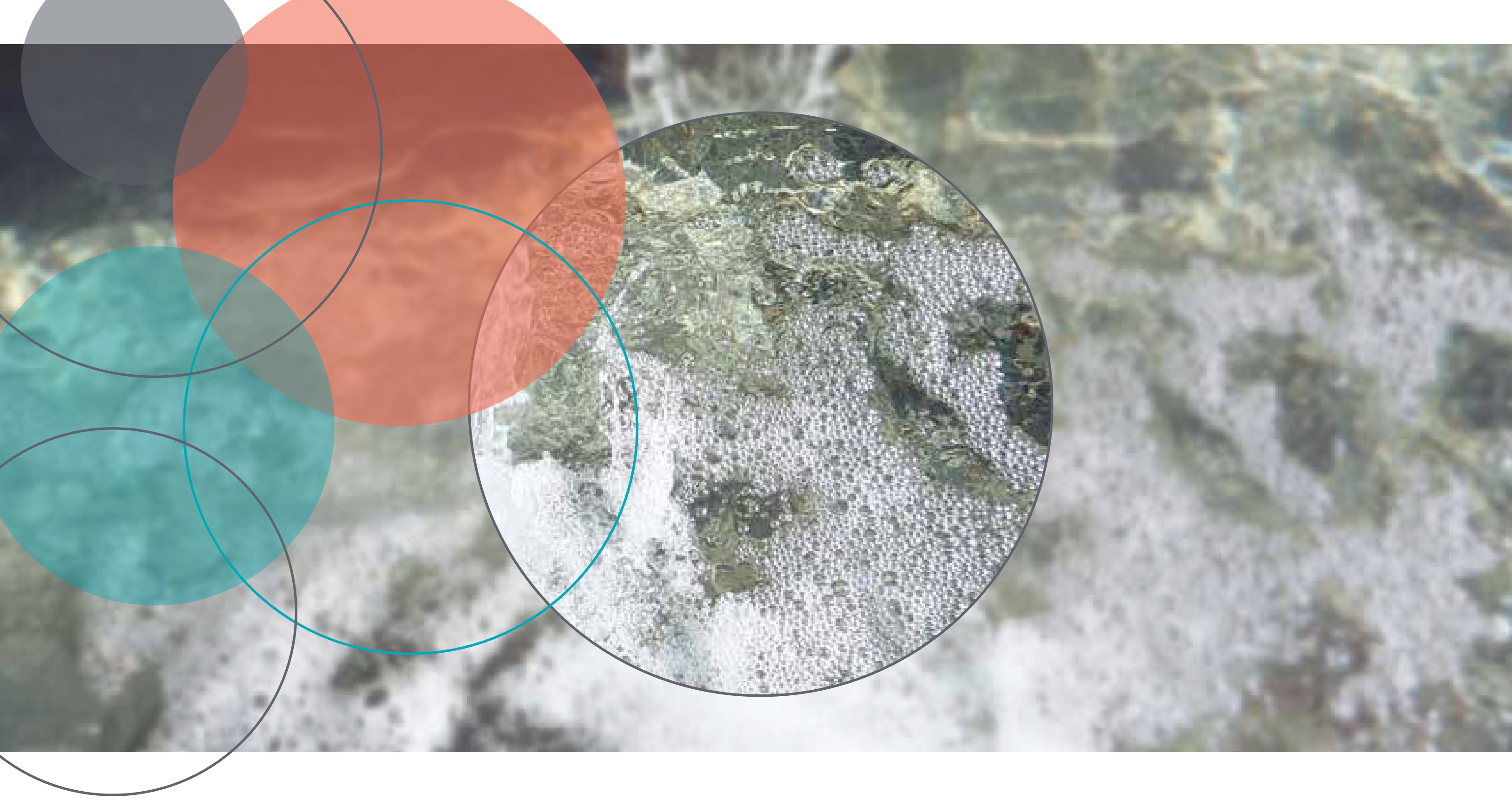


Treatment for Low Nitrogen and Phosphorus: Process Performance and Reliability

MARCH 2019

The 2018 *Treatment Processes for Low Nitrogen and Phosphorus Compendium* was written to identify knowledge gaps to be addressed by the Nutrient Removal Challenge. That document contains state-of-the-art knowledge to achieve reliable, cost-effective nutrient removal. The 2018 compendium included a number of questions and challenges to reduce nutrients in advanced treated wastewater. This 2019 compendium revision contains a summary of the findings presented in reports and documents generated by researchers and contributors.

THE
Water
Research
FOUNDATION

ACKNOWLEDGMENTS

We acknowledge the following contributors and reviewers (alphabetically).
The findings from the Nutrient Removal Challenge were incorporated into this 2019 edition by:

Bryce Figdore
HDR Inc.

JB Neethling
HDR Inc.

David Stensel
University of Washington

Please use the following citation for this document:

WRF (The Water Research Foundation). 2019. "Treatment for Low Nitrogen and Phosphorus: Process Performance and Reliability" from the Nutrient Removal Challenge.

1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445

6666 West Quincy Avenue
Denver, CO 80235-3098

info@waterrf.org
www.waterrf.org

TABLE OF CONTENTS

●●●● BACKGROUND

Why Do We Want to Know "How Low Can You Go?"

The current regulatory activity concerning nutrients has been focused on areas where extremely low nitrogen and/or phosphorus limits were deemed necessary to control eutrophication problems, such as: Chesapeake Bay, Everglades, Gulf of Mexico, Pacific Northwest, and Long Island Sound. The U.S. Environmental Protection Agency (EPA) rolled out a national nutrient strategy that established ecoregional nutrient criteria in 1998 and states are working toward adopting TMDLs for NPDES permits. The ecoregional criteria establishes very low nitrogen and phosphorus concentrations in streams and rivers—on the order of 10 to 50 ug/L TP and 300 to 600 ug/L TN for some regions. While mixing zones will provide some relief to certain dischargers, many others utilities have to meet these criteria in the discharge or end of pipe.

The prospect of having to achieve very low effluent nutrient concentrations as noted above raises concerns for plant managers:

- Is it possible to meet the effluent concentrations with existing technologies, improved or new technologies without resorting to reverse osmosis?
- What other technologies are available? How reliable is the performance of these technologies?
- How can existing facilities be best used to meet such new goals?

This compendium addresses these questions based on the research and findings from the Nutrient Removal Challenge.

PERFORMANCE VARIABILITY

What Factors Impact WRRF Performance Variability?

Water resource recovery facilities (WRRFs) operate under dynamic conditions. Diurnal and possibly seasonal variability in influent wastewater flows and loads inherently lead to variability in treatment process performance. Load variability originates from changes in the service area, the sources and the activities in the service area. Causes of WRRF performance variability can be grouped in three categories: explainable and anticipated, self-imposed, or out-of-control (acts of god).

Explainable and Anticipated Performance Variability

Daily fluctuations occur from resident life patterns, business, and industrial activities. In addition, weather patterns and inflow/infiltration not only increase the flows but often carry additional loads from flushing sewers and washing the surface area. Loads can change during the week, often with a repeatable pattern, but sometimes weekday and weekend patterns varies. Holidays and major sporting events are known to impose large load increases on the system.

Natural weather changes can be predicted to some extent. Liquid and air temperatures are very repeatable and fall within a range with cold winters and warm summers. If flow, load, or temperature patters of different years are plotted together, the result is typically a band with some characteristic range. Engineers can use this information and design accordingly to accommodate the changes.

Many uncertainties remain. Climate change is causing larger swings in temperature and rainfall patterns. Planners and engineers can anticipate these changes to some extent, but extremes can exceed the ability of the WRRF to adapt to the load changes. Predicting future wastewater characteristics is complicated by changes in water use patterns, development, and local industry. Utilities and designers face the challenge to determine the appropriate margin of safety (or degree of extreme conditions) to plan and design for, while maintaining a cost-effective and efficient operating WRRF. Over investment can lead to stranded assets; under investing can lead to overloading the process.

Variable Performance from Self-imposed Activities

Operators are continually facing critical process operational decisions. They anticipate process performance and adjust the process to remain stable and efficient. Decisions could be as simple as changing an operating setpoint such as dissolved oxygen (DO) level or chemical dose to optimize the process performance, placing basins in or out of service to accommodate seasonal changes, or changing the mode of operation. These changes are deliberate and planned to optimize WRRF performance.

Operators are typically guided by prior experience when making decisions. Introducing nutrient removal to existing plants creates new demands on operations and plant management. By pooling the knowledge of all the operators at a WRRF, one can reach a consensus operating strategy. However, during unexpected changes in process performance, an individual operator could changes the operating strategy and, since different operators have different prior experience, two operators at the same facility will often make two different adjustments. Both adjustments may work fine and keep the process stable, but the change in operational strategy will impact the process performance and increase the variability in the plant performance.

Internally generated recycle streams are an example of a self-imposed additional load. Reject water from dewatering processes not only contain very high nutrient concentrations, but the process is often operated intermittently, thereby magnifying the instantaneous return load during the time of return. These type impacts can be mitigated. But many existing (particularly small) WRRFs will continue to see variable recycle loads to the plant increasing the performance variability.

