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**FLEETWOOD BOROUGH AUTHORITY  
WASTEWATER TREATMENT FACILITY**  
RICHMOND TOWNSHIP, BERKS COUNTY, PENNSYLVANIA

NPDES Permit PA0021636



**DISSOLVED OXYGEN AND ORP STUDY**

-Prepared by-  
Marc Neville and Walter Higgins  
PA DEP & EPA Region III Water Division  
Infrastructure and Assistance Section (3WP32)  
Four Penn Center  
1600 John F Kennedy Blvd  
Philadelphia, PA 19103-2852



2023

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**Disclaimers:**

The mention of a brand of equipment is in no way an endorsement for any specific company. The Department urges the permittee to research available products and select those which are the most applicable for its situation and compatible with existing equipment.

The goal of the Department's Wastewater Optimization Program is to improve receiving water quality through troubleshooting, training, and monitoring. Permittees may be encouraged to achieve effluent quality above and beyond current permit requirements.

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### **Executive Summary**

In early 2023, technical Assistance staff from the U.S. EPA Region III Water Division (EPA) and the PA Department of Environmental Protection Wastewater Technical Assistance Program (WWTAP) partnered with Fleetwood Borough STP operators and their consulting engineer to demonstrate the benefits of using continuous monitoring dissolved oxygen (D.O.) and Oxidation/Reduction Potential (ORP) probes to monitor operating conditions in a three-stage, 0.70 MGD Orbal activated sludge treatment system presently operated with no feedback control of the brush rotor aerators. The facility's design organic loading limit is 1,706 pounds per day. Over the past year, the facility has averaged about 0.41 MGD flow and 700 lb./day of organic loading. The facility owner and engineer anticipate upgrading the facility to increase treatment efficiencies.

An additional concern arose, related to whether regulation of industrial users is sufficient. A food-processing industrial contributor to the waste stream operates pre-treatment lagoons, and the facility operators were concerned that the pre-treated wastewater from the lagoons was suppressing dissolved oxygen levels within the Orbal because of elevated organic loading. Use of the D.O. probes identified potential organic slug loads to the facility. Further surveillance for organic slug loads could be performed in the future using an organic carbon probe provisionally offered by WWTAP.

DEP provided Hach LDO2 dissolved oxygen sensor, ORP probe, and SC200 probe controller with mounting accessories. These instruments are lent to wastewater operators for their use in process monitoring and optimization projects under terms of a federal grant administered through the EPA Office of Water Infrastructure and Assistance Section.

### **Recommendations:**

Based on observations of consultants and facility staff, the following recommendations are offered for improving facility performance:

1. The Borough should equip each of the three ditches in the Orbal with dissolved oxygen continuous-immersion probes. Since plans are in place for a facility upgrade, these monitoring enhancements should be incorporated in the design.
2. The brush rotors should be powered by variable frequency drives, if possible, to regulate dissolved oxygen residual in the ditches. VFDs would be controlled by D.O. sensors incorporated into PLC/SCADA programs.
3. Probe data should be recordable for process monitoring, and it should be graphable for trending analyses. This may require modification of an existing SCADA program to include this data acquisition.
4. EPA staff would provide, on request, training in process control tests and data trending if these upgrades are adopted by the Borough.
5. Before and after cleaning, the ORP sensor data has indicated that trash and rags are entering the ditches and adversely affecting treatment performance. Enhanced influent screening is recommended for remove trash. Operators have indicated that this is planned in the future upgrade. The industry standard has moved away from comminutors to fine screening apparatus, where the trash and detritus is completely removed from the waste stream so that it cannot interfere with or harm downstream equipment such as pumps, valves, and control instrumentation.
6. Observed low DO levels indicate that a major industrial discharger may be releasing a

high BOD waste or partially treated effluent to the Borough's treatment facility. The Borough should review its ordinances regarding local limits on commercial and industrial users of its treatment system and, if necessary, enact more stringent controls on such waste, up to and including developing a formal pretreatment program to prohibit industrial wastes that adversely affect the collection and treatment system or which may pass through treatment without being adequately removed. At the least, there should be surcharges to the industrial and commercial users, based on exceedances of local limits, as they should be paying for what the facility is treating.

7. The operators and their engineer are working with the major industrial discharger to improve performance of their pretreatment lagoon and reduce organic loading to the public wastewater treatment system. It may prove useful to deploy a UVAS organic carbon probe to monitor the influent stream for slug loads. A six-to-eight-week study could be arranged with WWTAP for monitoring, similar to that which was done using the D.O. and ORP probes.

### **Discussion:**

Fleetwood Borough constructed a sewer system and sewage treatment plant to complement its public water system in 1965. The facility has been upgraded as the community and adjacent Richmond Township have grown. Presently, the facility is upgrading its headworks for enhanced detritus removal and its aerobic digesters to improve aeration and treatment efficiency. The current permit runs through 2024 and lists many nutrient substituents for monitoring and reporting, without specific limits. There may be plans to impose additional nutrient limits in future permit renewals, which when combined with upgraded treatment suggests that biological nutrient removal (BNR) would be the next logical step in the evolution of this facility.

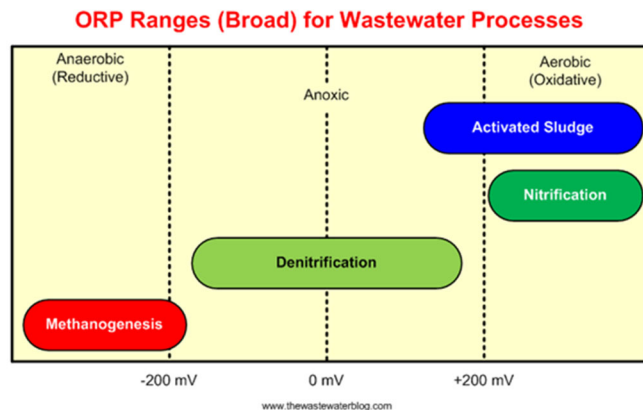
An Orbal oxidation ditch system is comprised of three concentric oxidation ditches that provide for flexibility of operation for variable hydraulic flow with high retention time, yielding highly efficient treatment at low food-to-mass ratio. The design promotes simultaneous nitrification and denitrification of ammonia and organic nitrogen as fluid moves through successive oxic and anoxic zones. Aeration is provided by mechanical mixers, usually brush or disk rotors, that may be interconnected or operated individually by drive motors and gear reducers. The action of the rotors maintains flow through the ditches while also aerating the activated sludge bacteria that consume the waste being treated.

The study objective was to show the benefits of using oxidation/reduction potential (ORP) and DO probes for monitoring for process monitoring and control, to demonstrate suitability for automated aeration control, to monitor DO slumps in relation to industrial slug loads in the influent wastewater, and to educate the operators on the benefits of automated process control for activated sludge and biological nutrient removal (BNR). It is more difficult to regulate dissolved oxygen in oxidation ditches that employ rotors when compared to using conventional air diffusers, but it can be achieved within limits. Operators can regulate aeration by increasing or decreasing the depth of immersion of the rotors; they can also remove individual brushes or disks, if necessary, to provide for different levels of dissolved oxygen in individual ditches. The motors driving brush rotors can be regulated using variable frequency drives (VFD), but the rotors usually span all the ditches. Using VFD on the rotors may require choosing which ditch to prioritize. For example, given three ditches, two aerobic and one anoxic, one would have to choose whether to optimize DO in the ditch that treats carbonaceous organic loading versus the one that provides for nitrification, all while assuring the DO levels in the anoxic ditch remain optimal for denitrification that requires anoxic, but not anaerobic, conditions. An ORP probe in an anoxic ditch or zone will

show the operator if conditions are truly anoxic, where DO is near zero mg/L, but not anaerobic, when ORP values fall below -150 millivolts (mV).

An attachment, following, discusses BNR in more detail. Nutrient control requires enhanced instrumentation for monitoring treatment and water quality throughout the process, and any upgrades should seriously consider addition of continuous-monitoring probes. The probes typically used are summarized here:

- Dissolved Oxygen (D.O.):** all activated sludge treatment facilities require considerable amounts of D.O. to support the biological activity that oxidizes waste into inert and harmless material. In modern facilities, D.O. probes are used to regulate the D.O. levels in the bioreactors to maintain enough available oxygen to see the activated sludge biomass through organic and nitrogenous waste oxidation. Typically, the range of dissolved oxygen residual required for nitrification is between 1.5 and 3.5 mg/L.<sup>1</sup> Because of the cost of energy used to produce D.O., experts recommend that D.O. concentration not exceed the upper limit for long, because excess D.O. is essentially wasted, increasing energy costs, as the excess is not needed for treatment. In fact, an excess of D.O. may inhibit denitrification of the nitrate produced by oxic treatment, resulting in less efficient treatment and increased amounts of nitrate-nitrogen released with the treated wastewater. Nitrate and nitrite act as fertilizer for algae growth in receiving streams, degrading surface water quality. Safe drinking water treatment facilities drawing water downstream of unimproved wastewater treatment facilities take in excessive concentrations of nitrates, and nitrate in drinking water has implications in human health.
- Oxidation/Reduction Potential:** A more recent control method uses oxidation/reduction potential (ORP) to monitor biological denitrification in the activated sludge during anoxic treatment phases, where nitrate is biologically converted to nitrogen gas that leaves the water to return to the atmosphere, essentially reducing harm from dissolved nitrate to receiving waters and its users.
- pH probes are used to monitor the quality of the activated sludge environment: ideally, pH for BNR is held between 7 and 8.6 s.u. Nitrification of organic and ammonia waste reduces pH in the bioreactor, and operators compensate for this by adding alkalinity to the system. Alkalinity acts as a buffer against rapid pH changes, and without it, nitrification can drop pH below 6.5, at which biological ammonia oxidation stops.
- Ammonium Ion-specific Electrode (ISE):** Some facilities are now using ammonium ISE probes to monitor ammonia removal. These probes may be placed in the bioreactor, clarifier supernatant, or final effluent. Continuous monitoring capability protects against ammonia excursions that may occur when the facility is unattended.
- Nitrate or Nitrite-Nitrate:** These probes are used in a similar fashion as the ammonium ISE probe. In fact, the ammonium and nitrate detection capabilities may be combined into

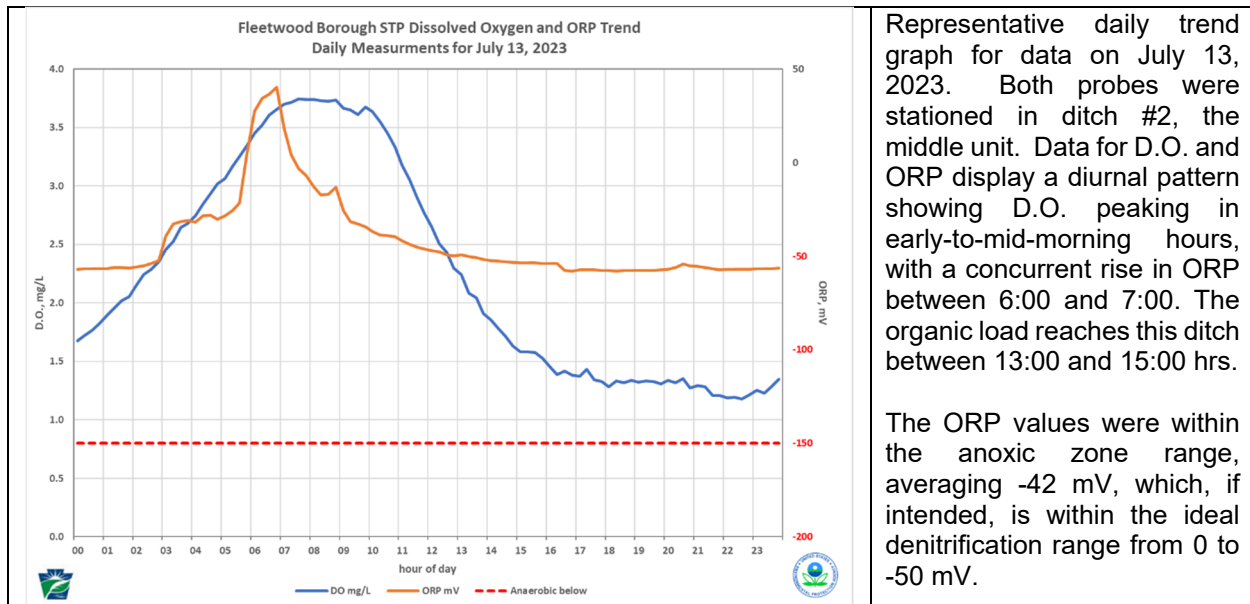


<sup>1</sup> Carbonaceous organic waste is consumed first; nitrification occurs after organic carbon has been depleted.

a single probe such as the ammonium & nitrite-nitrate ISE probe. Trending the data of ammonium and nitrate probes allows the operator to determine what occurs when the facility is unattended overnight. Rapid increases in ammonium in the wastewater may indicate industrial slug loads or decreasing nitrification efficiency due to loss of biomass, insufficient alkalinity and lowered pH, or toxic chemicals passing through the facility without treatment.

- **Suspended Solids:** Operating a biological treatment system such as the Orbal requires regular monitoring of the suspended solids concentration of the biomass. A suspended solids probe automates this task, providing reliable data for setting wasting rates or responding to unplanned solids losses due to hydraulic surges.
- **Organic Carbon:** Facilities dealing with industrial and commercial wastes may benefit from using continuous monitoring of the carbon in the waste stream. An organic carbon probe, called a “BOD probe” because it may be calibrated to mimic the 5-day BOD test, may be employed in the raw wastewater to monitor for incoming slug loads and surges. It can provide quicker insight into the organic loading entering the facility than the gold-standard 5-day BOD test that produces data long after a slug load has upset the treatment system.

