Operation and Control

Last Updated November 4, 2008

Acknowledgement

A formal technical review of the draft document was conducted by professionals with experience in wastewater treatment in accordance with WERF Peer Review Guidelines. While every effort was made to accommodate all of the Peer Review comments, the results and conclusions do not indicate consensus and may not represent the views of all the reviewers. The technical reviewers of this document included the following:

Lead Editor: Ryujiro Tsuchihashi, Ph.D. – Metcalf & Eddy, New York, NY)

Contributors/Reviewers (alphabetical):

Jeanette Brown, P.E. (Stamford WPCA, Stamford, CT)
Grant Davies, P.E. (Metcalf & Eddy, Wakefield, MA)
Sam Jeyanayagam, Ph.D., P.E., BCEE (Malcolm Pirnie, Columbus, OH)
Salil Kharkar, P.E. (District of Columbia Water and Sewer Authority, Washington DC)
Mark Laquidara, Ph.D., P.E. (Metcalf & Eddy, Wakefield, MA)
JB Neethling, Ph.D., P.E. (HDR Inc., Folsom, CA)
Rob Smith, P.E. (Malcolm Pirnie, Columbus, OH)

Table of Contents

Overview (November 4, 2008)

This section of the Nutrient Compendium summarizes the current understanding, gaps of knowledge, and research needs in the operations and control of various nutrient removal processes. The types of nutrient removal considered in this section include biological nitrogen removal, biological phosphorus removal, and physical/chemical phosphorus removal processes. Some of the topics or keywords are linked to other sections of this compendium.

As in the other sections of this compendium, the topics are described in the Question and Answer form. To help readers find specific topics, this section is divided in the following subsections:

- Acknowledgement
- Background and Definitions
- Design Considerations

- Process Fundamentals and Design Issues
- Operational Considerations
- Related Bibliography

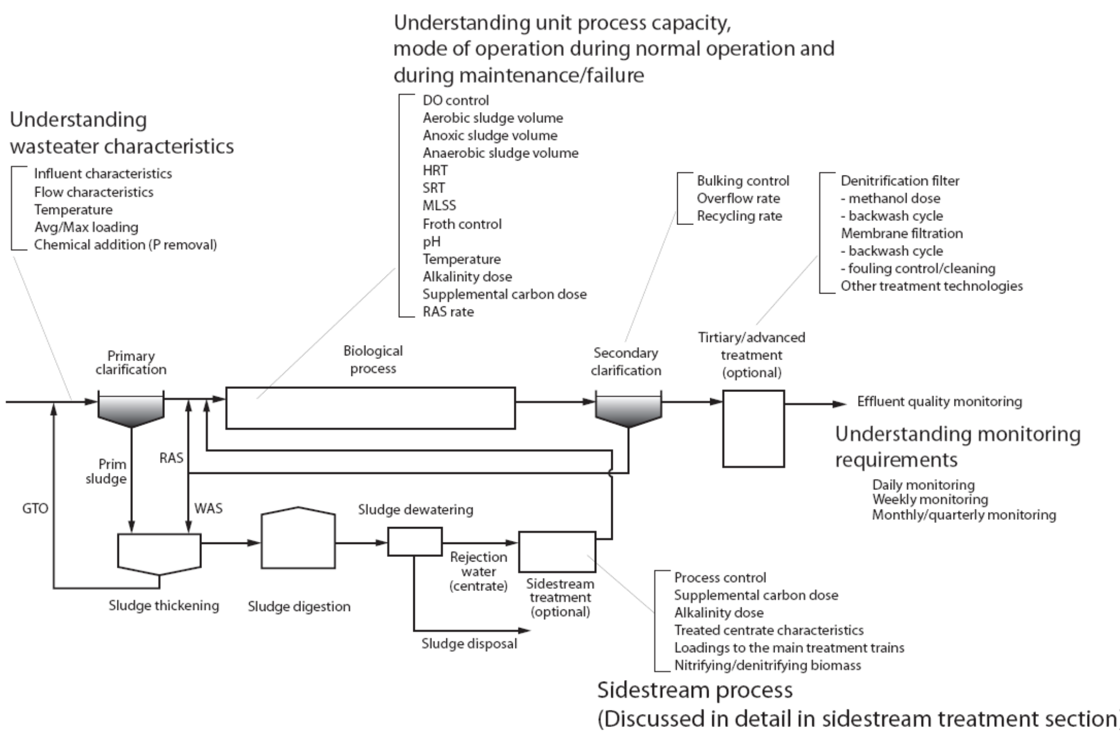
For the topics requiring further study, research needs are listed at the end of the answer.

