipitation of soluble phosphate in a separate reactor or prior to the secondary clarifier is typically the most feasible option for significant TP removal.

### 2.3.4 Primary Treatment

Primary treatment involves the removal of a portion of the solids from the raw wastewater by the settling process using primary sedimentation tanks or clarifiers. Nutrient removal is generally limited to whatever nitrogen and phosphorus is contained in the settled solids. Properly designed primary clarifiers typically remove 50–70 percent of suspended solids and 25–40 percent of BOD in the influent. Primary settling has been reported to remove 5–10 percent of influent TN and 10–20 percent of TP (Metcalf and Eddy 1991).

Settling can be improved by the addition of chemicals such as metal salts and polymer. Iron and aluminum salts are often used in primary clarifiers to precipitate phosphorus, allowing it to be removed with the settled solids.

A secondary treatment process designed for biological nutrient removal must be added for the biological removal of nitrogen and phosphorus. Primary clarifiers can be designed and/or operated to allow fermentation of the primary sludge providing soluble BOD for use in denitrification or EBPR.

Existing primary treatment facilities can (and often do) land-apply primary effluent for secondary and tertiary treatment in situ.

Note that the Clean Water Act requires secondary treatment, except for facilities that have 301(h) variances, which are specific to marine discharges.

## 2.3.5 Modified Discharge

Alternatives to direct surface water discharges of WWTP effluents are used for a number of different reasons, with further attenuation of regulated pollutants—including nitrogen and phosphorus—often a significant driver.

“Modified discharge” systems generally use some type of natural system to polish WWTP effluent prior to the effluent entering a receiving surface water.

*Land application* is a broad term used to describe systems that discharge effluent (which may be primary, secondary or tertiary treated) into a natural soil system for additional treatment and dispersal into the receiving environment. In most cases, the effluent will eventually reach a surface water. Land application encompasses many different system types. Some examples include:

- Septic systems, which use a septic tank for primary treatment followed by a gravity-flow subsurface drainfield.
- Cluster or community scale advanced treatment systems with surface (e.g., spray irrigation) or subsurface (e.g., drip irrigation) soil dispersal systems.
- High-rate infiltration systems where effluent is applied to a basin where it percolates rapidly through relatively coarse media.

In general, effluent dispersed in these soil-based treatment systems flows vertically through the soil profile to the ground water table, where it then moves horizontally toward a receiving water. The nutrient reduction performance of land application systems can vary widely (from virtually no nutrient reduction to virtually complete nutrient removal) depending on the specific characteristics of the pretreatment system, soil treatment system, and natural topographical and hydrological conditions between the system and receiving water. Nutrient reduction performance can be estimated where soil and hydrological conditions have been characterized appropriately.

Like most other treatment system types, nitrogen reduction in land application systems is predominantly through biologically mediated nitrification and dentrification. Phosphorus reduction is primarily due to sorption and immobilization reactions between soluble phosphate and soil particles. Physical filtration of solids-associated phosphorus also might occur. Depending on the type of land application system, vegetative uptake of nutrients can also be a significant removal mechanism (vegetation must be removed from the site for such removals to be permanent). Where conditions are not conducive to sufficiently reduce nutrients prior to impacting surface waters, “permeable reactive barriers” can be used to intercept and treat nutrient plumes.

*Wetland assimilation systems* have been allowed in some states (e.g., Florida, Louisiana), mainly in coastal regions where traditional soil-based treatment might not be practical (e.g., due to insufficient space, high ground water table), but stringent nutrient limits still need to be met in adjacent surface waters. In these systems, WWTP effluent is discharged into a natural, restored, or man-made wetland that further reduces nutrients prior to dispersing effluent back into receiving surface waters. Again biological nitrogen removal and phosphate sorption processes dominate.

Nutrient removal in modified discharge systems can be enhanced by considering the following:

- Nitrogen removal is predominantly through biological nitrification and denitrification, which is most efficiently designed as a sequential process. For land application systems, this means that effluent must first be nitrified under oxic conditions either prior to or within the natural treatment system.
- Within a soil treatment system, oxic/nitrifying conditions can best be established by applying effluent to the dispersal area periodically in small doses under pressure and maintaining sufficient unsaturated soil between the dispersal depth and ground water table (typically a minimum of 1 or 2 feet of unsaturated soil).
- Denitrification requires nitrates, anoxic conditions, and labile organic carbon. These conditions typically predominate in wetland assimilation systems being fed with nitrified effluent. Such conditions are more difficult to establish in land application systems, particularly if nitrification is occurring in the soil treatment system. Although the saturated zone (ground water) is typically anoxic, organic carbon is typically concentrated in surficial, unsaturated soil layers. However, riparian areas that include the ground water-surface water interface may provide conditions favoring denitrification.
- In land application systems, nutrient reduction is favored in fine textured soils versus coarse textured soils (e.g., sands). Phosphorus reduction, in particular, requires sorption sites as well as appropriate soil reactivity, both of which are going to be more favorable in finely texture soils, such as clays. Reclaimed effluent can also be used to irrigate crops which will take up nitrogen and phosphorous (although these nutrients will only be removed if the vegetation is harvested); however, build up of salts in the soil may need to be considered and/or mitigated.

Although considerations for optimizing the performance of existing modified discharge systems have been presented, in the context of this report, modified discharge systems are primarily presented as an approach to help existing WWTPs further reduce nutrients.

## 2.4 EVALUATING AND IMPLEMENTING NUTRIENT REDUCTION IMPROVEMENTS

The results of the case studies featured in this project suggest that WWTPs with informed and motivated managers or operators empowered to tweak operations can often identify ways to improve nutrient removal with relative ease. Because treatment systems are unique, it can be difficult to prescribe a single approach for no-cost or low-cost nutrient reduction for specific situations. The case studies in this report offer WWTP operators, managers and others insights into what could work for them. Table 2-3 provides some key questions and approaches for nitrogen removal at the three major categories of WWTPs considered in this document: activated sludge, lagoons, and trickling filters.

**Table 2-3. Decision considerations for enhancing nitrogen removal at existing WWTPs**

| WWTP type | Key questions to ask | Optimization efforts to consider |
|---|---|---|
| Activated Sludge | Is there excess plant capacity?<br>- Is peak daily flow < 75% design capacity?<br>- Are additional tanks/reactors available?<br>- Is flow equalization provided? | Create anoxic zone(s)<br>- On/off cycling for nitrification/denitrification in single reactor<br>- Feed influent and internal recycle to dedicated tank<br>- Denitrify in flow equalization with internal recycle |
| | Is there excess aeration capacity?<br>- Can aeration be throttled?<br>- Does aeration system have automatic control?<br>- Can contents be mixed without aerating? | Facilitate anoxic environments<br>- Maintain lower DO setpoint or dedicated anoxic zone<br>- Install DO and/or ORP meters for auto control<br>- Consider adding mixers |
| | Are process parameters sufficient?<br>- Can nitrified liquor be returned to low DO zone?<br>- Is alkalinity sufficient for full nitrification?<br>- Is carbon available to drive denitrification? | Modify process parameters as warranted<br>- Internal recycle to introduce nitrified liquor to anoxic<br>- Add alkalinity<br>- Consider step-feed, pre-fermentation additives |
| Lagoon | Is capacity available to store effluent? | Control discharge to take advantage of summer nutrient removal, while maintaining receiving water standards |
| | Is the lagoon mechanically aerated? If so, can it be controlled (see Activated Sludge rows above)? | Create anoxic zones for enhanced BNR |
| | Is a nondischarge alternative available? | Study alternative discharge methods |
| Trickling Filter | Does trickling filter currently nitrify? | Add post-denitrification unit<br>Study alternative discharge methods |

Opportunities for phosphorus optimization are more limited and come down to a couple key questions:

1. For activated sludge, are reactors/tanks available or can the existing process be segmented to provide an anaerobic selector reactor with an HRT of at least 30 minutes?
2. For lagoons, much like for nitrogen removal, is additional capacity available in order to store effluent during the winter and discharge during summer, when algal growth and phosphorous uptake and sequestration is highest?
3. For all systems, is it feasible to discharge either seasonally or year-round for land application or to wetland assimilation?

If the answer to these questions is “no”, then chemical precipitation is probably going to be the most cost-effective way to increase phosphorus removal without major infrastructure modifications.

In general, plant managers and operators should complete the following steps to screen, evaluate, and implement nutrient reduction improvements.

1. First, look at WWTP influent nutrient sources and concentrations. Can any nutrients be controlled at their source?

2. Second, evaluate whether nutrients are being loaded to the WWTP through internal recycle lines (particularly if the WWTP uses anaerobic digestion) and consider managing these loads through sidestream control or treatment.
3. Then, identify existing unit processes, design parameters, and actual operating conditions. For biological processes in particular, determine whether excess reactor or aeration capacity exists. Note that plants with highly variable flows (e.g., I&I) or loading may have excess capacity at most, but not all, times.
4. Compile TN and TP performance data and analyze process variables and other important characteristics (e.g., time of year/temperature) to determine whether trends are discernible.
5. Consider using quick field tests to analyze various nutrient species throughout the biological treatment process at different times and under different conditions.
6. Use this document to determine potential broad areas where performance can be optimized.
7. Change only one variable at a time, allow to reach steady-state, and document performance implications.

In the early 1980s, based on experiences inspecting and troubleshooting WWTP performance, EPA (1984) developed a framework for systematically improving system operation called the Composite Correction Program (CCP). Much more recently, an updated, robust CCP was developed for dischargers in the Grand River watershed in Canada (XCG Consultants 2010). The process has been used to systematically improve nitrification at area WWTPs and reduce ammonia discharges, and provides a useful framework for U.S.-based WWTPs seeking to formally implement operation improvements such as nutrient reduction optimization at their facilities. In addition to the CCP itself, the Canadian guidance provides a framework for coordinating operator training, system auditing, and process modeling, all to support improved performance. These systematic frameworks can be adapted by proactive WWTP staff to evaluate optimization opportunities within all aspects of plant performance, including nutrient removal.

# 3 Optimizing Nutrient Removal in Activated Sludge Systems

There are a variety of often simple and relatively inexpensive improvements or operational changes that can be made at existing WWTPs to improve energy efficiency, provide or increase biological nutrient removal, and reduce chemical costs.

A good understanding of the fundamental requirements for enhanced nitrogen and phosphorus removal in WWTPs is important for understanding available optimization opportunities. Table 3-1 summarizes the conditions required for biological nitrogen and phosphorus removal, and Table 3-2 summarizes the functions of anaerobic, anoxic, and aerobic (or oxic) zones in biological nutrient removal systems.

**Table 3-1. Required conditions for biological nutrient removal (Daigger and Littleton, 2014)**

| Biological nitrogen removal | Biological phosphorus removal |
|---|---|
| An aerated (aerobic) zone with a sufficiently long SRT and other environmental conditions sufficient to allow the growth of nitrifying bacteria. | An unaerated zone where dissolved oxygen, nitrate, and nitrite are absent and other environmental conditions sufficient to allow PAOs to take up and store volatile fatty acids. |
| An unaerated (anoxic) zone where dissolved oxygen is excluded and to which sufficient biodegradable organic matter is added | An aerated zone where appropriate environmental conditions are provided to allow PAOs to metabolize stored organic matter and grow. Cycling of biomass between the unaerated and aerated zones. |
| Recirculation of nitrate-containing liquid from the aerated to the unaerated zone. | Feed of wastewater containing volatile fatty acids (and also, possibly, readily biodegradable organic matter) first to the unaerated zone. |

**Table 3-2. Functions of zones in BNR processes (Grady et al., 2011)**

| Zone | Biochemical transformations | Functions | Zone required for: |
|---|---|---|---|
| Anaerobic | • Uptake and storage of VFAs by PAOs with associated phosphorus release<br>• Fermentation of readily biodegradable organic matter by heterotrophic bacteria | • Selection of PAOs | • Phosphorus removal |
| Anoxic | • Denitrification<br>• Alkalinity production | • Conversion of NO3-N to N2<br>• Selection of denitrifying bacteria | • Nitrogen removal |
| Aerobic | • Nitrification and associated alkalinity consumption<br>• Metabolism of stored and exogenous substrate by PAOs<br>• Metabolism of exogenous substrate by heterotrophic bacteria<br>• Phosphorus uptake | • Conversion of NH3-N to NO3-N<br>• Nitrogen removal through gas stripping<br>• Formation of polyphosphate<br>• Growth of nitrifiers Growth of PAOs | • Nitrogen removal<br>• Phosphorus removal |

In many cases, optimizing nitrogen reduction at non-advanced WWTPs focuses on maximizing simultaneous nitrification and denitrification, rather than creating new, dedicated anoxic zones, which may be infeasible and/or cost-prohibitive. Keys to effective simultaneous nitrification/denitrification include (Daigger and Littleton, 2014):

- An aerobic SRT that exceeds that needed for nitrification (considering the highest expected loads and lowest expected temperature)
- Promoting on-uniform hydraulic flow patterns with the aeration and/or mixing systems
- Having the ability to effectively manage oxygen input

For the purposes of this report and the associated case studies, optimization activities have been divided into five main categories. In addition to being referenced in the body of the report, case study summaries are provided as stand-alone documents in Appendix B. Characteristics of each case study are summarized in Table 3-3 and under the heading “Modification Type:”

- *Aeration* modifications include installation of efficient blowers or aerators, variable frequency drives, on/off cycling, dissolved oxygen (DO) or oxidation-reduction potential (ORP) control, and associated controls.
- *Process* modifications include adjustments to process control characteristics including SRT, MLSS, F/M ratio, recycle/return rate, and associated controls.
- *Configuration* modifications include adding recycle lines, step feed provisions, repurposing of tankage, and associated controls.
- *Chemical* modifications include use of metal salts to precipitate phosphorus, and alkalinity and organic carbon addition to support biological nitrogen removal.
- *Discharge* modifications are those made at the end of the treatment system to further reduce nutrients prior to delivery to receiving surface waters (e.g., land application, wetland assimilation discharge, etc.).

Brief descriptions of each specific modification, as referenced in Table 3-4, are provided below.

Aeration

- Aeration cycling – includes on/off cycling of aeration, including the creation of dedicated anoxic and oxic zones, and associated controls.
- Adjustable control aeration – use of variable frequency drives to control aerator output and/or use of on-line monitoring tools to inform aerator operational mode.
- Mixer addition – addition of mixers to facilitate on/off cycling or maintain suspension of solids when aerators are turned down.
- Equipment retrofit – replacement with energy efficient aeration equipment.

Process

- Flow equalization improvement – improving the influent flow to biological treatment process to improve performance consistency.
- Recycle rate control – modifying internal mixed-liquor recycle rate to optimize denitrification in primary anoxic zones.
- Sidestream control – modifying nutrient-rich internal plant return flows, such as sludge dewatering returns.
- Pre-digestion of primary sludge – modifying primary sludge wasting rate to facilitate biochemical oxygen demand (BOD) solubilization from settled sludge into secondary process influent.
- Batch program modifications - changes to SBR program settings.

Configuration

- Plug flow/series operation – conversion of complete mix reactor to plug flow to facilitate oxic/anoxic zonation.
- Anoxic zone bleed – introduction of influent wastewater or return activated sludge (RAS) into anoxic reactors to provide carbon for denitrification.
- Anaerobic zone VFA addition – introduction of RAS into anaerobic selector to provide carbon for enhanced biological phosphorus removal (EBPR).

Chemical

- Alkalinity feed improvements – modifications to alkalinity control systems to facilitate effective nitrification.
- Carbon product addition – addition of soluble BOD products to enhance denitrification or EBPR.

Discharge

- Soil dispersal – conversion of a surface discharging system into a soil discharging system.
- Wetland discharge – discharge into wetlands for further attenuation of nutrients prior to receiving water delivery.

Note that chemical modifications and discharge modifications, because they are not necessarily unique to activated sludge processes, are discussed in more detail in Section 6.

On average, the non-advanced WWTPs featured in these case studies were able to achieve effluent TN reductions of greater than 50 percent (from 10.5 mg/l, pre-optimization, to 5.0 mg/l, post-optimization, on average) and most realized net cost *savings* as a result of optimization efforts.

**Table 3-3. Summary of Case Studies (basic, non-advanced treatment plants shaded in gray).**

| Case Study | Design Flow (MGD) | WWTP Type | Modification Type | Pre/post TN (mg/l) | Pre/post TP (mg/l) | Capital Costs | Operational Costs/Savings |
|---|---|---|---|---|---|---|---|
| Bay Point, FL | 0.054 | AS (MLE) | Aeration, chemical | 6.33/3.99 | N/A | $170,365 | **Savings** not quantified |
| Bozeman, MT | 5.2 | AS | Aeration, configuration | 17.8/10.5 | 3.7/2.5 | $180,000 | Zero |
| Chinook, MT | 0.5 | AS (Oxidation Ditch) | Aeration | 20.3/5.44 | 4.13/1.72 | $81,000 | Energy **savings** more than offset $1,000/yr in maintenance |
| Crewe, VA | 0.5 | AS (Oxidation Ditch) | Aeration, chemical | 7.85/3.63 | N/A | $6,000 | $17,440/yr **savings** |
| Flagstaff, AZ | 6.0 | AS (IFAS) | Process | 14.0/8.5 | N/A | $10,000 | $1,000/yr |
| Hampden Twp., PA | 5.69 | AS (CSR) | Configuration, process | 4.66/3.64 | N/A | Zero | Zero |
| Layton, FL | 0.066 | AS (SBR) | Aeration, process | 7.88/3.33 | N/A | $53,000 | $13,500/yr **savings** |
| Montrose, CO | 4.32 | AS (Oxidation Ditch) | Aeration | Unk/14.7 | N/A | Zero | $34,000/year **savings** |
| Tampa, FL | 96 | AS (Separate Stage) | Aeration, configuration | 18.62/13.82 | N/A | Zero | $519,900/yr **savings** |
| Titusville, FL | 6.75 | AS (A2/O) | Discharge, configuration, process | 5.67/0.94 | 0.77/0.04 | $2,240,000 | $45,000/yr |
| Victor Valley, CA | 13.8 | AS | Aeration, process | 8.93/6.83 | N/A | $1,100,000 | 10% **savings** |
| Wolfeboro, NH | 0.6 | AS (Extended Aeration) | Aeration | 6.32/1.97 | N/A | $116,000 | **Savings** not quantified |

AS = activated sludge; MLE = modified Ludzack Ettinger; IFAS = integrated fixed film activated sludge; SBR = sequencing batch reactor; N/A = not applicable; CSR = continuously sequencing reactor.

**Table 3-4. Modifications Featured in Case Studies.**

| Modification | | Bay Point | Bozeman | Chinook | Crewe | Flagstaff | Hampden Township | Layton | Montrose | Tampa | Titusville | Victor Valley | Wolfeboro |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aeration** | Aeration cycling | | √ | √ | √ | | √ | √ | √ | | | | √ |
| | Mixer addition | | | √ | | | | | | | | | |
| | Adjustable control aeration | √ | √ | | √ | | √ | | | √ | | √ | √ |
| | Equipment retrofit | | | | | | | | | | | √ | √ |
| **Process** | Flow equalization improvement | √ | | | | | | | | | | | |
| | Recycle rate control | | | | | √ | | | | | | | |
| | Sidestream control | | | | | √ | | | √ | | | | |
| | Batch program modifications | | | | | | | √ | | | | | |
| | Predigestion of primary sludge | | | | | √ | | | | | | | |
| **Configurati** | Plug flow/series operation | | √ | | | | √ | | | | | | |
| | Anoxic zone RAS bleed | √ | | | | | | | | √ | √ | | |
| | Anaerobic zone VFA addition | | | | | | | | | | √ | | |
| **Chemica** | Alkalinity feed improvements | √ | | | √ | | | | | | | | |
| | Carbon product addition | | | | √ | | | | | | | | |
| **Disch** | Soil dispersal | | | | | | | | | | | √ | |
| | Wetland discharge | | | | | | | | | | √ | | |

Additional case studies were identified during the literature review, but were not developed further for this report as they did not meet one or more of the screening factors used in this study. Important characteristics of these case studies are summarized in Table 3-5 and Table 3-6. Readers are encouraged to refer to these references for additional information.

**Table 3-5. Case studies from Water Planet Company website**[2]

| Name | State | Flow (MGD) | Type | Approaches | TN | TP |
|---|---|---|---|---|---|---|
| Amherst | MA | 7.2 | AS-PF | Lower F:M ratio and operation in MLE/SBR mode, variable aeration based on in-line ORP, DO instruments, controlling ammonia removal to limit alkalinity consumption | 8 mg/l | |
| Colchester-East Hampton | CT | 3.8 | AS-MLE | Minimized internal recycle flows and bypassed influent around primary clarifiers directly to pre-anoxic zones, aeration cycling | 8 mg/l | |
| Columbia Falls | MT | 0.55 | AS-MLE | Adjusted equalization tank flow and internal recycle rates to convert existing pre-anoxic tanks to fermenters and enhance BPR | | 0.5 mg/l |
| Conrad | MT | | Modified Lagoon | Aeration cycling | 3.5 mg/l | |
| Hastings | PA | 0.45 | AS-EA | Conversion of equalization tank to combination fermentation/EQ, added digested sludge feed, aeration cycling and decoupling of air lift and aeration, monitoring and controls | x | x |
| Keene | NH | 6 | AS | Created fermentation zone for BPR by closing aeration valves and activating mixer in aeration cell | | 0.2 mg/l |
| Manhattan | MT | | | Increased RAS rate to 250% of the forward flow | 50% | |
| Montague | MA | 1.83 | AS | Conversion to sequenced aeration mode involving the installation of motor actuated RAS valve, aeration valves, and DO/ORP monitors | 5 mg/l | 0.75 mg/l |
| Northfield | MA | | AS-CM | Cyclic aeration, pre-fermentation of septage for BOD/VFAs | x | |
| Palmer | MA | 4.2 | AS | Cyclic aeration | 75% | |
| Plainfield | CT | 1.5 | AS | Drover$^{TM}$ process that recaptures BOD lost during primary treatment, by modifying primaries to pre-anoxic zone | 8 mg/l | 0.8 mg/l |
| Suffield | CT | 1.5 | AS-OD | Creation of pre-anoxic zone, pre-fermentation in sludge holding tanks | 2 mg/l | 0.5 mg/l |

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[2] http://www.cleanwaterops.com/

| Name | State | Flow (MGD) | Type | Approaches | TN | TP |
|---|---|---|---|---|---|---|
| Upton | MA | 0.4 | AS-EA | Aeration control to first two passes, increased RAS rate to increase nitrate return | 6 mg/l | |
| Westfield | MA | 6.1 | AS-PF | Operate first third of plug flow reactor as fermentation reactor fed with sludge, in-line Ortho-P measurement to control supplemental chemical dosing | | 1 mg/l |
| Windham | CT | 5.5 | AS | Mixed liquor return to primary clarifiers to create pre-fermentation zone for BPR | | x |

Note: In TN and TP columns, reported optimized effluent concentration is listed where reported; percent reduction is listed where reported; where no number is reported, an "x" indicates that plant was optimized to remove this nutrient.

AS = activated sludge; PF = plug flow; MLE = Modified Lutzack Ettinger process; OD = oxidation ditch; EA = extended aeration; CM = completely mixed

**Table 3-6. Additional case studies identified in literature.**

| Author | Year | System | Location | TN | TP | Summary |
|---|---|---|---|---|---|---|
| Block, et al. | 2008 | AS | Minneapolis, MN | | x | Upgrade to BPR by baffling existing reactors |
| Gangadharan, et al. | 2012 | AS-BNR | Chapel Hill, NC | x | | Convert existing BNR plant from plug flow to step feed to reduce TN with no capital costs |
| Greene | 2011 | AS-BNR | Various | x | x | Multiple case studies in PowerPoint presentation. |
| JJ Environmental | 2015 | Various | New England | x | | Paper study of 20 WWTPs in Upper Long Island Sound watershed. |
| Randall, et al. | 1999 | various | NY, PA, MD and VA | x | | Paper study of 51 WWTPs in the Chesapeake Bay watershed |
| Sadler, Stroud | 2007 | AS-BNR | North Carolina | x | x | Four case studies, relatively high level systems |
| Scheringer, et al | 2009 | AS-BNR | North Carolina | x | x | Chemical optimization, alternative carbon sources, swing zones, increased return flows, replaced aerators, optimized blower operation, control of digester supernatant |
| Solley, Barr | 1999 | AS | Australia | x | x | Zonation and aeration controls |
| USEPA | 2007b | AS-BNR | US | | x | Characterizes existing advanced treatment plants achieving low TP |
| USEPA | 2007a | AS-BNR | US | x | x | Summarizes costs for a variety of BNR system retrofits and replacements |
| Winkler, et al | 2007 | AS | Germany | x | x | Significant upgrades to BNR using existing structures |
| Young, et al | 2011 | AS-OD/BNR | Maryland | x | x | Review design and operation of two high level advanced treatment plant |

Note: In TN and TP columns, an "x" indicates that plant was optimized to remove this nutrient.

AS = activated sludge; OD = oxidation ditch; BNR = existing advanced nutrient removal

Several key references in Table 3-6 were evaluated for general comparison with the empirical data from the case studies associated with this project. Randall, et al. (1999) concluded that the costs of nitrogen removal were plant specific and ranged from a savings of $0.79/lb to a cost of $5.92/lb (for a target of 8 mg/l effluent TN), and that activated sludge systems, and oxidation ditches in particular, were generally most cost-effective to optimize. They do advise that BNR retrofits could impact design capacities and should be evaluated with this in mind.

JJ Environmental (2015) estimated 20-year life cycle costs of $0.36/lb to $3.85/lb effluent TN reduced based on the results of BioWin modeling; however, it appears that there was no set target effluent TN and in some cases, the modeled TN was very low (2 mg/l range). Therefore, it could be concluded that their scoping-level report may focus on somewhat more extensive retrofits. The empirical data presented in this report generally reflect efforts to address the most cost-effective optimization opportunities, rather than the greatest reductions that could be achieved without adding reactors.

Both reports conclude that low-cost optimization is feasible and cost-effective, and both reports should be considered useful supplemental resources for professionals pursuing an optimization strategy for nutrient reduction at their WWTPs.

USEPA (2010) provides useful information on optimization strategies for enhancing nutrient removal. Two key points are to have a process for analyzing existing operations and identifying tools to assist in an evaluation of optimization alternatives. Chapter 12 provides an existing system analysis framework, consisting of the following tasks:

- Compile existing data
- Collect additional data (see Table 3-7)
    - Optimize sampling and process monitoring to enable real time process control and troubleshooting in influent, process and recycle flows. Also use portable test kits as needed.
- Review and summarize data
- Evaluate relationships between key parameters
    - Simulation models can be good tools for describing such relationships and evaluating alternative strategies.

**Table 3-7. Recommended Parameters for Data Evaluation (USEPA, 2010)**

| Parameter[1] | Location(s) | Rationale |
|---|---|---|
| Flow | Influent, effluent, flow splits, recycles | Essential for developing mass balances, which are essential for a complete understanding of the treatment system. |
| Ratio of Total BOD/COD<br>Soluble[1] BOD/COD | Influent, primary effluent, effluent, anaerobic & anoxic zone effluents | Can be used to evaluate substrate availability for biological processes. High effluent BOD could indicate activated sludge performance problem. |
| TSS, VSS | Primary effluent, secondary effluent, final effluent | Important if phosphorus is removed chemically. Used to calculate ISS, determine clarification efficiency, and determine an accurate solids residence time (SRT) for the bacteria. |
| DO | Aerobic, anaerobic, and anoxic zones (multiple locations recommended) | Minimum DO of 2.0 is usually needed to minimize oxygen limitation of nitrification rates, which is important for low SRT/HRT systems. DO should not be present in anoxic or anaerobic zones. |
| pH | Influent, mixed liquors, effluent | Should be above 6.5 and below 9.0 for biological nitrogen removal. Low pH or wide swings in pH could mean significant industrial component. Could affect BPR and nitrification. |
| Alkalinity | Influent, primary effluent, mixed liquor supernatants, effluent | If effluent is below 50, there is probable nitrification inhibition, and process is susceptible to large pH drops as a result of nitrification or chemical addition for phosphorus removal. |
| Temperature | Influent, mixed liquors of reactors, effluent | Low temperatures can significantly reduce nitrification rate. For the typical range between 10 and 25 °C, the rate will drop by half for every 8 to 10 °C reduction in mixed liquor temperature. Reactor temperatures are likely to be significantly different from influent temperature because of aeration. |
| NH3-N and/or TKN | Influent, primary effluent, reactor mixed liquors, secondary effluent, effluent | Can be used to evaluate load to and performance of biological nitrification kinetics. |
| Nitrate | Influent, reactor mixed liquors, secondary effluent, effluent | A check on nitrification, and can be used with TKN to calculate denitrification. |
| Total Phosphorus | Influent, primary & secondary WAS, plant effluent | Used to calculate phosphorus removal efficiency by treatment processes. |
| Phosphate | Reactor mixed liquors, primary & secondary effluents, effluent | Used to determine release and uptake in reactors, release in secondary clarifier, and phosphorus removal efficiency. |
| ORP | Anaerobic & anoxic reactor mixed liquors | Measures the balance between oxidized and reduced compounds present in solution. Will detect presence of significant concentrations of oxidized compounds. Can be used for automatic detection of excess electron acceptors (DO, nitrate, and nitrite) in reactors. |

| Parameter[1] | Location(s) | Rationale |
|---|---|---|
| VFA or rbCOD | Influent, primary effluent | Can be used to evaluate substrate availability for enhanced biological phosphorus removal. |
| MLSS & MLVSS test and WAS test | MLSS & MLVSS: well-mixed location in aeration basin<br>WAS: well-mixed and representative sample from the WAS pipe (may need composite sample) | MLSS and WAS tests provide suspended solids concentrations and can be used to determine percent phosphorus in sludge. This information, in conjunction with aeration basin volume and WAS flow, can be used to calculate SRT. Maintaining SRT is critical for nitrification and, sometimes, for enhanced biological phosphorus removal. |

[1] BOD = biochemical oxygen demand (5-day unless otherwise noted)
COD = chemical oxygen demand
TSS = total suspended solids
DO = dissolved oxygen
TKN = total Kjeldahl Nitrogen
VFA = volatile fatty acids
MLSS = mixed liquor suspended solids
Total BOD/COD = unfiltered BOD/COD
Soluble BOD/COD = BOD/COD of filtrate from 0.45 µm pore size filter
VSS = volatile suspended solids
ORP = oxidation reduction potential
$NH_3$-N = ammonia Nitrogen
rbCOD = readily biodegradable COD
WAS = waste activated sludge
MLVSS = mixed liquor volatile suspended solids: Inorganic suspended solids (ISS) = MLSS - MLVSS
Source: WEF and ASCE (2006)

## 3.1 AERATION MODIFICATIONS

Aeration is one of the key operating parameters used to establish and control biological nutrient removal, since it determines the operating environment in a particular treatment basin (aerobic conditions for nitrification, anoxic conditions for dentrification, or anaerobic conditions for EBPR). Aeration is often also the single largest power demand in a WWTP, so it is a key operational consideration for energy efficiency. Therefore, aeration system modifications are one of the more common nutrient removal improvements at existing WWTPs. Every case study developed for this project that featured relatively basic (i.e., non-advanced) treatment included some kind of aeration optimization as part of their portfolio of nutrient reduction improvements.

Some key points that emerge from the literature regarding aeration and dissolved oxygen levels include:

- A minimum DO of 1.5 mg/l, or preferably 2.0, or greater is ideal for the initial (front-end) oxic zones. These DO levels ensure optimum phosphorus uptake (where EBPR is provided) and facilitate complete nitrification (provided other conditions are sufficient).
- If a dedicated anoxic zone is provided, zero DO is ideal for denitrification. The DO level in the internal recycle flow must be kept to a minimum and some type of internal recycle deoxygenation zone prior to mixing with the influent in an anoxic zone can be useful. Additionally, where dedicated anoxic zones are used, uniform mixing within the anoxic reactor is important.
- Likewise, it is important to maintain the integrity of the anaerobic zone for EBPR - a separate reactor (with minimal back mixing) is typically needed and conditions must be anaerobic.
- For simultaneous (single reactor) nitrification-denitrification processes, maintaining a low DO following the initial 1.5-2.0 mg/l or greater oxic zone is important. In other words, aeration should be tapered such that DO levels are highest at the influent end of the aeration zone and lower downflow.