Many WRRF changes are planned and can be accommodated in the process. These changes should not lead to an inability to meet the permit, but may increase the variability in effluent quality. For example, a scheduled maintenance event may take a unit process out of service and thereby reduce the treatment capacity. This change may increase variability to the loading per process unit and result in variability in WRRF effluent quality. Construction events similarly may temporarily change the process performance.

Variable Performance from Actions beyond Control of the WRRF (Acts of God)

These are events that would stress the process beyond the limits of the design or equipment, for example, a storm event that exceeds the capacity of the process (say pumping station). In some cases, a redundant (back up) pump may be available and allow the operator to pump more flow to the WRRF, exceeding the hydraulic flow capacity of the designed plant and may even flood some unit process but prevent a spill. A lightning strike or general power failure could cripple the plant. During 2012 Hurricane Sandy in New York, the duration of the storm and flooding event stressed the ability to refuel the standby generators and ultimately caused a loss of power when generator fuel could not be refilled.

Accidents can impose stress on the process, even failure. The crash of a delivery truck into the chemical feed process has eliminated the ability to add chemicals. Failure of a level switch in a wet well can lead to an uncontrolled spill. A dump from an industry or other (authorized or non-authorized) activity could impact performance. At one small plant, chemical addition by the City to the sewer for root control resulted in a loss of nitrification capacity at the treatment plant due to the inhibitory effect of the root control chemical added.

Some of these unforeseen circumstances are, in retrospect, explainable. However, they still happen and cause a change in performance. Large and sudden impacts such as the loss of nitrification clearly trigger attention and investigation, but smaller impacts are typically ignored and attributed to “process variability.”

It is appropriate to accept and expect some variability in process performance. Sewers remain a means to discard our reject water; and with it comes unknown consequences. Usually these consequences are diluted out in the sewer and only cause a modest change in performance. But at other times, the consequence is large.

ACCOMMODATING DYNAMIC LOAD CHANGES

How Well Do WRRFs Accommodate Dynamic Load Changes?

Engineers normally select a design load condition that represents the upper limit of the expected load. The design load anticipates the average and the extreme loading patterns that will reach the WRRF. By designing for these load variations, the process is stable and meets the permit as required.

When the influent load eventually reaches the average design load, the WRRF will receive the designed load for 50 percent of the time—half the time the load will be above average and half the time the load will be below average. This influent load variation from average to maximum month, maximum week, or peak loading condition, will cause variability in effluent.

It typically takes time for a process to adjust and respond to load changes. For example, an increase in organic and/or nutrient load will lead to an increase in biological growth, but there is a transition time to accumulate the additional biomass in the process. Other processes respond quickly, such

Table 1 - Time Scale Response of Processes

Process Type/ Element	Example Process	Time Scale of Response	Comment
Hydraulic	• Pumping Stations • Flow Measurement	Minutes	Hydraulic impact is near immediate and ripple through the WRRF based on flow routing. Control systems response is fast.
Physical Processes (Liquid)	• Primary Clarifier • Screening • Filtration	Hours	Performance deteriorates in these processes. Key concern is process becoming overloaded and "plugging" (like screen or filter) or "spilling" (like clarifier washout).
Chemical Processes (Liquid)	• Chemical Phosphorus Removal • Disinfection	Hours to Days	Chemical feed systems respond quickly. The result of chemical addition may be reduced due to reduced contact time.
Biological (Liquid)	• Fixed Films Processes (ex. Trickling Filter) • Suspended Growth (ex. Activated Sludge)	Hours and Days	Biological systems can accommodate short-term (diurnal) variations with sufficient biomass inventory. Load increases that cause a biomass inventory shift, require long time (1-3 times the SRT).
Biological (Solids)	• Digesters	Days	Digesters typically operate long SRTs and feed to digesters are attenuate with unit operations prior to the digester.
Physical (Solids)	• Thickening • Dewatering	Hours to Days	While shielded from influent variations, processes often see on/off loading and intermittent operation. Reject water can add significant short-term load to the liquid stream.
Control Systems	• SCADA • Operator Control	Continues to Hours and Days	Automated controls are adjusted to provide continuous stable operation. Operator adjustments (setpoints) will take hours (physical/chemical changes) to days (biological changes) to take effect.

as pumping or adjusting a chemical dose. The time sensitivity of unit processes to respond and adjust to changed conditions is summarized in Table 1.

The process performance variability of an operating WRRF is attenuated when current loading is below the design loading. By allowing for future increases in the loading over the WRRFs design period (typically 20 or more years), the processes have spare capacity during the operational life of the WRRF. Most treatment plants are upgraded by the time they reach 8 percent of their design capacity to ensure sufficient online capacity at all times. This extra capacity, which includes redundant process units, is virtual: i.e., it disappears when the WRRF reaches the design load. The virtual capacity can be utilized to increase process stability and performance or even to achieve nutrient reduction that will disappear when the influent reaches the design load. It adds an operational capacity (it is available when all process are in service) but does not add real capacity (since the capacity is lost when redundant units by design, are offline).

DESCRIBING PERFORMANCE VARIABILITY

How Do We Describe Performance Variability of a Treatment Process?

Neethling et al. (2009) presented a quantitative approach to describe the performance of a WRRF. This approach was adopted in Bott and Parker (2011) to describe the performance of WRRFs based on performance statistics. In this approach, Technology Performance Statistics (TPS) are calculated to express the normal variability in a plant discharge. Figure 1 contains three years of data from a full-scale WRRF operated for phosphorus removal. The data shows a typical variability with some potential outliers (see July 2005). This data is transformed (ranked) and placed on log normal distribution to understand the statistics. The TPS can be read as shown in Figure 2. In this case, three TPS values are shown:

- TPS-50 represents the median performance of this process of 0.08 mg TP/L. This represents the average performance achieved by the process.
- TPS-80 represents the 80th percentile performance of 0.11 mg TP/L. The process is below 0.1 mg TP/L for 80 percent of the time; or has an 80 percent reliability of meeting 0.11 mg TP/L.
- TPS-95 represents the 95th percentile performance of 0.23 mg TP/L. The process is below 0.1 mg TP/L for 95 percent of the time; or has a 95 percent reliability of meeting 0.23 mg TP/L.

Figure 1 - Effluent Data from Phosphorus Removal Plant

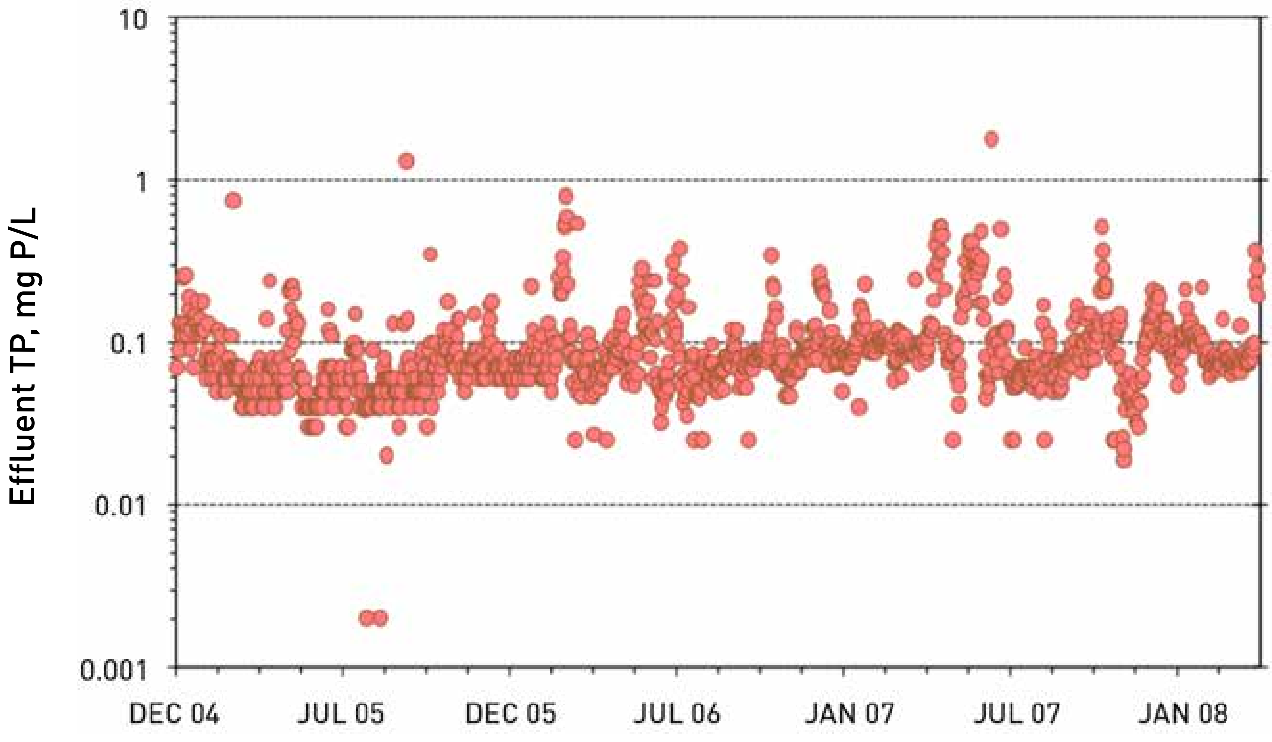
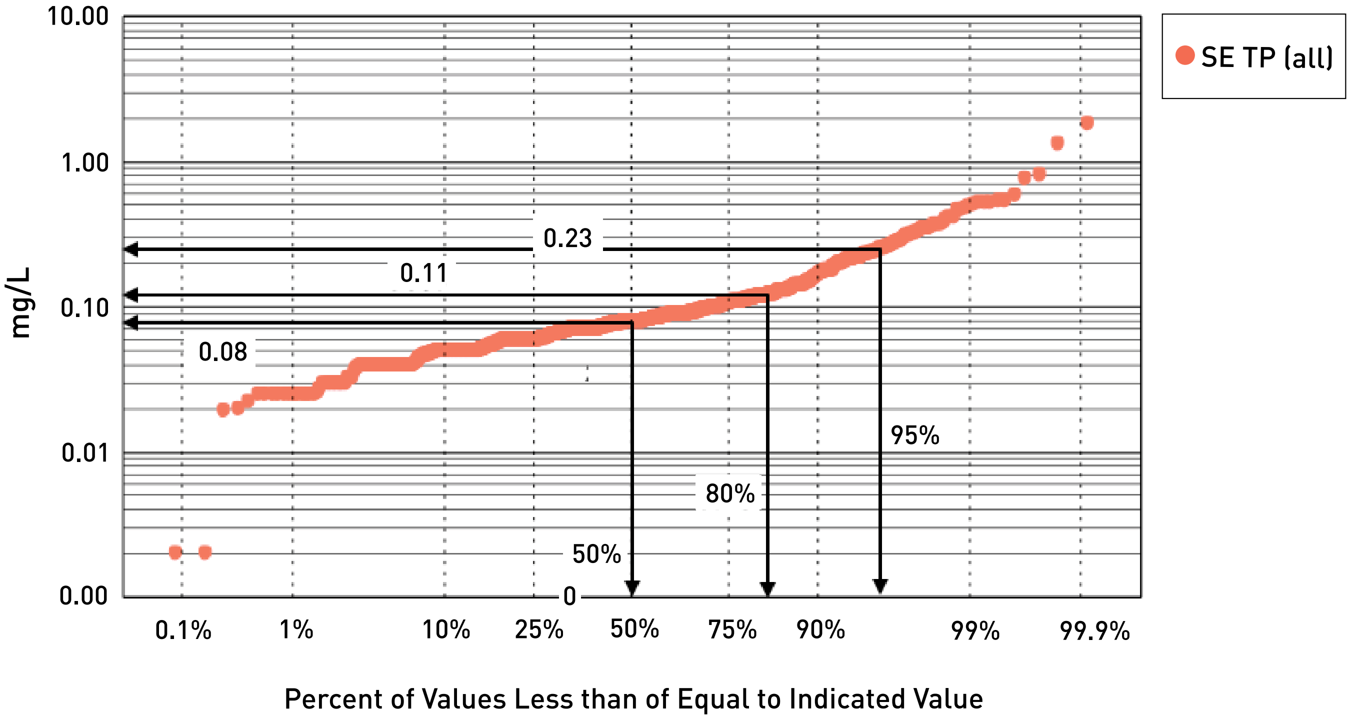


