THE Water Research FOUNDATION

Project 5087: Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems & Online Analytical Measurement Reliability & Accuracy

Project Report

2024

Woodard & Curran
Northeastern University
HATCH
UMass Amherst

Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems & Online Analytical Measurement Reliability & Accuracy

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City of Denver, Colorado

NYCDEP
New York, New York

City of Olathe
Olathe, Kansas

Town of Plymouth
Plymouth, Massachusetts

Silicon Valley Clean Water
Redwood City, California

Springfield Water & Sewer Commission
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Upper Blackstone Clean Water
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Survey Respondents:

1. Akron, OH Water Reclamation Facility
2. Amherst, MA Wastewater Treatment Plant
3. Ashbridges Bay Treatment Plant
4. Ballenger-McKinney Wastewater Treatment Plant
5. Bethel, ME Wastewater Treatment Plant
6. Billerica Water Resource Recovery Facility
7. Blue River Wastewater Treatment Plant
8. Boothbay Harbor Sewer District
9. Brockton Advanced Water Reclamation Facility
10. Cedar Creek Water Pollution Control Facility
11. Charles River Pollution Control District
12. Chicopee Water Pollution Control
13. Columbia Boulevard Wastewater Treatment Plant
14. Coos Bay, OR Wastewater Treatment Plant
15. Deep River Water Pollution Control Authority
16. Douglas L. Smith Middle Basin Plant
17. Durham Advanced Wastewater Resource Recovery Facility
18. East Bay Municipal Utility District
19. East Greenwich Wastewater Treatment Facility
20. Easthampton, MA Wastewater Treatment Plant
21. Fairfield-Suisun Sewer District
22. Fox Metro Water Reclamation District
23. Grass Island Wastewater Treatment Plant
24. Great Barrington, MA Wastewater Treatment Plant
25. Greenville, NC Utilities
26. Herkimer Country Sewer District Wastewater Treatment Plant
27. Holyoke, MA Water Pollution Control
28. Hominy Creek Water Reclamation Facility
29. Hornell, NY Water Pollution Control Plant
30. Humber Treatment Plant
31. Hunts Point Water Resource Recovery Facility
32. James C. Kirie Water Reclamation Plant
33. JD Phillips Resource Recovery Facility
34. Kennebunkport Wastewater Treatment Facility
35. Kishwaukee Water Reclamation District
36. Litchfield, CT Water Pollution Control Authority
37. Little Creek Resource Recovery Facility
38. Lynn, MA Wastewater Treatment Facility
39. Metro Water Recovery
40. Meriden, CT Water Pollution Control Facility
41. Mill Creek Regional Wastewater Treatment Plant
42. Moscow, ID Water Reclamation Facility
43. Neuse River Resource Recovery Facility
44. New Century - Little Bull Wastewater Treatment Facility
45. North Brookfield, MA Wastewater Treatment Plant
46. Old Forge, NY Wastewater Treatment Plant
47. Plant City, FL Wastewater Treatment Plant
48. Plainville, CT Water Pollution Control Facility
49. Plymouth, MA Wastewater Treatment Plant
50. Port Washington, NY Wastewater Treatment Plant
51. Princess Anne Wastewater Treatment Plant
52. Quonset Wastewater Treatment Facility
53. Rock Creek Water Resource Recovery Facility
54. Saco, ME Water Resource Recovery Department
55. San Jose Creek East Water Reclamation Plant
56. Sanford Sewer District
57. Silverton, OR Wastewater Treatment Plant
58. Smith Creek Resource Recovery Facility
59. South Hadley Water Pollution Control Division
60. South Windsor Water Pollution Control Facility
61. Springfield Regional Wastewater Treatment Facility
62. Stickney Water Reclamation Plant
63. Upper Blackstone Clean Water
64. Upper Occoquan Service Authority
65. Urbana & Champaign Sanitary District – Northeast Plant
66. Urbana & Champaign Sanitary District – Southwest Plant
67. Uxbridge, MA Wastewater Treatment Facility
68. Warren, RI Wastewater Treatment Facility
69. Wells, ME Sanitary District
70. Westerly, RI Wastewater Treatment Plant
71. Westfield, MA Water Recovery Facility
72. Yarmouth, ME Wastewater Treatment Plant

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Acronyms & Abbreviations

ADF	Average daily flow
AO	Anaerobic-oxic
A2O	Anaerobic-anoxic-oxic
ABAC	Ammonia-based aeration control
AvN™	Ammonia vs. NOx
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
CaRRBs	Centrate and RAS reaeration basins
CMMS	Computerized maintenance management system
COD	Chemical oxygen demand
DO	Dissolved oxygen
EBMUD	East Bay Municipal Utility District
EBPR	Enhanced biological phosphorus removal
FST	Final setting tank
HPO	High purity oxygen
HR	Hour
IMLR	Internal mixed liquor recycle
ISE	Ion selective electrode
LB	Pound
lbs/d	Pounds per day
MBBR	Moving bed biofilm reactor
mgd	Million gallons per day
mg/L	Milligrams per liter
MLE	Modified Ludzak-Ettinger
MLSS	Mixed liquor suspended solids
MOV	Most open valve
NA	Not Available
NaOH	Sodium Hydroxide
NH3	Ammonia
NH4	Ammonium
NO2	Nitrite
NO3	Nitrate
NOx	Nitrate and Nitrite
NSEC	North Secondary
O&M	Operations and maintenance

OP	Orthophosphate
ORP	Oxidation-reduction potential
pH	Acidity or alkalinity
PID	Proportional-integral-derivative
PO_4	Phosphate
RAS	Return activated sludge
S2EBPR	Sidestream enhanced biological phosphorus removal
SAR	Sidestream anaerobic reactor
SBR	Sequencing batch reactor
SCADA	Supervisory control and data acquisition
sCOD	Soluble chemical oxygen demand
SDEV	Standard Deviation
SRT	Solids retention time
SSEC	South Secondary
SVI	Sludge volume index
TIN	Total inorganic nitrogen
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSS	Total suspended solids
UBCW	Upper Blackstone Clean Water
ULR	Ultra-low range
UV	Ultraviolet
VFA	Volatile fatty acid
WAS	Waste activated sludge
WEFTEC	Water Environment Federation Technical Exhibition and Conference
WRRF	Water resource recovery facility
WWTF	Wastewater treatment facility
YR	Year

Executive Summary

The tools and training developed for this project are intended to help reduce the barriers to adoption and long-term implementation of biological nutrient removal (BNR) control systems utilizing sensors (in situ) and analyzers (wet chemistry) for real-time measurement of various wastewater constituents and characteristics.

ES.1 Key Findings

Key project findings include:

- Successful implementation of BNR control systems requires more than just the selection of the controls and associated instruments. A business case that quantifies not only the capital costs of the instruments and controls, but also the related capital and annual O&M costs, will allow a more complete assessment of the return on the investment.
- Some of the utility partners and case study participants have indicated that new BNR controls have a learning curve and the performance of the systems has benefited from making regular adjustments to the controls over time. Some have removed elements of on-line instrumentation from service to reduce costs and simplify the O&M related to the controls and instruments. Undue complexity can impede the progress toward achieving the desired benefits from implementation, and adding complexity over a period of time provides the advantage of making O&M changes more manageable and spacing out the learning and needed training.
- Building trust in the accuracy of the on-line instruments is important for long-term implementation of BNR controls at a WRRF. Validation sampling and regular cleaning of the in situ systems, which is often required more frequently than the minimum recommended by the instrument manufacturer, is critical to maximize measurement accuracy and maintain stability of the control system. Also, immediate field filtration of calibration check samples is imperative. Delaying filtration even to transport samples to an on-site laboratory can significantly impact results and lead to improper matrix adjustments.
- Ultimately, successful implementation of BNR controls with online instrumentation requires a commitment from all levels of the organization, a clear delineation of responsibilities, a robust training plan, and the adoption of a culture of data-driven operation and optimization of the BNR process.

ES.2 Background and Objectives

Expectations of water resource recovery facilities (WRRFs) have intensified over time as the primary concerns have evolved from simple sewage removal to management of the quality of effluent returned into the environment and the recovery of resources. One of the main challenges to achieving process intensification for nutrient removal is the effective deployment of control systems and their associated in-situ sensors and wet chemistry analyzers that are used to continuously measure a variety of parameters for both control and monitoring.

This research aims to fill the current gap in understanding of instrument-driven BNR control schemes and their reliability and performance. Currently, there is not a centralized summary of the various instrument-driven BNR control systems, the associated sensors and analyzers, their performance, and aggregated operations & maintenance (O&M) costs and procedures. Also lacking is a resource that seeks to convert this information into usable and accessible knowledge for individual facilities.

The project objective is to evaluate the technologies, configurations, performance, O&M requirements, and costs of BNR control systems utilizing sensors and analyzers for real-time monitoring and control to synthesize the current state of the art and develop a framework for practical implementation. The benefit will be to speed successful adoption of BNR control system innovation and maximize the value broadly across the sector at both large and small WRRFs.

ES.3 Project Approach

Our approach is founded on the belief that stakeholders are looking for actionable guidance and information. Therefore, the project deliverable is a set of usable tools that are intended to be an easy entry point for operators, engineers, and utility directors at small, medium, and large WRRFs to understand the breadth and applicability of BNR control systems and associated online instruments to their utility. The tools are based on the project and utility partners' experience and expertise, a literature search, a broad utility survey, and field testing of several sensors. The tools are easily accessed for viewing and downloading from an interactive website called the *BNR Instrumentation & Controls Selection Adventure* accessible from a link on the WRF website and hosted by Woodard & Curran.

An operations-focused training series was also developed for the project to reinforce understanding of BNR controls and support use of the project tools. The training utilizes a well-established, interactive process simulation software platform that is customized with training exercises for online instrument-based nutrient removal controls.

In addition to the self-guided training exercises, organized training sessions will be led by the project Co-PIs and will build on proven training approaches (based on thousands of student hours) through WRF and other established venues, including Water Environment Federation (WEF), regional WEF member associations, and operator associations.

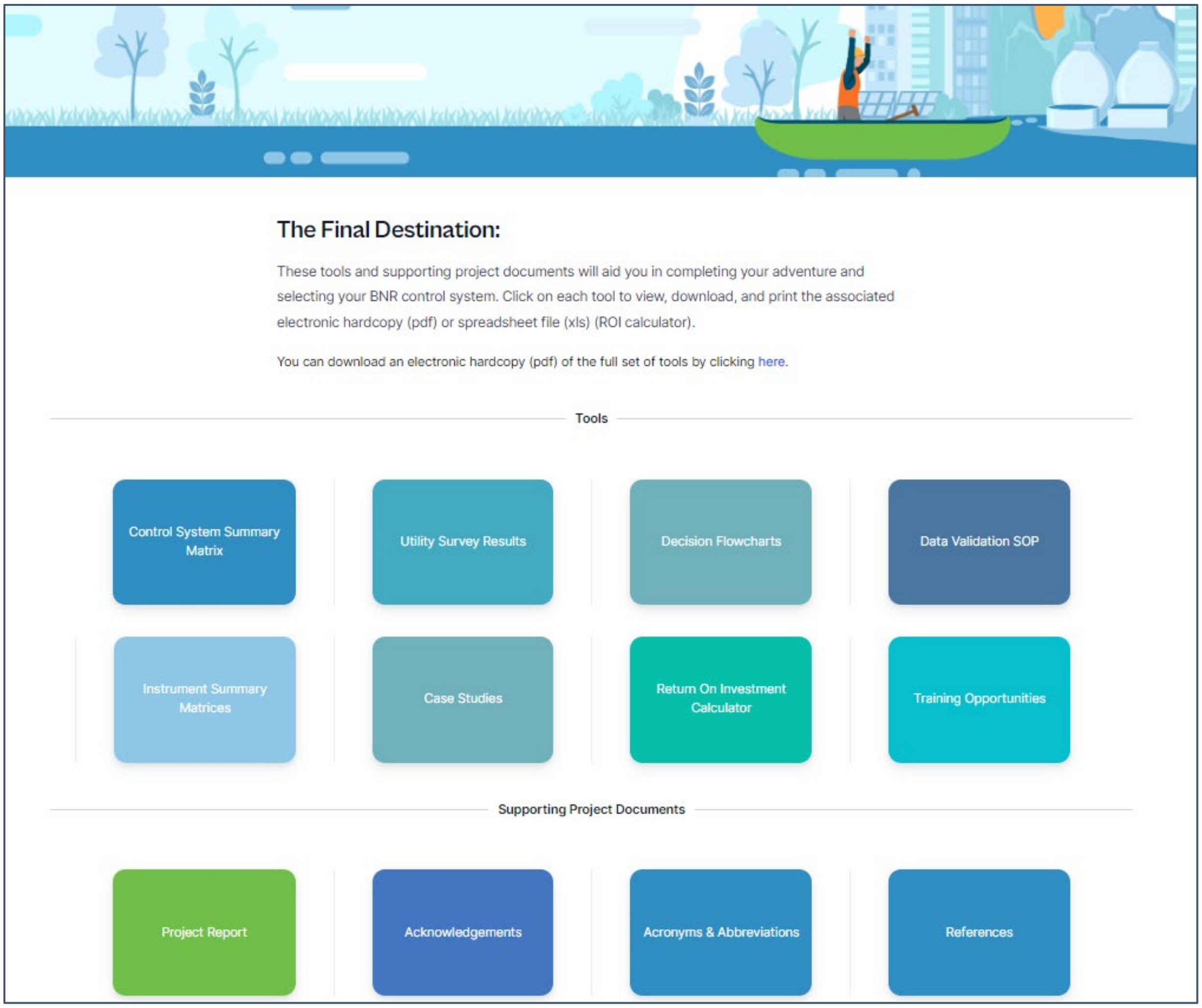

Figure ES-1. Example screenshot from the *BNR Instrumentation & Controls Selection Adventure* interactive website.