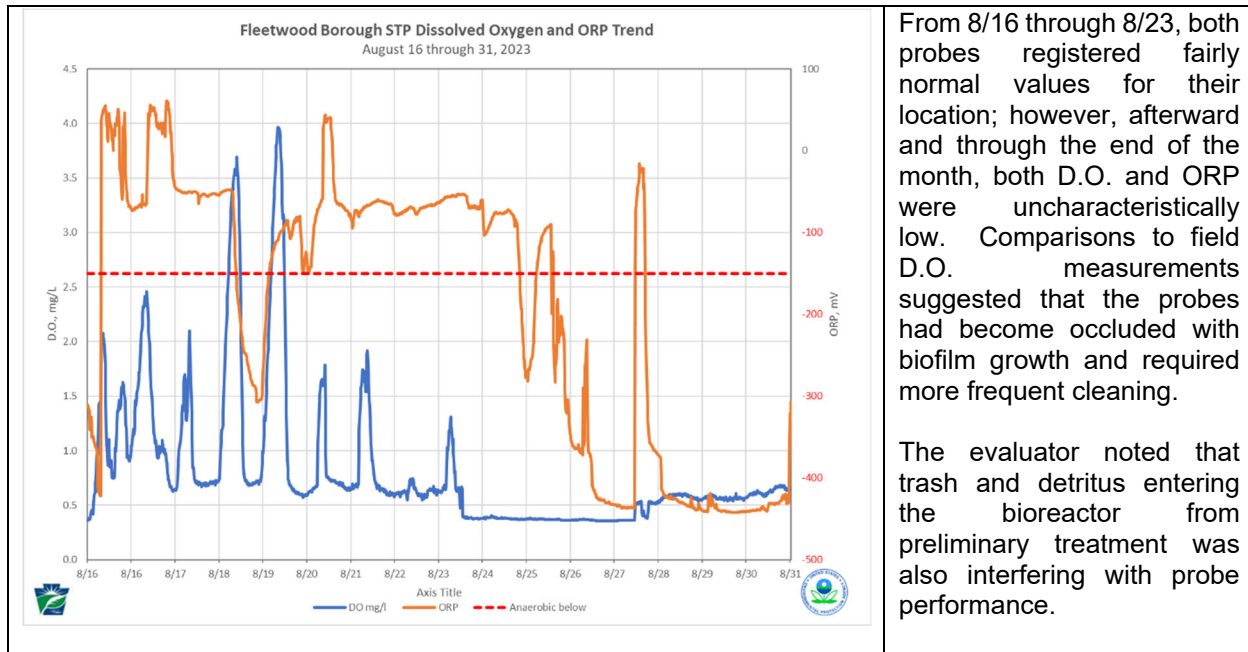
Using these probes, an operator can treat wastes more efficiently and avoid process upsets that lead to permit violations and downstream pollution events. Although Fleetwood had only DO and ORP probes available for this study, EPA’s evaluator was able to infer by trending data for dissolved oxygen in the Orbal that there may be high-strength organic waste entering the facility unexpectedly. In the graph shown below, the organic slug presents as a sudden and prolonged drop in dissolved oxygen content of the mixed liquor in different oxidation rings of the Orbal. Such drops in D.O. are an indicator to the operators that they should do additional testing of the wastewater to determine the nature and seriousness of organic slug loads. By the same method, excessively high D.O. residual in the bioreactor may indicate toxicity in the wastewater coming from cleaning solutions used in commercial and institutional users, to be followed up by further sampling and testing to determine a source and a substance. As a reminder, a facility’s NPDES Permit permits the operators to exclude any wastes that may pass through the facility untreated or that may interfere with proper treatment within the permitted facility.



Representative daily trend graph for data on July 13, 2023. Both probes were stationed in ditch #2, the middle unit. Data for D.O. and ORP display a diurnal pattern showing D.O. peaking in early-to-mid-morning hours, with a concurrent rise in ORP between 6:00 and 7:00. The organic load reaches this ditch between 13:00 and 15:00 hrs.

The ORP values were within the anoxic zone range, averaging -42 mV, which, if intended, is within the ideal denitrification range from 0 to -50 mV.

From about August 16 through 31, the D.O. and ORP probe were co-located in the center ditch, #2. Following is a graph showing the trends:



During the evaluation, the ORP and D.O. probes were relocated among the ditches, singly or as a pair, to characterize different phases of treatment. For Sept. 1 through 6, the graph following shows acceptable D.O. values at the inner ditch (#1, going from center outward.) The ORP values registered in the anaerobic zone for the middle ditch (#2.)

This brings up an important point: Continuous-monitoring probes require regular routine cleaning by the operators to remove biofilm that grows on the surface of the probe and inhibits proper operation. Also, the evaluator had noted that rags, plastic, and detritus passing through the plant headworks will accumulate on aerators and instrumentation downstream and will also eventually damage pumps and valves. Removal of this detritus will be very important in operating an upgraded facility, and replacement of the comminutor with a modern headworks screening system will be a valuable improvement to the treatment system.

### [A Note on Aerobic Digester Denitrification:](#)

Since the next upgrade will focus on digester performance, it is worth noting that the use of intermittent aeration in aerobic digesters has proved useful in denitrifying digester decant and sludge press side stream flows that might otherwise reintroduce excess nitrate into the Orbal bioreactor. EPA's earlier work at the [Borough of Adamstown](#) wastewater treatment facility demonstrated that dissolved nitrate in aerobic digesters may be successfully reduced through the natural process of denitrification simply by alternating aeration cycles with anoxic treatment cycles. Even larger reductions in electrical consumption were observed, due chiefly to the incorporation of blower "off" periods into digester operations. To make denitrification effective, though, anoxic mixing may be required to maintain three components in suspension: denitrifying bacteria wasted with biomass solids, nitrate dissolved in the water, and organic carbon as a food source, which in the case of aerobic digesters is the biomass itself that is being auto-digested.

**Acknowledgements:**

DEP WWTAP thanks the facility operators and the board of the Authority for the opportunity to examine dissolved oxygen control at this facility.

## **LIST OF ATTACHMENTS**

**Attachment A** lists the primary participants in this study.

**Attachment B** contains some record photographs of the project.

**Attachment C** consists of graphs of data recorded by the DO and ORP probes, plus graphs of trended operations data based on the previous thirteen months.

**Attachment D** is a discussion of biological nutrient removal.

**Attachment E** estimates the current costs for equipment similar to that employed during the study.

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**ATTACHMENT A: EVALUATION TEAM**

<b>U.S. Environmental Protection Agency</b>	<b>PA Dept. of Environmental Protection</b>
Walter Higgins EPA Region III Water Division Infrastructure and Assistance Section (3WP32) Four Penn Center 1600 John F Kennedy Blvd Philadelphia, PA 19103-2852  phone: (215) 814-5476 email: <a href="mailto:higgins.walter@epa.gov">higgins.walter@epa.gov</a>	Marc Neville, Water Program Specialist Bureau of Clean Water—Operations Section Rachel Carson State Office Bldg. 400 Market St; POB 8774 Harrisburg, PA 17105-8774  phone: (717) 772-4019 email: <a href="mailto:mneville@pa.gov">mneville@pa.gov</a>
<b>Owner Representative</b>	<b>Consulting Engineer</b>
Craig Conrad, Public Works Director Borough of Fleetwood 110 West Arch Street Fleetwood, PA 19522  phone: 610-987-9508 email: <a href="mailto:conrcraig@gmail.com">conrcraig@gmail.com</a>	Dale Miller, P.E. Entech Engineering 201 Penn Street, POB 32 Reading, PA 19603  phone: (800) 825-1372 email: <a href="mailto:DMiller@entecheng.com">DMiller@entecheng.com</a>
<b>Operations Staff</b>	
Chad DeLay, Operator Fleetwood STP 608 Crisscross Rd Kutztown, PA 19530  phone: (610) 944-9361 <a href="mailto:chadD@fleetwoodboro.com">chadD@fleetwoodboro.com</a>	Tim Keeling, Operator Fleetwood STP 608 Crisscross Rd Kutztown, PA 19530  phone: (610) 944-9361 <a href="mailto:tkeeling@fleetwoodboro.com">tkeeling@fleetwoodboro.com</a>

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**ATTACHMENT B: RECORD PHOTOGRAPHS**



Overview of Orbal bioreactor, a 3-ring oxidation ditch arrangement aerated by brush rotors.

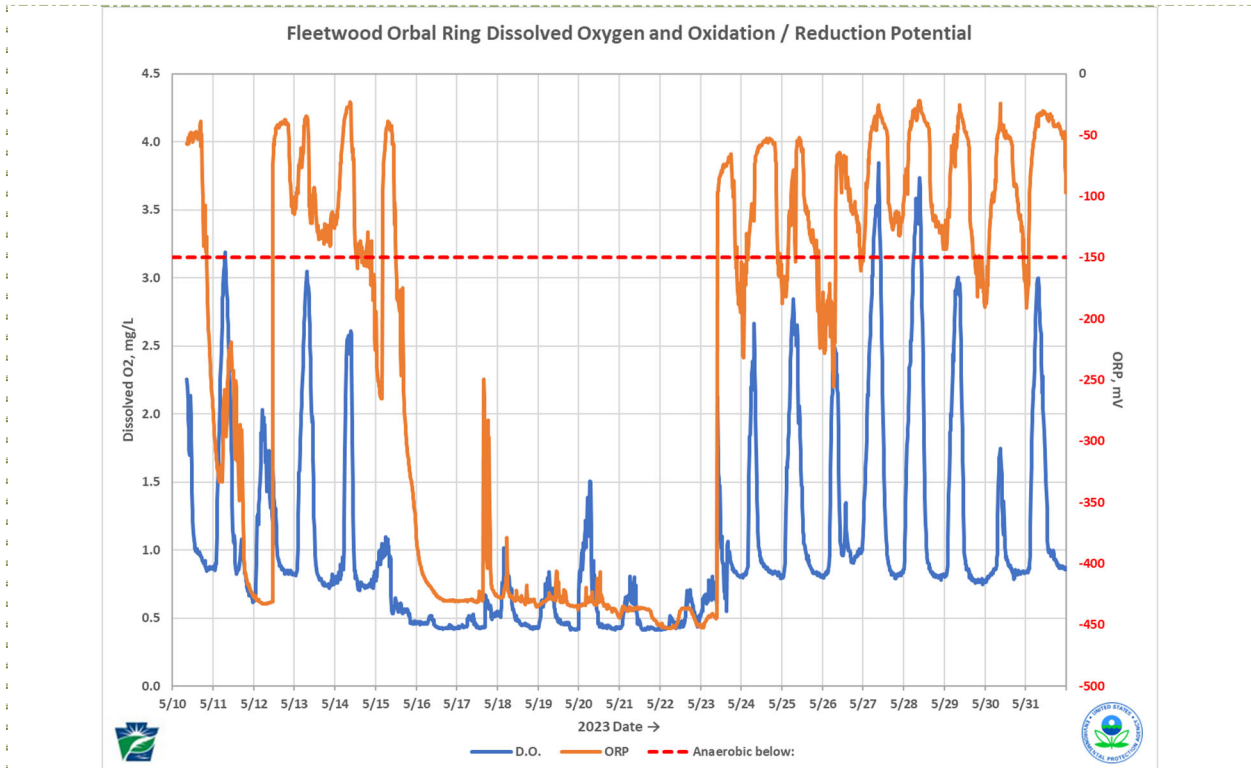


View of dissolved O<sub>2</sub> probe assembly in outer ring of Orbal, near brush rotor.

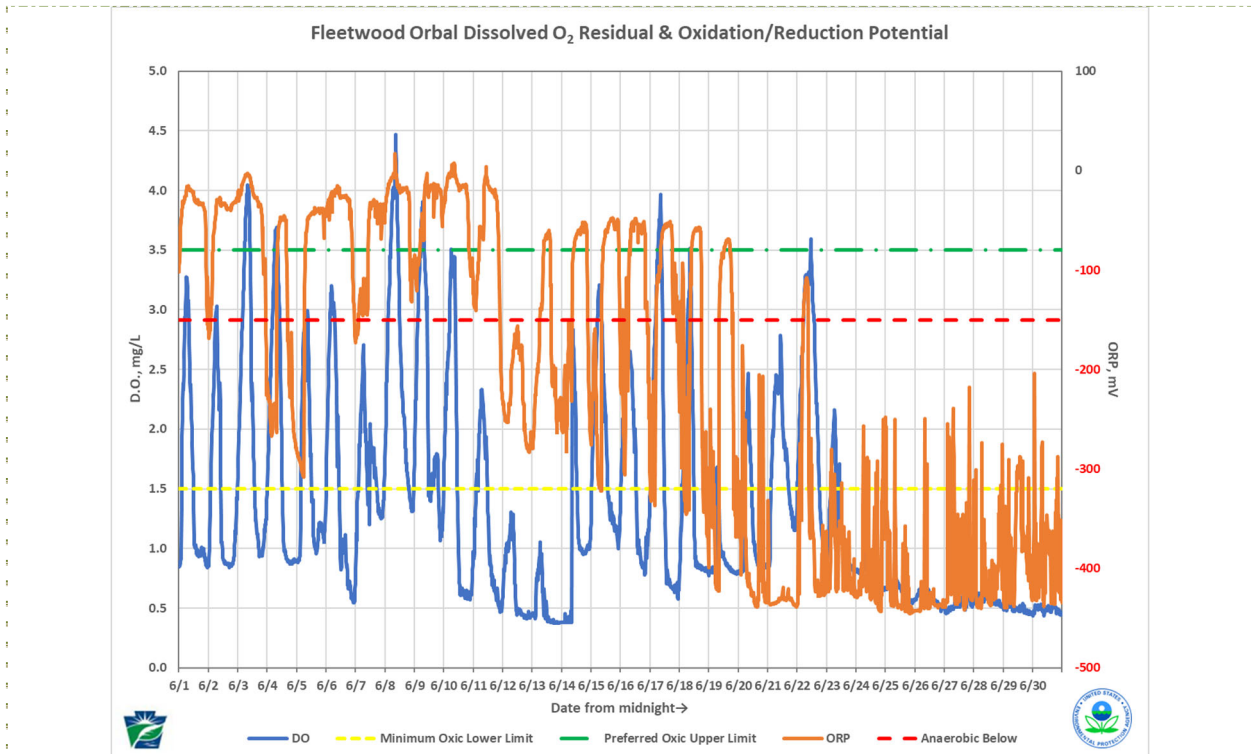


This photo shows how rags and detritus accumulate on diffusers and other appurtenances within aeration tanks and aerobic digesters. Comminutors worked well in the 1980s, when many facilities routinely shut down their process units once a year for inspection and cleaning, but today, more modern facilities have found that with the increased use of personal care products and the introduction of more sophisticated technology in the aeration tanks, rags and detritus have to be removed at the headworks rather than simply shredded to reknit downstream. Rags can damage pumps, valves, aerators, and instrumentation installed in bioreactors and digesters. Modern rotary fine screening headworks remove this trash from the waste stream before damage can be done, and most of these newer devices rinse organic matter from the trash before it is compacted for disposal off site, so that the organic matter can be utilized by bacteria in the activated sludge.