Background and Definition (November 4, 2008)

The diagram below illustrates a typical wastewater treatment system; the key operation and control issues relevant to nutrient removal are listed for each unit process. Each of the issues is further described in the following sub-sections.

It should be noted that there are many different wastewater treatment configurations and some of them may not match the general configuration shown in the illustrated diagram.

KEY OPERATIONS AND CONTROL ISSUES IN NUTRIENT REMOVAL



What are the key elements of nutrient removal plant operation?

(a) Understanding wastewater characteristics:

- Understanding wastewater characteristics, such as:
  - COD (and its bioavailability), BOD
  - TKN, ammonium
  - Alkalinity
  - Solids (suspended, dissolved)

- Conditioning of, or adapting to, wastewater characteristics to come in line with critical ratios
- Understanding hydraulic and solids/nutrient loading factors on diurnal, 7-day, 15-day, 30-day rolling averages
- Understanding flow and loading balance, including:
  - Influent
  - Return activated sludge (RAS)
  - Waste activated sludge (WAS)
  - Gravity thickener overflow (GTO)
  - Stream from sludge thickening and dewatering process (centrate/reject water)
  - Digester supernatant
  - Other flows

(b) Understanding process capacity/reliability, mode of operation during normal operations, and mode during maintenance/failure, including:

- Capacity of existing facilities to meet permit compliance parameters
- Ability to maintain plant performance under the cold wastewater temperature and max month loading conditions
- Ability to maintain plant performance under wet weather conditions.
- Ability to alleviate and recover from plant upset by means of process redundancy and operating protocols
- Adequate screenings and grit removal to prevent this material from entering biological systems
- Multiple barrier approach to achieve limit of technology nutrient removal levels
- Adequate instrumentation and control of biological treatment systems – close monitoring of key parameters and making proper adjustments is key to success
- Adequate aerobic solids retention time (SRT) for nitrification
- Sizing and configuring systems to achieve realistic biological nutrient reduction – too small and too big are both problematic
- Adequate mixing and oxygen transfer systems in appropriate stages with no back-mixing that would compromise effect of the reactor compartmentalization

(c) Understanding biological process kinetics:

- Minimum aerobic SRT to maintain nitrification
- Temperature effects
- Addressing inhibitory factors to reduced nitrification performance

(d) Understanding chemical/physical process optimization:

- Optimum chemical dosing for precipitation (P removal)
- Optimum loading rate for filtration processes (P, N)

(e) Understanding process control (to be discussed further below):

- Hydraulic flow balancing to biological reactor and settling basins
- SRT Control- positive control of RAS and WAS rates to maintain MLSS target
- Optimize F/M gradient across biological reactors for bulking sludge control
- Configure inter-stage baffling to prevent or minimize back mixing
- Control of hydraulic currents within biological reactor and settling basins
- Managing plant recycle streams and associated impact to treatment performance

(f) Understanding monitoring requirements

What are the key elements of nutrient removal plant operation?

(a) Control and maintenance of biomass

- SRT control – especially aerobic SRT – must stay away from the knee of the curve under maximum month loading conditions
- RAS/WAS rate control – must provide target F/M ratio and MLSS concentration that are consistent with the capacity of clarifiers

(b) Control and maintenance of the operational conditions to maintain biological activity

- Adequate and effective oxygen transfer in oxic zones – DO matching demand across reactor basins – first oxic zone most critical to monitor and control
- Monitoring of DO, nitrate (in and out of nitrification zones)
- Foster good floc forming organisms and control sludge bulking
- Adequate and effective mixing in each zone – MLSS profiling through reactor basins to confirm adequate or expose problems – portable MLSS probes are reliable – need to calibrate permanent MLSS probes on a regular basis

