THE Water Research FOUNDATION

Nutrients

THE CHALLENGE

Nutrients occur naturally in the environment and play a key role in a healthy aquatic system. But problems start to develop when additional amounts are introduced into our waterbodies through sources such as municipal wastewater, fertilizers, soaps, and detergent—and in some cases the products used to treat our water. These excess amounts can throw off the natural balance, prompting excessive algal growth, hypoxia, and other negative effects on water resources.

While regulations designed to maintain this natural balance are set using the best available knowledge, as new health data, analytical methods, and treatment technologies become available, these regulations can become more stringent and difficult to achieve. The challenge is exacerbated by the fact that both nitrogen and phosphorus come in a variety of forms that can behave differently in the environment, so an across-the-board solution for reducing or removing them is not that simple.

THE RESEARCH

With a body of nutrient research that spans more than 30 years and 200 projects, WRF is developing the science to manage sources, effectively identify and determine the real impact of nutrient species in water, and improve nutrient treatment and removal processes. As more wastewater utilities are realizing the value of nutrients as a renewable commodity, WRF is also helping to develop ways to recover nutrients during the treatment process.

Partnering with strategic organizations, including the U.S. Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE), and diverse state regulatory agencies, WRF has focused on nutrient treatment optimization, water quality impacts and modeling, algal metabolite detection and treatment, and nutrient recovery.

Sources

Because preventing extra nitrogen and phosphorus from entering our waterways is the first line of defense against negative impacts, WRF is exploring source management. In-depth research on stormwater and agricultural runoff, as well as nutrient discharges from treatment facilities, is helping to advance knowledge and prevent additional loadings. Key interest areas include integrated water and urban land planning, green infrastructure, stream restoration, and agricultural best management practices.

In 2017, WRF released findings from *Enhanced Removal of Nutrients and Trace Organic Contaminants in Pilot-Scale Stormwater Treatment Systems* (STAR_N4R14/4567), providing guidance on the design and operation of systems for controlling nutrients released into surface waters. The research tested combinations of media that capture and treat urban stormwater, highlighting effective processes.

While managing nutrient sources is key, understanding their actual impact is arguably more important. In 2010, WRF provided the water sector with one of the first methods for calculating these impacts in *Linking Receiving Water Impacts to Sources and to Water Quality Management Decisions* (WERF3C10/1811). The research lays out an approach for identifying links between nitrogen sources and predicted water quality impacts, as well as implementing control strategies that consider the costs and benefits of available options.

Zeroing in on specific nutrient sources can also help prevent unnecessary practices, like costly technologies, or protect beneficial uses. In 2018, as part of *Developing Tools for Surface Water Nutrient Loading Attributable to Reclaimed Water* (Reuse-13-11/4758), WRF released a tool to help water agencies track the extent to which their reuse practices contribute to nutrient impairment of surface waters, which could help utilities maintain reuse applications.

Treatment

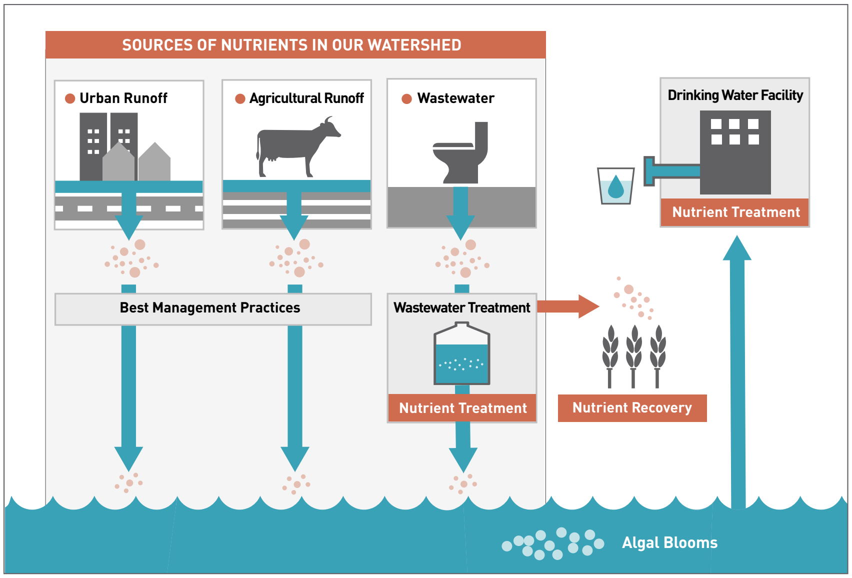
WRF was an early pioneer in advancing the treatment and removal of nutrients in wastewater, helping to improve water quality before it is returned to our rivers and streams. Research explores ways to improve commonly used processes, such as biological nutrient removal, as well as novel technologies that are challenging conventional treatment.