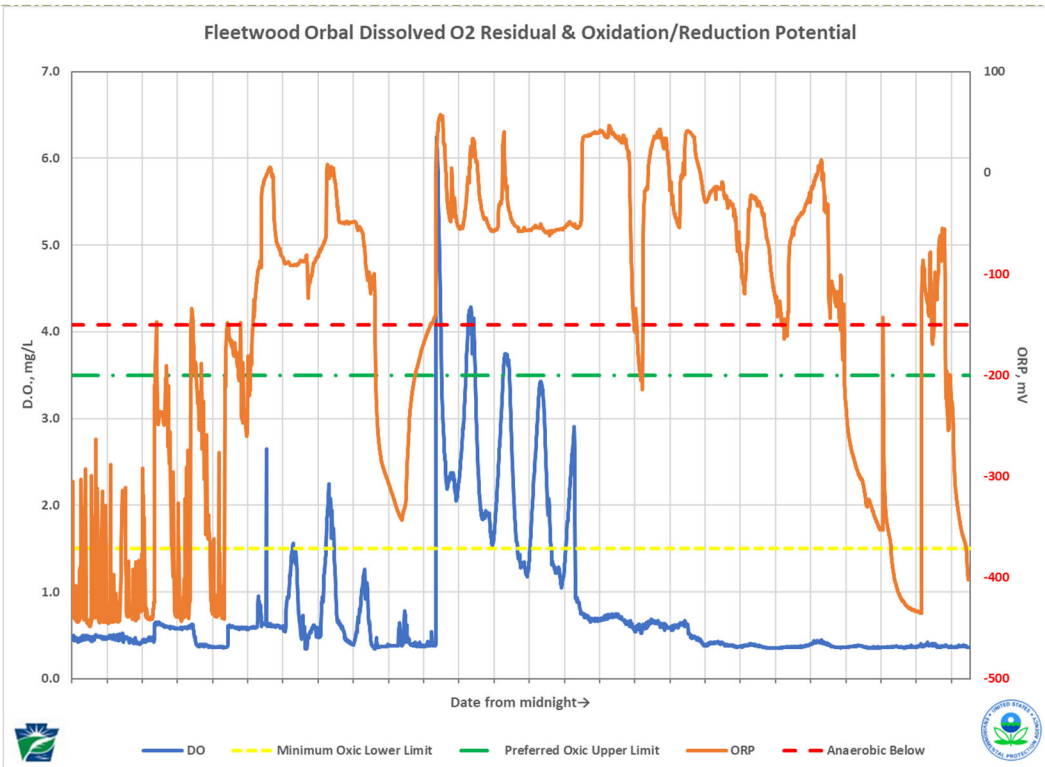
**ATTACHMENT C: GRAPHS**



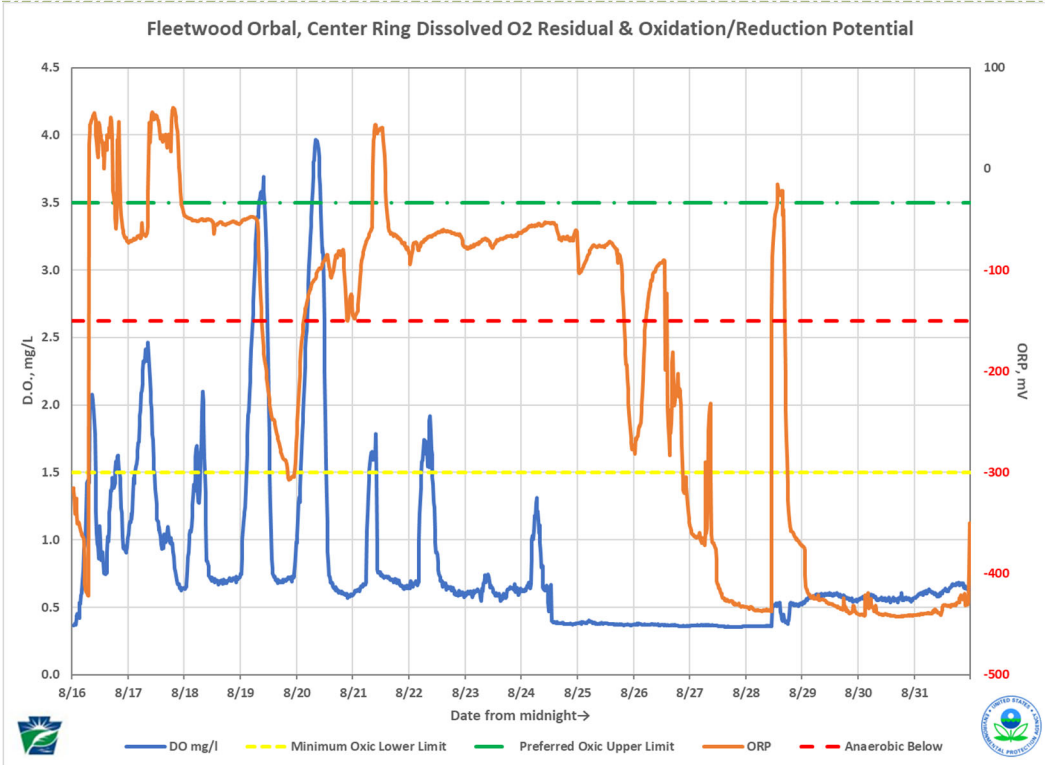
May Combined Data, D.O. & ORP: Probes may have been moved around to different locations.



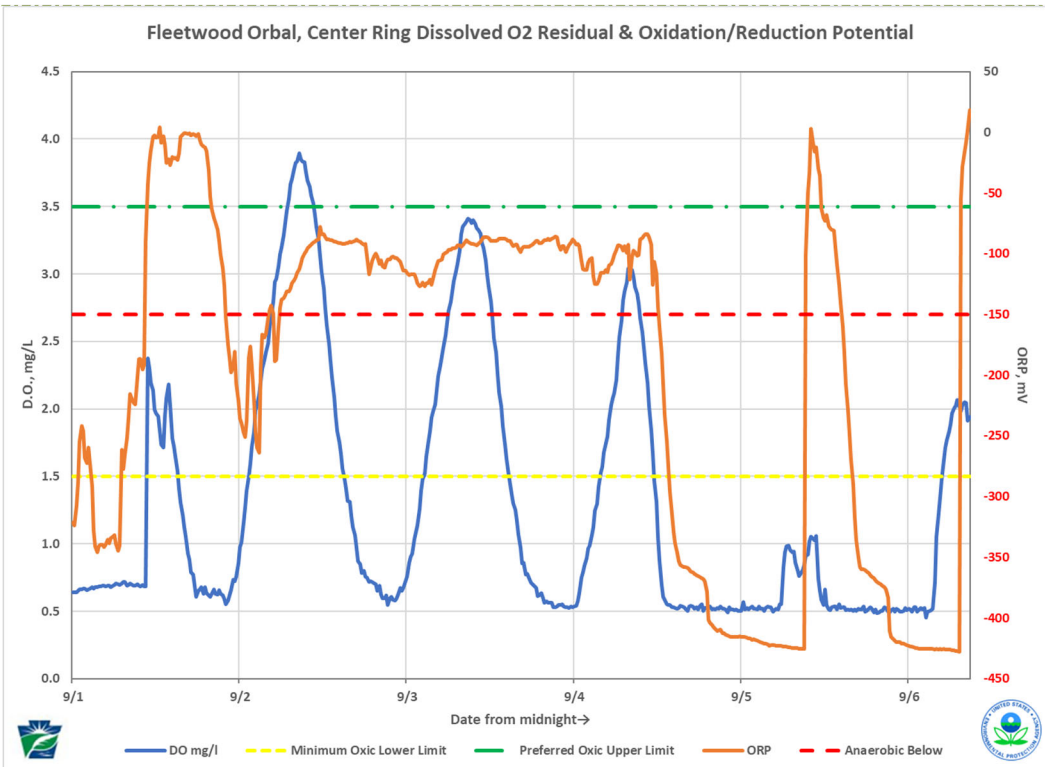
June Combined Data, D.O. & ORP



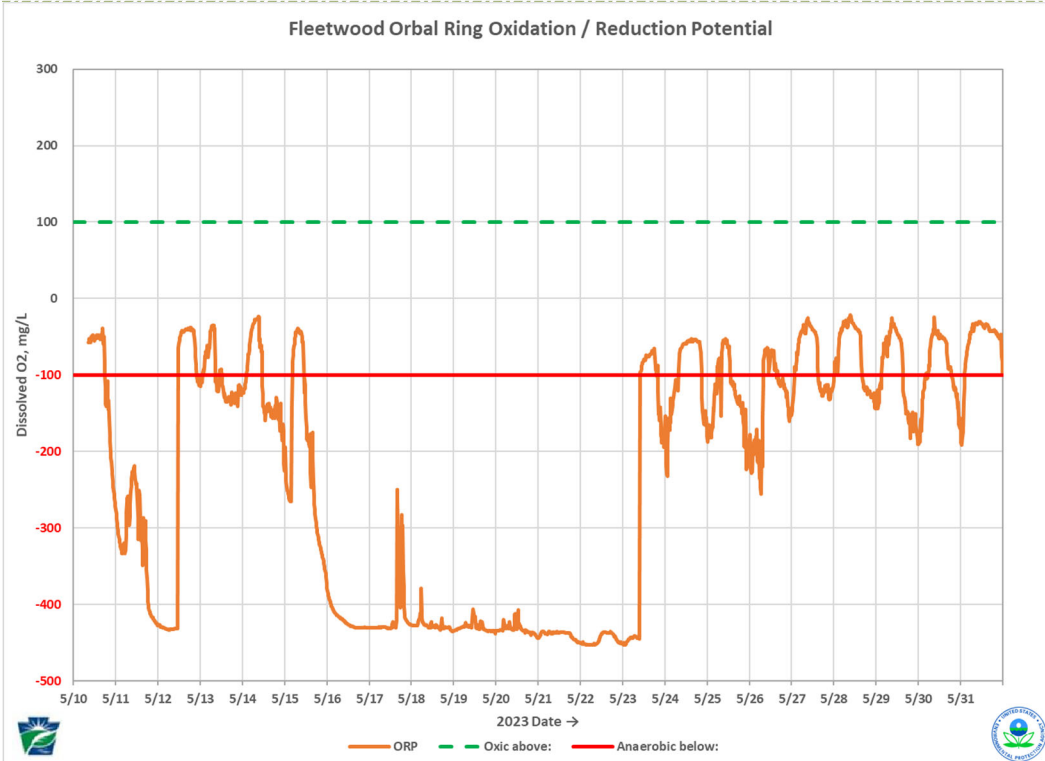
July Combined Data, D.O. & ORP: from July 6, both D.O. and ORP probes in middle ring.



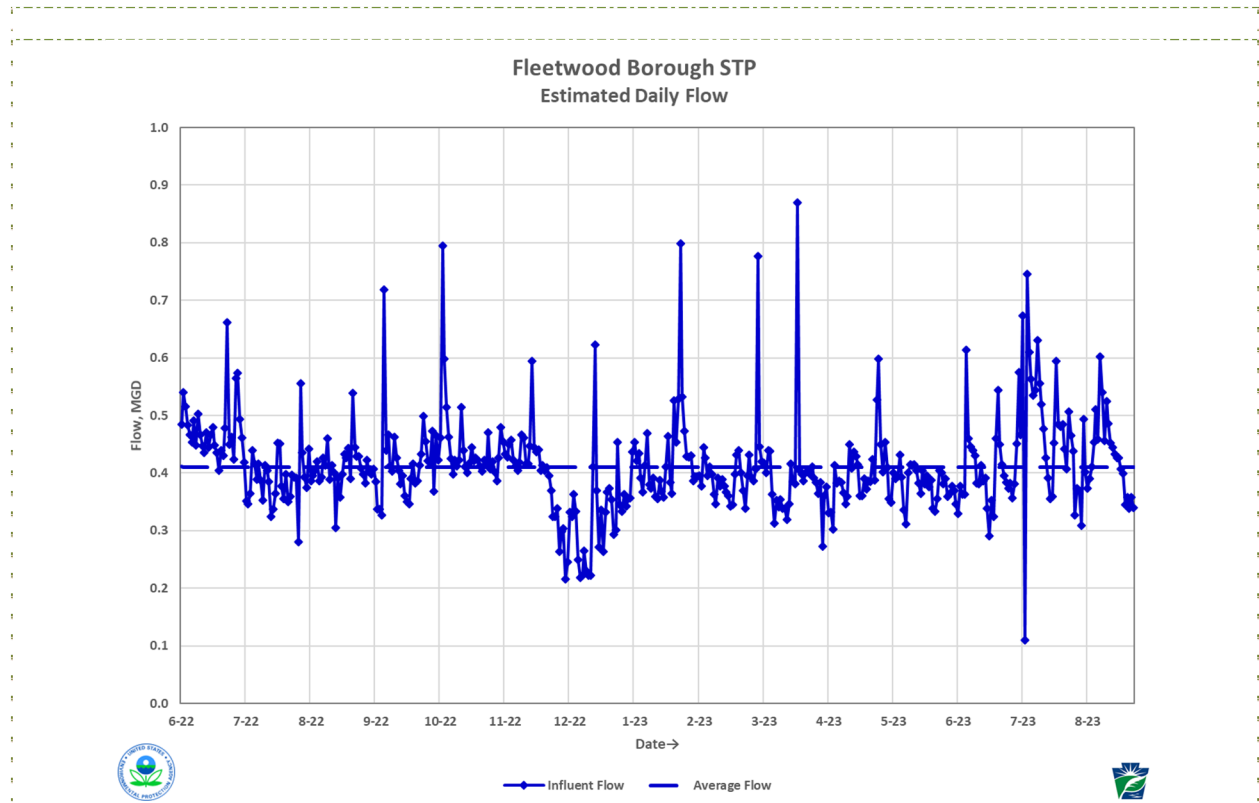
August Combined Data, D.O. & ORP



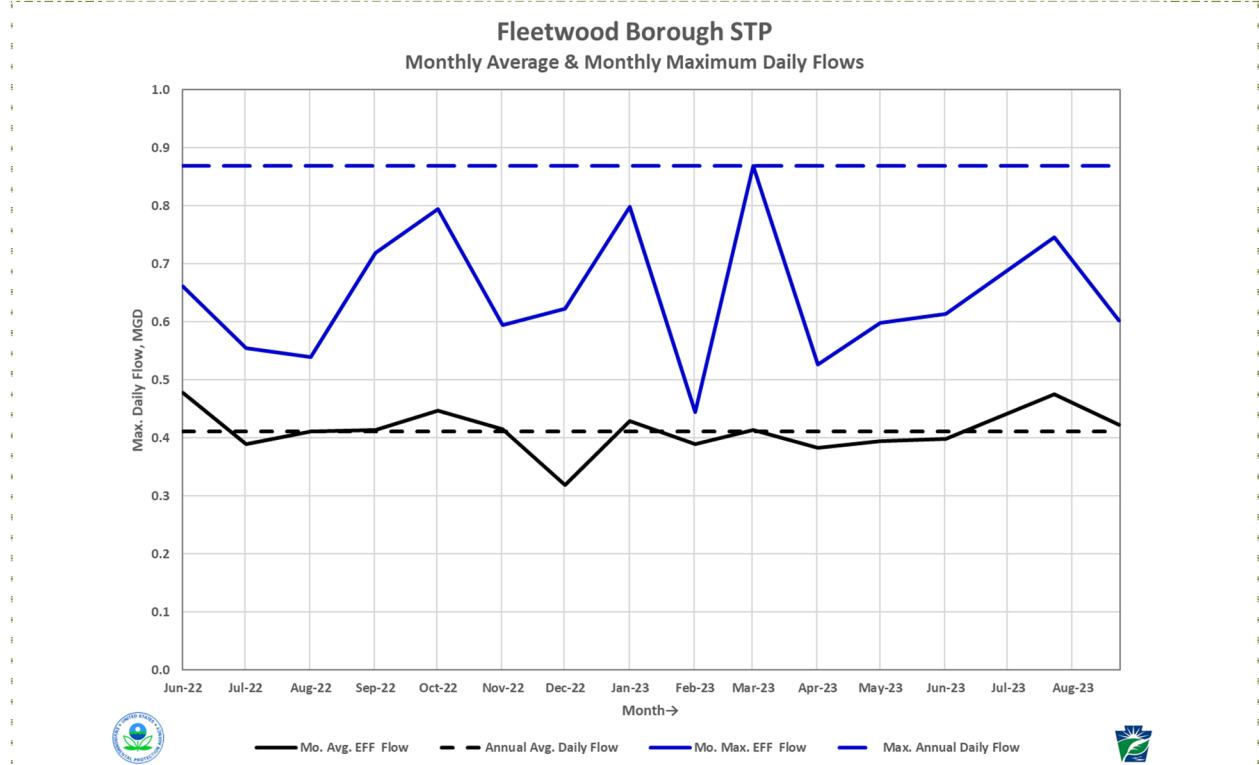
September Combined Data: D.O. & ORP: For Sept., D.O. in inner ring, ORP in middle ring.



