

The emergency DPR experience: water quality lessons from Wichita Falls, TX

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ABSTRACT

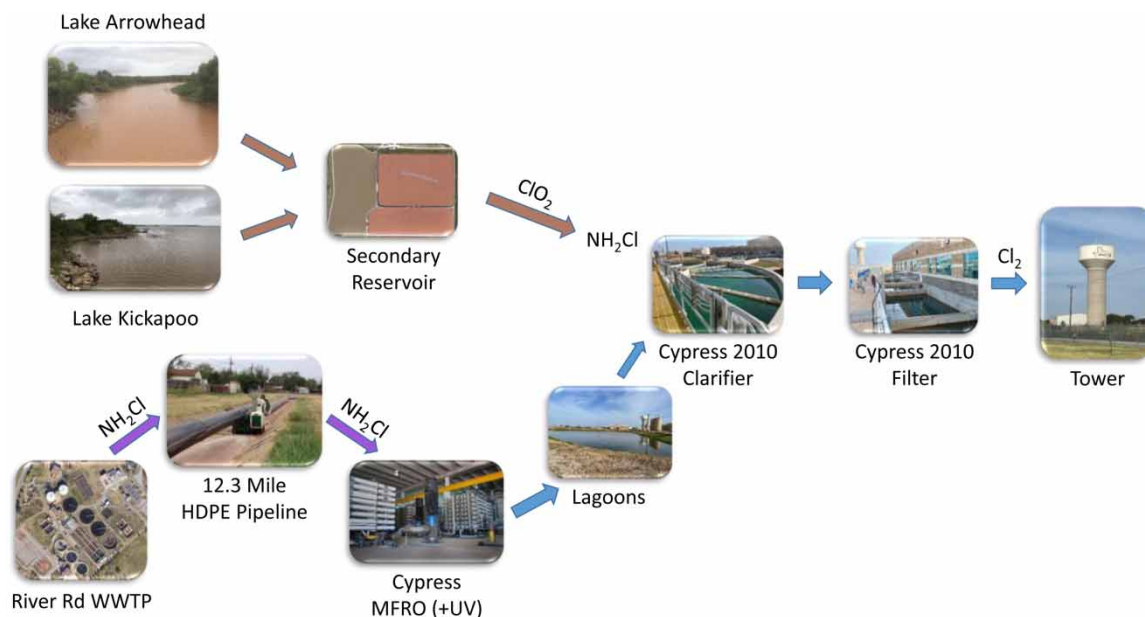
From 2011 to 2015, Wichita Falls, TX, faced a severe drought that dropped combined lake levels below 23%, prompting the city to implement an emergency direct potable reuse (DPR) system. The city proposed a plan to the Texas Commission on Environmental Quality (TCEQ) in 2012 to treat wastewater through existing advanced and conventional treatment plants. After constructing the necessary interconnections, two full-scale verification tests were conducted in 2014. Following TCEQ approval, the City operated the DPR treatment facility from 9 July 2014 through 21 July 2015. During its operation, more than 2 billion gallons (7.6 million cubic meters) of highly treated wastewater effluent were turned into potable water. After a historic rainfall event in May 2015, the system was decommissioned, having had no major incidents during its 377 days of full-scale operation. Wichita Falls' experience demonstrates the feasibility of large-scale potable reuse under emergency conditions and provides valuable operational and regulatory insights for utilities considering potable reuse implementation.

Key words: case study, direct potable reuse, MF–RO–UV, Texas, Wichita Falls

HIGHLIGHTS

- First emergency DPR system in Texas during a drought, ensuring safe drinking water.
- Achieved 9.2/12.3/9.3 LRVs for viruses, *Giardia*, and *Cryptosporidium* – exceeding TCEQ standards.
- Treated over 2 billion gallons (7.6 million cubic meters) of highly treated wastewater effluent into potable water.
- Demonstrated real-world scalability and regulatory compliance for emergency water reuse.