(c) Supplemental chemicals addition

- pH/alkalinity control – An automated caustic addition system with online pH probes is an effective control scheme. Where online probes are not installed, pH may be monitored by portable probes but may not be effective in responding to diurnal variations.
- Supplemental carbon source dose control – adequate monitoring of incoming nitrate/alkalinity/DO and outlet nitrate to optimize dose
  (Detailed discussion of supplemental carbon can be found in the External Carbon section.)
- Coagulants (for physical/chemical phosphorus removal)

(d) Control in response to variations in operational conditions

- Riding out the storm (literally and figuratively) – how to survive peak hydraulic conditions and reduce recovery period – peak shave where possible or protect the biomass from washout
- Managing recycle streams to smooth out spike loading events
- Using online probes to set up a control algorithm

Design Considerations (November 4, 2008)

Many of the operations and control issues are dictated by the plant design. In this subsection, some of the design considerations that would affect the operations and control issues are briefly described.

What instrumentation should be used?

(information under development)

For a suspended growth nitrogen removal processes, the following instrumentation should be considered during the design phase. Further discussion can be found in Question 10 below.

Absolutely necessary:

- Influent and effluent flow meters: At a minimum, the plant must adjust to the diurnal variations in flow.

Highly desirable:

- Online DO meter: Control aerators based on the online DO monitoring; monitor DO intrusion in anoxic zones.
- Online pH meter: Control alkalinity addition based on the online monitoring.

Desirable:

- Online NOx monitoring sensors (either as NOx or as nitrate and nitrite separately): Can be used in a feed-back control, or ammonium-N at the primary effluent; can be used in a feed-forward control for supplemental carbon addition.

What duty is not practical for instrumentation?

(Information under development)

What are the design considerations that would make operation and control easy and reliable?

- Biological reactor configuration to promote efficient kinetic rates
- Effective oxygen transfer and mixing system
- RAS/WAS system to provide adequate SRT control
- Simple and reliable online control scheme

Process Fundamentals and Design Issues (November 4, 2008)

What are the most important process elements for nitrification?

- Provide the adequate aerobic volume in biological reactor.
- Provide an effective oxygen transfer and mixing system in biological reactor with sufficient blower capacity to maintain a DO of 2 mg/L.
- Provide an adequate SRT control with a range of RAS/WAS rates to span start-up, design year, diurnal and seasonal operating conditions.
- Provide sufficient alkalinity to have at least 80 mg/L of $CaCO_3$ in the effluent. If there is insufficient alkalinity in the influent, provisions must be made for adding it. It is critical to maintain a pH greater than 6.5.

Research Needs:

- Free ammonia inhibition: It has been recognized that the presence of free ammonia can cause inhibition in the nitrification process, thus causing nitrite accumulation. Free ammonia inhibition is particularly important for the side-stream centrate treatment, where the high concentrations of ammonium would be treated.

  The pH of aerated zones should be maintained above 6.5, as mentioned above, to provide sufficient substrate for ammonia oxidizers. High pH can result in high free ammonia, thus creating free ammonia inhibition.

- Nitrous acid inhibition: It has been recognized that the presence of nitrous acid (un-ionized HNO_2) can cause inhibition in nitritation (ammonia oxidation), especially in the side-stream treatment process. However, it is not recognized as an important issue in the mainstream process since the concentration in the main stream is not likely to be high enough to have any effect.

What are the most important process elements for denitrification?

The most important process elements for denitrification are reliable mixing and nitrate recycling with minimum DO. The process must provide minimal DO in the anoxic zone and sufficient anoxic volume. For processes with secondary anoxic zones, a pre-secondary anoxic zone (deoxigenation zone) should be provided prior to the external carbon addition zone to "burn off" any DO carried over from the aerobic zone.

External carbon sources (discussed in detail in External Carbon section)

- Available carbon (electron donor)
- Volume
- Nitrate recycle
- DO (or lack thereof)
- Endogenous versus substrate level denitrification

Research Needs:

- Nitrous oxide generation: It has been reported that the denitritation process (reduction of nitrite) may generate nitrous oxide (N_2O), a potent greenhouse gas, at a much higher rate than denitrification from nitrate
- Two-step denitrification process: it has been recognized that reduction of nitrate and nitrite appears to occur at a slightly different rate, sometimes resulting in accumulation of nitrite

What is the most important process element for biological phosphorus removal?

