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Energy Research and Development Division

FINAL PROJECT REPORT

Gravity-Based, Low-Energy Biofilter With Low Backwash Rate for Nitrate Removal in Groundwater

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Gravity-Based, Low-Energy Biofilter with Low Backwash Rate for Nitrate Removal in Groundwater is the final report the gravity based, low energy biofilter with low backwash rate for nitrate removal in groundwater project (Contract Number EPC-15-092) conducted by Tomorrow Water. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Groundwater is an essential component of California's water supply. However, in the past 10 years, more than 6,934 wells and 1,149 wells statewide have been contaminated by nitrate and perchlorate, respectively. In this project, the recipient, Tomorrow Water, tested an energy-saving groundwater treatment system, Tomorrow Water Biofiltration, that can decontaminate groundwater to drinking-water standards. From the project site in the City of Barstow in Southern California, the project team performed tests required by the State Water Resources Control Board to secure conditional acceptance as a Title 22 drinking water treatment technology for perchlorate and nitrate removal. During this testing, influent nitrate and perchlorate concentrations were measured as 4 to 15 milligrams per liter (mg/L) and 4 to 30 micrograms per liter (ug/L), respectively. The Tomorrow Water Biofiltration system simultaneously removed nitrate, perchlorate, and turbidity from groundwater to bellow state-mandated maximum contaminate levels. At the same time, the system reduced energy consumption by 70 percent when compared with a conventional fluidized bed reactor. Both contaminants were treated until each maximum contamination level reached the project goals of 10 mg/L for nitrate and 6 ug/L for perchlorate based on California's Title 22 drinking water standard. The maximum level of influent water quality for this demonstration was 15 mg /L of nitrate and 53 ug/L of perchlorate. Empty bed contact time was between 45 minutes and 120 minutes depending on the influent groundwater quality, but the Tomorrow Water Biofiltration system showcased capabilities to treat both contaminants under Title 22 drinking water standard maximum contaminant level while saving 70 percent of energy. While the project did not achieve a Title 22 certification, Tomorrow Water continues to seek approval and is working with the Regional Water Board to solve the issue regarding real-time perchlorate data.The Tomorrow Water Biofiltration system also implemented advanced operational and control measures to mitigate the risk of incidental contaminant discharge. The safety logic was automatic once the system detected contaminants in effluent, such as during the high-nitrate and perchlorate-loading tests and during the carbon source failure test.

Keywords: Tomorrow Water Biofiltration system, nitrate removal, perchlorate removal, energy consumption, Barstow, up-flow biofilter treatment, groundwater treatment

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Introduction

California has faced periods of extreme drought throughout its recent history at the same time its population and productivity have steadily increased. This confluence of circumstances has increased the need to secure stable, long-term water supplies from surface and groundwater sources. In particular, during the dry season, groundwater is the most important water resource, providing two-thirds of the state's water demand from the underground aquifers. However, in the past 10 years, more than 6,934 wells and 1,149 wells statewide had been contaminated by nitrate and perchlorate, respectively.

Traditional fluidized bed reactors and ion exchange systems can remove nitrates or other contaminants from groundwater. Fluidized bed reactors remove contaminants with a biofilm surface, whereas ion exchange systems absorb contaminants with an ionic bond, replacing the contaminates with a positive ion, such as salt. However, these systems have drawbacks, including high operating and maintenance costs and high energy requirements. In response to California's drought, former Governor Edmund G. Brown Jr.'s Executive Order B-29-15 outlines bold steps to save water, increase enforcement of water use standards, streamline the state's drought response, and invest in new technologies to make California more drought-resilient. To help achieve this goal, Tomorrow Water developed a cost-effective system that removes dissolved organics and contaminants from groundwater, including nitrates and perchlorate, an emerging concern with gravity-forced water flows. This project was originally developed to demonstrate a low-energy treatment for contaminated groundwater and to address greenhouse gas-reduction targets established in the California Global Warming Solutions Act of 2006 (Assembly Bill 32, Núñez, Chapter 488, Statutes of 2006). This act requires that greenhouse gas emissions be reduced to 1990 levels by 2020. Providing low-energy water treatment options can reduce energy demand for the treatment and transport of clean water, as well as the need to pump and transfer water over long distances, a current necessity for many California municipalities. Taken together, these solutions will ultimately contribute to California's mandated targets for lowering greenhouse gas emissions and reducing the effects and pace of climate change.

Project Purpose

Two ways existing technology can remove nitrates and perchlorate from groundwater are through either ion exchange or biological processes. When used to treat highly contaminated water, the ion exchange treatment option requires frequent resin regeneration, which in turn requires pumping several tons of nitrate-laden, high-salinity brine off-site. Because appropriate discharge sites are unlikely to be available for inland treatment facilities, brine disposal costs are a major barrier to ion exchange for nitrate removal.

When compared with the ion exchange process, biological processes offer multiple advantages, including lower operating costs and complete removal of contaminants without generating hazardous waste, instead of simply separating them from the water. This makes biological processes, such as with a fluidized bed reactor, or Tomorrow Water's biofiltration system especially attractive for nitrate treatment systems where brine disposal may be either cost-prohibitive or infeasible for other reasons.

Several existing chemical processes use biological processes such as fluidized bed reactors, packed bed bioreactors, sequence batch reactors, fixed-film processes, etc. Biological processes are typically not utilized to treat wastewater; fluidized bed reactors are the most common biological process for waste water treatment. Compared with conventional fluidized bed reactor systems, the Tomorrow Water biofiltration system shows notable energy savings with fewer major energy-consuming processes, shown in Table ES-1. To ensure objective verification of the energy benefits of the systema consulting company, Khalil Kairouz Consulting, monitored and optimized the system for energy consumption and analyzed alternative technologies.

Table ES-1: Major Energy-Consuming Processes for Biological Treatment Systems

Process	Fluidized Bed Reactor	Tomorrow Energy Biofiltration
Raw water transfer pump	X	X
Recirculation pumping	X	
High-density media	X	
Backwash air scouring		X
Downstream filter needed	X	X
Downstream filter backwash pumping	X	X
Downstream filter air scouring	X	X
Annual topping off of media due to attrition loss	X	
Pumping for complete removal of spent media	X	
Pumping in of new media to replace degraded media	X	
Backwash pumping of fines after media replacement	X	

Source: Tomorrow Water

To ensure the effective performance of the Tomorrow Water biofiltration system and obtain required data for Title 22 Conditional Acceptance and National Sanitation Foundation/American National Standards Institute (NSF/ANSI) 61 certification, the research team continuously measured the water's nitrate level and turbidity (the degree to which water loses its transparency from suspended particulates). The team simultaneously evaluated the floating media permeability and components for compatibility with drinking water standards, and collected influent (untreated wastewater) and effluent (treated wastewater) samples for analysis at Eurofins Eaton Analytical, a laboratory certified by the United States Environmental Protection Agency's (USEPA) Environmental Laboratory Advisory Committee.

Project Approach

In 2016, the City of Barstow retained Tomorrow Water to construct and demonstrate the treatment system studied in this report. The demonstration plant is referred to as the Soapman Road site because the source of perchlorate originates from Soapman Road. The site is located at 682 Webster Road in Barstow, which is in San Bernardino County. The City of Barstow Wastewater Treatment Plant is south of the project site. The Soapman Road site is required to have a remediation system to reduce nitrate and perchlorate groundwater contamination.

The Tomorrow Water biofiltration system is capable of reducing concentrations to state regulated discharge limits. The proposed design contains several built-in safety factors that ensure this level of contaminant removal. The testing and demonstration of the capabilities and performance of the Tomorrow Water biofiltration system consisted of the following major efforts:

- Design, procurement, and fabrication: System design and drawing-set preparation began after finalization of the project agreement with Tomorrow Water. Tomorrow Water and Stantec prepared a Title 22 Conditional Acceptance test plan for drinking water, which was confirmed by the State Water Board's Division of Drinking Water. AATech fabricated the biofiltration system based on the engineering drawings, which was inspected by Tomorrow Water on May 10, 2017.
- Installation and construction: KANA Engineering provided design and engineering services. Tomorrow Water was on site July 7, 2017, to oversee and inspect the electrical equipment and biofiltration system installation. After the system installation was completed, Tomorrow Water conducted a final site inspection. The objectives of these inspections were to confirm that the installation and construction of system components complied with system specifications and that the whole system was operational. Before the system began operating, the City of Barstow's chief plant operator reported a fire at the Barstow site on February 26, 2018, which the sheriff's department determined was caused by an unidentified arsonist. The equipment listed in the damage report included two post-treatment processes; three storage tanks, including two effluent tanks and one spent-backwash tank; and electrical wiring. After repairs, the research team tested the biofiltration system in a batch process to ensure proper operation with the new components.
- Operation: Over 18 months, the full-scale system was operated for data collection and system optimization, including for conditional acceptance and safety-data-sheet (SDS) testing. NSF/ANSI Standard 61 certification was secured before beginning the Title 22 tests. Tomorrow Water prepared the original test protocol that was later revised by Stantec during project operation and confirmed by the State Water Board's Division of Drinking Water. The demonstration test's six phases appear in Table ES-2.
- Energy savings monitoring and evaluation of project benefits: The research team consistently monitored and verified the system's energy consumption and water savings throughout the test period.

Table ES-2: Testing Schedule for Drinking Water Conditional Acceptance Title 22

Test Phases	Description	Responsible Party
Phase 1	Process acclimation sampling	Tomorrow Water
Phase 2	Empty bed contact time optimization	Tomorrow Water
Phase 3	Carbon source optimization	Tomorrow Water
Phase 4	Trail loading test and acclimation phase for elevated influent nitrate	Tomorrow Water
Phase 5	Optimized normal operations	Stantec
Phase 6	Simulation of worst-case scenarios	Stantec

Source: Tomorrow Water

Energy Consumption Monitoring and Verification Plan

Energy monitoring and data acquisition for the water treatment facility included sensors that monitored amperage, watts, and voltage at the electrical panel. The power meter calculated energy consumption variables, and data was logged using a pulse data logger.

Researchers collected energy consumption data at several points: the main influent pump, effluent pump, chemical-feed system, air-scouring equipment, and associated treatment system electrical equipment.

Project Results

Continuous Operation Performance Test

For two weeks, the research team checked influent and effluent water samples for perchlorate and nitrate concentrations. Sample results showed that the system's influent perchlorate was around 14 micrograms per liter (µg/L), and influent nitrate concentration was approximately 4 milligrams per nanoliter (mg N/L), below the maximum contaminant level (MCL) of 10 mg N/L. The effluent nitrate and effluent perchlorate concentrations remained below 1 mg N/L and 4 µg/L, respectively.

Water Quality Verification During the Title 22 Conditional Acceptance Test

The Regional Water Board stopped the Title 22 testing early due to an issue involving discharging potentially perchlorate contaminated water into an uncontaminated portion of the well. The Regional Water Board requires companies to provide real-time perchlorate levels of their effluent to discharge legally into another source. Unfortunately, a real-time percolate system does not currently exist. Tomorrow Water is currently working to develop a measuring system that can meet the EPA requirements and thus the Water Board's standard for real-time percolate measurements.

Nitrate was also found in the effluent stream in concentrations around 1 mg N/L or 9 mg N/L below Califorrnia's MCL for nitrate. Though the data was not comprehensive enough to draw strong conclusions, parameters that could have affected nitrate removal included bioreactor pH, carbon-to-nitrogen ratios, and insufficient empty-bed contact times. Testing, unfortunately, concluded prematurely due to the lack of proper disposal place for the treated water due to perchlorate. Based on these findings, Stantec, the company carrying out the Title 22 test, recommended future testing of this biofiltration system under expanded conditions:

- A site with sufficient water-disposal capabilities so that off-spec water can be safely and continuously disposed of without interrupting system operations.
- A system design to allow testing of a wide range of empty bed contact times as a dedicated feed water system with variable-frequency pumps.
- A groundwater site contaminated by nitrate only, not perchlorate. This would allow the safe and continuous disposal of treated groundwater from a nitrate perspective; online monitoring techniques for perchlorate are currently unavailable.

Energy Consumption Monitoring and Verification

Energy data acquisition from the full-scale operation of the Tomorrow Water biofiltration water treatment system began on June 1, 2018 and continued until October 31, 2019. The team monitored, measured, and calculated the data to show the system's monthly energy consumption in kilowatt-hours (kWh). The energy cost was calculated at $0.12/kWh based on the current rate model at Southern California Edison. Utility data provided energy consumption from previous months.

For the monitoring and verification report, researchers compared the biofiltration energy efficiencies, savings, and costs against the fluidized bed reactor system.

The average energy savings for the biofiltration treatment system, compared with a fluidized bed reactor treatment system, were around 72 percent. Based on the measured energy consumption rate of the biofiltration system, Tomorrow Water and Khalil Kairouz Consulting calculated and confirmed operating energy costs for one year: December 2018 to December 2019. The annual energy consumption cost for a 100 gallon per minute biofiltration system was calculated to be $1,301, while a similarly sized fluidized bed reactor system was $4,586. The Tomorrow Water biofiltration system has a similar capital cost to a comparable fluidized bed reactor system; however, the Tomorrow Water biofiltration system has a greater influent tolerance, which may help avoid future capital costs required by the similar fluidized bed reactor system. This stems from the agitation process. Since the fluidized bed reactor and Tomorrow Water biofiltration systems do not use air to agitate the water, they must agitate the water by other means. In a fluidized bed reactor system, the effluent concentration is equal to the reactor concentration since the water is continuously stirred. The Tomorrow Water biofiltration system is a plugged flow reactor, thus allowing for a greater intake tolerance than a fluidized bed reactor system. Since the Tomorrow Water biofiltration system has a greater intake tolerance, the system can avoid potential rebuilds a fluidized bed reactor system would have to undergo if the influent stream changes.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Tomorrow Water has promoted the biofiltration system on its website and at various conferences, meetings, and tradeshows. Most potential projects in California require Title 22 designation for drinking water. This designation was unavoidably delayed for this project due to arson at the project site and issues with the discharge field. Since the certificate is an essential factor in end-user consideration of the technology, this regulatory barrier could hamper business development in the United States. Since 2016, Tomorrow Water's biofiltration system has been installed and is operating in 15 commercial facilities in Korea.

Tomorrow Water recently developed a novel cross-shape filtration media that is being tested and commercialized in Korea and the United States. The media has a 25 percent lower hydraulic resistance and longer backwash cycle when compared with previous rounded-type filtration media.

To overcome barriers from the State Water Resources Control Board, Tomorrow Water developed a system to monitor the perchlorate concentrations in groundwater using oxidation and reduction potential values in real-time. To date, many companies are building similar systems to monitor perchlorate in real-time using an ion-selective electrode or spectroscopy; however, there is no commercially available system capable of monitoring at the low microgram-per-liter scale. The oxidation and reduction monitoring process is one of the cheapest, most effective methods for tracking oxidation, measuring, and actively monitoring perchlorate levels. Tomorrow Water consistently measured perchlorate concentrations and the oxidation potential of groundwater in the operating area (to confirm that there was a relatively linear proportion) and reported it to the Regional Water Quality Control Board. Since the board and the Division of Drinking Water require a certified real-time perchlorate measurement system for the perchlorate Title 22 certification, Tomorrow Water could not complete the certification process. Tomorrow Water has requested approval from the regional water board to use this method for real-time perchlorate monitoring. The regional water board denied the Tomorrow Water's oxidation and reduction potential method because this method does not meet the USEPA requirement to read contaminate (perchlorate) levels directly. Although not approved for Title 22 certification, Tommorow Water's oxidation and reduction potential method was used to establish a system to prevent pollutant leakage during continuous operation. Tommorow Water continues to seek ways to work with the regional water board on how to achieve Title 22 certification for their system.

Benefits to California

The Lahontan Regional Water Quality Control Board monitored the concentration of perchlorate in a nearby well and determined that the biofiltration system decreased perchlorate to less than 20 micrograms per liter from more than 100 μg/L after one year of operation. In the influent system, the average perchlorate concentration in December 2018 was 16 μg/L and decreased to below the maximum contaminant level in July 2019.

According to a perchlorate groundwater investigation report of the Barstow area prepared by the URS Corporation, the perchlorate-impacted groundwater plume tapers from a maximum width of approximately 1,400 feet and extends at least 1.25 miles from 30433 Poplar Street and Golden State Water company Soap Mine Road production well. The Tomorrow Water biofiltration system is designed to treat unusable contaminated ground water at a maximum of 500 gallons per minute (720,000 gallons per day). While Tomorrow Water did not receive a Title 22 certification, they are continually seeking ways to work with the Regional Water Board to achieve a Title 22 certification for percolate and nitrate removal. If the project is granted the Title 22 certification, they could bring the following benefits if not the technology will be limited to other states and non-government treatment systems. If 12 of the biofiltration systems are operated at perchlorate contaminated wells, it could additionally save approximately $197,100 per year in operating power costs when compared with a fluidized bed reactor system, and much upwards of $1,000,000 when compared to traditional reverse osmosis and ion exchange processes.

CHAPTER 1: Introduction

Background

California continues to face periods of drought, which threaten the state's drinking water supplies. The state must use all available water sources, including groundwater, to ensure safe and reliable drinking water. In the past ten years, there have been 6,934 wells contaminated by nitrate in California ("GAMA GIS" 2020). Many of these wells also contain perchlorate (ClO_4) concentrations that exceed the California maximum contaminant level of 6 µg/L. These wells have been abandoned since there is not currently a cost-effective and widely available treatment process (Lahontan Regional Water Quality Control Board 2012; Pour-ghasemi et al. 2018). Nitrate and perchlorate are traditionally removed from water with an expensive ion exchange system. Depending on influent water quality and site conditions, traditional ion exchange systems have relatively high operating costs, especially resin change-out costs. To overcome the high operational costs of ion exchange systems, Tomorrow Water developed a biofiltration (BBF) system. The BBF system effectively removes contaminants, including nitrate, perchlorate, dissolved organics, and other contaminants of emerging concern. It also eliminates environmental issues stemming from disposal of brine, a by-product of the ion exchange process. Tomorrow Water's newly developed BBF system uses expanded polypropylene beads as the filtration media to remove suspended solids, while a biofilm growing on the filter media removes organic matter and nutrients. BBF can be used either independently or combined with filtration and disinfection systems to meet the most stringent water quality requirements.

Health and safety standards mandate that drinking water meet specific water quality criteria. In California, those standards are set by the California State Water Resources Control Board (SWRCB) in accordance with Title 22 of the California Code of Regulations (CCR). The SWRCB works collaboratively with the Regional Water Quality Control Board (RWQCB) to comply with federal standards established in the 1972 Clean Water Act. SWRCB developed an informational water-treatment technology document recognized by the SWRCB as conditionally acceptable for meeting the state's drinking water criteria.

To be officially listed as a conditionally accepted water treatment technology, the technology provider must:

- Prepare a demonstration study protocol that proves the proposed treatment technology complies with Title 22.
- Submit the demonstration study protocol for SWRCB review and approval.
- Conduct a demonstration study of the proposed treatment technology.
- Submit a final demonstration study report for SWRCB review.

Tomorrow Water worked with the City of Barstow, the State Water Board's Division of Drinking Water (DDW), and the RWQCB to identify a contaminated groundwater site for the BBF demonstration study. The Soapmine aquifer contains concentrations of nitrate and perchlorate that exceed California f (MCL) of 10 mg-N/L and 6 µg/L.

Project Objectives

A demonstration pilot project was set up to evaluate the BBF system's performance. Groundwater was treated with an anoxic reduction of nitrate and perchlorate contaminants. After the perchlorate and nitrate was removed thepost-treatment used membrane filtration to remove turbidity and a chlorination system for microbial disinfection. In this project, Tomorrow Water worked with the engineering consulting firm, Stantec Consulting Services, Inc., for a third-party evaluation of the treatment system.

The overall objective of this project was to evaluate the performance of the proposed system with respect to Title 22 requirements and energy savings. Specific subobjectives were to:

- Evaluate BBF's effluent water quality under various influent conditions.
- Evaluate post-treatment systems to produce potable effluent water under various operating conditions.
- Evaluate the robustness of biofilter processes with possible system upsets such as electron donor feed failure, process shut-downs, and spikes in feed-water oxidant concentrations.
- Evaluate energy consumption and compare it against a fluidized bed reactor (FBR) system. The evaluation criteria and methods for these sub-objectives are listed in Table 1 for each alternative.

Table 1: Project Objectives and Evaluation Criteria for Biofiltration System

Demonstration Objectives	Evaluation Criteria or Method
Title 22 effluent water quality requirement	Effluent turbidity: Average < 0.3 NTU
Additional effluent water quality requirement (daily average)	NO_3-N < 10 mg-N/L, ClO_4 < 6 ug/L
System performance and reliability	Operation under various hydraulic loads
Energy savings	70% of the FBR system

NTU=Nephelometric Turbidity unit

Source: Tomorrow Water

With the overall goal of securing Title 22 conditional acceptance for the BBF biofiltration technology, the project developed objectives to:

1. Determine optimum process parameters, including the Empty Bed Contact Time (EBCT) and carbon-to-nitrate ratio.
2. Assess the performance of the BBF process at high-nitrate and perchlorate loading rates.
3. Assess the impact of carbon-dosing system failure on process performance.
4. Evaluate system performance under intermittent operation.
5. Assess Disinfection Byproduct (DBP) formation potential.
6. Characterize the backwash-water quality.

Table 2 shows the regulatory requirements for nitrate, perchlorate, and turbidity used to evaluate the performance of the BBF system during Title 22 testing. Tomorrow Water retained the engineering consulting firm Stantec Consulting Services, Inc. as the third party that operated and evaluated system performance. The test protocol developed by Tomorrow Water was reviewed and approved by the DDW. This protocol was a guideline for the duration of system evaluation.