GRAPHICAL ABSTRACT



1. INTRODUCTION

1.1. The path to emergency DPR

The City of Wichita Falls, Texas (CWF) is in the northern part of Texas, which is a region that regularly experiences cyclical periods of drought. After the 1995–2001 drought, the CWF decided to put into service a brackish water reservoir, Lake Kemp, which at the time was mostly used for industry and irrigation. Since Lake Kemp is brackish, an advanced treatment plant using microfiltration (MF) and reverse osmosis (RO) membranes was constructed in 2008 to treat the water for potable consumption. Before that, Wichita Falls' water sources consisted of two surface water reservoirs: Lake Arrowhead and Lake Kickapoo. In 2011 and 2012, CWF had an abnormally high number of days with high temperatures and a significant reduction in rainfall. For context, the region typically sees only 28 days of temperatures above 100 °F (37.8 °C). In 2011, CWF had 100 days over 100 °F, and in 2012, 50 days over 100 °F. Rainfall for the region is normally 29 inches (734 mm) annually. However, 2011 produced only 13.5 inches (342 mm) of precipitation; 2012, only 19.8 inches (502 mm). The compounding impact of high temperatures, low precipitation, and high winds caused stored volume to decline from a combined 83% in 2011 to below 23% in 2014, which triggered a 'catastrophic' drought warning based on CWF monitoring criteria.

In the early phases of the drought, its intensity led the CWF to approach the Texas Commission on Environmental Quality (TCEQ) to determine if they could implement a direct potable reuse (DPR) project. At the time, CWF and its consultants were already designing an indirect potable reuse (IPR) project, but it would not be ready for another 4 years. Because TCEQ was more comfortable with the city pursuing the IPR project, it did not initially approve the move to DPR. However, the severity of the drought did not decrease, so the CWF again approached TCEQ and made the case for a temporary emergency DPR project, which was approved in January 2013 (Nix *et al.* 2021). At the time, Texas did not have any existing DPR regulations, so throughout 2013, the CWF staff worked closely with TCEQ officials to identify and develop the rules and regulations that would be used for the DPR operations, a monitoring plan, a set of alarms and shutdown triggers, and criteria to perform a full-scale verification (FSV) of the complete DPR treatment facility. The emergency DPR treatment facility was then operated from 9 July 2014 until 21 July 2015, when the drought ended with historic rainfall in the spring of 2015. During operations, CWF mounted an extensive public relations campaign that included an educational video, several newspaper articles in the *Times Record News* (a local newspaper), and televised interviews with public health experts to keep the public informed about what was going on (City of Wichita Falls 2013, 2014; Times Record News 2014), which resulted in an overall positive public perception of the project.

This paper presents selected findings from the water quality data collected during the verification and operational phases of the DPR treatment facility. Given the scarcity of full-scale water quality data from operational DPR facilities in the scientific literature (currently limited to only two facilities worldwide, the Colorado River Municipal Water District's Raw Water Production Facility in Big Spring, TX, and Windhoek's Goreangab Water Reclamation Plant in Namibia (Haarhoff & Merwe 1996; Lahnsteiner & Lempert 2007; Steinle-Darling 2015; Lahnsteiner *et al.* 2018)), this study provides valuable insights into DPR system performance. Additionally, this paper discusses observed process performance and explores how design and operational decisions might differ if the DPR treatment facility were constructed today, considering present-day industry standards and the evolving regulatory landscape.

2. METHODOLOGY

2.1. Emergency DPR project construction

A temporary pump station and a 12.3-mile-long (19.8 km) 32-inch (812.8 mm) diameter high-density polyethylene (HDPE) pipeline were constructed to convey 7.5 million gallons per day (MGD, 28,400 m³/d) of wastewater effluent from the River Road Wastewater Treatment Plant (WWTP), now known as the Wichita Falls Resource Recovery Facility, to the Cypress Water Treatment Plant (CWTP), as shown in Figure 1. The pipeline was not buried, as the intent was to reuse the pipeline for the impending IPR system.