Some of the most common aeration system improvements or upgrades include:

- individual zone airflow control,
- blower airflow modulation,
- aeration control feedback loops for DO, ORP or ammonia control,
- aeration on/off cycling or anoxic zone creation to allow for biological nutrient removal,
- mixer addition to keep solids in suspension when air is turned off or down, and
- replacement of old equipment with newer, more efficient equipment.

The Bozeman Water Reclamation Facility converted a conventional Complete Mix-Activated Sludge (CMAS) system to a 4-zone plug flow reactor by using cyclic aeration and step feed in the first two zones in order to meet new permit limits on effluent TN and TP discharge loads. Total nitrogen was reduced from an annual average TN of 17.8 mg/L to 10.5 mg/L and total phosphorus was reduced from an annual average TP of 3.7 mg/L to 2.5 mg/L. The original configuration included a basin divided into four equally sized cells with the flow split and fed to each cell from the outside wall and collected at the opposite wall shared by two cells, with all cells aerated. Using the existing tank and dividing wall, the basin was converted to plug flow with phased nitrification and denitrification by adding weir plates and using existing gates to change the flow through the basin. By adding new aeration controls, ORP probes, and mixers to the first two cells, the existing blowers and diffusers were used to implement cyclic aeration in the first two zones, providing partial denitrification and EBPR, while still keeping the last two zones sufficiently aerated to ensure consistent nitrification in order to meet the effluent ammonia limit.

In Chinook, MT, staff used knowledge gained during a State-sponsored training session to begin experimenting with on/off operation of the surface aerators (oxidation ditch rotors), eventually adding mixers (primarily for energy efficiency at the time) and automatic DO controls integrated with their SCADA system. Energy cost savings have more than paid for these optimization efforts.

Plant staff in Crewe, VA employed a similar approach, first experimenting with simple on/off aerator operation, and then advancing to DO-controlled, variable speed aeration, at a capital cost of only $6,000.

The Wolfeboro Wastewater Treatment Facility implemented cyclic aeration to lower their effluent TN. The existing aging ceramic diffusers were replaced with new diffusers with more efficient oxygen transfer, reducing the airflow requirement. The old and oversized blowers were also replaced with new lower horsepower blowers with VFDs and controllers. These equipment upgrades provided improved process performance and energy savings. The upgraded aeration controls include a timed cyclic aeration strategy and DO control based on readings from new DO probes when the basin is aerated. New ORP probes were also installed for monitoring system performance. Cyclic aeration provides nitrogen removal and also contributes to energy savings, resulting in reduced operating costs.

## 3.2 PROCESS MODIFICATIONS/OPERATIONAL CHANGES

Process improvements for nutrient removal include operational changes without necessarily requiring physical modifications to the existing facilities. Some of the key operational parameters for biological nutrient removal include DO, alkalinity/pH, MLSS/SRT, sludge blanket depth, and F/M ratio. Other more difficult to control variables that affect biological nutrient removal include temperature and inhibitory compounds, both of which particularly impact nitrification.

Some key points that emerge from the literature regarding process modifications and operational changes include:

- Increasing internal recycle (IR) rate typically increases denitrification until the rate becomes so high that recycled DO starts to inhibit denitrification. However, if the IR is too low, then nitrates can become fully depleted in the anoxic zone(s) and fermentation/release of phosphorus and foaming can occur. As a rule of thumb, the IR should be 4-6 times the forward flow provided that the IR dissolved oxygen is less than 1.0 mg/l. A deoxidation zone (20-30 min. HRT is standard) can be provided for the IR to lower the DO if necessary.
- RAS and WAS control is important for several reasons. Higher RAS rates can be used to facilitate denitrification for plants without internal recycle capabilities; however, high RAS rates can negatively impact EBPR. Controlling WAS rate is important for determining MLSS/MLVSS concentrations and SRT, which is particularly important for nitrification (anoxic SRT can also be important for denitrification). In general, RAS should be controlled to maintain secondary clarifier sludge blankets at 1 foot or less. Dedicated RAS controls/pumps for each clarifier can help with regard to maintenance of appropriate sludge blanket depths.
- VFAs and readily biodegradable organic matter are important for EBPR and BNR. For phosphorus removal, an rbCOD/TP ratio of 10-16 is typically targeted (Barnard 2006). VFAs can be provided in-process by fermenting primary sludge within the sludge blanket or in a separate reactor. Table 3-8 summarizes potential sources of VFAs at municipal WWTPs.

**Table 3-8. Potential sources of VFAs at municipal WWTPs (Jeyanayagam, 2005)**

| In-line sources | Off-line sources |
|---|---|
| • Fermentation in:<br>o Collection system<br>o Anaerobic zone of the bioreactor<br>o Primary clarifiers | • Fermentation in:<br>o Primary sludge fermenter<br>o Gravity thickener<br>o First stage of a two-phase anaerobic digester<br>• Purchased acetic acid |

- In general, it is important to maintain consistent operations and avoid frequent changes in operation. Improvements can include flow or load equalization, especially for small plants whose influents or internal process flows may have more variation. Adjusting SRT and HRT in response to seasonal changes can be important for getting the most nutrient removal out of a process. Another consistency-focused recommendation is to use flow- or load-paced recycle flows (IR and RAS).
- For effective nitrification, pH should be maintained between 6.5 and 8.0 and effluent alkalinity should be 80 mg/l as $CaCO_3$ or greater.

Improved sampling and monitoring can also provide valuable information for optimizing the performance of a process by identifying non-optimum conditions in the system. A couple of examples are presented below.

- If the DO is too high in an anoxic zone, then denitrification cannot occur until the DO is exhausted. Excess DO can come from a variety of sources, including an internal recycle stream with a higher flow than can be denitrified, over-aeration of the aerobic zone, or air entrainment in the influent and return streams caused by drops or free discharges into the basin. Once identified, these can often be remedied by fairly simple operational adjustments, such as turning the air down where the IR flow is collected and controlling the IR flow so only the quantity that can be denitrified is returned.

- Basin DO and nutrient concentrations (including $NO_3$-N, $NO_2$-N, $NH_3$-N, and $PO_4$-P) collected at different points throughout the basin can also be useful in assessing performance and determining if there is additional potential capacity for denitrification. For instance, if all the ammonia ($NH_3$-N) has been nitrified at a point approximately two-thirds of the way down a plug flow aeration basin, then there is potential for part of the basin to be operated as an anoxic zone, or cycling the aeration in order to operate the entire basin (or part of the basin) as an anoxic basin part of the time to provide some denitrification. Field trials with additional monitoring would need to be conducted to determine the best operating mode and the benefit of the alternate operation.

Table 3-9 provides a list of available on-line instruments along with measurement alternatives and their advantages and disadvantages. Table 3-10 provides recommendations for uses and locations for various online instruments.

**Table 3-9. Summary of Basic On-Line Instrumentation (USEPA, 2010)**

| Analyte | Type of Measurement | Advantages | Disadvantages |
|---|---|---|---|
| Flow | Mechanical | Accurate | Wear down |
| | Pressure Drop | Low cost | Highly dependent on installation, pressure drop |
| | Magnetic | No moving parts, no wear | High cost, inaccurate at low flow |
| | Reflective Sonic | No pressure drop, low maintenance,<br>low cost | Limited size of conduit, can't use aggregate lined pipe, inaccurate at low flow |
| | Parshall Flume | Simple, wide flow range | Pressure drop, requires cleaning, slow response |
| TSS | Light scattering (back scattered) | Better sensitivity, wider measuring range | Needs effective cleaning system |
| | Light Adsorption | Less sensitive, smaller range, inaccurate at low ranges | Able to handle fouling better without cleaning system |
| | Ultrasonic | Insensitive to color | Fouling, background reading required |
| | Microwave | Insensitive to interference | High cost, only works for high TSS |
| Sludge blanket monitor | Ultrasonic | Low maintenance | |
| | TSS or Turbidity | See TSS | |
| DO | Membrane electrode | Low cost | High maintenance |
| | Galvanic electrode | Durable, reliable | Interference from hydrogen sulfide, needs frequent calibration |
| | Optical probe | Durable, low maintenance, reliable | Higher initial cost |
| pH | Electrode | | Fouling |
| ORP | Electrode | Indicates true oxidizing environment<br>(anaerobic, anoxic, or aerobic) | Indirect measurement |

**Table 3-10. Recommended instrument locations for biological nutrient control (Tsuchihashi, 2008)**

| Location | Instrument | Purpose | Comments |
|---|---|---|---|
| Primary Effluent | Ammonia | Monitor loading | Helps in troubleshooting process upsets |
| Nitrate Recycle | NOx, DO | Need to maintain no or minimal DO, determine nitrate load on anoxic zone | Process monitoring and optimization |
| Pre Anoxic (first anoxic zone) | DO, NOx, possibly ORP | Need to maintain no or minimal DO, determine nitrate removal in anoxic zone, ensure reducing conditions | Monitoring and optimizing process |
| Aerobic zone | DO, pH, NOx | Controls blowers, ensures proper environment for organisms | Energy consideration and process monitoring |
| Pre (post anoxic zone) (just upstream of methanol addition) | DO, NOx | Maintain no DO present and also use nitrate concentration to pace methanol or other carbon source addition | Process optimization and cost control |

The effectiveness of preliminary treatment facilities (screens and grit removal equipment) can also impact the performance and operation of downstream treatment processes, including the ability to provide biological nutrient removal. Grit can accumulate in oxidation ditches, aeration basins, or other reactors, decreasing their effective treatment capacity. Similarly, rags and debris can plug or foul diffusers, mixers, and pumps, negatively impacting their performance as well. So, improvements or upgrades to preliminary treatment facilities, including the addition of fine screens or enhanced grit removal, can have the additional benefit of improving nutrient removal efficiencies. This can also include operational changes, such as regularly cleaning basins on a more frequent basis.

The Wildcat Hill WWTP in Flagstaff, AZ was able to reduce effluent TN by making operational changes and adding process controls. A combined nitrate/ammonia probe was installed at the end of the anoxic zone. The nitrate reading from the probe is used to control the internal recycle flow, so the optimum amount of nitrate is returned to the anoxic zone, also minimizing the amount of DO entering the anoxic zone. Primary clarifier sludge pumping was modified to increase the solids detention time in the primary clarifier to get additional conversion of particulate BOD to soluble BOD to provide more available carbon for denitrification in the primary effluent. The return flow from the dewatering processes is also controlled to avoid nitrogen loading spikes.

At the City of Layton (FL) Wastewater Treatment Plant, the effluent TN concentration was reduced by changing the control of the Sequencing Batch Reactor cycle from a level batch process to a timed batch process and adjusting the order and duration of aerobic and anoxic operation, including adding new online monitoring probes, in order to improve effluent consistency and optimize the fill, react, settle, and decant cycles.

At the Bay Point (FL) WWTP, the original manually cleaned static bar screen with large openings and a high approach velocity was replaced with a tighter bar screen with an approach channel and drying rack, which reduced the quantity of rags and debris passing into the treatment process. This solved the problem of frequent clogging in the flow equalization pumps and greatly reduced the build-up of debris on mixers and diffusers, improving performance and operation.

Victor Valley, CA uses DO, ORP, alkalinity and sludge age to optimize their process for simultaneous nitrification and denitrification.

## 3.3 CONFIGURATION MODIFICATIONS

Piping and flow or configuration modifications can include changing where the RAS or internal recycle is returned, splitting flows to go to more than one zone, providing sidestream treatment for centrate or filtrate from solids handling processes, and changing the zone in the reactor where backwash or dewatering streams are discharged. These may include physical modifications to the existing facilities including adding or improving flow equalization, modifying existing tankage, improving flow split mechanisms, and adding internal recycle lines.

Some key piping and configuration modifications include adding internal recycle capabilities (largely discussed in the previous section) as well as minimizing the impact of internal loads from solids handling systems and adding infrastructure to create dedicated redox zones.

The impact of recycle loads from solids processing can be managed by chemically precipitating side streams (for TP reduction), chemical addition to solids processing feed, and minimizing unaerated storage prior to sludge processing which can release phosphorus. Ammonia returned from dewatering operations can also negatively impact BNR. Baffling can be used to build aerobic/anoxic swing zones, to create high F:M conditions, and to approximate plug flow conditions to effectively taper DO and minimize back-mixing.

At the Blue Heron Water Reclamation Facility in Titusville, Florida, a RAS denitrification stage was added by creating a separate anoxic zone for just the RAS (also known as an exhauster zone) before combining the RAS with the influent in the anaerobic zone. This allows the nitrate to be removed from the RAS before it is introduced into the anaerobic zone. As a result, the influent is introduced into a truly anaerobic zone, improving biological phosphorus removal. A portion of the RAS was also sent to the front of the post-anoxic zone, which improved denitrification. Note that these modifications are effective because the RAS has a large equivalent endogenous oxygen demand even without an external carbon source or feed, in large part due to the high MLSS of the RAS stream.

In Tampa, a gate was opened to recycle nitrified effluent into the pump station for a newly created anoxic zone. Additionally, a portion of the influent was step fed around an initial nitrification zone to provide BOD for the first internal anoxic zone.

At Bay Point, the RAS air lift system was decoupled from the air header feeding the activated sludge and digester processes in order to allow for independent control as needed for effective nitrogen removal.

## 3.4 ANCILLARY BENEFITS OF ENHANCED BIOLOGICAL NUTRIENT REMOVAL

Improving nitrogen removal, particularly via biological nitrification and denitrification confers multiple additional operation benefits. For example, upgrading aeration equipment (e.g., adding VFDs) and improved aeration controls provide more efficient aeration, resulting in energy and operational cost savings. Adding denitrification also reduces the amount of air required, further reducing the energy requirement. Denitrification produces alkalinity and raises pH, recovering some of the alkalinity consumed by nitrification and resulting in a more stable process, potentially requiring less alkalinity to be added for nitrification and reducing the potential for nitrite lock or incomplete nitrification. Providing an anoxic zone in front of the aerobic zones, reduces the growth of filamentous bacteria and improves sludge settling. Since denitrification consumes BOD, it has the ancillary benefit of decreasing the amount of air required compared to a conventional nitrifying process, resulting in energy savings.

Like BNR, EBPR provides secondary operational benefits to the secondary treatment process. It is well documented that the creation of an anaerobic or anoxic selector zone in front of the aerobic zone will decrease the growth of filamentous bacteria that cause sludge bulking, improving settling and increasing biomass density. This is because the anaerobic and anoxic conditions favor floc-forming bacteria over filamentous bacteria. When used with conventional secondary clarifiers, the improved sludge settling characteristics allow the plant to be operated at a higher MLSS, increasing treatment capacity in most cases. RAS chlorination can also be used as a means to control filamentous growth. At plants where anaerobic or anoxic zones are added in front of the aerobic zone, the amount of chlorine used for filamentous control can be reduced or eliminated entirely. Therefore, some facilities include anaerobic or anoxic zones primarily for filamentous control. In the case of biological nutrient removal facilities, the improved settling characteristics provided by these zones and the reduced usage of chlorine for filamentous control are additional ancillary benefits.

If alkalinity addition is required to maintain stable nitrification, denitrification will have the ancillary benefit of reducing chemical usage and costs. Nitrification requires approximately 7.14 mg of alkalinity (as $CaCO_3$) per mg of ammonia oxidized to nitrate. Denitrification produces 3.57 mg alkalinity (as $CaCO_3$) per mg $NO_3$-N (or $NO_2$-N) reduced, recovering about half of the alkalinity used in nitrification. Therefore, nitrification generally lowers pH, while denitrification generally raises it. Denitrification helps recover alkalinity and keep the pH stable, preventing it from dropping into a range that is inhibitory to nitrification (pH values below 7.0 can cause a significant drop in ammonia oxidation rates).

# 4 Optimizing Nutrient Removal in Lagoon Systems

Lagoons have been used as low-cost wastewater treatment systems for many years, particularly in relatively small and/or rural communities where sufficient land is available to site a lagoon that generally has a larger footprint than more mechanically based treatment systems (e.g., activated sludge).

Lagoons are typically characterized by their operating redox state, with the main types being aerobic, anaerobic, and facultative lagoons.

Within the category of aerobic, lagoons are shallow “aerobic basins” (1–2 ft deep), aerated by contact with the atmosphere (aided by wind) and daytime photosynthesis of algae; and “partial mix aerobic”, which are deeper aerobic lagoons that include some type of mechanical aeration system (e.g., surface aerators, diffused air). In either case, aerobic lagoons typically have the shortest hydraulic retention time of the three major types. For this reason, they are sometimes called “high-rate” lagoons.

Anaerobic lagoons are deeper basins (typically over 15 ft deep) and are mainly used for treating high-strength wastewaters, such as those from concentrated animal feeding operations (CAFOs), food processing facilities, and other industrial process streams. Since they are of limited applicability to municipal WWTPs, they are not addressed further in this document.

Facultative lagoons are generally 5–8 ft deep and represent the most versatile and common type of lagoon used for WWTPs in the United States. As previously indicated, facultative lagoons typically feature aerobic conditions in the upper layer and anoxic or anaerobic conditions toward the bottom, with the transition depth depending on the influence of wind-driven mixing.

Lagoon systems were traditionally used to remove organics (i.e., BOD) and suspended solids, with their nutrient removal capability given little design consideration until recently. Nevertheless, lagoon systems—even without special design provisions—are often surprisingly effective in reducing total nitrogen.

As illustrated in Figure 4-1, influent TKN can be reduced via ammonia stripping to the atmosphere, assimilation into biomass, biological nitrification/denitrification, and sedimentation of insoluble organic nitrogen (USEPA 2011b). In facultative systems in particular, anoxic bottom sediments can effectively denitrify nitrates that have been produced in upper layers. The long retention time of these systems additionally favors relatively high levels of TN removal by various mechanisms. TN reduction processes in lagoon systems may be affected by temperature, DO concentration, pH, retention time, and wastewater characteristics. Alkalinity changes and potential pH fluctuations resulting from the interaction of algae and $HCO_3^-$ can be important because they affect the speciation of ammonia, which is more volatile under alkaline conditions.

Per EPA (2011b), “phosphorus removal in ponds occurs via physiochemical mechanisms such as adsorption, coagulation, and precipitation. The uptake of P by organisms in metabolic functions, as well as for storage, also contribute to its removal. Removal in wastewater ponds has been reported to range from 30–95 percent (Assenzo and Reid 1966; Pearson 2005; Crites et al. 2006)”.

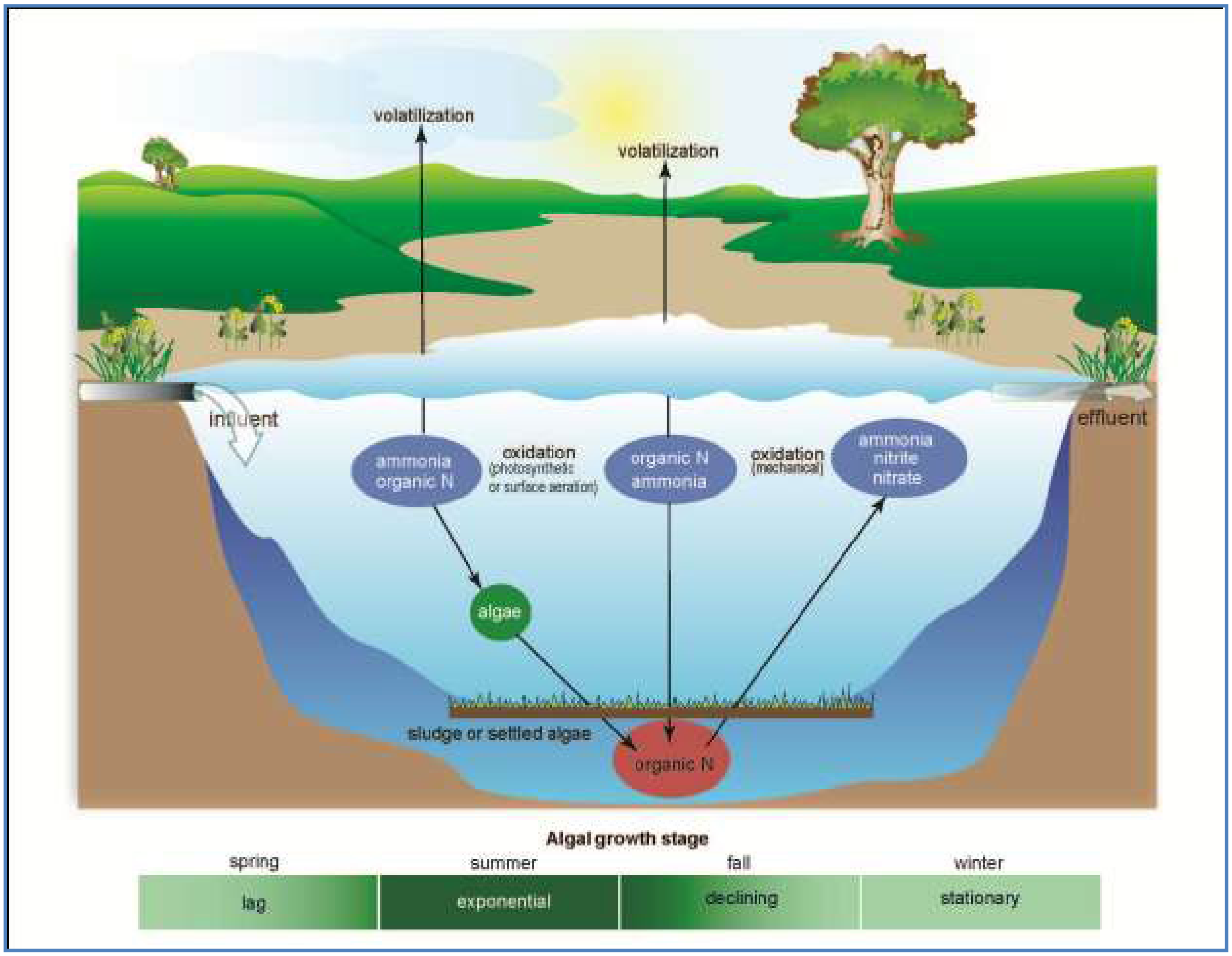
EPA undertook a number of studies of facultative wastewater pond systems in the late 1970s. The results verified the hypothesis that significant nitrogen removal occurs in pond systems. Data from the studies are summarized in Table 4-1. Facultative lagoons have been documented to achieve TN reductions ranging from 40–90 percent or greater, with higher reductions associated with warmer weather, when volatilization and algae growth are highest.

In aerated ponds, nitrogen can be removed by assimilation into biomass (algae and bacteria), biological nitrification/denitrification, and sedimentation of insoluble organic N. Volatilization can also play a role, although pH is usually less than 8.0 and may not be favorable to large removals by ammonia stripping.

**Table 4-1. Summary of main lagoon types and typical effluent concentrations.**

| | Effluent TN (mg/l) | | | Effluent TP (mg/l) | | | |
|---|---|---|---|---|---|---|---|
| **Lagoon Type** | **Low** | **High** | **Average** | **Low** | **High** | **Average** | **Mechanisms** |
| Facultative | 4 | 22 | 13 | 1 | 5 | 2.5 | Algae/wind provide DO in surface<br>Denitrification in bottom<br>Variable seasonal $NH_3$<br>Controlled discharge |
| Aerated | 6 | 29 | 17 | | | | Summer nitrification<br>Shorter detention time |

Source: Derived from data in EPA (2011b).



Source: USEPA, 2011b.

**Figure 4-1. Illustration of lagoon processes**

A more recent study of lagoon performance in Kansas from November 1997 to May 1999 concluded that a well-run lagoon could be expected to produce an effluent with a TN concentration of 5–7 mg/l and TP concentration of 1.5 mg/l (Tate et al. 2002). Time series data showed a more pronounced seasonal trend for TN than for TP.

Although no lagoon case studies were developed for this project, several were uncovered during a literature review. Important characteristics of these case studies are summarized in Table 4-2. Readers are encouraged to refer to these references for additional information, although it is noted that both examples represent fairly significant upgrades, which might not be warranted considering the frequently good overall nutrient removal performance of lagoon systems.

**Table 4-2. Lagoon case studies in literature.**

| Author | Year | System | Location | TN | TP | Improvements |
|---|---|---|---|---|---|---|
| Hodgson and Paspaliaris | 1996 | Lagoon | Melbourne, AUS | x |  | Describes operation of “new style” lagoon systems |
| Pattarkine, Chann, and Tharp | 2006 | Lagoon | Ashland, MO | x |  | Added internal separators to create zones |

Operators of facultative lagoon systems endeavoring to optimize nutrient removal should consider discharge methodologies as the primary approach. Two main options can be considered:

1. Controlling the lagoon discharge to coincide with times when effluent nutrient concentrations are lowest (as determined through spot or real-time sampling, nutrient profiling, or best judgement) and/or when receiving water impacts will be lowest.
2. Using a nondischarge options, such as land application/soil treatment system.

For both facultative and aerobic lagoons, operators can also consider adding post-lagoon treatment, which can vary from relatively passive constructed wetland systems (possibly including both aerobic and anoxic/anaerobic sections) to post-denitrification facilities such as biological filters. The latter option may be preferred where space is tight and the smaller footprint afforded by a mechanical system are desired. Aerobic lagoons, particularly those with mechanical aeration, may have available options for aeration control and development of aerobic and anoxic zones similar to those described in Section 3 for activated sludge systems. These options are discussed in more detail below, except for nondischarge (or modified discharges) and post-denitrification, which are addressed in Section 6.

## 4.1 CONTROLLED DISCHARGE

Facultative lagoons have relatively long hydraulic retention times and accumulate solids over long periods of time, both of which enhance nutrient removal. Most of the TN removal appears to be by volatilization of ammonia across the large surface area at relatively high operating pH (which is a result of algal respiration during daylight hours). The higher pH also facilitates phosphorus precipitation (USEPA 2011b). TN removal in particular can be highly seasonal, with removals up to 95 percent in the heat of summer, but down to 40 percent or less in winter (USEPA 2011b; WEF 2003). Accordingly, because of the relatively long residence time of facultative lagoons, these systems can be operated to hold water over the colder months and discharge during the summer when nutrient concentrations are expected to be lowest. This type of operation is called a “controlled discharge” lagoon.

Experience with controlled discharge lagoons is mostly from northern states that feature more pronounced seasonal and climatic influences on algal growth. Controlled discharge lagoons typically feature periodic, controlled discharge once or several times per year. A study of 49 controlled discharge ponds in Michigan indicated that discharge periods vary from less than 5 days to more than 31 days, and residence times were 120 days or greater (Pierce 1974). Ponds of this type have operated satisfactorily in the north-central United States using the following design criteria (USEPA 2011b):

- Overall organic loading: 20–25 lb $BOD_5$/ac/d
- Liquid depth: Not more than 6 ft for the first cell, not more than 8 ft for subsequent cells
- Hydraulic detention: At least 6 months of storage above the 2 ft liquid level (including precipitation), but not less than the period of ice cover
- Number of cells: At least three for reliability, with piping flexibility for parallel or series operation

Other fundamental design considerations include:

- Capacity of the lagoon to store wastewater for extended periods without infringing on required freeboard levels, affecting mechanical devices, etc.

- Ability of the lagoon effluent discharge structures to periodically discharge (i.e., gravity/demand versus pumped/controlled discharge system)
- Appropriate discharge schedule (new metering that may be required, etc.)

Winter storage typically aligns well with potential alternative end uses for effluent besides discharge, such as land application. Vegetative growth and thus water demand will, of course, be higher in the warmer months when lagoon effluent nutrient concentrations are expected to be lowest.

The decision to convert to a controlled discharge operation must also include an analysis of the impact of periodic discharge on receiving stream water quality standards. Some lagoons will operate in a mode that is the opposite of that suggested for optimizing nutrient removal (i.e., they store and/or land-apply wastewater in the summer, and discharge in the winter). This is due to higher demand for reclaimed water in the summer and low stream flows, and in turn less dilution, leading to more stringent effluent limits for surface discharge in the summer. In fact, hydrograph controlled release (HCR) systems represent a related strategy where discharges are controlled to correspond to hydrologic conditions in the receiving environment when the discharge is expected to have the least environmental impact.

Each situation is different and the specific context needs to be considered when developing a plan for discharging lagoon effluent. Selecting a discharge schedule is very important and must be determined well in advance. Conversion to controlled discharge operation will typically require discharge permit modifications.

## 4.2 AERATION MODIFICATIONS

Various operating strategies can also be employed to optimize TN reduction in aerated lagoons, particularly those with mechanical aeration, similar to those optimization strategies available for activated sludge processes. See Section 3 for additional information.

## 4.3 CONVERSION TO ADVANCED SECONDARY TREATMENT

Biological nitrogen removal (nitrification/denitrification processes) represents the state-of-the-art in terms of nitrogen reduction technologies for wastewater management. A number of different processes (some proprietary, some not) that use suspended growth, attached growth (i.e., a biological filter), or some combination thereof are available. Effluent TN concentrations of 5 mg/l are typically achievable, with some systems reducing TN to 2 mg/l or less. Although lagoons typically have a lot of space and “reactor volume” to allow for the creation of anoxic (denitrification) and aerobic (nitrification) zones, conversion may be complicated by several factors, including the need to add mechanical aeration and/or mixing equipment and recycle pumps and piping and the difficulty in doing so in a large earthen pond.

# 5 Optimizing Nutrient Removal in Trickling Filter Systems

Trickling filters are most frequently used for BOD removal and, in some cases, nitrification. The degree of treatment depends primarily on the organic loading of the system and the type of aeration used.

Natural draft aerated filters are typically low rate filters, only able to handle low organic loading rates due to the limited amount of air available. Trickling filters with forced draft aeration can be operated at higher organic loading rates. Recirculation of the trickling filter effluent allows for higher loading rates and improves performance and stability.

Nitrification can be achieved by using trickling filters with low organic loading rates. Multiple trickling filters can be staged so that the first trickling filter removes BOD and has a higher organic loading rate and a second trickling filter, loaded at a lower organic loading rate, is used for nitrification. Trickling filters are typically followed by secondary clarifiers to settle the solids resulting from the sloughing of the biofilm in the filters. Trickling filters have also been used as a tertiary process for the nitrification of secondary (i.e., activated sludge) effluent.

Under typical operating conditions, trickling filters at WWTPs can reduce influent TN loads by 10–30 percent and TP loads by 8–12 percent (Metcalf and Eddy 1991). However, it should be noted that many smaller (decentralized) attached growth systems are designed for relatively high levels of nitrogen removal, typically achieved by recirculating nitrified effluent back to an anoxic reactor (e.g., septic tank).

Although no trickling filter case studies were developed for this project, several were uncovered during a literature review. Important characteristics of these case studies are summarized in Table 5-1. Refer to these references for additional information.

**Table 5-1. Trickling filter case studies in literature.**

| Author | Year | Location | TN | TP | Improvements |
|---|---|---|---|---|---|
| Dai et al. | 2013 | Australia | 60% | | Return nitrate-rich stream from secondary clarifiers back to primaries |
| Dorias and Baumann | 1994 | Germany | 15 mg/l | | Denitrification in trickling filter plants by covering filters for anoxic operation |
| Kardohely and McClintock | 2001 | Penn State | | | Added BNR plant to blend effluent prior to disposal or land application |
| Morgan et al. | 1999 | Australia | | | Conversion to MLE-type BNR by adding secondary reactors |

As a general rule, trickling filter plant operators have limited opportunities to increase nutrient reduction short of significant and costly infrastructure modifications. Systems with excess nitrification capacity (flow and aeration) may have some opportunities to optimize aeration. Conversion to BNR or the addition of a post-denitrification system can be effective, but intensive.