Table 2: Title 22 Regulatory Requirements for Treated Water

Parameter	Criterion
Nitrate as Nitrogen (NO_3-N)	<10 mg-N/L
Nitrite as Nitrogen (NO_2-N)	<1 mg-N/L
Nitrate plus Nitrite as Nitrogen (NO_3-N + NO_2-N)	<10 mg-N/L
Perchlorate (ClO_4)	<6 µg/L
Turbidity: Effluent turbidity refers to post-filtration effluent turbidity	<0.3 NTU for 95% of the time; shall not exceed 1 NTU for more than one continuous hour

Source: Tomorrow Water

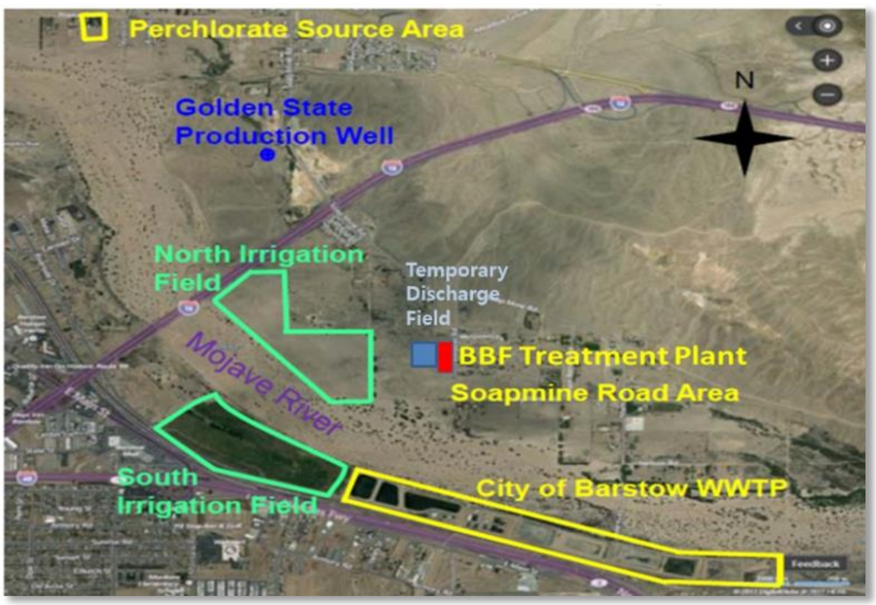
CHAPTER 2: Project Approach

Demonstration Test Site Location

The full-scale BBF pilot system was installed in the City of Barstow. The affected area is the Soapmine Road neighborhood, located in unincorporated San Bernardino County just north of the city's wastewater treatment plant (WWTP). In 2016, the city authorized Tomorrow Water to construct and demonstrate the proposed treatment system. The demonstration plant is located at 682 Webster Road in the City of Barstow (Figure 1). The Soapmine Road site in the city will require the installation of a remediation system in the coming years to remove groundwater contamination of both nitrate and perchlorate.

The system was acclimated for three months for Title 22 conditional acceptance and energy consumption tests.

Figure 1: Site Map Showing Demonstration Study Site



Source: Tomorrow Water

Feed Water Characteristics

The demonstration plant design was based on historical groundwater quality provided by the city and the Lahontan RWQCB. Under the design, the BBF system can reduce concentrations of the target constituent, NO_3-N, from an average of 26 mg-N/L in the influent water to below 5 mg-N/L, which is the target discharge limit of NO_3-N. Additionally, the proposed design has a number of built-in safety factors that will ensure adequate contaminant removal. Table 3 also shows the range of concentrations for the water-quality parameters, design values for the BBF demonstration system, and the observed range of these parameters during demonstration testing.

Table 3: Groundwater Characteristics for the BBF Demonstration

Parameter	Units	Design Value	Anticipated Range	Observed Range
ClO_4	µg/L	400	0–1,400	3.9–30
Dissolved Oxygen	mg/L	3.6	0.19–7.0	0.5–1.8
NO_3-N	mg-N/L	26	4.0–26	1.9–3.9
Oxidation Reduction-Potential	mV		–12.0–84.0	
pH	—	6.69	5.18–7.19	7.8–7.9
Total Dissolved Solids	mg/L	1,476	811–5,400	
Turbidity	NTU	<5	0.01–5.0	

Source: "Pilot Fluidized Bed Reactor Startup, Operation, and Monitoring Study," DPRA on behalf of City of Barstow, April 7, 2010

Description of Biofiltration System

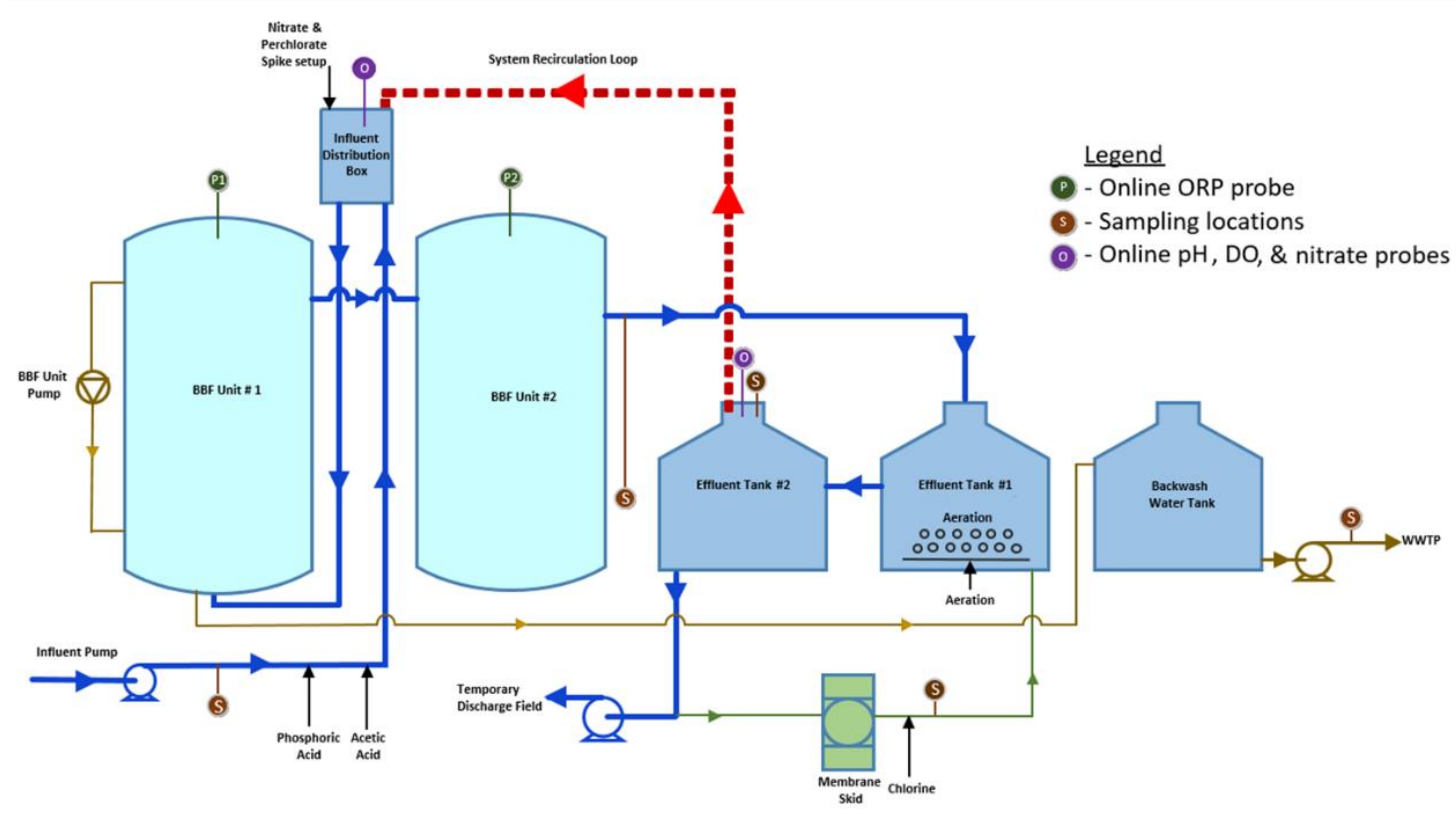
Process Flow Diagram

The BBF system treats water through physical filtration and biological removal using expanded polypropylene beads as the filter media to physically remove suspended solids, while biological growth attached to the filter media removes organic matter and nutrients through biological denitrification.

As shown in Figure 2, groundwater from a well was pumped into an influent distribution box, which then entered one or both of the BBF Unit vessels through the inlet valve at the bottom of each vessel. Acetic acid and nutrients were added to the influent before it reached the influent distribution box through an inline mixer. Water then flowed upward through the filtration media and the strainer block (to retain the media) before leaving the vessel. Treated effluent was collected in the BBF effluent tank. The filtered water was collected in BBF Effluent Tank #1, where it underwent post-aeration to raise dissolved oxygen (DO) levels before being discharged to the wastewater treatment plant, discharge field, temporary storage, or post-filtration process. Effluent tank #2 serves as a hold-up tank prior to discharging.

The BBF effluent tank was filled at an 80 gallons per minute (GPM) rate. A 5GPM stream fed a post-filtration process. The objective of the post-filtration process was to prove the system can produce turbidity levels bellow 0.3 NTU for 95 percent of the time and not exceed 1.0 NTU for more than one hour. The post-filtration process labeled as the membrane skid included a membrane (Microza microfiltration module UNV-3003, Pall corporation, US) that used 0.1 micrometer (um) hollow fiber polyvinylidene (PVDF) Microza microfiltration module. The control system for the membrane filtration system had a data logger and remote monitoring capabilities. The data logger was used to record and store turbidity data at 5-minute intervals. After polishing, the water was chlorinated and sent to Effluent Tank #1 where it was eventually discharged to either the wastewater treatment plant, discharge field, or held in a temporary storage tank.

Figure 2: Process Flow Diagram



Source: Tomorrow Water

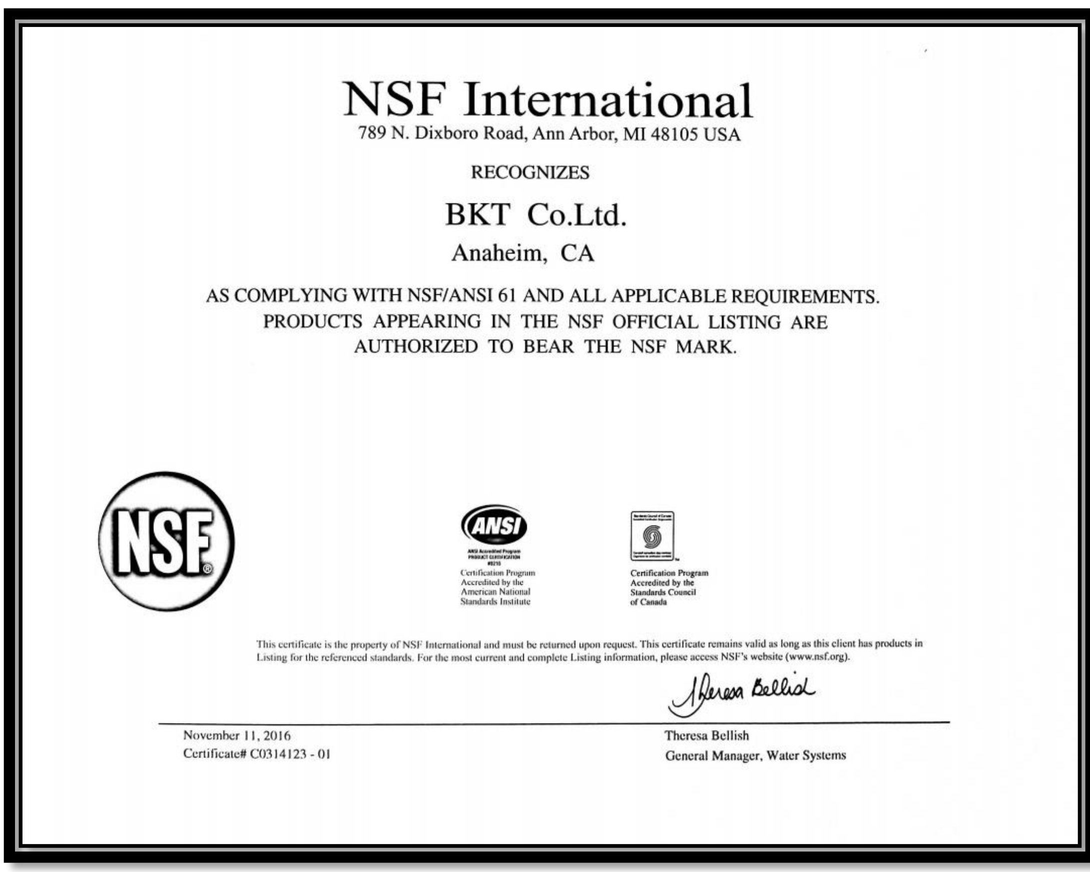
A backwash loop was initiated to keep the system running optimally when a pre-set pressure differential was reached across the media. During the backwashing loop, spent backwash water was cycled within each vessel then drained from the bottom of each vessel to a spent backwash storage tank before being pumped to the City of Barstow WWTP.

In the event the BBF effluent did not meet water-quality goals, the water was recirculated back through the BBF system through an emergency loop. The emergency loop circulates water from the effluent tank back to the influent distribution box and BBF unit vessels until the water meets the discharge MCL. In contrast, the backwash loop, loops the water within the BBF vessel and then is sent to WWTP for further processing. The following sections describe each unit process, the process and water quality monitoring systems, and the effluent and waste disposal practices.

Biofiltration Media

Tomorrow Water obtained National Sanitation Foundation/American National Standards Institute (NSF/ANSI) Standard 61 certification (C0314123-01) on November 11, 2016, as shown in Figure 3. The media is processed in expanded polypropylene form and classified into the halogen-based solution (HBS8) (2.2 x 2.1 x 2.6 millimeters [mm]), HBS20 (2.8 x 2.4 x 3.3 mm), and HBS30 (2.9 x 3.1 x 4.0 mm), according to size.

Figure 3: NSF/ANSI Standard 61 Certification (C0314123-01)



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November 11, 2016
Certificate# C0314123 - 01

Theresa Bellish
General Manager, Water Systems

Source: Tomorrow Water

Biofiltration System Design Parameters

A BBF system with a design capacity of 80 to 500 GPM evaluated the performance of the BBF for nitrate removal. As shown in Figure 2, the BBF system consisted of a filtration unit, pumps, backwash air blowers, a chemical dosing system, effluent tanks, on-line sensors (flow meter, nitrate, pH, turbidity, dissolved oxygen, oxidation-reduction potential [ORP]), a control panel, and an online monitoring system. Chemicals (carbon source and nutrients) were added to the influent water as needed based on the influent flow rate, influent nitrate concentration, and influent DO concentration. Table 4 shows the design parameters for the BBF system evaluated for Title 22 conditional acceptance. The key design parameters for nitrate and perchlorate removal included linear velocity, EBCT, the total suspended solids loading rate, hydraulic loading rate, and nitrate/perchlorate loading rates.

Table 4: Biofiltration System Design Parameters

Parameter	Units	Design (per vessel)	Expected Operating Range During Testing
Flow	GPM	250	80–180
NO_3-N	mg-N/L	26	1.2–26
ClO_4	µg/L	400	4–47
Configuration	—	—	—
Number of BBF Vessels	—	2	1
Flow through Each Vessel	GPM	250	80–180
Polypropylene Media Size	mm	2–4	2–4
Polypropylene Media Depth	ft	10.0	—
Total Polypropylene Media Volume	ft^3	785	—
Number of BBF Effluent Tanks	unit	2	2
BBF Effluent Tank Volume/Tank	gal	14,600	6,500
Number of Backwash Tanks	—	1	1
Backwash Tank Volume/Tank	gal	14,600	6500
Estimated Backwash Flow	gallon per day (GPD)	10,000	500–8,000
Backwash Flow per Total Flow	%	2.8	2.8
Backwash Air/Vessel	Standard cubic feet per minute (SCFM)	58	58
NO_3-N Loading Rate	lb/1,000 ft^3/d	10–120	2.1–47.7
Total Suspended Solids Loading Rate	lb/1,000 ft^3/d	10–300	130–220
ClO_4 Loading Rate	lb/1,000 ft^3/d	0–8	7.3–86.2
Hydraulic Loading Rate	GPM/ft^2	0.5–2.9	1.5–2.3
EBCT	hr	0.3–3.0	0.5–1.0
Linear Velocity	ft/hr	7.0–33	10.0–20.0

Source: Tomorrow Water

Biofiltration System Construction and Installation

The most appropriate lead firm was selected for management and completion of each project task. Descriptions of the project's major tasks follow.

Task 1: General Project Tasks

The first Project Manager was, Joon Min, assisted by Co-Project Manager David Rhu, was responsible for supervising and scheduling all meetings and reports required for this project. The second project manager was Ehsan Mazinani. Beginning in November 2018, Edgar Kim handled general project tasks.

Task 2: Design, Specification, and Test Plan

System design and preparation of the drawing set began following the finalization of the project agreement. A test plan to obtain Title 22 conditional acceptance for drinking water was prepared before operation. The test protocol was changed at every phase to comply with DDW requests.

Task 3: Procurement and Fabrication

A California-based system integrator was fabricated upon approval of engineering drawings. Tomorrow Water staff (Ehsan Mazinani and Dr. Joon Min) inspected the BBF reactor, which was completed on May 10, 2017 (Figure 4). AATech fabricated a 500-GPM BBF treatment system to demonstrate the bio-filtration technology for nitrate and perchlorate removal in the City of Barstow.

Figure 4: Fabricated Biofiltration System Vessel and Connection Devices

Source: Tomorrow Water

Task 4: Installation and Construction

Project construction began with a 0.5 million-gallon-per-day full-scale unit, which operated in the City of Barstow throughout the project. Tomorrow Water conducted an on-site inspection on July 7, 2017, to inspect electrical equipment and the BBF system installation, shown in Figure 5. KANA Engineering Group provided the design and engineering services outline in the scope of work, tools, equipment, labor, transportation, and material required for the project.

When the installation and system configuration of the BBF was complete, a final inspection was conducted to confirm that BBF system components were installed and constructed according to system specifications and the entire BBF system would be operational.

Figure 5: Installed View of Biofiltration System in Barstow by KANA Engineering Group

Source: Tomorrow Water

Fire Incident

The BBF system was damaged by arson, as shown in Figure 6. Before operation, on February 26, 2018, the Barstow WWTP Chief Plant Operator reported that the BBF system was on fire. According to the sheriff, the fire was started by an unidentified arsonist. The male arsonist's motives are unknown, but security footage clearly shows a man leaving the scene and returning to add more fuel to the fire. Law enforcement reported that the same individual probably set three other fires the same night, including one directly adjacent to a diesel storage tank. It is believed that these fires were set maliciously with the intent to cause maximum property damage. The fire damaged:

- Two post-treatment processes.
- Three storage tanks, including effluent tanks and a spent backwash tank.
- Electrical wiring.

After the damaged parts were replaced, the BBF system was tested under a batch process. There was no inoculation of microorganisms during the test run but, at the Lahontan RWQCB 's request, acetic acid was injected into the top of the BBF and the recirculation pump was operated to confirm the system's performance. This process was performed, also at the request of the Lahontan RWQCB, to confirm the removal of perchlorate in the influent groundwater. The collected samples were sent to TestAmerica to measure residual perchlorate concentrations. Detailed water-quality data are described in the following chapter.

Figure 6: Damaged View of Storage Tanks and Post-Treatment Process

Source: Tomorrow Water

Task 5: Operation and Permitting

The full-scale system operated for fine-tuning and to collect data over the course of one-and-a-half years, which included testing for both SWRCB conditional acceptance and safety data sheet (SDS) testing. NSF/ANSI 61 certification was obtained before beginning Title 22 tests.

Task 6: Energy Saving Monitoring

Energy consumption and water savings were monitored consistently throughout the test period.

Task 7: Evaluation of Project Benefits and Knowledge Transfer

Three project questionnaires were prepared by Tomorrow Water at the beginning, middle, and conclusion of the project. For the knowledge transfer plan, Tomorrow Water presented project results at several conferences.

Preparation for the Title 22 Conditional Acceptance Test

Chemical Injection System

For the continuous run of the Title 22 Conditional Acceptance test, the chemicals required for denitrification, NSF/ANSI 61 certified acetic acid (56 percent), and phosphoric acid (85 percent), were stored on-site in high-density polyethylene chemical tanks. The tanks were set up in a concrete secondary containment structure.

Since the influent nitrate was below the MCL, influent nitrate concentration was artificially increased by injecting sodium nitrate into the influent water. The sodium nitrate was stored on-site in a chemical tank on a double intermediate bulk container spill containment pallet.

The sodium perchlorate injection system was prepared for the Title 22 high-perchlorate loading test protocol. Perchlorate stock was prepared from sodium perchlorate powder the day before the loading test and brought on-site for testing. Chemical stock solutions were stored in a refrigerator at 39°F (4°C) until their use.

Online Process and Water Quality Monitoring System

Influent and effluent nitrogen species (NO_3-N + NO_2-N), pH and DO were monitored continuously during the Title 22 test protocol. Effluent ORP, used as a surrogate for perchlorate, was monitored continuously. Perchlorate concentrations were determined by regular grab samples sent to a laboratory for analysis. The monitoring locations for each parameter appear in Figure 2.

Data generated by the sensors were recorded and stored by the BBF system data logger at 1-minute intervals. These data were extracted periodically to observe and study system performance. The online trends were also on the system's screen interface.

In addition to online monitoring, grab samples were collected regularly according to the sampling schedule described in the test protocol and shown in Table 5.

Post-Aeration System

A post-aeration process of effluent from the biological treatment filtration was essential for the achievement of four water quality objectives:

1. DO enhancement: Following the reduction of nitrate and perchlorate in an anaerobic condition, the dissolved oxygen of the effluent water is increased by sparging air into the effluent tank. This achieves the Water Board required DO concentration for discharging and removes residual acetic acid, which can react with chlorine and produce toxic byproducts.. The aeration system consisted of four diffusers, two blowers, and moving-bed media.
2. Residual carbon source removal: To remove perchlorate and nitrate, acetic acid was injected into the BBF system. Post-aeration therefore reduced the level of excess acetic acid in the effluent tank and minimized the formation of disinfection by-products (DBP) in the effluent.
3. Sulfide removal: The anaerobic condition produces a potential sulfite-reducing condition that in turn generates an unpleasant odor. The post-aeration process, therefore, removed sulfide, which can be accomplished through either biological oxidation or air stripping.
4. Biomass separation: The moving-bed media inside the effluent tank provided sufficient surface area to capture biological matter.