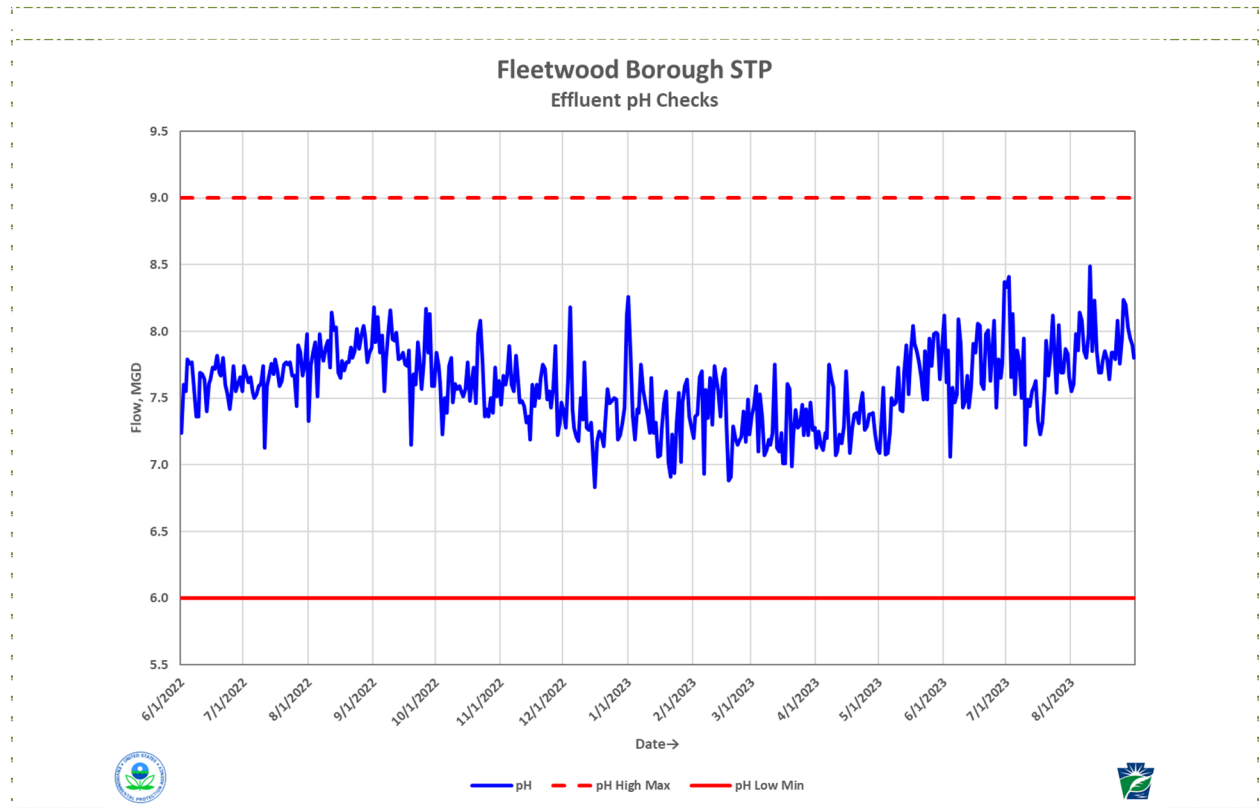
ORP drops into the -300 to -400 mV range indicate a fouled probe that requires cleaning.



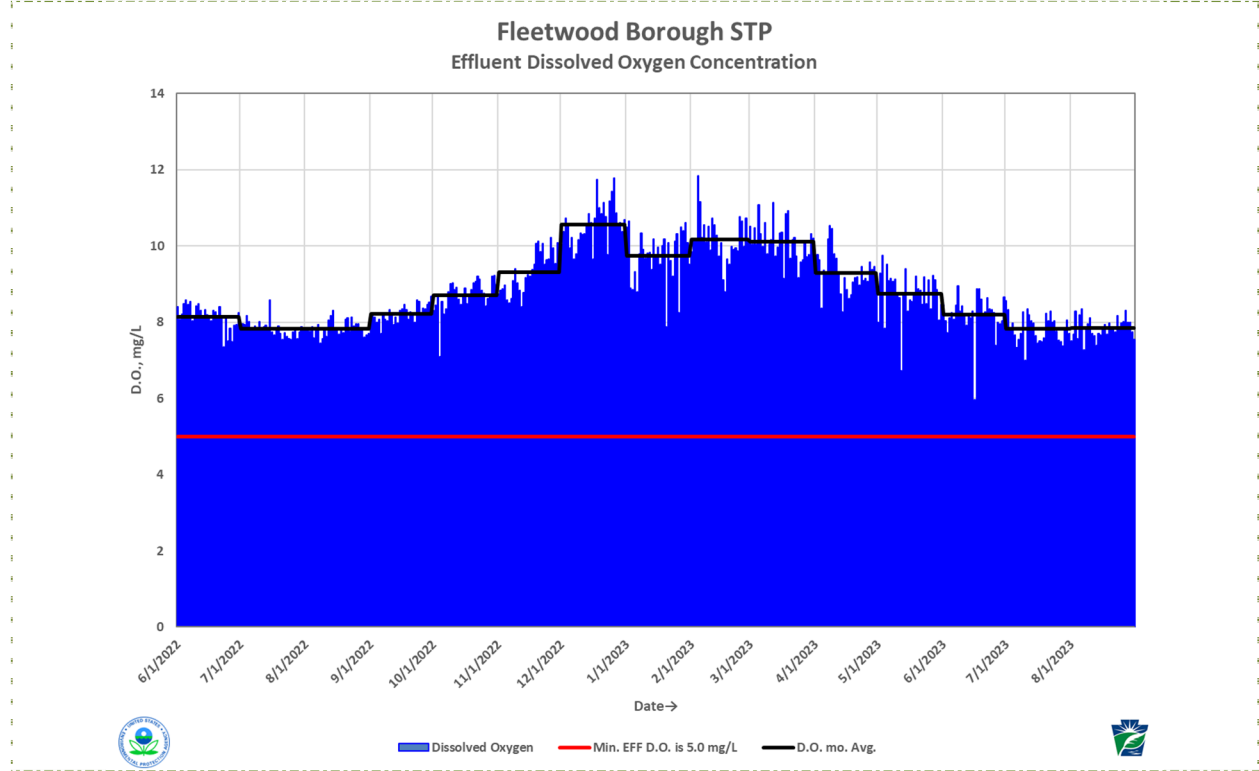
Reported daily flow through facility



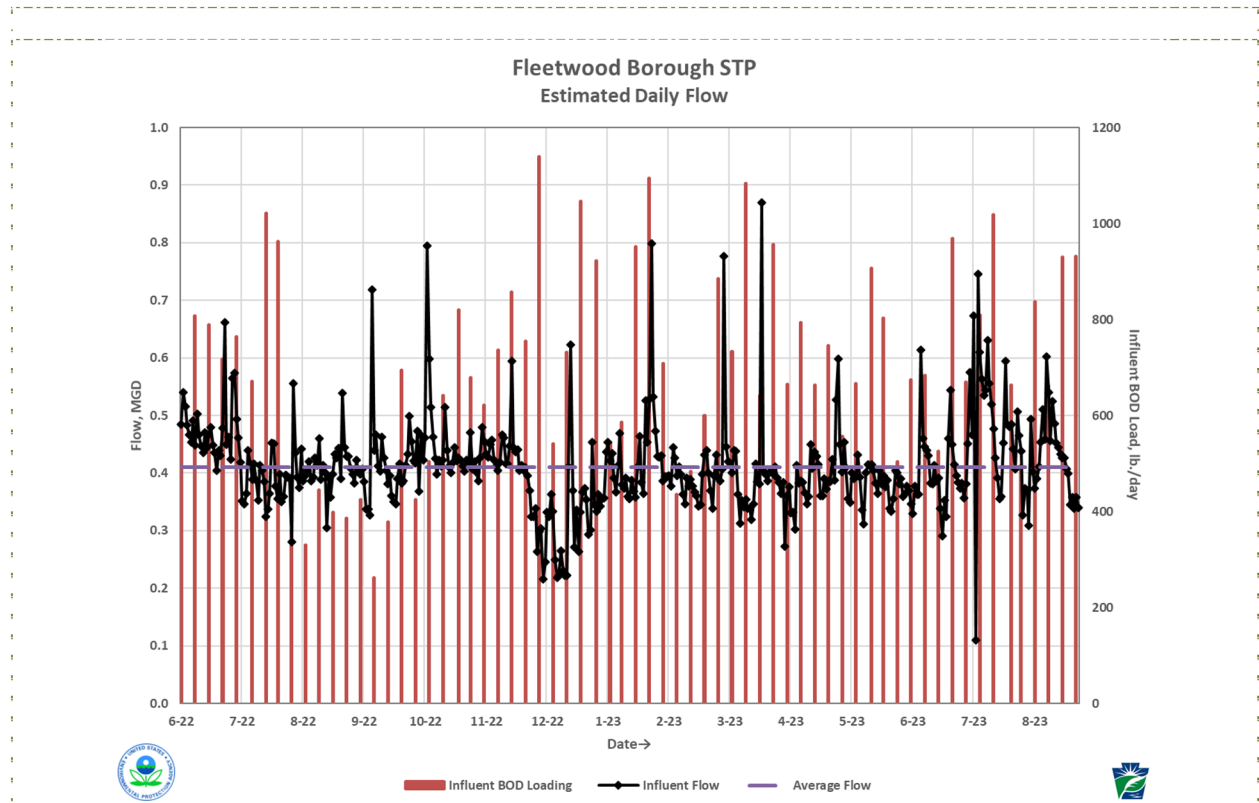
Monthly average and monthly maximum daily flows



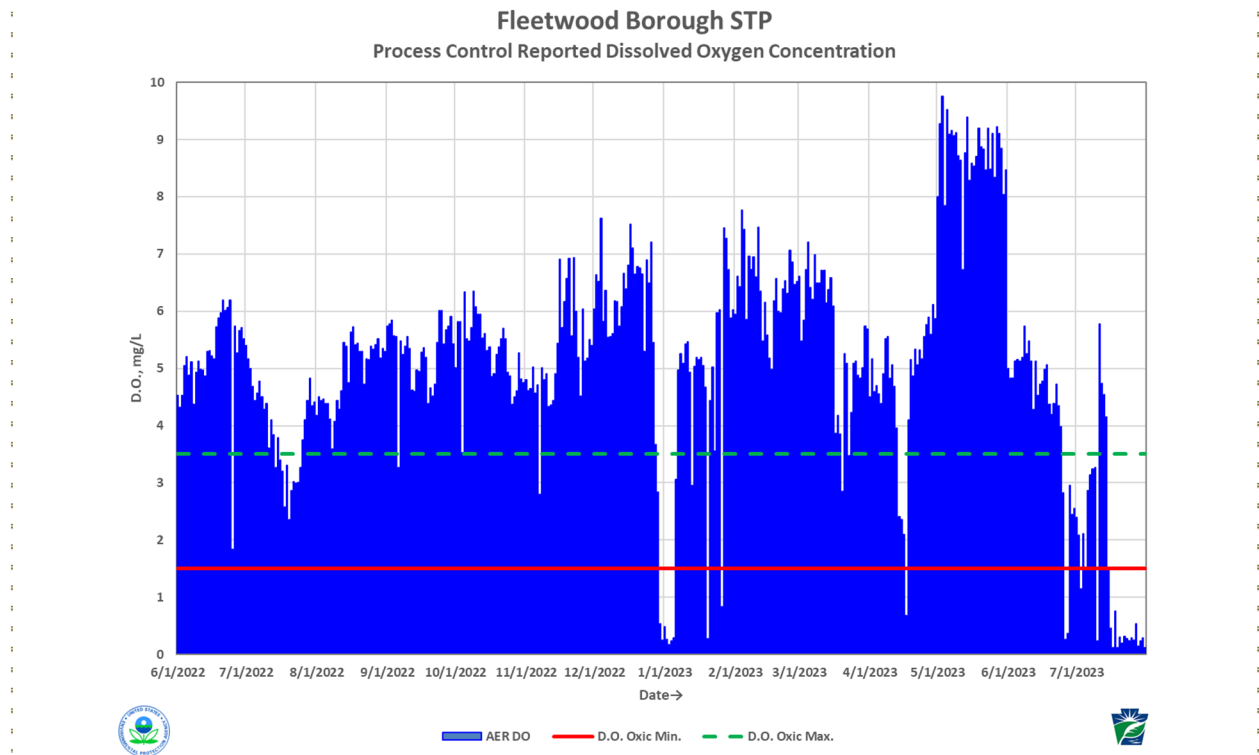
Reported effluent pH



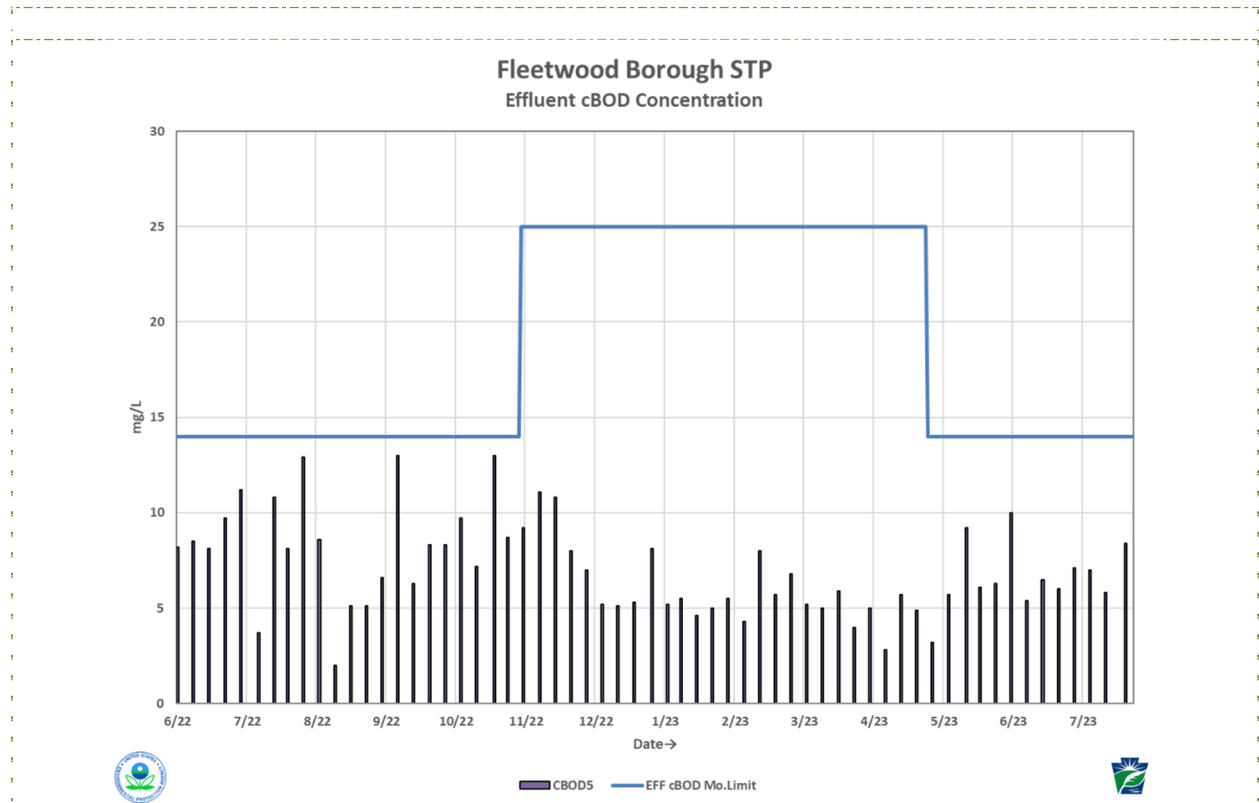
Reported effluent dissolved oxygen concentration