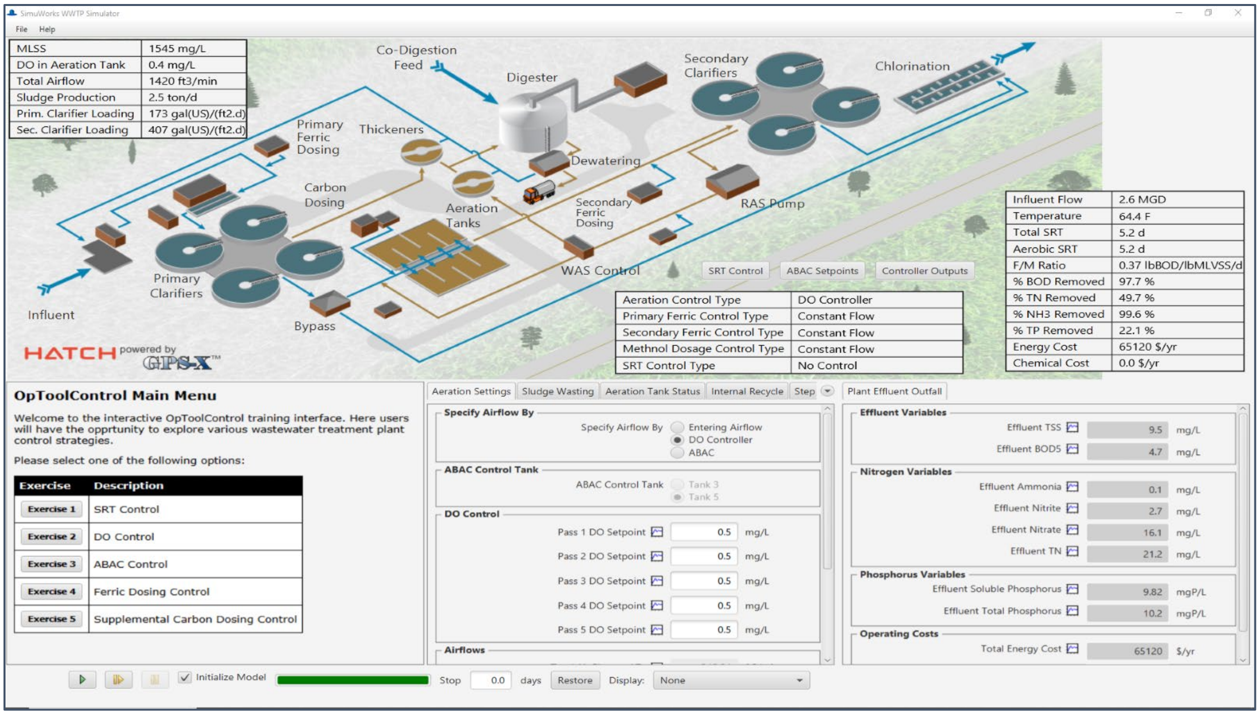

Figure ES-2. Example screenshot from Simulator used in interactive operations-focused training.
Source: Hatch 2023.

ES.4 Results

The tools are based on the project and utility partners' experience and expertise, a literature search, a broad utility survey, and field testing of several sensors. The results of the literature review highlighted the criticality of implementing the utility survey to gather additional relevant data for this project. The survey questions incorporated objective inquiries (e.g., frequency of calibration) in addition to more subjective inquiries (e.g., ease of calibration and acceptability of calibration requirements).

Listed below are key findings based on the literature review, utility survey and field testing:

- Dissolved oxygen control was the most common BNR control system used by the utility survey respondents. Use of dissolved oxygen (DO) sensors for control is pervasive, and almost 75% of respondents think they are reliable for use in a controller. Respondents thought the cleaning, calibration, and maintenance are generally easy and acceptable. Utilities have a good understanding of the needed cleaning and calibration cadence and how much to trust the data.

- Use of nitrate sensors and analyzers for control is established but not as prevalent. Nitrate systems generally require more O&M effort than dissolved oxygen sensors. Trust in their reliability in control systems is variable, and WRRF's that use them for control seem to have developed a stronger level of trust in their accuracy and reliability. Utilities that implement them generally find the ease of cleaning and maintenance acceptable, but the ease of calibration of the analyzers is relatively more challenging than the sensors.

- Use of ammonium sensors and analyzers for control is established but not as prevalent; these systems generally require more O&M effort than dissolved oxygen sensors. The ISE sensor rated relatively lower for reliability for use in a controller than the analyzer; in part this is due to the sensors themselves (accuracy and stability limitations prevent putting the sensor in locations with low ammonium concentrations such as at the end of secondary treatment), which then cascades into needing to build a process dynamics model to know how to properly use the signals to tune. These systems are often used in cascaded aeration controls with dissolved oxygen sensors.

- Use of orthophosphate and total phosphorus analyzers is emerging. These analyzers are relatively costly, and maintenance is more intensive than for other systems. These systems have been implemented primarily for monitoring purposes only.

- Despite installation of ORP sensors at many facilities, trust in these sensors is insufficient for them to be frequently used for automated controls (the majority of facilities providing data for this study used them for monitoring only).

- Use of suspended solids sensors is emerging, primarily for monitoring purposes only. There is interest measuring flocs (quality or quality). O&M related to suspended solids sensors is generally viewed as acceptable, and existing sensors are thought of as reliable.

- There is interest in organic carbon sensors for both process monitoring and regulatory compliance, yet deployment of emerging commercial options remains limited. Feedback from utility survey respondents was limited on this point.

- Most survey respondents with aeration controls thought they were extremely or very worth it and cited several benefits, including nutrient removal, energy savings, and improved monitoring and control. Sensor accuracy and system complexity were cited as challenges by over 50% of the respondents with aeration control systems utilizing nutrient sensor and/or analyzers for control (e.g., ABAC and AvN™).

- O&M is important. Weekly cleaning is common for most sensors and analyzers. The costs associated with O&M were considered significant or burdensome by many survey respondents. In addition to upfront costs, the O&M costs must also be considered in budgeting and decision making.

- Filtration is often critical for wet chemistry analyzers, and accessories such as filtration and cleaning systems should also be included in evaluations for sensor and analyzer systems.

- Physical placement of sensors was considered critical for ensuring useability of the data. Placement was primarily dictated by manufacturer recommendations but also requires consideration of accessibility (for frequent cleaning), selecting a location to minimize fouling (e.g., ensuring consistent flow), with sufficient water depth, and where conditions of the target analyte are within the detection range of the sensor. Placement of analyzers may further require consideration of solids loading or other potential interferences.

The literature search and utility survey identified areas in need of further understanding, including how to build trust in the accuracy of the sensor and analyzer measurements from the operations teams. The project includes field studies at the University of Massachusetts Water and Energy Testing (WET) Center and the Amherst, MA WRRF where sensors and instrumentation were tested in the aeration tanks, and the results were utilized to build a template for a Standard Operating Procedure (SOP) for collecting instrumentation verification samples and analyses that is integrated into the project tools.

Gaps in understanding of BNR controls with in situ sensors and wet chemistry analyzers remain, and the following future research is recommended for continuing to improve treatment efficiency and performance and to intensify treatment processes:

- Generating case studies of teams/facilities with excellent data management practices and capabilities unlocked through data analytics; leveraging these case studies to generate best practices recommendations and highlight missing capabilities where new approaches may be needed.
- Developing a common set of data collection guidelines and having WRRFs update the way they collect the data to promote development and use of digital twins. Currently, enough of the right kind of data at the right locations in the WRRFs is lacking.
- Continuing to develop sensor and analyzer technologies. The lack of commercial phosphorus sensors is a major gap; only wet chemistry analyzers are commonly deployed at WRRFs. Continuing development of microfluidic analyzers would enhance the ability to collect more accurate, real-time data for many targeted nutrient parameters.
- Continuing to leverage high quality sensors available to mitigate interferences or other deficiencies on nutrient sensors, e.g., through “soft sensor” configurations that facilitate online signal corrections via multi-sensor packages.
- Building an understanding of how to apply generative artificial intelligence and machine learning (AI/ML) to automation challenges, which has the potential to impact predictive control capabilities and overcome the challenge of making the models transferrable in spite of the uniqueness of individual WRRFs.

ES.5 Benefits

The project tools will allow WRRF operators, engineers, and utility directors who are moving forward with BNR projects to:

- Gain a baseline understanding of the current and evolving state of in-situ sensor and wet chemistry analyzer technology
- Learn from the experiences at different WRRFs and connect with those utilities

- Streamline the decision-making process and focus detailed evaluation on the most applicable systems by matching treatment targets and utility needs to recommended control system and sensors
- Increase chances of successful implementation—and alignment with utility budgets and operational resources—through evaluation of important factors such as reliability, maintenance, complexity, cost, etc. using an evaluation framework that weighs benefits and costs within the context of the goals and infrastructure of individual facilities
- Receive operations-focused, hands-on training utilizing a process simulator to learn and reinforce the concepts of BNR control utilizing online instrumentation

Proven, widely-adopted and innovative BNR control systems and related sensors and analyzers were included in the project, making the tools more relevant to a broad cross-section of the market, rather than only those few pioneers who are already far along the innovation path. The benefit will be to speed-up successful adoption of BNR control systems and maximize the value widely across the sector at both large and small WRRFs. With greater adoption, the innovation will also continue to accelerate.

1. TASK SUMMARY & OUTCOMES

The project consisted of the following tasks:

1. Literature Review
2. Utility Survey
   2.1. Broad Digital Survey (Round 1)
   2.2. Detailed Survey of Utility Partners and Additional Utilities Identified in Broad Digital Survey (Round 2)
   2.3. Case Study Development
3. Sensor Testing
4. Tool Development
5. LIFT Webcast
6. Simulator Training Platform Development

The following subsections summarize the scope and outcomes of each task.

1.1 Task 1 – Literature Review

The literature review performed for this project builds on the work "Enabling Wastewater Treatment Process Automation: Leveraging Innovations in Real-Time Sensing, Data Analysis, and Online Controls" by Zhang, Tooker, and Mueller published in 2020 and related published sources, while also focusing more on (1) understanding the specific role of instrumentation in each case study and (2) cataloguing results quantitatively with respect to key metrics. The literature review considered the following:

- Biological nutrient removal (BNR) control approaches being employed by water resource recovery facilities (WRRFs)
- Sensor, analyzer, and controller technologies supporting these processes
- Potential for impact (e.g., improved nutrient removal, lowered energy use, automation and operation and maintenance as relates to workforce costs)

Sources for the work included peer-reviewed scientific literature (leveraging Web of Science and the wide range of journals available through Northeastern University Libraries) and results of current and prior WRF projects (ASCE 2017, Doody and Neville 2017, EPA 2013, Guswa et al. 2020, Innovation in Wastewater Treatment — Community Workshop Series 2019, Neethling 2020-2021, Tsuchihashi 2015, Water Environment Federation 2021). Additionally, sources include commercial literature from equipment manufacturers as noted in the references section since some emerging technologies and approaches are proprietary.

The table in Appendix A catalogues information for individual facilities collected through the literature review. The project team was not able to collect the full spectrum of desired information on each facility based on published literature. This is consistent with the findings documented in Zhang, et. al. (2020), which noted a lack of information in scientific publications that would allow operators to make an informed cost-benefit analysis on implementation of sensor-based control systems and new technologies with explicit comparison to existing operational baselines as well as a lack of consistent or clear reporting metrics across the scientific literature.

The project team was typically able to gather basic background information on each WRRF, such as type of BNR process, size of the facility, and effluent permit limits, and was often able to document the sensor target parameter (e.g., DO, ORP) and type of control scheme implemented. Information on sensor type and manufacturer was more limited, but a basic understanding of the role of instrumentation in each case study typically was gained.

Evaluating the performance of individual sensors was not possible since data related to operation and maintenance of sensors were extremely limited. Performing a quantitative evaluation of achievable results based on case studies is also challenging because results are not presented with consistent metrics and are often not presented relative to baseline operational conditions. Capital cost information is also limited in the published literature.

1.2 Task 2 - Utility Survey

The project team conducted a survey of water resource recovery facilities (WRRFs) in 2022 to understand firsthand the real-world experiences with BNR sensor-based control systems. The utility survey focused on performance and O&M. The results of the survey were used to develop case studies and inform the development of the other project deliverables.

The results of the literature review highlighted the criticality of implementing the utility survey to gather relevant data for this project. The results also informed the design of the survey, including specific questions asked and the format of the questions. In addition to gathering general background information about each WWRF, such as design capacity, effluent limits and biological processes, the survey requested that respondents identify the type of control systems being utilized, the type of sensors and analyzers installed, and the outcomes from implementing more advanced controls. The survey questions incorporated both objective inquiries (e.g., frequency of calibration) and more subjective inquiries (e.g., ease of calibration and acceptability of calibration requirements). A copy of the utility survey is included in Appendix B.

Our utility partners formed the core of the surveyed group, and we also reached out widely to WRRFs, including WRF's subscriber network. Our utility partners spanned the U.S. and include WRRFs with a variety of configurations, bringing diverse perspectives and real-world experiences. The utility partners also provided feedback on which questions to ask in the survey and completed the survey.

The survey was administered through Survey Monkey, and a link to the survey was included in an email to the recipients along with an electronic hardcopy of the questions. We distributed over 800 requests via email and coordinated with WRF to have the survey links posted on the

WRF website. The survey was sent to utilities across the United States of America and several in Canada. It was sent to most utilities in New England and utilities with flows greater than 0.25 mgd in New York. It was also sent to several utilities in Illinois, Maryland, Virginia, North Carolina, Florida, Texas, Colorado, California, Georgia, Arizona, and Toronto, including the contacts shared with us by our PAC members Phil Ackman and Heng Zhang. Additionally, we sent the survey to contacts in several professional associations including the Pacific Northwest Clean Water Association (Manufacturers and Representatives Committee, Operations Challenge Committee, Plant Operations and Maintenance Committee, and Utility Management Committee chairs), Bay Area Clean Water Agencies, North Carolina Water Quality Association, and Florida Water Environment Association.

We received 72 responses for a response rate of approximately 9%. The data collected from the survey responses were organized and visualized in a Microsoft Power BI dashboard. Figure 1-1 is a snapshot of the first page on the data dashboard showing a summary of the facilities that responded to the survey. Additional results are included with the other deliverables for this project described in Chapter 2.