(Information under development)

What is the most important process element for chemical phosphorus removal?

- Multipoint chemical injection
- Low effluent total phosphorus (TP) limits may require the removal of TP prior to denitrification and the controlled addition of phosphoric acid necessary for denitrification

Operational Considerations (November 4, 2008)

What are the primary operational and control considerations?

a. Nitrogen

   i. Nitrification

   Primary operational and control considerations include maintaining DO at or above 2 mg/L. Aerobic SRT is in the range of 6 to 8 days and possibly higher. Other considerations include maintaining a pH greater than 6.5 by adding alkalinity, if necessary; understanding the metabolic needs of the autotrophic organisms; understanding the in-line instruments to monitor ammonia and nitrate concentration, as well as DO; and being able to taper the air at the discharge end of the aerobic zone if the plant is also doing denitrification with mixed liquor recycle.

   DO Control: If an online DO control system is not available, the operator needs to keep eyes on the DO level. Sometimes the operator may adjust the air flow on the safer side, resulting in a much higher than 2 mg/L DO. While this may be more than adequate for nitrification, setting the aeration to a higher than necessary DO level can be a waste of energy and also potentially result in DO intrusion in the subsequent anoxic zone to prevent effective denitrification.

SRT Control: Control of aerobic SRT is based on the inventory in the aerated biomass in terms of MLVSS versus VSS leaving the system. Minimum SRT requirements depend on the temperature; aerobic SRT must be longer under the cold weather conditions. Depending on the temperature, the minimum aerobic SRT is typically in the range between two and six days (WEF and ASCE/EWRI, 2005). Appropriate safety factors should be considered in order to operate the process not too close to the minimum SRT.

pH Control: If the current system does not have an automated alkalinity addition, it is relatively easy to set up an online pH meter integrated with the alkalinity addition system to automatically adjust the alkalinity addition. Otherwise, alkalinity addition must be adjusted according to the daily pH monitoring data.

ii. Denitrification

General Approach: The anoxic zone must be maintained with low to no DO and uniform mixing throughout. DO monitoring in the anoxic zone is recommended. To achieve low to no DO in the anoxic zone, a deoxygenation zone prior to the anoxic zone is often included to minimize the introduction of DO from the mixed liquor recycle. It is recommended to maintain an SRT greater than 12 days. It is important to understand the metabolism of heterotrophic organisms.

DO Control: As mentioned above, high DO levels in the aerated zones may result in DO intrusion in the anoxic zone. DO levels should be maintained at less than 2 mg/L in the zone immediately before the anoxic zone. A deoxygenation zone can help reduce the chance of DO intrusion in the anoxic zones.

Mixed Liquor Recycling: The purpose of the mixed liquor recycle is to have a large mass of nitrate for the denitrification in the anoxic zone. The recycle flow rate should be controlled so that DO introduced to the anoxic zone will not adversely affect denitrification. The deoxygenation zone may be needed to minimize the DO intrusion into the anoxic zone.

b. Phosphorus

(Under Development)

What kind of instrumentation would improve the process control?

The following are all in-line, continuous read-out instruments with data feeding back through a SCADA system:

- Ammonia analyzer in primary effluent feed to biological system
- DO sensor in anoxic zone
- pH sensor, DO sensor and ammonia analyzer at end of first aerobic zone

- Nitrate analyzer at the end of the pre-secondary anoxic zone to pace methanol or other carbon source addition
- Nitrate and ammonia analyzer on secondary effluent.

What kind of parameters must be monitored, and how frequently should they be monitored?

Daily: pH, MLSS, MLVSS, TKN, SKN, COD, SCOD. If in-line instruments are not available, then NO_3, NO_2, Ammonia, and DO should be added to the daily list (daily means 5-days per week).

Three times per week: BOD_5

Once per week: $sBOD_5$, TP and orthoP.

What types of instruments should be considered for use in a nitrification/denitrification process?