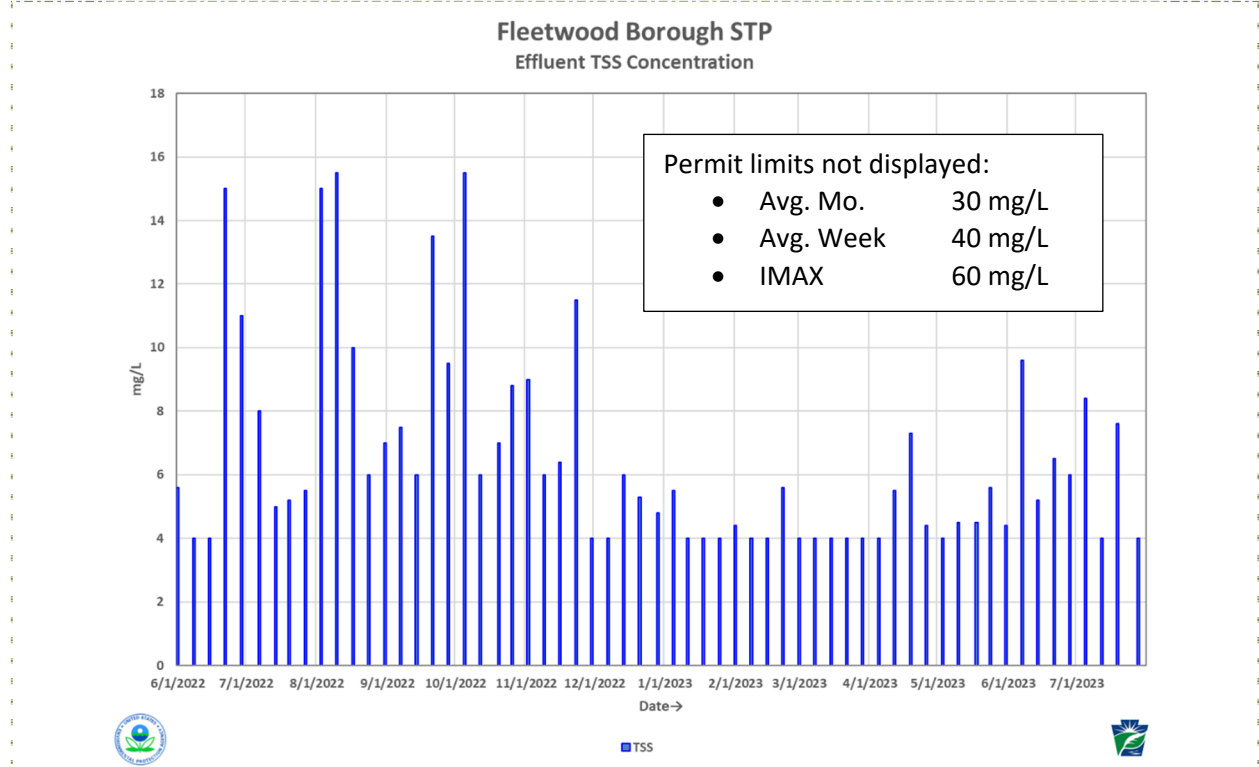
Flow & Organic Loading: No detectable correlation between load & hydraulic peaks, but the organic data is based on once per week testing. Using the BOD probe may help finding slug loads.



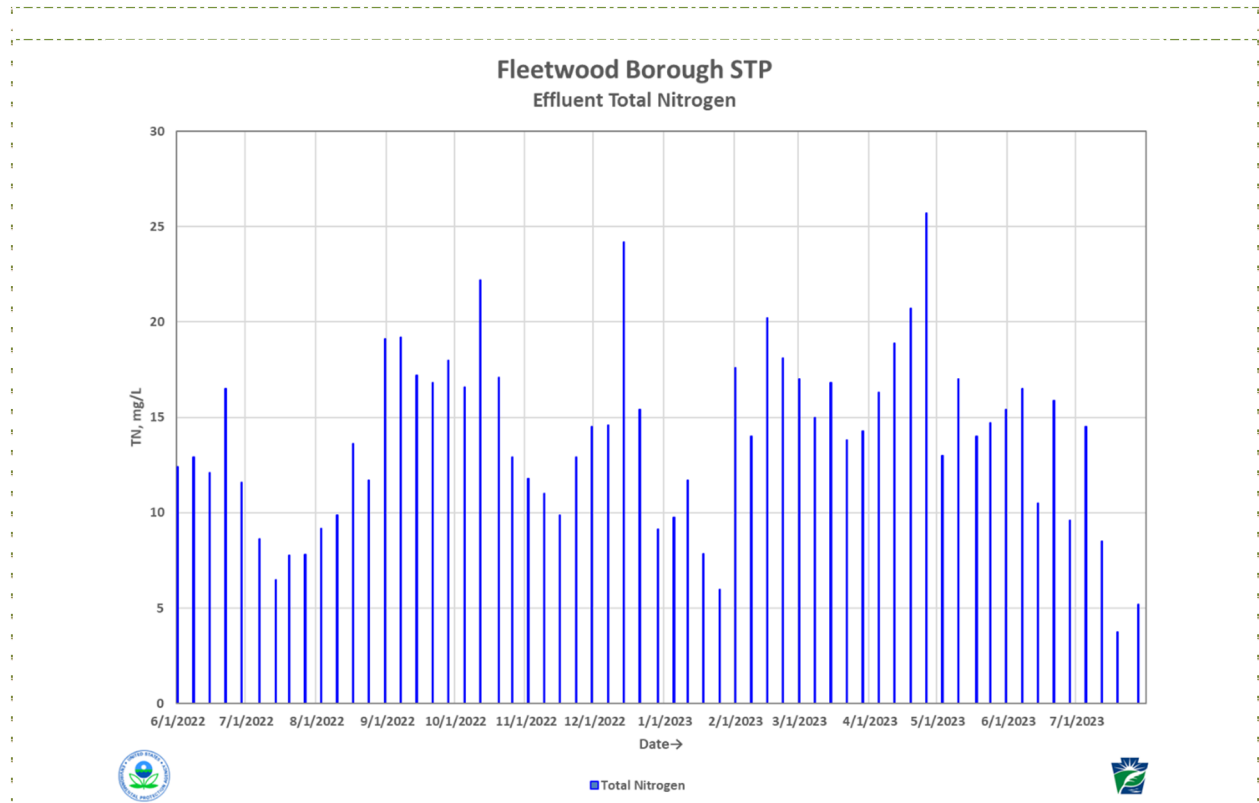
Reported process control dissolved O2 concentrations could be controlled within oxidic limits shown.



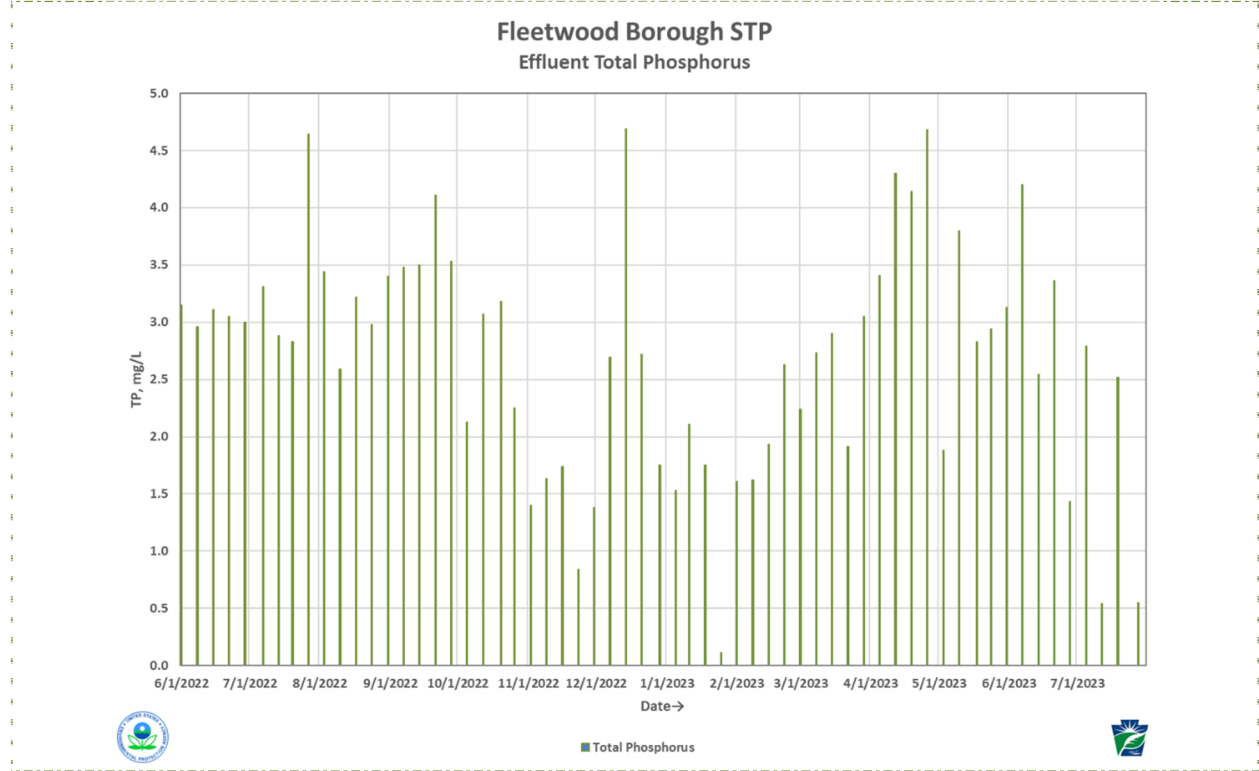
Reported weekly effluent cBOD<sub>5</sub> concentrations



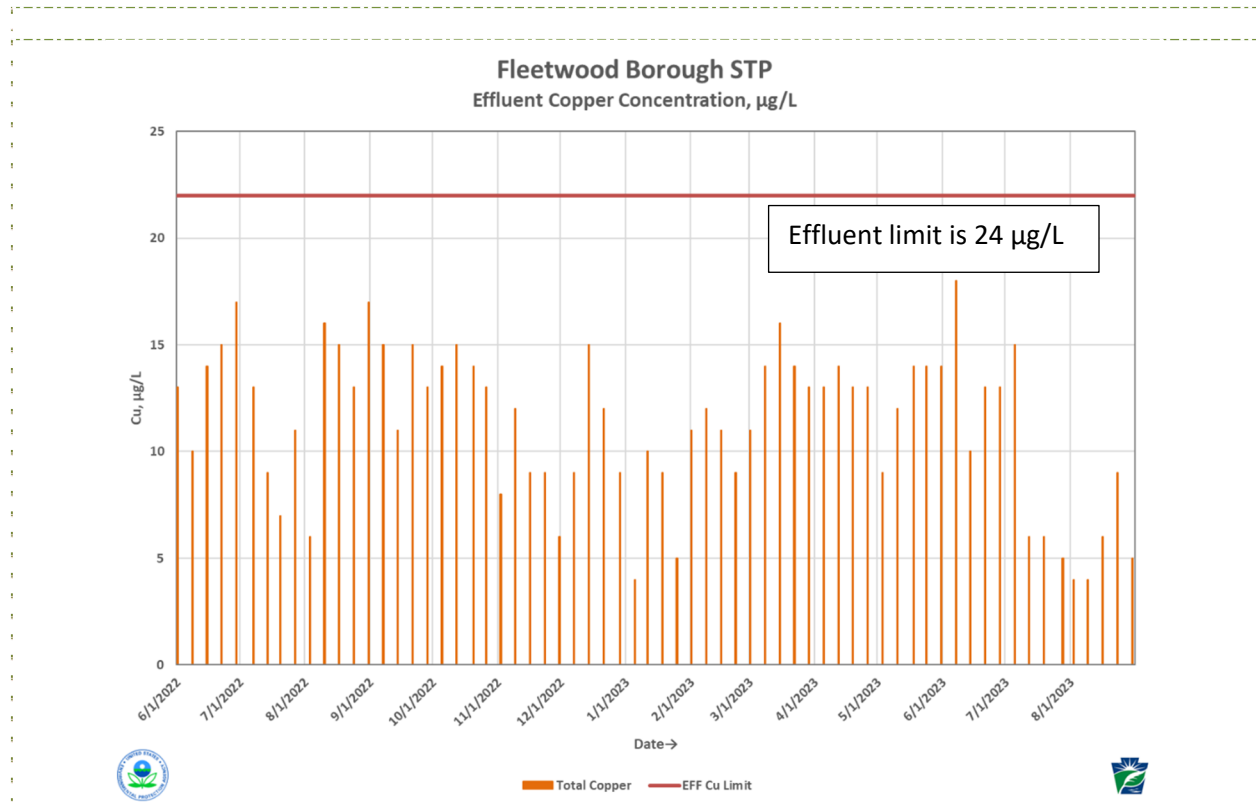
Reported weekly effluent Total Suspended Solids concentrations



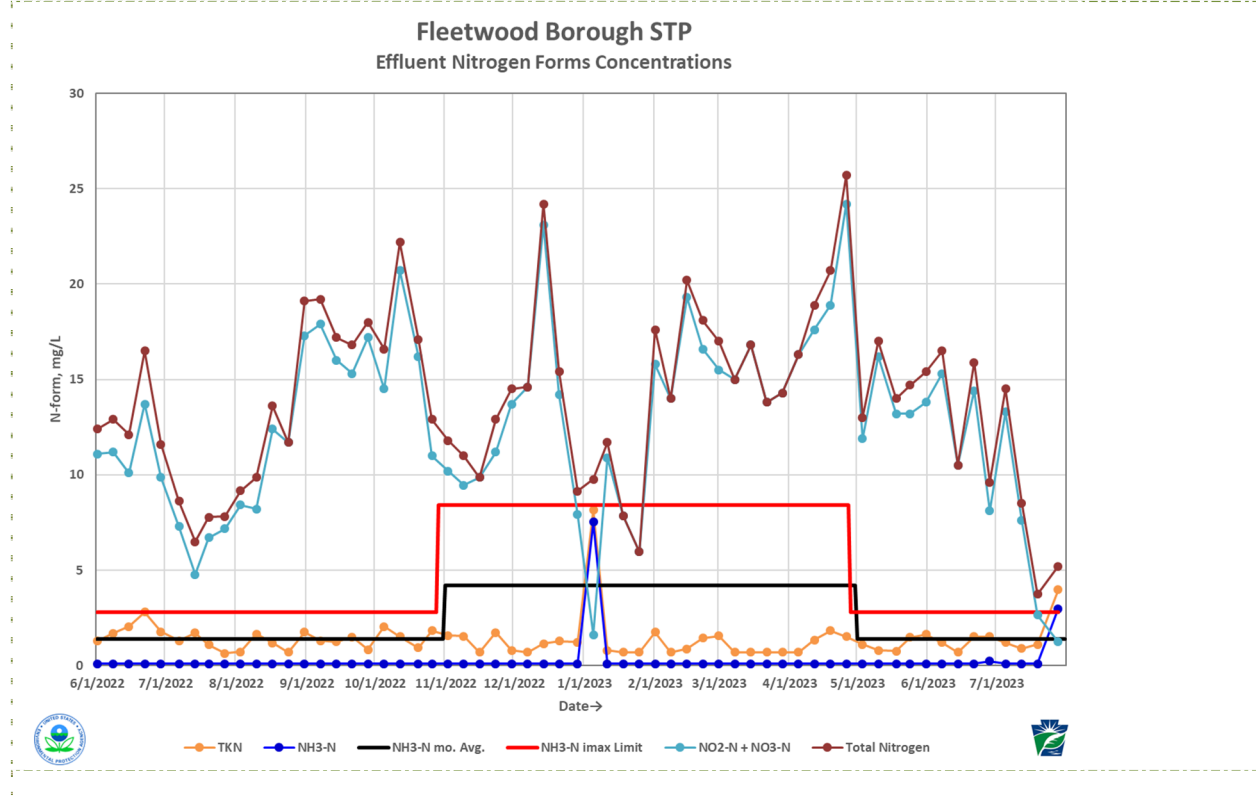
Reported weekly effluent total nitrogen concentrations, currently a “report on DMR” requirement.