Table 5: Analytical Methods and Analyzers Used for Online and Grab Samples

Parameter	Analytical Method
Total Alkalinity	SM 2320B
Ammonia Nitrogen	EPA350.1
Aluminum	EPA200.8
Biodegradable Dissolved Organic Carbon (bDOC)	Allgeier – 1996
Chloride	EPA 300.0A
Color	SM 2120B
Copper	EPA200.8
Dissolved Oxygen	In-line DO meter, HACH
Fecal Coliform Bacteria	SM 9221B
Fluoride	SM 4500F-C
Haloacetic Acids	SM 6251B
Heterotrophic plate counting	SM 9215B
Hydrogen Sulfide	SM4500-S
Nitrate/Nitrite (Grab)	EPA 300.0A
Nitrate (In-line)	In-line NITRATAX HACH analyzer
ORP	In-line ORP meter, HACH
Perchlorate	EPA 314.0
pH	In-line pH meter, HACH
Silver	EPA200.8
Sulfate	EPA 300.0A
Temperature	In-line pH meter, HACH
Trihalomethanes	EPA 524.2
Total Organic Carbon and Dissolved Organic Carbon	SM 5310C
Total Coliform Bacteria	SM 9221B
Turbidity	In-line turbidity meter, Thermo
Zinc	EPA200.8
Chlorine	In-line free-chlorine meter, HANNA

Source: Tomorrow Water

Test Protocol for Drinking Water Conditional Acceptance

Demonstration testing consisted of six phases, shown in Table 6. Each test phase was developed with support from Stantec and DDW. Grab samples were collected according to a sampling schedule and sent to Eurofins Eaton Analytical Laboratory for analysis. The analytical methods/analyzer was used for monitoring various water-quality parameters during the test. Detailed test plans and results are described in Chapter 3.

Table 6: Testing Schedule for the Drinking Water Conditional Acceptance Title 22

Test Phases	Description	Responsible Party
Phase 1	Process acclimation sampling	Tomorrow Water
Phase 2	EBCT optimization	Tomorrow Water
Phase 3	Carbon source optimization	Tomorrow Water
Phase 4	Trail loading test Acclimation phase for elevated influent nitrate	Tomorrow Water
Phase 5	Optimized normal operations	Stantec
Phase 6	Simulation of worst-case scenarios	Stantec

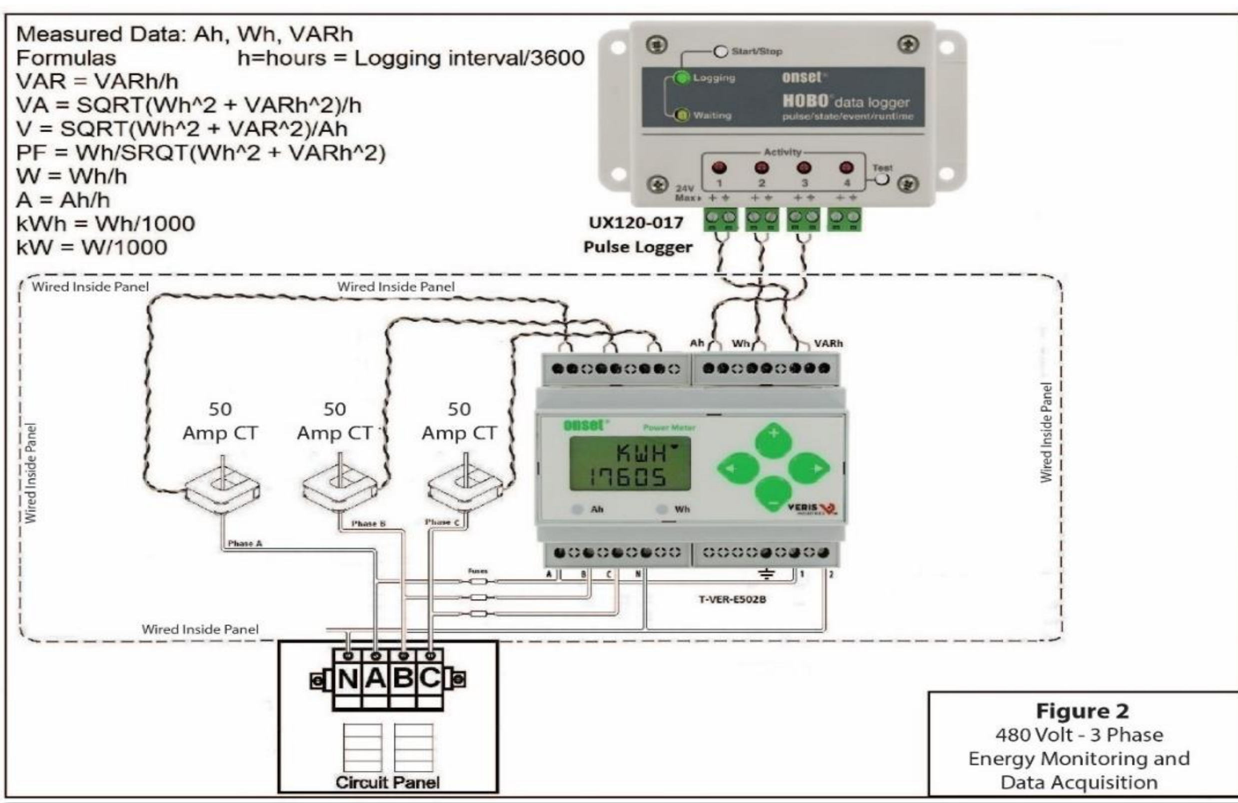
Source: Tomorrow Water

Energy Consumption Monitoring and Verification Plan

Energy monitoring and data acquisition for the BBF water treatment facility included sensors that monitored amperage, watts, and voltage. The power meter calculated energy-consumption variables, and the data were logged with a pulse data logger.

Energy consumption data were collected from the main influent pump, effluent pump, chemical feed system, air-scouring equipment, and other electrical equipment. Figure 7 shows the energy monitoring and data acquisition setup. The purpose of the energy monitoring and verification was to demonstrate project benefits: energy savings, cost savings, and economic and environmental benefits.

Figure 7: Energy Monitoring and Data Acquisition Setup



Source: Tomorrow Water

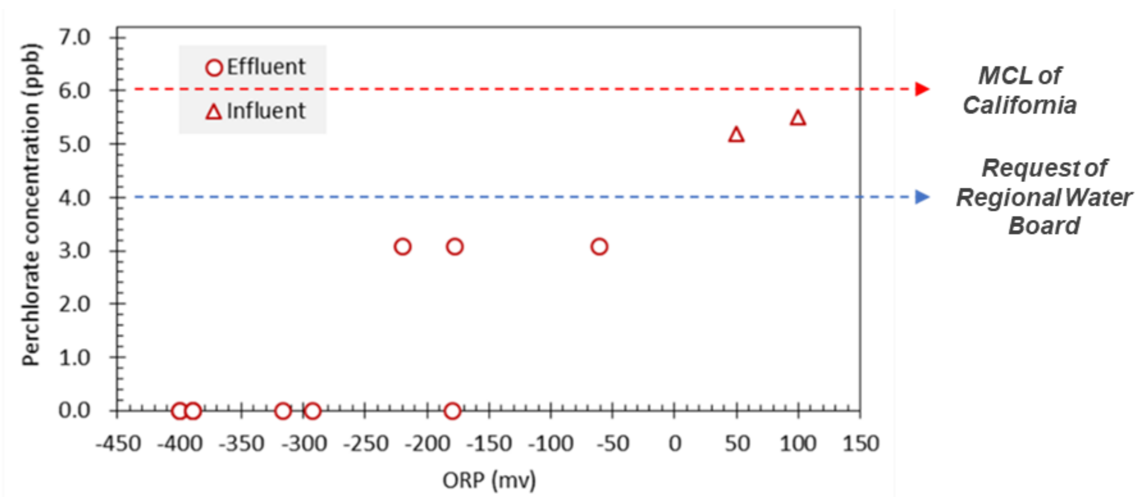
CHAPTER 3: Project Results

Monitoring Water Quality on the Batch and Continuous Operation

Tomorrow Water used ORP as a perchlorate monitoring parameter for the effluent water. Effluent water was sampled at each ORP location and analyzed using the United States Environmental Protection Agency (U.S. EPA) 314.0 by EPA-certified Lab, TestAmerica. Influent and effluent samples were collected and analyzed.

Figure 8 shows the correlation between the ORP and perchlorate concentrations in a batch mode. From August 7, 2016 to September 28, 2018, the BBF effluent was discharged following approval by the Lahontan RWQCB. All effluent samples satisfied both the California MCL and the Lahontan RWQCB. Project stakeholders, including DDW, the Lahontan RWQCB, Stantec, and Tomorrow Water had a conference call and concluded that the BBF system should operate in continuous mode.

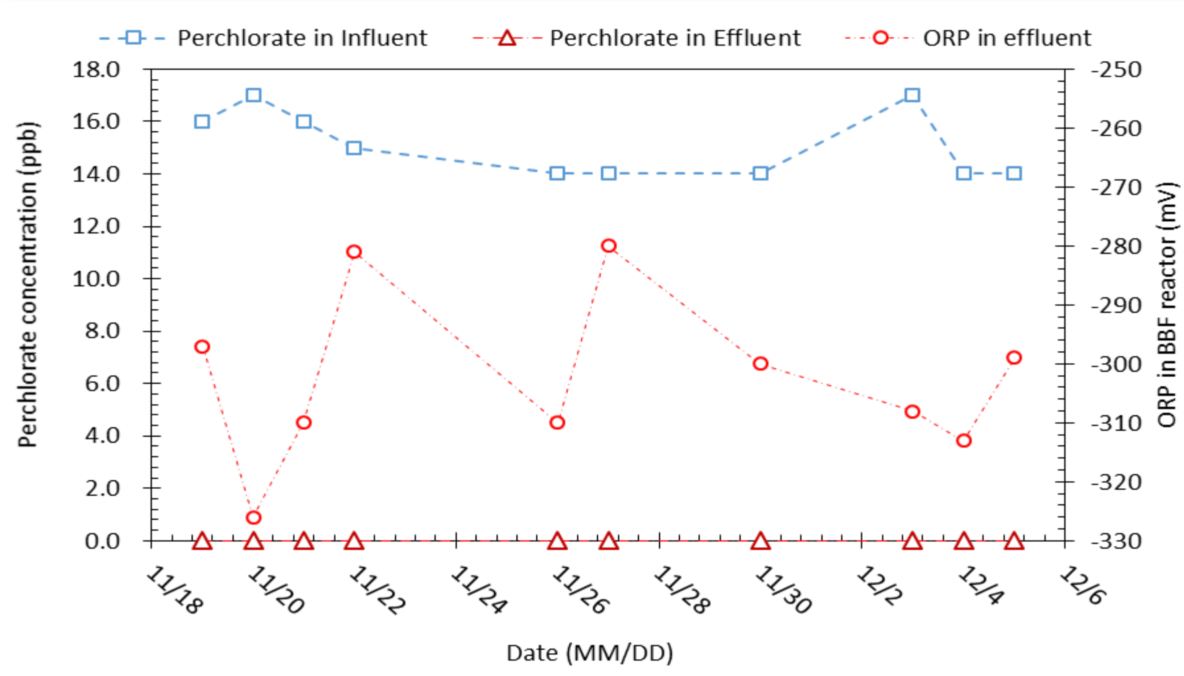
Figure 8: Correlation Between Oxidation Reduction Potential and Perchlorate Concentration



Source: Tomorrow Water

After running continuously for two weeks, influent and effluent water samples were analyzed by TestAmerica to determine perchlorate concentrations. As shown in Figure 9, the BBF system treated the influent water to a perchlorate range of 14 ug/L to 17 ug/L to a non-detect level (<4 ug/L), with ORP ranging from –328 mV to –299 mV.

Figure 9: Perchlorate Removal Performance of Biofiltration System in Continuous Operation Mode



Source: Tomorrow Water

Test Protocol for Drinking Water Conditional Acceptance

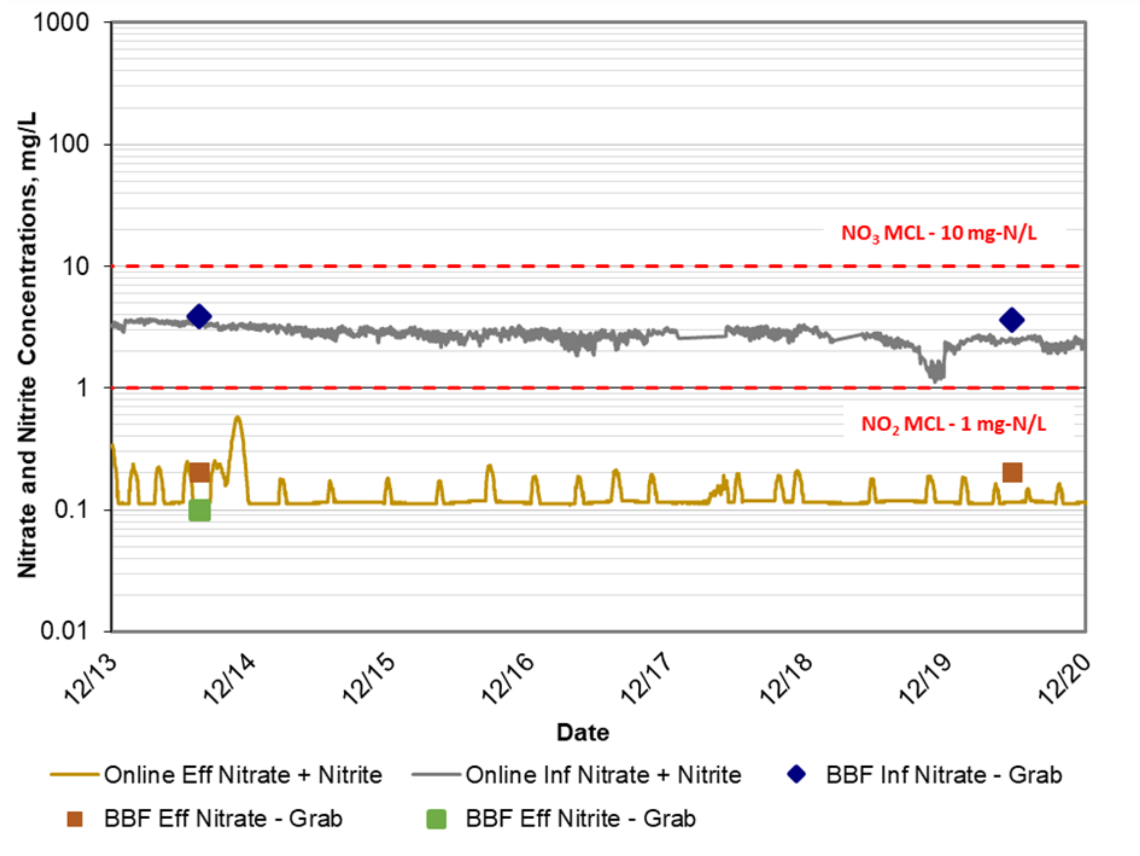
Tomorrow Water completed phases 1 to 4 of the project. Since data from phases 1 to 4 showed that the influent nitrate was consistently below the evaluation criteria, sodium nitrate was introduced into the influent stream to increase influent nitrate concentration to 3 to 15 mg-N/L. Stantec monitored the system through Phases 1 to 4 and monitored the Title 22 Conditional Acceptance Test as a third-party operator through phases 5 and 6.

Phase 1: Process Acclimation

Phase 1 acclimated nitrate-reducing indigenous microorganisms present in the Soapmine aquifer in the BBF system. During the entire test period, NSF/ANSI Standard 61-certified acetic acid and phosphoric acid were added to the influent water as both an electron donor for nitrate reduction and a nutrient for the biological reaction. Once BBF effluent nitrate and perchlorate concentrations met the evaluation criteria (nitrate: <10 mg-N/L, perchlorate: <6 ug/L) for one week of operation, Phase 2 began.

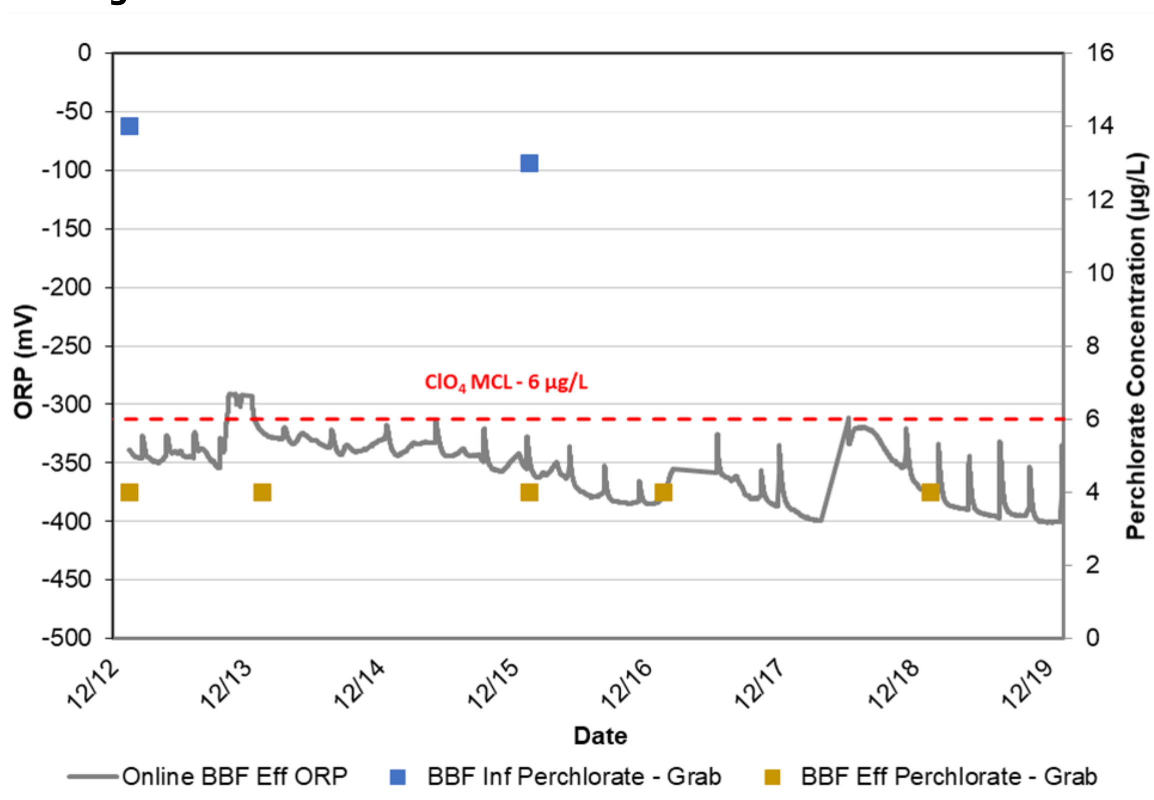
During this phase, the BBF system operated for a week at an EBCT of 45 minutes, with acetic acid dosing at two times the stoichiometric demand. Figure 10 and Figure 11 show the nitrate and perchlorate trends and grab sample results in influent and effluent water during this phase. These results show that the influent perchlorate was around 14 µg/L, and influent nitrate concentration was approximately 4 mg-N/L (below the MCL of 10 mg-N/L). As shown in the figures, the effluent nitrate and effluent perchlorate concentrations consistently remained below 1 mg-N/L and 4 µg/L, respectively. Effluent nitrite concentration also consistently remained around 0.1 mg-N/L.

Figure 10: Influent and Effluent Nitrate Trends for Phase 1



Source: Tomorrow Water

Figure 11: Influent and Effluent Perchlorate Trends for Phase 1



Source: Tomorrow Water

Phase 2: Empty Bed Contact Time Optimization

Phase 2 determined the optimum EBCT required to produce acceptable BBF effluent nitrate and perchlorate concentrations. During this phase, system performance at three different EBCTs was evaluated, each for approximately one week, as shown in Table 7. The acetic acid dosage was maintained at twice the stoichiometric demand. If BBF effluent nitrate and perchlorate concentrations met the evaluation criteria for at least one continuous week during testing, the EBCT was lowered to the next testing condition. If nitrate or perchlorate concentrations exceeded the evaluation criteria at any time during a testing condition, the EBCT was returned to the previous testing condition. Upon determination of optimum EBCT by the end of Phase 2, the system was set to operate at that EBCT for at least 24 hours before initiating Phase 3.