## 5.1 PROCESS OPTIMIZATION

As indicated above, nutrient reduction for typical trickling filter WWTPs is generally quite modest. Likewise, nutrient reduction optimization opportunities are limited.

Some modest nitrogen reduction improvements can be achieved by optimizing the internal recycle rate for systems with recycle capabilities. Provided that significant nitrification is occurring, a higher recycle rate should result in opportunities for denitrification by 1) contacting nitrified effluent with attached microorganisms, and 2) creating more anoxic sites by increasing the hydraulic loading. However, this is a delicate balance, as operational problems (including loss of nitrification) may occur if recycle rates are too high and the hydraulic capacity of the trickling filter is exceeded and anaerobic conditions predominate.

Operators of trickling filters with forced-draft aeration can throttle aeration or use on/off aeration controls to increase denitrification. However, controlling redox conditions in trickling filters is more difficult than in activated sludge (and other suspended growth) systems, where inline monitoring can be easily installed at representative reactor locations and feedback between aeration controls and redox conditions is typically relatively consistent and easy to observe.

## 5.2 CONVERSION TO ADVANCED SECONDARY TREATMENT

Specially designed denitrification filters can be added after a nitrifying trickling filter to provide more significant TN reductions, although some supplemental carbon addition will likely be needed. Additionally, if the plant is not currently nitrifying, treatment may need to be added to ensure consistent nitrification.

Trickling filter plants can be expanded to a more traditional activated sludge-type BNR process by adding new BNR reactors after the trickling filter system. In this case, the existing trickling filters are often used as “roughing filters” to decrease the organic load on the activated sludge system and to remove toxic inhibitory compounds that decrease the performance of Ammonia-Oxidizing Bacteria (AOB) and Nitrite-Oxidizing Bacteria (NOB). Although this strategy reduces the oxygen requirements for the activated sludge system, it can have negative implications for EBPR and denitrification by consuming soluble BOD in the influent.

# 6 Other Nutrient Reduction Approaches

## 6.1 POST-DENITRIFICATION

In lieu of a complete conversion to BNR, “post denitrification” can be implemented after nitrification within a treatment system (see Section 2.1.1); however, this approach usually requires the addition of an external source of carbon such as methanol, which typically requires the installation of chemical feed equipment in addition to the carbon additive itself. Biological filters are often used for post-denitrification in WWTPs, which may have relatively low levels of operator oversight.

## 6.2 DISCHARGE MODIFICATION/LAND APPLICATION

As described in Section 2.3.4, removing a direct discharge and diverting effluent to a nutrient polishing process, such as a land application system or wetland, can be a very effective approach for reducing WWTP effluent nutrient loads. However, modifying a discharge can be a difficult and, at times, infeasible, option. Some of its potential limitations include the following:

- In general, a significant amount of land is needed for these options. Therefore, WWTPs in urban or other land-constricted areas, might find it difficult to acquire suitable land to be used for effluent dispersal.
- Construction of a modified discharge system can be more expensive than other options that may be available for reducing nutrient loads.

On the other hand, modifying the discharge has some significant potential benefits:

- Ability to phase in dispersal (nondischarge) capacity over time as land or other resources become available.
- Ability to acquire effluent dispersal land that can be used to serve multiple community purposes (e.g., recreation, food production, ecological enhancement, aquifer recharge).
- Ability to use decentralized systems to “shave” influent nutrient loads and treat/reuse nutrients locally.
- Ability to make relatively small improvements to enhance nutrient removal at an existing discharge. For example, many WWTP discharges include channels that convey effluent to the main receiving water. Simply vegetating or adding appropriate filtration media to the channel could provide significant nutrient reduction benefits without adversely affecting existing operations.

Although the project team pursued several modified discharge case studies, only two of the final case studies include this approach. For the Blue Heron Water Reclamation Facility in Titusville, Florida, discharge to a restored wetland was an original feature of the design and permit, not a retrofit or optimization effort. It has been, however, a very effective process for nutrient polishing. The case study for Victor Valley Wastewater Treatment Facility also includes a land application component, but again this was an original design component. Because many alternative discharge systems are for small facilities, it proved especially difficult to obtain project information in sufficient detail to support a full case study.

Nevertheless, the use of soil treatment systems is well-documented in the literature and understanding of the nutrient reduction attributes of various types of systems continues to improve. Cost estimates can be developed using widely accepted guidance published by EPA, the Water Environment Research Foundation (WERF), and others.

As described previously, modified discharge systems can be extremely effective in reducing nutrients. The Blue Heron case study includes pre- and post-wetland nitrogen and phosphorus performance data that shows reductions from 5.67 to 0.94 mg/l TN (83 percent TN reduction) and 0.77 to 0.04 mg/l TP (95 percent TP reduction).

The states of Florida and Louisiana provide detailed permitting and other information about wetland assimilation/discharge systems in their states.

Properly sized and sited land application systems can effectively reduce phosphorus loadings to very low levels (virtually complete removal has been documented for many systems, but cannot be reliably predicted without a site-specific analysis). Converting an existing point discharge to land application, however, requires substantial amounts of land and can be quite expensive.

Land application systems that disperse secondary effluent to carbon-rich surficial soil horizons under pressure can be an effective control strategy for nitrogen, compared with surface water discharges, although again, a site-specific analysis must be conducted first to ensure that the soil and site conditions are suitable and to determine appropriate design criteria.

## 6.3 CHEMICAL TREATMENT

Previous sections have primarily focused on BNR. Chemical addition can also be used directly for phosphorus removal (by precipitating with metal salts), to support nitrification (by adding alkalinity), or for both TN and TP removal (supplemental carbon addition).

### 6.3.1 Chemical Phosphorus Removal

Metal salts (typically alum or ferric chloride) can be added to chemically precipitate phosphorus, which is subsequently removed and wasted with the primary sludge or WAS. The addition of metal salts can also improve the settling characteristics of the primary sludge or secondary sludge. Compared to WAS from an EBPR process—which can re-release soluble phosphorus if exposed to anaerobic conditions—phosphorus that is precipitated with metal salts is less likely to be released back into solution in the solids handling and treatment process.

Chemical precipitation using alum or other metal salts can be used to precipitate phosphorus and is capable of achieving very low effluent TP levels, frequently down to 0.5 mg/l and sometimes down to 0.1 mg/l or less when paired with highly efficient solids removal processes (e.g., tertiary filtration). Process modifications for chemical precipitation are relatively simple and the approach can be implemented at most treatment facilities. Primary disadvantages are chemical costs and chemical sludge management.

Lagoons are relatively well-suited for chemical phosphorus removal in that their large volume can provide for long-term storage of chemical sludge. Both batch and continuous chemical dosing approaches can be used.

USEPA (2011b) describes a batch, in-pond chemical treatment (alum, ferric chloride, and lime) in controlled-discharge ponds that was developed in Canada to meet a P requirement of 1 mg/L for effluent discharge to the Great Lakes. Chemical additives were dosed to the pond by boat. The costs for this method were reported to be reasonable and significantly less than those for conventional phosphorus removal methods (although “conventional methods” are not defined). USEPA (1992) reports that this approach has also been applied successfully in several midwestern states.

Studies of continuous in-pond precipitation of phosphorus were also conducted in Canada, using ferric chloride and alum to successful maintain effluent TP concentrations below 1.0 mg/l, although the use of lime was not able to consistently meet the effluent limit (USEPA 2011b). Additionally, 37 pond systems in Michigan and Minnesota using chemical treatment to remove P were studied (USEPA 1992). In general, facilities in both states were (and continue to be) able to consistently meet a 1.0 mg/L effluent TP requirement with the majority using alum. Chemical treatment has been applied to facultative and aerated lagoons both continuously and just prior to the seasonal spring and fall discharges for controlled discharge systems. In Michigan, phosphorus removal has been successful as long as the chemical precipitant is added at the appropriate rate at the end of the pond system.

Chemical precipitation of soluble phosphate in a separate reactor or prior to the secondary clarifier is typically the most feasible option for significant TP removal in trickling filter systems.

### 6.3.2 Alkalinity Adjustment

Nitrification, which consumes alkalinity, is also pH-dependent and inhibited under acidic conditions. Therefore, sufficient alkalinity is required to prevent deleterious pH depression and support stable nitrification. Some influent streams do not contain enough alkalinity to support nitrification to the extent required to meet effluent limits, particularly when the influent water is soft and/or the TKN concentrations are high. In these cases, alkalinity can be added in the form of lime or a caustic solution in order to optimize nitrification and process performance. Further optimization can be achieved by upgrading a manual chemical feed system to an automated chemical feed system with a flow-paced or pH control loop.

### 6.3.3 Supplemental Carbon Addition

Carbon can be another limiting factor in both the denitrification process and EBPR, especially if both nutrients are being removed biologically in the same single-sludge system. In these cases, a supplemental carbon source can be added to improve denitrification and phosphorus removal.

Historically, a common supplemental carbon source used for denitrification has been methanol. Denitrification using methanol requires a specific microbial population, so an acclimation period is required, and methanol must be fed continuously to maintain the population. However, because methanol is highly flammable, there are safety concerns associated with its storage and use. Consequently, other carbon sources such as sodium acetate, sugar water, glycerol, molasses, and proprietary products manufactured for use as supplemental carbon sources have also been used for both denitrification and EBPR. These alternative carbon sources can be used by common denitrifying heterotrophic bacteria and, therefore, do not need to be fed continuously—another operational benefit compared to the use of methanol. Carbon feed systems can be automated and controlled by flow-pacing, proportional to nitrate loading, and anoxic effluent nitrate/nitrite feedback loops. Automated control methods reduce wasted chemicals, which saves money and minimizes the amount of additional biomass that will be generated from the additional carbon added to the system. This can also help prevent overdosing of the carbon feed, which can lead to bleed-through of BOD into the effluent.

Operators at the WWTP in Crewe, Virginia, started adding lime for alkalinity control and molasses as a supplemental carbon source. The plant later switched to a proprietary carbon source called EnhanceBio$^{P+N}$, a molasses product with added nutrients and minerals to improve biological phosphorus removal. The plant saw increased biological removal of phosphorus, while maintaining their level of nitrogen removal, which in turn reduced the amount of alum that was needed to remove the remaining phosphorus. Using chemical addition along with modified aerator controls, operators were able to significantly reduce the effluent TN concentrations from a pre-optimization concentration of 7.85 mg/l to 3.63 mg/l, while maintaining excellent phosphorus removal (an average of 0.06 mg/l effluent TP).

## 6.4 EMERGING NUTRIENT REMOVAL APPROACHES AND TECHNOLOGIES

Although beyond the technical scope of this report, various innovative approaches are available to reduce nutrient loading of receiving waters associated with WWTP effluent discharges, and deserve mention.

### 6.4.1 Discharge Reduction through Water/Nutrient Reuse

Similar to the land application alternatives previously described, removing the discharge or reducing the volume of a discharge, particularly if the nutrients will be recycled, can be a very effective approach for reducing nutrient loading to surface waters.

Water reuse, particularly where the reclaimed water will be used for irrigation (and thus additional soil treatment and/or vegetative uptake of nutrients), can be an effective nutrient removal approach. Unfortunately, many state standards for reclaimed water quality include strict limits on nutrient concentrations, mostly in an attempt to limit biological growth/regrowth in reclaimed water distribution piping networks and water use fixtures. This limitation can be overcome, however, by limiting the extent of reclaimed water piping networks, siting reclamation facilities closer to reuse areas using satellite and other decentralized reuse system approaches, and by limiting such reclaimed water uses to irrigation as opposed to indoor water uses.

Employing a “fit-for-use” type of treatment approach, where nutrients are left in reclaimed water so they can be recycled for irrigating vegetation, has multiple secondary benefits that are consistent with EPA’s mission:

- Offsets the use of inorganic fertilizers that contribute to nonpoint source loading and require significant amounts of energy (and associated greenhouse gas emissions) to produce.
- Reduces energy use for treatment of reclaimed water.
- Enhances landscapes that sequester carbon, produce food, reduce heat island effect, improve physical and psychological health, and have other cascading benefits.

### 6.4.2 Nutrient Product Recovery and Reuse

Section 3.4.1 described an approach for reducing nutrient loading of surface waters by leveraging reclaimed water systems in a way that recycles nutrients for purposes that result in multiple benefits. Another approach to precluding the loading of WWTP-associated nutrients to surface waters is to recover them during treatment and use the resulting product to offset the use of other nutrient/fertilizer sources.

The advantage to the aforementioned fit-for-purpose treatment is that the energy and effort to remove and concentrate nutrients into a product never have to be expended. Instead, treatment is limited (which *saves* energy) and nutrients are provided in solution with reclaimed water.

Nutrient recovery during treatment is viable and gaining in popularity, particularly where existing centralized infrastructure does not allow for widespread water and nutrient reuse. For example, the Ostara’s Pearl® process for the controlled production of struvite (which, uncontrolled, presents a significant operational problem in WWTPs) produces a slow-release fertilizer containing nitrogen, phosphorus, and other essential plant growth nutrients.

### 6.4.3 Source Control/Separation

When considering how to control nutrient loading associated with wastewater treatment, it is important to consider the source of nutrients in wastewater. In domestic (noncommercial, nonindustrial) wastewaters, human urine contributes the majority of nitrogen and phosphorus. Volumetrically, however, urine is a small fraction of the total wastewater flow (the vast majority of the wastewater volume is water used for flushing, washing, etc.). As indicated in Section 2, urine contains about 90 percent of the nitrogen excreted by humans, and unlike feces which are high in biodegradable organic compounds and pathogens, urine is relatively low in pathogenic organisms. Urine is self-disinfecting when held under natural alkaline conditions for a sufficient period of time (Fewless, et al., 2011). Treated urine makes an excellent liquid fertilizer that is typically diluted by a factor of 10 to 20 before application.

Urine diversion is indeed simple and practical and is being used as a nutrient control and recovery technique in the United States (at a demonstration scale) and abroad. The main challenges associated with urine diversion include:

- Difficulty procuring separating toilets (most of which are made and sold in Europe).
- Difficulty in providing dual plumbing systems (one for urine, one for blackwater) in existing buildings.
- Current lack of capacity to manage treated urine (market for end product, institutional arrangements for collecting and distributing product, etc.).

Related to source control, pretreatment at large dischargers, industrial facilities, or even within the piping network, could also be considered to reduce the influent nutrient loading to the WWTP.

# 7 Conclusions and Recommendations

This technical report was prepared to help fill gaps in published information about improving nutrient reduction performance at existing, non-advanced WWTPs using relatively low-cost techniques. Although many published reports and papers address the nutrient removal performance of WWTPs, this report represents one of the first documented efforts to present empirical data via a compendium of case studies of non-advanced WWTPs that have been optimized to improve nutrient reduction without requiring costly infrastructure upgrades.

The results of this project illustrate the following.

Optimization is often feasible and cost-effective

No- or low-cost activities can be implemented at existing WWTPs to significantly reduce effluent nutrient discharges with minimal negative impacts on operations. In fact, in most cases, the secondary impacts are overwhelmingly positive and include energy efficiency, lower operational costs, and improved process stability.

Although most of the case studies did not specify the capital costs savings associated with their optimization approach over alternative approaches, several did. Crewe's effort had a capital cost of $6,000, compared with an estimated upgrade cost of $800,000. Victor Valley spent $1.1M instead of $80M for a new treatment train. Two other case study contacts indicated that optimization saved significant money versus more capital intensive alternatives.

Some excess treatment capacity is ideal

Low-cost nutrient reduction improvements are most feasible for activated sludge plants, where excess capacity (volumetric and/or aeration) can typically be leveraged to facilitate nitrification and denitrification without requiring physical infrastructure modifications.

Aeration modifications (typically some kind of control of redox conditions or lowering of average dissolved oxygen concentrations) represent the most common optimization approach. However, these modifications are often supplemented with process modifications (e.g., control of internal recycle rates, installation of inline monitoring equipment), configuration modifications (e.g., adding internal recycle lines, step-feed provisions, dedicated anoxic or anaerobic zonation), and chemical modifications (chemical phosphorus precipitation, alkalinity addition, carbon supplementation).

Utilizing excess capacity may limit the ability of a WWTP to increase its flow rate in the future without an expansion. For the case studies featured in this project, only one contact indicated that their plant (Victor Valley, CA) needed to be rerated as a result of their optimization efforts. It should be noted, however, that EPA did not specifically ask WWTP contacts about impacts on design capacity.

Phosphorus removal is often complimentary to nitrogen removal

Modestly improved phosphorus reduction often co-occurs as a result of improvements in biological nitrogen removal. To achieve more significant phosphorus reductions, most WWTPs opt for chemical precipitation, which is a well-established technology widely adapted to different plant types and configurations. Enhanced biological phosphorus removal (EBPR) generally requires significant physical infrastructure modifications at existing plants (e.g., creation of anaerobic selector zones).

Other opportunities for reducing phosphorus discharges include control or side-stream treatment of return flows and enhancing volatile acid production for driving EBPR in existing anaerobic selectors (only applicable for an existing advanced treatment system). Soil- and plant-based treatment systems are also particularly effective for reducing phosphorus, which is removed from wastewaters by solid-phase sequestration.

### Low-cost nutrient optimization is currently underreported

Low-cost nutrient reduction improvements, particularly for relatively basic treatment systems, are underreported in the literature. In spite of extensive efforts at identifying and developing relevant case studies, relatively few met the qualification criteria established by EPA, typically due to insufficient monitoring or cost data, difficulty identifying prospective case study plants (because of underreporting in the white and grey literature), and limited responses from plant contacts during the time available for data collection for this study. EPA concluded that the primary limitation in prospective case studies was that most efforts at improving small or non-advanced plants are unpublished or otherwise under documented. Most published literature focuses on optimizing existing biological nutrient removal systems.

EPA intends to identify additional case studies and update this document. EPA will also consider additional capacity development activities.

### Lagoon systems appear to have optimization opportunities

Although none of the case studies were for lagoon systems, it appears that low-cost reduction of nutrient discharges associated with facultative lagoon systems should focus on strategically timing discharges to coincide with times of low effluent nitrogen and phosphorus concentrations. Nitrogen and phosphorus levels are typically lowest in the summer due to algal nutrient assimilation and sequestration in sediments, and enhanced volatilization of ammonia under conditions of elevated pH and temperature. Discharges can also be timed, so nutrient discharges coincide with natural hydrologic conditions that facilitate nutrient assimilation within the receiving environment.

Facultative lagoons unable to store water and control their discharge, as well as trickling filters, are usually limited in their ability to reduce nutrients beyond baseline performance without significant infrastructure modifications, which may include the addition of pretreatment facilities to ensure effective nitrification or post-treatment denitrification processes.

### Other approaches can also be considered on a case-by-case basis

Other nutrient load reduction opportunities (which in many cases would be too intensive to be considered “optimization”) include removal or modifications to discharges (e.g., using land application/soil-based treatment or constructed wetlands discharges), post-denitrification, and nutrient reuse (water reuse for irrigation, nutrient product recovery, and urine diversion).

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# Appendix A

# List of Nutrient Reduction Resources

## U.S. Environmental Protection Agency (EPA)

- EPA Office of Wastewater Management, Municipal Technologies website: http://water.epa.gov/scitech/wastetech/mtb_index.cfm.

## Water Environment Research Foundation (WERF)

- WERF main website: http://www.werf.org.
- Nutrient Research at a Glance: http://www.werf.org/c/KnowledgeAreas/NutrientRemoval/Nutrients_Research_at_a_Glance.aspx.
- Nutrient Management Compendium Documents: http://www.werf.org/c/KnowledgeAreas/NutrientRemoval/Nutrients_Compendium.aspx.

## Other Resources

- Water Environment Federation (WEF) Nutrient Knowledge Center: http://www.wef.org/AWK/pages_cs.aspx?id=1067.

# Appendix B

# Case Study Summary Documents

# BAY POINT, FLORIDA

# USBF ACTIVATED SLUDGE—PROCESS CONTROL AND MECHANICAL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** Bay Point Wastewater Treatment Plant (WWTP)

**Location:** 3116 Overseas Highway, MM15, Key West (Bay Point), FL 33040. Monroe County. Florida Keys (latitude: 24° 37′ 39″ N; longitude: 81° 35′ 40″ W)

**Permitted design flow:** 0.054 MGD

**Service area:** The Bay Point system serves approximately 429 EDUs[1] within the service area, which includes the Bay Point subdivision and Blue Water RV park in the Saddlebunch Keys

**System type:** Activated sludge/Modified Ludzack-Ettinger (MLE) and upflow sludge blanket filtration (USBF) to Class V injection wells

**Initial year of operation:** 2005

**Upgrade type:** Improved process controls and minor mechanical modifications

**Upgrade year of operation:** 2008

**Permitted effluent nitrogen limit:** 12.5 mg/l, monthly average TN; 10 mg/l, annual average TN

**Pre- and post-upgrade effluent nitrogen performance:** 6.63 mg/l average, pre-upgrade; 3.99 mg/l average, post-upgrade

**Permitted effluent phosphorus limit:** 1.25 mg/l, monthly average TP; 1.0 mg/l, annual average TP

**Pre- and post-upgrade phosphorus performance:** 0.47 mg/l average, pre-upgrade; 0.42 mg/l average, post-upgrade

---

[1] EDU = equivalent dwelling unit, which is the approximate number of residences served by the facility.

| | Effluent Total Nitrogen | | Effluent Total Phosphorus | | |
|---|---|---|---|---|---|
| | **Average Concentration** | **Standard Deviation** | **Average Concentration** | **Standard Deviation** | **Units** |
| **Pre-upgrade** | 6.63 | 4.98 | 0.47 | 4.96 | mg/l |
| **Post-upgrade** | 3.99 | 2.50 | 0.42 | 0.49 | mg/l |

## DECISION PROCESS

The Florida Keys Aqueduct Authority (FKAA) chose this approach as it appeared to be the most economical way to consistently meet permitted nutrient requirements mandated by Section 6 of Chapter 99-395 of the Laws of Florida, which defines best available technology (BAT) performance standards for wastewater treatment systems in the Florida Keys.

## SYSTEM OPTIMIZATION DESCRIPTION

The upgrades to Bay Point's WWTP consisted of minor modifications and improvements to multiple system components including:

- Headworks
- Flow splitter box
- Air delivery system
- Alkalinity feed system
- Return activated sludge and digester

### Headworks

The original headworks used a manually cleaned, static bar screen with very large openings and an excessive approach velocity, which allowed most gross solids to pass. That system was replaced with a tighter bar screen with an approach channel, and a drying rack. These improvements prevented previously observed clogging of the flow equalization pumps and buildup of debris on mixers and diffusers, improving overall system operation and process performance.

### Flow Splitter Box

A flow splitter box was installed to improve operational control of the flow splitting and dosing of raw wastewater (originally, equalization pumps needed to be throttled, which could exacerbate clogging). The new splitter box allows for continuous operation of the equalization pumps, dosing a small amount of raw wastewater to the anoxic tank and returning some flow back to the equalization tank, the ratio of which is controlled via adjustable gates.

### Air Delivery System

The original system included two 10-HP positive displacement (PD) blowers controlled via six adjustable timers, which was not adaptable to the changing loading and flow conditions routinely experienced at the size and type of this facility. Additionally, power consumption was high and biological treatment could be improved with a more responsive air delivery control system. The new air delivery system included the installation of variable frequency drives (VFDs) for the blower motors, a programmable logic controller (PLC), a dissolved oxygen (DO) analyzer, and a control panel.

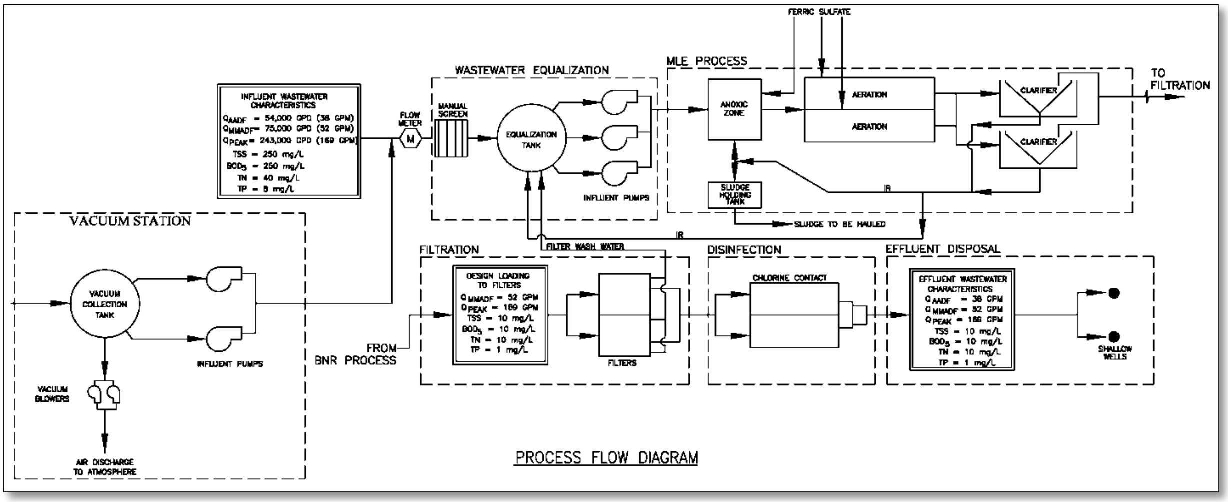
The PLC-based system allows the operator to set the desired DO concentration while the VFDs adjust blower output accordingly. The system also allows for timed operation of the blowers to ensure complete operational control under any circumstances.

### Alkalinity Feed System

Insufficient alkalinity in the influent wastewater required manual batch dosing of sodium bicarbonate or hydrated lime to the flow equalization basin to ensure reliable nitrification. Although that method worked in maintaining sufficient alkalinity, periodic problems with overfeeding and underfeeding of chemicals caused other treatment issues. Accordingly, a simple, permanent, duplex chemical feed system interlocked with the flow equalization pumps was installed to provide reliable and flow-proportionate delivery of alkalinity. Installation included two chemical feed pumps, poly tank with electric mixer, water supply, control panel, wiring, and ancillary components.

### Return Activated Sludge and Digester

The original piping configuration included interconnection between the main air header, digester, and return activated sludge (RAS) piping. Therefore, adjustments made to process air rates or digester levels caused fluctuations in the RAS and recycle rates, making control of the biological nutrient removal process difficult. Accordingly, the RAS and digester functions were isolated from the process blower header by installing two independent blowers—one for the digester aeration and the second to supply air for returning RAS. One spare blower was installed to be used as a backup for either system.



## COSTS AND OTHER IMPACTS

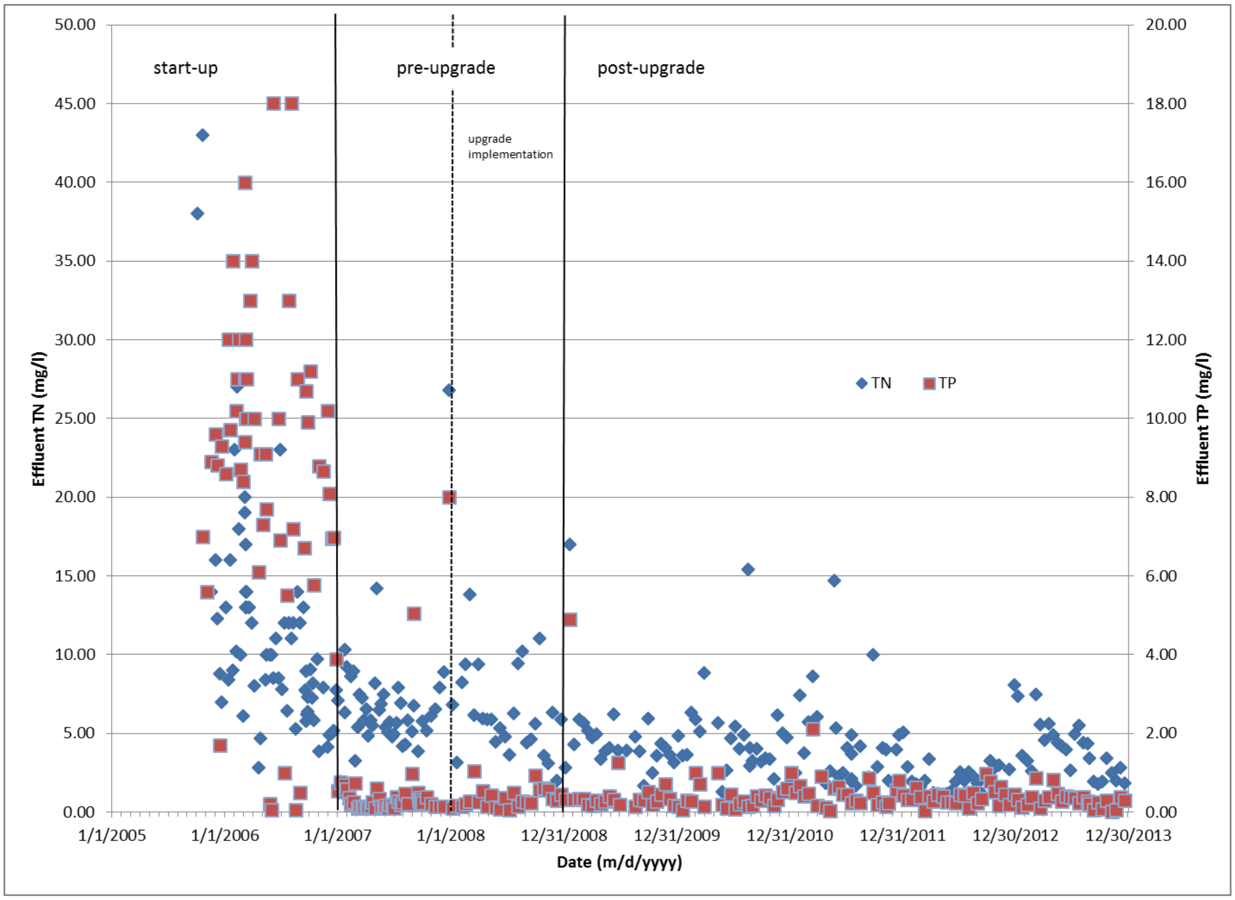
**Capital costs:** Approximately $170,365.

**Operational costs:** Not quantified, but significant labor cost savings were realized. Additionally, operational costs for energy and chemicals have been reduced.

**Technical assistance received or needed:** Significant training was needed. From a regulatory standpoint, operators at the Bay Point WWTP are required to have only a Florida Class C WWTP operator's license (a Class C-licensed operator is required to know only basic wastewater treatment techniques; nutrient removal is not introduced until Class B licensing). The FKAA recognized early that it would be necessary to train operators to meet the treatment standards required by their permits. FKAA currently has all in-house trained operators except one who was trained outside FKAA.

## PERFORMANCE

Pre- and post-upgrade TN and TP statistics are summarized below.



## FUTURE IMPROVEMENTS

If cost were not an issue, adding automatic throttling valves to each side of the common aeration header would help control aeration even more. Alternatively, installing a third blower and replacing the common air header with two single headers, one for each treatment train, would also allow independent control of aeration for each train. However, effluent quality is currently excellent and the costs associated with further improvements are not justified at this time.

## CONTACT INFORMATION

Tom Pfiester. Florida Keys Aqueduct Authority, 3375 Overseas Highway, Marathon, FL 33050. Phone: (305) 481-2015. Email: tpfiester@fkaa.com.