Figure 2 - Relationship between Operation Target and Reliability



The effluent performance distribution can be used to determine the reliability of meeting a certain limit.

IMPACT OF PERMIT AVERAGING PERIODS ON PERFORMANCE RELIABILITY

How Do Permit Averaging Periods Impact Reliability of WRRF Performance?

WRRF permits set numeric discharge limits (load and or concentration) and associated averaging periods. Short averaging periods could trigger a violation based on a single sample; long averaging periods will allow some higher effluent loads to be offset by lower effluent loads.

The negative water quality impacts associated with nutrient pollution may be slow. Excessive algal growth is the trigger for nutrient enrichment and is impacted by temperature, light penetration, hydrodynamic conditions, and many other factors that attenuate the immediate impact. On the other hand, acutely toxic compounds (such as high levels of ammonia) create a short term response and require a short term permit limit.

Variability, reliability, and risk of treatment compliance are interrelated. Reduced variability will typically lead to higher reliability and lower risk. Decisions on the reliability and risk play directly into the cost and sustainability of the facility. Achieving low limits at short averaging periods, demands a lower operational target to provide the desired reliability of performance. Typically, that reliability comes at the expense of larger facilities, higher redundancy, and increased chemical usage.

Neethling et al. (2019) describes the relationship between process performance and permit compliance as follows:

"The relationship between performance and reliability for meeting an annual, a monthly, or a daily permit limit can be selected based on the appropriate TPS value. For example, suppose a plant wants to achieve a reliability of 80 percent. That means that it must operate below the permit level 80 percent of the time. The risk associated with this decision, is that it also exceeds the permit 20 percent of the time; i.e., for 20 percent of the time it operates above its limit or "violates" the permit level. In a 5 year period, the plant would exceed the permit 20 percent of the time, and be at risk 20 percent of the time, or 1 year in a 5 year period (i.e., the plant would potentially exceed permit once every 5 years). If this were a monthly permit limit, the 80 percent reliability would be exceeded 20 percent of the time, or for 20 percent of the 60 months in a 5-year period, i.e., 20 percent of 60 = 12 times in a 5 year period. If 12 potential exceedances are too risky for the owner, then a higher reliability is required, say 95 percent (5 percent exceedance, and 5 percent of 60 months = 3 times in a 5-year period).

Selecting the TPS statistic is a judgment of the plant operator and owners to balance the risk and performance. Operating to meet the permit on average would place the owner at risk every reporting period (month, year, daily). For longer periods, the operator may be able to adjust performance toward the end of the period to make up for poor performance earlier. For short periods (weekly or daily) the ability to do so would be limited."

The relationship between the design level and the risk of exceedance for annual, monthly, or daily limits developed are presented in Table 2. Using this information, the utility managers can assess the balance between the required reliability of the WRRF process (higher reliability will require more investment) and reliability of meeting permit. Similarly the facility designer can determine the appropriate design goals to provide the level of reliability to the design. Based on the desired reliability and acceptable risk of exceedance, the designer can determine the appropriate target design value to meet the permit value reliably. In this example, the design target can be 73 percent for an annual average limit and as low as 13 percent for a daily limit. The designer can apply judgment to adjust the values as appropriate.

Table 2 - Relationship between Design Level and Permit Compliance Period

Averaging Period	Reliability (%)	Risk of Exceedance	Design/Operating Factor[a] Example
Annual	80.0	1 in 5 Years	0.73
Monthly	95.0	5 in 5 Years	0.35
Daily	99.0	18 Times in 5 Years	0.13

[a] Design/operating factor is 50 percent performance divided by reliability performance level, calculated from performance shown in Figure 2. (from Neethling et al. 2019)

Similarly, TPS can also guide the operational targets (Neethling et al. 2019) to provide the reliability for meeting permit. The required performance reliability can be determined based on operator experience, site specific conditions, load variability, and expected performance during the permit averaging period.

NUTRIENT SPECIES OF INTEREST

What Are Nutrient Species of Interest?

From a treatment perspective, the individual nutrient species can be grouped as follows:

- **Soluble vs. Particulate.** The analytical definition of particulate (or filterable) is dependent on the pore size of the filter. Typically, a 0.45 um filter size is used to distinguish between filterable (particulate) and non-filterable (soluble) species. Tertiary solids separation processes such as filters and membranes, are able to remove particulate nutrients but soluble nutrients pass through the process.
- **Inorganic vs. Organic.** Inorganic species and small molecules are readily removed by chemical and biological process. Complex organics are generally removed slower biologically and entrapped/reacted/adsorbed chemically.

The nitrogen species commonly measured at WRRFs and the key species of interest are shown in Table 3. Inorganic species included total ammonical nitrogen (TAN) calculated as the sum of the ammonium and ammonia (TAN = $NH_3 + NH_4^+$) and total oxidized nitrogen (NOx = $NO_2^- + NO_3^-$). Organic species are not specifically defined chemical compounds but measured as the difference between TKN and TAN. The soluble nitrogen (SN) species include TAN plus soluble organic nitrogen (SON). Particulate nitrogen includes only particulate organic nitrogen (pON). There are some less common particulate nitrogen species that should be accounted for when they are present. Most important of these are struvite or other nitrogen-containing particles.

Phosphorus species are more complex since there are a myriad different phosphorus species as orthophosphate, pyrophosphate, tripolyphosphate and organic phosphate. The main phosphorus specie is orthophosphate. Orthophosphate is readily available for uptake by bacteria, algae, and plants as an essential nutrient for biomass growth and participate in many chemical reactions with metal salts and other chemicals. The common analytical methods for measuring phosphate in wastewater samples use colorimetric methods such as the Ascorbic Acid Method in Standard Method 4500-PE (APHA 2005). The test is selective for orthophosphate but due to the lab procedure, it can contain small amounts of other forms of phosphorus as well to form a color complex.