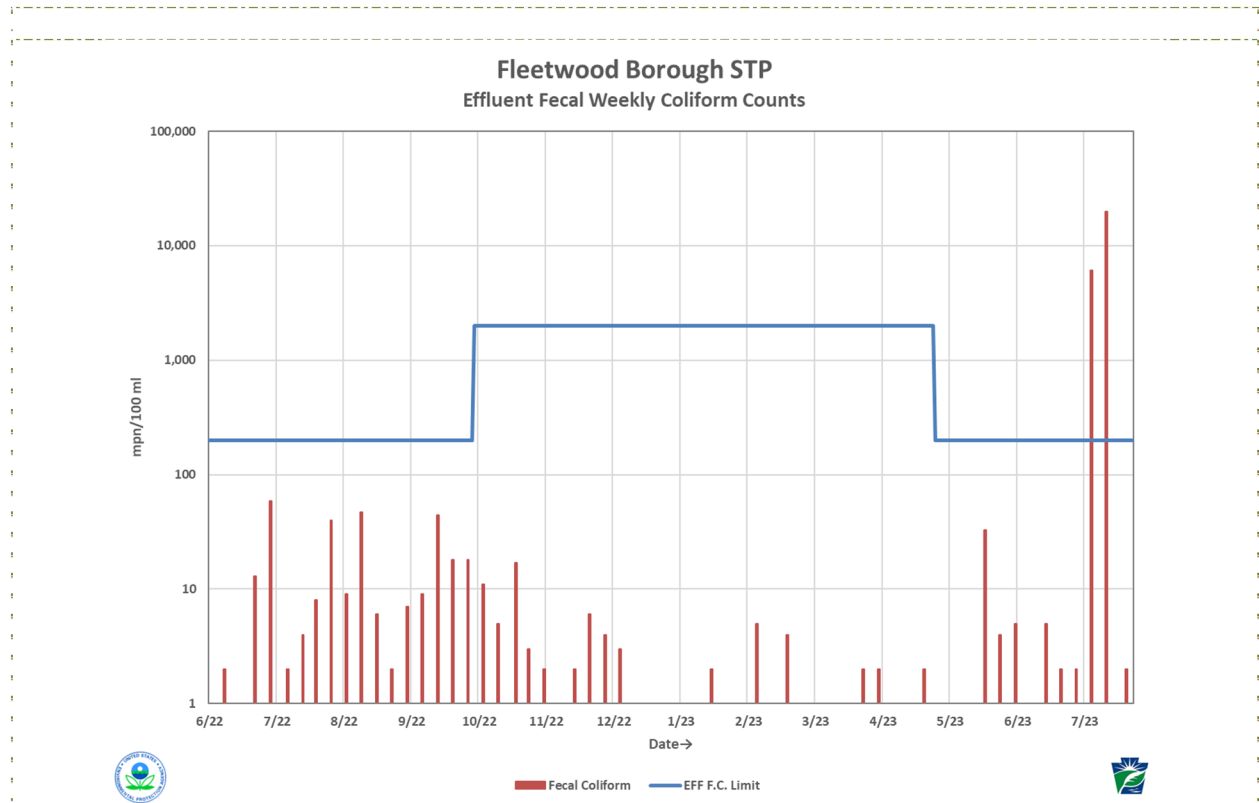


Reported weekly effluent total phosphorus concentrations, “report” only, no set limit.

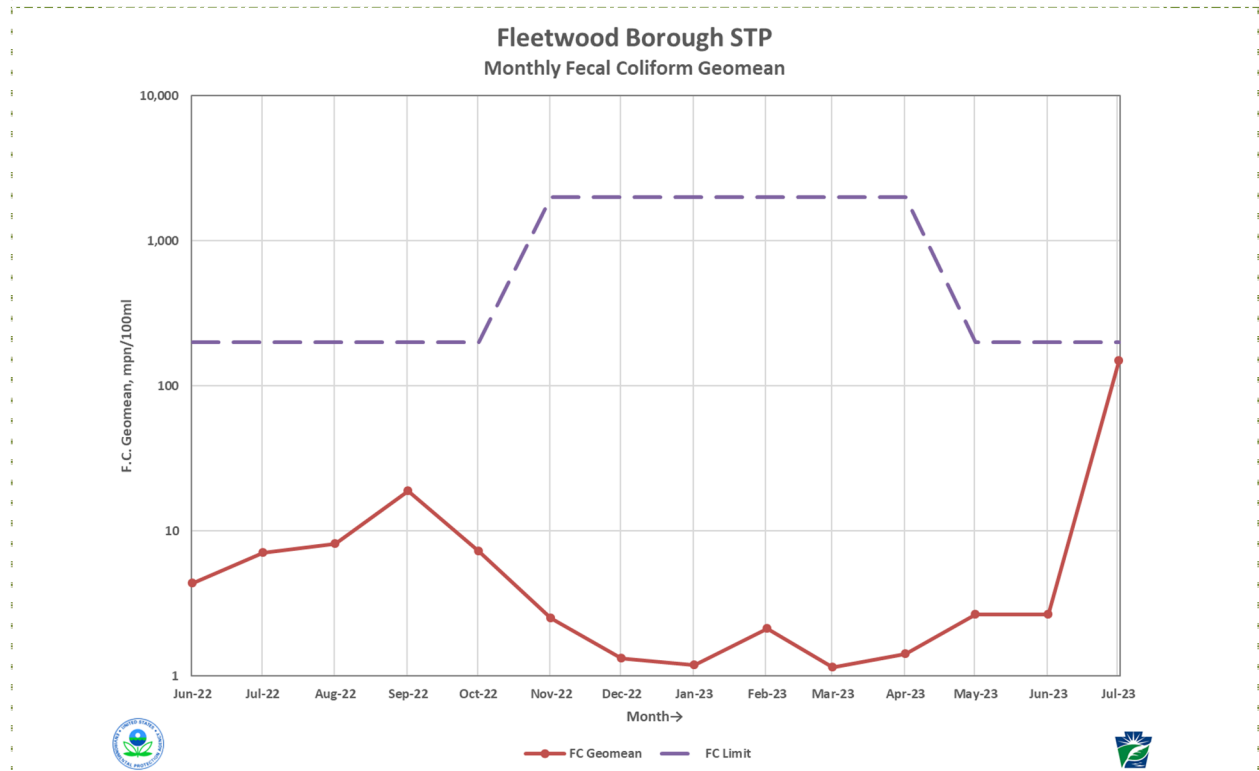


Reported weekly effluent total copper concentrations, in micrograms per liter ( $\mu\text{g/L}$ ).

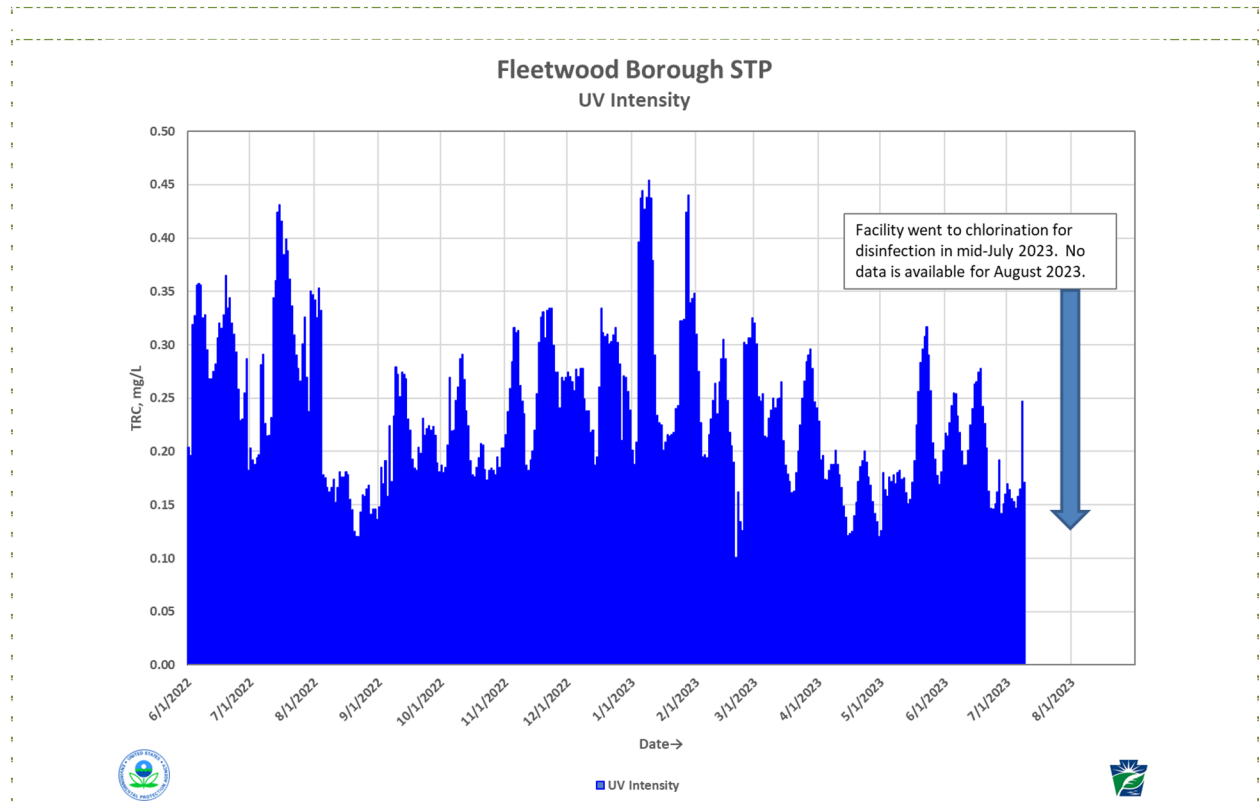




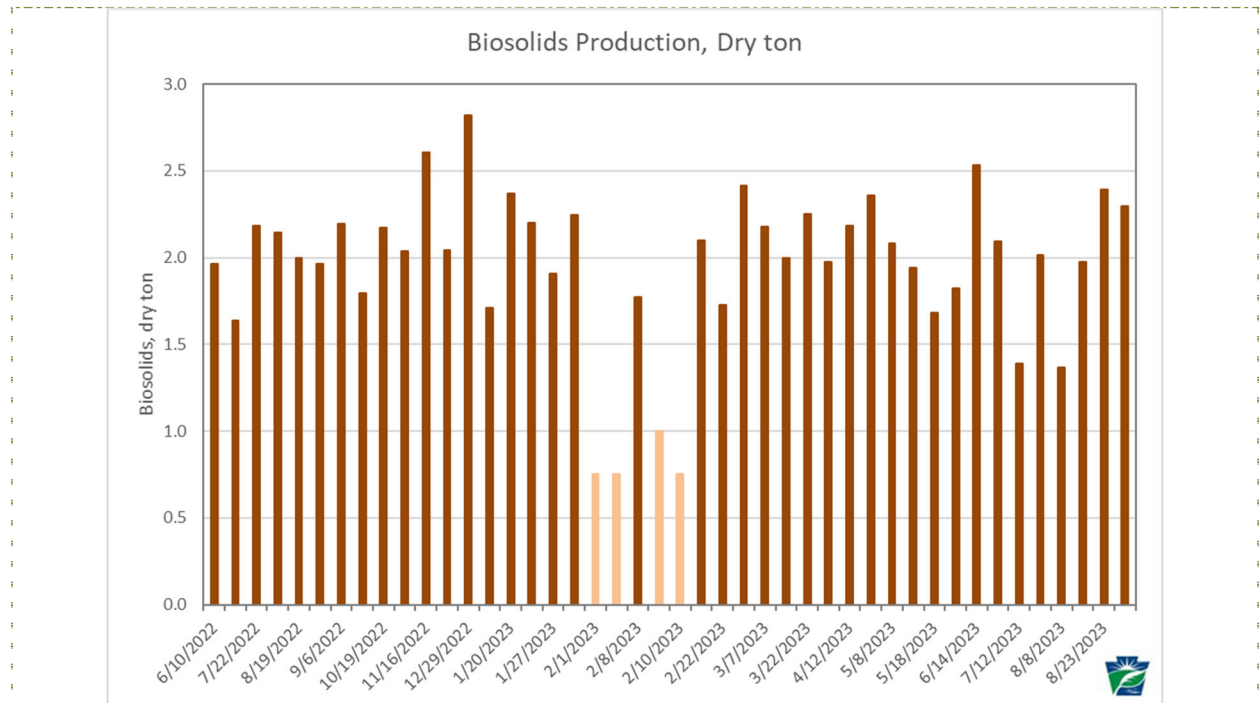
Fecal Coliform Test Results, based on weekly testing. Non-detects are not graphed.



Disinfection of Fecal Coliforms, based on reported monthly geomean.



UV Disinfection Intensity through mid-July 2023, after which chlorine has been in use.



Biosolids production, June 2022 through August 2023: 12-month average: 72.60 dry ton

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## **ATTACHMENT D: DISCUSSION OF BIOLOGICAL NUTRIENT REMOVAL (BNR)**

### **Why Nutrients in the Effluent are a Concern:**

Dissolved nutrients such as nitrate-nitrite and phosphorus in treated wastewater effluents create both environmental and health concerns. Nitrate and phosphorus cause over-fertilization of algae and plant growth that sets up a cycle of excessive growth followed by eutrophication and decay. The excessive growth robs the natural environment of its capacity to support local biota that are the source of food for aquatic organisms and displaces native plant species. Once eutrophication has been established, large algal die-offs result in decay that robs the aquatic environment of D.O., causing entire aquatic populations to suffer and die. This degrades water quality for higher uses, as well, including withdrawals for drinking water filtration, swimming and recreation, angling, and other activities.

DEP has an operator training manual covering this topic, found [here](#) .

Nitrate and nitrite are pollutants of concern in surface waters filtered for human consumption and in groundwater sources for drinking water wells. EPA has set an enforceable standard called a MCL in potable drinking water for nitrates at 10 parts per million (ppm) (10 mg/L) and for nitrites at 1 ppm (1 mg/L). Many regulators are calling for similar limits for point-source and ground water discharges. Within the Delaware River watershed, the DRBC is currently seeking to regulate nitrate to the drinking water maximum concentration limit (MCL) of 10 mg/L in both surface and groundwater discharges, while the Susquehanna River Basin Commission (SRBC) has adopted a more stringent average concentration limit of 6.2 mg/L for discharges into the Susquehanna River basin, which is the largest contributor of nutrient pollution to the Chesapeake Bay.<sup>2</sup>

Human health concerns are a major factor in regulatory efforts to reduce nitrate in wastewater discharges. Exposure to nitrate also increases the risk of thyroid disease,<sup>3</sup> and may lead to certain types of cancers of the colon and bladder,<sup>4</sup> as well as a very specific birth defect called neural tube disorders caused early in pregnancies.<sup>5</sup> Nitrate acts on hemoglobin in red blood cells to form methemoglobin, reducing the oxygenation of organs and tissues.<sup>6</sup> Acquired methemoglobinemia in infants may occur when they consume nitrate in water used to mix infant formula or in nitrate-rich foods, medications such as benzocaine or dapsone, or through household exposure to naphthalene found in mothballs, toilet deodorants, plastics, and chemicals.<sup>7</sup> Nitrate may also be implicated in

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<sup>2</sup> The SRBC recommended concentration-based limit for total phosphorus is 0.8 mg/L

<sup>3</sup> Epidemiology: [May 2010 - Volume 21 - Issue 3 - p 389-395](#) (Nitrate converts to nitrite in vitro which becomes nitrosamines, leading to a host of health issues.)