## OTHER RESOURCES

Keys Wastewater Plan: http://www.monroecounty-fl.gov/DocumentCenter/Home/View/478

Florida Keys Aqueduct Authority: http://www.fkaa.com/

# BOZEMAN, MONTANA

# ACTIVATED SLUDGE—PROCESS CONTROL MODIFICATIONS AND STEP FEED

## SYSTEM SUMMARY

**Official Name:** Bozeman Water Reclamation Facility (WRF)

**Location:** 2245 Springhill Road, Bozeman, Montana 59771 (latitude: 45° 43' 25" N; longitude: 111° 04' 08" W)

**Permitted design flow:** 5.2 MGD, annual average; 6.5 MGD, peak month

**Service area:** City of Bozeman (population of approximately 36,000)

**System type:** Complete-mix conventional activated sludge

**Initial year of operation:** 1985

**Upgrade type:** Conversion of complete mix to plug-flow/step-feed cyclic aeration

**Upgrade year of operation:** 2008

**Permitted effluent nitrogen limit:** 782 lb/d TN (16.2 mg/l at annual average, 12.8 at peak month flows) from June 1 to September 30 (daily maximum of 971 lb/d); 864 lb/d TN from October 1 to May 31 (daily maximum of 1,072 lb/d)

**Pre- and post-upgrade effluent nitrogen performance:** 2007 annual average of 17.8 mg/L TN pre-upgrade; 2008 annual average of 10.5 mg/L TN post-upgrade

**Permitted effluent phosphorus limit:** 160 lb/d TP (5.2 mg/l at annual average, 4.1 at peak month flow) from June 1 to September 30 (daily maximum of 199 lb/d); 170 lb/d TP from October 1 to May 31 (daily maximum of 211 lb/d)

**Pre- and post-upgrade phosphorus performance:** 2007 annual average of 3.7 mg/l pre-upgrade; 2008 annual average of 3.0 mg/L post-upgrade; 2009–2010 annual average of 2.5 mg/L

## RATIONALE AND DECISION PROCESS

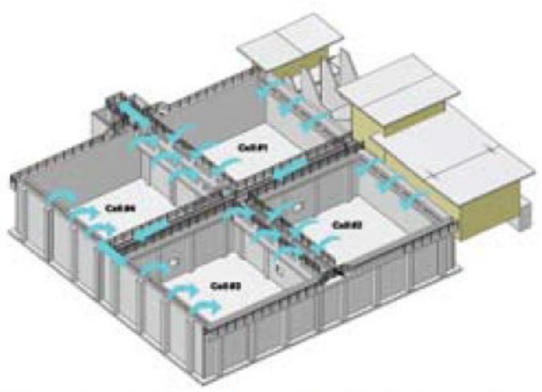
The Bozeman WRF used a complete-mix, conventional activated sludge process designed to handle an annual average flow of 5.8 MGD and a maximum monthly flow of 7.3 MGD. In 2007, when the upgrades were made, its average monthly flows were as high as 7.7 MGD and influent biochemical oxygen demand (BOD) and total suspended solids (TSS) concentrations were higher than was typical, because Bozeman had been tightening its collection system to eliminate infiltration and inflow.

The project team's goal was to achieve interim compliance with new nutrient limits imposed by the Montana Department of Environmental Quality. To do this, the team decided to modify the existing activated sludge system so it would operate as a plug-flow process with phased nitrification and denitrification.

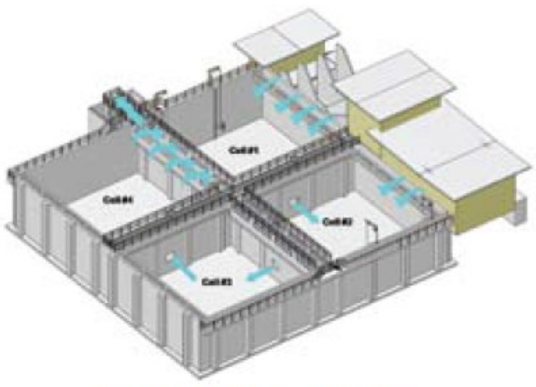
## SYSTEM OPTIMIZATION DESCRIPTION

Phased nitrification and denitrification is an operating strategy in which one basin provides both nitrification and denitrification sequentially by cycling the aeration system on and off. When the aeration is on, the basin nitrifies the wastewater; when it is off, the basin denitrifies it. Operators control the aerobic and anoxic times via a supervisory control and data acquisition (SCADA) timer and an online oxidation-reduction potential (ORP) sensor.

The project team also split primary effluent between the first two cells of the aeration basin. Operators use existing control gates to send 60 percent of primary effluent to Cell 1 and 40 percent to Cell 2. Only Cell 1 and Cell 2 shift between aerobic and anoxic conditions; Cell 3 and Cell 4 are aerated continuously to ensure that all remaining ammonia is completely removed.



**Original Configuration Complete Mix Process Flow**



**Modified Plugflow PNDN Flow**

**PNDN = phased nitrification and denitrification.**

For this process change to succeed, the project team had to make some minor retrofits. For example, the team added four submersible mixers in Cell 1 and Cell 2 to provide mixing during anoxic periods (when the blowers are off). Those mixers had to be at least 4 feet above the existing membrane diffusers. The team also upgraded some diffuser mounting brackets on the basin floor. The new ones can withstand higher mixing velocities. In addition, the project team fabricated new basin weir plates to facilitate the conversion to plug flow. Team members also made fairly extensive changes to the existing SCADA blower controls to enable on/off operations and implement ORP setpoint control.

The operators typically adjust the ORP setpoint so that a new aerobic cycle will begin after a pH plateau has been maintained for about 10–15 minutes. They review the process weekly and adjust the setpoint as needed. The ORP results showed a definite “nitrate knee” and were used to control the anoxic cycle in the last 2 years of PNDN operation.

## COSTS AND OTHER IMPACTS

**Capital costs:** Less than $180,000.

**Operational costs:** No increase or decrease in operating costs were noted.

**Technical assistance received or needed:** A consulting firm designed the upgrade and modifications to the SCADA controls. They also provided construction oversight.

## PERFORMANCE

Process modifications have worked well under various flow and loading conditions. Effluent ammonia levels remained steady, total effluent nitrogen dropped 40 percent, bulking improved, and the solids volume index dipped slightly.

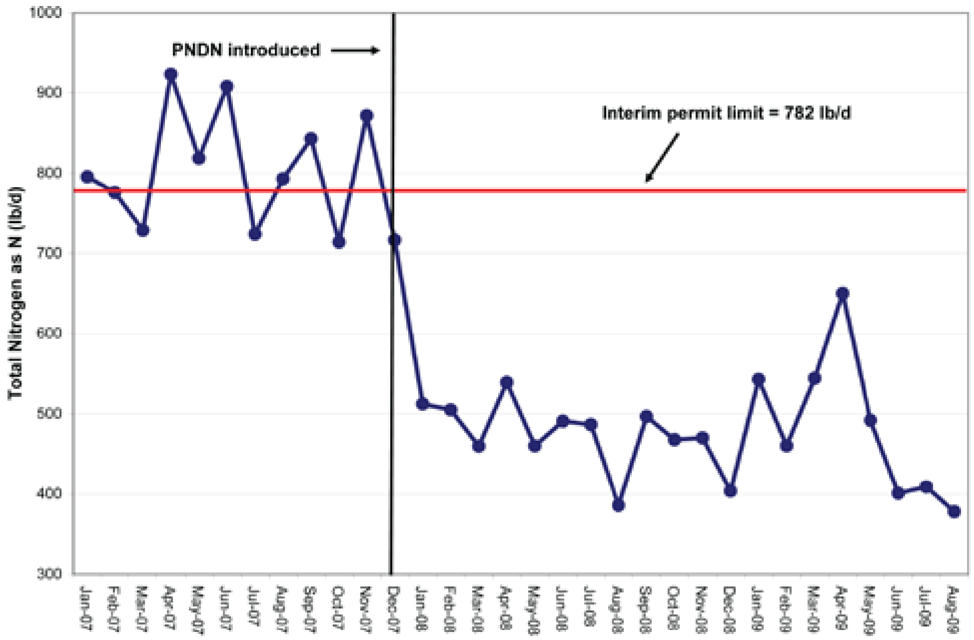
Ammonia. The process change did not compromise ammonia removal. Both before and after, effluent ammonia levels averaged 0.22 mg/L—well below the plant's effluent ammonia limit of 1.52 mg/L (30-day average).

TN. Despite water temperatures of about 52°F (11°C), the effluent TN concentration dropped in less than a week—from 18.4 mg/L in December 2007 to 13.3 mg/L in January 2008. Likewise, the aeration basins' pH rose almost immediately, enabling operators to quickly establish the aeration cycles.

Effluent TN concentration continued to improve as water temperature warmed, even though flows increased. By summer 2008, the treatment plant was producing a final effluent that contained 40 percent less TN than it had before the change.

TP. While influent phosphorus concentrations remained largely steady, effluent phosphorus levels dipped from 3.7 to 2.5 mg/L.

Bulking. Average annual chlorine use dropped from 52 to 32 ton/yr (47 to 29 Mg/yr) because operators did not have to chlorinate return activated sludge as often as before. Air cycling reduced and limited the growth of filamentous organisms in the basins, reducing the need for chemical treatment.



PNDN = phased nitrification and denitrification.

## CHALLENGES

Operating at a low enough solids retention time to prevent 021N filamentous bacteria blooms.

To cut costs, only an online pH probe (instead of both ORP and pH probes) could be used to control the anoxic cycle.

## FUTURE IMPROVEMENTS

Upgrading the plant to remove nitrogen and phosphorus with a 5-Stage Bardenpho process.

## CONTACT INFORMATION

Herb Bartle, Superintendent, Bozeman Water Reclamation Facility, 2245 Springhill Road, Bozeman, Montana 59771. Phone: (406) 582-2928. Email: hbartle@bozeman.net.

## OTHER RESOURCES

City of Bozeman WRF:
http://www.bozeman.net/Departments-(1)/Public-Works/Water-Reclamation/Home

Montana PDES Permit: http://deq.mt.gov/wqinfo/mpdes/majorpermits.mcpx

McInnis, A., H. Bartle, T. Adams, and C. Revis. 2010. Minor changes, major improvements. *Water Environment and Technolog*y 22(7). http://www.wef.org/publications/page_wet.aspx.

# CHINOOK, MONTANA

# OXIDATION DITCH/ACTIVATED SLUDGE—PROCESS CONTROL AND MECHANICAL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** Chinook Wastewater Treatment Plant (WWTP)

**Location:** 300 Daffy Hills Lane, Chinook, MT 59523 (latitude: 48° 34′ 46″N; longitude: 109° 12′ 52″ W)

**Permitted design flow:** 0.500 MGD

**Service area:** City of Chinook (2010 population of 1,203)

**System type:** Activated sludge/oxidation ditch

**Initial year of operation:** 1984

**Upgrade type:** Improved process controls and made mechanical modifications

**Upgrade year of operation:** Mixers added in 2004; oxidation-reduction potential (ORP)/supervisory control and data acquisition (SCADA) added in 2013

**Permitted effluent nitrogen limit:** 31.1 lb/d annual average TN (7.46 mg/l at 0.5 MGD)

**Pre- and post-upgrade effluent nitrogen performance:** 20.3 mg/l pre-mixer upgrade; 17.3 mg/l pre-luminescent dissolved oxygen (LDO)/ORP upgrade; 5.44 mg/l post-upgrades

**Permitted effluent phosphorus limit:** 5.7 lb/d annual average TP (1.37 mg/l at 0.5 MGD)

**Pre- and post-upgrade phosphorus performance:** 4.13 mg/l pre-mixer upgrade; 2.48 mg/l before pre-LDO/ORP upgrade; 1.72 mg/l post-upgrades

| Average Monthly Concentration | Pre-Mixer Upgrade | Post-Mixer Upgrade | Post-ORP/LDO Control Upgrade | Units |
|---|---|---|---|---|
| **Effluent Total Nitrogen** | 20.3 | 17.3 | 5.44 | mg/l |
| **Effluent Total Phosphorus** | 4.13 | 2.48 | 1.72 | mg/l |

## DECISION PROCESS

In 2004, mixers were added in the oxidation ditch to save on energy costs. In 2012, nitrogen removal was required for permit reissuance. Shortly thereafter, staff received nutrient removal training and applied their newfound knowledge to demonstrating how process changes can significantly reduce nitrogen. The upgrades described were the most economical way to consistently meet new permit requirements. A motivated, educated, empowered staff—using upgraded monitoring equipment—achieved effective, consistent nitrogen removal in a 1984-vintage oxidation ditch treatment plant that was modified in 2004 for energy efficiency, but never designed for nutrient removal.

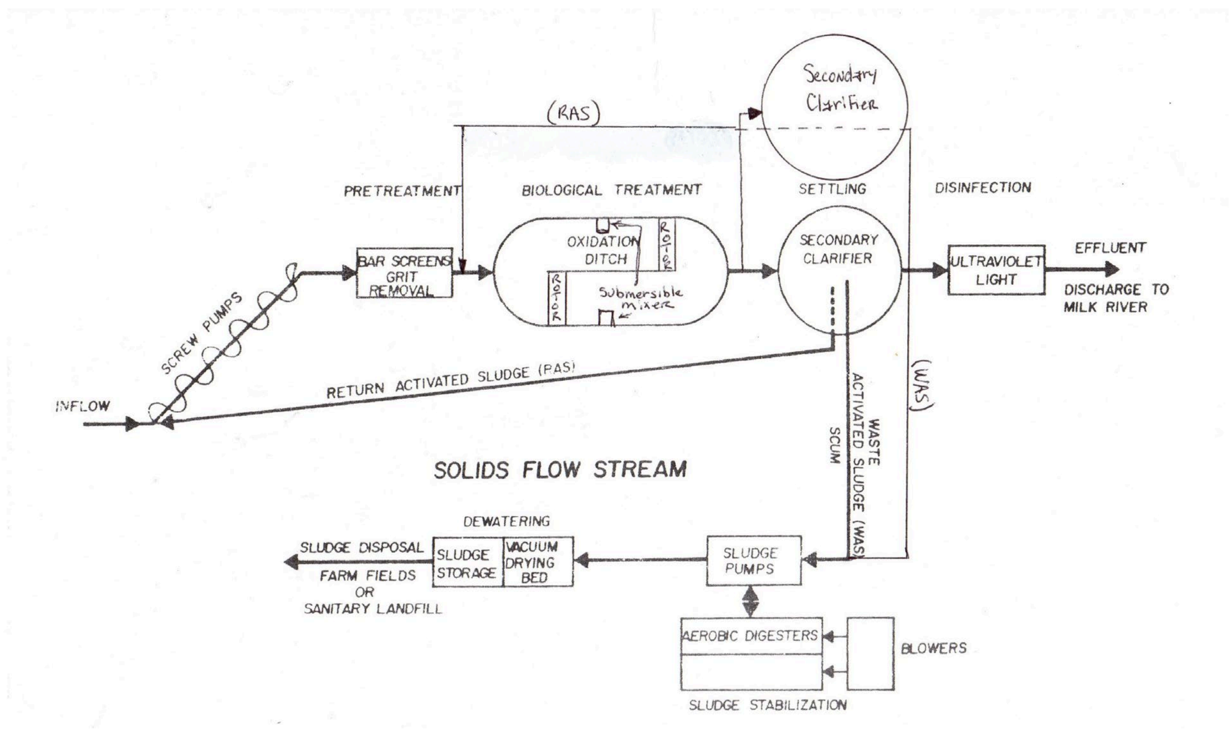
## SYSTEM OPTIMIZATION DESCRIPTION

Improvements came about as a result of process changes. A series of minor physical upgrades provided tools that were used to support the process changes, but were not the cause of the improvements. The biggest capital expense was for energy savings equipment that later proved to provide a dual benefit: nutrient removal and energy savings. Process optimization proceeded in four steps.

1. In 1984, a single oxidation ditch equipped with dual aeration rotors was constructed to provide TSS and BOD removal. The original installation was designed for ammonia removal, not for TN or TP removal.
2. In 2004, minor changes were made to improve energy efficiency. As originally constructed, both of the oxidation ditch rotors ran continuously. As a result, the original equipment provided a surplus of dissolved oxygen (DO). To allow for the cycling of the fixed-speed aeration equipment, rail-mounted mixers were installed so the flow would continue to stay suspended and circle the oxidation ditch with the rotors turned off. A DO probe was installed and integrated with the SCADA system to maintain a DO setpoint of 4–5 mg/L by cycling the rotors on and off. At the lower DO concentration resulting from the energy savings changes, incidental improvements in nitrogen and phosphorus removal occurred.

3. In 2012, Chinook staff attended a 2-day training class sponsored by the Montana Department of Environmental Quality (DEQ). Using the knowledge they gained, staff experimented with extended air-off cycle times. By allowing the DO in the ditch to cycle between anoxic and oxic conditions, an immediate 50 percent improvement was observed in nitrogen removal. No equipment was purchased; no funds were expended. In fact, because of reduced rotor operating time, electrical costs were reduced. For zero capital investment and at reduced operating expense, Chinook staff reduced TN by 50 percent. And, as a result of the lower tank DO concentrations, some incidental improvements in TP removal also occurred.

4. In 2013, an ORP probe was installed to provide improved process control. At the same time, the old DO probe (2004 vintage) was replaced with a new LDO probe. Both probes were integrated with the plant's SCADA system. Using the new instrumentation, plant staff have been able to maintain optimal conditions for biological nitrogen removal and incidentally provide some level of enhanced biological phosphorus removal, while enjoying additional energy savings.



## COSTS AND OTHER IMPACTS

**Capital costs:** Approximately $5,000 for ORP probe and integration with SCADA.

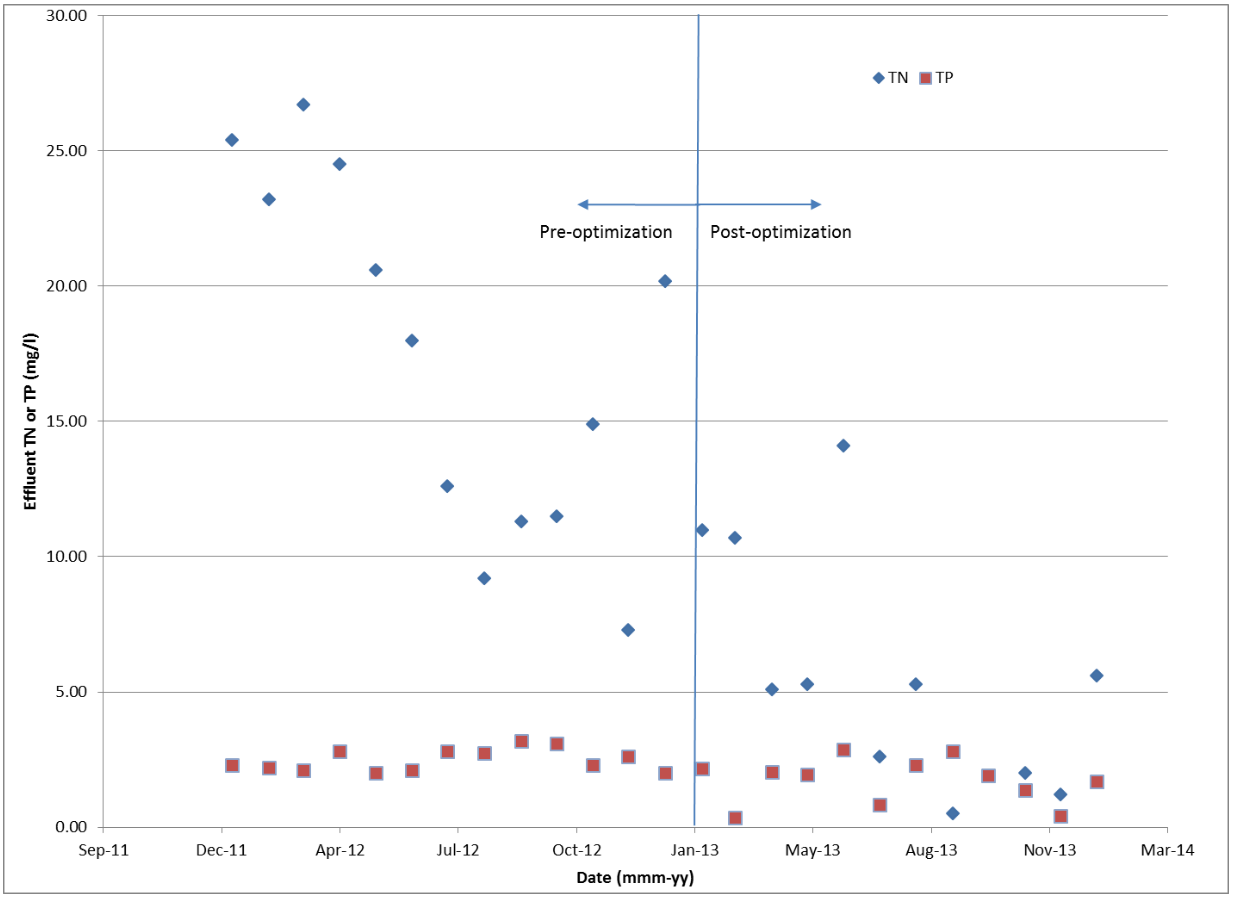
The energy savings improvements implemented in 2004 (i.e., mixers, DO probe, SCADA) cost $68,200. In 2013, the DO probe was replaced with LDO equipment for $8,000.

**Operational costs:** Less than $1,000/year (oil and grease for mixers and 1–2 hours/year to change the oil). Cost savings have been realized. The reduced electrical consumption more than offsets the expense of cleaning, calibrating, and maintaining the ORP probe.

**Technical assistance received or needed:** In 2012, Chinook staff attended a 2-day training class sponsored by the Montana DEQ. Using the knowledge they gained, staff felt empowered to experiment with extended air-off cycle times and other process modifications.

## PERFORMANCE

Pre- and post-upgrade TN and TP statistics are summarized in the chart below.



## FUTURE IMPROVEMENTS

No improvements are planned at this time. Nitrogen removal is still a relatively new requirement, so the plant is currently working on refining the process.

## CONTACT INFORMATION

Eric Miller, P.O. Box 1177, Chinook, MT 59523.
Phone: (406) 357-2188. Email: chinookwwtp@gmail.com

## OTHER RESOURCES

City of Chinook: http://www.cityofchinook.com/index.html

State of Montana MPDES Permits: http://deq.mt.gov/wqinfo/mpdes/majorpermits.mcpx

# CREWE, VIRGINIA

# OXIDATION DITCH ACTIVATED SLUDGE—PROCESS CONTROL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** Town of Crewe Wastewater Treatment Plant (WWTP)

**Location:** 370 Tyler Lane Court, Crewe, VA 23930 (latitude: 37° 11' 14" N; longitude: 78° 07' 23" W)

**Permitted design flow:** 0.5 MGD

**Service area:** Population of 2,386 over 2.0 square miles; 8 Wastewater Pump Stations; 11 miles of underground piping

**System type:** 3-channel Orbal oxidation ditch activated sludge; phosphorus precipitation using alum

**Initial year of operation:** 1956 (trickling filter plant); 1997 (oxidation ditch upgrade)

**Upgrade type:** Process control modifications

**Upgrade year of operation:** 2007

**Permitted effluent nitrogen limit:** 9,137 lb/yr TN, equivalent to a TN concentration of 6.0 mg/L at design flow of 0.5 MGD

**Pre- and post-upgrade effluent nitrogen performance:** Pre- and post-upgrade TN statistics are summarized below.

| | Effluent Total Nitrogen | | Flow | |
|---|---|---|---|---|
| | Average Concentration | Units | Average | Units |
| **Pre-upgrade (2005–2006)** | 7.85 | mg/l | 0.27 | MGD |
| **Post-upgrade (2007–2013)** | 3.63 | mg/l | 0.24 | MGD |

**Permitted effluent phosphorus limit:** 761 lb/yr TP, equivalent to a TP concentration of 0.5 mg/L at design flow of 0.5 MGD

**Pre- and post-upgrade phosphorus performance:** 2005–2013 annual average of 0.06 mg/l (effluent TP limits have never been an issue; however, the plant now uses fewer chemicals to affect similar effluent concentrations)

## RATIONALE AND DECISION PROCESS

In 2007, regulatory changes in Virginia required the majority of wastewater treatment facilities to significantly reduce the discharge of nitrogen and phosphorus in their final effluents. While most facilities required significant physical upgrades to comply with the new requirements, the town of Crewe operating staff instead evaluated their existing treatment facility for optimizing nitrogen and phosphorus removal through operational modifications.

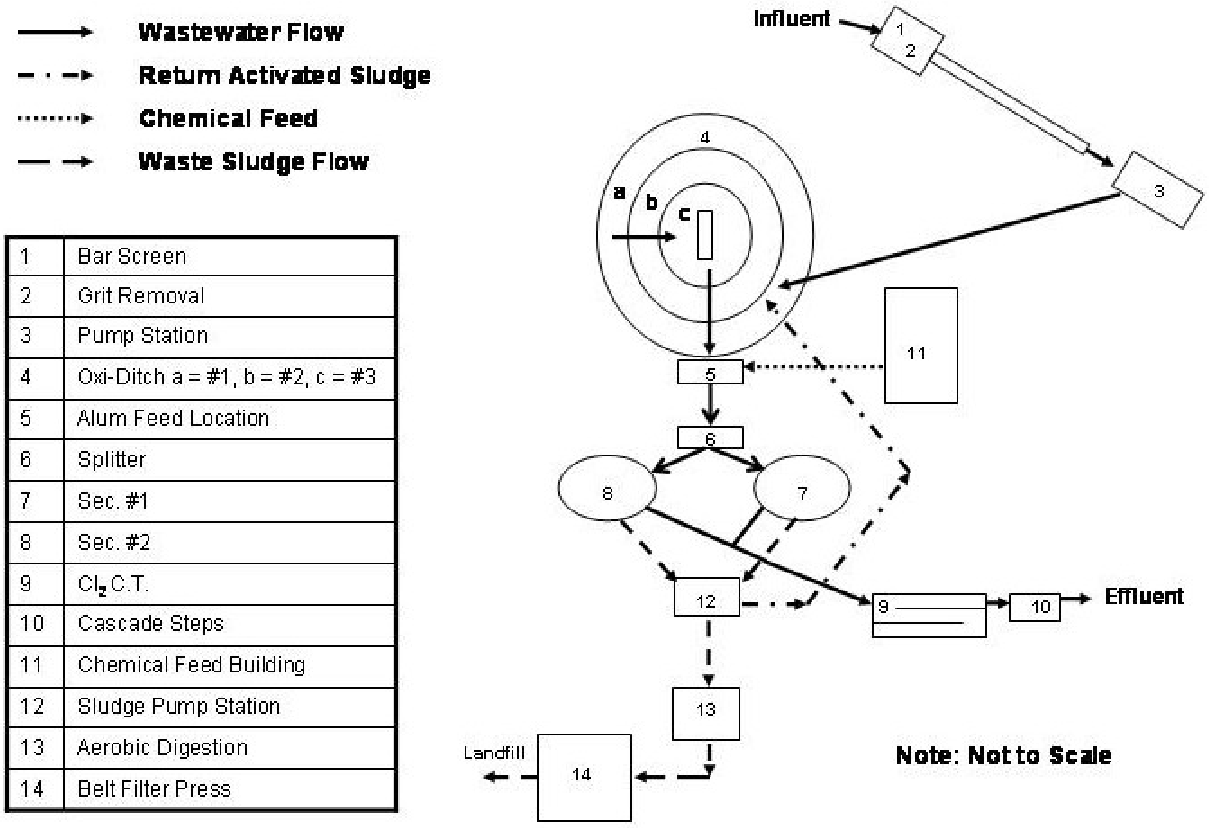
In discussing the challenge in 2006, staff estimated that upgrade costs were in excess of $250,000, with the possibility of nearing $800,000 for anticipated equipment changes, which included installing independently controlled means of delivering dissolved oxygen (DO) to each oxidation ditch channel. This would require increasing the number of motors from two to six, with variable frequency drives (VFDs) installed to control each motor independently.

In an effort to find an alternative, town staff began several years of operational experimentation. Although the facility relies upon chemical precipitation to remove phosphorus, plant staff made adjustments to several treatment process characteristics in an attempt to reduce effluent TN levels. Although the facility was not designed for TN removal, their oxidation ditch process does offer several operational control options to improve upon the plant’s nutrient removal performance.

The town first visited a number of different facilities to see how they achieved success and to help formulate how the town might do things differently. Understanding that they could not necessarily imitate the physical equipment used by other facilities (e.g., subsurface mixing in an anaerobic/anoxic zone; independent control of DO to each zone; VFDs) their challenge was how to best imitate the *treatment* by establishing and maintaining the proper environments for nitrification and denitrification simultaneously, with minimal upgrades of existing equipment.

## SYSTEM OPTIMIZATION DESCRIPTION

Beginning January 1, 2007, the facility began operating under the General Permit for Total Nitrogen and Total Phosphorus Discharges and Nutrient Trading in the Chesapeake Bay Watershed (9-VAC-25-82-70). Under the general permit, the Crewe WWTP has an annual waste load allocation (WLA) of 9,137 pounds for TN and 761 pounds for TP. At design flow, this WLA equals a TN concentration of 6.0 mg/L and TP 0.5 mg/L, respectively.



| | |
|---|---|
| 1 | Bar Screen |
| 2 | Grit Removal |
| 3 | Pump Station |
| 4 | Oxi-Ditch a = #1, b = #2, c = #3 |
| 5 | Alum Feed Location |
| 6 | Splitter |
| 7 | Sec. #1 |
| 8 | Sec. #2 |
| 9 | $Cl_2$ C.T. |
| 10 | Cascade Steps |
| 11 | Chemical Feed Building |
| 12 | Sludge Pump Station |
| 13 | Aerobic Digestion |
| 14 | Belt Filter Press |

Plant operating staff have put in a tremendous amount of effort to improve upon the plant's nutrient removal performance. The following actions were taken to optimize the facility for nitrogen removal.

## Alkalinity Control

The nitrification process consumes about 7.14 pounds of alkalinity per pound of ammonia converted to nitrate. Without sufficient alkalinity, process performance will decrease. Facility staff add approximately 100 pounds of lime to the first channel of the oxidation ditch daily to maintain enough alkalinity for nitrification.

## Carbon Source for Denitrification

The denitrification process utilizes heterotrophic bacteria to convert nitrate to dinitrogen gas. These organisms must have a readily available carbon source to effectively support their life functions. Typically, in a pre-anoxic mode of denitrification (e.g., Modified Ludzack Ettinger [MLE] process), influent carbon (BOD) is used to supply this food source. Additional BOD can be added to increase nitrogen reduction if necessary. The town of Crewe add approximately 150 pounds of dried molasses daily to the first channel of the ditch to provide an additional carbon source for denitrification.

## Dissolved Oxygen Control

The pre-upgrade operational strategy (during which the plant had no permit limit on TN, but a permit limit on total Kjeldahl nitrogen [TKN]) was to keep dissolved oxygen levels in the nitrification zone as high as possible by continuously running aeration on “high”.

Improved control of DO levels and aeration rates can enhance nitrification/denitrification performance by providing a controlled aerobic/anoxic environment. Typically, in an Orbal oxidation ditch process, DO levels are kept at less than 0.5 mg/L in the outer channel and between 1.0 – 3.0 mg/L in the inner channel(s). At the town of Crewe WWTP, whenever DO levels in the oxidation ditch were lowered to attempt to improve denitrification, an increase in effluent TKN occurred. Beginning in January 2007, plant operating staff decided to develop an effective yet low cost alternative to controlling the DO level in each channel of the ditch to improve denitrification while maintaining effective TKN reduction (nitrification).

One method of controlling DO in an oxidation ditch that uses disc aeration, is to add or remove aeration discs. Plant staff considered this method but were concerned that mixing might be negatively impacted, causing settling or solids in the ditch.

Plant staff therefore decided to experiment with operating the ditch aerators in an on/off operation mode. A 24-hour timer with 15 minute on/off cycles was used in initial tests to determine the effectiveness of this approach in maintaining the DO at the desired levels. The timer was wired to one of the two available aeration motors. The timer cycled on/off effectively, but lacked the ability to alter the speed of the motor. Plant performance improvements were marginal with this modification.