It is practical to divide the phosphorus species based on analytical method used to measure them. The key species of interest are shown in Figure 3. The common phosphorus species commonly measured at WRRFs are reactive phosphorus (RP) and total phosphorus (TP). The difference between these two measurements represents the non-reactive phosphorus (NRP). The NRP species are poorly understood and may include polyphosphates, condensed phosphates, and soluble organic phosphorus species. Reactive phosphorus species include (soluble) orthophosphate (SRP is mainly orthophosphate, PO_4^{3-} species) but particulate orthophosphate compounds (such as precipitants with metal salts or struvite or calcium phosphate [brushite]). Note that the many of the particulate species will dissolve during the analytical procedure and measure as pRP. The majority of RP is orthophosphate under normal circumstances. NRP represents the more complex forms of phosphorus and is usually organic phosphorus.

Particulate phosphorus species (filterable phosphorus) include pRP (for example struvite or metal salt precipitants) or pNRP (for example particulate organics, bacteria, and phosphorus-accumulating organisms). Soluble phosphorus species (filterable phosphorus) can also measure SRP (for example orthophosphate, the main SRP) or SNRP (for example soluble organics, condensed and polyphosphates).

Figure 3 - Nitrogen Species in Wastewater Treatment

<table>
<tr><th colspan="5">Total N (TN)</th></tr>
<tr><th colspan="4">Soluble N (SN)</th><th>Particulate N (pN)</th></tr>
<tr><td>Nitrate (NO_3)</td><td>Nitrite (NO_2)</td><td>Ammonia (NH_3) + Ammonium (NH_4)</td><td>Soluble Organic N (SON)</td><td>Particulate Organic N (pON)</td></tr>
<tr><td colspan="2">Total Oxidized N (NOx)</td><td colspan="3">Total Kjeldahl Nitrogen (TKN)</td></tr>
<tr><td colspan="3">Total Inorganic N (TIN)</td><td colspan="2">Total Organic N (TON)</td></tr>
</table>

Figure 4 - Phosphorus Species in Wastewater Treatment

<table>
<tr><th colspan="6">Total P (TP)</th></tr>
<tr><th colspan="3">Soluble P (SP)</th><th colspan="3">Particulate P (pP)</th></tr>
<tr><td rowspan="2">Soluble Reactive P (SRP)</td><td colspan="2">Soluble Non-reactive P (SNRP)</td><td rowspan="2">Particulate Reactive P (pRP)</td><td colspan="2">Particulate Non-reactive P (pNRP)</td></tr>
<tr><td>Soluble Acid Hydrolyzable P (SAHP)</td><td>Soluble Organic P (SOP)</td><td>Particulate Acid Hydrolyzable P (pAHP)</td><td>Particulate Organic P (pOP)</td></tr>
</table>

The differentiation of nutrient species into the functional categories (organic/inorganic, reactive/non-reactive, particulate/soluble) provides a way to understand not only the measurements but opportunities and implications for nutrient removal. Most inorganic or reactive species will the readily consumed by bacteria and react to chemical treatment. Organic and complex molecules will react slow and may degrade slowly in a WRRF. Similarly, particulate nutrient species can be removed with solids separation processes such as filters or membranes. Soluble species will pass through solids separation processes. Care needs to be taken to preserve samples for phosphorus measurements since the species can change between the time of sampling and analysis. Of particular concern is release of accumulated phosphorus in PAOs during sample storage and analysis.

Approach to Establish Nutrient Removal Process Design Targets to Meet Permit Limits

As discussed in Section "How do permit averaging periods impact the reliability of WRRF performance?" the average performance of WRRFs must be below the permit target to reliably meet the permit. The result in Table 2 is based on an acceptable risk of approximately one exceedance per permit cycle (once in five years). The process requires that the performance must meet the target between 80 percent and 95 percent of the time (for annual and monthly limits). The TPS-80 and TPS-95 values are a measure of the performance level achievable 80 percent or 95 percent of the time; i.e., the performance is likely to be exceeded about once every five years. If that performance level is higher than the design target or permit value, a more reliable process is required to reduce the risk of exceeding the target.

Studies under the Nutrient Removal Challenge evaluated various data sets to observe the variation and reliability for different nutrient species at different WWRFs. Neethling and Stensel (2013) analyzed data from full-scale operating WRRFs, special studies, and pilot studies to determine the nutrient removal performance and effluent nutrient speciation for various nutrient removal processes of individual nutrient species. Their approach used data collected from various sources:

- Data from plants reported by Bott and Parker (2011), Gu and Onnis-Hayden (2010), and Pellegrin et al. (2015) were re-analyzed to calculate TPS-80 and TPS-95 performance levels for individual nutrient species.
- Supplemental data taken from selected full-scale plants that the authors had access to and analyzed for TPS-80 and TPS-95.
- Special data collected by Gu and Onnis-Hayden (2010) to determine phosphorus species removal through full-scale WRRFs were used to guide removal efficiencies.
- The "Soluble Organic Nitrogen in Biological Nutrient Removal" Compendium (WRF 2019) contains data from various sources on effluent SON concentrations.
- US EPA Municipal Nutrient Removal Technologies Reference Document (Kang et al. 2008). The document presents performance data from different technologies and presents the reliability in terms of the coefficient of variance of the data.
- EPA Region 10 investigation in low phosphorus removal (EPA 2007) presents results from a field survey of 23 low chemical phosphorus removal plants.

The first two sources provided data that was used to recalculate TPS-80 and TPS-95 values for various full-scale WRRFs. Gu and Onnis-Hayden (2010) was used for better phosphorus speciation removal performance and WRF (2019) was used for SON species. The last two sources provide general guidance in judging the expected reliably achievable performance.

Nutrient species data from these sources (see Attachment A) were analyzed to determine the 80 percent and 95 percent achievable concentrations individual nutrient species. TPS-50, TPS-80, and TPS-95 values determined for large sets of operational data from various WRRFs. Summaries of some selected WRRFs are shown in Tables 3 and 4 for nitrogen species. Similarly, Table 4 and Table 5 contains summaries for phosphorus species. These tables include the permit limits targeted by the plants. See Attachment A for the data analysis for individual nutrients species, as well as data from special sampling conducted during various studies.

The performance results in these tables and in Attachment A are used to select the best reliably achievable performance for each nutrient species.

Table 3 - Long-term Data for Nitrogen Removal

Plant	NH_4 Limit[a] mg/L	TN Limit[b] mg/L	NH_4-N			NOx			TN		
			50%	80%	95%	50%	80%	95%	50%	80%	95%
NDN AS + Tertiary Denitrification, Add Carbon	-	- / 3	0.005	0.078	0.24	0.03	0.10	1.15	1.04	1.73	2.71
Separate Stage, Add Carbon	1.5	- / 3	0.036	0.083	0.52	0.64	1.2	2.04	1.47	2.18	3.20
Separate Stage, Add Carbon	-	- / 2	0.05	0.45	2.04	0.1125	0.264	0.54095	1.70	2.38	3.74
BNR	-	- / 11	0.17	1.158	2.79						
Tertiary Ammonia Removal	-	- / 9	0.28	0.4	0.60	0.43	0.74	1.0635	2.50	2.88	3.37
NDN, Carbon Added	2	- / 7	0.1	0.1	1.68	2.2	2.8	3.8	3.30	4.20	6.20
BNR	-	3 / 5	0.1	0.99	4.81				3.67	5.19	8.20
BNR, Fermenter	-	6 /	0.3	0.73	1.16				4.65	5.25	6.40
NDN AS, Add Carbon	1	6 / -	0.1	0.1	0.31	3.67	6.39	8.90	4.72	7.72	10.17
NDN AS, Add Carbon	-	- / 7.5	0.38	1.31	3.07	3.43	5.09	7.22	5.33	7.13	9.68
BNR 1	-	- / -				6.635	7.34	7.9545	8.79	11.86	20.45
BNR 2	-	- /n.a.	0.04	0.06	0.12	9.96	11.808	13.4	10.51	12.31	13.91
BNR 3	0.21-1.4	- / -	0.049	0.24	2.81						
BNR 4	8	- / -	0.05	0.1	0.63						
BNR 5	-	- / 5	0.05	0.05	0.34	0.69	1.05	2.15			
BNR 6	2.5	- / -	0.06	0.12	1.18						
BNR 7	0.41	- / -	0.08	0.08	0.09						
BNR 8	0.41	- / -	0.08	0.08	0.28						
BNR 9	0.5	- / -	0.1	0.3	0.50						
BNR 10	5	- / -	0.1525	0.373	1.20						
BNR 11	?	- / ?	1.63	2.32	3.42						

[a] Max day limit

[b] Limits for Annual Average/Max Month

Table 4 - Long-term Data for Nitrogen Removal (Continued)

Plant	NH_4 Limit[a] mg/L	TN Limit[b] mg/L	OrgN			SON			pN		
			50%	80%	95%	50%	80%	95%	50%	80%	95%
NDN AS + Tertiary Denitrification, Add Carbon	0.90	1.33	1.95							0.90	1.33
Separate Stage, Add Carbon	0.71	0.91	1.14							0.71	0.91
Separate Stage, Add Carbon	1.44	1.72	2.03	1.31	1.52	1.70				1.44	1.72
BNR											
Tertiary Ammonia Removal	1.70	1.95	2.20							1.70	1.95
NDN, Carbon Added	0.90	1.20	1.60							0.90	1.20
BNR	1.80	3.63	12.61							1.80	3.63
BNR, Fermenter	1.39	1.59	1.80							1.39	1.59
NDN AS, Add Carbon	0.90	1.20	1.50							0.90	1.20
NDN AS, Add Carbon	1.05	1.35	1.87	0.70	0.89	1.20	0.33	0.62	0.99	1.05	1.35
BNR 1											
BNR 2	0.28	0.79	1.22							0.28	0.79
BNR 3											
BNR 4				0.58	0.78	1.02					
BNR 5											
BNR 6											
BNR 7											
BNR 8											
BNR 9											
BNR 10											
BNR 11	0.80	1.15	1.41							0.80	1.15