To supplement the results of the Utility Survey, the project team selected a subset of respondents, including the project utility partners, for a more in-depth inquiry focused on the O&M activities and costs of maintaining the BNR control system and associated on-line instrumentation. The results of the utility survey and these follow up inquiries were used to develop a series of case studies. A copy of the utility survey and the follow-up survey are included in Appendix B.

Case study summaries were developed to provide the opportunity for peer-to-peer learning. Generally, the case studies include an overview of the WRRF BNR process and describe the BNR control scheme, sensors used, performance, O&M experience, and O&M costs for the instruments. They summarize key takeaways and lessons learned and include contact information of the WRRF representative if additional follow up by the reader is desired.

The utilities supplied estimated annual costs for parts, third-party maintenance contracts, and labor hours for annual operation and maintenance of the instruments. Total annual costs associated with each instrument were estimated by summing the annual costs of the parts and third party maintenance contracts with the labor costs, which were calculated by multiplying the O&M hours provided by an average hourly labor rate of $50 per hour. While actual labor rates will vary by utility, the estimated annual costs allow for relative comparison between instruments.

Table 1-1 contains a summary of the case studies developed for this project. The first four case studies listed in the table contain additional details about the configuration of the BNR controls systems. The results of the utility survey and the case studies are integrated into the project tools.

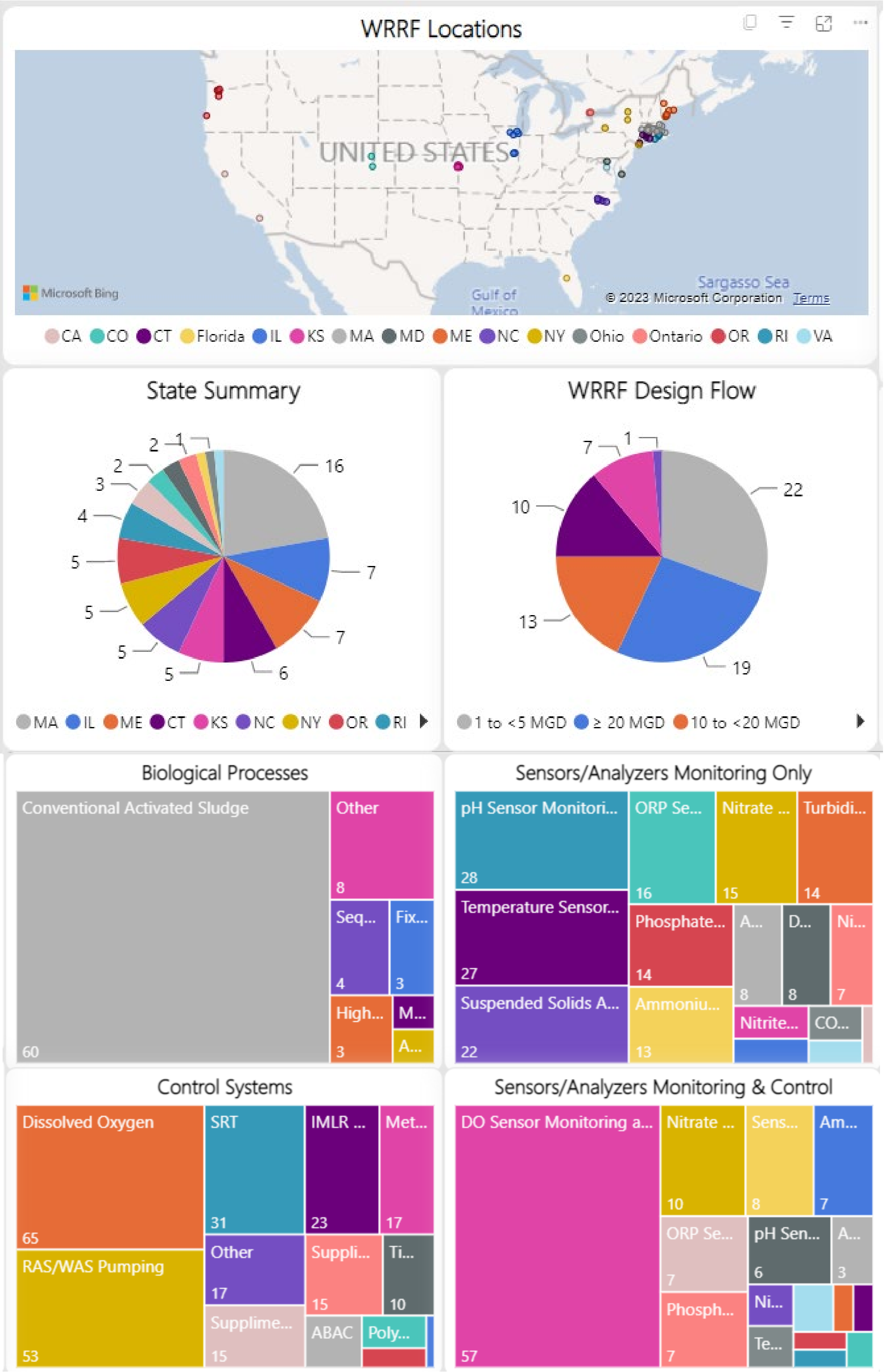

Figure 1-1. Example screenshot from Utility Survey summary dashboard.

Table 1-1. Case Study Summary.

	Utility/WRRF & Location	BNR Process(es)	BNR Control System(s)	Associated Instruments
1	City of Roseville WRRF Roseville, CA	MLE with supplemental carbon addition	ABAC	Control: DO, NH4
2	Metro Water Recovery Robert W. Hite WRRF Denver, CO	A2O (with sidestream annamox) and MLE with S2EBPR	ABAC & DO (when not using ABAC)	Control: DO, NH4, TSS Monitoring: COD/sCOD, TSS, NH4, NO3, NO2, OP, ORP, pH
3	Upper Blackstone Clean Water Millbury, MA	A2O	DO (Flow-based MOV), Supplemental Carbon (MicroC) Addition (third-party), Supplemental Alkalinity Addition	Control: DO, pH, NO3 Monitoring: NH4, OP, TSS, temperature
4	Town of Warren WRRF Warren, RI	4-Stage Bardenpho or MLE or Modified Contact Stabilization	DO (Flow-based MOV with variable speed mixer-aerators), SRT control, IMLR control, Supplemental Carbon (MicroC) Addition, Supplemental Alkalinity Addition (NaOH)	Control: DO, NO3, pH
5	Cedar Creek WWTF Olathe, KS	5-State Bardenpho with in-line MLSS fermenter	DO, SRT & Metal Salts addition, IMLR Pumping, RAS/WAS Pumping	Control: DO, OP Monitoring: TSS, NH4, NO3, ORP, pH, temperature
6	Clean Water Services Durham, OR	5-Stage Bardenpho with MLSS Fermenter	DO, SRT, RAS/WAS Pumping & Metal Salt Addition	Control: DO, NO3 Monitoring: NH4, NO2, OP, TSS, temperature
7	Holyoke WPCF Holyoke, MA	HPO activated sludge with modified anoxic zone	DO	Control: DO
8	Meriden WRRF Meriden, CT	A2O	DO, Supplemental Carbon Addition (methanol), Supplemental Alkalinity Addition, Metal Salts Addition	Control: DO, pH, NO3, OP, ORP Monitoring: NH4
9	Town of Plymouth WRRF Plymouth, MA	SBR	Timer-based aeration control	Monitoring: DO, NH4, NO3/NO2, ORP, TSS pH, temperature
10	Springfield Water and Sewer Commission Springfield, MA	Step Feed with Two Anoxic Zones	ABAC & DO when not using ABAC	Control: DO, NO3, NH4, TSS, Temperature
11	Westfield Water Recovery Facility Westfield, MA	Modified AO	DO & ABAC	Control: DO, NH4 Monitoring: TSS, OP, ORP, pH, temperature

1.3 Task 3 – Sensor Testing

The literature search and utility survey identified areas in need of further understanding, including how to build trust in the accuracy of the sensor and analyzer measurements from the operations teams. Task 3 included field studies at the University of Massachusetts Water and Energy Testing (WET) Center and the Amherst, MA WRRF where sensors and instrumentation were tested in the aeration tanks. The results of this work were utilized to build a template for an SOP for collecting instrumentation verification samples and analyses. The SOP is integrated into the project tools.

The Amherst WRRF is operated in a Modified Ludzack-Ettinger (MLE) configuration, with an IMLR system and also intermittent aeration of the aerobic zone using mechanical surface aerators (110 minutes aerated and 100 minutes with aerators at slow speed to maintain mixing). This results in high variability in nitrate concentrations, making it a favorable location for the field testing.

One ion selective electrode (ISE) and one spectrophotometric (UV) nitrate sensor manufactured by YSI were mounted near the midpoint of the aerated zone, adjacent to an existing DO sensor, to minimize possibility of damage and capture a representative measurement of the process. A microfluidic nitrate analyzer with filtration system from Southwest Sensor was installed adjacent to the ISE and UV sensors. An ammonium ISE sensor (YSI) was also installed to provide data enabling the team to assess tracking of nitrogen as it is transformed between different chemical species. A summary of the sensors installed for the field testing program is included in Table 1-2.

Table 1-2. Sensors and Analyzers in Field Testing Program.

Analyte	Sensing Mechanism	Detection Limit	Sampling Rate (Delay)	Interferences
Southwest Sensor – Environmental Analyzer				
NO_3^-	colorimetric (optical)	0.3uM (4 ug-N/L)	10 seconds (5 min up to 60 min)	Particle load (has filter on inlet)
NO_2^-	colorimetric (optical)			Particle load (has filter on inlet)
YSI				
NO_3^-	Spectrophotometer (UV)	0.1 mg N/L	1 minute (none)	None
NO_3^-	Ion Selective Electrode			Chloride
NH_4^+	Ion Selective Electrode			Potassium
NO_2^-	Spectrophotometer (UV)			None

These instruments were selected for testing based on utility survey results, which indicated that while they are utilized in many WRRFs, there is a wide range of comfort and O&M experience with nitrate instruments generally. The goal of the testing was to better understand the O&M associated with maintaining the performance of these various options for nitrate measurement.

Installation of the sensors occurred in July 2022. The filtration system utilized by the Southwest Sensor nitrate analyzer, designed originally for post-secondary installation, quickly became clogged, and an upgrade implemented by the company in August to support long-term deployments (doubling capacity of reagent bags) resulted in airlock in the system with inconsistent reagent flow. Despite multiple troubleshooting attempts, we were unsuccessful in obtaining usable real-time nutrient data from the microfluidic analyzer in the mixed liquor suspended solids (MLSS) and testing of the sensor was discontinued after a few weeks.

For all other sensors, initial calibrations (setting sensor software parameters based on known concentrations in measured samples) and matrix adjustments were done in collaboration with the sensor vendor. Subsequent sensor data was logged following a similar sampling frequency as would be expected for a typical plant (i.e., 1-5 minutes). Initial maintenance (cleaning/calibrating) programs followed manufacturer recommendations and are summarized here:

- Twice weekly cleaning of sensors using a soft brush/cloth or gentle spray with water (note that cleaning frequency was based on all manual cleaning recommended by the manufacturers and no automated air blast system).
- Twice weekly validation check to compare grab sample values analyzed in the lab with values measured by the sensor.
- Sensor “matrix adjustment” if the sensor value was > 10% different from the reading measured in a grab sample (note grab samples were collected at a time when the concentration of parameters was > 1.0 mg/L as recommended by the manufacturer).

Testing with the YSI sensors continued through November 2022. Testing occurred in two phases. During the first phase, the instruments were cleaned, maintained, and calibrated (note that in this case “calibration” refers to a minor field adjustment, also called “matrix adjustment” that was used to adjust sensor reading to align with lab measurements when a difference of >10% was observed) in accordance with the manufacturer’s recommendations. Grab samples were collected twice per week to validate readings from the instruments, with samples collected from the aerated and non-aerated parts of the cycle to capture a range of nitrate concentrations. These samples were immediately field filtered with a standard, non-bleached coffee filter and transported to the lab immediately after collection to minimize additional biological reactions that may have otherwise occurred. Lab measurements included nitrate and ammonia. During the Phase 1 test period, the manufacturer-recommended O&M was sufficient to maintain reliability and performance.

During Phase 1, two different laboratory test kits (Hach Test ‘n’ Tube and Hach TNTplus) were evaluated for accuracy and ease of use. While both test kits had a similar level of accuracy, the TNTplus kits were much easier to use than the Test ‘n’ Tube kits and were therefore less prone to human error. Minimizing chances for human error can be particularly important in facilities where operators may only infrequently be conducting lab analyses.

During the second phase of the pilot study, the instruments were “stress tested” by suspending cleaning and calibration while maintaining the same lab measurements for nitrate and ammonia at the same frequency (twice weekly), to monitor instrument drift. Lack of cleaning had a more immediate negative impact on the accuracy of the ISE measurements than the spectrophotometric (UV) sensors. Sensor drift from laboratory values for ISE sensors was apparent after approximately one week without cleaning, while the UV sensor was able to maintain readings close to laboratory values for up to four weeks without cleaning.

Subsequently, additional testing was conducted to provide guidance on standard operating procedures for sample collection and analysis of routine validation check samples. Samples were collected and either immediately filtered with a coffee filter in the field or not (two conditions run in parallel on identical samples). Filtered and unfiltered samples were taken back to the lab for analysis and one set of samples was refrigerated while the other was not. Because the refrigerated samples were periodically removed for testing, their temperature stabilized at ~12 °C, rather than 4 °C as would be typical of a laboratory refrigerator.

As can be seen in Figure 1-2, filtering samples in the field with a coffee filter resulted in a more stable nitrate value over time, independent of refrigeration at 12 °C (blue circles and diamonds).