Treatment started at the River Road WWTP. The River Road WWTP treatment process began with wastewater entering the plant through two 42" (1,070 mm) and 48" (1,220 mm) interceptor sewers, which discharged to the influent lift station. Wastewater was then pumped from the lift station to the headworks, where bar screens and grit chambers removed large solids and abrasive materials. The wastewater was then treated using primary clarification, biological treatment in aeration

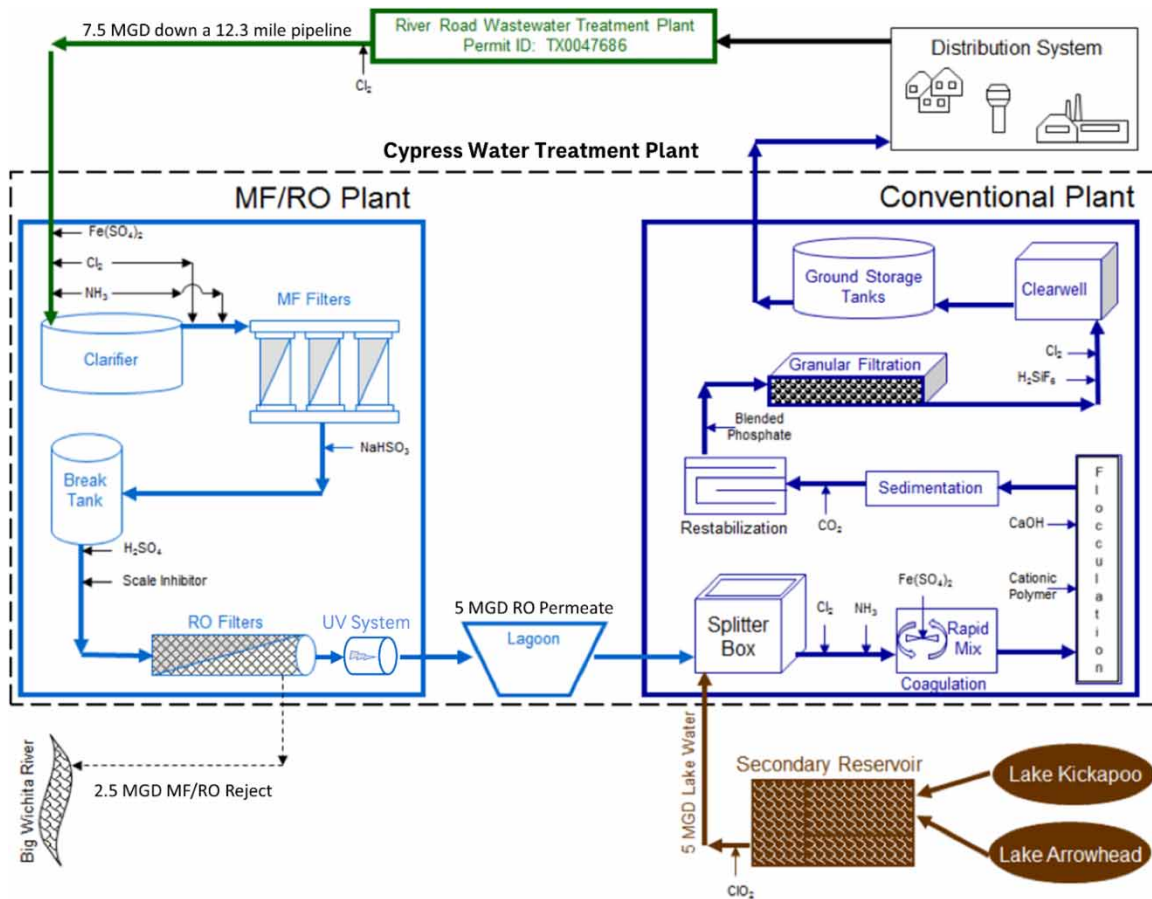


Figure 1 | CWTP DPR system process flow diagram.

basins, secondary clarification, and then disinfection to produce secondary wastewater effluent. Up to 7.5 MGD (28,400 m³/d) of wastewater effluent was collected at the River Road WWTP chlorine contact basin, where it was chloraminated (average chlorine dose of 9 mg/L as Cl₂) to maintain a residual through the 12.3-mile (19.8 km) pipeline to the CWTP and to minimize disinfection by-product formation. The average monochloramine residual exiting the River Road WWTP was 5.5 mg/L, and the average monochloramine residual entering the CWTP was 1.3 mg/L, indicating a consistent residual through the pipeline.