[a] Max day limit

[b] Limits for Annual Average/Max Month

Table 5 - Long-term Data for Phosphorus Species Removal

Plant	TP Limit[a]	TRP			TNRP			TP		
		50%	80%	95%	50%	80%	95%	50%	80%	95%
ChemP (Multiple)	- / 180	25	25	25	25	55	80	50	80	120
BioP, Chem/Sed/ Filter	50 / -							29	40	54
ChemP (Multiple)	- / 180	40	90	140	35	60	90	70	120	180
ChemP (Single, in AS)	- / 500	90	134	203	17	47	83	71	119	196
BioP, Chem/Sed/ Filter	- / 140	19	44	152	60	78	102	80	116	233
BioP, MBR	- / 130	50	80	120	30	40	60	80	110	160
BioP, Chem/Sed/ Filter	- / 140	30	57	119	50	71	92	83	113	177
BioP, Chem/Sed/ Filter	- / 100	16	31	141	53	85	169	83	148	329
BioP, Filter	- / 1000	40	60	78	80	120	260	110	160	270
BioP, MBR	- / 36	49	498	2,522	11	15	60	51	184	1,795
BioP, Filter	- / 640							114	240	480
ChemP (Water Sludge)	- / 1000	100	300	740	60	100	199	140	310	730
BioP, Filter	250 / 1000	40	70	110	110	140	180	150	190	324
BioP and ChemP, Chem/Filter	- / 170	130	210	810	50	60	150	170	250	950
BioP, Filter	1000/2000	100	216	487	80	120	190	190	310	635
BioP, Filter	- / 540	140	210	350	110	140	190	270	350	490
BioP, Chem/Filter	- / 170	130	250	610	160	210	304	320	440	770
BioP	2000 / -	105	205	511	177	272	593	340	518	1,505
BioP, Filter	300 / 800	230	390	642	180	220	290	400	590	890
BioP	- / 1000							423	662	1,200
ChemP (Single), Filter	- / 1000	420	652	950	40	70	140	500	750	972
BioP and Chemical	- / 2000							651	1,364	1,762

[a] Limits for Annual Average/Max Month

Table 6 - Long-term Data for Phosphorus Species Removal

Plant	TP Limit[a]	sTP			SRP			SNRP			pTP		
		50%	80%	95%	50%	80%	95%	50%	80%	95%	50%	80%	95%
ChemP (Multiple)	- / 180												
BioP, Chem/Sed/ Filter	50 / -												
ChemP (Multiple)	- / 180	40	90	140							30	50	75
ChemP (Single, in AS)	- / 500												
BioP, Chem/Sed/ Filter	- / 140												
BioP, MBR	- / 130	80	110	160	50	80	120	30	40	60			
BioP, Chem/Sed/ Filter	- / 140												
BioP, Chem/Sed/ Filter	- / 100												
BioP, Filter	- / 1000												
BioP, MBR	- / 36	51	452	2,808	40	160	1,826	11	15	60	1	10	48
BioP, Filter	- / 640												
ChemP (Water Sludge)	- / 1000												
BioP, Filter	250 / 1000												
BioP and ChemP, Chem/Filter	- / 170				70	72	78						
BioP, Filter	1000/2000												
BioP, Filter	- / 540	240	310	440							30	50	80
BioP, Chem/Filter	- / 170				80	200	530						
BioP	2000 / -												
BioP, Filter	300 / 800												
BioP	- / 1000	298	517	1,121							122	168	191
ChemP (Single), Filter	- / 1000												
BioP and Chemical	- / 2000												

[a] Limits for Annual Average/Max Month

TREATMENT RELIABILITY

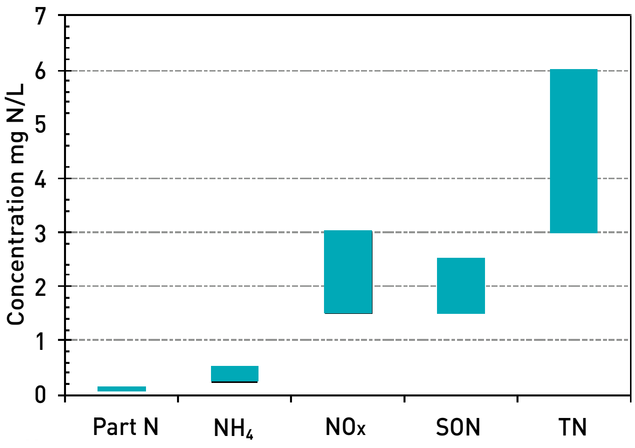
This section presents the anticipated performance for different nutrient species with conventional and tertiary nutrient removal (CNR and TNR) processes.

How Reliably Can Technologies Remove Individual Nutrient Species?

Neethling et al. (in review) presents a summary of reliably achievable nutrient species concentrations. See Attachment A for the data summaries from various sources. They describe the achievable effluent concentrations as follows:

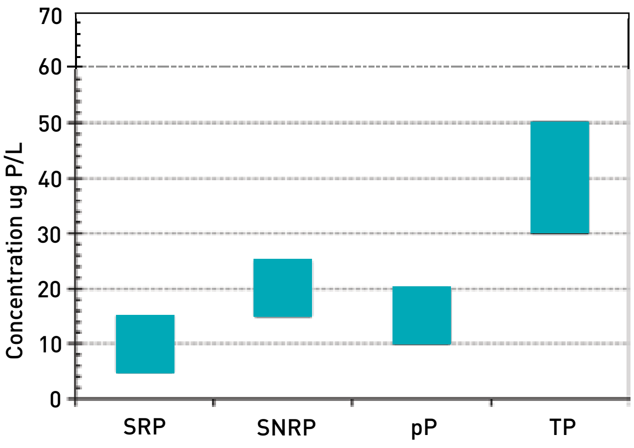
Reliably achievable nitrogen species are shown in Figure 5. Effluent particulate N concentration can be reduced to low values by improving solids captured in the secondary process or provide very efficient solids filtration with membrane or conventional filtration in the tertiary process. Nitrification can produce low NH_3-N concentrations; however, some treatment plants can experience variability due to side stream return streams or storm and/or cold events. The biological process design can be adjusted to offset some of the dynamic impacts imposed by these events (Khunjar et al. 2014). A low effluent ammonia concentration may be achievable over a long averaging period (annual) but not for a short period (daily). Internal recycle streams also need to be attenuated through proper design to avoid bleed-through during diurnal or other peak events. Effluent NO_x-N concentrations are typically higher at operating plants than shown in Figure 5 and would require tertiary carbon addition to be reduced to or perhaps below the concentrations in Figure 5.

Figure 5 - Range of Effluent Nitrogen Concentrations Reliably Achievable with TNR Technologies



Part N = Particulate P
NH_3 = Ammonia N
NOx = Nitrate + Nitrite
SON = Soluble Organic Nitrogen
TN = Total Nitrogen

Figure 6 - Range of Effluent Phosphorus Concentrations Reliably Achievable with TNR Technologies



SRP = Soluble Reactive P
SNRP = Soluble Nonreactive P
pP = Particulate P
TP = Total P

Source: Neethling and Stensel 2013

Phosphorus species shown in Figure 6 follows a similar fate as nitrogen. Inorganic SRP is efficiently removed by either chemical or biological processes to concentrations at and below the nutrient [discharge] criteria. Similarly, particulate P is very effectively removed by using very good effluent filters. Low effluent phosphorus concentrations can be reliably met with tertiary chemical addition and filtration. This requires a robust filtration process that can accommodate tertiary chemical addition, typically a flocculation/sedimentation/filter or membrane filtration process. Direct filtration has been proven effective in some cases.

What Is Limiting Our Ability to Reduce Nutrients to Lower Concentrations?

The results above identified SON and SOP as the nutrient species limiting the ability to reduce nutrient concentrations using CNR and TNR. Advanced nutrient removal (ANR) processes such as reverse osmosis can reduce nutrients through molecular separation.

Treatment and control of SON and SOP with TNR processes remains a topic of research and discussion. Oxidation of the organic molecules does not completely oxidize the organics but may change the nature of the molecules making it biodegradable and removed in CNR and TNR processes (Gu and Tooker 2015). Other potential TNR processes include adsorption, chemical, and membrane treatment.

Internal recycles from solids processing streams and some industrial discharges (for example pulp and paper plants) typically contains high concentrations of SON and SOP. Managing these streams and pretreating them to reduce SON and SOP or redirecting to alternative treatment and disposal routes are also strategies to pursue.

REFERENCES

APHA (American Public Health Association). 2005. *Standard Methods for the Examination of Water and Wastewater*. 21st ed. Washington, DC: APHA.

Bott, C.B., and D.S. Parker. 2011. *Nutrient Management Volume II: Removal Technology Performance and Reliability*. Project NUTR1R06k/1512. Alexandria, VA: Water Environment Research Foundation, and London: IWA Publishing.