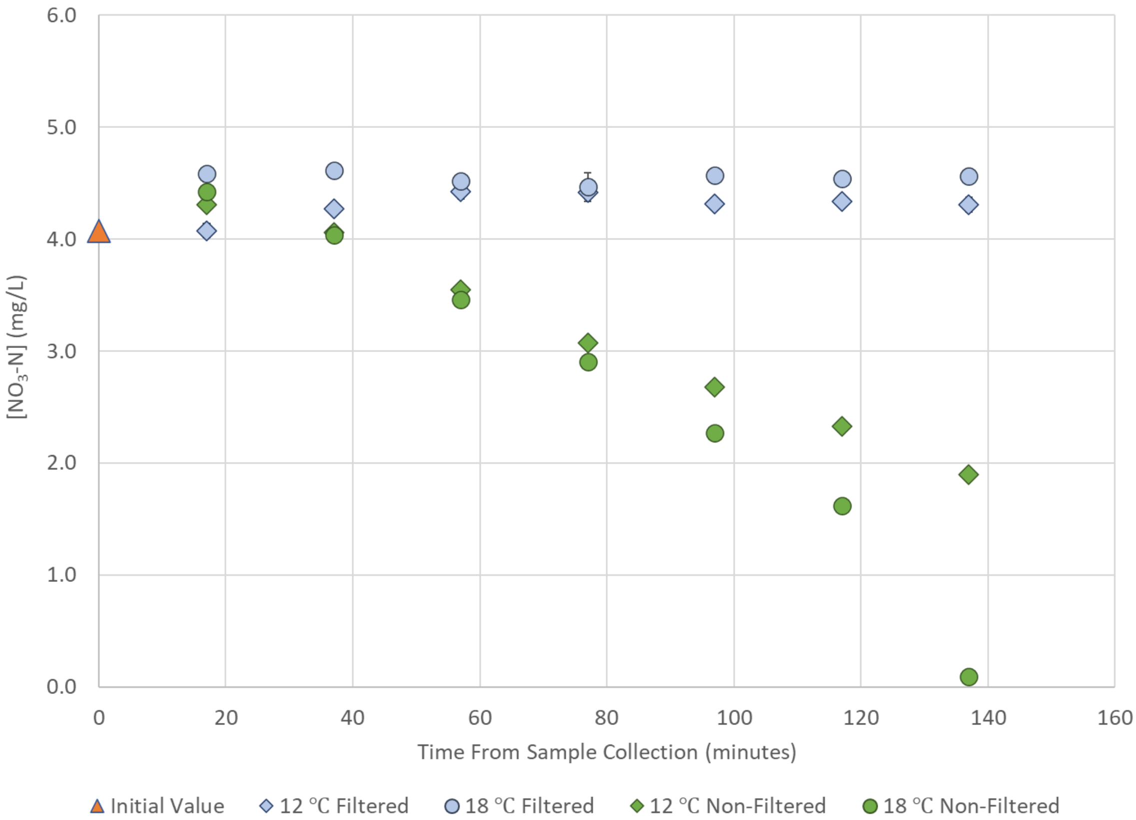

Figure 1-2. Nitrate Concentration as a Function of Time After Sample Collection With and Without Filtration and Refrigeration.

The measured concentrations in non-filtered samples (green circles and diamonds) decreased by approximately 1 mg NO3-N/L within one hour of sample collection and continued to decrease until the end of the experiment. Refrigeration of samples at a temperature of 12 °C without filtering (green diamonds) was not an effective method to maintain nitrate concentrations at the same level as filtered samples.

Findings from field work in Task 3 include:

- Routine cleaning of sensors (e.g., twice weekly wiping sensors with a soft cloth) resulted in improved accuracy compared to laboratory measurements. It is suggested to follow manufacturer recommendations for cleaning. Simply cleaning a sensor that had drifted from laboratory measured values resulted in an improvement in observed accuracy. It is noted that some sensors have built-in cleaning systems, such as rotating brushes or air-blast capability to remove materials from an area that needs flow. While such systems were not explicitly tested in this work, it is noted that these may reduce the frequency of routine cleaning required, but manufacturer recommendations do not consider these sufficient to entirely remove the need for routine cleanings such as was described above. Operators may need to adjust cleaning frequency and intensity based on type of sensor, sensor installation location, season (i.e., winter or summer; strict or more relaxed permit requirements), and operator experience.
- Spectrophotometric (UV) sensors required less frequent cleaning compared to ISE sensors. Sensor drift from laboratory values for ISE sensors was apparent after approximately one week without cleaning, while the UV sensor was able to maintain readings close to laboratory values for up to four weeks without cleaning.
- Use of pre-packaged test kits (e.g., Hach TNTplus) can help minimize user error, particularly in cases where operators or lab staff conduct tests infrequently.
- Immediate field filtration of calibration check samples is imperative. Delaying filtration even to transport samples to an on-site laboratory can significantly impact results and lead to improper matrix adjustments. Values measured on unfiltered samples tended to drift from filtered values after less than one hour, independent of sample temperature/refrigeration.

1.4 Task 4 – Interactive Screening Tool

Our approach is founded on the belief that stakeholders are looking for actionable guidance and information. Therefore, the project deliverable is a set of usable tools that is intended to be an easy entry point for operators, engineers, and utility directors at small, medium, and large WRRFs to understand the breadth and applicability of BNR control systems and associated online instruments to their utility. The tools are based on the project and utility partners' experience and expertise, a literature search, a broad utility survey, and field testing of several sensors. The tools are easily accessed for viewing and downloading from an interactive website called the *BNR Instrumentation & Controls Selection Adventure* accessible from a link on the

WRF website and hosted by Woodard & Curran. Figure 1-3 is an example screenshot from the *BNR Instrumentation & Controls Selection Adventure.*

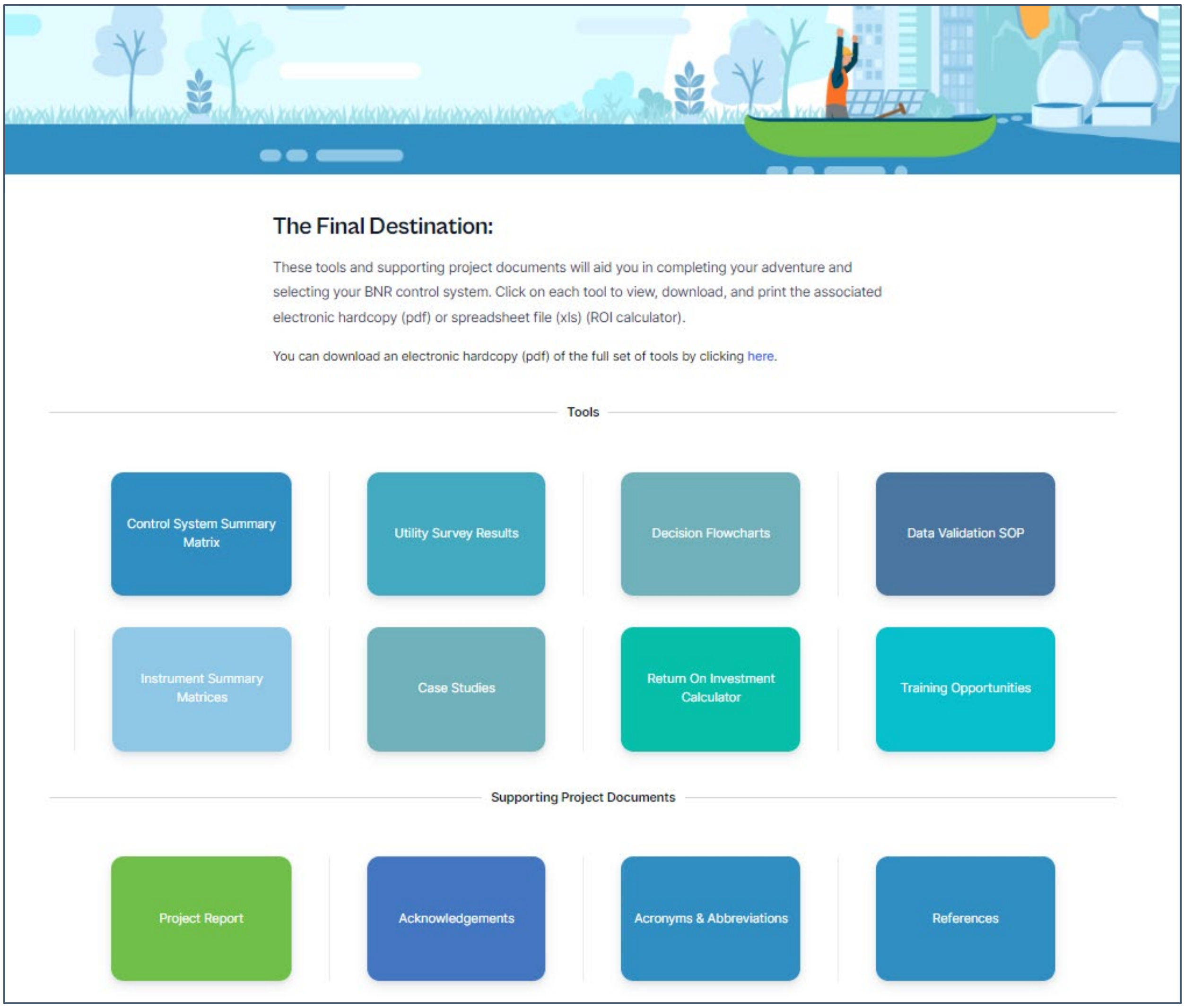

Figure 1-3. Example screenshot from the *BNR Instrumentation & Controls Selection Adventure* interactive website.

The *BNR Instrumentation & Controls Selection Adventure* contains an interactive screening tool to help the users narrow down the universe of possible BNR control systems/sensors to a customized short list of potential BNR controls that may be most applicable to them. Additionally, the *BNR Instrumentation & Controls Selection Adventure* contains a series of downloadable tools to assist users in analyzing the options.

The Interactive Screening Tool component is the entry-point into the application and is designed with a cascaded series of questions to help utilities/municipalities narrow down the universe of possible BNR control systems/sensors to a short list that may work best for them based on their treatment system, effluent limits, desired O&M complexity, and risk appetite.

Depending on the answer to each question, a short list of potential BNR control systems is customized to the user.

The user is then directed to the downloadable tools to aid in further analysis of the potentially-applicable BNR control system, including:

1. **Control system summary matrix:** Summary table that includes control system descriptions, outcomes & performance, potential configuration, related instrumentation and additional considerations. Control systems contained in the matrix include:
    a. Dissolved Oxygen (DO)
    b. Ammonia-Based Aeration Control (ABAC)
    c. Simultaneous Nitrification & Denitrification (SND)
    d. Ammonia versus Nitrate (AvN™)
    e. Timer-based Aeration Control
    f. Internal Mixed Liquor Recycle (IMLR) Pumping with a nitrate sensor
    g. RAS/WAS Pumping
    h. Aerobic Solids Retention Time (SRT)
    i. Supplemental Carbon Addition with a nitrate analyzer/sensor
    j. Supplemental Alkalinity Addition
    k. Metal Salts (Alum, Ferric, PAC, etc.) Addition with a phosphate analyzer
    l. Polymer Addition
    m. Load-based equalization
    n. Other (digital twin)
2. **Instrument summary matrices:** Series of summary tables organized by analyte that includes sensor/analyzer type, manufacturer, model, detection range, accuracy/precision, manufacturer-recommended O&M, associated accessories, reported interferences, and instrument costs. Analytes contained in the instrumentation matrices include:
    a. Ammonium
    b. COD/BOD
    c. Conductivity
    d. Dissolved oxygen
    e. Nitrate
    f. Nitrite
    g. ORP
    h. Orthophosphate
    i. pH & temperature
    j. Suspended solids
    k. Total phosphorus
    l. Turbidity
3. **Utility survey results:** Summary of results, including dashboard screenshots, of the utility survey.

4. **Case studies:** The case studies include an overview of the WRRF BNR process and describe the BNR control scheme, sensors used, performance, O&M experience, and O&M costs. They summarize key takeaways and lessons learned and include contact information of the WRRF representative. Refer to Table 1-1 for a list of the case studies included in the project.

5. **Decision flowcharts:** Tool containing a series of questions and criteria to communicate the scope of what is required for successful implementation of BNR controls & evaluate potential options, including those identified during the *Selection Adventure*. The tool is structured around three rounds of evaluation: 1) initial screening; 2) return on investment calculation; and 3) evaluation of critical success factors.

6. **Return on investment calculator:** Excel-based spreadsheet tool that can be used to aid in the quantification of the Return on Investment (ROI) of BNR controls and associated on-line instrumentation. The calculator has four main sections: 1) capital costs; 2) annual operating & maintenance (O&M) costs; 3) annual savings; and 4) ROI. The ROI is a simple payback calculation (in years) based on the cost and savings inputs.

7. **Data validation SOP:** Sample standard operating procedure that users can adapt for use at their WRRFs. The SOP contains guidance on sample collection, analysis, and results interpretation/visualization.

8. **Training opportunities:** Overview of process model simulator with customized BNR control logic scenarios, list of training opportunities, and trainer contact information.

These tools are in the format of downloadable hardcopy (.pdf) except for the Return on Investment Calculator, which is an Excel (.xlsx) file.

With the continuing rapid evolution of sensor and control systems, we recognize that the BNR controls and instrument summaries will become dated without on-going annual updates. While the technology will continue to evolve, the approach to evaluating control and sensor alternatives will remain largely unchanged. Therefore, another core component of this work is the decision flowchart tool, return on investment calculator, and data validation SOP. The decision flowcharts include key criteria to help utilities quantify the costs and benefits of process control systems and identify approaches to achieve sustained, reliable BNR performance.

Draft tools were reviewed by the WRF PAC, project utility partners, and Woodard & Curran operators, and their feedback were incorporated into the published tools.

1.5 Task 5 – LIFT Webcast

The LIFT webinar conveys the objectives of the research, provides a summary of the data collected and demonstrates the functionality of the *BNR Instrumentation & Controls Selection Adventure* App to WRF subscribers and invited parties. Additionally, the webcast introduces the associated interactive operations-focused training program, which is described in the following subsection.