Plant personnel and designers should consider the installation of dissolved oxygen, nitrate, ammonia, MLSS and pH sensors. ORP may also be considered depending on the owner's preference. These instruments will allow the operators to better monitor, control and optimize the process.

Where should these instruments be located?

The following table shows the recommended locations for the instruments.

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
Reaeration	NOx	Monitor denitrification efficiency	Process optimization
Pre or post disinfection	NOx, DO	Allows determination of denitrification occurring in secondary clarifiers	Process monitoring, nitrogen balances

How will aerobic SRT affect the nitrification process, and what should be considered for process optimization?

Generally, an aerobic SRT of 4 days or more is desirable under moderate to warm weather conditions when maintaining nitrifying biomass. A longer aerobic SRT will be required during the cold weather season, when the wastewater temperature falls below 15°C.

What kind of process control schemes can be used for external carbon feed?

Carbon augmentation feed control strategies include manual control; automatic flow-paced control; automatic feed-forward control using flow and influent nitrate concentration; and automatic feed-forward and feedback control using flow, as well as influent and effluent nitrate concentrations. The last two modes, although increasingly complex, are considered essential when low TN levels are required. They rely heavily on online monitoring systems and, fortunately, there have been recent advances on this regard with newer instruments that are more durable and maintain their calibration for longer periods. Also, there are patented instrumentation packages available, aimed at providing very low effluent nitrate levels while maintaining low BOD and TOC levels as well.

What kind of automated process control schemes has not been successfully been implemented?

The use of an ORP (oxidation-reduction-potential) for chemostat type treatment processes has been investigated and reported to not be reliable and practical. It should be noted, however, that ORP has been used for the control of sequencing batch reactor (SBR) operations successfully.

(Information under Development)

What kind of permitting may be required?

When external carbon is used to enhance denitrification, specific permits may be required to handle and store it. For example, the use of 100 percent methanol is subject to a permit by the fire department for the handling and storage of flammables (Class 1B). Depending on the characteristics of the external carbon, other types of permits may be required.

What are the safety issues associated with methanol utilization as a carbon augmentation source?

Methanol is a colorless volatile liquid with a faintly sweet pungent odor similar to ethyl alcohol. The substance is fully soluble in water. Vapors of methanol are slightly heavier than air and may travel some distance to a source of ignition and flash back. Accumulations of vapors in confined spaces, such as buildings or sewers, may explode if ignited. Methanol is highly flammable, with a flash point of 12°C (54°F). There is the potential for containers of the liquid to rupture violently if exposed to fire or excessive heat for a sufficient duration of time. Methanol is listed as a "Poison-Class B." It is harmful if swallowed or absorbed through the skin. Ingestion of as little as one ounce can cause irreversible injury to the nervous system, blindness, or death. It cannot be made nonpoisonous. Methanol also causes eye and respiratory system irritation and may cause skin irritation. Liquid, mist, or vapor contact should be avoided. Vapor inhalation or liquid penetration of the skin can also cause central nervous system depression.

What are the challenges in process control?

- Wet weather, cold weather conditions. The prevention of washout of the mixed liquor during extreme wet weather events.
- Filamentous and foaming organisms, their control and impact on population of desired organisms.

- Reestablishing the process after a significant wet weather/cold weather event.

What are the appropriate strategies for bulking and foaming?

The most effective strategy to deal with foaming is to eliminate the conditions that encourage the growth of nocardiaforms. However, this is not always easy because the exact cause-and-effect relationships have not been fully established.

Click here to see a supplemental document describing this issue in detail.

What are final clarifier design and operational considerations?

Clarifier design is crucial to the successful operation of BNR facilities. This is particularly true when targeting low nitrogen and phosphorous levels because of the solids-associated nitrogen and phosphorous.