EPA (U.S. Environmental Protection Agency). 2007. *Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus*. EPA 910-R-07-002. Seattle, WA: Office of Water and Watersheds.

Gu, A.Z., L. Liu, and A. Onnis-Hayden. 2014a. *Bioavailability and Characteristics of Dissolved Organic Nutrients in Wastewater Effluents*. Project NUTR1R06o/1516. Alexandria, VA: Water Environment Research Foundation, and London: IWA Publishing.

Gu, A.Z., L. Lui, A. Onnis-Hayden, S. Smith, H. Gray, D. Houweling, and I. Takács. 2014b. *Phosphorus Fractionation and Removal in Wastewater Treatment: Implications for Minimizing Effluent Phosphorus*. Project NUTR1R06l/1513. Alexandria, VA: Water Environment Research Foundation, and London: IWA Publishing.

Gu, A.Z., and N. Tooker. 2015. *Impact of Advanced Oxidation Processes on the Composition and Biodegradability of Soluble Organic Nutrients in Wastewater Effluents*. Project NUTR5R14e/1530. Alexandria, VA: Water Environment Research Foundation, and London: IWA Publishing.

Jimenez, J.A., T. Madhanagopal, H. Schmidt, J. Bratby, H. Meka, and D.S. Parker 2007a. Full-Scale Operation of Large Biological Nutrient Removal Facilities to Meet Limits of Technology Effluent Requirements: The Florida Experience. In *Proceedings of the Water Environment Federation Annual Conference*. San Diego, October 2007.

Jimenez, J.A., D.S. Parker, W. Zdziebloski, R.L. Pope, D. Phillips, J.A. Nissen, and H.E. Schmidt. 2007b. Achieving Limits of Technology (LOT) Effluent Nitrogen and Phosphorus Removal at the River Oaks Two-Stage Advanced Wastewater Treatment Plant. In P*roceedings of the Water Environment Federation Annual Conference*. San Diego, October 2007.

Kang, S.J., K. Olmstead, K. Takacs, and J. Collins. 2008. *Municipal Nutrient Removal Technologies Reference Document*. EPA 832-R-08-006. Washington, DC: EPA Office of Wastewater Management.

Khunjar, W., M. Strahota, P. Pitt, and W.J. Gellner 2015. *Evaluating the Impacts of Cold and Wet Weather Events on Biological Nutrient Removal in Water Resource Recovery Facilities*. Project NUTR1R06s/1520. Alexandria, VA: Water Environment Research Foundation, and London: IWA Publishing.

Neethling, J.B., and H.D. Stensel. 2013. Nutrient Species Implications for Technology Performance and Water Quality Impacts. Presented at WEF/IWA Nutrient Removal and Recovery Conference, Vancouver, BC. July 28–31, 2013.

Neethling, J.B., B. Bakke, M. Benisch, A. Gu, H. Stephens, H.D. Stensel, and R. Moore. 2005. *Factors Influencing the Reliability of Enhanced Biological Phosphorus Removal*. Project 01-CTS-3/1051. Alexandria, VA: Water Environment Research Foundation, and London: IWA Publishing.

Neethling, J.B., D.L. Clark, H.D. Stensel, J. Sandino, and R. Tsuchihashi. 2019. *Nutrient Removal Challenge Synthesis Report*. Project NUTR5R14g/4827g. Alexandria, VA: The Water Research Foundation.

Neethling, J.B., H.D. Stensel, D.S. Parker, C. Bott, S. Murthy, A. Pramanik, and D. Clark. 2009. What Is the Limit of Technology (LOT)? A Rational and Quantitative Approach. Presented at WEF/IWA Nutrient Conference, Baltimore, 2009.

WRF (The Water Research Foundation). 2019. "Soluble Organic Nitrogen in Biological Nutrient Removal" from the Nutrient Removal Challenge.

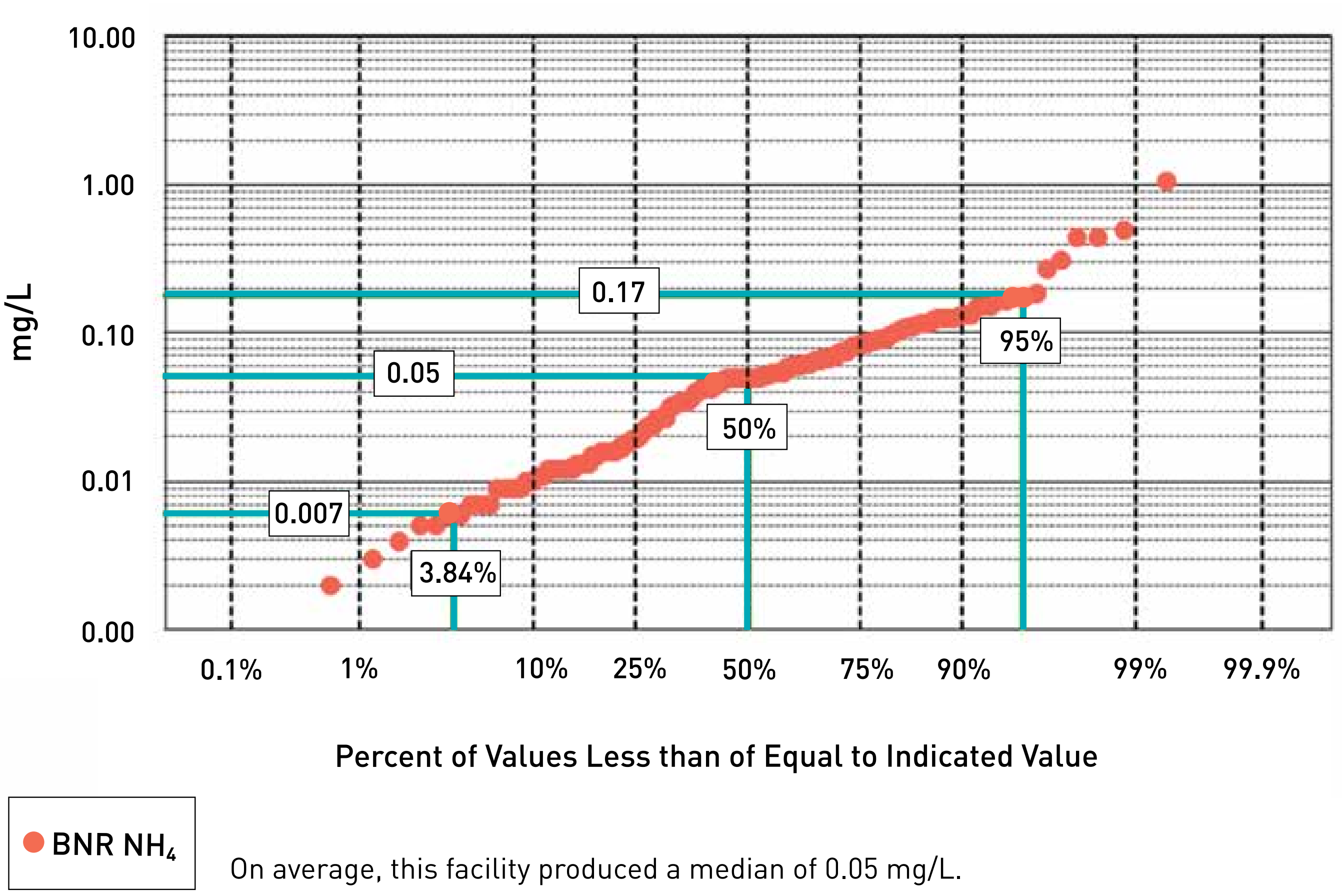
ATTACHMENT A

This attachment includes graphs from Neethling and Stensel (2013) showing the datasets used to determine the reliable species removal. The reliable values are generally values achievable at TPS-80 and TPS-90 confidence level. Supplemental data is used determine the reliably achievable performance as discussed in Section "How Reliably Can Technologies Remove Individual Nutrient Species?"

Ammonia Nitrogen Performance

The following is an example of performance achievable with an activated sludge process achieving full nitrification. Ammonia is removed to very low values.