Table 7: Testing Conditions for Phase 2

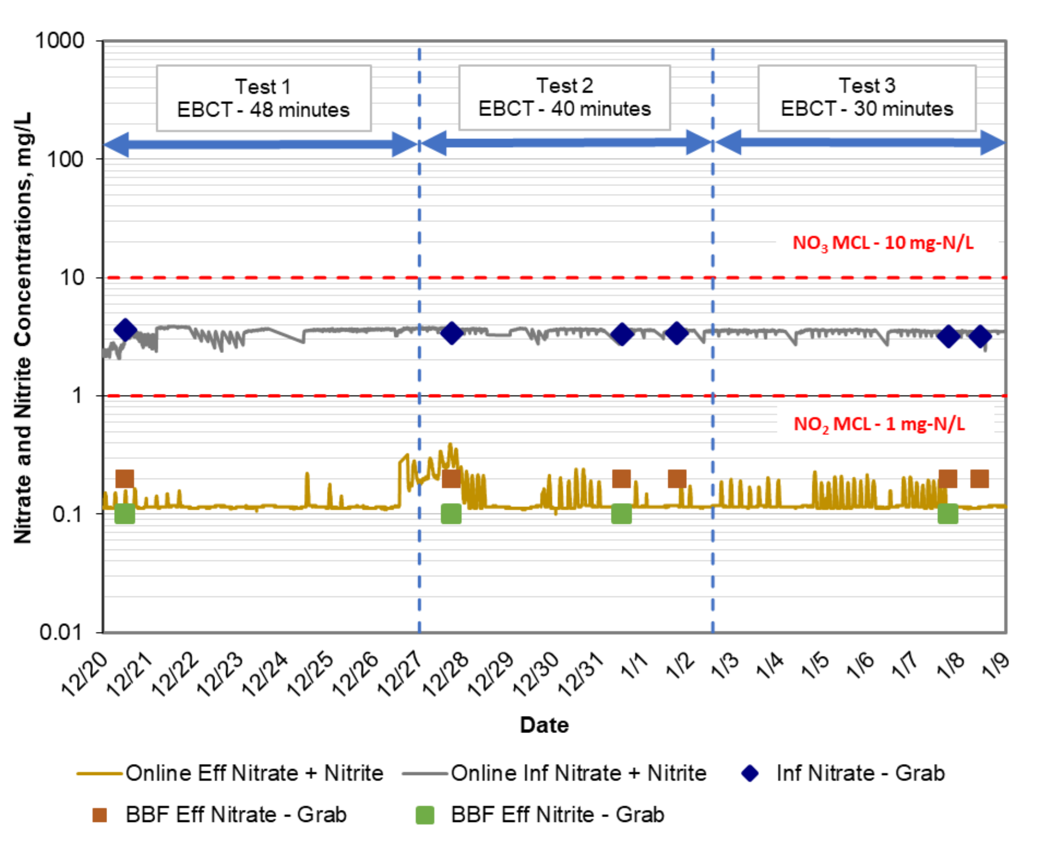
Parameter	Test 1	Test 2	Test 3
EBCT (minutes)	48	40	30
Flow Rate (GPM)	120	144	181
Feed acetate (56%) dosing rate (GPD)	23.2	35.1	44.1
Current feed NO_3-N concentration (mg/L)	7.2	7.2	7.2
Current feed ClO_4 concentration (μg/L)	16	16	16

Source: Tomorrow Water

The calculation for testing conditions is based on 3.5 mg/L DO, 7.2 mg/L NO_3-N, and well-water pump flow rate in the feed with acetic acid of 56 percent.

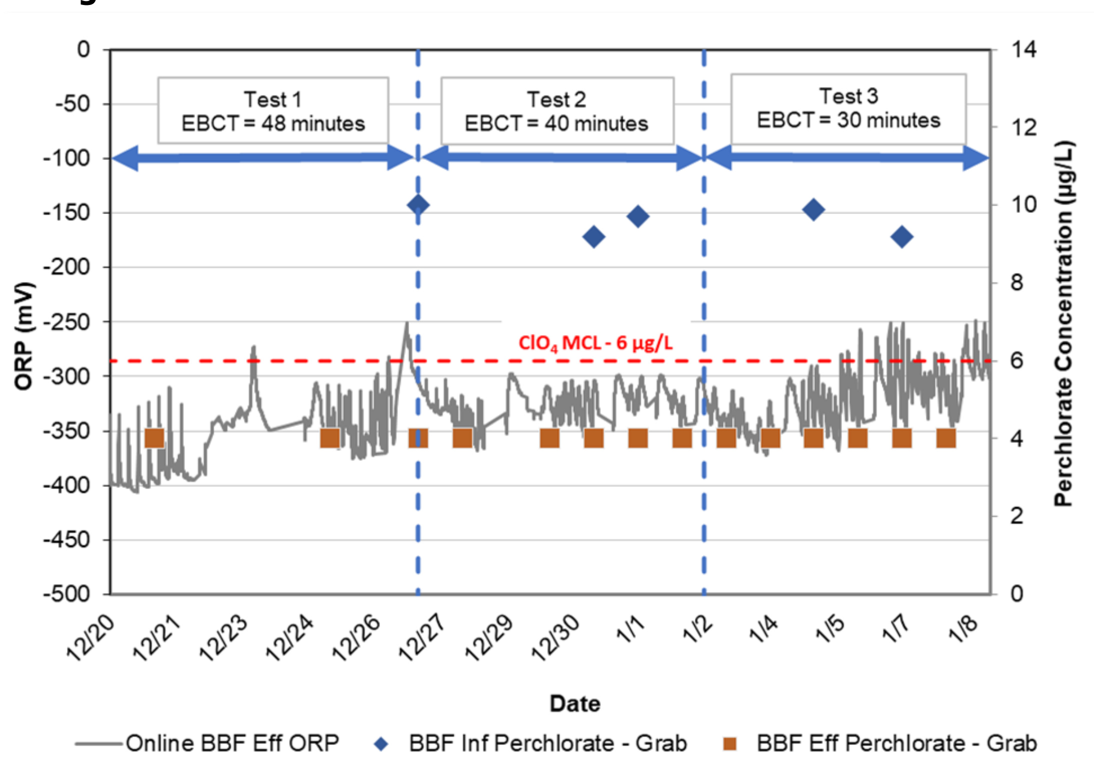
Figure 12 and Figure 13 show nitrate and perchlorate trends and grab-sample results in both influent and effluent water. Results show that over the test duration, the influent perchlorate gradually decreased from 12 μg/L to 9 μg/L. Similarly, the influent nitrate concentration gradually decreased to below 3.5 mg-N/L. Under all three test scenarios, the effluent nitrate and perchlorate concentrations remained consistently below 1 mg-N/L and 4 μg/L, respectively. The effluent nitrite concentration also consistently stayed around 0.1 mg-N/L. An EBCT of 30 minutes caused frequent backwashing cycles when compared with an EBCT of 48 minutes. Based on these results, an EBCT of 35 minutes was selected for immediate subsequent testing, and 45 minutes eventually became the basis for Phases 5 and 6.

Figure 12: Influent and Effluent Nitrate Trends for Phase 2



Source: Tomorrow Water

Figure 13: Influent and Effluent Perchlorate Trends for Phase 2



Source: Tomorrow Water

Phase 3: Carbon Dosing Optimization

Phase 3 determined whether the acetic acid dosage could be further reduced while complying with nitrate and perchlorate effluent limits, using the optimum EBCT determined during Phase 2. During this phase, the BBF system operated at an EBCT of 35 minutes and the acetic acid dosing was reduced to two times the stoichiometric demand. If the nitrate or perchlorate concentrations exceeded the evaluation criteria at any time during the 1-week period of low COD dosing, then the acetic acid dosage reverted to the previous testing condition. Table 8 shows the sampling schedule for this phase.

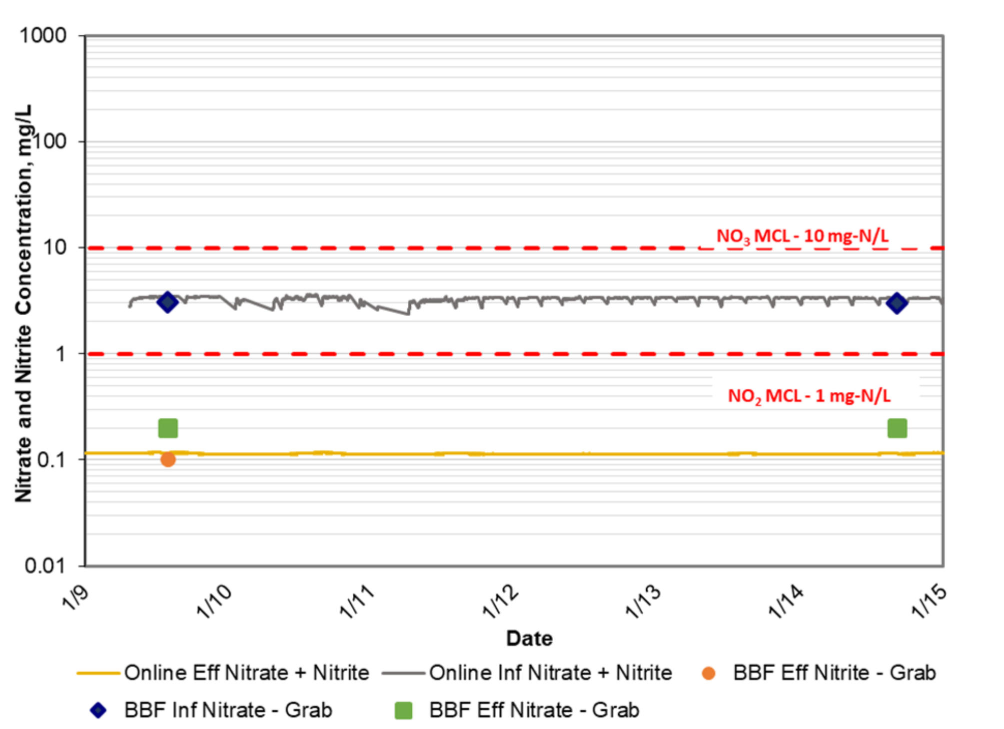
Table 8: Sampling Plan for Phase 3

Parameters	Influent Sampling Frequency	BBF Effluent Sampling Frequency	BBF Backwash Water Sampling Frequency
ClO_4	2/week	5/week	1/week
NO_3-N	2/week	2/week	1/week
NO_2-N	1/week	1/week	1/week
NH_3-N	1/week	1/week	1/week
SO_4	1/week	1/week	1/week
H_2S	1/week	1/week	1/week
Alkalinity	1/week	--	--
bDOC	1/week	1/week	1/week
Total Organic Carbon	2/week	5/week	1/week

Source: Tomorrow Water

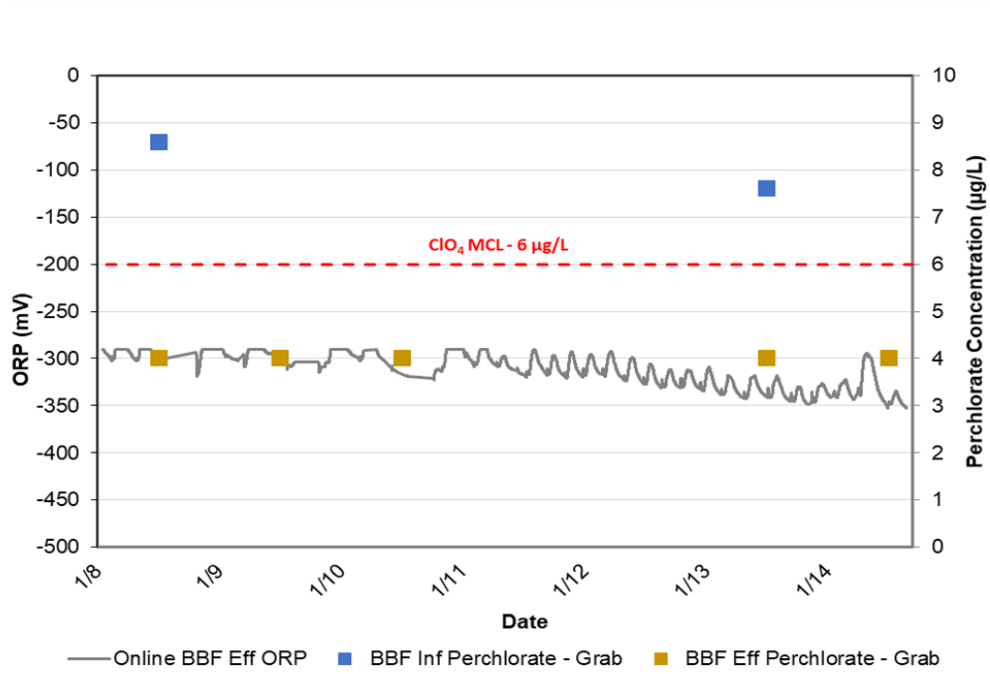
Figure 14 and Figure 15 illustrate nitrate and perchlorate trends and grab sample results in both influent and effluent water during this phase. Results show that over the test duration, the influent perchlorate gradually decreased from 9.2 µg/L to 7.6 µg/L. Similarly, influent nitrate concentration also steadily decreased to 3 mg/L. These results show that even at the reduced carbon dose of 1.7 times the stoichiometric demand, the BBF system continued to meet effluent water quality goals. Effluent nitrate and effluent perchlorate concentrations consistently stayed below 1 mg-N/L and 4 µg/L, respectively. Effluent nitrite concentration also remained consistently around 0.1 mg-N/L. Under these influent water quality conditions, the carbon-to-nitrogen ratio of 1:1.7 met water quality goals. The higher carbon-to-nitrogen ratio (C/N ratio) was required to treat Soapmine aquifer groundwater because of its perchlorate contamination.

Figure 14: Influent and Effluent Nitrate Trends for Phase 3



Source: Tomorrow Water

Figure 15: Influent and Effluent Perchlorate Trends for Phase 3



Source: Tomorrow Water

Phase 4: Nitrate Trial Loading Test and Acclimation

After Phase 3, a nitrate and perchlorate trial-loading test was performed where influent nitrate and perchlorate concentrations were artificially increased to 12 mg-N/L and 300 µg/L, respectively. The test was conducted for only two EBCTs to send effluent to storage instead of discharging it offsite in case contaminants exceeded effluent limits. Both effluent tanks and BBF

2 units were drained before testing, and the effluent pumps were turned off manually. All the treated water was collected and stored in effluent tanks and BBF 2 units until water quality results from the laboratory were received. A backwash was also performed before the test to avoid interruption during the test. The acetic acid dosage was maintained at 1.7 times the stoichiometric demand (based on influent nitrate concentration observed during the phase). Table 9 shows the sampling plan for this trial. Perchlorate and nitrate spiking ended after the last grab sample. The system was then allowed to stabilize to pre-spiking conditions until the effluent water quality met evaluation criteria.

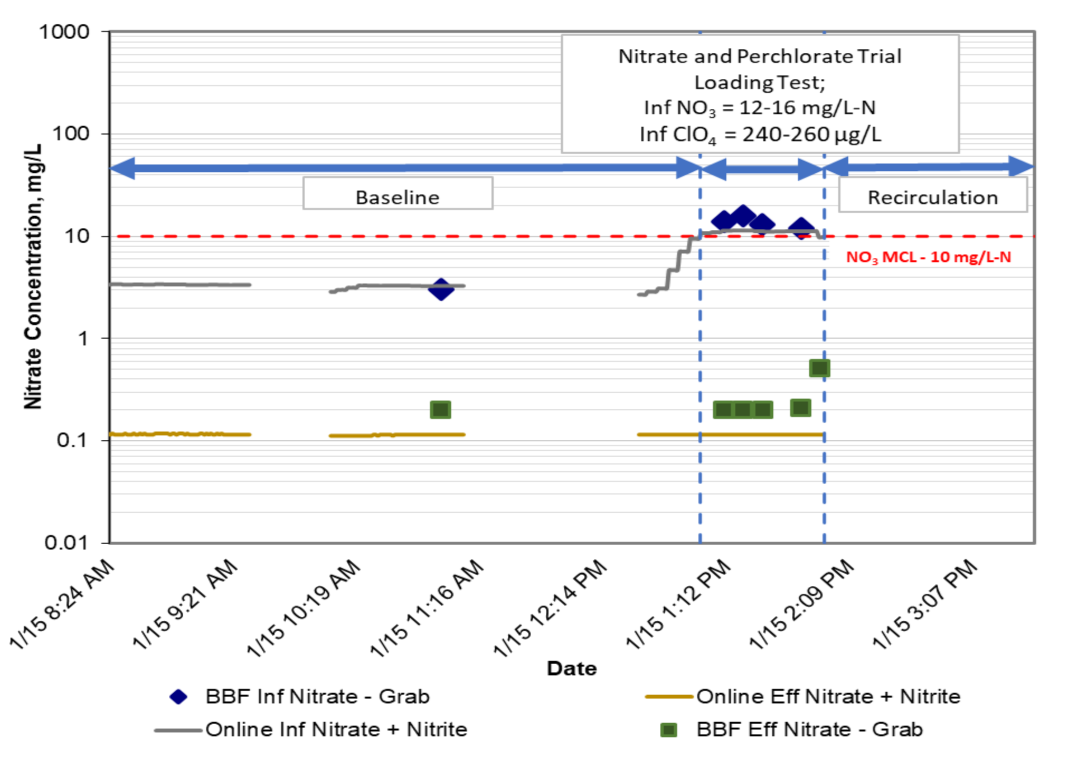
Table 9: Sampling Plan for Phase 4

Sampling Time	Sampling Locations	Parameters	Comments
T = 0 min	Influent, BBF Effluent	NO_3-N, ClO_4	Baseline concentrations before spiking Start nitrate and perchlorate spiking at T=0 EBCT
T = 1.0 BCT	Influent, BBF Effluent	NO_3-N, ClO_4	
T = 1.25 EBCT	Influent, BBF Effluent	NO_3-N, ClO_4	
T = 1.5 EBCT	Influent, BBF Effluent	NO_3-N, ClO_4, TOC	
T = 2.0 EBCT	Influent, BBF Effluent	NO_3-N, ClO_4	Stop spiking at T=2.0 EBCT
T = 2.25 EBCT	Influent, BBF Effluent	NO_3-N, ClO_4	

Source: Tomorrow Water

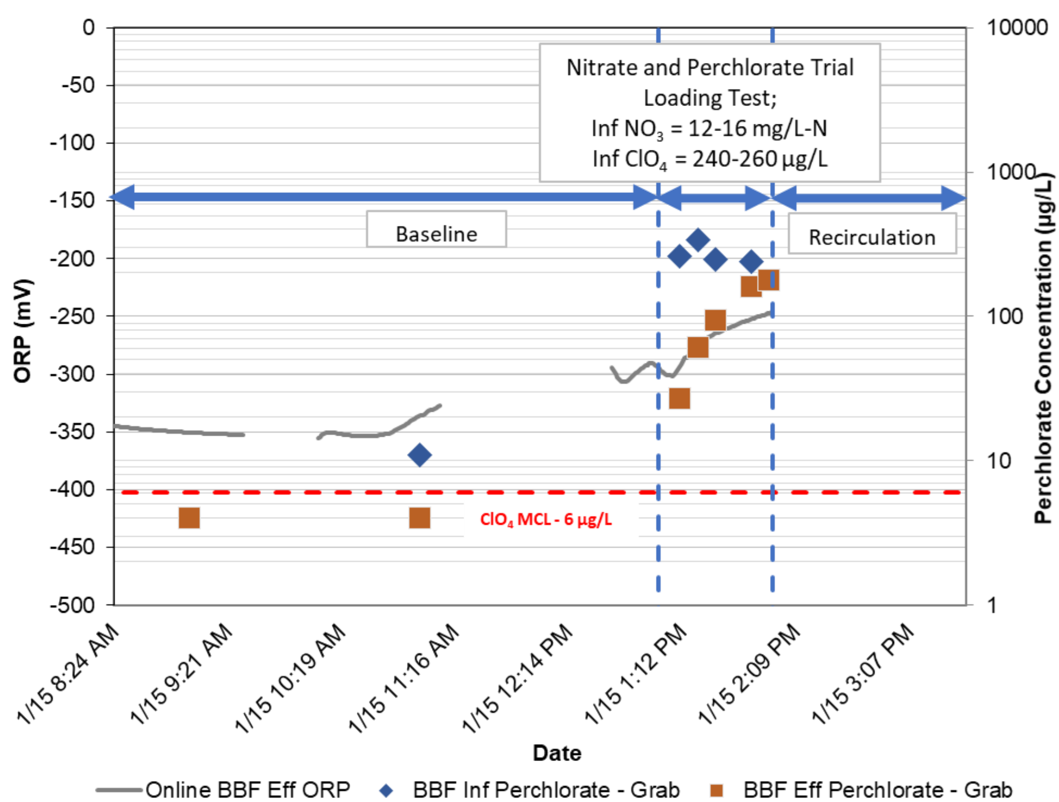
The test results show that the effluent nitrate was consistently below 1 mg-N/L throughout the test period, as shown in Figure 16 and Figure 17. Effluent nitrite was not analyzed during this test. Effluent perchlorate concentration gradually increased during the test. By the end of testing, effluent perchlorate was detected at 180 µg/L. These results indicate that the denitrifying bacteria in the BBF system has a higher preference for nitrate as a source of electron acceptors than perchlorate. After 2 EBCT, the effluent perchlorate concentration exceeded the effluent water criteria. This also shows that a richer bacterial community is required to reduce both high concentrations of nitrate and perchlorate. Since the effluent perchlorate concentration was high, the water was recirculated through the system for several hours. After recirculation, grab samples were collected and sent to a laboratory for analysis. The water was discharged to the temporary irrigation field after receiving the laboratory test results.