Several facilities have reported improved sludge settleability with the conversion to enhanced biological phosphorus (EBPR) removal. This may be attributed to the storage products, such as glycogen and polyphosphate, which have reported densities of 1.25 to 1.29 g/mL (Ford *et al.*, 1983), and 1.23 g/mL (Friedberg and Avigad, 1968), respectively. These values are higher than the value of 1.04-1.06 g/mL for the activated sludge (Dammel and Schroeder, 1991). Nonetheless, due to the sensitivity of effluent TN and TP to effluent TSS levels, care must be taken in designing and operating final clarifiers. The following are some of the key elements:

- The resolubilization of phosphorus in the sludge blanket can lead to elevated effluent TP. This can be reduced by increasing the side water depth (SWD) of the clarifier so that the released phosphorus is more likely to exit with the underflow. Within limits, the RAS flow rate may be increased to prevent the phosphorous from migrating to the effluent overflow.

- Many EBPR facilities have a supplemental chemical feed system to enhance process reliability with the chemical being added to or just prior to the final clarifier. Clarifier design must consider the increased solids produced as a result of chemical phosphorous removal.

- Deep clarifier sludge blankets promote denitrification, which could result in poor settleability due to buoyancy caused by the released nitrogen gas. It can also result in secondary phosphorous release and higher SVI. These issues can be resolved by providing a clarifier SRT of 2 to 3 days or less under average day conditions. In order to maintain a shallow sludge blanket of no more than 1 to 2 feet, a sludge collection mechanism with adequate capacity to withdraw sludge quickly should be provided. The use of clarifiers for sludge storage or for maximizing RAS thickening should be avoided.

- Maintaining a shallow sludge blanket will also provide sufficient space for the blanket to expand in response to wet weather conditions when a net transfer of solids occurs from the bioreactor to the clarifiers. If the clarifier can not accommodate the increased solids, washout may result. Significant solids washout has multiple process impacts, including elevated effluent total solids, elevated effluent total phosphorus, and loss of nitrification.

- Even flow split to final clarifiers is critical for realizing the full capacity of the units provided. Poor performance of an overloaded clarifier generally cannot be compensated by good performance of an underloaded clarifier.

The following features are often included to improve clarifier performance:

- Full radius scum collection mechanism for more efficient removal of surface foam and scum.
- Proper sludge collection mechanism (discussed above)
- Baffles
- Adequately sized flocculating well to promote bioaccumulation
- Energy dissipating inlets
- Stand by polymer feed system (particularly for wet weather solids control

Stress testing and computational fluid dynamic models can be used to identify performance bottlenecks. More information on clarifier design, operation, and testing may be found in WEF (2005).

What are strategies available for managing streams from sludge operations?

Stream from the sludge dewatering process (often called "centrate" as many wastewater treatment plants use a centrifuge for dewatering; also referred to as "reject water") generally contains high concentrations of nutrients. Because this topic involves varying characteristics of the stream and various treatment options, a detailed discussion of this topic is posted as a separate document here.

How do you determine the maintenance requirements and priorities?

There is a need to have a preventive and predictive maintenance program on all equipment if possible, particularly on mixers, recycle pumps, alternate carbon source pumps, and clarifiers. Whatever impacts permit limits is a priority including blowers, mixers, recycle pumps, alternate carbon storage and delivery system, and secondary clarifiers.

When starting up a new plant or an upgraded plant, what kind of training would be required for operators, process engineers, maintenance staff?

All staff needs to understand the theory of nutrient removal, to understand the metabolic requirements of the organisms and their by products, to understand what process control parameters need to be monitored and how to optimize the process. They need training in the operation and an overview of maintenance on all equipment. The maintenance staff needs detailed and extensive training on electrical and mechanical needs of the equipment and lubrication and cleaning requirements. The operators and process engineers must be trained in proper sampling techniques and interpretation of data.

In order to cite this document for reference, please use the following citation:

Ryujiro Tsuchihashi, "Operation and Control Compendium," Water Environment Research Foundation, November 2008, http://www.werf.org/nutrients/

Related Bibliography

What are the primary operational and control considerations?

WEF and ASCE/EWRI (2005) *Biological Nutrient Removal (BNR) Operation in Wastewater Treatment Plants*, WEF Manual of Practice No. 29, ASCE/EWRI Manuals and Reports on Engineering Practice, No. 109, WEF Press, McGraw-Hill, New York.

Water Environment Federation (2005) *Clarifier Design*, WEF Manual of Practice FD-8, WEF Press, McGraw-Hill, New York.