The CWTP includes two treatment plants – an MF/RO plant and a conventional water treatment plant containing flocculation, sedimentation, granular media filtration (GMF), and disinfection. The MF/RO plant is an existing facility constructed in 2008 to treat water from Lake Kemp, which is a brackish water reservoir. Due to the impacts of the drought and dropping lake levels, the salinity in Lake Kemp was elevated and out of spec for the MF/RO plant, and could not be treated using the existing equipment, which is why the Lake Kemp MF/RO system was available for conversion as part of the emergency DPR treatment facility. The MF/RO plant had a design capacity of 12 MGD (45,400 m³/d) but was limited to 5 MGD of RO permeate (18,900 m³/d) during the emergency DPR period. The MF/RO-treated effluent was limited to 50% of the total conventional water treatment plant influent. RO permeate was sent from the MF/RO plant to a 3-million-gallon (11,400 m³) lagoon, where it was held until it was blended with 5 MGD of lake water from Lake Arrowhead and/or Lake Kickapoo in a splitter box before being treated by the conventional treatment plant at the CWTP. The conventional plant was a surface water treatment plant that included coagulation, flocculation, sedimentation, GMF, and disinfection. Beginning in February 2015, by TCEQ requirement, the DPR system began using ultraviolet (UV) disinfection of the treated RO permeate prior to blending with the raw surface water to gain additional disinfection credits.

The CWTP remained in operation as an emergency DPR system until 21 July 2015, after which the MF/RO system was able to treat water from Lake Kemp again due to a historic rain event that brought the Lake Kemp water back into spec. Design criteria for the MF, RO, and UV systems are summarized in Table 1.

Table 1 | MF, RO, and UF system design criteria

Criteria	Value
MF system	
Configuration	5 cells (3 MGD (11,400 m ³ /d) each) 504 membranes per cell
Membrane model	MEMCOR S10 V submerged system
Membrane material	Polyvinylidene fluoride (PVDF)
Membrane nominal pore size	0.04 µm
RO system	
Configuration	6 skids (2 MGD (7,600 m ³ /d) each) 2-stage system (36:12) 75% recovery
Membrane model ^a	1st stage: Hydranautics ESPA2/ESPA2-LD 2nd stage: Hydranautics ESPA4/ESPA4-LD
Membrane nominal salt rejection	ESPA2/ESPA2-LD: 99.6% ESPA4/ESPA4-LD: 99.2%
Membrane spacer thickness	ESPA2/4: 28 mil (0.71 mm) ESPA2/4-LD: 34 mil (0.86 mm)
UV system	
Configuration	2 reactors (2.5 MGD (9,500 m ³ /d) each) 8, 9.6 kW UV lamps per reactor
Model	Trojan UV SwiftECT
Average UV dose	18.8 mJ/cm ²

^aWhen the DPR system started operations, the RO elements were 6-year-old ESPA2 and ESPA4 elements. The RO elements were replaced in October 2014 with new elements to increase nitrate removal. ESPA2-LD and ESPA4-LD elements were chosen since they have a wider spacer, which decreases the feed pressure requirements.

Note that pathogenic removal is a critical aspect of any DPR treatment process, and so is a key component of the design criteria for the DPR system. At the time, the TCEQ required that all DPR facilities have a minimum virus/*Giardia*/*Cryptosporidium* log removal value (LRV) of 8/6/5.5 with site-specific adjustments made if WWTP effluent sample results demonstrated the need for treatment levels higher than the stated minimum levels. Note that this logic is still followed in the TCEQ's latest guidance on pathogenic removal for DPR systems (TCEQ 2022). In the case of the CWF DPR system, the virus removal requirement was increased to 9 log since preformed chloramines were used for disinfection, and the *Giardia* log removal requirement was increased to 8 log based on the maximum cyst count detected, for a final virus/*Giardia*/*Cryptosporidium* LRV of 9/8/5.5. Additional detail on the efficacy of the pathogen removal process is in Section 3.3 – Pathogen Removal/Inactivation.