A second test was initiated using the same timer to alter the speed of the motor in cycles. This was accomplished by having the timer set-up to operate the aerators in “high mode” normally. However, when the timer triggered a cycle, it changed the aerator speed from high to low for the preset duration, returning to high mode upon completion of the cycle. Delay timers were employed to stop and start the motors, limiting the impact the cycling would have on the mechanical equipment.

After the second test, a DO probe was installed to monitor DO concentration of the mixed liquor and send a signal to a controller used to adjust the disc aerators to high or low speed by opening and closing relays in response to predetermined setpoints.

Through trial and error, it was discovered that the most effective location for the DO probe was in the third channel. Experience had shown that when DO levels fell below 3.0 mg/L in the third channel, a significant increase in TKN levels occurred. Although the corresponding DO in the first channel was low enough to increase denitrification and thus further reduce nitrates, the increase in TKN resulted in no substantial change in total nitrogen levels. After further experimentation, it was discovered that a setpoint range between 3.6–4.0 mg/L offered the most balanced approach to controlling both total nitrogen and TKN levels.

This operational method has provided the plant a measure of control beyond a simple on/off approach to limiting DO levels within the ditch. Total costs for the system were approximately $6,000; however, it should also be noted that the facility staff designed and installed the system themselves, which resulted in a significant cost savings to the town.

### Process Monitoring

Increased process monitoring has been helpful in understanding plant performance and establishing appropriate control strategies. Facility staff now perform additional process control sampling and testing to characterize and monitor the treatment process. Nitrogen profiling has been used to determine where adjustments are needed and whether adjustments are effective in improving nutrient removal. Samples are analyzed in-house and by an outside source. A good working relationship with an outside laboratory has proven to be essential in the town’s efforts to reduce nutrients. They are able to verify in-house results in a timely fashion and allow the town to adjust the process based on the results.

### Phosphorus Removal Enhancements

Back in 2006, during the process of assessing carbon sources for improving denitrification, plant operational staff, after trying a number of products, discovered that the most "bang for the buck" came from the use of molasses. Considerations in their choice of a product included cost versus benefit, reliability of product availability and operator safety.

In June 2011, the plant operator was contacted by a company developing molasses based products specifically for the wastewater industry. They proposed a free trial of "Enhance Bio-P", which is molasses with micronutrient additives formulated to enhance biological TP removal. The product was successful in consistently reducing the plant’s use of liquid alum by more than 50 percent. Anaerobic micro-environments within the plant’s two anoxic channels allow for biological phosphorus reductions that are improved by the Enhance Bio-P product.

The plant repurposed a 5,000-gallon tank that was previously used to store magnesium hydroxide which they stopped using in 2005. The system pumps the molasses product to the influent pump station, where it mixes with influent flow immediately prior to the influent being pumped to the first of the anoxic oxidation ditch channels. Addition of the Enhance Bio-P product lowers the plant's TP concentration, prior to liquid alum addition from an average of more than 1.00 mg/L to less than 0.50 mg/L, significantly lowering liquid alum demand and associated costs.

## COSTS AND OTHER IMPACTS

**Capital costs:** $6,000 for DO control system.

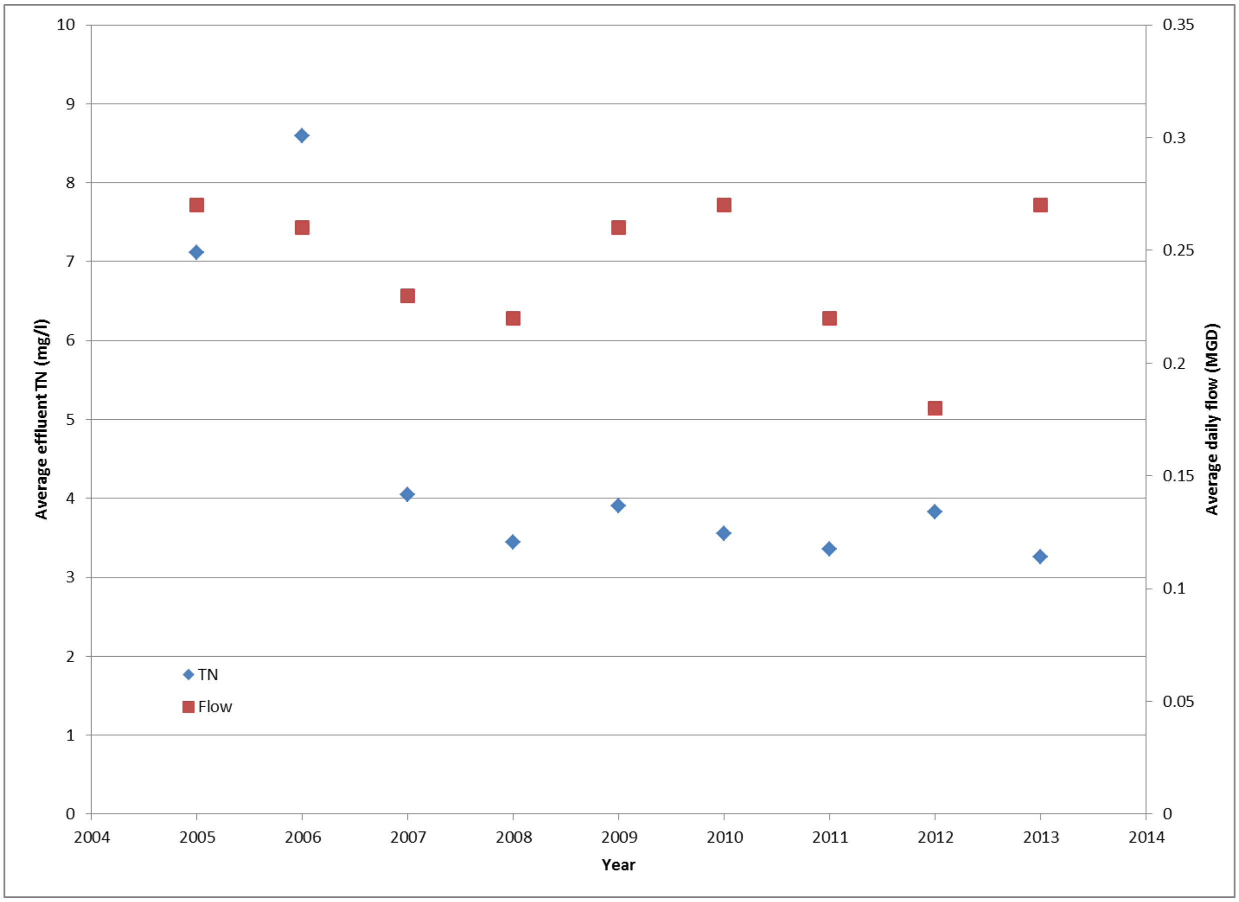
**Operational costs:** Carbon source control costs are about $30,000 per year. However, switching from molasses and alum to Enhance BioP and alum has resulted in an estimated annual savings of $26,200.

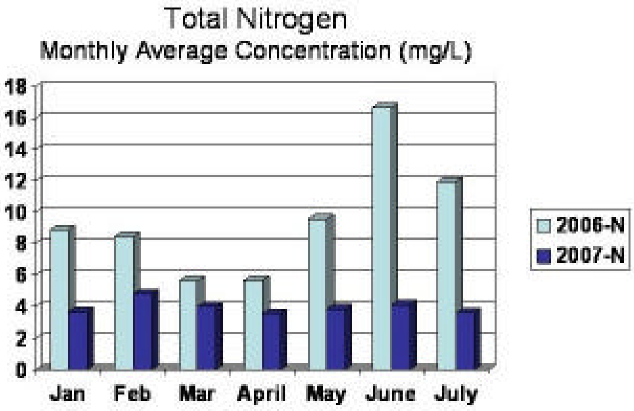
Alkalinity addition is approximately $24/day or $8,760/year.

**Technical assistance received or needed:** Most technical support was provided by in-house operational staff.

## PERFORMANCE DISCUSSION

Pre- and post-upgrade TN statistics are summarized on page 1. A graphical summary of average annual effluent TN concentration is provided below (upgrades were implemented in 2007) and a monthly comparison between 2006 (pre-upgrade) and 2007 (post-upgrade) is presented below that.





## CHALLENGES

Several other operating factors are currently being addressed to potentially increase the efficiency of TN removal.

### Inflow and Infiltration (I/I)

The town has dealt with significant I/I problems, which may have directly impacted the ability of the system to achieve optimal nutrient removal. The town is currently working diligently to address the I/I issues and increase the pumping and storage capacity of the plant. The town has completed slip lining several problem pipeline areas within the collection system, which has resulted in an immediate decrease in the amount of inflow and infiltration flow received at the plant during rain events.

### Internal Recycle

Typically, facilities operating for nitrogen removal use an internal recycle system to return a much greater quantity of flow (2–4 Q), rich in nitrate nitrogen, to the anoxic zone for conversion to dinitrogen gas. The current plant configuration does not include an internal recycle, but the facility is performing a pilot test on using a temporary internal recycle system, using a submersible pump and polyvinyl chloride (PVC) piping, to determine its effectiveness in further reducing nitrogen levels. The pump recycles nitrates from the third channel (aerobic) back to the first channel (anoxic) at approximately 130 GPM. Plant staff have determined a 1:1 ratio works best to maximize nitrate removal.

### Oxygen Addition into Anoxic Channel

Excessive agitation occurred where the influent and return activated sludge (RAS) entered the anoxic zone (first channel) of the oxidation ditch. DO measurements indicated a DO of 0.4 mg/L before and 0.8 mg/L after the influent discharge and 1.4 mg/L after the RAS discharge. This DO must be used up by biological activity before denitrification will occur. In an attempt to decrease DO at this location, the operating staff extended both the influent and RAS piping below the water surface in the first ditch. Results were immediate, decreasing DO by as much as 1.0 mg/L where the influent and RAS enter the ditch.

### Sidestream Flows

An often overlooked contributor of nutrients in plant influent results from internal plant processes. If not managed properly, sidestream flows can significantly affect the plant’s ability to consistently remove nitrogen and phosphorus. Crewe’s operating staff observed that, whenever they decanted their aerobic digester and/or operated the belt filter press, an increase in plant influent nitrate levels occurred. Currently, the aerobic digester is being operated in an on/off mode (i.e., 2 hours on/1 hour off) to reduce the nitrates before they enter the plant influent. This operational mode has resulted in an increase in ammonia and TKN levels, but the process appears to be handling the load effectively. Plant staff are continuing to monitor the nutrient levels to determine if any adjustment to the operational strategy is required.

## FUTURE IMPROVEMENTS

There are no plans for any other nutrient reduction upgrades at this time. Crewe is well-positioned to generate modest capital returns by selling generated nutrient credits (through the Virginia Nutrient Credit Exchange Association). With consistent TN averages well below permit limits, even if the limit is decreased, Crewe's current process performance gives the plant plenty of safety factor. The added benefit of cost-saving with regards to liquid alum use, through its choice of carbon source addition, has Crewe in a great position with respect to TP reduction.

## CONTACT INFORMATION

John Hricko, plant manager. Phone: (434)-645-9436. Email: hricko@hovac.com.

## OTHER RESOURCES

Town of Crewe: http://www.townofcrewe.com/

State of Virginia Department of Environmental Quality case study:
http://www.deq.state.va.us/Portals/0/DEQ/Water/WastewaterTreatment/crewe_case_study.pdf

*Treatment Plant Operator Magazine* article:
http://www.tpomag.com/editorial/2009/09/top-performer-plant-a-little-creativity

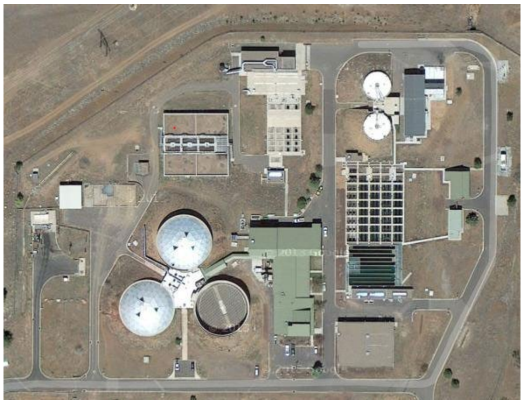
# FLAGSTAFF, ARIZONA

# IFAS ACTIVATED SLUDGE—PROCESS CONTROL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** Wildcat Hill Wastewater Treatment Plant (WWTP)

**Location:** 2800 North El Paso Road, Flagstaff, AZ 86004 (latitude: 35° 13’32”N; longitude: 111° 33’25”W)



**Permitted design flow:** 6.0 MGD

**Service area:** City of Flagstaff (2010 population of 66,067)

**System type:** Integrated fixed-film activated sludge (IFAS) in Modified Ludzack-Ettinger (MLE) configuration

**Initial year of operation:** 2010 (converted from biotowers)

**Upgrade type:** Improved process controls

**Upgrade year of operation:** Improvements initiated in late 2013

**Permitted effluent nitrogen limit:** 10.0 mg/L TN (8.0 mg/L TN alert level) on 5 sample rolling geometric monthly mean basis

**Pre- and post-upgrade effluent nitrogen performance:** 14 mg/l pre-upgrade; 8.5 mg/l post-upgrade

**Permitted effluent phosphorus limit:** None

**Pre- and post-upgrade phosphorus performance:** N/A

## RATIONALE AND DECISION PROCESS

Performance of the MLE process was insufficient to achieve consistent compliance with Flagstaff’s effluent TN limit during periods of high nitrogen loading. A 2013 plant evaluation recommended steps to optimize performance of the MLE process and upgrades to improve upon it. The relatively easily implemented instrumentation and operational improvements were implemented in late 2013 and 2014 while upgrades requiring more extensive design and budget were targeted for 2015.

## SYSTEM OPTIMIZATION DESCRIPTION

A combined ammonia/nitrate probe (ISE type) was installed in the effluent end of the anoxic zone. Nitrate concentration is monitored and internal mixed liquor recycle is adjusted as needed to maintain a nitrate level of 0.5–1.0 mg/L nitrate-N at that point in the process to avoid overloading anoxic zones and further decreasing nitrogen removal by unnecessarily decreasing anoxic detention time.

Control of nitrogen sources (mainly sludge processing recycle) to decrease loading spikes was essential. The new nitrate probe indicated that the nitrate concentration at the anoxic zone effluent was often greater than 1 mg/L, indicating that more nitrate was being recycled than the anoxic zone could effectively remove. Excessive nitrate leaving the anoxic zone indicates either insufficiently anoxic conditions or insufficient oxygen demand (due to insufficient readily degradable carbon) at the anoxic zone.

Monitoring indicated that the BOD-to-nitrogen ratio in the primary effluent was low at times. Therefore, the primary clarifier operation was modified to encourage greater hydrolysis and/or fermentation of influent BOD. Pumping of settled sludge from the primary clarifiers was modified to provide longer detention time for solids in the primaries to allow additional conversion of particulate BOD to soluble BOD available for denitrification.

Oxidation-reduction potential profiling in the anoxic zone indicated that much of the zone was too aerobic (oxidizing) to expect denitrification, likely due to excessive oxygen loading from the internal mixed liquor recycle. Consequently, internal recycle rate control was modified.

Other operational changes included decreasing the rate of return from biosolids dewatering processes as needed to manage nitrogen loading spikes.

## COSTS AND OTHER IMPACTS

**Capital costs:** Approximately $10,000 for ammonia/nitrate probe and installation.

**Operational costs:** Sensor cartridge replacement approximately $1,000 every 6 months. Probe cleaning and calibration weekly.

**Technical assistance received or needed:** A consultant was hired to recommend modifications to improve nutrient removal.

## PERFORMANCE

Pre- and post-upgrade total nitrogen statistics are summarized below.

| Parameter | April 2013 | April 2014 |
|---|---|---|
| Flow | 3.3 mgd | 3.9 mgd |
| Temp | 18.3° C | 18.4° C |
| Influent BOD | 595 mg/L | 498 mg/L |
| Primary Effluent BOD | 203 mg/L | 269 mg/L |
| Primary Effluent $NH_3$-N | 22.1 | 32.6 |
| Final Effluent $NO_3$ | 12.5 | 7.0 |
| Final Effluent TN | 14.0 | 8.5 |

## FUTURE IMPROVEMENTS

Installation of additional ammonia and nitrate probes to allow continuous monitoring of primary effluent and secondary effluent is underway. Addition of supplemental carbon storage and feed are planned as well as the addition of an anoxic tank downstream of the aeration basins to provide additional denitrification when necessary to decrease nitrogen to less than the levels attainable with the MLE process.

## CONTACT INFORMATION

Larry Lemke, 2800 North El Paso Road, Flagstaff, AZ 86004. Phone: (928) 526-2520. Email: llemke@flagstaffaz.gov.

## OTHER RESOURCES

City of Flagstaff: http://www.flagstaff.az.gov/index.aspx?NID=21

# HAMPDEN TOWNSHIP, PENNSYLVANIA

# CONTINUOUS-FLOW SEQUENCING REACTOR ACTIVATED SLUDGE—AERATION CYCLING

## SYSTEM SUMMARY

**Official Name:** Roth Lane Wastewater Treatment Plant (WWTP)

**Location:** 4200 Roth Lane, Mechanicsburg, PA 17050 (latitude: 40° 16' 27" N; longitude: 76° 58' 38" W)

**Permitted design flow:** 5.69 MGD, annual average

**Service area:** Hampden Township, East Pennsboro Township, Silver Spring Township, and Camp Hill Borough in Cumberland County, Pennsylvania

**System type:** Activated sludge (continuous-flow sequencing reactor [CSR])

**Initial year of operation:** 1982

**Upgrade type:** Flexibility of series operation of dual-train CSR system

**Upgrade year of operation:** 2010

**Permitted effluent nitrogen limit (2014 compliance year):** 114,558 lb/yr TN (6.6 mg/l TN at permitted flow)

**Pre- and post-upgrade effluent nitrogen performance:** 4.66 mg/l (1.20 mg/l standard deviation) TN during parallel operation (pre-upgrade); 3.64 mg/l (0.63 mg/l standard deviation) TN during series operation (post-upgrade)

**Permitted effluent phosphorus limit (2014 compliance year):** 14,094 lb/yr TP (0.81 mg/l TP at permitted flow)

**Pre- and post-upgrade phosphorus performance:** 0.81 mg/l (0.28 mg/l standard deviation), average June 2010–April 2014 (no TP removal improvements were made)

| | Series Operation | | Parallel Operation | | |
|---|---|---|---|---|---|
| | Average Concentration | Standard Deviation | Average Concentration | Standard Deviation | Units |
| **Ammonia** | 0.98 | 0.62 | 0.67 | 0.71 | mg/l |
| **Nitrite+Nitrate** | 1.90 | 0.48 | 2.73 | 0.72 | mg/l |
| **TKN** | 0.98 | 0.62 | 0.67 | 0.71 | mg/l |
| **TN** | 3.64 | 0.63 | 4.66 | 1.20 | mg/l |

## RATIONALE AND DECISION PROCESS

The Roth Lane WWTP has to comply with strict nitrogen and phosphorus removal requirements associated with Pennsylvania's Chesapeake Bay Nutrient Reduction Strategy. The facility's current National Pollutant Discharge Elimination System (NPDES) permit includes TN and TP effluent mass load limits, which are enforced on a 12-month "compliance year" basis from Oct. 1 through Sept. 30 of the following year. The flexibility of series operation of the existing CSR system helped lower sludge wasting, power consumption, and chemical use and could be easily implemented using existing infrastructure at the facility.

## SYSTEM OPTIMIZATION DESCRIPTION

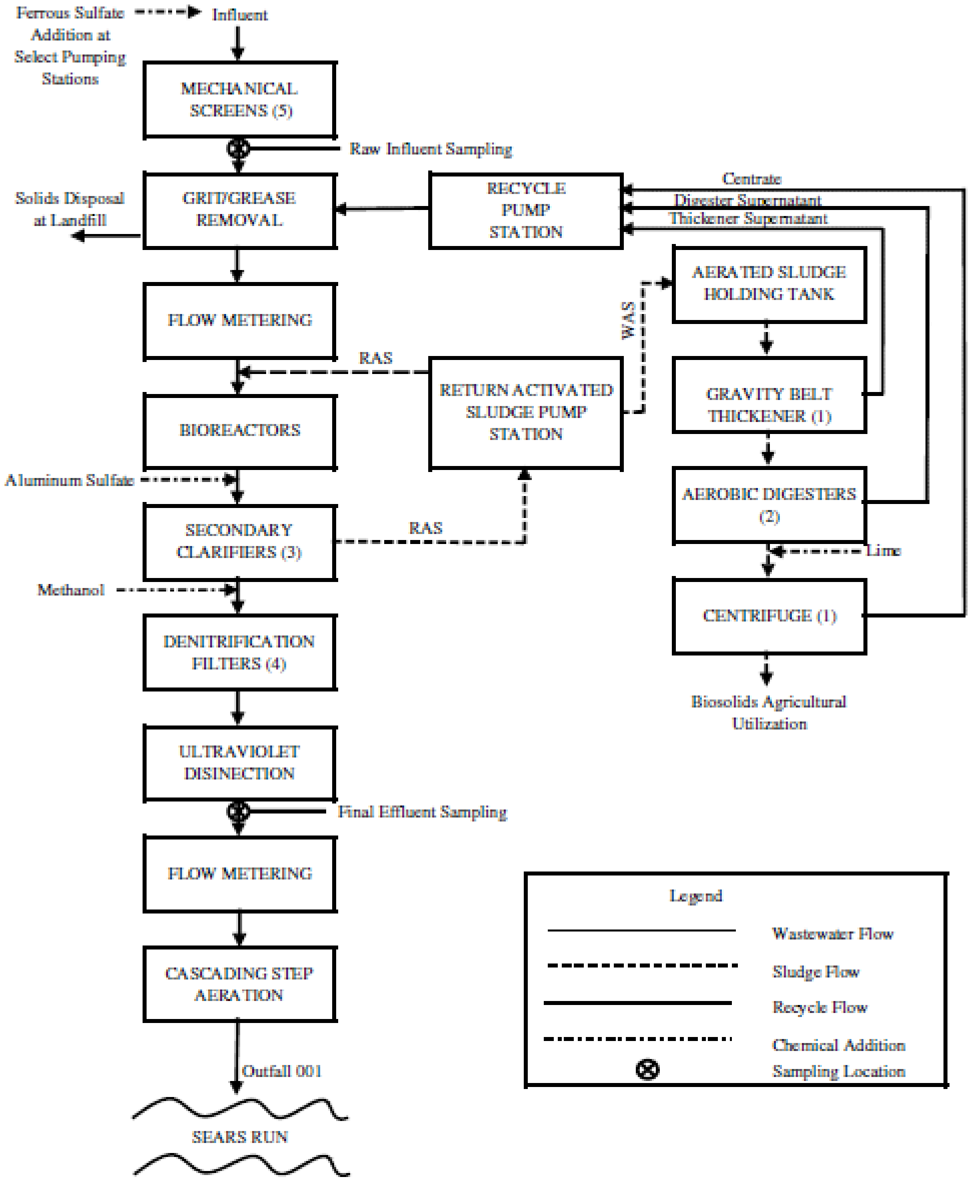
The Roth Lane WWTP discharges treated effluent to Sears Run under NPDES Permit No. PA0080314. The WWTP includes the following treatment processes:

- Screening
- Grit removal
- Grease removal
- CSR activated sludge process
- Chemical phosphorus removal
- Final clarification
- Filtration
- Ultraviolet (UV) disinfection
- Effluent discharge to Sears Run

Roth Lane has two CSRs that are normally operated in parallel (i.e., as separate treatment trains). Each reactor is equipped with a rotating aeration bridge with membrane tube diffusers—which are mounted on retrievable rack assemblies and suspended from the bridge—and stationary membrane tube diffusers above the floor on retrievable rack assemblies attached to the tanks' walls. Aeration in each CSR basin is supplied by three positive displacement blowers, each equipped with variable-frequency drives. For each bioreactor, one of the blowers is dedicated to the stationary diffusers and the second blower is dedicated to the rotating diffusers. The third blower serves as a redundant standby blower for either set of diffusers.

A small plant upgrade in 2008 added a third clarifier and a distribution box between the aeration units, which incidentally provided staff with the flexibility to run the CSR basins in series. In addition to improving nitrogen removal, series operation reduced waste sludge volumes by about 40 percent.

Additional upgrades in 2010 added a process control system capable of continuously monitoring dissolved oxygen (DO) and nitrate. Signals are sent to a programmable logic controller (PLC) to establish process phasing through oxic, anoxic, and anaerobic cycles. A proportional-integral-derivative (PID) control loop is used to modulate the blower speed in each reactor to maintain the DO setpoint. To allow operational flexibility, the PLC enables the user to adjust the DO setpoint and stage timers for each phase.



## COSTS AND OTHER IMPACTS

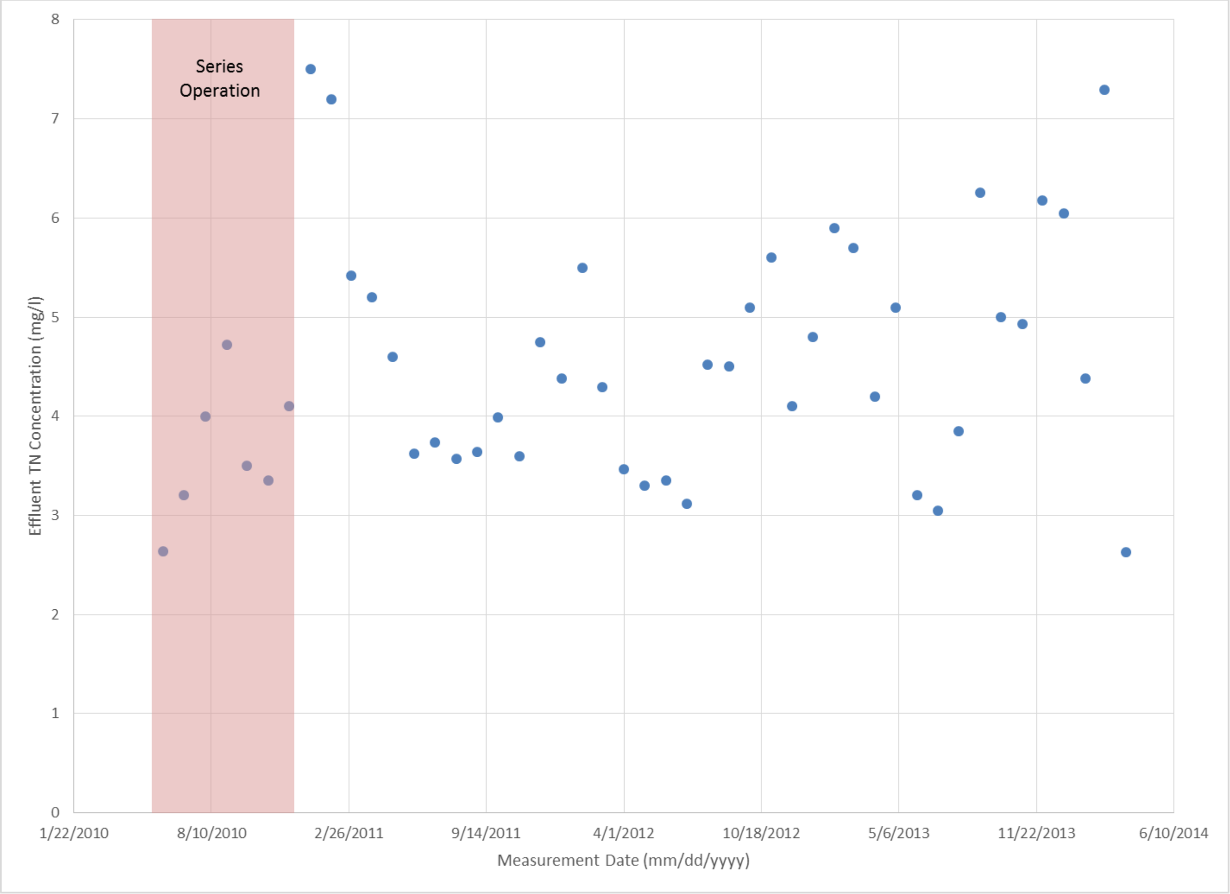
**Capital costs:** None.

**Operational costs:** None.

**Technical assistance received or needed:** None.

## PERFORMANCE

As expected, TN removal was more efficient during series operation (figure below), with the improvements associated with enhanced denitrification (table above, which shows lower nitrate+nitrite concentrations during series operation).



## CHALLENGES

The Roth Lane system has significant problems with infiltration and inflow (I/I) and rain events that push flow above about 5 MGD, which require the staff to return to a parallel operational mode.

## FUTURE IMPROVEMENTS

The Roth Lane WWTP is currently expanding to accommodate additional flows and loadings from a nearby municipality. As part of the expansion project, denitrification filters with methanol addition will be installed to enhance nitrogen removal at the projected design flows and loadings.

## CONTACT INFORMATION

Diane Fox, Superintendent. Jeffrey Klahre, Operations Supervisor. Hampden Township, Public Works—Wastewater Division, 4200 Roth Lane, Mechanicsburg, PA 17050. Phone: (717) 761-7963. Email: DFox@hampdentownship.us; JKlahre@hampdentownship.us.

## OTHER RESOURCES

Hampden Township Wastewater Division:
http://www.hampdentownship.us/township-department/public-works-wastewater-division/

Shawwa, A.R., and D.C. Shope. 2013. Dynamic modeling of cyclic aeration process for biological nutrient removal. *Water Environment and Technology* 25(7):30–34.

Schreiber Continuously Sequencing Reactor:
http://www.schreiberwater.com/CSRAeration.shtml

# LAYTON, FLORIDA

# SEQUENCING BATCH REACTOR—PROCESS CONTROL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** City of Layton Wastewater Treatment Plant (WWTP)

**Location:** 67711 Overseas Highway, Long Key, FL 33001. Monroe County. Florida Keys (latitude: 24° 49' 16.5593" N; longitude: 80° 49' 14.4679" W)

**Permitted design flow:** 0.066 MGD, monthly average

**Service area:** Approximately 350 EDUs[1], including Long Key State Park

**System type:** Sequencing batch reactor (SBR)

**Initial year of operation:** 2007

**Upgrade type:** Process control modifications

**Upgrade year of operation:** 2009

**Permitted effluent nitrogen limit:**
12.5 mg/l TN, monthly average; 10 mg/l TN, annual average

**Pre- and post-upgrade effluent nitrogen performance:** Pre- and post-upgrade TN statistics are summarized below

| | Influent Total Nitrogen | Effluent Total Nitrogen | | |
|---|---|---|---|---|
| | Average Concentration | Average Concentration | Standard Deviation | Units |
| **Pre-upgrade** | 89.3 | 7.88 | 4.26 | mg/l |
| **Post-upgrade** | 64.1 | 3.33 | 1.87 | mg/l |

**Permitted effluent phosphorus limit:** 1.25 mg/l TP, monthly average; 1.0 mg/l TP, annual average

**Pre- and post-upgrade phosphorus performance:** 0.58 mg/l TP, average 2007–2013 (no TP removal improvements were made)

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[1] EDU = Equivalent Dwelling Unit, which is the approximate number of residences served by the facility.