Starting in 2007, WRF engaged nearly 250 partners to build foundational work on nutrients and their fate during treatment. This research improved the reliability of nutrient removal, including aspects such as cost, energy, chemicals, and greenhouse gas emissions. The results, found in the *Nutrient Removal Challenge Synthesis Report* (NUTR5R14g), cover the occurrence and measurement of nutrient species, facility design and operations, and process optimization.

Characterizing, Categorizing, and Communicating Next-Generation Nutrient Removal Processes for Resource Efficiency (4976) helped to increase the understanding of treatment options, synthesizing information on newly developed nutrient management technologies (both removal and recovery) and benchmarking them against established processes. Taking this further, *Guidelines for Optimizing Nutrient Removal Plant Performance* (4973) is developing a road map to assist water resource recovery facilities (WRRFs) in optimizing nutrient removal to reduce costs, increase efficiency, and reduce nutrient discharges. A 2021 webcast series based on this research is available on-demand on the WRF website.

Practices to Enhance Internal Fermentation of Side-Stream Secondary Sludge and Mixed Liquor Suspended Solids for Biological Phosphorus Removal (4975) is exploring ways to improve the traditional enhanced biological phosphorus removal (EBPR) process, strengthening the understanding of sidestream EBPR—which can improve stability and minimize chemical and energy costs. This research will provide guidelines and best practices for facilities implementing EBPR processes.

WRF is also investigating solutions like deammonification, an anammox process that doesn't rely on external carbon, decreasing chemical demand and requiring less oxygen, which translates to less power consumption. While side-stream deammonification technologies are installed around the world, two new WRF projects are advancing a different shortcut nitrogen removal pathway called partial denitrification anammox (PdNA). *Partial Denitrification Anammox as Alternative Pathway to Achieve Mainstream Short-Cut Nitrogen Removal* (5027) and *Mainstream Deammonification with Biological Phosphorus Removal* (5095), part of an EPA Science to Achieve Results (STAR) grant, could help to significantly improve cost and operational benefits of nitrogen removal, including added treatment capacity and reduced carbon addition and aeration energy.



TRACKING NUTRIENTS IN OUR WATER: Sources, Treatment, and Recovery

The discovery of complete ammonia oxidizing (comammox) bacteria could have significant implications for the design and operation of nitrogen removal systems. Understanding the prevalence, abundance, and activity of comammox bacteria in these systems is critical to ensuring the stability and efficiency of existing processes and potentially innovate new processes. *Estimating the Comammox Contribution to Ammonia Oxidation in Nitrogen Removal Systems* (4884) evaluated the prevalence of comammox bacteria in a range of nitrogen removal processes and the impact of process configuration, operations, and environmental variables.

Resource Recovery

Because more facilities are taking nutrient treatment a step further and extracting these valuable resources, WRF is exploring practices to make the most of everything, from nutrient-rich biosolids to phosphorus and ammonia in liquid waste. In 2014, WRF was awarded a $2.2 million EPA STAR grant to create a National Research Center for Resource Recovery and Nutrient Management. Working with top universities and non-profit organizations, WRF helped the water sector shift their view of nutrients—recognizing them as a valuable product. The research center demonstrated breakthroughs such as urine separation to collect nutrients for agricultural use and commercial-scale generation of energy and bio-fertilizers. Research has also helped utilities meet regulatory goals at lower costs, with less energy, and with a smaller chemical footprint.

In 2021, WRF was awarded a $2.2 million grant from DOE to lead the project *Data-Driven Process Control for Maximizing Resource Efficiency* (5141). This research will develop process controls in full-scale facilities for five promising technologies that offer substantial energy and resource recovery benefits: (1) carbon diversion: high-rate contact stabilization, (2) biological nutrient removal: ammonia-based aeration control/ammonia vs. NOx control + mainstream partial denitrification with anammox (PdNA), (3) disinfection: peracetic acid, (4) phosphorus recovery: MagPrex™, and (5) holistic biosolids optimization.

Additional information on WRF's research in this area can be found in the Resource Recovery Topic Overview.

Effects

While WRF is taking significant steps to reduce the amount of nutrients in our waterbodies, critical research is also looking at the other side of the coin—managing the impacts once they are in our ecosystems. Relevant science helps utilities offset devastating effects like algal blooms, eutrophication, and loss of aquatic life.