Figure 7 – Example Statistical Analysis of Ammonia Data Illustrating Reliable Performance at 80th and 95th Percentiles

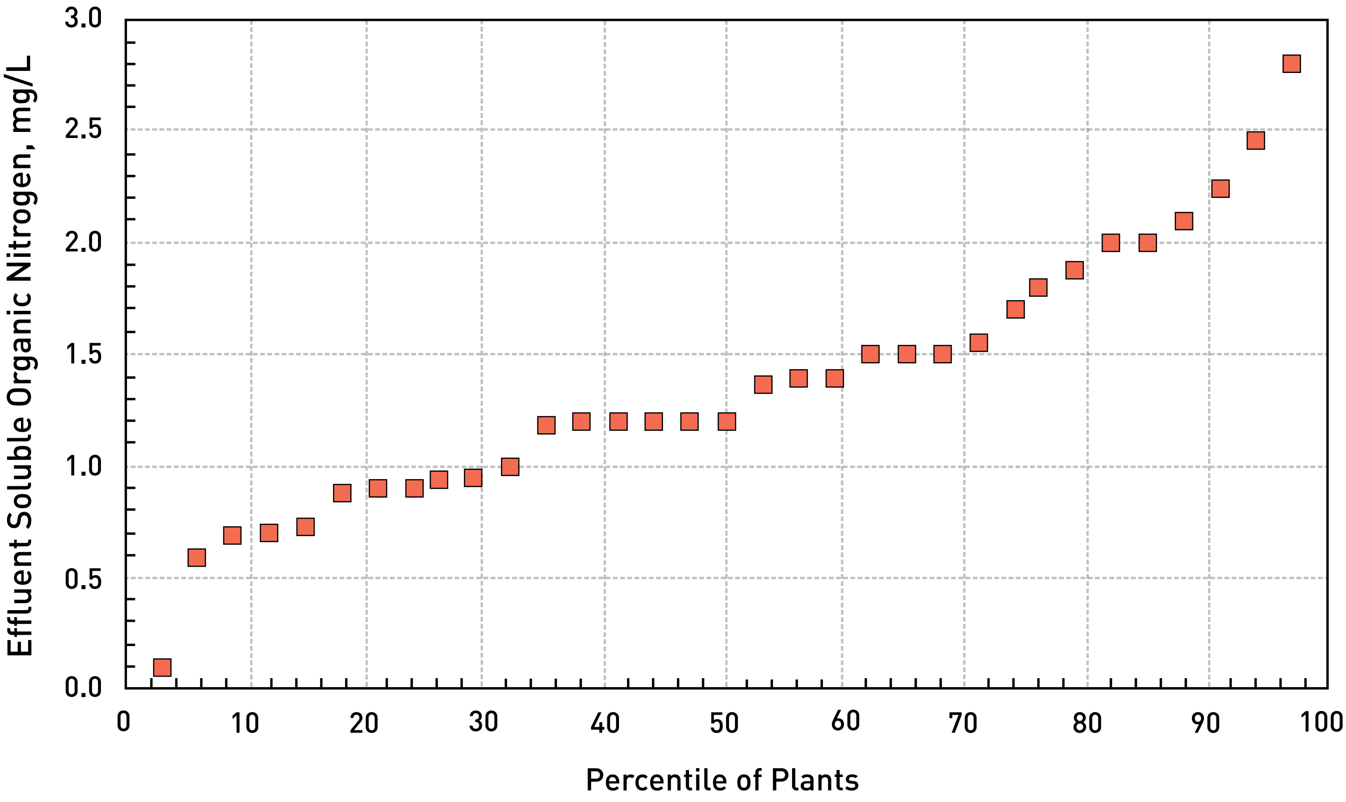


On average, this facility produced a median of 0.05 mg/L.

Soluble Organic Nitrogen Survey

A ranking of effluent SON concentrations in Figure 8 from data reported assembled by Jimenez et al. (2007a) and tabulated in Table 3 shows effluent SON concentration ranged from 0.6 to 2.8 mg/L. The 50 percentile SON concentration for these data is 1.2 mg/L.

Figure 8 - Effluent SON Concentrations from Survey of Biological Nitrogen Removal Facilities

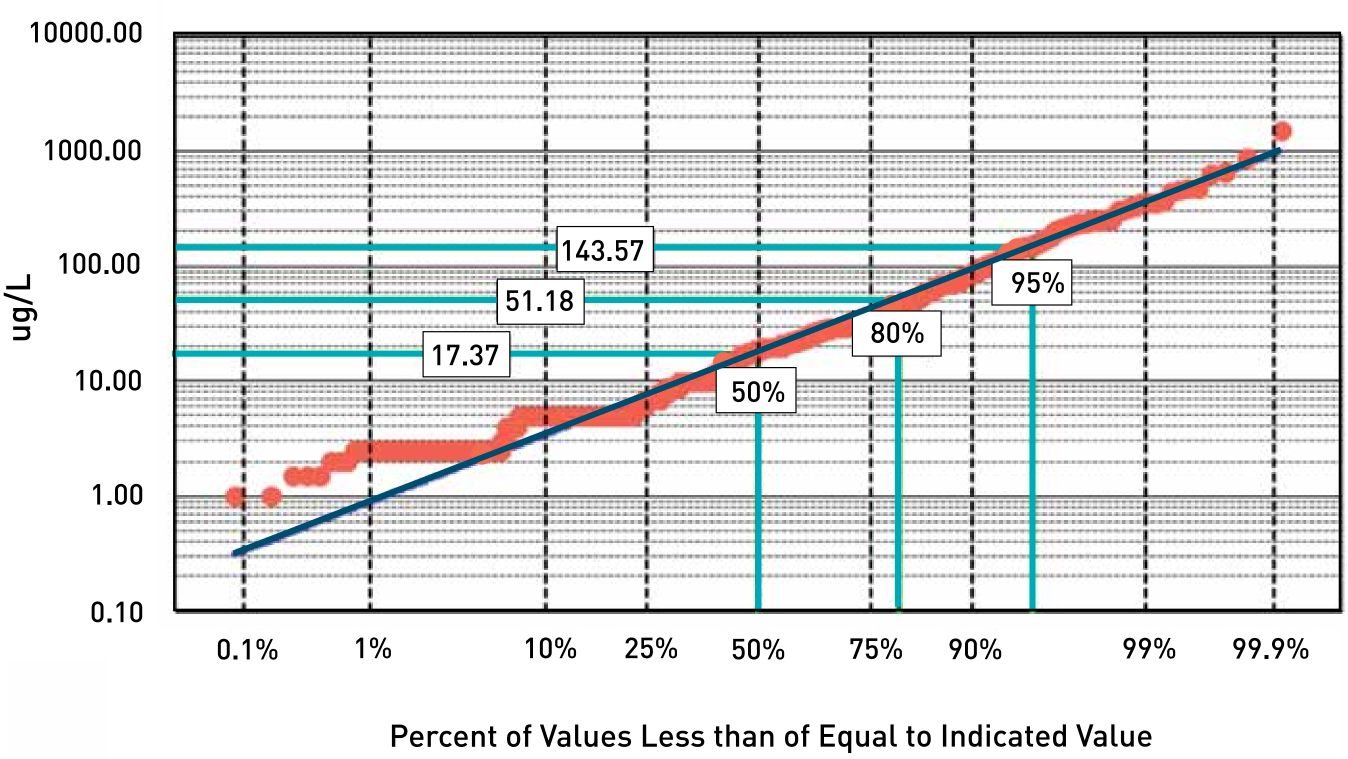


Source: Adapted from Jimenez et al. 2007a

Soluble Reactive Phosphorus (Orthophosphate)

Long-term performance from a plant achieving very low SRP. Orthophosphorus is removed to low microgram per liter concentrations.

Figure 9 - Example Statistical Analysis of Soluble Reactive Phosphorus Data Illustrating Reliable Performance at 80th and 95th Percentiles

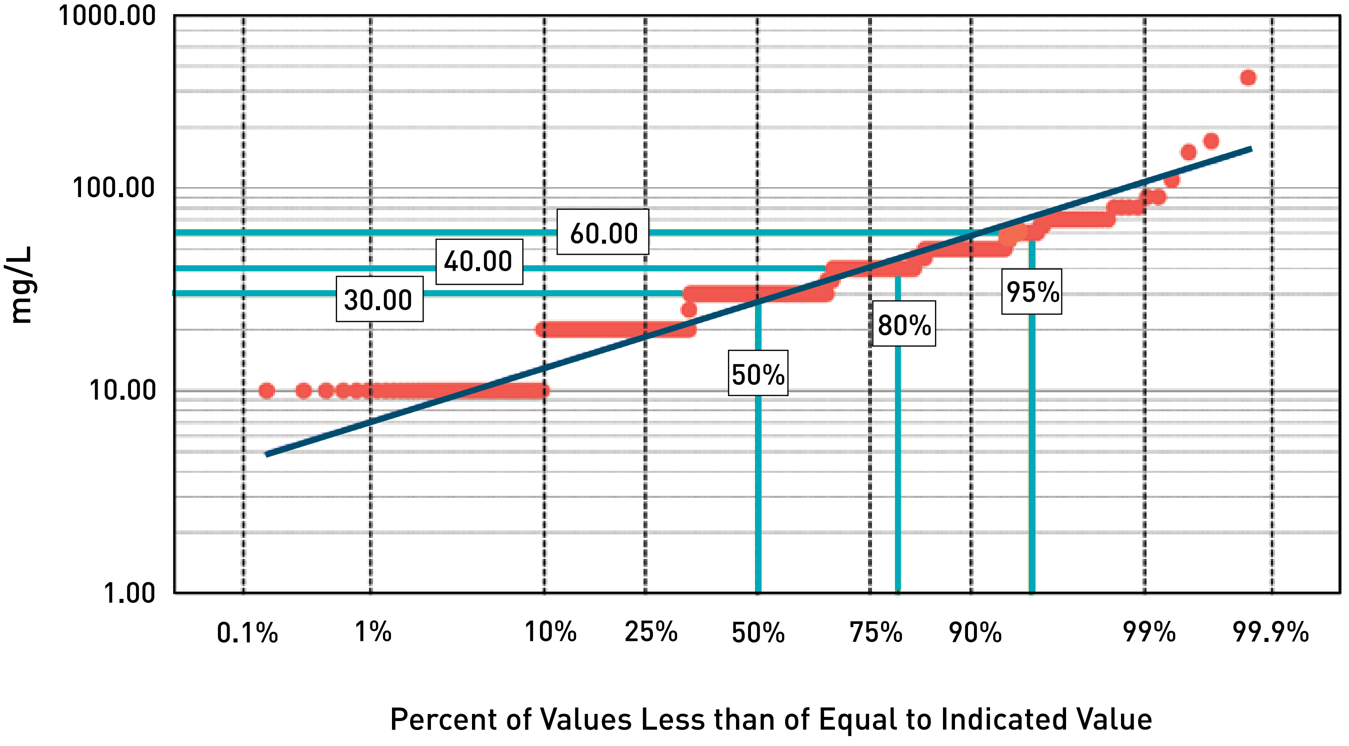


On average, this facility produced a median below 17 ugP/L soluble reactive phosphorus. 25% of the data is below 5 ug/L.