Figure 16: Influent and Effluent Nitrate Trends for the Trial-Loading Test



Source: Tomorrow Water

Figure 17: Influent and Effluent Perchlorate Trends for the Trial-Loading Test

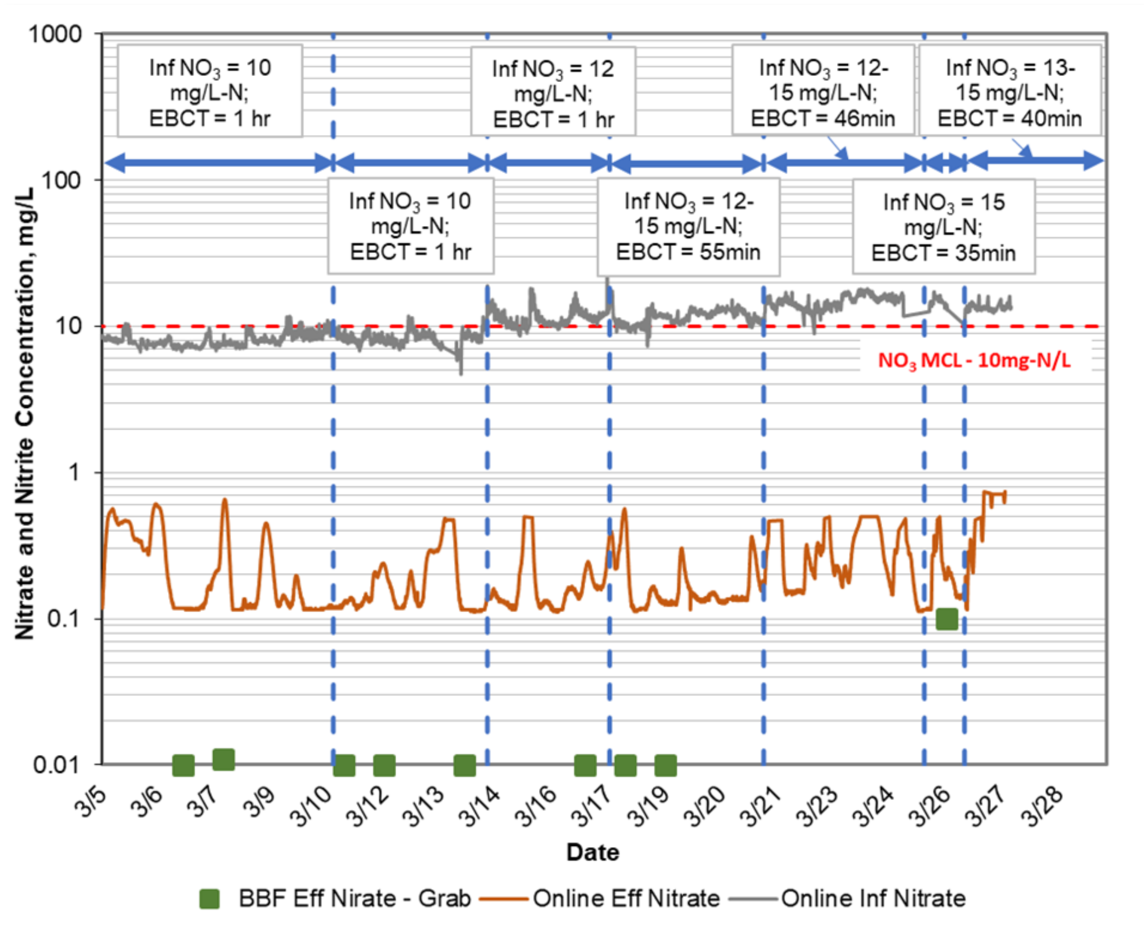


Source: Tomorrow Water

Since influent nitrate and perchlorate concentrations were consistently below water-quality goals, sodium nitrate was introduced into the influent stream to meet a target influent nitrate concentration of 15 mg-N/L (per discussion with DDW). Influent nitrate concentrations were monitored with an online sensor located in the influent distribution box. Influent and effluent perchlorate and effluent nitrate grab samples were collected regularly to monitor system performance. EBCT was increased to 60 minutes during acclimation, and the influent nitrate concentration was gradually increased so that effluent nitrate and perchlorate concentrations did not exceed water-quality goals.

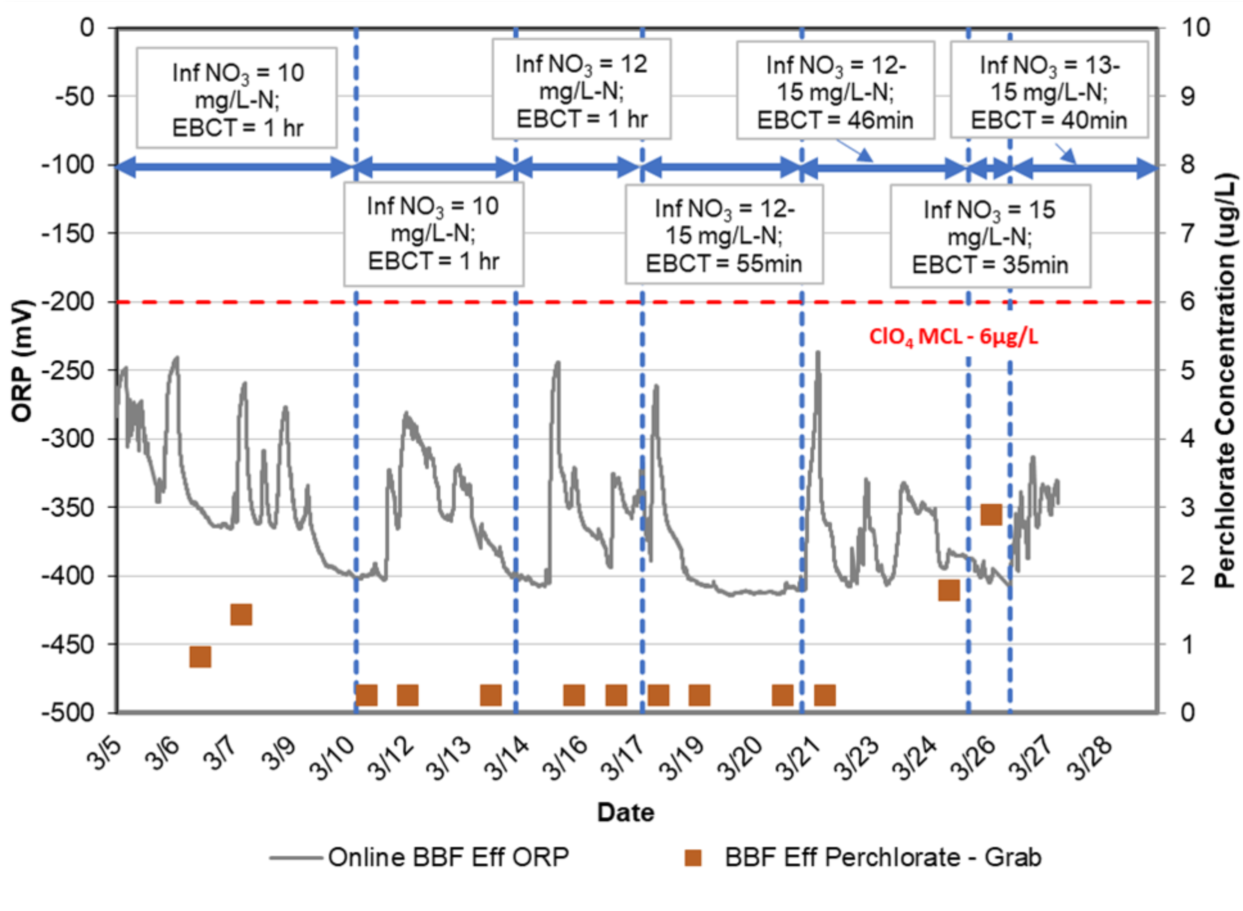
After water-quality goals were met, EBCT was slightly reduced while still maintaining effluent water-quality goals. An EBCT of 45 minutes was the basis for Phase 5 and Phase 6 testing. This increase from the minimum of 30 or 35 minutes from Phase 2 provided additional leeway for treating elevated nitrate levels, as well as providing an additional buffer for spiking tests after Phase 4 trial-loading test results were reviewed. The reacclimation phase lasted eight weeks. During this period, the acetic acid dosage was maintained at 1.7 times the stoichiometric demand (based on influent nitrate concentration). Figure 18 and Figure 19 show nitrate and perchlorate trends during a portion of this phase.

Figure 18: Influent and Effluent Nitrate Trends for Phase 4



Source: Tomorrow Water

Figure 19: Influent and Effluent Perchlorate Trends for Phase 4



Source: Tomorrow Water

Phase 5: Optimized Normal Operation

The objective of this phase was to operate the system for one week under optimum EBCT, with carbon dosing rates determined during the re-acclimation phase. During this phase, the system operated for a week at an EBCT of 45 minutes, with acetic acid dosing at 1.7 times the stoichiometric demand. The nitrate concentration in the influent stream was kept at >15 mg-N/L by dosing sodium nitrate to the influent stream. Water quality samples were collected, as shown in Table 10. Disinfected filtered effluent samples were also collected and analyzed for Trihalomethanes, haloacetic acids, and microbial indicators to determine the disinfection byproduct formation potential of the process under normal operation.

Table 10: Sampling Plan for Phase 5

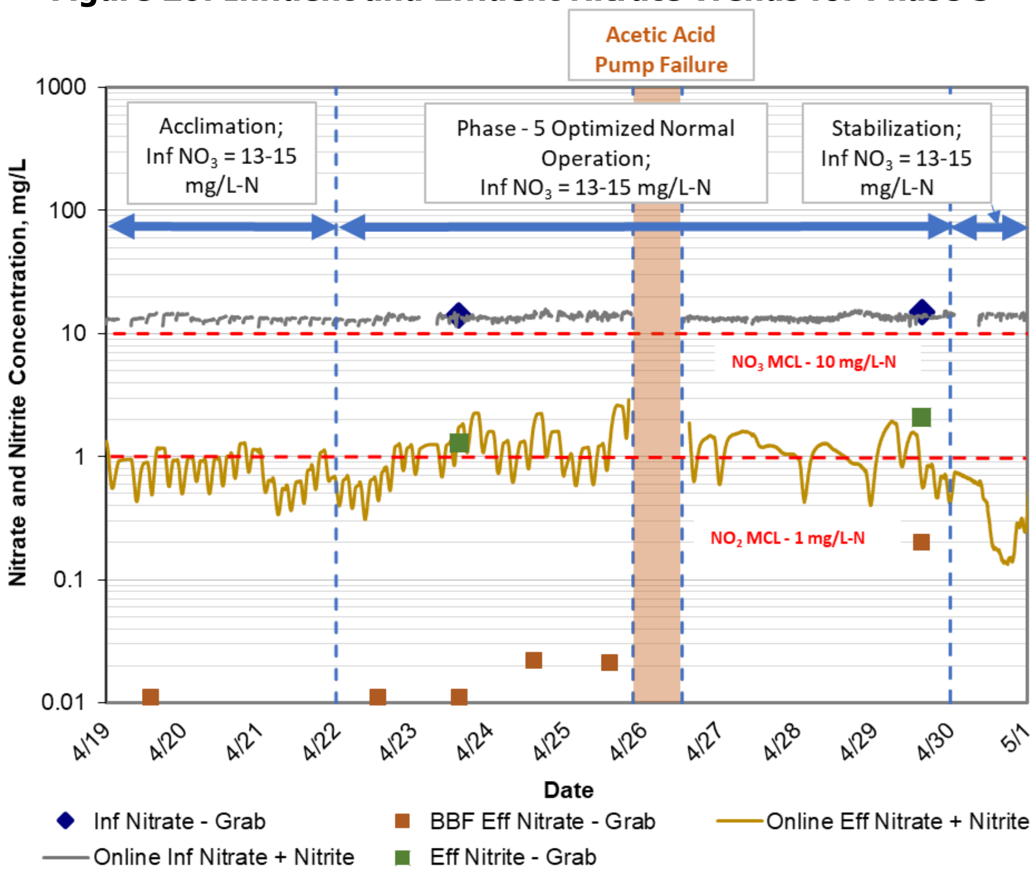
Parameters	Influent Sampling Frequency	BBF Effluent Sampling Frequency	Disinfected Filtered Effluent Sampling Frequency	BBF Backwash Water Sampling Frequency
ClO_4	2/week	5/week	—	2/week
NO_3-N	2/week	5/week	—	2/week
NO_2-N	1/week	2/week	—	2/week
NH_3-N	1/week	1/week	—	2/week
SO_4	1/week	1/week	—	—
H_2S	1/week	1/week	—	—
Alkalinity	2/week	—	—	—
bDOC	1/week	1/week	—	2/week
TOC	1/week	1/week	—	2/week
Trihalomethanes	—	—	2/week	—
Haloacetic acids	—	—	2/week	—
Heterotrophic plate counting	—	—	2/week	—
Total Coliform Bacteria	—	—	2/week	—
Fecal Coliform Bacteria	—	—	2/week	—
Aluminum	—	—	2/week	—
Chloride	—	—	2/week	—
Color	—	—	2/week	—
Copper	—	—	2/week	—
Fluoride	—	—	2/week	—
Foaming Agents	—	—	2/week	—
Silver	—	—	2/week	—
Zinc	—	—	2/week	—

Source: Tomorrow Water

Figure 20 and Figure 21 present the nitrate and perchlorate trends and grab sample results in influent and effluent water during this phase. As shown in these figures, the effluent nitrate and effluent perchlorate concentrations remained below 1 mg-N/L and 4 μg/L, respectively. During this phase of testing, the effluent nitrate and perchlorate concentrations were increasing, which likely was caused by a malfunctioning acetic acid pump. . Effluent nitrite concentration was also above MCL (10 mg-N/L) during this test period, indicating incomplete biological denitrification, which could be attributed to either improper functioning or failure of the acetic acid pump. The presence of nitrite may also have been caused by other factors such as low operating pH, high carbon-to-nitrogen ratios, or slower kinetics at low nitrite concentrations, which require longer EBCT. During this phase, only one set of influent and effluent total organic carbon (TOC) grab samples was collected. The influent and effluent TOC concentrations were 24.2 mg/L and 9 mg/L, respectively, indicating that there was sufficient carbon for denitrification; however, the data was insufficient and, therefore, inconclusive.

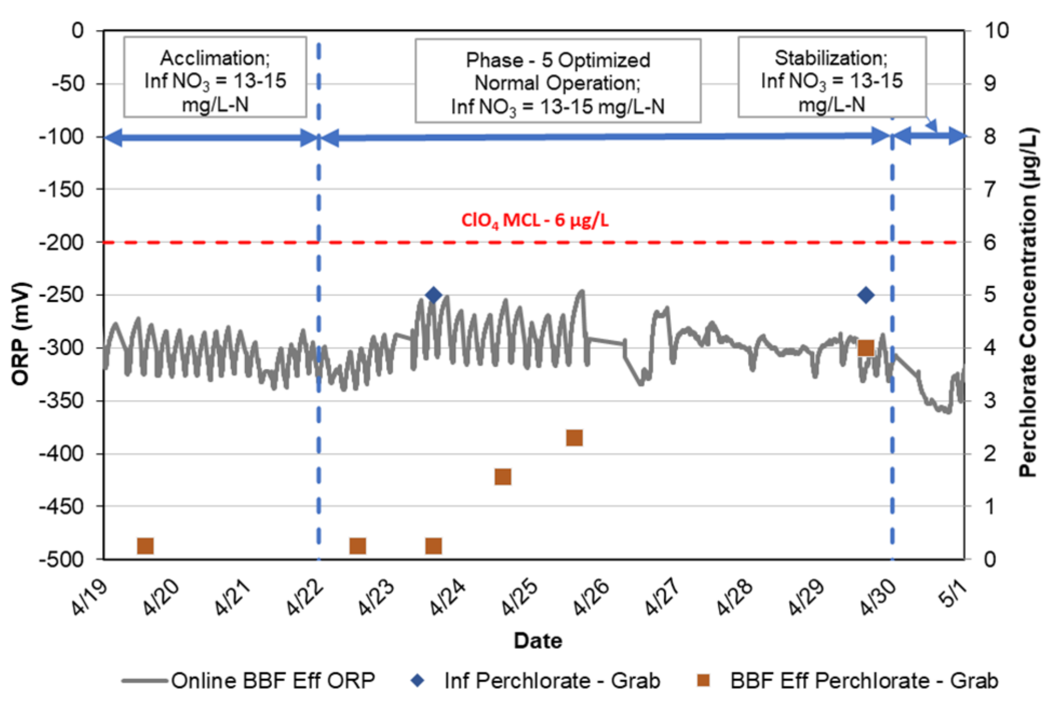
During Phase 5, along with influent and effluent nitrate and perchlorate, the turbidity of treated effluent from the membrane filtration system was monitored. The monitoring data showed that the membrane filtrate turbidity stayed below 0.3 NTU for 95 percent of the time and never exceeded 1.0 NTU, which met DDW requirements for filtered water.

Figure 20: Influent and Effluent Nitrate Trends for Phase 5



Source: Tomorrow Water

Figure 21: Influent and Effluent Perchlorate Trends for Phase 5



Source: Tomorrow Water

Phase 6: Simulation of Worst-Case Scenario

The impact of various worst-case scenarios on system performance was assessed during Phase 6. The optimum EBCT and acetic acid dose, which were determined in previous phases, were used during this phase. The following four worst-case scenarios were simulated:

1. High-nitrate loading
2. High-perchlorate loading
3. Electron-donor failure
4. Intermittent operation (in progress)

High-Nitrate Loading Scenario

The impacts of high-nitrate and high-perchlorate loadings on BBF system performance were evaluated during this phase. The high-nitrate loading scenario was conducted first, followed by the high-perchlorate loading scenario. Before the start of each scenario, influent and effluent perchlorate and nitrate grab samples were taken to record baseline conditions. The optimum EBCT and C/N ratio (determined during the re-acclimation phase) were used for these scenarios. In cases where effluent water quality, particularly ORP values and nitrate concentrations, exceeded the discharge criteria, the BBF system initiated emergency recirculation. Once water quality goals were met, the system resumed normal operation.

For the nitrate-loading scenario, the influent nitrate was artificially raised from 15 to 25 mg-N/L for 24 hours. The sampling plan for this scenario is shown in Table 11. Nitrate spiking ended after the last grab sample. The system was then stabilized for pre-spiking conditions, with a nitrate concentration of 15 mg/L in the influent for at least 20 EBCTs. The BBF system operated at an EBCT of 45 minutes, with acetic acid dosing 1.7 times the stoichiometric demand.

Table 11: Sampling Plan for High Nitrate Loading Scenario

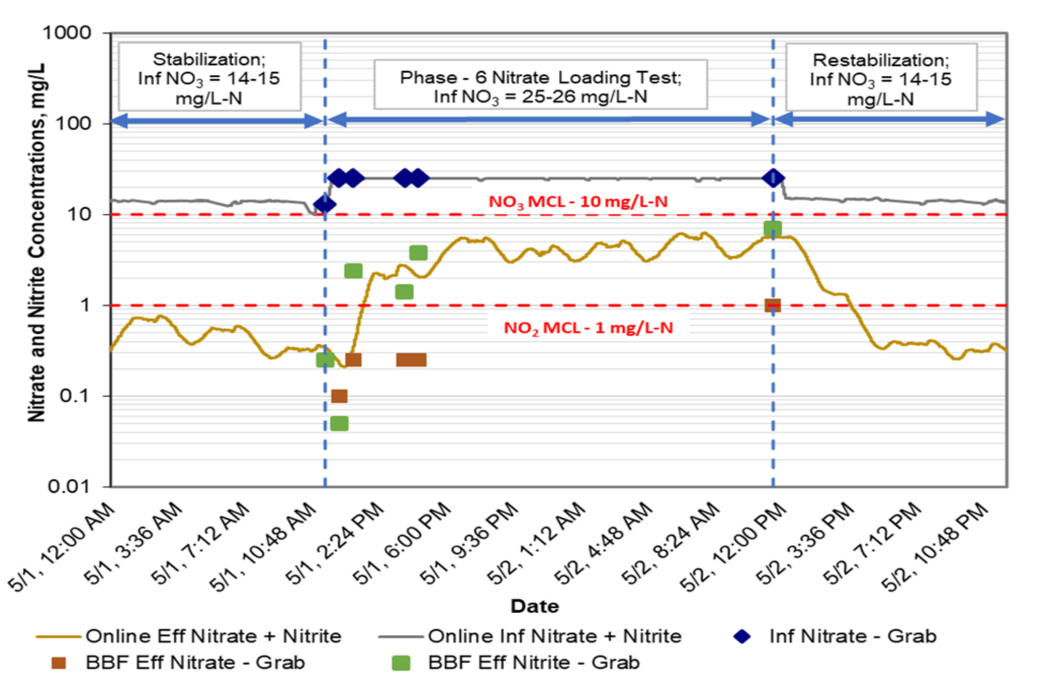
Sampling Time	Sampling Locations	Parameters	Comments
T = 0 minutes	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, bDOC, TOC	Baseline concentrations before spiking Start nitrate spiking at T=0 EBCT
T = 1.0 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 2.0 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 3.0 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 4.0 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 24 hours	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Stop spiking at T=24 hours after sample is taken

Source: Tomorrow Water

Figure 22 and Figure 23 show the nitrate and perchlorate trends and grab sample results in influent and effluent water during this phase. As shown in the figures, the effluent nitrate and effluent perchlorate grab sample concentrations remained at or below 1 mg-N/L and 4 µg/L, respectively.

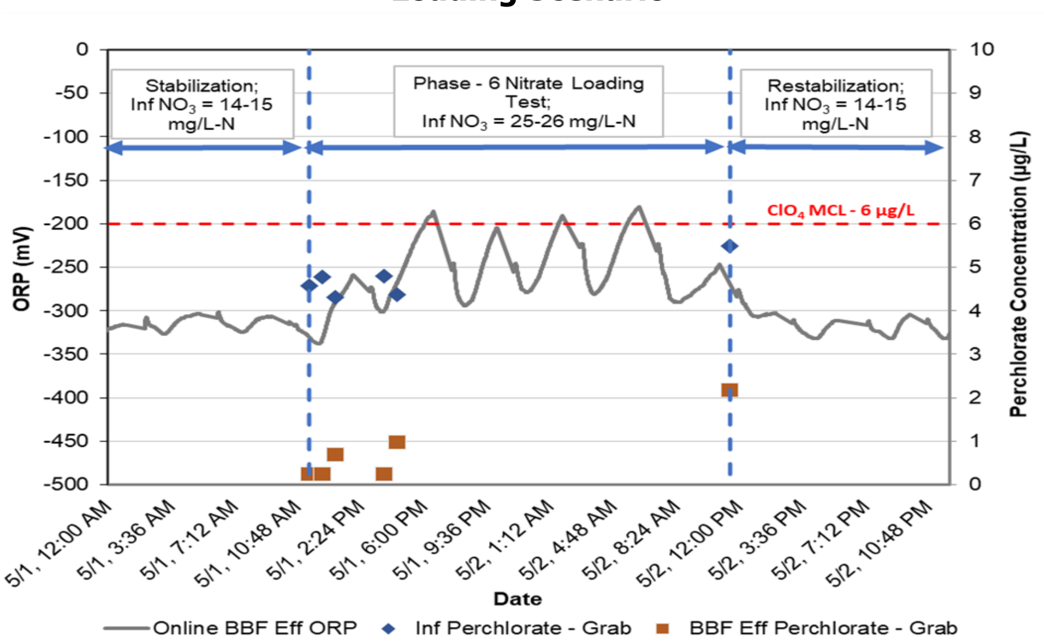
Although the effluent nitrate concentration was below 1 mg-N/L, effluent nitrite concentration increased gradually, as shown in the grab sample results and as indicated on the online (nitrate + nitrite) analyzer. Additionally, effluent nitrate, nitrite, and perchlorate concentrations increased gradually throughout the test. This could indicate that, during a short duration of elevated higher nitrate loading, the BBF system could require longer EBCT to achieve maximum removal of nitrite and perchlorate. Alternatively, the presence of nitrite might be attributable to low operating pH conditions or to a high carbon-to-nitrogen ratio. Water quality results showed effluent TOC at around 7 to 11 mg/L, and influent TOC at more than 40 mg/L, indicating that there was sufficient carbon for both steps in the denitrification process. Further testing is required to fully understand the diversity and distribution of denitrifiers.