1.6 Task 6 – Simulator Training Platform Development

The project team developed an interactive, operations-focused simulator platform that allows users to integrate and evaluate various BNR control logic scenarios. The platform consists of a WRRF process model developed in GPS-X™ software using industry-accepted activated sludge and ancillary models. This GPS-X™ model is then combined with an overlay software, SimuWorks™, that serves as an easy-to-use platform that allows professionals who may not be proficient with process modeling to use the previously-constructed WRRF process model simulator to investigate changes to inputs and control strategies.

The process model and SimuWorks™ overlay include the following control logic scenarios:

- DO control of airflows
- ABAC control of DO setpoints
- Orthophosphate control of metal salt addition

It includes five pre-loaded BNR control exercises that can be completed in a self-guided manner as well as numerous features that allow simulation of BNR sensor-based process control system concepts in different combinations. A screenshot of the simulator interface is shown in Figure 1-4.

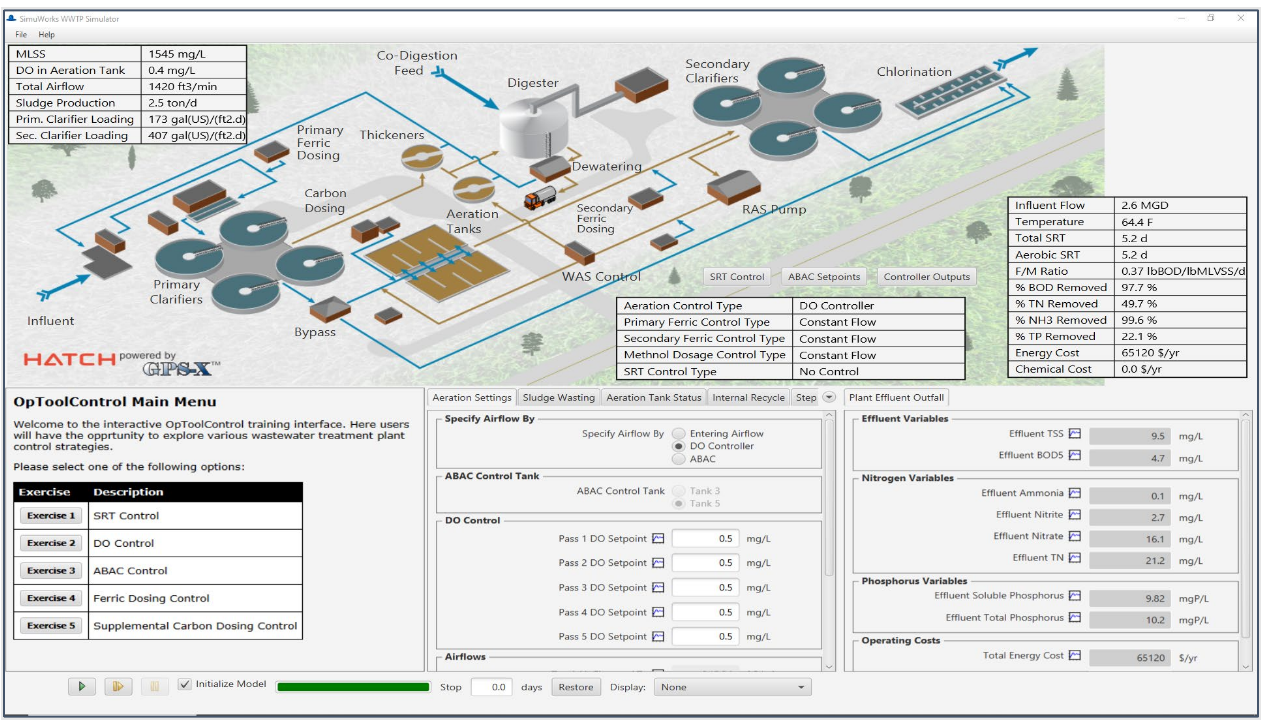

Figure 1-4. Example screenshot from Simulator used in interactive operations-focused training.
Source: Hatch 2023.

Training Opportunities

This training platform will be used in various training courses ranging from fundamental BNR training up to courses in advanced use and assessment of sensors and controls to optimize process performance. Training was included as part of the project LIFT webinar for WRF Subscribers and also will be offered at several conferences and through operator training organization such as:

- WEFTEC and WEF Specialty Conferences
- Regional WEF Member Association Conferences
- NEIWPCC
- State operator organizations

Software Access

The GPS-X™ and SimuWorks™ simulator training software is owned by Hydromantis who is a member of Hatch Ltd., and Hydromantis will retain ownership of the BNR Controls Simulator developed for this project. Hydromantis is a project partner, and Woodard & Curran holds licenses for use of the software and those licenses will remain in effect through the duration of this project for delivery of various training events. To the extent needed for training participants, temporary software licenses will be made available for registrants of the training courses for use during the classes.

For one year from the release of the project deliverables (through September 2025), Hydromantis will provide temporary licenses to any WRF subscriber for the SimuWorks™ BNR Controls Simulator for independent use. The SimuWorks™ software will be downloadable from a Hydromantis (Hatch Ltd.) website, and please contact Spencer Snowling via email at spencer.snowling@hatch.com to request the link.

Trainer Contact Information

If you would like to find out about upcoming trainings or create a customized training program for your organization, please contact the trainers:

Paul Dombrowski, PE, PLS, BCEE, F.WEF
Woodard & Curran
pdombrowski@woodardcurran.com

Spencer Snowling, PhD
Hatch
spencer.snowling@hatch.com

APPENDIX A

Summary of WRRF Information from Literature Review

Appendix A - Literature Review

	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	Permit Limits for the plant [find from EPA if not in original pub]				Scale (full/pilot)	MGD (annual average)	Sensor implemented				
					BOD	TSS	N	P			Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
1	Duck Creek Wastewater Treatment Plant	KAUFMAN, TX	trickling filter/solids contact and activated sludge						full	40	DO	Luminescent	HACH	15	2005
2	The Delaware County Regional Sewer District	DELAWARE COUNTY, Ohio	denitrification				10 mg/L	1.0 mg/L	full	6 (still expanding)	ORP, DO	ISE (ammonium, nitrate), Digital electrochemic al (DO)	YSI	5	2012
3	The Springfield Metro Sanitary District	SPRINGFIELD, ILLINOIS	nitrification, denitrification and biological phosphorus removal.						full	32	DO, pH and ORP	Digital electrochemic al (DO)	YSI		2012
4	The Littleton Englewood Wastewater Treatment Plant	LITTLETON ENGLEWOOD, COLORADO	nitrification and denitrification				15 mg/L	1 mg/L	full	25 (targeting up to 50)	DO, ammonium, and nitrate sensors	Nitrate (Optical UV), ammonium (ISE)	YSI		2009
5	The Missoula WWTP	MISSOULA, MONTANA	phosphorus removal		5 mg/L	5 mg/L	7.5 mg/L	1 mg/L	full	12	DO	Optical UV	YSI	20	

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		Sensor implemented									
	Plant Name	Where in the process is it installed (primary/secondary/etc. & start/middle/end)	What is the purpose - to drive controller, collect data, other	Cleaning process (& compare to manufacturer process)	Cleaning frequency	Maintenance/Calibration frequency	Maintenance/Calibration process (e.g., different monthly vs annually?)	Accuracy (compared to lab samples)	What is Accuracy based on? (n # samples, etc.)	What is lab method used for comparison (type, detection limit)	Reported interferences (type & level)
1	Duck Creek Wastewater Treatment Plant	12 in the activated sludge aeration basin and three in the older trickling filter/solids contact system.	to maintain optimum DO level, optimize the aeration process	periodically wipe the end of the sensor	periodically wipe the end of the sensor	The only replacement part, an inexpensive sensor cap, should be replaced once a year	(self-calibrating)	controller is designed to receive data from up to two sensors simultaneously	operators systematically check probe readings		
2	The Delaware County Regional Sewer District	Anoxic Zone with floating mixer; TriOxmatic (dissolved oxygen), VARiON (ammonium, nitrate), and SensoLyt (pH, ORP) sensors in background	new permit for TIN and growing population								
3	The Springfield Metro Sanitary District	various process stages for nitrification, denitrification and biological phosphorus removal	more stringent treatment requirements	Most of the sensors are self-cleaning, so very little maintenance is necessary							
4	The Littleton Englewood Wastewater Treatment Plant	aeration basin	discharge limits for ammonia and total inorganic nitrogen (TIN)								
5	The Missoula WWTP	each end of each aeration basin	DO monitoring to makes Aeration Control Optimization Possible			1 hour per week					

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		Sensor implemented		Controls							Results/Improvements	
	Plant Name	Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
1	Duck Creek Wastewater Treatment Plant										save energy (reduction in blower usage)	
2	The Delaware County Regional Sewer District										TIN within Ohio EPA compliance per the new guidelines	
3	The Springfield Metro Sanitary District			SCADA						a $54.4 million upgrade (sensor monitoring and SCADA)		
4	The Littleton Englewood Wastewater Treatment Plant			SCADA								
5	The Missoula WWTP										energy efficiency has improved with substantial cost savings	

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	Plant Name	Operational Considerations						Reference	Contact
		Who is responsible for sensors? (Lab tech, sensor plan, other)	Any special skills required?	O&M budget (for this sensor if possible)	what does O&M budget cover? (# sensors?)	Cost savings? E.g., via automation, decreased lab analyses, etc.	Notes on other issues (complexity, reliability)		
1	Duck Creek Wastewater Treatment Plant	plant operators	(operators still prefer having "hands on" control to adjust blowers)					Dabkowski 2020	Bob Dabkowski (Hach Wastewater Specialist)
2	The Delaware County Regional Sewer District							1. Xylem n.d. 2. HDR 2017	Mark Chandler, operations superintendent for Delaware County
3	The Springfield Metro Sanitary District							Xylem n.d.	Brian Tucker, The Springfield Metro Sanitary District operations supervisor
4	The Littleton Englewood Wastewater Treatment Plant							1. Xylem n.d. 2. City of Englewood 2017	John Kuosman, Littleton Englewood WWTP Director
5	The Missoula WWTP							Xylem n.d.	Gene Connell, Missoula WWTP treatment supervisor

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					Permit Limits for the plant [find from EPA if not in original pub]						Sensor implemented				
	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	BOD	TSS	N	P	Scale (full/pilot)	MGD (annual average)	Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
6	Douglas L. Smith Middle Basin advanced wastewater treatment facility	Johnson County, KS	secondary clarifier				8 mg/L	1.5 mg/L	full	14.5	TSS	Optical UV	YSI		
7	Northeast Ohio Regional Sewer District	NORTHEAST, OHIO	nitrification						full	2	pH, TSS, DO	Optical UV	YSI	7	
8	Environmental Services Department (ESD) Wastewater Treatment Operations Devision (WTO)	LONDON, ONTARIO							pilot	10	DO, TSS, pH, ammonia	Optical UV	YSI		
9	Chinook Wastewater Treatment Plant	Chinook, MT	nitrification				7.46 mg/L	1.37 mg/l	full	0.5	ORP, LDO				2013

Appendix A - Literature Review

	Plant Name	Sensor implemented									
		Where in the process is it installed (primary/secondary/etc. & start/middle/end)	What is the purpose - to drive controller, collect data, other	Cleaning process (& compare to manufacturer process)	Cleaning frequency	Maintenance/Calibration frequency	Maintenance/Calibration process (e.g., different monthly vs annually?)	Accuracy (compared to lab samples)	What is Accuracy based on? (n # samples, etc.)	What is lab method used for comparison (type, detection limit)	Reported interferences (type & level)
6	Douglas L. Smith Middle Basin advanced wastewater treatment facility	in an aeration basin, and at the oxic end of each of the four treatment trains			Sensors are removed from the process and manually cleaned every 6 months	Sensors are removed from the process and manually cleaned every 6 months.		Accuracy was verified with gravimetric analysis of grab samples collected near the sensors			
7	Northeast Ohio Regional Sewer District		continuous process monitoring and control.			maintenance requires not more than 15 minutes of operator attention per week					
8	Environmental Services Department (ESD) Wastewater Treatment Operations Devision (WTO)										
9	Chinook Wastewater Treatment Plant	aeration	maintaining the DO at the desired levels.								