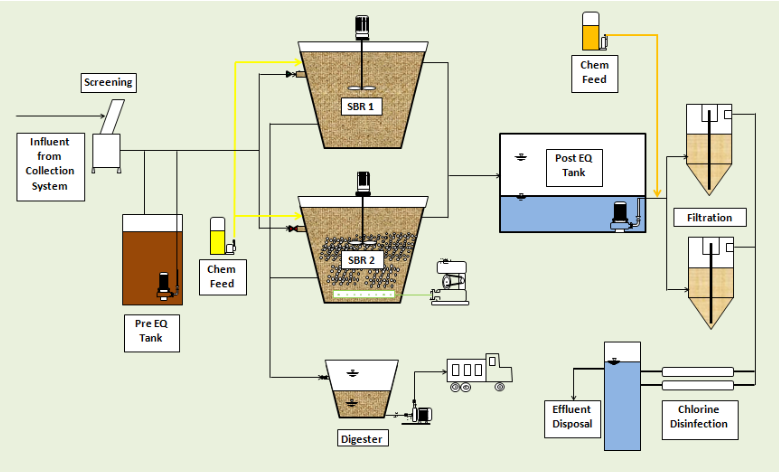
## RATIONALE AND DECISION PROCESS

The plant was not consistently meeting permitted effluent TN limits. Therefore, Layton's approach focused on improving the control of their SBR system to achieve much more consistent effluent TN concentrations. Based on Florida Keys Aqueduct Authority (FKAA) experience with other similar SBR systems, operations staff were aware that programming adjustments to the control system could allow for better control of conditions during the batch cycle by mixing only for the fill cycle and then cycling blowers on and off as needed to ensure consistent nitrification-denitrification. Improved controls are supplemented by real-time dissolved oxygen (DO) and oxidation-reduction potential (ORP) monitors.

## SYSTEM OPTIMIZATION DESCRIPTION

As indicated above, the focus of FKAA was to improve the control of the SBR cycle to maximize nitrification-denitrification. Biological nitrogen removal is a sequential process, first requiring aerobic conditions for converting ammonia and organic nitrogen to nitrate (nitrification) and then anoxic conditions to convert nitrate to harmless dinitrogen gas (denitrification). The aerobic conditions needed for nitrification can be maintained by actively aerating the mixed liquor (the contents of the reactor), while anoxic conditions are induced by suspending the mixed liquor using submerged mixers, with no aeration.

The original SBR wastewater facility was put into operation in 2007 and cost approximately $5.7 million. Upgrades to the City of Layton WWTP consisted mainly of reprogramming of the SBR control scheme. The original manufacturer of the SBR did not provide sufficient operational control over the "fill" and "react" cycles in each batch process to facilitate optimal nitrification and denitrification.



Each batch starts at bottom water level (BWL). At BWL, the tank is at a predefined depth that is established by the elevation of the fixed-hood decanter; this elevation cannot be adjusted. Next, the fill valve is opened and raw influent is pumped into one of the reactors. Raw influent pumping is controlled by floats in the collection system lift stations. This is important, because it can control the batch time, which had been targeted to be 4 hours, but could be longer if flows were insufficient or shorter if there was a hydraulic surge (e.g., from a storm event). Each batch includes a fill cycle, react cycle, settle cycle, decant/waste activated sludge (WAS) cycle, and idle cycle.

Under the original setup, oxic (aeration and mixing) and anoxic (only mixing) timers alternated while raw influent was pumped in during the fill cycle. This process repeated until a float was tripped at approximately 13 feet of liquid depth, which triggered the fill valve to close and oxic (aerated and mixed) and anoxic (just mixed) conditions to alternate for 45–60 minutes, followed by a settling cycle (no aeration or mixing) for another 45–60 minutes. Then the decant valve opened and clarified effluent would be decanted down to the BWL while the unit remained in an idle/fill cycle waiting for the float to trip at 13 feet and the batch process to repeat.

Process control optimization consisted of modifying the programming to a timed batch rather than a level batch process. Using a fixed timed batch of 6 hours, operational control of all 360 minutes was implemented to ensure a more consistent effluent. Within the current 6-hour batch are 3 hours for filling and 3 hours for the react, settle, decant, and WAS cycles (and the idle cycle, if necessary). During the first 180 minutes, mixed fill is employed for 45 minutes. For the remaining 135 minutes, blowers are controlled using on/off timers to affect almost complete nitrification. During the subsequent react cycle, only mixing is used—although there is an option to aerate if necessary. The operator can then set the settling cycle for between 45–60 minutes, followed by decant and idle cycles.

## COSTS AND OTHER IMPACTS

**Capital costs:** Approximately $53,000 for new online monitoring of DO, ORP, and total suspended solids (TSS) probes in each SBR. DO and ORP are monitored to quickly determine the oxidation state during anoxic or aerobic cycles. The TSS probe is used strictly as a time-saving factor, as a surrogate for laboratory mixed liquor suspended solids (MLSS) analysis.

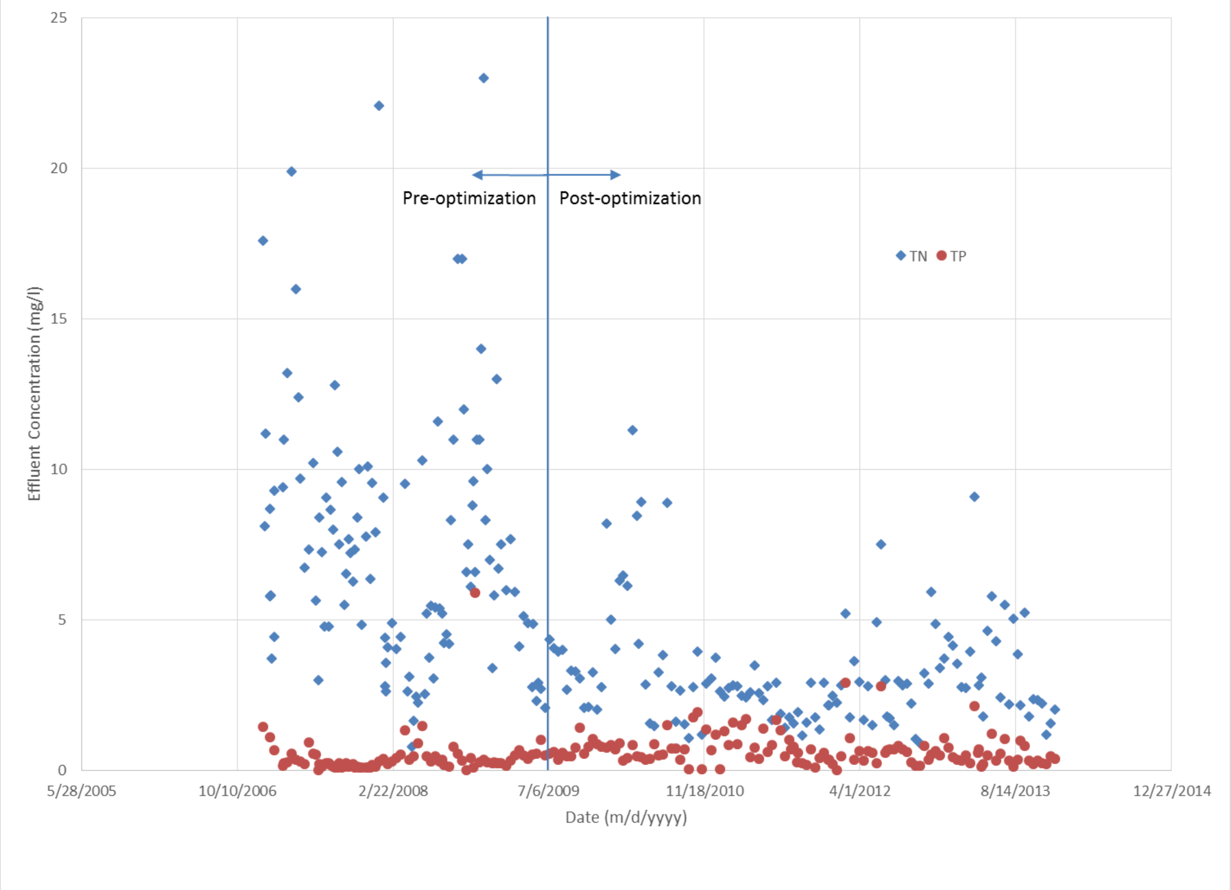
**Operational costs:** The biggest change was in sludge hauling and lab testing. Once nutrient removal was optimized, the plant was able to cut down on laboratory discovery sampling. They also were able to operate proactively by focusing on dewatering and biosolids removal. For the City of Layton WWTP, this equated to approximately $12,000–15,000 in **savings** (compared with an annual $80,000 budget), not including labor.

**Technical assistance received or needed:** Significant training was needed. Layton used the not-for-profit Florida Rural Water Association (FRWA) in a joint effort with their technical staff on specific nutrient removal training and spends approximately $4,000 annually on microscopy and microbiological training through a company called Environmental Leverage.

From a regulatory standpoint, operators at the Layton WWTP are only required to have a Florida Class C WWTP operator's license (a Class C-licensed operator is required to know only basic wastewater treatment techniques; nutrient removal is not introduced until Class B licensing). The FKAA recognized early that it would be necessary to train operators to meet the treatment standards required by their permits. FKAA currently has all in-house trained operators except one who was trained outside FKAA.

## PERFORMANCE

Pre- and post-upgrade TN statistics are summarized on page 1. A graphical illustration of effluent TN and TP concentrations versus time and a summary of average annual effluent concentrations for nitrogen species are provided below (upgrades were implemented in early 2009).



| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | Units |
|---|---|---|---|---|---|---|---|
| **TN** | 7.29 | 4.29 | 4.37 | 2.72 | 3.01 | 3.44 | mg/l, average effluent concentration |
| **TON** | 1.76 | 1.36 | 1.50 | 1.51 | 1.53 | 1.48 | mg/l, average effluent concentration |
| **TKN** | 2.11 | 1.83 | 2.00 | 1.73 | 1.71 | 1.89 | mg/l, average effluent concentration |
| **$NH_3$** | 0.36 | 0.43 | 0.50 | 0.30 | 0.18 | 0.42 | mg/l, average effluent concentration |
| **$NO_3$** | 5.39 | 2.38 | 2.31 | 0.87 | 1.27 | 1.35 | mg/l, average effluent concentration |

## FUTURE IMPROVEMENTS

TN removal could be improved even further by outfitting the blowers with variable frequency drives (VFD) coupled with the DO control system. However, effluent quality is currently excellent and the costs associated with further improvements are not justified at this time.

## CONTACT INFORMATION

Tom Pfiester. Florida Keys Aqueduct Authority, 3375 Overseas Highway, Marathon, FL 33050. Phone: (305) 481-2015. Email: tpfiester@fkaa.com.

## OTHER RESOURCES

City of Layton: http://www.cityoflayton.com/

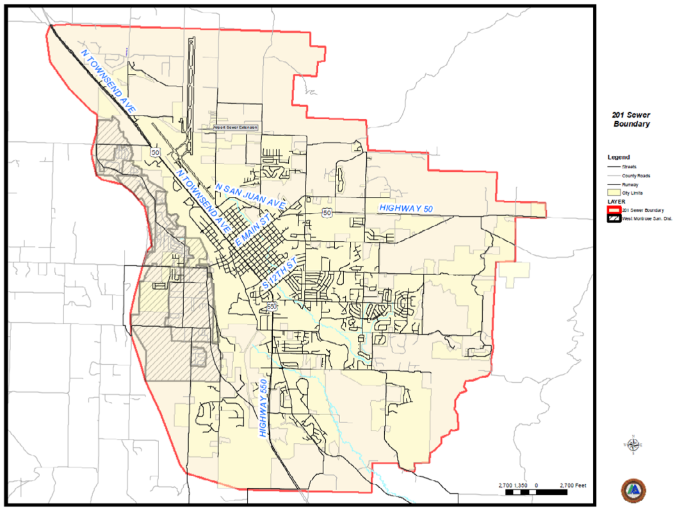
Keys Wastewater Plan: http://www.monroecounty-fl.gov/DocumentCenter/Home/View/478

Florida Keys Aqueduct Authority: http://www.fkaa.com/

# MONTROSE, COLORADO

# ACTIVATED SLUDGE—AERATION CONTROL

## SYSTEM SUMMARY



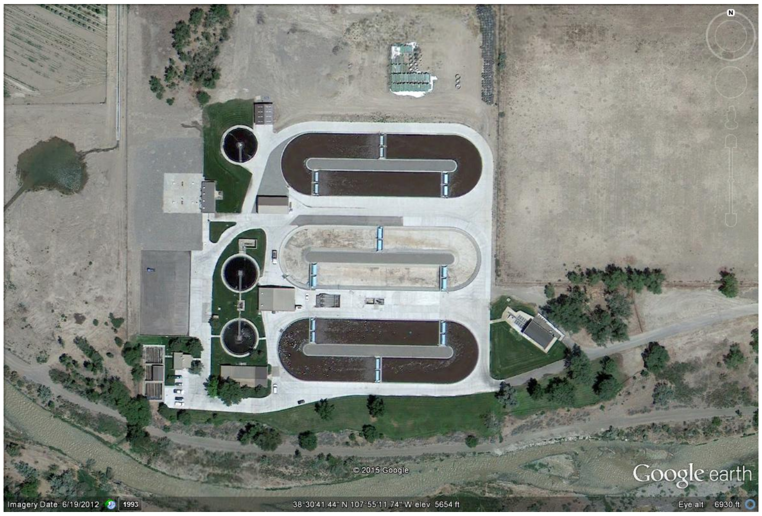
**Official Name:** Montrose Wastewater Treatment Plant (WWTP)

**Location:** 3315 North Townsend Avenue, Montrose, CO 81402 (latitude: 38° 30’ 41.44” N; longitude: 107° 55’ 11.74” W)

**Permitted design flow:** 4.32 MGD (expanded from 2.88 MGD in 2008)

**Service area:** Shown at right

**System type:** Extended aeration activated sludge/oxidation ditch



**Initial year of operation:** 1984; expansion in 2008

**Upgrade type:** Aeration control

**Upgrade year of operation:** 1997

**Permitted effluent nitrogen limit:** Total inorganic nitrogen (TIN)—report only (limits expected after 2020)

**Pre- and post-upgrade effluent nitrogen performance:** 14.7 ± 4.3 mg/l TIN, post-upgrade (2012–2014)

**Permitted effluent phosphorus limit:** N/A

**Pre- and post-upgrade phosphorus performance:** 3.0 ± 0.8 mg/l TP, post-upgrade (2012–2014)

## DECISION PROCESS

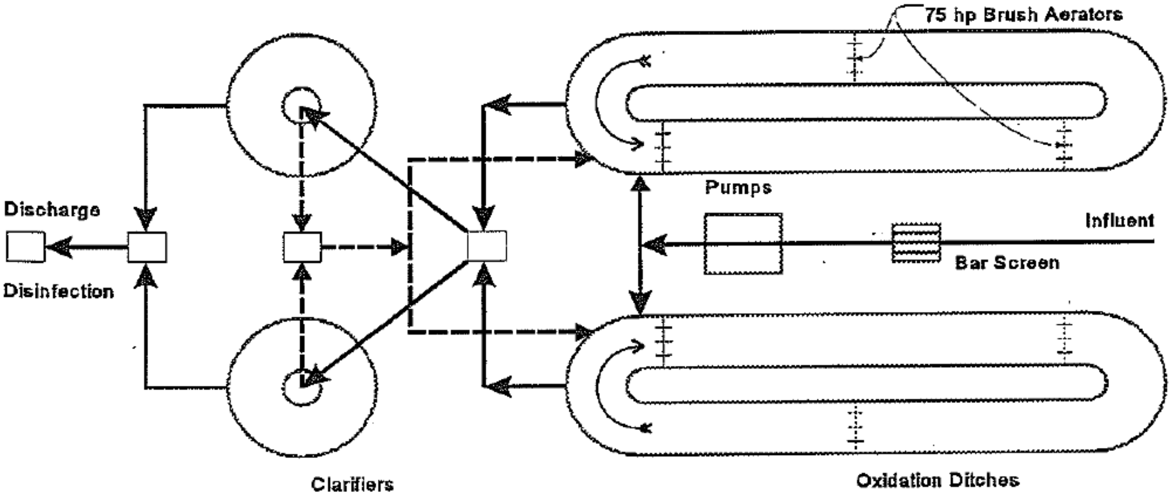
The project was mainly initiated as a way to cut energy costs; however, improved nitrogen removal has proven to be a major benefit.

## SYSTEM OPTIMIZATION DESCRIPTION

The extended aeration process, which is used at the Montrose facility, uses low organic loading and high detention time. Extended aeration can use aeration tanks of various shapes including square, rectangular, and "endless" ditch, often called an oxidation ditch. Extended aeration systems use high mean cell residence times (MCRTs), also known as sludge age, which typically range from about 15–30 days. However, certain conditions might require that values outside that range be used. When the higher MCRTs are used, autotrophic bacteria feed on inorganic matter and grow slowly on compounds such as ammonia ($NH_3$) and convert it first to nitrite ($NO_2^-$), then to nitrate ($NO_3$). Almost all extended aeration systems nitrify, especially in summer, whether intended or not.

On/off aeration has been used since initial experiments with activated sludge, and is commonly used in package treatment plants today. However, many package plant systems are destined to fail because they are operated with short periods of "on" and short periods of "off"—such as 15 minutes on and 15 minutes off. Half hour on/half hour off is also common, as are similar variations. However, when used properly, on/off aeration can be very effective, especially when the air is left off long enough to affect complete denitrification.

At the time of the optimization effort, the Montrose WWTP operated two ditches, each with 1.4 MG volume, and two 68-foot diameter clarifiers. Aeration was provided by six brush aerators each powered by 75-hp motors. The facility also has an aerobic sludge digestion system with large-bubble diffused aeration system.



The oxidation ditch had been well-operated and controlled so that, from January 1996 to November 1997, the monthly average effluent BOD was 2.55 mg/l, TSS was 3.75 mg/l, and $NH_3$ was 0.34 mg/l. The operators tried to maintain a dissolved oxygen (DO) level between 3.0–4.0 mg/l based on recommendations from consultants and the literature, which indicated that relatively high DO levels were required for nitrification. However, even at the high DOs, it appears that the oxidation ditch still allowed denitrification to occur in the ditch because of the good effluent suspended solids concentrations. High clarifier denitrification rates would have caused increased suspended solids concentrations in the effluent.

Indeed, oxidation ditches with brush aerators are known for nitrifying and denitrifying in the same tank by carrying a low DO down the tank, ahead of the next brush aerator. As the mixed liquor travels around the tank, it provides for sections with zero DO ahead of the next brush. However, maintaining low DO sections of the reactor would be more difficult if the DO following the brushes ranged as high as 3–4 mg/l. So, in November 1997, staff began turning off the brush aerator nearest to the influent to see if power could be saved by carrying a lower DO around the entire tank and maintaining an anoxic section all the way to the next brush aerator. The ditches are currently being operated at a DO of less than 1 mg/l.

Aerobic digesters can also play an important part in the nitrification/denitrification process. Most aerobic digesters are aerated 24 hours per day unless the operator is trying to decant a clear supernatant during the thickening process. Continuous aeration can completely oxidize the available carbon as well as nitrify all of the available nitrogen. Thus, high DO is common as is very low pH in the range of 4–5 units. Even if the air is turned off for a period of time during decanting, there is so little available oxygen demand that denitrification is minimal. Starting in January 1997, a daily off-period was provided from about 9:00 a.m. to 3:00 p.m. daily rather than just during decanting.

## COSTS AND OTHER IMPACTS

**Capital costs:** None.

**Operational costs:** The combined data indicates that on/off aeration in the oxidation ditch and in the aerobic digesters accounted for about 29,000 kWh/month and about $2,825/month savings. Pre-optimization energy costs for the wastewater system averaged $4,161 for 60,968 kWh/month to process 1.66 MGD; post-optimization costs averaged $2,979 for 53,810 kWh/month to process 1.54 MGD (1995–1999 costs).

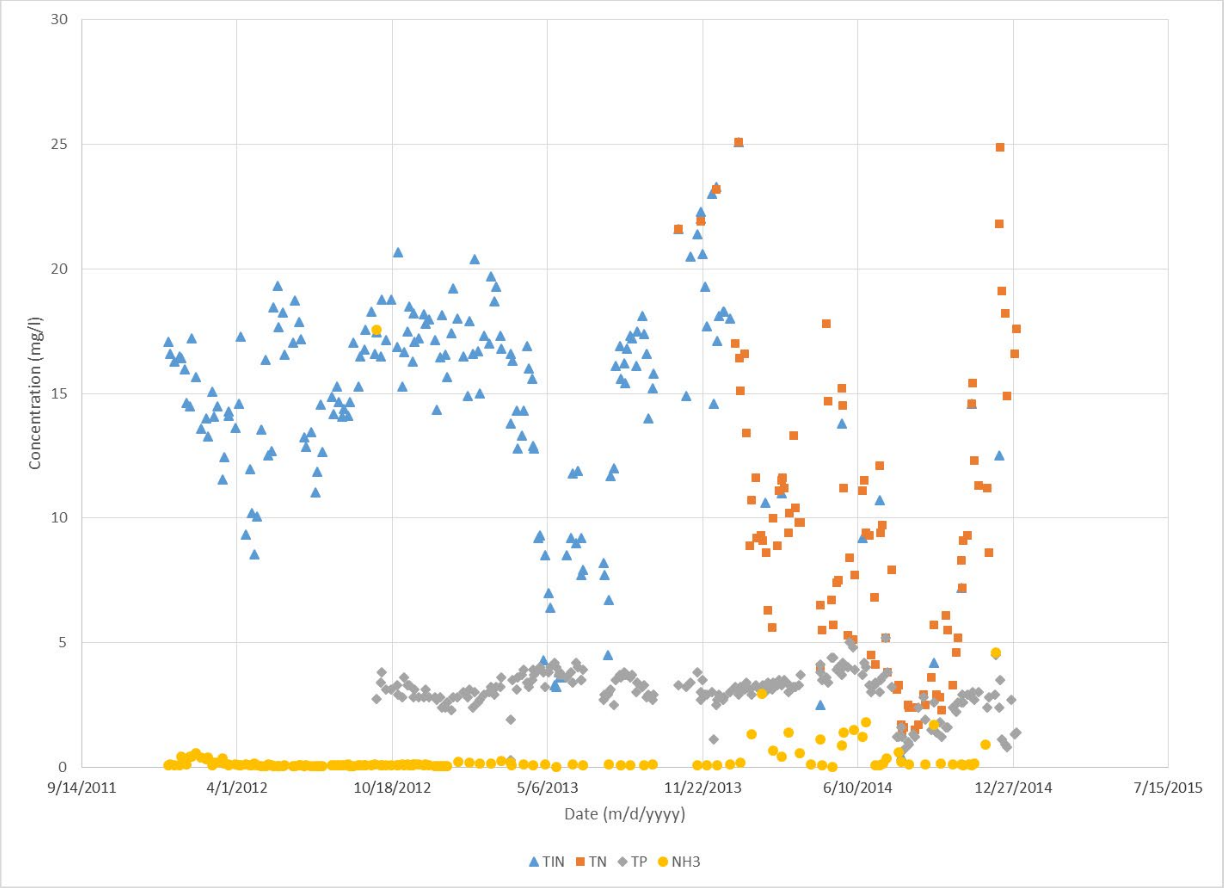
**Technical assistance received or needed:** Consultants advised the Montrose staff on energy and nutrient optimization strategies.

## PERFORMANCE

The plant staff has always produced an effluent with extremely good quality. Prior to on/off being initiated, the effluent BOD, TSS, and ammonia were 2.55 mg/L, 3.75 mg/L, and 0.34 mg/L, respectively.

Results after on/off was initiated showed substantial improvement in TSS and ammonia. The TSS dropped by 36 percent while the ammonia dropped by almost 68 percent. Effluent nitrate concentrations varied from below 5 mg/l to approximately 10 mg/l. Recent time series data are plotted in the chart below.

The operators had theorized that on/off aeration during digestion would not only save money, but would also reduce the amount of nitrate returned and increase the pH of the supernatant returned to the aeration tank. The nitrate concentration in the supernatant can easily approach 30 mg/L or more at the beginning of the off cycle. No actual data is available to support the observation that digested sludge quality has remained as good, or been better than before relative to sludge dewatering. However, there have been no noticeable problems with sludge dewatering. Nor have there been problems meeting Class B biosolids regulations as the specific oxygen uptake rate (SOUR) typically runs 0.7–0.8, or about half of that allowed.



## FUTURE IMPROVEMENTS

Since the original optimization efforts, the only improvements made at the Montrose WWTP have been the variable frequency drives (VFDs) installed on the rotors. VFDs are operational in two of the ditches now, and the third should be running by the end of 2015. The cost for the VFDs was about $30,000 per ditch. The plant is also installing DO, oxidation-reduction potential, and TSS probes in the ditches. This project should also be completed by the end of the year.

By experimenting with rotor speeds and rotor submergence depths, it has been determined that an anticipated effluent limit of 15 mg/l TN could be met some of the time, but not all of the time. Upgrades would need to be made to meet the anticipated phosphorus limit of 1.0 mg/l.

## CONTACT INFORMATION

Allen Coriell, Superintendent, City of Montrose Wastewater Treatment Plant. Phone: (970) 240-1452. Email: acoriell@ci.montrose.co.us.

## OTHER RESOURCES

City of Montrose Wastewater Treatment:
http://www.cityofmontrose.org/160/Wastewater-Treatment

Schuyler, R.G., A. Coriell, and M. Carrano. *On/Off Aeration Energy Savings*.

# TAMPA, FLORIDA

# SEPARATE STAGE NITRIFICATION ACTIVATED SLUDGE—OPERATIONAL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** Howard F. Curren Advanced Wastewater Treatment Plant

**Location:** 2400 Guy North Verger Boulevard, Tampa, FL 33605 (latitude: 27° 55’33”N; longitude: 82° 26’06”W)

**Permitted design flow:** 96 MGD annual average (actual flow: 57 MGD, annual average)

**Service area:** City of Tampa (2010 population of 335,709)

**System type:** Multi-stage:
Stage 1 High-purity oxygen activated sludge for carbonaceous BOD removal
Stage 2 Dissolved aeration activated sludge for nitrification
Stage 3 Biological filters for denitrification

**Initial year of operation:** 1977

**Upgrade type:** Modified operational strategy

**Upgrade year of operation:** Improved operation initiated July 1, 2013

**Permitted effluent nitrogen limit:** 3.0 mg/L TN annual average, 3.75 mg/L TN monthly average, 4.5 mg/L TN weekly average, 6.0 mg/L TN single sample

**Pre- and post-upgrade effluent nitrogen performance:** Stage 2 bioreactor effluent: 18.62 mg/L 10-month average pre-upgrade; 13.82 mg/L 10-month average post-upgrade; denitrification filter effluent remained below 3.0 mg/L annual average throughout

**Permitted effluent phosphorus limit:** None

**Pre- and post-upgrade phosphorus performance:** N/A

## DECISION PROCESS

A 2013 preliminary engineering study for replacement of the aeration system at the nitrification tanks included modeling the tanks in several operating modes. Some of the modeled modes considered the excess capacity available at the current flow compared to the design flow. A key observation was that complete nitrification could be achieved with less aerobic volume than was being used. By temporarily operating a portion of the nitrification tanks in a low-dissolved oxygen (DO) or no-DO mode, anoxic conditions could be generated and some denitrification achieved. Any denitrification achieved at the nitrification tanks decreases the nitrogen removal required at the denitrification filters, allowing the feed of methanol as supplemental carbon source for denitrification to be decreased.

## SYSTEM OPTIMIZATION DESCRIPTION

Upgrade was through operational changes only. Aeration was decreased in initial zones (1 and 2 of 6) in each of the three operating nitrification tanks to create an initial low-DO region for simultaneous nitrification and denitrification. DO concentrations were decreased from 2.5 mg/L to less than 0.5 mg/L, average.

The nitrate content of return activated sludge (RAS) was low so internal recycle of nitrates into the low-DO region was accomplished by opening a gate to allow a portion of the nitrification tanks effluent (approximately 35 percent) to flow into the stage 2 influent pump station. Also, a portion of the plant influent (approximately 20 percent) was diverted around the stage 1 activated sludge process to provide influent BOD as a carbon source for denitrification.

A 4 mg/L decrease in nitrate nitrogen out of the second stage (pre-optimization average of 17 mg/L $NO_3$-N lowered to 13 mg/L $NO_3$-N) and into the denitrification filters allowed the operators to decrease the feed of methanol as supplemental carbon source by approximately 31 percent. The decrease in methanol feed resulted in chemical savings and decreased sludge production at the denitrification filters.

## COSTS AND OTHER IMPACTS

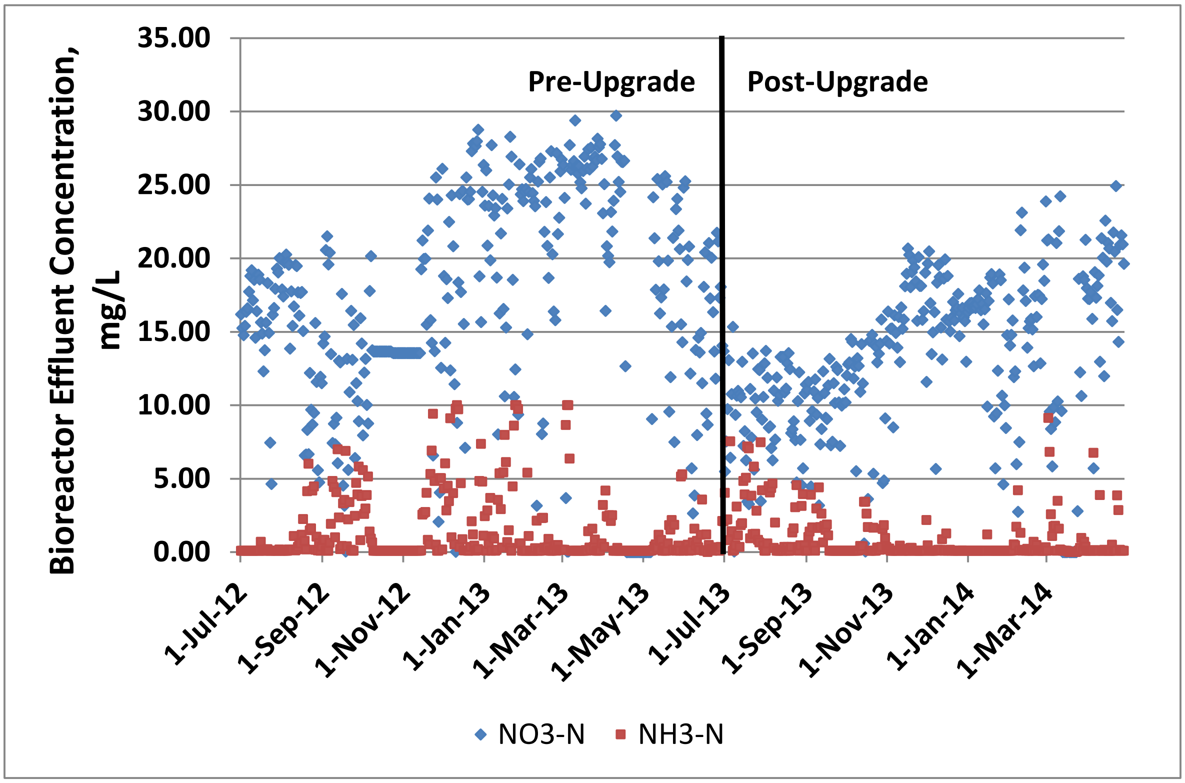
**Capital costs:** None.

**Operational costs:** Internal recycle pumping increased energy required at stage 2 influent pump station by approximately 50 hp (37.3 KW). At $0.07/KWhr, the additional energy cost is approximately $22,900. The methanol feed was decreased by an average of 1,487 gallons per day for an annual chemical savings of approximately $542,800. Net savings is approximately $519,900.

**Technical assistance received or needed:** A consultant was hired to recommend modifications to improve nutrient removal.

## PERFORMANCE

Pre- and post-upgrade total nitrogen statistics are summarized in the chart below.



## FUTURE IMPROVEMENTS

Installation of a new aeration in the nitrification tanks will allow the fourth nitrification tank to be placed into service, thereby providing additional bioreactor volume that can be converted to anoxic or low-DO conditions to increase the nitrogen removal capacity at stage 2. Low power mixers will be added at zones 1 and 2 of each nitrification tank to maintain solids in suspension without aeration in those zones, allowing aeration in zones 1 and 2 to be eliminated entirely to approach true anoxic conditions for improved denitrification. The new aeration system will include controls to provide the flexibility for cyclical or on/off aeration in any of the six zones of each nitrification tank to maximize stage 2 denitrification. Dedicated recycle pumps will be added in zone 6 of each nitrification tank to provide more efficient (lower head) internal recycle than is achieved using the stage 2 influent pump station for recycle.