Figure 22: Influent and Effluent Nitrate Trends for Phase 6 High-Nitrate Loading Scenario



Source: Tomorrow Water

Figure 23: Influent and Effluent Perchlorate Trends for Phase 6 High-Nitrate Loading Scenario



Source: Tomorrow Water

High-Perchlorate Loading Scenario

For the high-perchlorate loading scenario, the influent perchlorate concentration was intentionally raised to 45 µg/L for two EBCTs. The BBF system operated at an EBCT of 45 minutes during this phase, with acetic acid dosing at 1.7 times the stoichiometric demand. The nitrate concentration of the influent stream was maintained at 15 mg-N/L.

All water produced during this test was captured and stored onsite until effluent perchlorate concentrations were verified at a non-detect level, <4 µg/L per EPA method 314. When the test was completed, the nitrate spiking pump was turned off and the system operated in recirculation mode until laboratory results confirmed that perchlorate levels met water-quality goals.

The sampling plan for this scenario appears in Table 12. The perchlorate spiking ended after the grab sample at 2 EBCT was taken. The system was stabilized at pre-spiking conditions for at least 20 EBCTs.

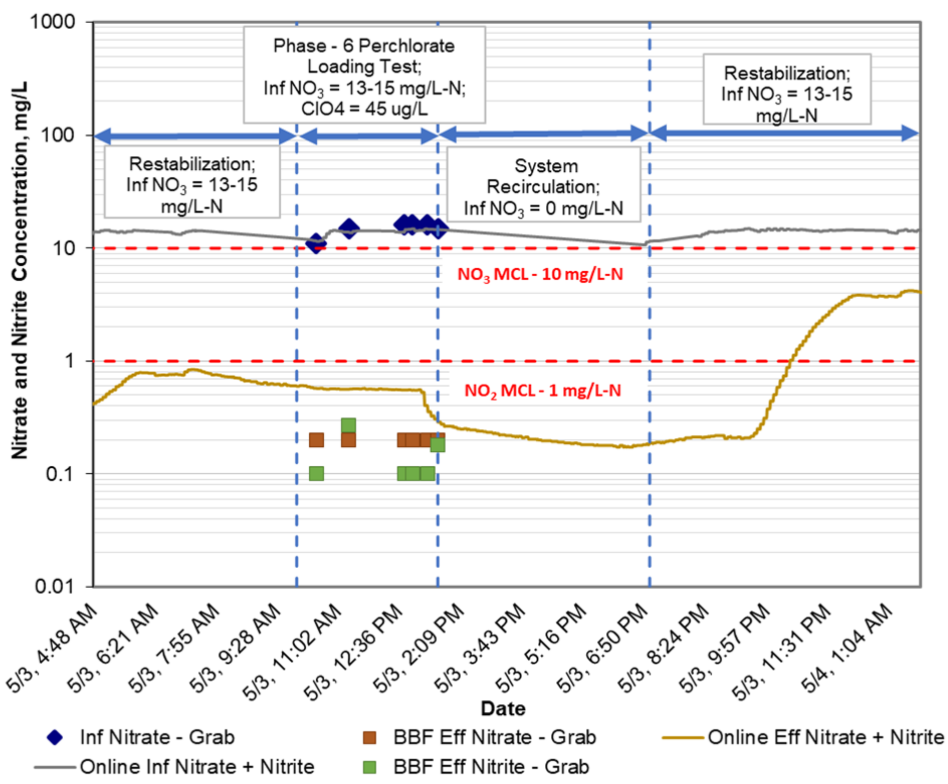
Table 12: Sampling Plan for High-Perchlorate Loading Scenario

Sampling Time	Sampling Locations	Parameters	Comments
T = 0 minutes	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, bDOC, TOC	Baseline concentrations before spiking Start perchlorate spiking at T=0 EBCT
T = 1.0 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 1.25 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 1.5 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4	
T = 2.0 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Stop spiking at T=2.0 EBCT
T = 2.25 EBCT	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	

Source: Tomorrow Water

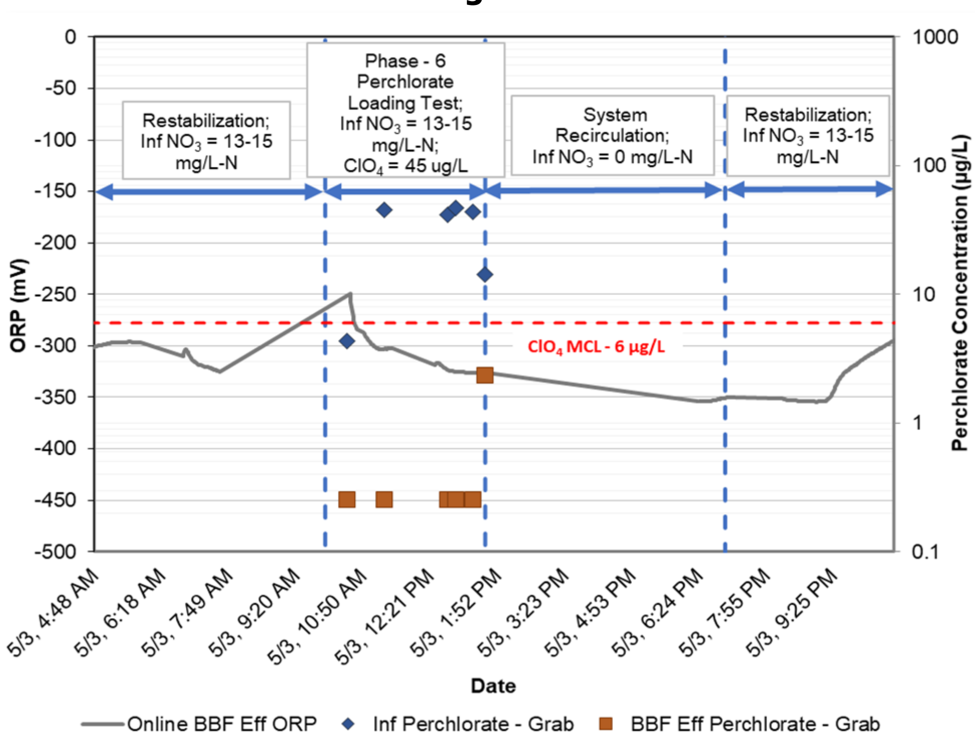
Figure 24 and Figure 25 shows both the nitrate and perchlorate trends and the grab sample results in influent and effluent water. As shown in the figures, the effluent nitrate and effluent perchlorate concentrations consistently remained below 1 mg-N/L and 4 µg/L, respectively. The test was performed for only a duration of 2.25 EBCTs. Results show that the effluent perchlorate increased from <1 µg/L to 2.3 µg/L in fewer than 2.5 EBCTs over three hours. Before this test, the system was acclimated with influent perchlorate and nitrate of <5 µg/L and 15 mg/L, respectively. The higher concentration of nitrate makes it the dominant and preferred electron acceptor for denitrifiers. Results indicate that under these operating conditions, the system cannot be operated for more than 3 hours (2.25 EBCTs) before treatment performance is affected.

Figure 24: Influent and Effluent Nitrate Trends for Phase 6 High Perchlorate-Loading Scenario



Source: Tomorrow Water

Figure 25: Influent and Effluent Perchlorate Trends for Phase 6 HighPerchlorate-Loading Scenario



Source: Tomorrow Water

Electron Donor Failure Scenario

The failure of the electron donor (carbon source and nutrient) on nitrate removal was evaluated during this phase. Before beginning this test, influent and effluent perchlorate and nitrate grab samples were taken. The acetic acid dosing pump was then shut off, and the online BBF effluent nitrate concentrations were monitored.

It was predetermined that if nitrate exceedance were observed before the end of the sampling schedule, the system would operate in recirculation mode, and a sample would be taken following one EBCT from the time of the observed exceedance. The BBF system operated at an EBCT of 45 minutes during this phase, with the acetic acid dosing at 1.7 times the stoichiometric demand. The nitrate concentration in the influent stream was maintained at 15 mg-N/L during this phase.

The sampling plan is shown in Table 13. Grab samples were taken according to the sampling schedule if the online nitrate analyzer detected an exceedance. After grab samples were taken, the acetic acid pump was turned on to optimum dosing conditions, and the system was stabilized to pre-failure conditions for 20 EBCTs.

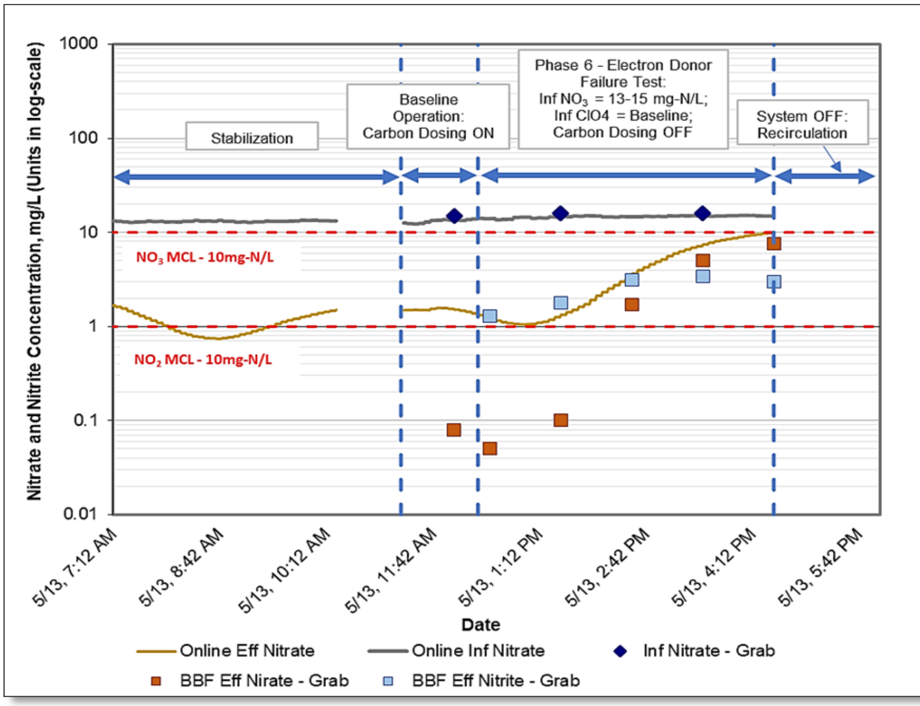
Table 13: Sampling Plan for Electron Donor Failure Scenario

Sampling Time (minutes)	Sampling Locations	Parameters	Comments
T = 0	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, bDOC, TOC	Baseline concentrations
T = 30	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Concentrations after shutting down carbon dosing pump; shut down carbon dosing pump 10 minutes before T=30 minutes
T = 90	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 150	BBF Effluent	NO_3-N, NO_2-N, ClO_4	
T = 210	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4	
T = 270	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Turn on the carbon dosing pump after sample is taken
T = 330	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
T = 390	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Baseline concentrations after restarting the carbon dosing pump
T = 420	BBF Effluent	NO_3-N, NO_2-N, ClO_4	Baseline concentrations after restarting the carbon dosing pump
T = 450	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4	Baseline concentrations after restarting the carbon dosing pump

Source: Tomorrow Water

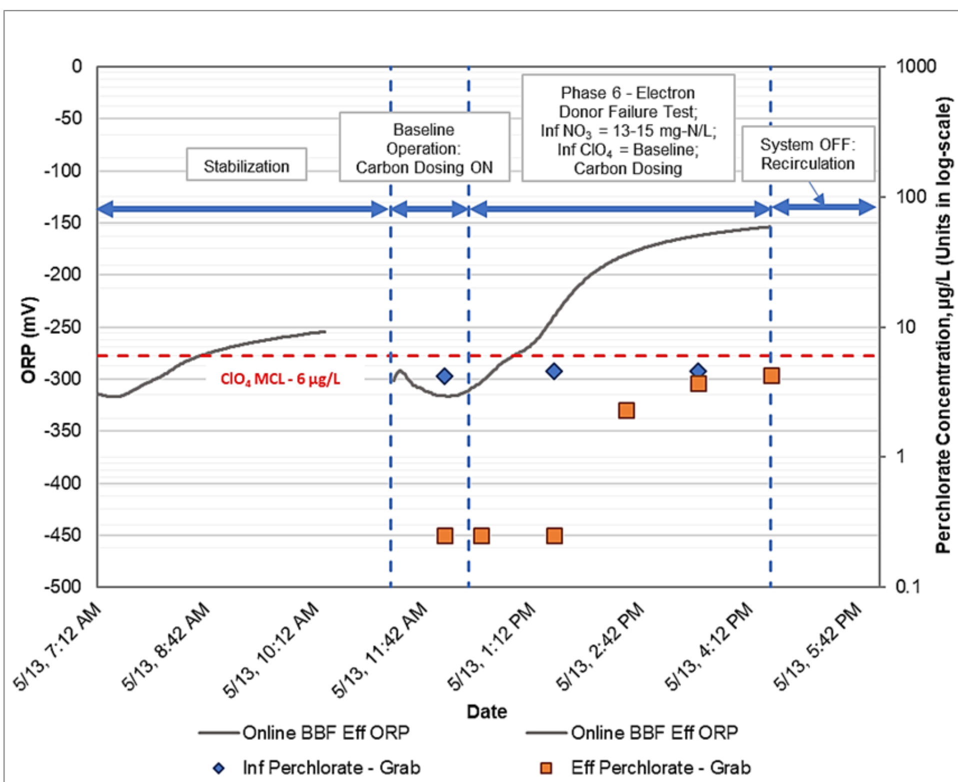
Figure 26 and Figure 27 illustrate both nitrate and perchlorate trends and grab sample results in influent and effluent water.

Figure 26: Influent and Effluent Nitrate Trends for Phase 6 Electron Donor Failure Scenario



Source: Tomorrow Water

Figure 27: Influent and Effluent Perchlorate Trends for Phase 6 Electron Donor Failure Scenario



Source: Tomorrow Water

As shown in these figures, effluent nitrate and effluent perchlorate concentrations remained below 1 mg-N/L and 4 µg/L, respectively, for the first 2 EBCTs (1.5-hour duration). The effluent nitrate and perchlorate concentrations then increased gradually. Results also indicate that after 4 hours (more than 5 EBCTs) without carbon addition, and maintaining 15 mg-N/L influent nitrate as nitrogen concentration, the system failed to remove nitrate and perchlorate to the target effluent limits of 1 mg-N/L and 4 µg/L. These results indicate, therefore, that operational and control measures should be implemented both to mitigate the risk of carbon dosing failure and to protect public health in the event of carbon dosing failure.

Intermittent Operation Scenario

Several different intermittent-operation scenarios were evaluated during this phase to evaluate the impact of these operations on nitrate and perchlorate removal. Each scenario had specific run-time and down-time periods, as shown in Table 14. Before the start of each scenario, influent perchlorate and nitrate grab samples were taken. Between each scenario, the BBF system was restabilized for 20 EBCTs.

Table 14: Testing Conditions for Intermittent-Operation Scenarios

Scenario	Run-Time	Down-Time	Operating Notes
1	20 hours	4 hours	
2	12 hours	12 hours	
3	6 hours	18 hours	
4	45 minutes	15 minutes	Repeated for 12 hours on and 12 hours off
5	30 minutes	30 minutes	Repeated for 12 hours on and 12 hours off
6	100 hours	68 hours	
7	1 week	1 week	

Source: Tomorrow Water

Table 15 and Table 16 shows the sampling plan for intermittent-operation scenarios. A graphic representation of Phase 6.3 operations and sampling is provided in the submitted Title 22 Conditional Acceptance Test Protocol. The BBF system operated at an EBCT of 45 minutes during this phase, with acetic acid dosing at 1.7 times the stoichiometric demand. Nitrate concentration in the influent stream was maintained at >15 mg-N/L during this phase.

The previous Phase 5 results show that the BBF system needs further acclimation to meet both nitrite and nitrate effluent goals. But the treated effluent must be discharged to a receiving body able to accept it continuously. System operation was therefore suspended due to the receiving water field's lack of capacity.

The limited capacity of the receiving discharge water field resulted in its saturation and ultimately caused flooding at the site. Insufficient storage capacity for the treated water at the demonstration site before lab verification and disposal also posed a challenge when conducting high loading experiments. Due to a lack of online monitoring methods for perchlorate, the project team had to rely on lab results before being able to dispose of water when conducting high loading experiments.

Table 15: Sampling Plan for Intermittent-Operation Scenarios 1, 2, 3, 6, and 7

System Status	Sampling Time (minutes)	Sampling Locations	Parameters	Comments
Before Shutdown	T = 60	BBF Effluent	NO_3-N, NO_2-N, ClO_4	Baseline concentrations
Before Shutdown	T = 40	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, bDOC, TOC	Baseline concentrations
Before Shutdown	T = 20	BBF Effluent	NO_3-N, NO_2-N, ClO_4	Baseline concentrations; shut down the system after this sampling event
After Restart	T = 30	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Restart the system; first sample after system restart
After Restart	T = 60	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
After Restart	T = 90	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
After Restart	T = 120	Influent	NO_3-N, NO_2-N, ClO_4	
After Restart	T = 120	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	

Source: Tomorrow Water

Table 16: Sampling Plan for Intermittent-Operation Scenarios 4 and 5

System Status	Sampling Time (minutes)	Sampling Locations	Parameters	Comments
Before Shutdown	T = 20	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, bDOC, TOC	Baseline concentrations; shut down the system after this sampling event
After Restart	T = 30	Influent, BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	Restart the system; first sample after system restart
After Restart	T = 60	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
After Restart	T = 90	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	
After Restart	T = 120	BBF Effluent	NO_3-N, NO_2-N, ClO_4, TOC	

Source: Tomorrow Water

Overall testing indicated the ability of the treatment system to remove nitrate and perchlorate under specific operational scenarios. Results show the presence of nitrite at or above MCL in the treated effluent. The presence of nitrite may be attributed to low bioreactor pH, carbon to nitrogen ratio, and slower kinetics at lower nitrite concentrations, requiring higher EBCT. Due to site constraints and system limitations, the testing had to be terminated prematurely, thereby not providing any solid conclusions.

Energy Consumption Monitoring and Verification

The purpose of the energy monitoring and verification was to demonstrate the project's potential energy and cost savings, including both economic and environmental benefits.

The energy-data acquisition of the full-scale BBF water treatment operation began on June 1, 2019, and continued until October 30, 2019. The measured and calculated values for energy consumption included volt-hour, amp-hour, watt-hour, power factor, volts, amps, kilowatts, and kilowatt-hours. The data monitored was measured, calculated, and summarized to show the monthly energy consumption in kWh. The energy cost was calculated at the rate of $0.12/kWh.

For this Measurement and Verification report, the energy data and cost of the BBF system are compared with the FBR water treatment system to show the energy efficiency and savings comparison between both treatment technologies. Table 17 shows the measured energy consumption and costs of the BBF system. Table 18 shows the estimated energy consumption and costs of a comperable FBR system based on measurements of FBR systems taken in the past. Both tables include an estimated energy consumption based on data from June 1, 2019, to October 30, 2019. The energy data for the months before June and after October 2019, were calculated from utility data.

Table 17: Energy Analysis Consumption for the Biofiltration System

Date	Average System Flow (GPM)	Influent Pumping Sub Meter Panel Energy Consumption (kWh)	Effluent Pumping Sub Meter Panel Energy Consumption (kWh)	Total System Energy Consumption (kWh)	Energy Cost (at $0.12/kWh)
Dec. 2018	100	480	392	872	$104.64
Jan. 2019	100	476	381	857	$102.84
Feb. 2019	100	458	375	833	$99.96
Mar. 2019	100	463	367	830	$99.60
Apr. 2019	100	478	377	855	$102.60
May 2019	100	471	369	840	$100.80
June 2019	100	473	382	855	$102.6
July 2019	100	465	372	837	$100.2
Aug. 2019	100	457	369	826	$99.12
Sep. 2019	100	446	360	806	$96.72
Oct. 2019	100	451	365	816	$97.92
Nov. 2019	100	443	360	803	$96.36
Dec. 2019	100	454	365	819	$98.28
Annual Energy Consumption					$1301.88

Source: Tomorrow Water

Table 18: Energy Analysis Consumption for the FBR System

Date	Average System Flow (GPM)	Influent Pumping Sub Meter Panel Energy Consumption (kWh)	Effluent Pumping Sub Meter Panel Energy Consumption (kWh)	Total System Energy Consumption (kWh)	Energy Cost (at $0.12/kWh)
Dec. 2018	100	1752	1406	3158	$378.96
Jan. 2019	100	1691	1457	3147	$377.64
Feb. 2019	100	1784	1438	3186	$382.32
June 2019	100	1610	1207	2817	$338.04
July 2019	100	1590	1216	2806	$336.72
August 2019	100	1620	1245	2865	$343.8
Sep. 2019	100	1603	1200	2803	$336.36
Oct. 2019	100	1590	1210	2800	$336.03
Nov. 2019	100	1662	1278	2940	$352.80
Dec. 2019	100	1593	1225	2818	$338.16
Annual Energy Consumption					$4,586.28

Source: Tomorrow Water

From Table 17 and Table 18, average energy savings were calculated and compared between the two groundwater-treatment technologies.

Energy Consumption Savings: [((kwh (FBR) – kWh (BBF))/kwh (BBF)] x 100%

Energy Cost Savings: [($ cost (FBR) – $ cost (BBF))/$ cost (BBF)] x 100%

Table 19 measurement-period data show that the average energy consumption savings of the BBF treatment system (over the FBR treatment system) are around 70 percent. For the annual estimated data, average energy consumption savings for the BBF system over the FBR system are around 72 percent.