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	Plant Name	Sensor implemented		Controls							Results/Improvements	
		Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
6	Douglas L. Smith Middle Basin advanced wastewater treatment facility			SCADA								
7	Northeast Ohio Regional Sewer District			PLC							Over 98% of TSS and CBOD5 are removed on average and monthly average effluent ammonia-nitrogen did not exceed 0.3 mg/L during the most recent three-year period.	
8	Environmental Services Department (ESD) Wastewater Treatment Operations Devision (WTO)			SCADA							early stages of a $54.4 million upgrade, complete with an IQ SensorNet monitoring and control system, tied into SCADA	
9	Chinook Wastewater Treatment Plant			SCADA						~ $68,200 for ORP probe and integration with SCADA, $8,000 for LDO	Energy savings more than offset $1,000/yr in maintenance	total-N dropped from 26 to 15 mg/L, total-P reduced from 2.8 mg/L to 0.3 mg/L

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	Plant Name	Operational Considerations						Reference	Contact
		Who is responsible for sensors? (Lab tech, sensor plan, other)	Any special skills required?	O&M budget (for this sensor if possible)	what does O&M budget cover? (# sensors?)	Cost savings? E.g., via automation, decreased lab analyses, etc.	Notes on other issues (complexity, reliability)		
6	Douglas L. Smith Middle Basin advanced wastewater treatment facility							1. Xylem n.d. 2. Gabel et. al. 2011	Doug Nolkemper, P.E. and Susan Pekarek, P.E., Johnson County Wastewater engineer
7	Northeast Ohio Regional Sewer District							Xylem n.d.	
8	Environmental Services Department (ESD) Wastewater Treatment Operations Devision (WTO)							Xylem n.d.	Mark Spitzig, Wastewater Treatment Operations/Maintenance manager for the City of London.
9	Chinook Wastewater Treatment Plant							Clean Water Ops 2016	Eric Miller, Chief Operator mt_dude@hotmail.com (406) 357-3160

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	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	Permit Limits for the plant [find from EPA if not in original pub]				Scale (full/pilot)	MGD (annual average)	Sensor implemented				
					BOD	TSS	N	P			Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
10	Town of Crewe Wastewater Treatment Plant	Crewe, VA					6.0 mg/L	0.5 mg/L	full	0.5	DO				2007
11	Wildcat Hill WWTP	Flagstaff, AZ	Modified Ludzack-Ettinger (MLE) configuration				10.0 mg/L	-	full	6	combined ammonia/nitrate probe	ISE			2013
12	Roth Lane Wastewater Treatment Plant	Hampden Twp., PA	nitrification				6.6 mg/L	0.81 mg/L	full	5.69	DO, nitrate				2010
13	City of Layton (FL) Wastewater Treatment Plant	Layton, FL	nitrification and denitrification				10 mg/L	1.0 mg/L	full	0.066	DO, ORP, TSS				2009
14	Montrose Wastewater Treatment Plant	Montrose, CO	nitrification				-	-	full	4.32	DO, ORP, TSS				2011

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		Sensor implemented									
	Plant Name	Where in the process is it installed (primary/secondary/etc. & start/middle/end)	What is the purpose - to drive controller, collect data, other	Cleaning process (& compare to manufacturer process)	Cleaning frequency	Maintenance/Calibration frequency	Maintenance/Calibration on process (e.g., different monthly vs annually?)	Accuracy (compared to lab samples)	What is Accuracy based on? (n # samples, etc.)	What is lab method used for comparison (type, detection limit)	Reported interferences (type & level)
10	Town of Crewe Wastewater Treatment Plant	in the third channel of oxidation ditch	reduce effluent TN by making operational changes and adding process controls								
11	Wildcat Hill WWTP	at the end of the anoxic zone	Improved process controls			Sensor cartridge replacement approximately $1,000 every 6 months. Probe cleaning and calibration weekly					
12	Roth Lane Wastewater Treatment Plant		reduce the effluent TN concentration and improve effluent consistency							laboratory mixed liquor suspended solids (MLSS) analysis	
13	City of Layton (FL) Wastewater Treatment Plant	SBR	meet permit on TN and TP effluent								
14	Montrose Wastewater Treatment Plant		to cut energy costs								

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		Sensor implemented		Controls							Results/Improvements	
	Plant Name	Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
10	Town of Crewe Wastewater Treatment Plant									~ $6000 for DO control system.		
11	Wildcat Hill WWTP		~ $10,000 for ammonia/nitrate probe and installation									
12	Roth Lane Wastewater Treatment Plant			PLC, PID								
13	City of Layton (FL) Wastewater Treatment Plant		~ $53,000 for new probes									
14	Montrose Wastewater Treatment Plant										TSS dropped by 36 percent while the ammonia dropped by almost 68 percent.	

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	Plant Name	Operational Considerations						Reference	Contact
		Who is responsible for sensors? (Lab tech, sensor plan, other)	Any special skills required?	O&M budget (for this sensor if possible)	what does O&M budget cover? (# sensors?)	Cost savings? E.g., via automation, decreased lab analyses, etc.	Notes on other issues (complexity, reliability)		
10	Town of Crewe Wastewater Treatment Plant							Connor 2015	John Hricko, plant manager hricko@hovac.com (434)-645-9436
11	Wildcat Hill WWTP							Connor 2015	Larry Lemke, plant staff llemke@flagstaffaz.gov (928) 526-2520
12	Roth Lane Wastewater Treatment Plant							Connor 2015	Diane Fox, Superintendent. Jeffrey Klahre, Operations Supervisor DFox@hampdentownship.us; JKlahre@hampdentownship.us. (717) 761-7963
13	City of Layton (FL) Wastewater Treatment Plant							Connor 2015	Tom Pfiester tpfiester@fkaa.com (305) 481-2015
14	Montrose Wastewater Treatment Plant							Connor 2015	Allen Coriell, Superintendent acoriell@ci.montrose.co.us (970) 240-1452

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	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	Permit Limits for the plant [find from EPA if not in original pub]				Scale (full/pilot)	MGD (annual average)	Sensor implemented				
					BOD	TSS	N	P			Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
15	Howard F. Curren Advanced Wastewater Treatment Plant	Tampa, FL	BOD removal, nitrification and denitrification				3.0 mg/L	-	full	96	DO				2013
16	City of Titusville Blue Heron Water Reclamation Facility (WRF) and Wetland	Titusville, FL	denitrification		5 mg/L	5 mg/L	3 mg/L	1 mg/L	full	6.75					2013
17	Victor Valley Wastewater Reclamation Authority (WRA)	Victor Valley, CA	nitrification and denitrification				10.3 mg/L	-	full	13.8	DO, ORP				2008
18	Wolfeboro Wastewater Treatment Facility	Wolfeboro, NH	nitrification				10 mg/L	-	full	0.6	DO, ORP				2008
19	Bozeman WRF	BOZEMAN, MONTANA	Phased nitrification and denitrification				16.2 mg/l	5.2 mg/l	full	5.8	ORP			1	2008
20	Big Sky Water & Sewer District	BIG SKY, MONTANA	nitrification and denitrification						full	0.75	ORP				

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		Sensor implemented									
	Plant Name	Where in the process is it installed (primary/secondary/etc. & start/middle/end)	What is the purpose - to drive controller, collect data, other	Cleaning process (& compare to manufacturer process)	Cleaning frequency	Maintenance/Calibration frequency	Maintenance/Calibration process (e.g., different monthly vs annually?)	Accuracy (compared to lab samples)	What is Accuracy based on? (n # samples, etc.)	What is lab method used for comparison (type, detection limit)	Reported interferences (type & level)
15	Howard F. Curren Advanced Wastewater Treatment Plant		less aerobic volume to complete nitrification								
16	City of Titusville Blue Heron Water Reclamation Facility (WRF) and Wetland		further reduces nutrients								
17	Victor Valley Wastewater Reclamation Authority (WRA)		to optimize process for simultaneous nitrification and denitrification								
18	Wolfeboro Wastewater Treatment Facility		maintain an adequate dissolved oxygen (DO) concentration								
19	Bozeman WRF	aeration basin	compliance with new nutrient limits imposed by the Montana Department of Environmental Quality								
20	Big Sky Water & Sewer District		process control for total-nitrogen								

Appendix A - Literature Review

		Sensor implemented		Controls							Results/Improvements	
	Plant Name	Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
15	Howard F. Curren Advanced Wastewater Treatment Plant										NO3-N lowered from 17 mg/L to 13 mg/L	
16	City of Titusville Blue Heron Water Reclamation Facility (WRF) and Wetland											
17	Victor Valley Wastewater Reclamation Authority (WRA)			SCADA								
18	Wolfeboro Wastewater Treatment Facility			PLC, SCADA						$18,000		
19	Bozeman WRF			SCADA						< $180,000	TN dropped from 18.4 mg.L to 13.3 mg/L	
20	Big Sky Water & Sewer District									$10,000	TN dropped from 25 mg/L to 5 mg/L	

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		Operational Considerations							
	Plant Name	Who is responsible for sensors? (Lab tech, sensor plan, other)	Any special skills required?	O&M budget (for this sensor if possible)	what does O&M budget cover? (# sensors?)	Cost savings? E.g., via automation, decreased lab analyses, etc.	Notes on other issues (complexity, reliability)	Reference	Contact
15	Howard F. Curren Advanced Wastewater Treatment Plant							Connor 2015	Rory Jones, Wastewater Design Rory.Jones@ci.tampa.fl.us (813) 274-7045
16	City of Titusville Blue Heron Water Reclamation Facility (WRF) and Wetland							Connor 2015	Matt Hixson matt.hixson@Titusville.com (321) 567-3891
17	Victor Valley Wastewater Reclamation Authority (WRA)							Connor 2015	Logan Olds, General Manager lolds@vvwra.com (760) 246-8638
18	Wolfeboro Wastewater Treatment Facility							Connor 2015	Russ Howe, Plant Manager rhowe@woodardcurran.com (603) 569-3185
19	Bozeman WRF							Connor 2015	Herb Bartle, Superintendent hbartle@bozeman.net (406) 582-2928
20	Big Sky Water & Sewer District							Clean Water Ops 2018	Grant Burroughs, Superintendent grantburroughs@gmail.com 406.995.2660

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	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	Permit Limits for the plant [find from EPA if not in original pub]				Scale (full/pilot)	MGD (annual average)	Sensor implemented				
					BOD	TSS	N	P			Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
21	Columbia Falls WWTP	Columbia Falls, MONTATNA	biological phosphorus removal and enhance biological nitrogen removal					1.0 mg/L	full	0.55	DO, ORP				
22	Helena WWTP	Helena, MONTANA	EBPR				5 mg/L	2 mg/L	full	5.4	ORP				
23	City of East Helena Wastewater Treatment Plant	East Helena, MT	ammonia removal		30 mg/L	30 mg/L	1.2 mg/L	0.1 mg/L	full	0.44	ORP				
24	Empire Utility Agency Regional Water Recycling Plant	Ontario, California	Nitrification						pilot	44	DO, TSS, UV nitrate, ammonia				
25	Sawgrass WWTP	Sunrise, Florida	Nitrification						full	8	DO, ammonium				
26	Central WWTP	Nashville, Tennessee	Nitrification				10 mg/L	1 mg/L	full	6	DO, ammonium				

Appendix A - Literature Review

		Sensor implemented									
	Plant Name	**Where in the process is it installed (primary/secondary/etc. & start/middle/end)**	**What is the purpose - to drive controller, collect data, other**	**Cleaning process (& compare to manufacturer process)**	**Cleaning frequency**	**Maintenance/Calibration frequency**	**Maintenance/Calibration process (e.g., different monthly vs annually?)**	**Accuracy (compared to lab samples)**	**What is Accuracy based on? (n # samples, etc.)**	**What is lab method used for comparison (type, detection limit)**	**Reported interferences (type & level)**
21	Columbia Falls WWTP		support biological phosphorus removal without chemicals								
22	Helena WWTP		To increase organic loading on the plant bioreactors' anoxic zones for nitrate removal								
23	City of East Helena Wastewater Treatment Plant										
24	Empire Utility Agency Regional Water Recycling Plant										
25	Sawgrass WWTP										
26	Central WWTP						$1,900 annual maintenance				

Appendix A - Literature Review

		Sensor implemented		Controls							Results/Improvements	
	Plant Name	Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
21	Columbia Falls WWTP										0.5 mg/L TP in effluent without chemicals while discharging 5-6 mg/L total nitrogen	
22	Helena WWTP		$5,000 for ORP									
23	City of East Helena Wastewater Treatment Plant										reduced total-N by 50%, 20 to 10 mg/L.	
24	Empire Utility Agency Regional Water Recycling Plant			SCADA								
25	Sawgrass WWTP			ABAC								
26	Central WWTP		$47,800 for total sensors	ABAC							20-30% aeration energy savings compare to DO setpoint control	

Appendix A - Literature Review

	Plant Name	Operational Considerations						Reference	Contact
		Who is responsible for sensors? (Lab tech, sensor plan, other)	Any special skills required?	O&M budget (for this sensor if possible)	what does O&M budget cover? (# sensors?)	Cost savings? E.g., via automation, decreased lab analyses, etc.	Notes on other issues (complexity, reliability)		
21	Columbia Falls WWTP							Clean Water Ops 2018	Gene Woods Chief Operator cfwwtp@cityofcolumbiafalls.com (406) 892-4430
22	Helena WWTP							1. Clean Water Ops 2018 2. Clean Water Ops 2016	Mark Fitzwater Chief Operator mfitzwater@helenamt.gov (406) 457-8558
23	City of East Helena Wastewater Treatment Plant							1. Clean Water Ops 2018 2. Clean Water Ops 2016	Steve Leitzke Chief Operator sleitzke@easthelenamt.us (406) 227-5321
24	Empire Utility Agency Regional Water Recycling Plant							Medinilla et al. 2020	Travis Sprague tsprague@ieua.org
25	Sawgrass WWTP							Miller et al. 2019	
26	Central WWTP							Miller et al. 2019	

Appendix A - Literature Review

					Permit Limits for the plant [find from EPA if not in original pub]						Sensor implemented				
	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	BOD	TSS	N	P	Scale (full/pilot)	MGD (annual average)	Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
27	Nansemond Treatment Plant	Virginia Beach, VA	5-Stage BNR + struvite recovery				8 mg/L	1 mg/L	full	30	(2) Orthophosphate analyzers (2) Ammonium analyzers (1) Combination nitrate, nitrite, TSS probe (1) Ammonium ISE probe (3) Ammonium ISE probe (21) DO probes (5) Blanket indicator	2013		33	
28	H.L. Mooney Advanced Water Reclamation Facility	Woodbridge, VA	2-step (MLE or 4-stage) + denitrification filters				3 mg/L	0.18 mg/L	full	24	(1) Nitrate optical probe (2) Nitrate, nitrite, ammonium analyzers (30) DO probes			31	
29	Broad Run Water Reclamation Facility	Ashburn, VA	5-stage BNR + MBR				4 mg/L	0.1 mg/L	full	11	(9) DO probes (3) Oxidation–reduction potential probe (4) pH probe (1) Blanket indicator			16	
30	The Eagles Point publicly owned treatment works (POTW)	Cottage Grove, Minnesota	EBPR					1 mg/L	full	10	DO				

Appendix A - Literature Review

		Sensor implemented									
	Plant Name	Where in the process is it installed (primary/secondary/etc. & start/middle/end)	What is the purpose - to drive controller, collect data, other	Cleaning process (& compare to manufacturer process)	Cleaning frequency	Maintenance/Calibration frequency	Maintenance/Calibration process (e.g., different monthly vs annually?)	Accuracy (compared to lab samples)	What is Accuracy based on? (n # samples, etc.)	What is lab method used for comparison (type, detection limit)	Reported interferences (type & level)
27	Nansemond Treatment Plant		for process monitoring and control			once to three times per week	routine efforts for all sensors takes approximately 26 hours per week				
28	H.L. Mooney Advanced Water Reclamation Facility		to control blower operations and air supply control valves			routine efforts for all sensors takes approximately 15 to 18 hours per week				Grab samples are collected 5 days per week	
29	Broad Run Water Reclamation Facility		for controlling aeration at various points	Daily cleaning and validation of the DO probes is performed by operations staff		routine efforts for all sensors takes approximately 2 to 4 hours per week	s full-time I&C personnel available for intensive maintenance and calibration of sensors				
30	The Eagles Point publicly owned treatment works (POTW)										