SOLUTIONS IN THE FIELD: WSSC Water

Availability and transformation of organic carbon at different stages in the activated sludge process impact biological N and P removal efficiency. Conventional BNR flowsheets often do not take advantage of influent carbon and favorable influent C/N and C/P ratios for N and P removal and are resource intensive. WSSC Water, which has a strong desire to reduce operating costs of their BNR systems while fully utilizing existing infrastructure, tapped into WRF's Tailored Collaboration Program to fund *Demonstration of Progressive Carbon-Efficient Nitrogen with Biological Phosphorus Removal in a Conventional BNR Facility* (5071). The research is investigating whether carbon-efficient N and P removal could occur in concert—reducing energy and chemical use while the facility reliably meets stringent nutrient limits.

According to Carla A. Reid, WSSC Water's General Manager/CEO, "This pilot project uses less energy and chemicals and has the added benefit of achieving process stability and lowering operational costs. This process will benefit all of our WRRFs and should guide the water sector on new methods to intensify the ENR treatment process." In 2022, the Water Environment Federation selected this project for their Operational Design Awards, which recognizes organizations that have made outstanding contributions to the water environment profession.

Cyanobacteria continue to be one of the most problematic organisms in freshwater systems. Without clear guidance or consensus regulations, many utilities struggle with responding to events. WRF has completed more than 30 research projects on these organisms and the cyanotoxins they produce, helping facilities detect, monitor, and manage them—as well as communicate with the public.

While it is known that cyanobacteria growth is favored by high nutrient concentrations, elevated temperatures, thermal stratification, and high levels of sunlight; the dynamic seasonal and temporal combinations of these factors is not well understood. Because there is a narrow window for detecting taste and odor issues before complaints begin, WRF is providing the science to stay on top of these events. *Assessment of Vulnerability of Source Waters to Toxic Cyanobacterial Outbreaks* (5080) will advance interpretable artificial intelligence, which uses water quality and weather station data, as well as satellite imagery to compute risk of cyanobacterial harmful algal blooms.

In watersheds where advanced treatment practices have already been implemented to reduce nutrient discharges, the next step utilities can take is to explore holistic policies and partnerships to further advance watershed restoration. To advance understanding in this area, WRF recently completed *Holistic Approach to Improved Nutrient Management* (4974). This study details an approach to address barriers to watershed nutrient management, suggesting improved strategies to affect change in a constructive manner.

WRF has also released guidance and modeling tools to set waterbody-specific nutrient goals, including Numeric Nutrient Criteria and allowable nutrient loadings. However, more information is needed on effective practices, stakeholder engagement, and the linkages between management practices and water quality and ecosystem responses. *Linking Nutrient Reductions to Receiving Water Responses* (5078) will collect available information on nutrient controls, implementation of total maximum daily loads, water quality, and ecosystem responses, which will aid in the development of a web-based benchmarking tool to evaluate the strengths and weaknesses of regulatory and management actions.

INNOVATION

WRF is leading the way on pilot projects to advance nutrient removal. One such project, *Nitrogen Reduction Technology Solutions for Ocean Discharges* (5117), is comparing early-stage technologies for nitrogen reduction to treat wastewater in Everett, WA. The technologies include integrating partial denitrification, enhanced biological phosphorus removal, and anammox in a single-stage process bioreactor; a membrane bioreactor with anammox and a hydrogel reactor with anammox and comammox; and a partial nitrification/denitrification/anammox (PANDA) reactor. These technologies harness advanced microbiological kinetics within novel reactor designs for increased effectiveness in mainstream nitrogen remediation. Using this as a platform, WRF is moving these and other innovative technologies to bigger scales at different geographic locations to test their effectiveness in the field.

WHAT'S NEXT?

An ongoing suite of WRF projects is investigating whether various innovative technologies and approaches could improve cost savings and lower energy use for BNR systems. *Transforming Aeration Energy in WRRFs through Suboxic Nitrogen Removal* (5148) is exploring model predictive aeration control (MPAC) and machine learning to lower WRRF energy use and reduce greenhouse gas emissions. This $4.6 million project is funded in part by a $2 million DOE grant. *Development of Innovative Predictive Control Strategies for Nutrient Removal* (5121) is testing a hybrid (machine learning + mechanistic model) nutrient management controller at three different WRRFs. The controller offers both short-term optimization functions and long-term predictive capabilities. Finally, *Implementation of Innovative Biological Nutrient Removal Processes through Improvement of Control Systems and Online Analytical Measurement Reliability and Accuracy* (5087) is evaluating technologies, configurations, performance, O&M requirements, and costs of BNR control systems and online sensors to expedite adoption of BNR control system innovation and maximize the value across the sector.

Biorecovery of Nutrients from Municipal Wastewaters with Co-Production of Biofuels and other Bioproducts (5146) will demonstrate the promising application of algae for phosphorus control at a lower cost than conventional biological phosphorus removal. Algal technologies offer pathways for resource recovery and have the potential to support energy neutrality through biofuel production. This project is also supported by a DOE grant.