## CONTACT INFORMATION

Rory Jones, Wastewater Design, 306 East Jackson Street 6N, Tampa, FL 33602. Phone: (813) 274-7045. Email: Rory.Jones@ci.tampa.fl.us.

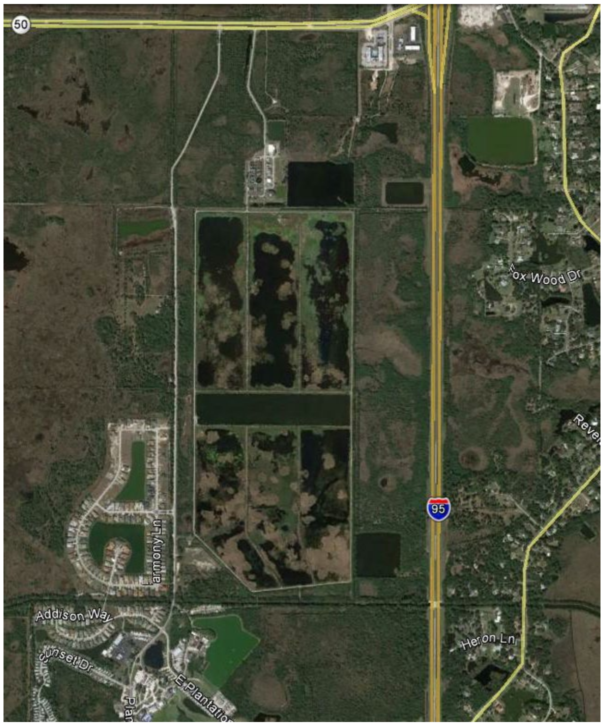
## OTHER RESOURCES

City of Tampa: http://www.tampagov.net/wastewater

# TITUSVILLE, FLORIDA

# A$^2$/O WITH SECONDARY ANOXIC AND WETLAND DISCHARGE

## SYSTEM SUMMARY



**Official Name:** City of Titusville Blue Heron Water Reclamation Facility (WRF) and Wetland

**Location:** 4800 Deep Marsh Road, Titusville, FL 32780 (latitude: 28° 32' 58" N; longitude: 80° 51' 41" W)

**Permitted design flow:** 6.75 MGD, average daily flow

**Service area:** City of Titusville

**System type:** Anaerobic/anoxic/oxic (A$^2$/O) process with secondary anoxic zones

**Initial year of operation:** 1996

**Upgrade type:** Process optimization and discharge into constructed/restored wetland (part of original design)

**Upgrade year of operation:** 1996

**Permitted effluent nitrogen limit:** 6 mg/l TN, annual average from plant; 1.6 mg/l TN, annual average from wetland

**Pre- and post-upgrade effluent nitrogen performance:** Wetland influent and effluent TN statistics are summarized below for the years 2009 through 2013

**Permitted effluent phosphorus limit:** 1.75 mg/l TP, annual average from plant; 0.16 mg/l TP, annual average from wetland

**Pre- and post-upgrade phosphorus performance:** Wetland influent and effluent total phosphorus statistics are summarized below for the years 2009 through 2013

| | Wetland Influent Concentration | | Wetland Effluent Concentration | | |
|---|---|---|---|---|---|
| | Average Concentration | Standard Deviation | Average Concentration | Standard Deviation | Units |
| **Total Nitrogen** | 5.67 | 2.28 | 0.94 | 0.41 | mg/l |
| **Total Phosphorus** | 0.77 | 0.66 | 0.04 | 0.03 | mg/l |

## RATIONALE AND DECISION PROCESS

The Blue Heron Water Reclamation Facility was originally designed to achieve Florida Class III Surface Water requirements (i.e., Fish Consumption, Recreation, Propagation and Maintenance of a Healthy, Well-Balanced Population of Fish and Wildlife) through a combination of biological nutrient removal (BNR), water reuse, and, for water not reused, treatment using constructed wetlands prior to discharge into the Addison Canal, which is a tributary of the nutrient-impaired St. Johns River estuary.

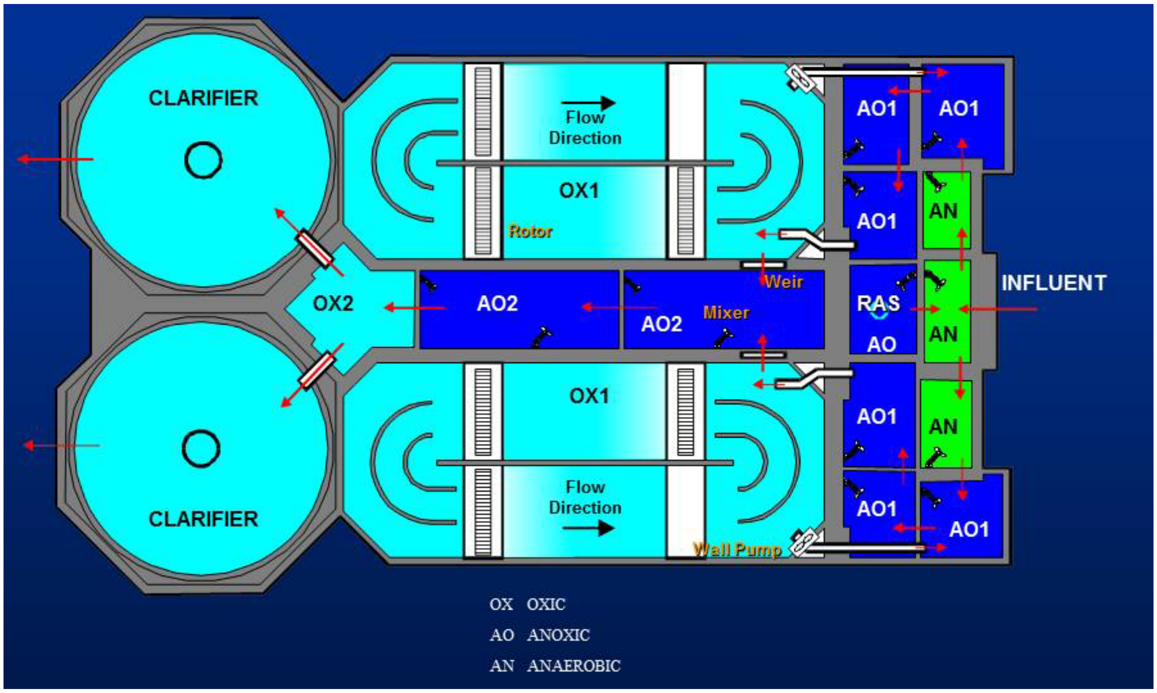
The original BNR process was installed in 1996 and initially optimized by plant staff in collaboration with the technology vendor through 1997. The treatment wetland was a feature of the initial plant design, and the reuse system was put into operation several years later. This case study discusses initial BNR optimization efforts, as well as the treatment wetland, which further reduces nutrients prior to the receiving water.

## SYSTEM OPTIMIZATION AND PERFORMANCE DESCRIPTION

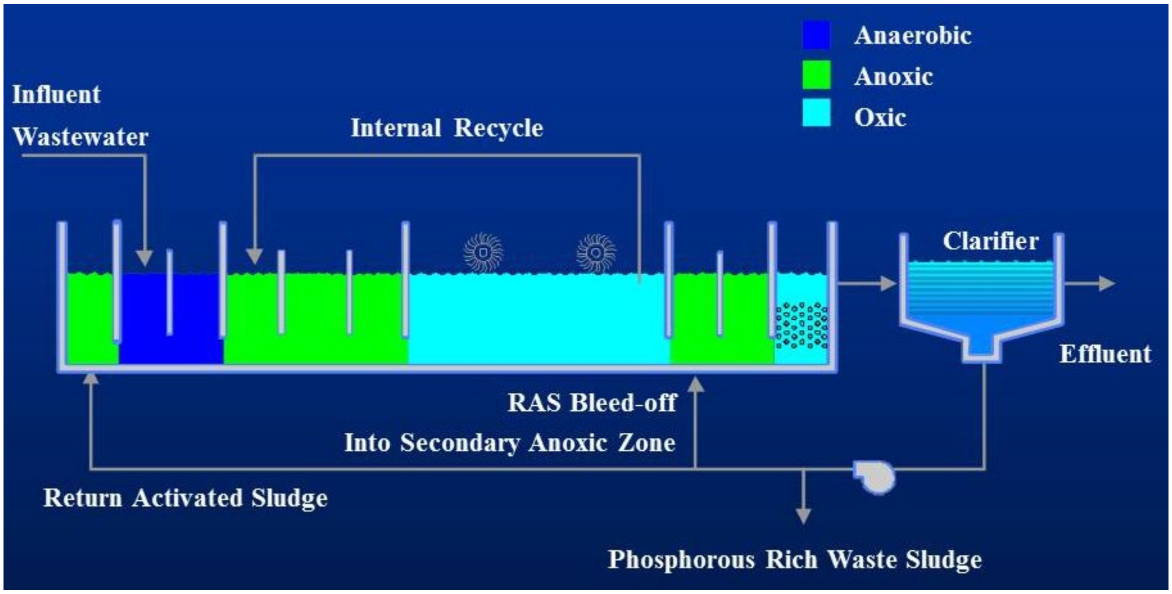
### Initial BNR Process Optimization

During start-up and initial process optimization efforts, modifications were successfully applied to the $A^2/O$ process to consistently meet stringent permitted effluent limits of 5 mg/l BOD, 5 mg/l TSS, 3 mg/l TN, and 1 mg/l TP without the addition of metal salts for precipitating phosphorus or a supplemental carbon source to facilitate denitrification. These initial optimization improvements included the return activated sludge (RAS) denitrification stage modification for improved phosphorus uptake and removal, and the RAS bleed-off improvement for increasing denitrification within the secondary anoxic zones.

The Blue Heron WRF utilizes a 2-train $A^2/O$ (anaerobic/anoxic/oxic) process, which is configured with anaerobic selectors, primary anoxic zones, oxidation ditches equipped with mechanical brush aerators, secondary anoxic zones, and a reaeration basin followed by secondary clarifiers. The unaerated stages of the process (the anaerobic and anoxic stages) are each equipped with submersible mixers to suspend the mixed liquor and facilitate biological processes. Each oxidation ditch is also equipped with submersible wall pumps that return nitrified mixed liquor to the primary anoxic stages where denitrification occurs.

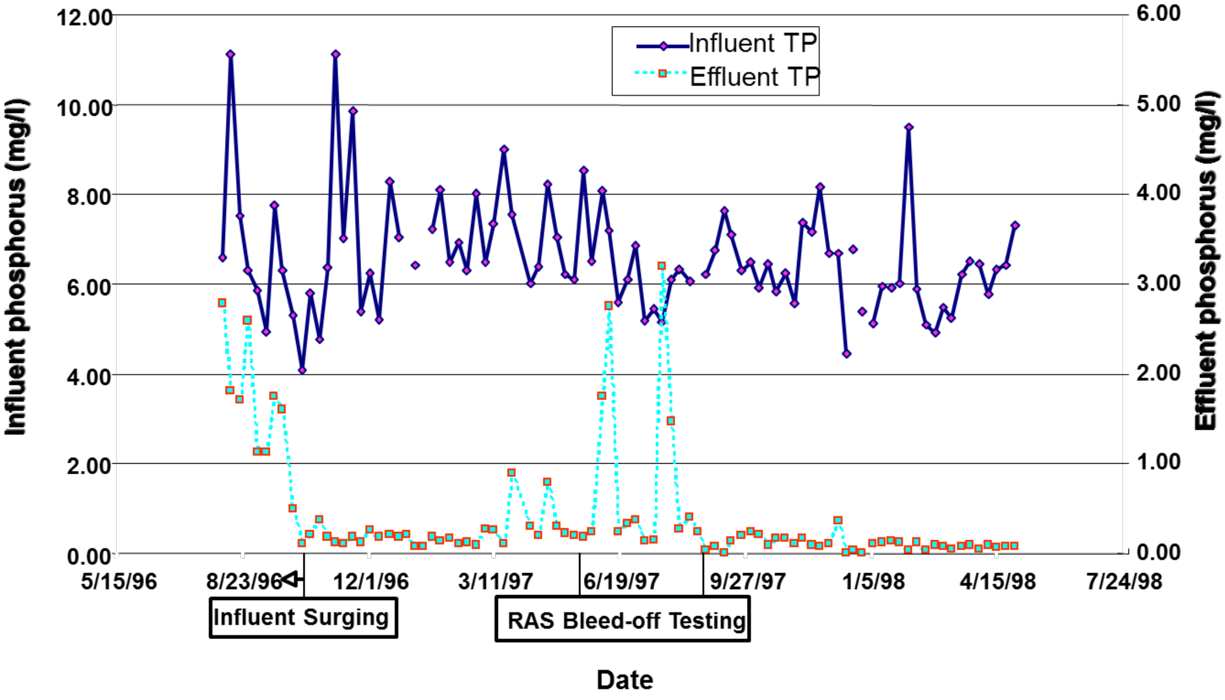


The RAS Denitrification Stage modification—also known as the Block and Hong Process—refers to the strategy of staging the introduction of RAS and influent into the anaerobic selector. As depicted in the diagram below, RAS only is introduced to the first stage of the anaerobic selector, while the denitrified RAS and influent are mixed in the second and subsequent stages. This modification ensures that ideal anaerobic conditions are maintained and that the availability of substrate for the phosphorus-removing organisms within the anaerobic selector is maximized in the subsequent stages. In most biological phosphorus removal processes, sludge collected in the secondary clarifiers and containing nitrates is combined with influent wastewater and fed into a selector. The introduction of nitrates from the RAS into the selector compromises the phosphorus removal process by inhibiting the metabolism of organisms responsible for enhanced biological phosphorus removal by allowing other organisms to consume soluble carbon substrates (i.e., BOD), thereby lowering the soluble BOD:P ratio below optimal levels and compromising biological phosphorus removal.



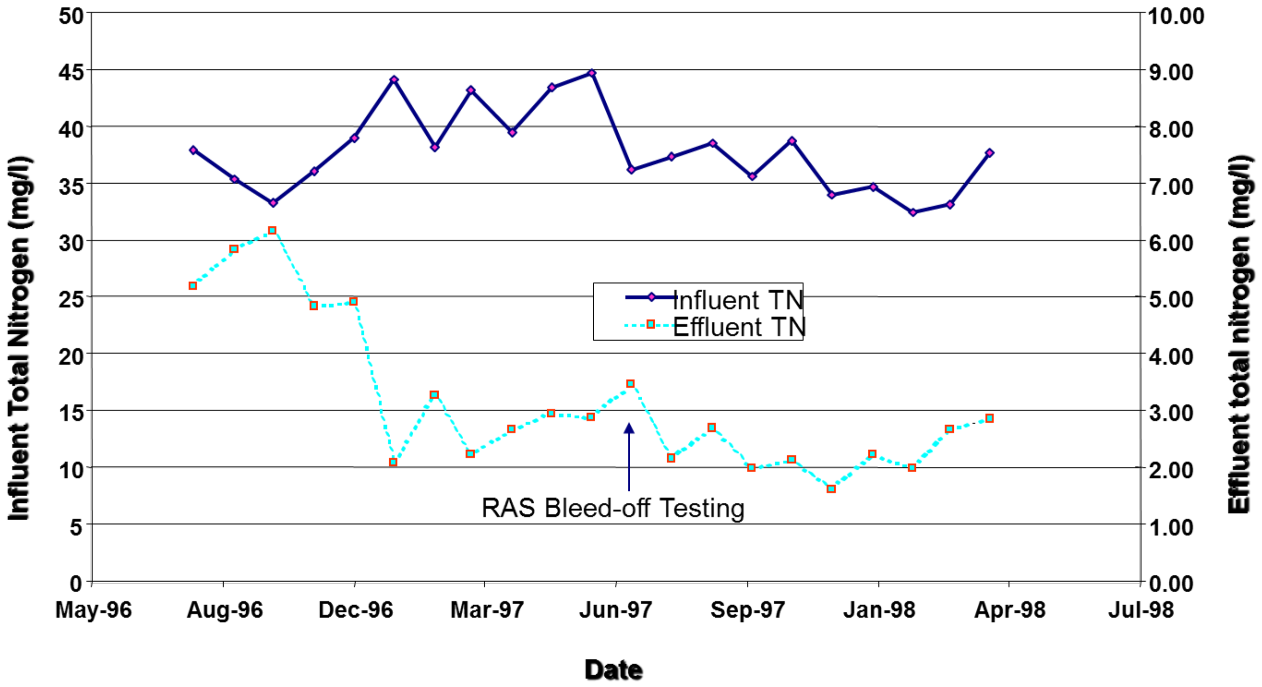
There were several periods when the effluent phosphorus concentration was unusually high. When the plant was initially started up, the influent pumping scheme delivered influent to the biological process in surges. For example, the influent pumps might have fed the process for 5 minutes at a relatively high flow rate and then been inactive for a one-half hour or more. This "all-or-nothing" feeding sequence appeared to result in hydraulic surges through the anaerobic selector as well as a discontinuous organic loading to the organisms responsible for taking up high levels of phosphorus. The amount of phosphorus uptake and removal was compromised, as documented in the effluent phosphorus measurements during plant start-up (August and September 1996). In October 1996, the influent pumping scheme was modified to minimize influent flow surges, which greatly improved the performance of the phosphorus removal system. Influent wastewater was directed into the Blue Heron WRF by gravity flow from the South Master Pump Station, resulting in a relatively consistent influent flow rate to the plant. The pumps in this basin activate only when the influent flow is high and the water level within the station exceeds a preset limit.

In the summer of 1997, the return activated sludge (RAS) bleed-off improvement for nitrogen removal was being tested and optimized. For several periods during that time, too little RAS was being returned to the first stage of the anaerobic selector. As a result, the amount of phosphorus released in the anaerobic selector was not sufficient and did not adequately promote enhanced phosphorus uptake in the oxic stage of the process. At high RAS bleed-off rates and, therefore, correspondingly lower RAS return rates to the head of the biological plant, phosphorus uptake was temporarily compromised.

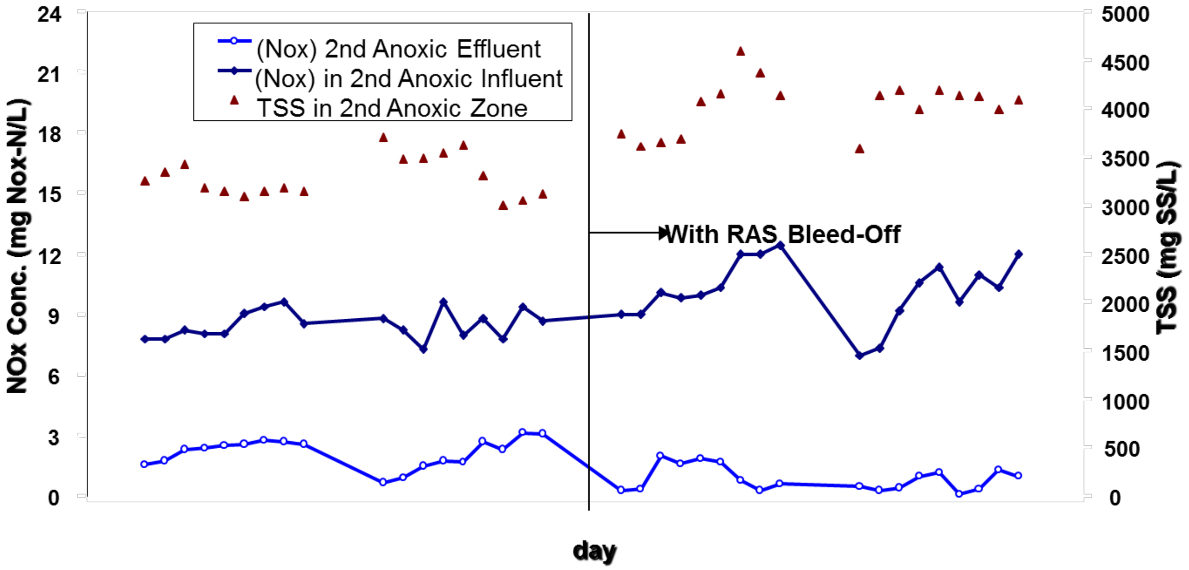


The treatment process at the Blue Heron WRF includes secondary anoxic zones for supplemental denitrification, required to meet the stringent effluent TN limit of 3 mg/l as N. The efficiency of typical secondary anoxic reactors is often low due to the lack of a readily degradable carbon source in the mixed liquor following oxic treatment. The RAS bleed-off improvement allows for a portion of the RAS to be introduced directly into the secondary anoxic zones, as indicated in the flow schematic above, to increase the extent and rate of denitrification. Unique to the $A^2/0$ process, the RAS bleed-off improvement increases the biomass and degradable carbon to stimulate denitrification.

Influent and effluent nitrogen profiles for the Blue Heron WRF indicate that denitrification via the primary and secondary anoxic zones has been effective and, after the start-up period, consistently averaged below 3 mg/L (monthly average basis). In June 1997, the RAS bleed-off system was being tested and the resulting average effluent TN exceeded 3 mg/l. Once optimized, the RAS bleed-off system has resulted in lower effluent TN than did the process without the RAS bleed-off.



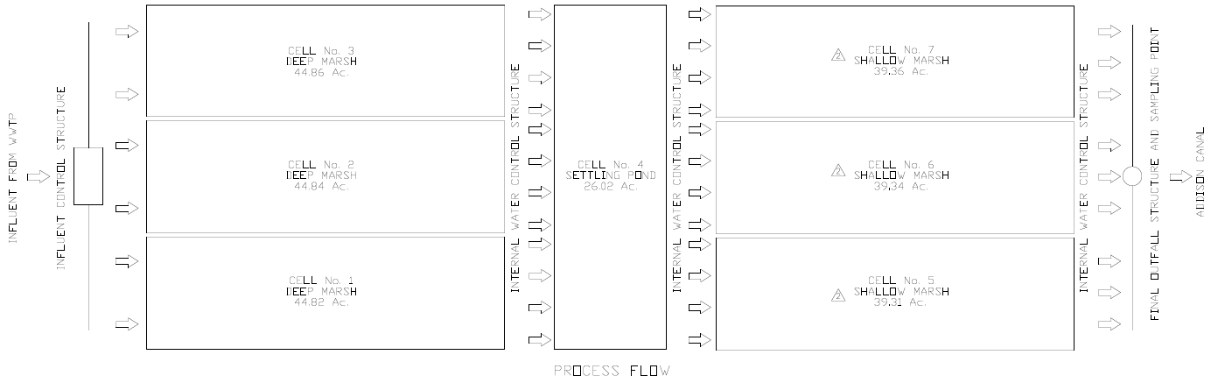
The figure below shows how the RAS bleed-off and associated increase in mixed liquor suspended solids (MLSS improved denitrification within the secondary anoxic zones. In the Blue Heron WRF, the MLSS concentration of the secondary anoxic zone was increased by about 20 percent, while the average effluent TN was reduced by nearly one-half during the test period profiled.



## Blue Heron Wetland Treatment System

The Blue Heron Wetland Treatment System was designed so that any effluent not used in the reclaimed water distribution system can be diverted to the wetland area. The man-made wetlands, including berms and upland area, cover almost 300 acres and can process around 6.75 million gallons a day (MGD) of wastewater: 4.0 MGD of wastewater coming from the city's Blue Heron WRF and 2.75 MGD coming from the Osprey/North facility. The wetlands are designed for influent characteristics of 5 mg/l CBOD, 5 mg/L TSS, 6 mg/L TN, and 1.75 mg/L TP.

The Blue Heron Wetland Treatment System was designed as a flow-through system that uses visible and microscopic aquatic plants (macrophytes and phytoplankton) to remove nutrients from the treatment plant effluent. The wetland is divided into seven cells: one pond cell, three deep (2’–4’) marsh cells, and three shallow marsh cells. The cells are separated by earthen berms. Water flows by gravity through the seven cells to a collection system along the south side of the site, which drains to the Addison Canal. Flows from the wetland discharge to the Addison Canal, which is a tributary of the St. Johns River.



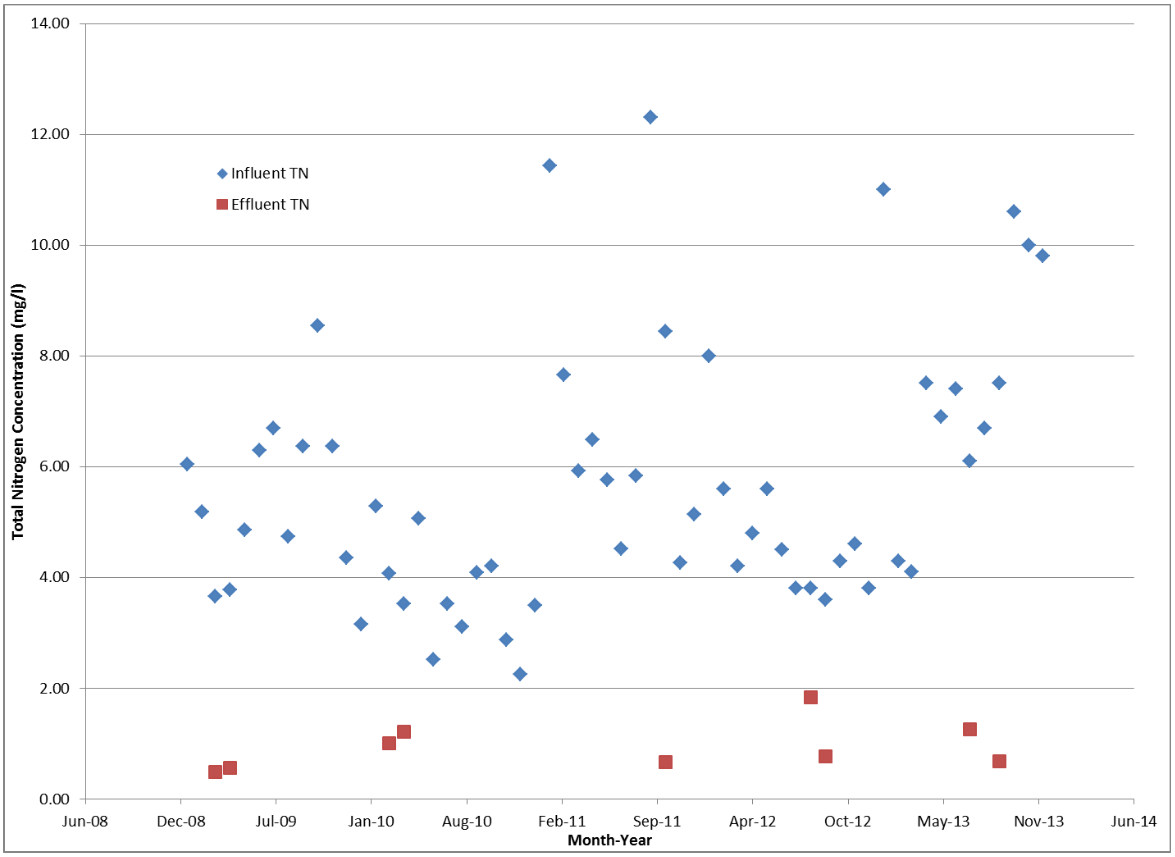
The berms are designed to maintain the water levels so that target vegetation species receive adequate water supply. The berms also provide storage for a 100-year 24-hour storm event. The average detention time for water in the wetland is approximately 60 days. The minimum detention time is 14 days. Removing or adding flash boards to the weir structures located in each cell controls water depth and internal flow routing.

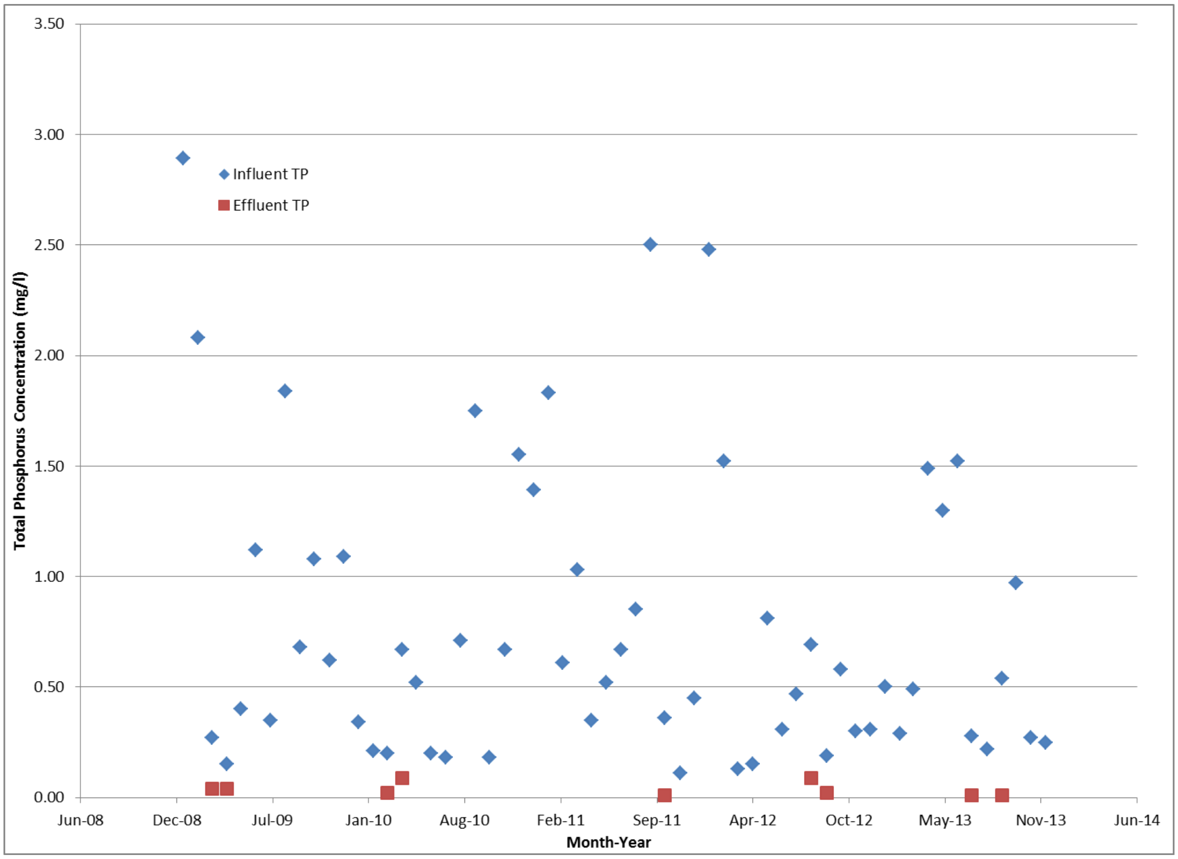
The Blue Heron wetland area is open to the public and a popular site for bird watching and photography enthusiasts and is listed on the Great Florida Birding Trail. It is often included as a field trip for the renowned annual Space Coast Birding and Wildlife festival. The total distance around the perimeter is 2.8 miles. The predominant plant species found in the wetland include Arrowhead, Bladderwort, Bulrushes, Duckweed, Naiad, Pickerelweed, Sand Cordgrass, Seashore Paspalum, Smartweed, Spikerush, and Watergrass.

Some of the birds observed at the wetland include:

- Blue Heron
- Great, Common, and Snowy Egret
- Moore Hen
- Mourning Dove
- Green Heron
- Anhinga
- Pied-Billed Grebe
- Great Blue Heron
- Red-Shouldered Hawk
- White Ibis
- Mottled Duck
- Purple Gallinule
- Yellow- and Black-Crowned Night Heron
- Northern Shrike
- Northern Mockingbird
- Red-Winged Blackbird
- Common Grackle

Pre- and post-upgrade TN and TP statistics are summarized on page 1. Detailed nutrient removal data for the wetlands discharge are presented in the graphs below.