Table 19: Energy Consumption Saving Summary

Period	BBF Total System Energy Consumption (kWh)	FBR Total System Energy Consumption (kWh)	BBF Energy Consumption Savings (%)	BBF Energy Cost Savings (%)
Annual	10,849	38,219	72.55%	72.55%

Source: Oluleye, A. E. and Ogungbemi, A. A.. 2012. Design and Fabrication of a Low Cost Fluidized Bed Reactor, Innovative Systems Design and Engineering. P29 – TABLE 1.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

How to Share Project Knowledge with the Public

Tomorrow Water described this project's technology several times at meetings and conferences. Most potential projects are in California, which is a major target region but requires Title 22 certification for drinking water. Because the project was delayed by the project site's arson incident, the Title 22 conditional acceptance process was delayed and is still ongoing. Because this certification is a major deciding factor for end-users, meeting the requirements for this process poses a significant hurdle for business development.

Tomorrow Water has also promoted BBF on its website and at several trade shows and meetings as a leading technology.

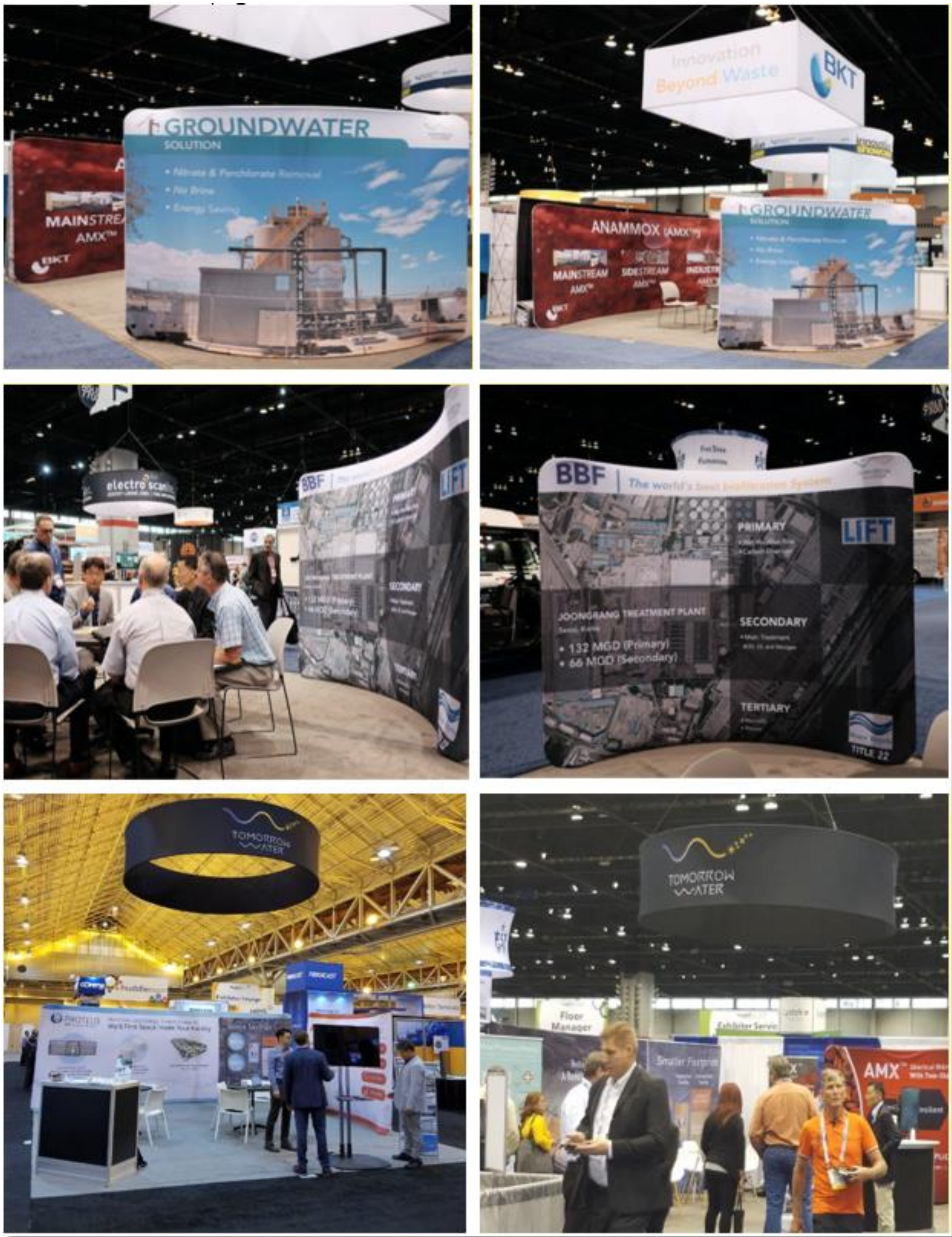
Conference

Water Environment Federation's Technical Exhibition and Conference

- Period: September 30 to October 4, 2017
    - September 29 to October 3, 2018
    - September 21 to September 25, 2019
- Venue: McCormick Place, Chicago, Illinois (2017)

  New Orleans Morial Convention Center, New Orleans, Louisiana (2018)
    - McCormick Place, Chicago, Illinois (2019)
- Water Environment Federation's Technical Exhibition and Conference (WEFTEC) is the largest exhibition and conference venue for the water and wastewater industries. Tomorrow Water introduced the project and shared preliminary results, shown in Figure 28.
- The key message was to emphasize three primary findings from the technology.
    - Efficiency: Nitrate and Perchlorate removal using a biological treatment process
    - Cost savings and convenience: No brine water generation required
    - Energy efficiency: No need to install influent and recirculation pumps
    - Low maintenance: No need to replace resin or media

Figure 28: Groundwater Introduction Banner



Source: Tomorrow Water

Meetings

Golden State Water

- When: October 16, 2018
- Where: Barstow plant site

- Who: Perry Dahlstrom (Barstow General Manager) and two other engineers from the same office.
- Agenda: Golden State Water has wells with high nitrate levels and was seeking treatment options for its removal.
- Purpose: Introduce the BBF system for biological nitrate removal treatment

  Feedback: Golden State Water has used an ion exchange technology and wants to know more about the technology once Tomorrow Water obtains Title 22 certification.

Sunny Slope Water Company

- When: July 6, 2016
- Where: Sunny Slope Water Company
- Agenda: Sunny Slope has five wells, some with Volatile Organic Carbon (VOC), 1,2,3-Trichloropropance (123-TCP), and nitrate.
  - Liquid-Phase granular active carbon is used for VOC/123-TCP.
- Feedback: Competing technologies have been testing their biological system for three years for nitrate and have received Title 22 certification.

  The full-scale system is under development and due to be installed in September.

Acton/Los Angeles County Waterworks Districtis (LACWD) – Palmdale

- When: July 6, 2016
- Where: Palmdale office
- Agenda: Water Quality and Treatment Solution (WQTS) pilot-tested its biological nitrate system in 2012.
- Feedback: Water quality in the town of Acton fluctuates depending on the rain, including nitrate concentration, but nitrate levels are not much higher than the MCL. The cost of the WQTS biological system was a deterrent at $1,000/AF so LACWD did not install it. LACWD is open to a trial, especially if Tomorrow Water can show that the project cost can be decreased.The estimated capital costs for deployment of Tomorrow Water's Biofiltration system at scale are discussed below in the section titled "Scalability for Commercialization" and are shown in Figure 33.
- Los Angeles Department of Water and Power (LADWP) – San Fernando
- When: November 22nd, 2016
- Where: LADWP
- Agenda: Introduction to the BBF groundwater technology.
- Feedback: Although there is some nitrate and perchlorate in their well field, LADWP's main focus is volatile organic compounds (VOC). Its well field is massive, and it complies with nitrate and perchlorate limits in a small number of wells by blending while the utility plans for VOC treatment. LADWP was interested in learning more about the system in the event that future plans change.

City of Pomona

- When: March 2nd, 2016
- Where: City of Pomona

- Agenda: Introduction to BBF groundwater technology.
- Feedback: The City of Pomona is interested in testing a pilot, but it's not its priority at this time. The city is facing high concentrations of VOCs in one of its blending wells, and is interested to see BBF can reduce VOC levels from 5 ug/L to 2 ug/L.

Meeting with Consulting Firm

- Stantec
- Carollo
- Tetra Tech
- Montrose

Online Consulting

Tomorrow Water conducts active marketing and consulting through various online media outlets including its home page, Facebook, and LinkedIn, as shown in Figure 29.

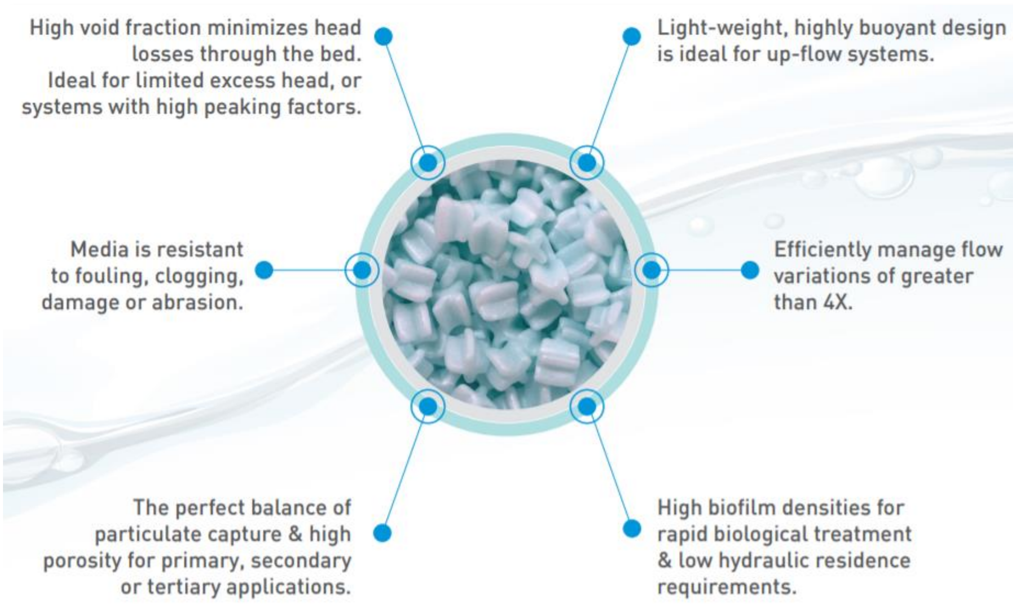
Figure 29: Tomorrow Water Website, Biofilter System Reference, and Social Media Page

Source: Tomorrow Water

New Filtration Media Development and Application

Tomorrow Water is developing the BBF system with new filtration media, as shown in Figure 30. BBF is an up-flow-based biofiltration process. The shape and size of filtration media are two of the most important design and operating factors in determining the system's overall performance. Tomorrow Water has developed a noble cross-shaped expanded polypropylene media, which is being tested and commercialized in both Korea and the United States. The media is being tested for primary and storm-water treatment in a pilot-scale BBF system in Genesee County, Michigan. Tomorrow Water has also applied to the Jungnang and Ockjeong wastewater treatment plant for primary and secondary treatment processing in the Republic of Korea. The new media has a 25 percent lower hydraulic resistance and longer backwash cycle compared with previous rounded-type filtration media. Based on the results of previous municipal wastewater or storm-water treatment operations, the application of new filtration media for groundwater treatment will also significantly reduce energy costs.

Figure 30: New Cross-Shaped Expanded Polypropylene Filtration Media for Biofilter System Application

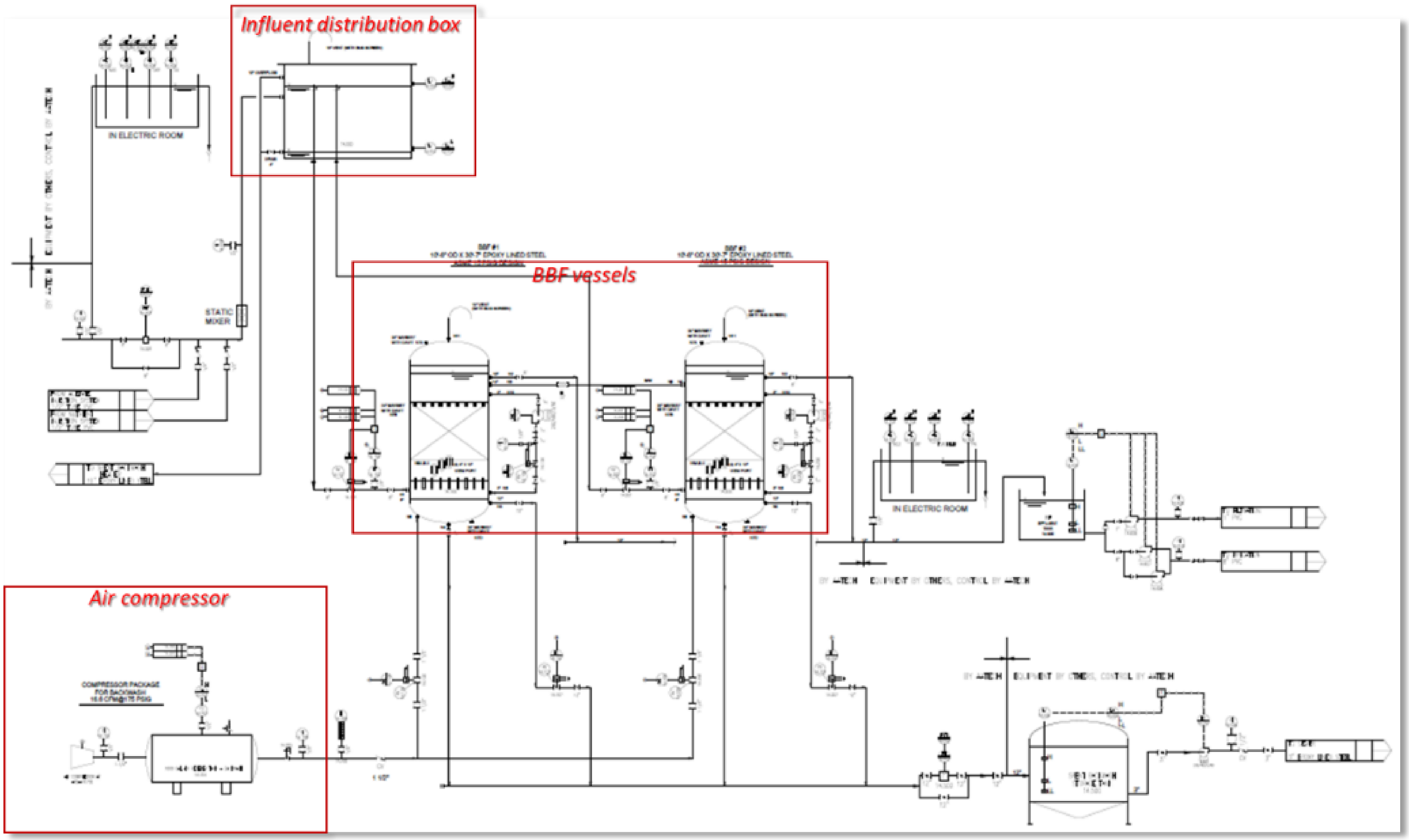


Source: Tomorrow Water

Scalability for Commercialization

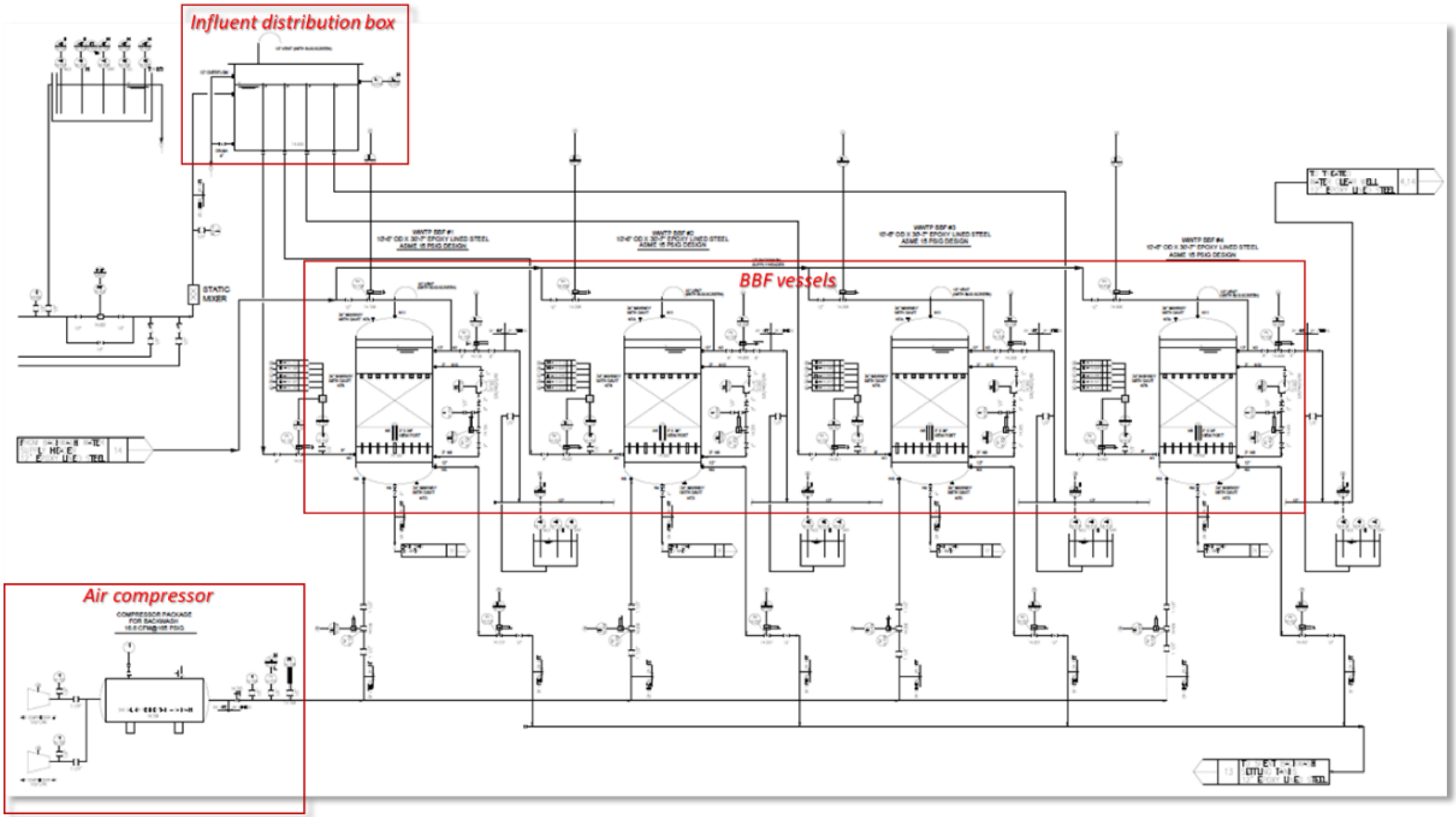
The BBF system that Tomorrow Water installed for this project has two up-flow biofilter reactors. The maximum treatment capacity of a BBF vessel is 250 GPM based on a design factor of NO_3-N removal. An influent distribution box can connect up to 10 vessels for a total flow rate of 2,500 GPM. As shown in the piping and instrumentation diagram of double-vessel and quadruple-vessel configurations in Figure 31 and Figure 32, the BBF system structure is the same except for vessel connection points. The final product price therefore depends mainly on the number of vessels.

Figure 31: Piping and Instrumentation Diagram of Double-Vessel Configuration of Biofilter System



Source: Tomorrow Water

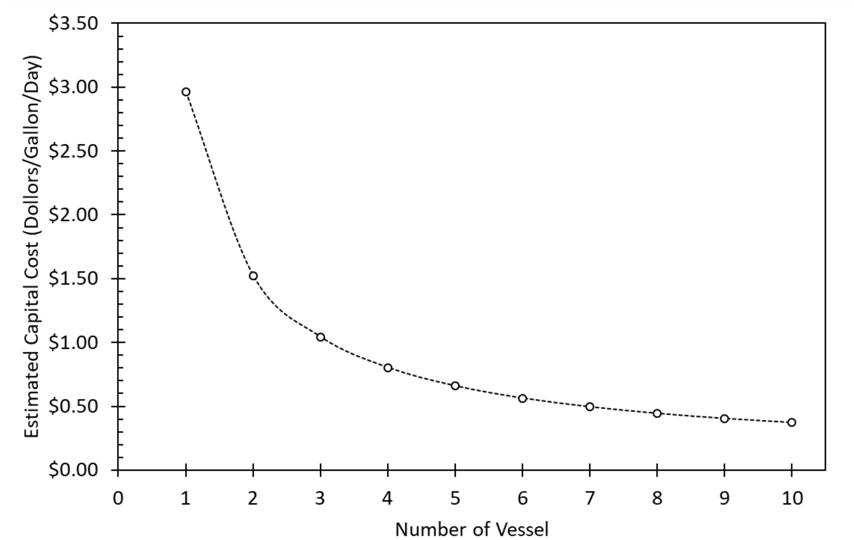
Figure 32: Piping and Instrumentation Diagram of Quadruple-Vessel Configuration of Biofilter System



Source: Tomorrow Water

The project's two BBF vessels were fabricated by AATech, and their cost was $214,581 per vessel. The scalability for BBF commercialization, shown in Figure 33, includes additional pipe installation, a monitoring system, and media costs. The estimated capital cost for the single-vessel BBF system is $2.96 per GPD, and decuple-vessel BBF system is $0.37 per GPD. The capital cost will gradually decrease, based on the number of vessels.

Figure 33: Estimated Capital Cost for Biofilter System at Various Capacities



Source: Tomorrow Water

Capacity Constraints by Target Contaminants

The vessel-based BBF system design for the Barstow Soap Mine clean-up project treated influent water of 26 mg-N/L to meet the target discharge limit of 5 mg-N/L. The minimum capacity of the BBF system included a single BBF vessel with a flow rate of up to 250 GPM. The maximum capacity of the BBF system had multiple BBF vessels (up to 10 units), with a flow rate of up to 2,500 GPM. Generally, the operating capacity of a single vessel depends upon the flow rate of the influent pump.