Soluble Non-Reactive Phosphorus

Long-term operating data from MBR plant. The effluent membrane eliminate particulate species and the TP measurements become soluble total phosphorus (SP) concentrations.

Figure 10 - Example Statistical Analysis of Soluble Non-reactive Phosphorus Data Illustrating Reliable Performance at 80th and 95th Percentiles

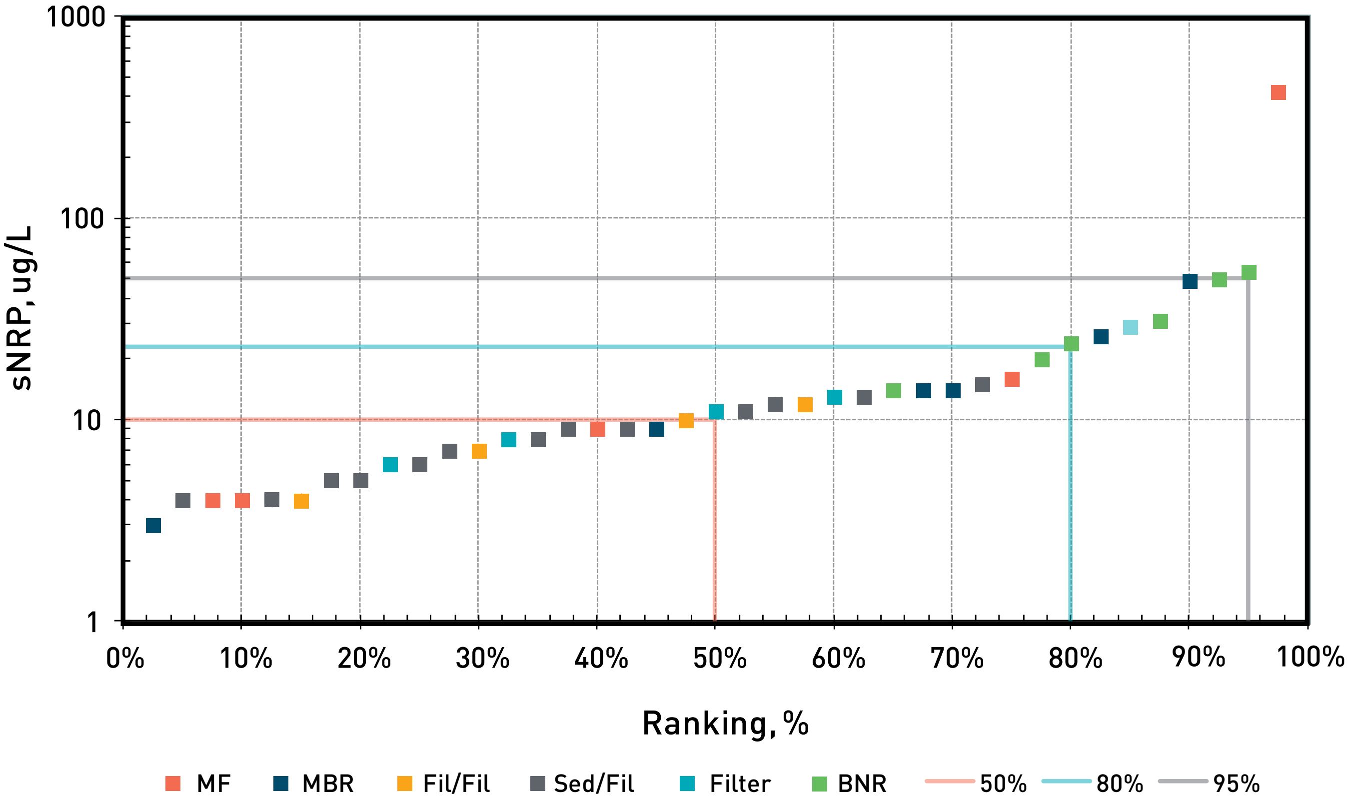


On average, this facility produced a median of 30 ugP/L soluble non-reactive phosphorus.

Soluble Non-Reactive Phosphorus

Long-term operating data from MBR plant. The effluent membrane eliminate particulate species and the TP measurements become soluble total phosphorus (SP) concentrations.

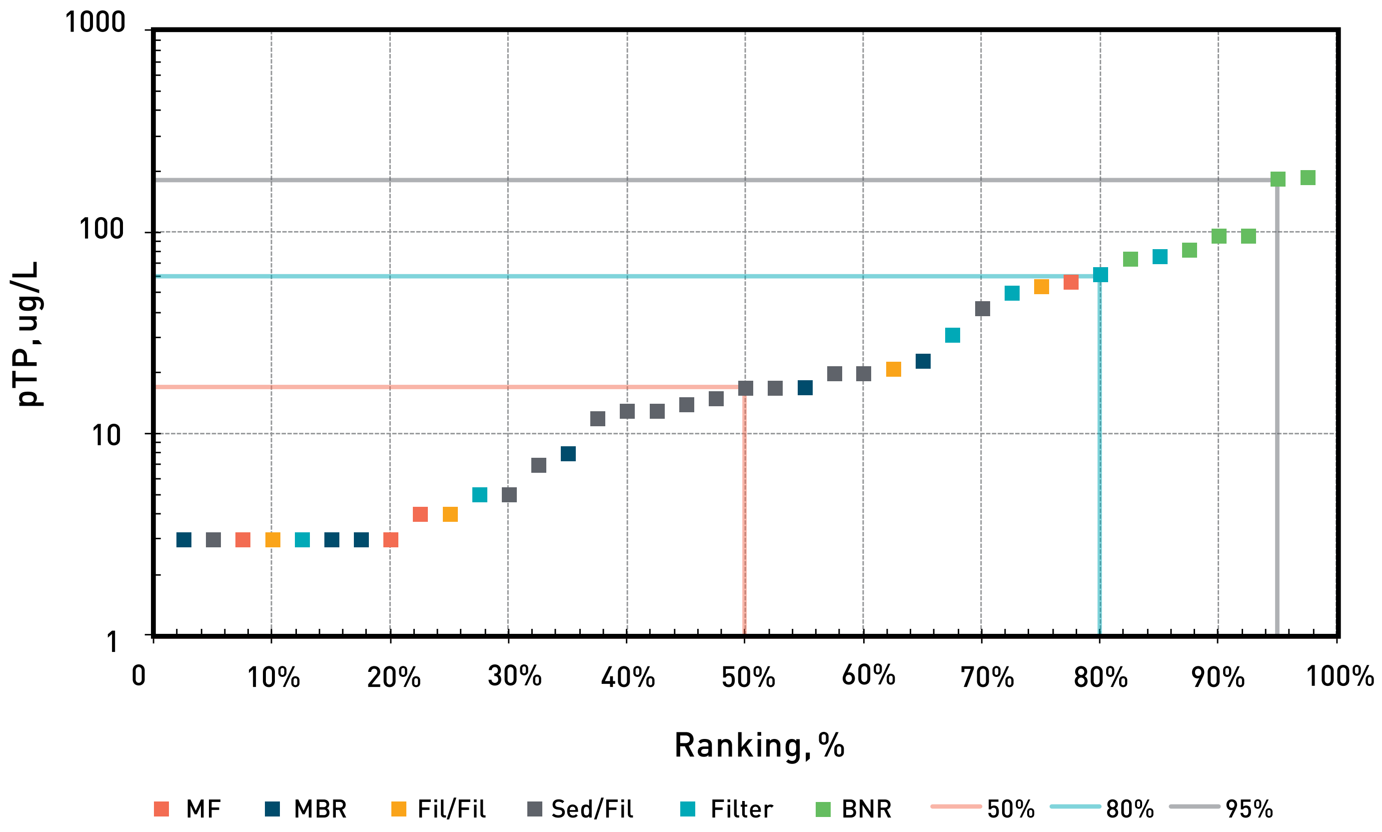
Figure 11 - Soluble Non-reactive Phosphorus Data from Special Study Surveying a Number of Technologies and Processes



The 50th, 80th and 95th percentiles are shown as a reference. Since the data comes from various sources/ technologies, it does not provide reliability measures, but does reflect the performance from various technologies.

Particulate Total Phosphorus

Figure 12 - Particulate Total Phosphorus Data from Special Study Surveying a Number of Technologies and Processes



The 50th, 80th and 95th percentiles are shown as a reference. Since the data comes from various sources/technologies, it does not provide reliability measures, but does reflect the performance from various technologies.