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	Plant Name	Sensor implemented		Controls							Results/Improvements	
		Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
27	Nansemond Treatment Plant											
28	H.L. Mooney Advanced Water Reclamation Facility											
29	Broad Run Water Reclamation Facility											
30	The Eagles Point publicly owned treatment works (POTW)										effluent TP concentration reached an historical low of 0.3 mg/L	

Appendix A - Literature Review

		Operational Considerations							
	Plant Name	**Who is responsible for sensors? (Lab tech, sensor plan, other)**	**Any special skills required?**	**O&M budget (for this sensor if possible)**	**what does O&M budget cover? (# sensors?)**	**Cost savings? E.g., via automation, decreased lab analyses, etc.**	**Notes on other issues (complexity, reliability)**	**Reference**	**Contact**
27	Nansemond Treatment Plant							Yi et al. 2014	Maureen O’Shaughnessy, process engineer
28	H.L. Mooney Advanced Water Reclamation Facility							Yi et al. 2014	
29	Broad Run Water Reclamation Facility							Yi et al. 2014	Michael Rumke, superintendent
30	The Eagles Point publicly owned treatment works (POTW)							EPA 2021	Tim O'Donnell tim.odonnell@metc.state.mn.us 651-602-1269

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	Plant Name	Location	Type of process	Any unusual (e.g., industrial waste, plant additions) components of influent WW	Permit Limits for the plant [find from EPA if not in original pub]				Scale (full/pilot)	MGD (annual average)	Sensor implemented				
					BOD	TSS	N	P			Sensor target parameter	Sensor type (ISE, colorimetric, etc.)	Sensor manufacturer	# of this sensor installed?	Age of sensor (year of installation)
31	Empire Wastewater Treatment Plant	Farmington, Minnesota	EBPR		25 mg/L	45 mg/L	3 mg/L	1 mg/L	full	24	DO				

Appendix A - Literature Review

	Plant Name	Sensor implemented									
		Where in the process is it installed (primary/secondary/etc. & start/middle/end)	What is the purpose - to drive controller, collect data, other	Cleaning process (& compare to manufacturer process)	Cleaning frequency	Maintenance/Calibration frequency	Maintenance/Calibration process (e.g., different monthly vs annually?)	Accuracy (compared to lab samples)	What is Accuracy based on? (n # samples, etc.)	What is lab method used for comparison (type, detection limit)	Reported interferences (type & level)
31	Empire Wastewater Treatment Plant	in the aeration basins	Process control								

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		Sensor implemented		Controls							Results/Improvements	
	Plant Name	Any influence of mixing/aeration (consideration for location of installation of sensor)	Capital Cost	Type of Controller	Maintenance/ update frequency	Set point (concentration)	Accuracy (bias from set point)	Target precision	Actual precision (variability from set point - e.g., 90% CI)	Capital Cost	Metric (e.g., energy, effluent concentration, ...)	Improvement (% and absolute change)
31	Empire Wastewater Treatment Plant										cut its average effluent TP concentration in half, from 0.4 mg to 0.2 mg/L.	

Appendix A - Literature Review

		Operational Considerations							
	Plant Name	Who is responsible for sensors? (Lab tech, sensor plan, other)	Any special skills required?	O&M budget (for this sensor if possible)	what does O&M budget cover? (# sensors?)	Cost savings? E.g., via automation, decreased lab analyses, etc.	Notes on other issues (complexity, reliability)	Reference	Contact
31	Empire Wastewater Treatment Plant							EPA 2021	Heidi Hutter, Principal Engineer Heidi.Hutter@metc.state.mn.us 612-602-1026

APPENDIX B

Utility Survey

Utility Survey

Water Research Foundation – Project 5087:
Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy

Survey Introduction

Welcome! The Water Research Foundation (WRF) Project 5087 titled *Implementation of Innovative Biological Nutrient Removal (BNR) Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy* is underway, and we invite you to take part in this utility survey. Feedback about your experiences with BNR control systems and online sensors is critical. Your responses will be compiled with those from other WRRFs and will be used to synthesize the current state of the art and develop a framework for the practical and cost-effective implementation of BNR control systems with sensor technologies.

This survey is administered through Survey Monkey, and responses will be shared directly with the WRF project team. If you have multiple WRRFs in your system, please submit a separate completed survey for each applicable WRRF. Please don't forget to hit "Submit" at the end of the survey once you are finished. Once you hit "Submit," the survey will be closed, and if you have any information that you'd like to change, please contact us at *jfortin@woodardcurran.com*.

Don't hesitate to reach out to any of the Co-PIs on the project with questions. Please refer to the introductory email for additional guidance and contact information.

Thank you!

Utility Survey

Water Research Foundation – Project 5087:
Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy

Contact Information

Please provide contact information for your Water Resource Recovery Facility (WRRF). If your utility has multiple facilities, please complete a separate survey for each facility.

1. Contact Information for Person Completing the Survey:

   *Name:

   *Position:

   *Email address:

   *Phone number:

2. Contact Information for Utility Director (*if different from Question 1 above*):

   Name:

   Position:

   Email address:

   Phone number:

3. Water Resource Recovery Facility (WRRF) Name and Address:

   *Name:

   Address:

   City/Town:

   State/Province:

   ZIP/Postal Code:

   Country (if other than United States):

**required response*

Utility Survey

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Facility Overview

Please answer the following questions based on your Water Resource Recovery Facility (WRRF). *If you have seasonal/multiple limits, please indicate the most stringent limit.*

4. WRRF design capacity:
   a. <1 MGD
   b. 1 to <5 MGD
   c. 5 to <10 MGD
   d. 10 to <20 MGD
   e. ≥ 20 MGD
   f. Other (please specify):

5. Discharge permit limit for ammonia (NH_3):
   a. No permit limit
   b. ≤1 mg/L
   c. >1 to 5 mg/L
   d. >5 to 10 mg/L
   e. > 10 mg/L
   f. Load based limit (please specify allowable load and equivalent concentration at permitted flow):

6. Discharge permit limit for total nitrogen (TN):
   a. No permit limit
   b. <3 mg/L
   c. >3 to 5 mg/L
   d. >5 to 10 mg/L
   e. > 10 mg/L
   f. Load based limit (please specify allowable load and equivalent concentration at permitted flow):

7. Discharge permit limit for total phosphorus (TP):
   a. No permit limit
   b. <0.1 mg/L
   c. 0.1 to <0.2 mg/L
   d. 0.2 to <0.5 mg/L
   e. 0.5 to 1 mg/L
   f. > 1 mg/L
   g. Load based limit (please specify allowable load and equivalent concentration at permitted flow):

8. Please provide any additional comments on your WRRFs flows and permit limits:

Utility Survey

Water Research Foundation – Project 5087:
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BNR Process & Controls

Please answer the following questions based on the biological process(es) and related controls systems at your Water Resource Recovery Facility (WRRF).

9. Indicate the biological process(es) present at your WRRF (check all that are applicable):

    a. Conventional activated sludge (e.g. complete mix, plug flow, MLE, A2O, Step Feed, 4- or 5-Stage Bardenpho)
    b. Membrane bioreactor (e.g. complete mix, plug flow, MLE, A2O, Step Feed, 4- or 5-Stage Bardenpho)
    c. Aerobic granular sludge
    d. Sequencing batch reactor
    e. High purity oxygen system
    f. Fixed-film process
    g. Other (please describe):

10. Describe the configuration(s) of the biological process(es) at your WRRF and provide any additional clarifying comments:

11. Indicate the Control System(s) associated with your biological process(es) (check all that are applicable):

    a. Dissolved Oxygen
    b. Ammonia-Based Aeration Control (ABAC)
    c. Simultaneous Nitrification & Denitrification (SND)
    d. Ammonia versus Nitrate (AVN)
    e. Timer-based Aeration Control
    f. Internal Mixed Liquor Recycle (IMLR) Pumping
    g. RAS/WAS Pumping
    h. SRT
    i. Supplemental Carbon Addition
    j. Supplemental Alkalinity Addition
    k. Metal Salts (Alum, Ferric, PAC, and etc.) Addition
    l. Polymer Addition
    m. Other (please describe):

12. Please provide any additional descriptions or clarifying comments, including the year your control system(s) was installed and/or phasing of any major upgrades:

Utility Survey

Water Research Foundation – Project 5087:
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13. Indicate the online sensors (in situ) and analyzers (wet chemistry) that are associated with your biological process(es). For each type, note which are used for monitoring only and which are used for monitoring & control (select all that apply):

	Monitoring **(e.g. trending, operator manual adjustments)**	**Control** **(e.g. blower speeds, IMLR pump speeds, chemical feed pumps)**
Dissolved Oxygen sensor		
pH sensor		
Ammonium sensor		
Ammonium analyzer		
Nitrate sensor		
Nitrate analyzer		
Nitrite sensor		
Nitrite analyzer		
Phosphate analyzer		
COD/BOD sensor		
COD/BOD analyzer		
Suspended solids sensor		
Turbidity sensor		
ORP sensor		
Conductivity sensor		
Temperature sensor		
Other (please describe)		

14. Please provide any additional description and clarifying comments:

Utility Survey

Water Research Foundation – Project 5087:
Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy

Sensors & Analyzers

The following questions ask details about the performance and maintenance for the online sensors & analyzers used in your biological process(es) for monitoring and control.

15. Note the quantity and describe location of the online sensors and analyzers:

Sensor	Monitoring Only (e.g. trending, operator manual adjustments to blower speed)		Monitoring & Control (e.g. blower speeds, IMLR pump speeds, chemical feed pumps, adjusting valve positions)	
	Number	Location	Number	Location
Dissolved Oxygen sensor				
pH sensor				
Ammonium sensor				
Ammonium analyzer				
Nitrate sensor				
Nitrate analyzer				
Nitrite sensor				
Nitrite analyzer				
Phosphate analyzer				
COD/BOD sensor				
COD/BOD analyzer				
Suspended solids sensor				
Turbidity sensor				
ORP sensor				
Conductivity sensor				
Temperature sensor				
Other (please describe)				

16. Please provide any additional description and clarifying comments *(e.g. auxiliary cleaning system):*

Utility Survey

Water Research Foundation – Project 5087:
Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy

17. In general, how do the online sensor(s) and analyzer(s) perform? (Check all that apply):

	Meets qualitative accuracy needs (e.g. detecting trends)	**Meets quantitative accuracy needs**	**Reliable for use in controller**	**Signal drift is minimal**	**Signal interference/bias due to process water is minimal**	**Other – please describe**
Dissolved Oxygen sensor						
pH sensor						
Ammonium sensor						
Ammonium analyzer						
Nitrate sensor						
Nitrate analyzer						
Nitrite sensor						
Nitrite analyzer						
Phosphate analyzer						
COD/BOD sensor						
COD/BOD analyzer						
Suspended solids sensor						
Turbidity sensor						
ORP sensor						
Conductivity sensor						
Temperature sensor						
Other (please describe)						

18. Please provide any additional description and clarifying comments:

19. Describe the typical calibration associated with the sensor(s) and analyzer(s)? Select responses for the sensors present in your system.

	Calibration frequency *(1/year - Quarterly - 1/month - 2/month - 1/week - >1/week)*	**Ease of Calibration** *(Very Easy – Easy – Hard - Very Hard)*	**Acceptability of Calibration Requirements** *(Minimal – Acceptable – Significant – Burdensome)*
Dissolved Oxygen sensor			
pH sensor			
Ammonium sensor			
Ammonium analyzer			
Nitrate sensor			
Nitrate analyzer			
Nitrite sensor			
Nitrite analyzer			
Phosphate analyzer			
COD/BOD sensor			
COD/BOD analyzer			
Suspended solids sensor			
Turbidity sensor			
ORP sensor			
Conductivity sensor			
Temperature sensor			
Other (please describe)			

20. Please provide any additional comments related to calibration.

21. Describe the typical manual cleaning associated with the sensor(s) and analyzer(s)?

	Cleaning frequency *(1/year - Quarterly - 1/month - 2/month - 1/week - >1/week)*	**Ease of Cleaning** *(Very Easy – Easy – Hard - Very Hard)*	**Acceptability of Cleaning Requirements** *(Minimal – Acceptable – Significant – Burdensome)*
Dissolved Oxygen sensor			
pH sensor			
Ammonium sensor			
Ammonium analyzer			
Nitrate sensor			
NItrate analyzer			
Nitrite sensor			
Nitrite analyzer			
Phosphate analyzer			
COD/BOD sensor			
COD/BOD analyzer			
Suspended solids sensor			
Turbidity sensor			
ORP sensor			
Conductivity sensor			
Temperature sensor			
Other (please describe)			

22. Please provide any additional comments related cleaning.

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23. Describe the typical maintenance associated with the sensor(s) and analyzer(s)?