<sup>4</sup> Schullehner J, Hansen B, Thygesen M, Pedersen CB, Sigsgaard T. Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study. [Int J Cancer. 2018 Jul 1;143\(1\):73-79](#). doi: 10.1002/ijc.31306. Epub 2018 Feb 23. PMID: 29435982.

<sup>5</sup> Epidemiology: [July 2004 - Volume 15 - Issue 4 - p S184](#); The Lancet, [Volume 14, 100286, March 1, 2022](#)

<sup>6</sup> Kross BC, Ayebo AD, Fuortes LJ. [Methemoglobinemia: nitrate toxicity in rural America](#). Am Fam Physician. 1992 Jul;46(1):183-8. PMID: 1621630

<sup>7</sup> Wisconsin Dept. of Health Services website, [Infant Methemoglobinemia \(Blue Baby Syndrome\)](#) , (rev. 04/15/2021)

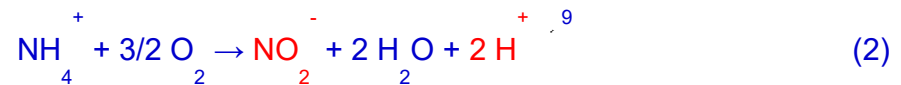
diabetes, miscarriages, and acute respiratory infections. The medical science on the effects of nitrates continues to develop.

### Nitrification and Denitrification:

During the 1970s, treatment facilities were required to nitrify ammonia wastes to eliminate this pollutant that was killing aquatic life in receiving waters. Nitrification employs autotrophic bacteria in highly aerated conditions to convert ammonia to nitrate. The bacteria, normally found in topsoil, are found in activated sludge. During the past thirty years, microbiologists have discovered that there exist many genera of nitrifying bacteria, some of which are capable of completely nitrifying inorganic ammonia to nitrate.<sup>8</sup> *Nitrospira* and *nitrococcus* come to mind. Traditional explanation of nitrification, prior to these discoveries, focused on a two-step process performed by two different genera of bacteria. These two genera of nitrifiers work in tandem: *nitrosomonas*, an ammonia-oxidizing bacteria (AOB), converts ammonium to nitrite, after which *nitrobacter*, a nitrite-oxidizing bacteria (NOB) converts nitrite to nitrate. The net reaction is shown below:



The first step reaction by *nitrosomonas* is shown here:



Additional oxygen and detention time are necessary to allow *nitrobacter* to oxidize the biologically active nitrite ion to chemically inert nitrate ion.<sup>10</sup>



Nitrification requires several factors to complete the process. These include

- Sufficient detention time, 10 to 14 days: most of the Carbonaceous Biochemical Oxygen Demand (cBOD) must first be consumed by heterotrophic and facultative bacteria in the activated sludge.
- Dissolved oxygen residual between 1.5 mg/L and 3.5 mg/L in the bioreactor.
- 4.6 lb. of oxygen consumed per pound of ammonia converted to nitrate: this can double the amount of oxygen required, compared to only treating for cBOD.
- pH generally above 7.0 S.U., ideally between 7.3 and 8.6, but no lower than 6.5 S.U.
- 7.14 pounds of alkalinity is needed to convert every 1 lb. of ammonia.
- Alkalinity in the raw wastewater should be over 200 mg/L as CaCO<sub>3</sub> or be supplemented to assure effluent alkalinity remains between 50 mg/L and 100 mg/L after treatment.
- Water temperature above 5 degrees Celsius (41 deg. Fahrenheit).

<sup>8</sup> van Kessel, M., Speth, D., Albertsen, M. et al. [Complete nitrification by a single microorganism](https://doi.org/10.1038/nature16459). Nature 528, 555–559 (2015). <https://doi.org/10.1038/nature16459>

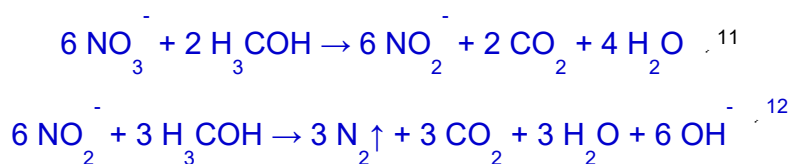
<sup>9</sup> This is the first half of the reaction, converting ammonium to nitrite. The nitrite, in red, associates with the hydrogen, also in red, as nitrous acid, resulting in lower pH if alkalinity is inadequate.

<sup>10</sup> The chemical oxidation state of nitrate ion is such that it does not necessarily associate with hydronium to produce more acid. It more typically associates with metal ions and is inert.

Nitrosomonas and nitrobacter are very sensitive to toxicity, as well, and one or the other can easily be suppressed by the presence of many household and commercial cleaners, excessive metals, and other contaminants.

Considering these factors, it is important for wastewater operators to regularly perform process control testing to determine whether the conditions are favorable for nitrification. If nitrification breaks down, these tests may help to determine what conditions are affecting the bacteria and which, *nitrosomonas* or *nitrobacter*, are most affected. Testing for pH, alkalinity, and dissolved oxygen residual are critical to maintaining effective nitrification.

Many wastewater treatment facilities built or upgraded in recent times have been equipped for BNR. Denitrification is a process by which facultative, heterotrophic bacteria in the activated sludge will reduce nitrate to nitrogen gas that leaves the water and returns to the atmosphere. The balanced chemical equations are shown below:



For successful denitrification, the following conditions are necessary:

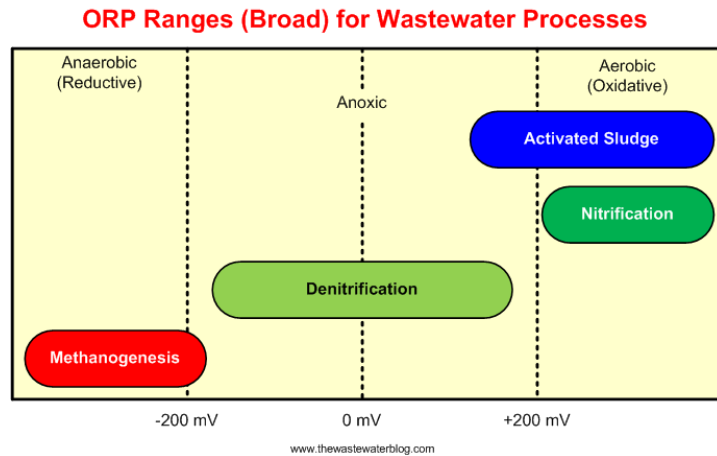
- anoxic treatment conditions, where no dissolved oxygen is present. Generally, dissolved oxygen should be below 0.3 mg/L for denitrification.
- nitrate-rich environment: nitrification should be complete to the best extent possible. Nitrate dissolved in the water will provide the oxygen needed by the bacteria for metabolism.
- Presence of organic carbon as a food-source for the bacteria: usually, this comes from the raw wastewater but sometimes is required as supplemental cBOD in form of simple chemicals like methanol, citrate, or glycerol, or as food manufacturing wastes such as molasses sugar, fruit juice waste, or whey powder.

Denitrification is a rapid reaction under the right conditions. If a treatment facility can successfully nitrify, there should be little or no problems denitrifying. In fact, in conventional and extended aeration facilities, denitrification is sometimes observed occurring in secondary clarifiers when the sludge blanket there has been retained too long: fine bubbles form in the floc causing clumps of sludge to rise to the surface. This “lava lamp” effect, called “rising sludge,” can cause effluent violations when solids are carried over the clarifier weirs to the outfall. Excessive solids carryover will also inhibit downstream disinfection processes by consuming available chlorine or by occluding the penetration of ultraviolet light.

<sup>11</sup> In this equation, H<sub>3</sub>COH represents methyl alcohol, a simple organic carbon most often used in denitrification filters.

<sup>12</sup> The carbon dioxide and hydroxyl ion combine in water to produce carbonate alkalinity. Almost half of the alkalinity consumed by nitrification is returned to the treatment process by denitrification, resulting in reductions of alkalinity needed up front as well as energy consumed in oxygenating the water.

The illustration to the right shows that it is possible to use Oxidation / Reduction Potential (ORP) to monitor nitrification and denitrification in activated sludge treatment. The bacteria that provide these necessary steps are highly efficient within specified ranges of ORP. This is measured in millivolts using portable or continuous monitoring, submersible probes. The favored range for denitrification is between +150 and -150 millivolts (mV), with ideal treatment “sweet spots” usually in the range from 0 mV to -50 mV. Nitrification, being strictly aerobic, requires ORP ranges from approximately 200 mV to 400 mV. Using ORP probes to monitor denitrification is more favorable than using D.O. probes, because D.O. probes cannot reliably demonstrate ideal anoxic conditions.



### Alkalinity is Critical

During nitrification, the nitrifying bacteria consume inorganic carbon in the form of dissolved carbonate / bicarbonate in the water. Alkalinity provides buffering against rapid and drastic pH changes, but it also provides a source of inorganic carbon. For every pound of ammonia oxidized, 7.14 pounds of alkalinity are consumed. (Given water chemistry and cellular metabolism, this amount is often rounded up to 7.2-to-7.5 lb. alkalinity per 1 lb. ammonia oxidized.)

If the biomass is deficient of alkalinity, the AOB conversion of ammonia to nitrite will lower the pH. This is because the nitrite released from the bacteria, as a waste product, is the anionic half of nitrous acid. The metabolism of ammonia produces hydronium ion that acidifies the water. To counteract this, supplemental alkalinity is often required in many parts of Pennsylvania where, excepting the limestone-rich geology of the Great Valley and similar areas, most of the geography is naturally deficient in alkalinity. Acid-mine drainage also contributes to lowering the pH of surface and ground waters.

While the rule-of-thumb holds that a facility is in good stead if effluent alkalinity is 100 mg/L and influent alkalinity is over 200 mg/L, experience has demonstrated that facility operators should calculate alkalinity demand in the course of their routine process monitoring and control tests. DEP has developed alkalinity calculator spreadsheet tools to aid in this, found at this [website](#).

Using the calculator, operators enter test value for influent ammonia concentration and for influent alkalinity. Entering the estimated flow in million-gallons-per-day (MGD) calculates the ammonia and alkalinity loads present, the alkalinity required to oxidize the ammonia, and the equation produces a net result of how much additional alkalinity to add to the process.

It should be noted that conversion factors should be applied, based on the type of alkalinity chemical being deployed. These are found in a table on the following page. To use this table, select the ratio for the chemical being used and divide this into the estimated amount required to treat the ammonia to meet the ammonia effluent limit.

E.G., from the calculator and table:

$$51.7 \text{ lb./day as CaCO}_3 \div 1.06 = 48.8 \text{ lb./day as Soda Ash}$$

For practical purposes, the operator could round this example result up to 50 lb./day, since the Soda Ash is provided in 50 lb. sacks.

<p><b>Alkalinity Required for Nitrification</b></p> <p><i>Alkalinity is needed for nitrification to meet effluent limits for Ammonia-Nitrogen (NH3-N). For every pound of NH3-N that must be removed / nitrified, 7.2 lbs of alkalinity is required. A residual alkalinity of 50 mg/L is assumed for final effluent to meet pH limits but this value can be adjusted.</i></p> <p>Check box if treatment plant has primary clarifier(s): <input type="checkbox"/></p> <table border="1"> <thead> <tr> <th>Influent Flow (MGD)</th> <th>Influent NH3-N Concentration (mg/L)</th> <th>Influent Alkalinity Concentration (mg/L)</th> <th>Average Monthly NH3-N Effluent Limit (mg/L)</th> <th>Alkalinity Desired in Final Effluent (mg/L)</th> </tr> </thead> <tbody> <tr> <td>0.012</td> <td>88</td> <td>206</td> <td>1.5</td> <td>100</td> </tr> </tbody> </table> <p><b>NH3-N that must be removed / nitrified:</b>  <i>(88 mg/L - 1.5 mg/L) x 0.012 MGD x 8.34 = 8.65692 lbs/day</i></p> <p><b>Alkalinity needed for nitrification:</b>  <i>8.65692 lbs/day x 7.2 = 62.329824 lbs/day</i></p> <p><b>Alkalinity available for nitrification:</b>  <i>(206 mg/L - 100 mg/L) x 0.012 MGD x 8.34 = 10.60848 lbs/day</i></p> <p><b>51.721344 lbs/day or 516.8 mg/L of alkalinity must be added for nitrification to meet NH3-N effluent limits</b></p>	Influent Flow (MGD)	Influent NH3-N Concentration (mg/L)	Influent Alkalinity Concentration (mg/L)	Average Monthly NH3-N Effluent Limit (mg/L)	Alkalinity Desired in Final Effluent (mg/L)	0.012	88	206	1.5	100	<table border="1"> <thead> <tr> <th>Compounds</th> <th>Alkalinity-Ratio, ppm/ppm CaCO<sub>3</sub></th> </tr> </thead> <tbody> <tr> <td>Soda Ash</td> <td>1.06</td> </tr> <tr> <td>Acetate</td> <td>0.82</td> </tr> <tr> <td>Hydrated Lime</td> <td>0.74</td> </tr> <tr> <td>Quick Lime</td> <td>0.56</td> </tr> <tr> <td>Bicarbonate</td> <td>1.68</td> </tr> <tr> <td>Caustic soda</td> <td>0.8</td> </tr> <tr> <td>Magnesium hydroxide</td> <td>0.5</td> </tr> </tbody> </table>	Compounds	Alkalinity-Ratio, ppm/ppm CaCO <sub>3</sub>	Soda Ash	1.06	Acetate	0.82	Hydrated Lime	0.74	Quick Lime	0.56	Bicarbonate	1.68	Caustic soda	0.8	Magnesium hydroxide	0.5
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<b>Example alkalinity calculator</b>	<b>Alkalinity ratios to use in converting alkalinity doses</b>																										

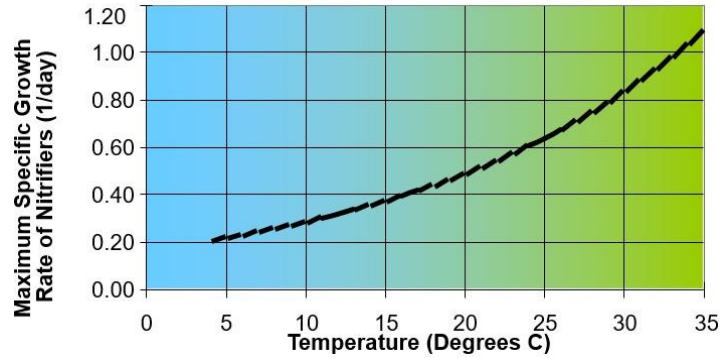
When adding any chemical to a biological treatment process, it helps if the chemical is dosed over the course of the day rather than dumped as a bulk or slug load. Therefore, it is beneficial to mix powders with water as a diluted solution and use metering pumps to deliver the chemical dose in a twenty-four-hour period. For example, if a 50 lb. sack of Calcium carbonate is dissolved into 100 gallons of water in a day tank, the metering pump should be set to deliver 4.2 gallons per hour.