14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Total Nitrogen Concentration (mg/l)
◆ Influent TN
■ Effluent TN
Jun-08
Dec-08
Jul-09
Jan-10
Aug-10
Feb-11
Sep-11
Apr-12
Oct-12
May-13
Nov-13
Jun-14
Month-Year


3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Total Phosphorus Concentration (mg/l)
◆ Influent TP
■ Effluent TP
Jun-08
Dec-08
Jul-09
Jan-10
Aug-10
Feb-11
Sep-11
Apr-12
Oct-12
May-13
Nov-13
Jun-14
Month-Year

## COSTS AND OTHER IMPACTS

**Capital costs:** $2.24 million (1996 costs) for wetland.

**Operational costs:** Approximately $45,000 annually for the wetlands, which includes monitoring responsibilities (water quality sampling, vegetation monitoring, soil sampling, detritus sampling, and denitrification studies), operational responsibilities (inspection, water-level adjustment, vegetation maintenance, evapotranspiration monitoring, annual reporting, permitting assistance, public education), and maintenance responsibilities (weir structures, control of invasive plants).

**Technical assistance received or needed:** Process supplier provided start-up and optimization services for the BNR system. No particular technical assistance has been required for the wetland.

## CHALLENGES

If the system could be designed over again, plant staff would like to have the ability to recirculate the water within the wetland (back to front) to achieve an even higher level of nutrient removal.

## FUTURE IMPROVEMENTS

Aeration upgrade for the Blue Heron WRF treatment unit. No plans for wetland system improvements.

## CONTACT INFORMATION

Matt Hixson. City of Titusville Water Reclamation, 4800 Deep Marsh Road, Titusville, FL 32780. Phone: (321) 567-3891. Fax: (321) 383-5646. Email: matt.hixson@Titusville.com.

## OTHER RESOURCES

City of Titusville: http://www.titusville.com/

Domestic wastewater wetland sites in Florida: http://www.dep.state.fl.us/water/wastewater/dom/wetsites.htm

Blue Heron Wetlands: http://www.dep.state.fl.us/water/wastewater/dom/wetheron.htm

D’Amato, V.A., M. Hixson, and S.N. Hong. 1998. Environmental Protection through Innovative Wastewater and Sludge Treatment Strategies in Florida. In *Proceedings of Water Environment Federation 71st Annual Conference and Exposition*, Vol. 1, Pt. II. Municipal Wastewater Treatment, Session 2. Biological Nutrient Removal, Orlando, Florida, October 1998, pp. 487–498.

# VICTOR VALLEY, CALIFORNIA

# ACTIVATED SLUDGE—PROCESS CONTROL AND MECHANICAL MODIFICATIONS

## SYSTEM SUMMARY

**Official Name:** Victor Valley Wastewater Reclamation Authority (WRA)

**Location:** 20111 Shay Road, Victorville, CA 92394 (latitude: 34° 37’ 14.76”; longitude: 117° 21’ 26.47” W)

**Permitted design flow:** 13.8 (originally 18) MGD

**Service area:** Victor Valley WRA’s four member agencies: the Town of Apple Valley, the City of Victorville, the City of Hesperia, and San Bernardino County Service areas 42 and 64 (including Spring Valley Lake and Oro Grande). Population of approximately 400,000.

**System type:** Conventional activated sludge

**Initial year of operation:** 1981

**Upgrade type:** Improved process controls and mechanical modifications

**Upgrade year of operation:** 2007–2008 (additional upgrades in 2013)

**Permitted effluent nitrogen limit:** 10.3 mg/l TN, monthly average

**Pre- and post-upgrade effluent nitrogen performance:** 8.93 mg/l TN average, pre-upgrade; 6.83 mg/l TN average, post-upgrade

**Permitted effluent phosphorus limit:** N/A

**Pre- and post-upgrade phosphorus performance:** N/A

| | Influent | Effluent - Pre-Upgrade | | Effluent - Post-Upgrade | | |
|---|---|---|---|---|---|---|
| | Average Concentration | Average Concentration | Standard Deviation | Average Concentration | Standard Deviation | Units |
| **Ammonia** | 26.6 | 0.84 | 0.91 | 0.26 | 0.37 | mg/l |
| **Nitrite** | | 0.54 | 0.40 | 0.22 | 0.13 | mg/l |
| **Nitrate** | | 7.55 | 1.45 | 5.30 | 1.72 | mg/l |
| **TKN** | 39.2 | 1.43 | 0.84 | 1.28 | 0.57 | mg/l |
| **TN** | | 8.93 | 1.06 | 6.83 | 1.58 | mg/l |

## DECISION PROCESS

Around 2006, Victor Valley WRA's regulatory authority, the Lahontan Regional Water Quality Control Board, suggested a 6.0 mg/l TN effluent discharge standard for the facility. A subsequent feasibility report recommended the addition of a treatment train at an estimated capital cost of about $80 million with no increase in treatment capacity. At that time, a director of operations was hired to determine how the WRA could improve the efficiency of their existing operation and address about 10 years of deferred maintenance.

## SYSTEM OPTIMIZATION DESCRIPTION

The Victor Valley WRA Shay Road plant includes two mechanically cleaned 5mm X 20 mm bar screens and aerated grit removal with cyclone separators for headworks. From the headworks, wastewater flows through primary clarifiers (four parallel trains) and then onto secondary treatment (with the option to use flow equalization to mitigate wet weather flows and diurnal peaks). Eight secondary treatment basins are aerated by centrifugal blowers. Six secondary clarifiers are used and waste activated sludge (WAS) is sent to dissolved air flotation thickeners and then to anaerobic digesters. Secondary effluent is typically treated with alum and polymer prior to tertiary filtration in either traveling bridge or moving bed filters, followed by chlorine disinfection and dechlorination using bisulfite. The disinfected and dechlorinated effluent is either reclaimed for irrigation (at the plant or nearby golf course), industrial process water, or other beneficial purposes, or it is discharged directly to the Mojave River. Additionally, secondary effluent can be discharged directly to any one of six percolation ponds, which have a combined surface area of about 13 acres.

In the 2007–2008 time frame, the WRA performed upgrades to primary clarifiers including improved grease removal, aeration basin rebuilds (replacing existing soft diffusers), installation of high-speed turbo blowers, and a multitude of operational changes, including switching from an extended aeration activated sludge operation to conventional activated sludge and adding recirculation pumps, dissolved oxygen (DO) probes, and oxidation-reduction potential (ORP) sensors. This first phase of optimization cost approximately $1.1 million over 3 years and allowed the WRA to be able to meet their new nitrogen limits of 8.3 mg/l nitrate (revised from the originally suggested 6.0 mg/l TN).

Subsequent operational and process control modifications included optimizing wasting rates by targeting a sludge volume index (SVI), which improved settling and process stability. Staff also continued to upgrade the monitoring system, including integrating DO and ORP sensors into their supervisory control and data acquisition (SCADA) system. They also converted from engine-driven blowers to electric blowers for energy efficiency.

The Victor Valley VWRA is currently into the third phase of process optimization, which includes installing membrane diffusers and rebuilding the air distribution system. They are also rebuilding their existing aeration basins to allow for better control of aeration/redox conditions using baffle walls to facilitate tapered aeration. Their current effluent discharge limits are 10.3 mg/l TN.

In summary, plant staff currently monitor and control DO, ORP, alkalinity, and sludge age (typically 8–15 days), which varies based on the time of year and the temperature of the water. The facility's current operation uses a process referred to as "plug-flow extended aeration", although the plant is designed so the operators can also use step-feed, contact stabilization, or conventional aeration treatment. Process objectives include:

- Using simultaneous nitrification and denitrification in the aeration zones for nitrate removal. This is achieved by profiling the DO concentration in the aerobic zones of the aeration basins, which is necessary as the anoxic recycle pump capacity is limited and the anoxic zones do not have spare volumetric capacity to deal with much more recycle.

- Operating the facility at the minimum sludge age to achieve both nitrification and denitrification. This limits the biomass carried in the aeration basins and, therefore, reduces the solids load to the clarifiers. The most critical process conditions are maximum month loadings during winter conditions, which result in decreased aerobic solids retention time (SRT) values that make nitrification during winter months the controlling factor. Simulation modeling indicates that the current configuration of aeration basin volume and DO profile will continue to result in compliant effluent as flow increases provided a minimum sludge age of around 7 days is maintained. Maintaining a 7-day SRT as flows increase requires that the total reactor biomass be increased proportionally. That increase in biomass can be accomplished by raising the mixed liquor suspended solids (MLSS) concentration or by adding additional reactor volume. Although SRT can be increased by raising the MLSS concentration, doing so results in increased solids loading on the secondary clarifiers. When a clarifier is loaded beyond capacity, the TSS concentration from the clarifiers to the downstream filters can increase to a very high level, which will result in plugging up the filters.

## COSTS AND OTHER IMPACTS

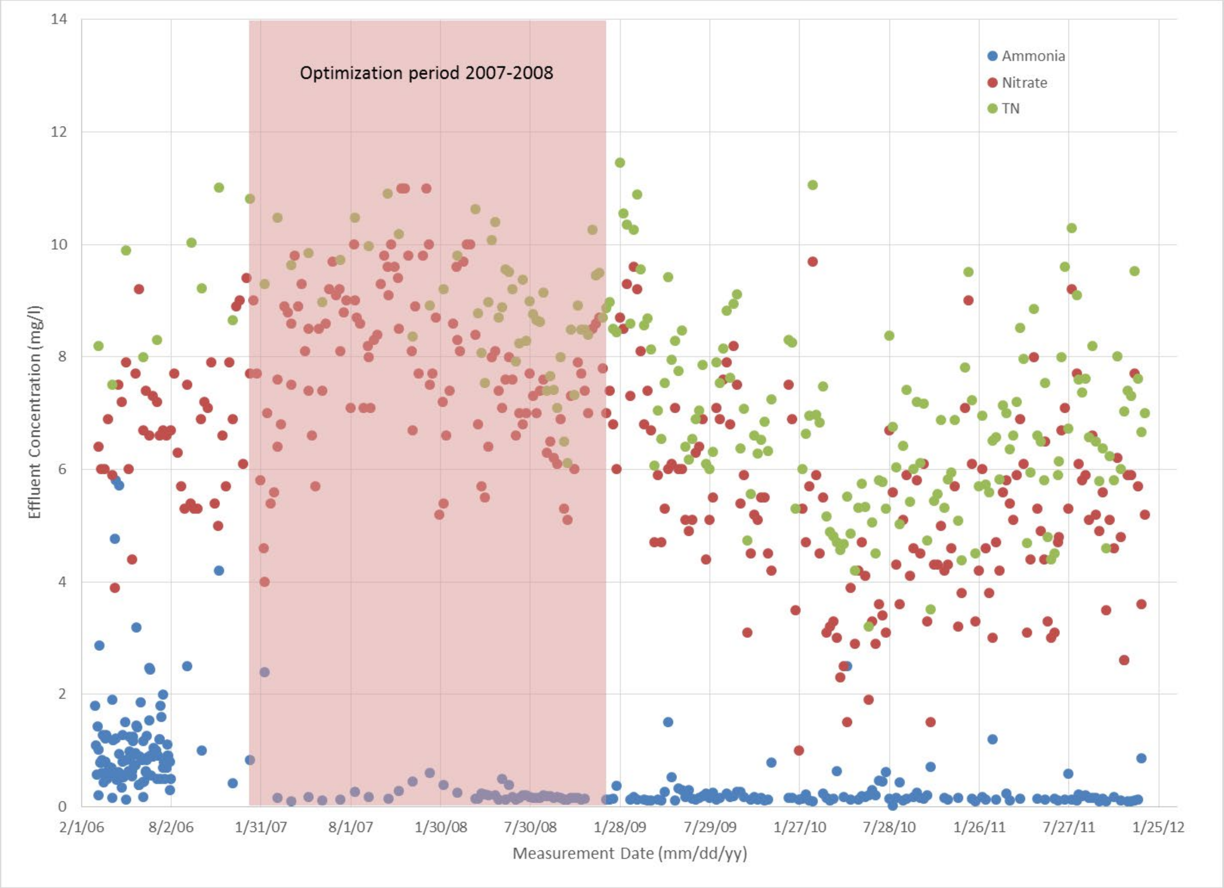
**Capital costs:** Phases 1 and 2: approximately $1.1 million over 3 years. Phase 3 (ongoing): approximately $1.2 million.

**Operational costs:** Operational cost-savings of approximately 10 percent.

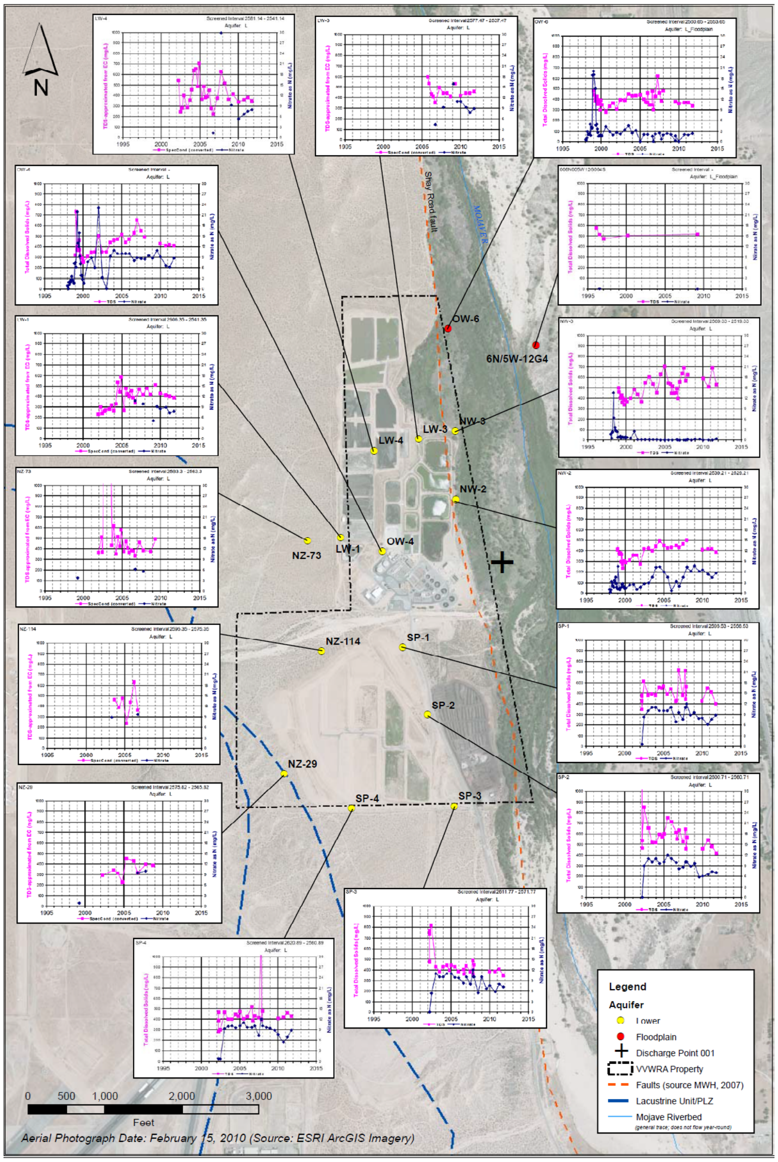
**Other implications:** Process changes caused some loss in hydraulic capacity, from the original rating of 18 MGD to about 14 MGD now.

## PERFORMANCE

Pre- and post-upgrade TN and T statistics are summarized in the "System Summary. Time series data are presented in the chart below.



Nitrate concentrations in ground water monitoring wells continue to fall with less loading to the percolation ponds (see the figure below).



## FUTURE IMPROVEMENTS

Into phase 3 now, as described above, which includes adding high-speed turbo blowers, installing membrane diffusers, and rebuilding the air distribution system. They are also rebuilding the aeration basins to control loading/time of year with baffle walls to facilitate tapered aeration.

## CONTACT INFORMATION

Logan Olds, General Manager, Victor Valley Wastewater Reclamation Authority. Phone: (760) 246-8638. Email: lolds@vvwra.com.

Gilbert Perez, Director of Operations, Victor Valley Wastewater Reclamation Authority. Email: gperez@vvwra.com.

## OTHER RESOURCES

Victor Valley Wastewater Reclamation Authority: http://vvwra.com/

# WOLFEBORO, NEW HAMPSHIRE

## EXTENDED AERATION ACTIVATED SLUDGE—CYCLIC AERATION

## SYSTEM SUMMARY

**Official Name:** Wolfeboro Wastewater Treatment Facility (WWTF)

**Location:** 46 Filter Bed Road, Wolfeboro, NH 03894 (latitude: 43° 35' 33" N; longitude: 71° 13' 06" W)

**Permitted design flow:** 0.6 MGD

**Service area:** Town of Wolfeboro, population of approx. 6,000

**System type:** Activated sludge (extended aeration)

**Initial year of operation:** 1975

**Upgrade type:** Cyclic aeration

**Upgrade year of operation:** 2007

**Permitted effluent nitrogen limit:** 10 mg/l TN in rapid infiltration basin monitoring wells

**Pre- and post-upgrade pond effluent nitrogen performance:** 6.32 mg/l TN pre-upgrade; 1.97 mg/l TN post-upgrade

**Permitted effluent phosphorus limit:** N/A

**Pre- and post-upgrade phosphorus performance:** 0.71 mg/l (no upgrades were made to TP removal processes)

## RATIONALE AND DECISION PROCESS

The Wolfeboro WWTF was initially built in the 1970s as a temporary facility to replace a primitive system that discharged to a tributary of Lake Winnipesaukee. The temporary plant was built as an interim measure until the Winnipesaukee River Basin Program (WRBP) could be planned and implemented. The WRBP is a regional treatment system that collects wastewater from many communities on the western side of the lake. Wolfeboro on the eastern side of the lake is not yet served.

In 1975, the extended aeration activated sludge WWTF initially treated an average daily flow of approximately 200,000 gallons per day (gpd) in the summer and 100,000 gpd in the winter. Initially, the treated effluent discharged to Front Bay. A land application, ground water recharge effluent spray irrigation system was brought online in 1978. The effluent spray system initially consisted of a 93-million-gallon storage reservoir (which accepts effluent flow from the WWTF) and approximately 140 acres of land divided into five spray fields.

In the early 2000s, the WWTF was approaching its 30-year anticipated lifespan and the summer resort town was under threat of an administrative order due to limited effluent disposal capacity (winter storage limitations and spray capacity) and a noncompliant sludge composting area (that could not meet new siting/permitting requirements). In general, the aging WWTF needed significant equipment upgrades to meet New Hampshire Department of Environmental Services (NHDES) requirements, which were eventually negotiated in an administrative order by consent (AOC) issued in the early 2000s.

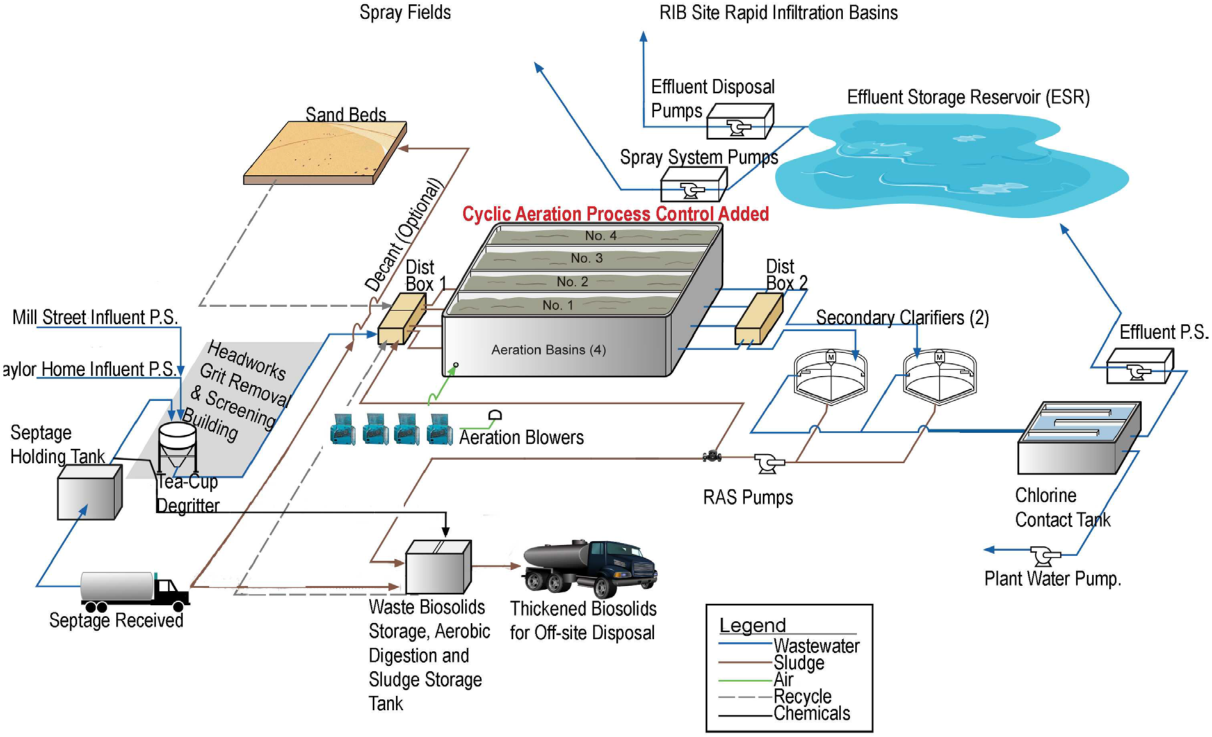
The AOC outlined actions needed to improve effluent management and address the residuals disposal issues. Wolfeboro commissioned several facility and disposal option evaluations. The proposed solutions to the WWTF and effluent disposal issues led to a new discharge permit with more stringent limits on total nitrogen (10 mg/l) and ammonia (5 mg/l) and triggers for actions to improve overall plant performance. The action levels tied the town to the potential need for a major WWTF upgrade. In December 2007, the town’s wastewater consultant issued a Basis of Design Report that recommended a major upgrade that included a new sequencing batch reactor (SBR) at a cost of $15 million.

Wolfeboro needed to determine whether a new plant was inevitable or it was feasible to rehabilitate the existing WWTF in a low-cost manner to comply with the proposed permit limits and extend its useful life another 10–20 years. The town also chose to construct rapid infiltration basins (RIBs) to address the effluent disposal capacity issues. Because of the cost of the effluent disposal project (approximately $7 million), the town wanted to explore low-capital cost WWTP upgrades that would help avoid or delay the costs of a major capital upgrade anticipated to meet the new permit limits. The use of cyclic aeration was chosen as the alternative method.

## SYSTEM OPTIMIZATION DESCRIPTION

While the various facility and disposal option evaluations were being conducted, Wolfeboro began an effort to update several pieces of process equipment to keep the aging infrastructure operational.

The WWTF had struggled to maintain an adequate dissolved oxygen (DO) concentration in the aeration process. To increase oxygen transfer, the antiquated ceramic dome diffusers were replaced. Wolfeboro and Woodard & Curran, the plant’s contract operator/consultant,



decided that it would be most cost-effective to retain the current air distribution piping and replace only the diffusers. The improvement in DO became apparent immediately upon start-up with the new diffusers, resulting in improved DO transfer and steady DO concentrations in the tanks. The improvements enabled one of the three aeration blowers to be turned off for all but the highest flow and loading conditions.

During a peer review meeting to discuss the facility upgrade evaluation, the idea of cyclic aeration was proposed as an alternative to a major plant upgrade. Based on the discussions and the fact that some capital upgrades were already underway, the town and its contract operator/consultant pursued the cyclic aeration alternative on a trial basis to improve the efficiency and performance of the activated sludge system.

With new, more efficient diffusers, the next improvement was to replace the system's aging and oversized blowers, which would increase reliability, save energy costs, and improve process performance. The replacement blowers were chosen to save on power costs and provide improved controls for process optimization techniques like cyclical aeration. As a part of the new blower installation, new blower programmable logic controllers (PLCs) and variable frequency drives (VFDs) were installed. During a follow-up phase of the upgrade, online DO and oxidation-reduction potential (ORP) instrumentation was installed in the two main aeration tanks. The probes were connected to a HACH SC1000 terminal to give operators continuous access to the probes' readings.

With the risk of mechanical equipment failure reduced, the upgrade made it possible to deviate from conventional aeration methods and experiment with cyclical aeration. The blowers could now be controlled based on DO levels and/or timers. ORP readings are used to monitor performance of the cyclic aeration system.

In July 2007, with the aeration upgrades completed, Woodard & Curran began implementation of the new process control strategy (using cyclical aeration as a means for optimizing activated sludge treatment and efficiency). Based on their experience with cyclic aeration at other locations in New England, operational staff settled on an operator-adjustable aeration cycle that typically runs at 45 minutes on and 1 hour off. The cycle timing is adjusted seasonally to ensure treatment efficiencies. When the blowers are on, the PLC controls the aeration tank's DO from becoming too high by decreasing the output of the blowers and will increase the blowers output when the DO is too low.

Cyclical aeration saves operating costs by reducing blower run times, and it can provide process benefits including a healthier, more stable mixed liquor and improved nutrient removal.

## COSTS AND OTHER IMPACTS

**Capital costs:**

| Capital Project | Year | Cost |
|---|---|---|
| New Aeration Diffusers ( and RAS/WAS valve project) | 2006 | $48,000 |
| Upgraded Aeration Blowers | 2007 | $50,000 |
| Online Plant Process Instrumentation | 2008 | $18,000 |

**Operational costs:** Operation and maintenance costs have decreased since the upgrade, mainly due to the decreased energy usage in the aeration process. Reducing the blower horsepower and incorporating cyclical aeration into the process has reduced the energy usage by up to 60 percent, saving thousands of dollars a year in energy costs. Additionally, the cyclical aeration process reduces the average run time of the blowers, potentially extending the capital lifespan of the equipment.

Monitoring the additional instrumentation and managing the cyclical aeration requires a small amount of additional labor, but that time is very well invested and provides returns in a smoother process that performs better and requires less troubleshooting.

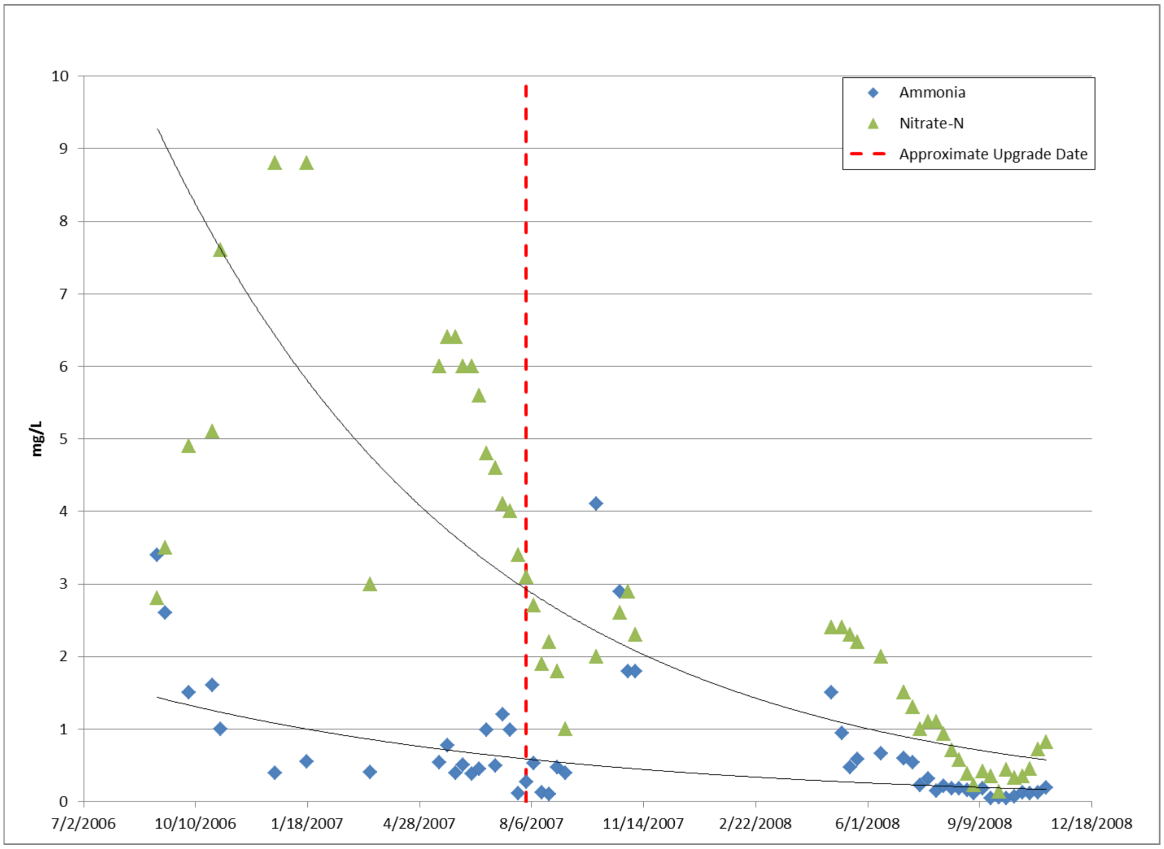
The primary cost-savings metric has been the ability to meet the permit requirements and improve plant safety and reliability. Currently, the need for a major capital upgrade (the $15-million SBR project) has been not been triggered in the AOC and Wolfeboro can continue to pay down the bonds from the discharge upgrade without the need for another major capital request.

**Technical assistance received or needed:** The upgrades at the Wolfeboro WWTP have made the facility more intuitive to operate. The new blowers are set to automatic setpoints and run times and do not require sustained attention. The new HACH process instrumentation allows for more transparent system performance and enables the operator to optimize the processes.

Site operators were required to participate in additional operator training classes on cycling air systems. Woodard & Curran brought in biological treatment process experts to work with staff and evaluate system operation.

## PERFORMANCE DISCUSSION

Pre- and post-upgrade total nitrogen statistics are summarized on page 1. A time-series plot of average annual effluent concentrations for ammonia and nitrate is provided below (for storage pond effluent).



## CHALLENGES

With the aging plant and the likelihood that a major upgrade would be needed, there was an initial perception that funding minor equipment upgrades was not worth the investment since replacement equipment would most likely need to be replaced again when a new system was installed. So, a major hurdle was resolved when the town of Wolfeboro agreed to invest in incremental capital improvements even though the full WWTF evaluation had not been completed.

A technical issue was to ensure efficient nitrification during colder weather. To address this, Woodard & Curran has been experimenting with the use of temporary biomedia tubes. They are 3-inch round tubes perforated, weighted, and filled with fixed media to which the biogrowth can adhere. During the winter period, the fixed-film media tubes are added to each active tank to increase SRT.

## FUTURE IMPROVEMENTS

Performance could be further improved in the facility by integrating more instrumentation and supervisory control and data acquisition (SCADA) process control. The plant currently lacks automation for the majority of its processes. The aeration upgrades have highlighted the positive effects that automation has on treatment performance and operational costs. Further automation and controls would provide the operators with more control over the process, allowing further optimization of the activated sludge process and other processes throughout the plant. The SCADA upgrades would enhance treatment reliability but would not necessarily reduce costs.

## CONTACT INFORMATION

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Russ Howe, Plant Manager, Woodard & Curran, 46 Filter Bed Road, Wolfeboro, NH 03894. Phone: (603) 569-3185. Email: rhowe@woodardcurran.com.

## OTHER RESOURCES

Town of Wolfeboro Wastewater Treatment Facility:
http://www.wolfeboronh.us/pages/wolfeboronh_water/wastewater

Town of Wolfeboro Water and Sewer Utilities:
http://wolfeboronh.us/Pages/WolfeboroNH_Water/index