	Preventive Maintenance Frequency *(1/year - Quarterly - 1/month - 2/month - 1/week - >1/week)*	**Ease of Maintenance (e.g., accessibility, complexity, special tools, specialized personnel)** *(Very Easy – Easy – Hard - Very Hard)*	**Acceptability of Maintenance** *(Minimal – Acceptable – Significant – Burdensome)*
Dissolved Oxygen sensor			
pH sensor			
Ammonium sensor			
Ammonium analyzer			
Nitrate sensor			
Nitrate analyzer			
Nitrite sensor			
Nitrite analyzer			
Phosphate analyzer			
COD/BOD sensor			
COD/BOD analyzer			
Suspended solids sensor			
Turbidity sensor			
ORP sensor			
Conductivity sensor			
Temperature sensor			
Other (please describe)			

24. Please provide any additional comments related to the maintenance.

Utility Survey

Water Research Foundation – Project 5087:
Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy

25. In general, how much cost and additional support is associated with the sensor(s) and analyzers?

	O&M Costs *(Minimal – Acceptable – Significant – Burdensome)*	**Need for Training** *(Minimal – Acceptable – Significant – Burdensome)*	**Use of Third-Party Service Contract (e.g., annual contract with manufacturer)** *(Yes or No)*
Dissolved Oxygen sensor			
pH sensor			
Ammonium sensor			
Ammonium analyzer			
Nitrate sensor			
Nitrate analyzer			
Nitrite sensor			
Nitrite analyzer			
Phosphate analyzer			
COD/BOD sensor			
COD/BOD analyzer			
Suspended solids sensor			
Turbidity sensor			
ORP sensor			
Conductivity sensor			
Temperature sensor			
Other (please describe)			

26. Please provide any additional comments related to cost and additional support.

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Outcomes

The following questions speak to the benefits, and challenges of your BNR controls and sensors/analyzer systems. Please respond for each control system at your WRRF. Also, we'd like your perspective on how you would improve your system(s) and what you would recommend to others implementing new BNR Control systems with sensors/analyzers.

27. What **process improvements** are associated with the control system(s)? Check all that apply:
    a. Improved nutrient removal
    b. Improved settleability and MLSS characteristics
    c. Improved operations - More control
    d. Improved operations - More monitoring
    e. Improved reliability and less variability

    Comments and additional description:

28. What other **benefits** are associated with the control system(s)? Check all that apply:
    f. Energy savings
    g. GHG reduction
    h. Chemical savings
    i. Sludge generation reduction
    j. O&M labor savings
    k. Other:

    Comments and additional description:

29. What are your biggest **challenges** associated with the control system(s)? Check all that apply and provide additional detail, as applicable:
    l. Capital cost
    m. O&M costs
    n. Control system stability
    o. Sensor accuracy
    p. System complexity

    Comments and additional description:

30. Was the implementation of the sensor based control system worth the investment?

31. If you could do it again, **what would you do differently**?

32. Based on your experience, what **factors are important** to consider for a new sensor/analyzer-based control system? Check all that apply:

    a. Input from WRRF team during design (including operators, lab personnel, maintenance, controls and instrumentation techs)
    b. Operator familiarity with the control system though prior use based on past experience
    c. Information from the sensor/analyzer manufacturers
    d. Information from controls vendors
    e. Information from other WRRFs who operator similar control systems and/or sensors
    f. Training
    g. Implementation of Standard Operating Procedures (SOPs)
    h. Understanding of O&M requirements for sensors/analyzers
    i. Understanding of controls tuning
    j. Availability of on-going manufacturer field support (e.g., via annual service contracts)
    k. Other

    Comments and additional description:

33. Please share any other information you'd like to provide:

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Follow Up

Thank you for completing the survey! The results will be aggregated with responses received from other WRRFs and used to develop tools to guide others in implementing BNR controls with online sensor and analyzers. A member of our project team may reach out for clarifications and additional details about your experience with BNR controls and sensors either through a supplemental survey or through a phone discussion with a member of our team in Winter-Spring 2022.

34. Does the information you provided in this survey need to remain anonymous and only presented in aggregate with the overall data collected?
    a. No
    b. Yes - all information should remain anonymous.
    c. Yes - a portion should remain anonymous. Please describe:
35. Would you be willing to have your experience shared as a case study for the project:
    d. No
    e. Yes

Utility Partner Extended Survey

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Utility Partner Extended Survey Introduction

Thank you for returning the initial survey for the Water Research Foundation (WRF) Project 5087 titled *Implementation of Innovative Biological Nutrient Removal (BNR) Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy*. We sent out over 800 surveys to utilities from across the United States of America and several in Canada, and we received 75 responses (a response rate of approximately 9%). To better summarize the current state of the art and develop a framework for the practical and cost-effective implementation of BNR control systems with sensor technologies, we request that our Utility Partners compete this additional survey.

The project team has pre-filled in portions of this extended survey based on initial survey responses, and we are asking you to supplement that information with more detailed responses. Please fill out the survey in Word and return the survey via email. The responses submitted will be used to create case studies that WRF subscribers can reference to gain a better understanding of how BNR control systems are being implemented, the costs associated with implementation, and the benefits and challenges associated with implementation.

Please don’t hesitate to reach out to any of the Co-PIs on the project with questions.

Thank you!

Utility Partner Extended Survey
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Contact Information

Please provide contact information for your Water Resource Recovery Facility (WRRF). If your utility has multiple facilities, please complete a separate survey for each facility.

1. Contact Information for Person Completing the Survey:

   *Name:

   *Position:

   *Email address:

   *Phone number:

2. Contact Information for Utility Director (*if different from Question 1 above*):

   Name:

   Position:

   Email address:

   Phone number:

3. Water Resource Recovery Facility (WRRF) Name and Address:

   *Name:

   Address:

   City/Town:

   State/Province:

   ZIP/Postal Code:

   Country (if other than United States):

**required response*

Utility Partner Extended Survey

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Facility Overview

Please answer the following questions based on your Water Resource Recovery Facility (WRRF).

4. Please provide the following graphics for use in the case studies:
    a. Aerial photo of the WRRF
    b. Process Flow Diagram for the WRRF
    c. Any other figure that could help clarify location of sensors and/or analyzers

BNR Process & Controls

Please answer the following questions based on the biological process(es) and related controls systems at your Water Resource Recovery Facility (WRRF).

5. Confirm the biological process(es) present at your WRRF:
    a. Correct
    b. Incorrect (please describe):

Utility Partner Extended Survey

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6. Indicate the manufacturer and model name for the online sensors (in situ) and analyzers (wet chemistry) associated with your biological process(es):

	Manufacturer	Model/Type (if multiple options available)	Year of Installation
DO sensor			
pH sensor			
Ammonium sensor			
Ammonium analyzer			
Nitrate sensor			
Nitrate analyzer			
Nitrite sensor			
Nitrite analyzer			
Phosphate analyzer			
COD/BOD sensor			
COD/BOD analyzer			
Suspended solids sensor			
Turbidity sensor			
ORP sensor			
Conductivity sensor			
Temperature sensor			
Other (please describe)			

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7. Describe the typical validation procedure used for the sensor(s) and analyzer(s):

	Check/Comparison of instrument readings to lab data Frequency *(Never - 1/year - Quarterly - 1/month - 2/month - 1/week - >1/week)*	**Sampling/Testing procedure for comparing instrument values to lab data** *(Note field filtering technique (if applicable), sample hold times, specific analytical methods used, other pertinent information)*
DO sensor		
pH sensor		
Ammonium sensor		
Ammonium analyzer		
Nitrate sensor		
Nitrate analyzer		
Nitrite sensor		
Nitrite analyzer		
Phosphate analyzer		
COD/BOD sensor		
COD/BOD analyzer		
Suspended solids sensor		
Turbidity sensor		
ORP sensor		
Conductivity sensor		
Temperature sensor		
Other (please describe)		

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8. Provide additional information regarding calibration performed on sensor(s) and analyzer(s):

	Onsite Calibration Frequency *(Never - 1/year - Quarterly - 1/month - 2/month - 1/week - >1/week)*	**Threshold for determining when onsite, minor adjustment/calibration required**
DO sensor		
pH sensor		
Ammonium sensor		
Ammonium analyzer		
Nitrate sensor		
Nitrate analyzer		
Nitrite sensor		
Nitrite analyzer		
Phosphate analyzer		
COD/BOD sensor		
COD/BOD analyzer		
Suspended solids sensor		
Turbidity sensor		
ORP sensor		
Conductivity sensor		
Temperature sensor		
Other (please describe)		

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	Factory Calibration Frequency *(Never - 1/every 10 years – 1/every 5 years, 1/every 2 years, 1/year Quarterly)*	**Threshold for determining when factory calibration required**
DO sensor		
pH sensor		
Ammonium sensor		
Ammonium analyzer		
Nitrate sensor		
Nitrate analyzer		
Nitrite sensor		
Nitrite analyzer		
Phosphate analyzer		
COD/BOD sensor		
COD/BOD analyzer		
Suspended solids sensor		
Turbidity sensor		
ORP sensor		
Conductivity sensor		
Temperature sensor		
Other (please describe)		

Utility Partner Extended Survey

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9. Provide purchase cost information for the online sensors (in situ) and analyzers (wet chemistry) you have installed.

	Sensor/Analyzer *(purchase price)*	**Accessories** *(annual cost)*	**Maintenance Plan** *(annual cost, if applicable)*	**Total Cost**
DO sensor				
pH sensor				
Ammonium sensor				
Ammonium analyzer				
Nitrate sensor				
Nitrate analyzer				
Nitrite sensor				
Nitrite analyzer				
Phosphate analyzer				
COD/BOD sensor				
COD/BOD analyzer				
Suspended solids sensor				
Turbidity sensor				
ORP sensor				
Conductivity sensor				
Temperature sensor				
Other (please describe)				

Utility Partner Extended Survey

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10. Quantify the annual cost associated with the sensor(s) and analyzers:

	Labor (cleaning, validation, calibration) *(hours/week)*	**Parts** *($ per year)*	**Service Contracts** *($ per year)*	**Total O&M Costs** *($ per year)*
DO sensor				
pH sensor				
Ammonium sensor				
Ammonium analyzer				
Nitrate sensor				
Nitrate analyzer				
Nitrite sensor				
Nitrite analyzer				
Phosphate analyzer				
COD/BOD sensor				
COD/BOD analyzer				
Suspended solids sensor				
Turbidity sensor				
ORP sensor				
Conductivity sensor				
Temperature sensor				
Other (please describe)				

11. Do you follow manufacturer recommendations for O&M?
    a. Yes
    b. No
        i. If not, for which sensors/analyzers do you differ? Why not? And how did you develop your process?
12. Who is responsible for O&M?
    a. Sensor/analyzer manufacturer via O&M contract
    b. Sensor/analyzer manufacturer via ad hoc requests
    c. Combination of plant staff and sensor/analyzer manufacturer
    d. Full time technician
    e. Other (please provide title of position)

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13. Estimate the amount of training required for the sensor(s) and analyzers and identify who received training.
Please select from the following options for training time: none, 0.5 hrs -2 hrs, >2 hrs - 4 hrs, >4 hrs – 8 hrs, >8 hrs
Please select from the following options for trainees: supervisor, operator, instrumentation, maintenance, laboratory, other – please specify

	Training Time *(Estimated total number of hours)*	**Trainee(s)** *(Identify all who received training)*
Dissolved Oxygen sensor		
pH sensor		
Ammonium sensor		
Ammonium analyzer		
Nitrate sensor		
Nitrate analyzer		
Nitrite sensor		
Nitrite analyzer		
Phosphate analyzer		
COD/BOD sensor		
COD/BOD analyzer		
Suspended solids sensor		
Turbidity sensor		
ORP sensor		
Conductivity sensor		
Temperature sensor		
Other (please describe)		

Utility Partner Extended Survey

Water Research Foundation – Project 5087:

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Outcomes

The following questions speak to the benefits, and challenges of your BNR controls and sensors/analyzer systems. Please respond for each control system at your WRRF. Also, we'd like your perspective on how you would improve your system(s) and what you would recommend to others implementing new BNR Control systems with sensors/analyzers.

14. Listed below are the process improvements associated with the control system that were identified in the original survey. Please confirm the information is correct and provide any additional comments/description regarding the biggest benefits of the control system implementation.
    a. Improved nutrient removal
    b. Improved settleability and MLSS characteristics
    c. Improved operations - More control
    d. Improved operations - More monitoring
    e. Improved reliability and less variability

Comments and additional description:

15. For the noted project outcomes, please provide additional context and quantification. Specific examples are included below for reference, but please note the metric you use to define a successful outcome.
    a. If noted improved nutrient removal, how much reduction in nitrogen and/or phosphorus occurred? What were the pre and post nitrogen and phosphorus discharge concentrations? Any other notable changes in effluent characteristics?
    b. If noted improved settleability and MLSS characteristics, what were the pre and post SVI levels?
    c. If noted improved operations – more control, what was the % energy savings/% chemical savings/%sludge reduction experienced?
    d. If noted improved operations – more monitoring, was there a quantifiable benefit to the process improvement? If so, please explain.
    e. If noted improved reliability and less variability, was there a quantifiable benefit that hasn't already been presented? If so, please explain.
    f. Please provide any additional context or quantification not covered by previous questions.

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16. Listed below are the process improvements associated with the control system that were identified in the original survey. Please confirm the information is correct and provide any additional comments/description regarding the biggest benefits of the control system implementation.
17. Listed below are the biggest challenges associated with the control system(s) that were identified in the original survey. Please confirm the information is correct and provide any additional comments/description regarding the biggest challenges of the control system implementation.
    a. Capital cost
    b. O&M costs
    c. Control system stability
    d. Sensor accuracy
    e. System complexity

    Comments and additional description:

18. Was the implementation of the sensor-based control system worth the investment?
19. Did your sensor-based control system project achieve its objective?
    a. Yes
    b. No.
    c. If no, why not?
20. Did you calculate a return on investment (ROI)?
    a. No
    b. Yes. If yes, what was the ROI?
        i. Does the actual equal the initial estimate?
        ii. How do you calculate it? (capital, labor, energy, O&M, service contracts, parts, and etc.)
21. Please share any other information you'd like to provide:

References

**References denoted with an asterisk (*) were part of the Task 1 Literature Review.*

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Equipment Manufacturers

Information accessed between October 2021 and August 2023:

Electro Chemical Devices (https://ecdi.com)
Endress+Hausser (https://www.endress.com/en)
HACH® (https://www.hach.com)
HORIBA (https://www.horiba.com/usa)
In-Situ (https://in-situ.com/us)
MANTECH Inc. (https://mantech-inc.com)
S::CAN (https://www.s-can.at/en)
Sentry (https://www.sentrywatertech.com)
Shimadzu (https://www.shimadzu.com)
SouthWestSensor LTD. (http://southwestsensor.com)
YSI (https://www.ysi.com)