The actual operating capacity was constrained and dictated by the contaminant species. Biodegradation requires the presence of favorable geochemical conditions. Electron acceptor utilization in biodegradation takes place in sequential order:

O_2 (Aerobic respiration) → NO_3^- (Denitrification) → ClO_4^- (Perchlorate reduction) → SO_4 (Sulfate reduction) → CO_2 (methanogenesis)

Simply put, denitrifying bacteria first consumes O_2 completely before nitrate is removed. After the depletion of nitrate, perchlorate removal follows.

At the request of the DDW, the nitrate concentration of the influent was artificially increased to >15 mg-N/L. The water chemistry of the influent is therefore a decisive factor in determining the actual treatment capacity of the BBF system for commercialization.

CHAPTER 5: Conclusions and Recommendations

Overall testing demonstrated the ability of the treatment system to remove nitrate and perchlorate in operational scenarios. Based on the contaminant removal test, the BBF system showcased capabilities to process a maximum level of 15 mg-N/L of influent nitrate and 30 ug/L of influent perchlorate under the 80-to-120 GPM operating conditions. In addition, the BBF system automatically stopped operations when out-of-range nitrate or ORP (for perchlorate detection) were detected in the discharge line, including in the effluent storage tank.

Over the testing period, influent perchlorate concentrations gradually declined from 14 µg/L to 4 µg/L. This made it difficult for the project team to demonstrate perchlorate removal since the influent concentration was already close to the MCL. The groundwater nitrate concentration was also much lower than initially anticipated, so sodium nitrate was injected in the water to increase the nitrate concentration artificially. These operating conditions, from a testing perspective, were neither cost-effective nor ideal.

The limited capacity of the receiving discharge water field caused its saturation, ultimately flooding the site. Insufficient storage capacity for treated water at the demonstration site before lab verification and disposal created problems during high-loading experiments. Due to a lack of online monitoring methods for perchlorate, the project team relied upon lab results before disposing of water during high-loading experiments. Due to these site constraints and system limitations, testing was prematurely terminated without providing solid conclusions. Given these conditions, the third-party operation consulting firm, Stantec, recommended: (a) a site with sufficient water disposal capabilities to safely and continuously dispose of off-spec water without interrupting system operation; (b) a system design capable of testing a wide range of EBCTs as a dedicated feed-water system with variable-frequency driven pumps; (c) a bioreactor pH control system (such as a sodium-hydroxide dosing system) to neutralize pH rise from the addition of phosphoric acid (as nutrient); (d) a groundwater site contaminated by nitrate only, which would allow the safe and continuous disposal of nitrate from treated groundwater since online monitoring techniques for perchlorate are currently unavailable to ensure no perchlorate contaminated water is released.

For energy consumption monitoring and verification, energy data for the BBF and costs were compared with the FBR system. It showed average energy consumption savings of around 70 percent for the BBF treatment system over the FBR treatment system.

The BBF system offers additional potential savings, listed here:

- Low operation and maintenance costs from a primarily gravity-based system
- Energy-savings from light-floating media (no recirculation pump)
- Simultaneous biological removal and physical filtration
- No replacement or addition of fixed floating media (semi-permanent media with neither attrition nor loss)
- Minimal waste generation discharged to WWTP

- Redundant design with multi small vessels
- Easily expandable design with modular configuration
- Compact footprint
- Reliable, proven, custom design
- Ease of implementation and stable performance
- Demonstrable reduction of nitrate and perchlorate in groundwater
- Air pollution emission reductions

CHAPTER 6: Benefits to Ratepayers

Cost and Benefits for Electric and Water Utility Ratepayers

This section classifies benefits by avoided cost. Based on this project, Tomorrow Water included a complete set of potential benefits to electric and water ratepayers, the environment, and society in general. The following sections define these benefits, who or what receives them, and assumptions made in this analysis.

Additional Costs and Benefits Considered When Analyzing Project Cost Effectiveness

Both energy and societal benefits should be considered when assessing this technology. The categories of unique energy benefits from this project are captured in the current energy-efficiency cost-effectiveness framework, which recognizes a variety of avoided costs from reduced energy consumption.

1. Avoided cost of electricity generation (both energy- and capacity-related avoided costs)
2. Avoided cost of electricity transmission and distribution capacity

The project's cost-effectiveness is a dynamic equation, dependent upon current circumstances, and updates are under consideration.

Developing this BBF system could therefore be a high priority for supporting energy programs that reduce costs and bring other additional benefits to ratepayers.

Finally, societal benefits include the avoided costs and adverse impacts associated with environmental degradation from the growing depletion of scarce water resources.

Project Environmental and Societal Benefits

Environmental

Potential environmental benefits accrue when contaminated groundwater can be treated and consumed by residential, commercial, institutional, agricultural, and industrial customers instead of remaining in the environment.

When treated, clean groundwater is left in the environment, it joins California's natural and artificial hydrologic cycles.

When considering environmental cost, many positive effects can be realized when more water remains in the environment whether as groundwater or in aquifers or artificial reservoirs. There are additional environmental benefits:

1. Ecological benefits from higher aquifer levels and groundwater tables
2. Water quality
3. Surface water quality benefits: More BBF systems mean more available wells, more useful groundwater, and more surface water and reservoirs, which together reduce emissions of greenhouse gases in California.

4. Ecological Benefits: Wildlife habitat creation and restoration, increased fish populations, protection of other species

Other environmental benefits from this project include reductions in waste-water flows and septic system loads from individual wells

Societal Benefits

Societal benefits could also be realized from increased water use and system efficiency, ultimately leading to decreased consumption for residential, commercial, agricultural, and industrial purposes.

Societal benefits from water efficiency projects could also lead to greater food production and improve food quality.

Treated water could enable growers to use their groundwater allotments to grow more crops and increase production. It should be noted that water-use efficiency in agriculture does not necessarily equate to water savings, but more often to higher yields of greater quality.

Groundwater benefits from increased water-use efficiency represent a unique subset of potential societal benefits, including the water-security benefit of storing more water in aquifers for future use. This water would be highly valuable in drought years. Groundwater benefits would also reduce contaminant concentrations, making more groundwater fit for drinking water. In fact, if contaminated groundwater basins required the public to purchase water from alternative sources, the avoidance of this cost would represent a real societal benefit. In some cases, what is a contaminant in drinking water is not necessarily so for agriculture. So, where there is a benefit to better match a water source with its intended use, there could be real societal, economic benefits.

LIST OF ACRONYMS

Term	Definition
123-TCP	1,2,3-Trichloropropane
BBF	Tomorrow Water Biofiltration system
bDOC	Biodegradable dissolved organic carbon
CCR	California Code of Regulations
C/N ratio	carbon to nitrogen ratio
COD	Chemical oxygen demand
DBP	Disinfection byproduct
DDW	Division of Drinking Water
DO	Dissolved oxygen
DOC	Dissolved organic carbon
EBCT	Empty bed contact time
EPA	Environmental Protection Agency
GPD	Gallon per square feet per day
GPD	Gallon per Day
GPM	Gallon per minute
GHG	Greenhouse gas
LACWD	Los Angeles County Waterworks Districts
LADWP	Los Angeles Department of Water and Power
MCL	Maximum contaminant level
NSF	National Sanitation Foundation
NTU	Nephelometric turbidity unit
ORP	Oxidation reduction potential
P&ID	piping and instrumentation diagram
SDS	Safety data sheet
SWRCB	State Water Resources Control Board
TDS	Total dissolved solids
TOC	Total organic carbon
VOC	Volatile Organic Compound
WEFTEC	Water Environment Federation’s Technical Exhibition and Conference
WQTS	Water quality and treatment solution
WWTP	Wastewater treatment plant

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APPENDIX A: Gravity-Based, Low-Energy Biofilter with Low Backwash Rate for Nitrate Removal in Groundwater

Introduction

This appendix presents the results of the energy monitoring and Verification data for the full scale BBF Groundwater Treatment Project in the City of Barstow. The report describes the energy monitoring plan that was used to collect the energy data and compares energy conservation with a ground water system that uses a different technology.

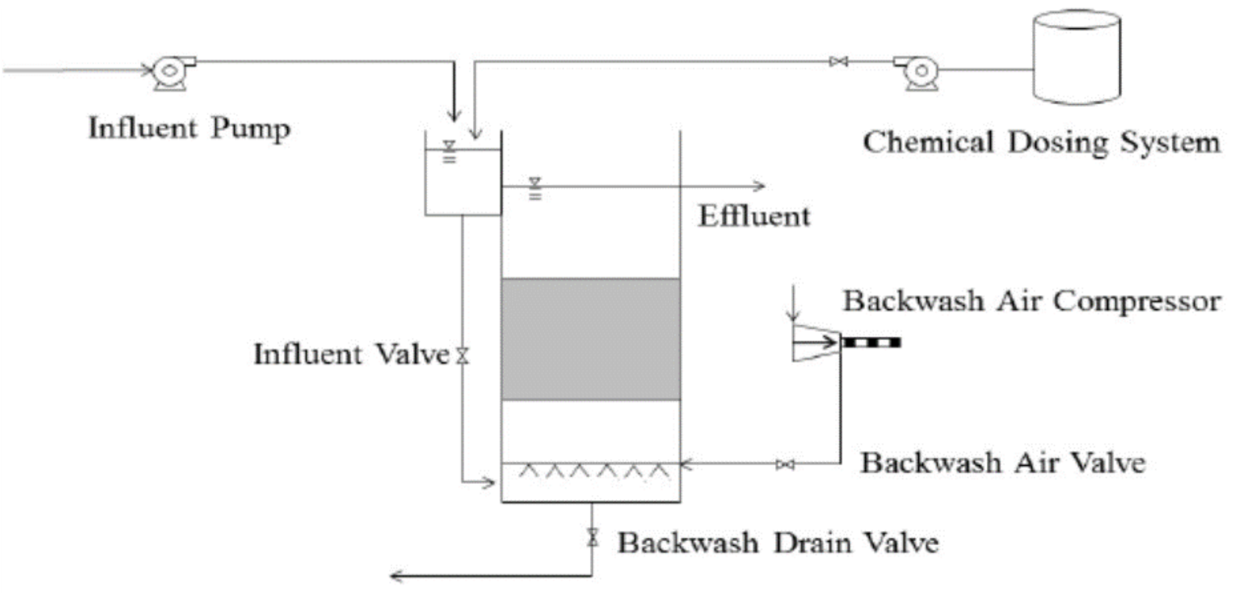
The energy monitoring and verification (M&V) of data collection adheres to the specifications set forth in the International Performance Measurement and Verification Protocol (IPMVP) Core Concepts – 2014. The M&V involves the process of using measurements to reliably quantify actual energy savings from an energy savings project within a facility and how savings are determined from measurements of energy use before and after implementation of an energy or water savings project, with appropriate adjustments made for changes in conditions.

The goal of this project is to achieve energy savings through energy and water efficient treatment system using a gravity based, low energy biofilter (BBF) with low backwash rate for nitrate removal in ground water as opposed to other treatment technologies have higher energy consumptions such as Fluidized Bed Reactor (FBR) and Ion exchange (IX) systems. For this M&V report, the base treatment technology selected is the FBR system which will be compared the energy consumptions of the BBF system.

Treatment System Technologies comparison

BBF treatment system employs physical and biological treatment methods instead of IX to reduce the nitrate concentrations in the City’s groundwater. Denitrification is achieved by the biofilm coating on a packed floating media while solids are removed by physical filtration. Periodic backwashing is initiated to remove solids buildup and excessive biomass in the system. Figure A-1 shows the process flow diagram of a BBF system.

Figure A-1: Process Flow Diagram of the Biofilter System

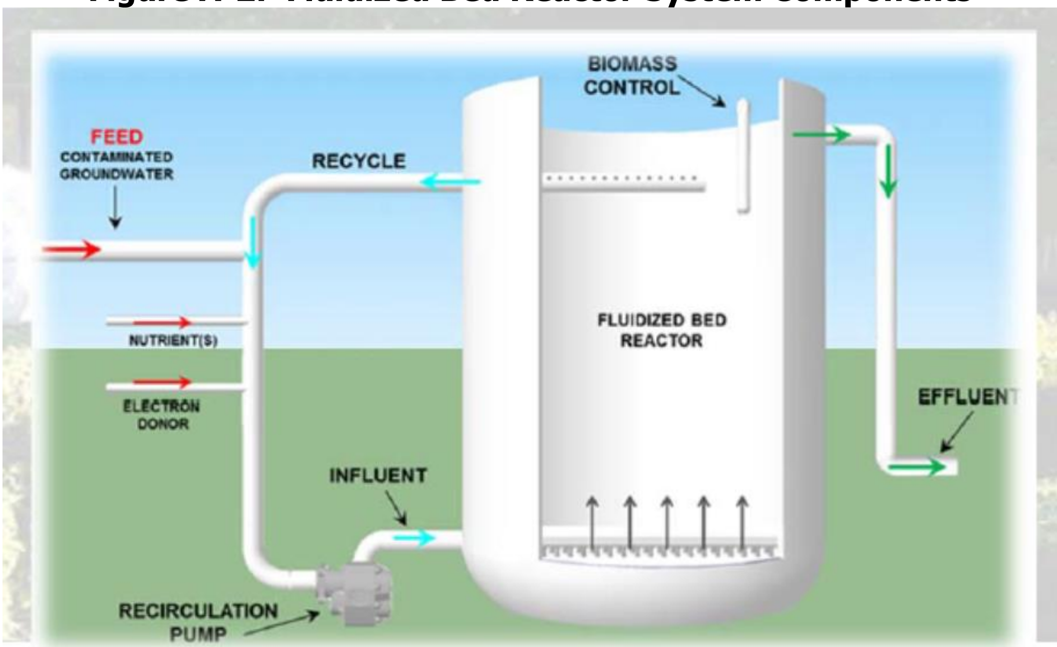


Source: Tomorrow Water

The FBR treatment system is a fixed-film reactor in which the biological media (granular activated carbon) is suspended, or fluidized, within the reactor vessel by the upward flow of water through the system. Because the media particles are small and suspended, they present a large surface area for microbial growth. An electron donor is provided to the FBR where, under anoxic conditions, the attached microorganisms perform an oxidation/reduction reaction to reduce the contaminants. The byproducts of the process are nitrogen gas, carbon dioxide, heat generation and additional biomass.

Figure A-2 shows a typical system component of an FBR system.

Figure A-2: Fluidized Bed Reactor System Components



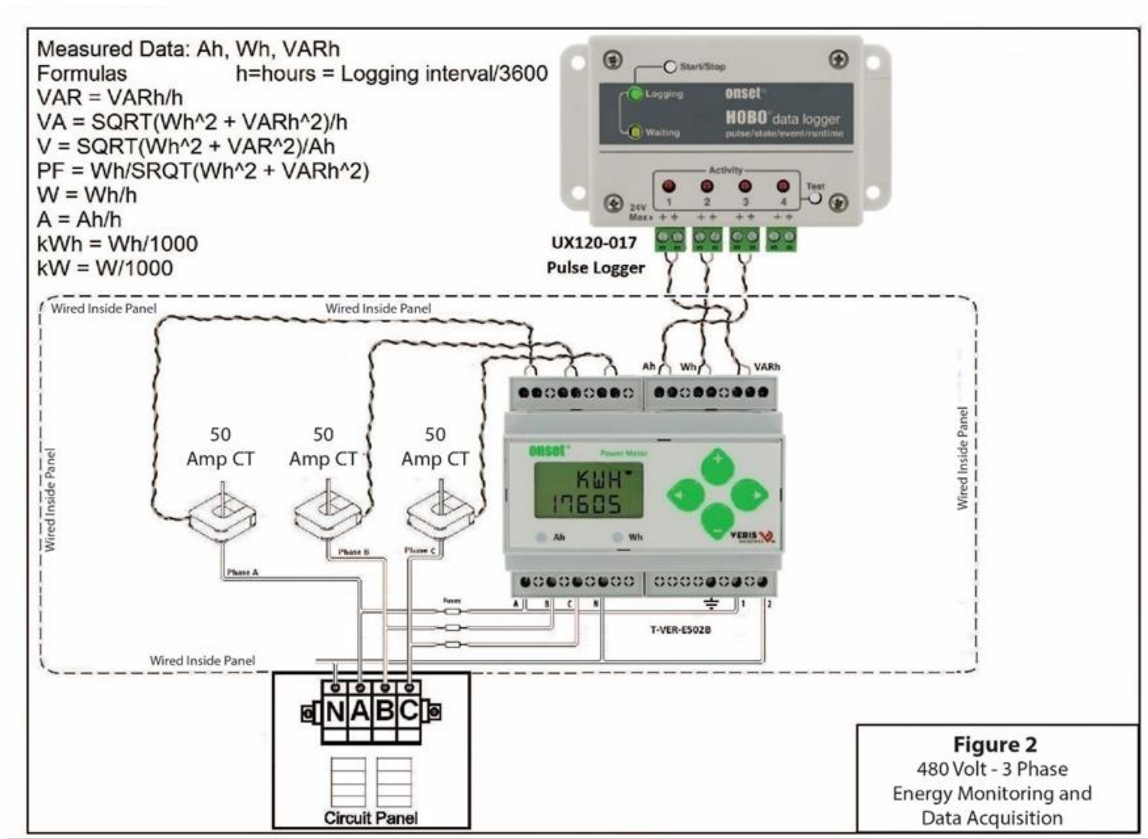
Source: Tomorrow Water

In this report, the results of the energy monitoring and acquisition data of a full scale BBF system will be compared to the energy consumptions to the FBR treatment system and the energy savings will be determined.

Measurements and Analysis Procedures

The energy monitoring and data acquisition for the BBF water treatment facility included current sensors connected a power meter that measure the amperage, watt-hour and the voltage at the power feeder of the electrical panel sub meter. The power meter calculates energy consumption variables and the data are logged using a pulse data logger. Figure A-3 shows the energy monitoring and data acquisition setup.

Figure A-3: Energy Monitoring and Data Acquisition Setup



Source: Tomorrow Water

Energy consumptions are collected at the main influent pump sub-meter and associated electrical equipment that feeds the BBF treatment system. Energy consumption measurements are also collected at the effluent pump sub-meter and associated electrical chemical feed system and air compressor scouring equipment of the BBF treatment system.

The energy data acquisition of the full-scale operation of the BBF water treatment system started in June 1st, 2019 and continued until October 30, 2019. The measured and calculated values energy consumptions values include: volt-hour, amp-hour-watt-hour, power factor, volts, amp, watt, kilowatt, and kilowatt-hour. The data are monitored, measured and then calculated and summarized to show the monthly energy consumption in kWh. The energy cost was calculated at a rate of $0.12/kWh.

For this M&V report, the energy data for the BBF and cost are then compared to the FBR water treatment system to show the energy efficiency and savings comparison between both treatment technologies. Associated cost and energy consumptions are shown in Table A-1 for BBF and Table A-2 for FBR.

Table A-1: Energy Analysis Consumption for the Biofilter System

Date	Average System Flow (GPM)	Influent Pumping Sub Meter Panel Energy Consumption (kWh)	Effluent Pumping Sub Meter Panel Energy Consumption (kWh)	Total System Energy Consumption (kWh)	Energy Cost (at $0.12/kWh)
December 2018	100	480	392	872	$104.64
January 2019	100	476	381	857	$102.84
February 2019	100	458	375	833	$99.96
March 2019	100	463	367	830	$99.60
April 2019	100	478	377	855	$102.60
May 2019	100	471	369	840	$100.80
June 2019	100	473	382	855	$102.6
July 2019	100	465	372	837	$100.2
August 2019	100	457	369	826	$99.12
September 2019	100	446	360	806	$96.72
October 2019	100	451	365	816	$97.92
November 2019	100	443	360	803	$96.36
December 2019	100	454	365	819	$98.28
Annual Energy Consumption					$1301.88

Source: Tomorrow Water

Table A-2: Energy Analysis Consumption for the FBR System

Date	Average System Flow (GPM)	Influent Pumping Sub Meter Panel Energy Consumption (kWh)	Effluent Pumping Sub Meter Panel Energy Consumption (kWh)	Total System Energy Consumption (kWh)	Energy Cost (at $0.12/kWh)
December 2018	100	1752	1406	3158	$378.96
January 2019	100	1691	1457	3147	$377.64
February 2019	100	1784	1438	3186	$382.32
June 2019	100	1610	1207	2817	$338.04
July 2019	100	1590	1216	2806	$336.72
August 2019	100	1620	1245	2865	$343.8
September 2019	100	1603	1200	2803	$336.36
October 2019	100	1590	1210	2800	$336.03
November 2019	100	1662	1278	2940	$352.80
December 2019	100	1593	1225	2818	$338.16
Annual Energy Consumption					$4,586.28

Source: Tomorrow Water

From Table A-1 and Table A-2, the average energy savings comparison between the 2 treatment technology are calculated as follows:

Energy Consumption savings: [{(kwh (FBR) – kWh (BBF)}/kwh (BBF)] x 100%

Energy Cost savings: [{$ cost (FBR) – $ cost (BBF)}/$ cost (BBF)] x 100%

Table A-3: Energy Consumption Savings Summary

Period	BBF Total System Energy Consumption (kWh)	FBR Total System Energy Consumption (kWh)	BBF Energy Consumption Savings (%)	BBF Energy Cost Savings (%)
Annual	10,849	38,219	72.55%	72.55%

Source: Tomorrow Water

Table A-2 shows that the average energy consumption savings of the BBF treatment system over the FBR treatment system is around 70%.

However, there are additional potential savings the BBF system can also offer, such as the following:

- Low O&M cost due to mostly gravity-based system
- Energy saving system using light floating media (no recirculation pump)
- Biological removal and physical filtration system simultaneously
- No replacement and addition of fixed floating media (semipermanent media with no attrition or loss)
- Small waste generation that can be discharged to WWTP without high TDS
- Redundancy design using multi small vessels
- Easily expandable design with modular configuration
- Compact footprint
- Reliable, proven, custom design approach
- Ease of implementation and stable performance
- Reduction of nitrate and perchlorate in groundwater
- Air pollution emissions reduction