PA DEP has a training manual for chemical feed systems, found [here](#).

**Inhibition of Nitrification**

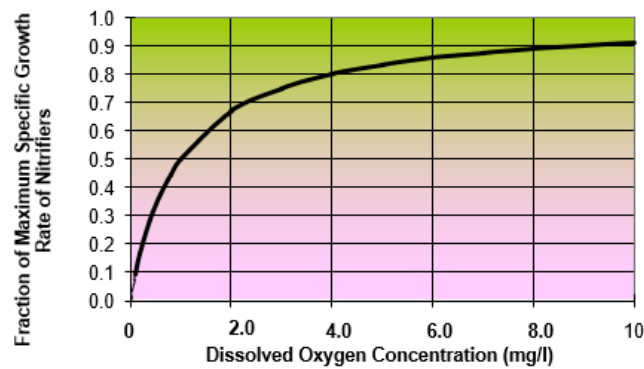
Many factors may lead to inhibition of nitrification. These include:

- pH out of range for the biomass, causing nitrifiers to stop reproducing and get washed out of the system.
- Low water temperature: Below 5 degrees Celsius, the biological reaction slows considerably, as see in this graph:



Growth of nitrifiers is dependent on temperature, and at colder temperatures, they do not replicate quickly enough to be effective

- Dissolved oxygen:



- Mean Cell Residence Time:
- Alkalinity concentration should be sufficient to maintain pH within a range from 7.0 S.U. to 8.6 S.U., and the effluent alkalinity residual should remain between 50 and 100 mg/L.
- cBOD removal:
- Toxic compounds in the wastewater will inhibit the metabolism and reproduction of nitrifying bacteria that are more sensitive to environmental changes than are the facultative heterotrophs that consume cBOD and denitrify nitrate.
- Facility design affects nitrification because of detention time, limits on hydraulic loading, quality of aeration and mixing, removal of trash and detritus, and capacity of waste sludge holding.
- Wet weather operation and inflow/infiltration affects nitrifiers because they reproduce slowly and are easily washed out of the system by hydraulic surges and overloads.

### Effect of Partial Nitrification on Chlorine Disinfection

If conditions are unfavorable for complete nitrification, nitrite level will rise and exert a chlorine demand by reacting with both free chlorine and chloramines. This is called “nitrite lock.” Low D.O., insufficient alkalinity, or acidic pH; high temperature or pH; and toxic or inhibitory substances will inhibit the final oxidation step from nitrite to nitrate. Nitrite lock also may occur during facility startup or during seasonal transitions, because *nitrobacter* grow more slowly than *nitrosomonas*. For example, in the seasonal temperature transition range from 10° C to 17° C, the rate of nitrite formation is slower than the rate of nitrite disappearance. 1 mg/L of nitrite will consume 5 mg/L of

chlorine as  $\text{Cl}_2$ . When the nitrite concentration in the clarified effluent exceeds 1 mg/L, nitrite lock makes it seem like operators cannot add enough chlorine to their disinfection process; TRC becomes non-detectable even at high chlorine doses, and fecal coliform counts exceed permit limits.

Since nitrite lock has many potential causes, the remedies for it are also variable. Maintaining desirable pH and alkalinity in the mixed liquor is important. Eliminating toxic or inhibitory substances in the waste stream will help, too. Sometimes these substances may be generated internally, too. For example, using small doses of liquid bleach to control filamentous growth in the biomass will likely inhibit *nitrobacter* before it affects *nitrosomonas*, resulting in higher nitrite concentrations. While water temperature cannot be easily controlled, low water temperatures generally call for longer MCRT, and this may be achieved by building up the concentration of biomass through reducing the sludge wasting rate.

For more immediate remedies to nitrite lock, if a treatment process has more than one treatment train and both are independent of one another, it may be possible to blend low-nitrite effluent with the problematic high-nitrite effluent to dilute the nitrite. Also, if the facility permit allows it, increasing the concentration of ammonia in the effluent above that of the nitrite concentration may solve the problem, because chloramines forming in the disinfection process appear to be less prone to nitrite lock than free chlorine.

Most treatment facilities test for nitrite and nitrate together. From a process control standpoint, though, it may be better to test the two separately to ensure the operator(s) can be alerted to rising nitrite concentration in time to avert problems.

### Nitrogen Removal Without Major Process Changes

In modern treatment facility design, BNR has become common. Many process designs exist to support both nitrification and denitrification. However, it is not necessary for older treatment facilities to be radically redesigned to achieve nitrogen removal. The simplest method is called “intermittent” or “on / off” aeration, where the aeration blowers are cycled to provide either full-on aeration for oxidation of organic and ammonia waste, or turned off to provide periods of anoxic treatment where denitrification reduces nitrate to nitrogen gas in the bioreactor, preventing rising sludge from occurring in the clarifier.

Intermittent aeration requires some minor modifications to make it work successfully:

- Dissolved oxygen control: Ideally, D.O. during oxidative periods should range from 1.5 mg/L to 3.5 mg/L to achieve complete nitrification.
- Anoxic, subsurface mixing: During air “off” period, denitrification will be optimal if mechanical mixing is present in the bioreactor to maintain the bacteria, cBOD, and dissolved nitrate all in contact with one another. Without anoxic mixing, the denitrification reaction will occur mostly at the top of the sludge blanket that forms, although rising sludge (as in a clarifier) does occur, showing that denitrification will occur, albeit inefficiently, throughout the sludge blanket.
- Organic carbon: Facultative, heterotrophic bacteria that denitrify require a carbon source for cellular metabolism and reproduction. Usually, this organic carbon comes from raw wastewater continuing to enter the bioreactor while it is in the “off” period. If necessary,

supplemental carbon in the form of commercially prepared additives or otherwise as simple food processing wastes, sugar, rabbit or fish food, may be substituted.

### Operational Benefits of Biological Nitrogen Removal

It is said that if a facility is required to nitrify ammonia wastes as part of its NPDES permit, it should denitrify the nitrate, as well, because of the economic benefit of doing so. Nitrification is energy intensive, and there are costs associated with power consumption, maintenance costs for aeration systems, chemical expenses associated with alkalinity addition, and use of polymer for sludge settling aids that counteract rising sludge in clarifiers.

Denitrification reduces the overall amount of power and chemicals consumed. These may be quantified as follows:

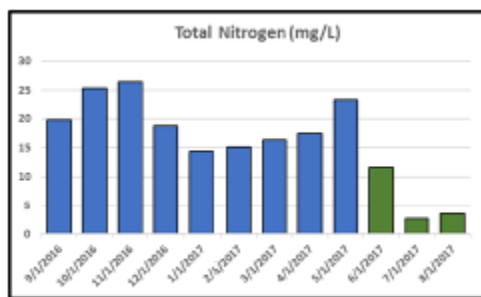
- 3.57 lb. of alkalinity as CaCO<sub>3</sub> is recovered for every 1 lb. NO<sub>3</sub>-N reduced to nitrogen gas, N<sub>2</sub>. Remember, 7.14 lb. of alkalinity are consumed by nitrification of ammonia, so roughly 50% of alkalinity is returned.
- 2.86 lb. O<sub>2</sub> is recovered for every 1 lb. NO<sub>3</sub>-N reduced. This means the work required of motor-driven air compressors brush rotors, or surface aerators is reduced.
- Electricity conservation is observed in the use of intermittent aeration in conventional activated sludge treatment, where aeration run times may be reduced by as much as sixty percent. Activated sludge aeration need not be constant.

### Case History

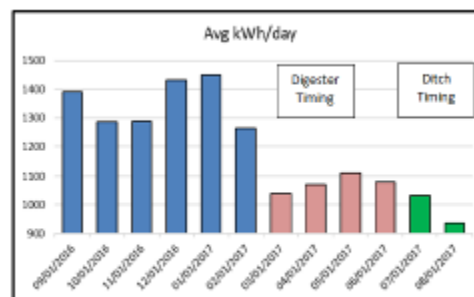
Intermittent aeration was tried at the Adamstown, Lancaster County, wastewater treatment facility to reduce effluent total nitrogen—mostly nitrate—so that the facility operators could save money by avoiding annual purchase of nitrogen credits to meet their Chesapeake Bay nutrient reduction goals. The facility includes two secondary bioreactors as oxidation ditches, aerated through surface mechanical aerators.

Using instrumentation to monitor dissolved oxygen, pH, and ORP, and installing simple timers on the aerators’ motor controls, the operators were able to reduce aeration time from 24/7/365 to 2 hours “on” and 3 hours “off” for every five-hour cycle.

Based on feedback from the instrumentation, the operator manipulated the timing regime from 24hr/day ON to 9.6 hours/day ON to optimize denitrification (TN removal). At the close of the project, effluent Total Nitrogen (TN) and energy consumption were reduced by 74% and 30%, respectively.



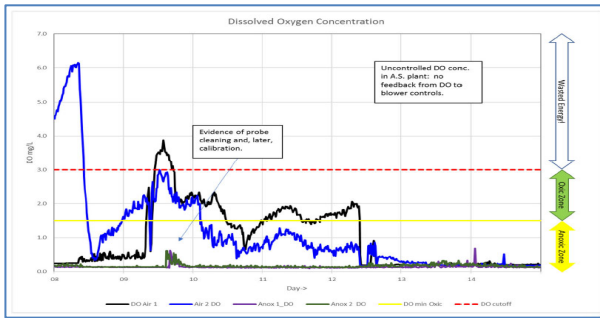
Figures: Effluent Nitrogen Reduction



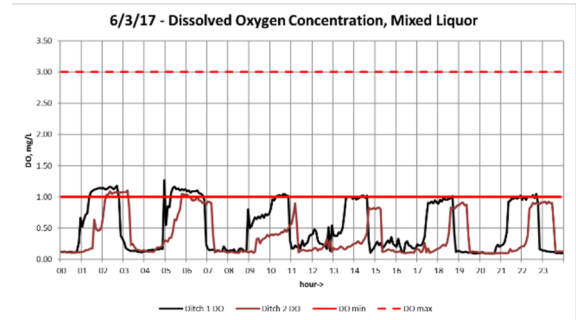
Electrical Consumption

### Instrumentation and Automation

Excessive dissolved oxygen residual in bioreactors could be controlled by using variable frequency motor drives (VFD) to regulate the motors driving aeration blowers. The principle is to install continuous monitoring dissolved oxygen probes in the bioreactors and using a 4-to-20 milliamp signal from the probe controller to signal the VFD to maintain blower speed that maintains D.O. residual between 1.5 mg/L and 3.5 mg/L. The graphs below compare unregulated D.O. residual to controlled residual within aeration tanks:



**Unregulated D.O. residual in bioreactor**



**Controlled D.O. residual via VFD feedback loop**

The technology of the D.O. probes is limited at the lower end of the scale, where any reading below 0.3 mg/L may be considered to be zero. To better understand the effective ranges for denitrification, ORP probes are used, where anoxic process is favorable between 150 mV and -150 mV. In practice, the denitrification “sweet spot” occurs between 0 mV and -50 mV, although experience may be different among differing treatment technologies. ORP probes are installed in the same bioreactor in the cases of intermittent aeration, sequencing batch reactors (SBR), oxidation ditches, Orbals, Schreiber process tanks, membrane bioreactors (MBR), and the like. Where anoxic processes occur in separate tanks, the ORP probes are placed in anoxic (denitrification) tanks or in anaerobic selectors. Process automation may use ORP probes to regulate the addition of supplemental carbon or to control the nitrate recycle rate as ways to optimize denitrification.

Because nitrifier bacteria are very sensitive to pH changes, and because the action of AOB to oxidize ammonia to nitrite produces acidification of the biomass, it is important to monitor pH in the aeration tank. Automation may use pH set points to regulate the addition of alkalinity to control pH. Nitrosomonas has an optimal pH between approximately 7.0 and 8.0 S.U., and the optimum pH range for Nitrobacter is approximately 7.5 to 8.0 S.U.

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## ATTACHMENT E: ESTIMATED COST FOR DISSOLVED OXYGEN PROBES

The equipment deployed at this wastewater treatment facility was chiefly comprised of Hach products. In this attachment, the estimated cost for purchasing this equipment and maintaining it is listed, excluding installation costs. Modifications to the SCADA system to incorporate these probes would have to be contracted with the SCADA provider at additional programming cost. Engineering costs for design and for regulatory approvals are not included.

This information does not account for any already existing probes or probe controllers. Probe controllers may be customized for their application, such as wireless communications or industrial communications protocols. Other add-ons may include cellular modem and cloud-based data storage subscription, for additional cost.

Following is a table listing equipment needed for dissolved oxygen probe installation into three rings of the Orbal bioreactor. This configuration accounts for two oxic ditches and one anoxic ditch:<sup>13</sup>

No.	Item	Hach Cat.	Unit Price	Qty.	VWR Line Cost
10	Hach LDO sc Model 2, DO Probe	9020000	\$ 2,996.00	2	\$ 5,992.00
20	Hach ORP Sensor, pHD sc	PHDsc	\$ 1,595.00	1	\$ 1,595.00
30	Pole Mount Set for 1" NPT Sensors	9253000	\$ 754.00	3	\$ 2,262.00
40	SC4500 Controller, Prognosis, LAN + mA Output, 2 digital Sensors, 100-240 VAC, without power cord	LXV525.99A1B551	\$ 3,321.00	2	\$ 6,642.00
50	ORP Probe Sensor Guard	1000F3374-002	\$ 84.25	1	\$ 84.25
60	Salt bridge PEEK, PVDF junctions, for pHD sensor	SB-P1SV	\$ 124.00	1	\$ 124.00
70	Standard Cell Solution, Concentrated pH 7.0 Buffer (Equi-Transferrant), 500 mL	25M1A1025-115	\$ 113.00	1	\$ 113.00
80	ORP buffer solution, 200 mV, 1L	25M2A1001-119	\$ 115.00	1	\$ 115.00
90	LDO Replacement Sensor Cap Kit for LDO2sc	9021100	\$ 350.00	2	\$ 700.00

Total Hach Pricing: \$ 17,627.25

The costs listed here may not be current and do not include installation costs for physical and electrical work, engineering, regulatory approvals, nor for modifications to a SCADA system to incorporate the data and controls. For updated cost estimates, the operators should contact equipment manufacturers and vendors, comparing products and prices across more than just one brand of equipment. Costs for incorporating variable-frequency drives for aeration blower systems should be evaluated separately by the facility's consulting engineer.

An annual budget for maintenance costs should be included for renewal parts such as do-it-yourself LDO replacement sensor cap ORP salt bridge and calibration standard for each of the dissolved oxygen probes, shown in the table above.

<sup>13</sup> Costs are estimated based on current catalog pricing and are presented only for estimating purposes. Facility owners and operators should check and compare with equipment vendors as to the most appropriate equipment and pricing before drafting budgets. DEP makes no endorsement of any particular brand of equipment.

Service plans are available for these probes, but the costs are not entirely listed. Hach offers differing levels of service:

- LDO Model 2 Probe Bench Service Preventative Maintenance Partnership, once per year, at \$387 per probe or \$1,161 total;
- Bench Service Partnership for SC4500, once per year, at \$202 per year;
- Field Service Partnership, one or two services per year, pricing not available;
- Warranty Service Partnership, one or two services per year, pricing not available.

The higher-level service plan costs may be obtained from the manufacturer or vendor. On-site service plans will reduce the maintenance turn-around time from approximately eighteen days to one or two. This is an important consideration when a facility does not have back-up equipment in reserve.

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