In terms of costs, the DPR system was able to avoid significant construction costs since CWF was able to repurpose the CWTP instead of building a new plant. The bulk of construction costs was from building the 12.3-mile-long (19.8 km) pipeline to transport water from the River Road WWTP to the CWTP.

While there were additional operational costs from raw water pumping, enhanced microbial monitoring, and running the UV system, operating costs were also offset due to a reduced demand for lime and CO₂. These two chemicals had a reduced demand since the RO permeate was blended with the surface water, so remineralization was not needed. Overall, budgeted operating costs for the emergency DPR at the CWTP were \$1.94M per year, which was only \$83k higher than operating the conventional and brackish water treatment facilities.

2.2. Data description

Before the emergency DPR system was allowed to distribute water to the public, the TCEQ mandated that the CWF conduct two FSV tests to prove the integrity of the DPR process and the safety of the purified water. The first FSV test (FSV-1) ran for 43 days from 27 January 2014 to 11 March 2014. The TCEQ required the DPR system to be monitored at 42 locations, which are summarized in Table 2. A total of 596 water quality parameters were measured during FSV-1, with a majority being individual water quality parameters that are regulated under the U.S. Environmental Protection Agency's (USEPA's) National Primary and Secondary Drinking Water Regulations (NPDWRs and NSDWRs). A total of 422,181 individual data points were collected during this period, which averaged out to 9,818 data points per day.

The second FSV test (FSV-2) was designed to capture additional data that the TCEQ requested based on the results of FSV-1 and ran for 30 days from 16 May 2014 to 14 June 2014. The TCEQ required the DPR system to be monitored at 19 locations during FSV-2 to provide additional monitoring data, with some additional parameters added that were not included in FSV-1. A total of 202 parameters were measured during this period, with 81,577 individual data points collected. Overall, this averaged out to 2,813 data points per day. The FSV-2 locations are noted in Table 2.

After the two FSV tests were successfully completed, the CWTP was allowed to produce water that could be distributed to the public. This TCEQ approval marked the transition to the full-scale operation (FSO) phase, which ran for 377 days from 9 July 2014 to 21 July 2015. During the FSO phase, more than 2 billion gallons of wastewater effluent were successfully treated into potable drinking water. A total of 42 parameters were measured during this period, with 1,616,290 individual data points collected. Overall, this averaged out to 4,242 data points per day, with 66% of this data being online MF, GMF, and wastewater effluent turbidity data collected on a 5-min interval. The FSO sample locations are noted in Table 2. Note that a statistical summary of all data collected during both the FSV and FSO periods can be found in Supplementary Table S1.

3. RESULTS AND DISCUSSION

3.1. Source and finished water quality characterization

The CWTP treated wastewater effluent from the River Road WWTP and surface water from Lake Arrowhead and Lake Kickapoo for the FSV test periods and the FSO operational period. All raw water sources contained parameters at concentrations that, if left untreated, would exceed the primary maximum contaminant levels (PMCLs) and secondary maximum contaminant levels (SMCLs) established by the USEPA's NPDWRs and NSDWRs. These parameters were addressed through treatment at the CWTP to ensure compliance with drinking water standards before the water could be delivered to the public.

Table 3 presents water quality data from the wastewater effluent source (sample location 01J) for parameters that were present at concentrations higher than the PMCLs and SMCLs from the FSV and FSO periods. Parameters that required treatment were color, nitrate, nitrite, odor, total dissolved solids (TDS), chloride, and turbidity. Total nitrate–nitrite and individual nitrate in the wastewater effluent were at concentrations that exceeded the PMCLs by 10–100% across all samples.

Table 2 | Sample locations for FSV-1,^a FSV-2,^b and FSO^c

Code	Description	Code	Description
01J ^{a,b,c}	Wastewater effluent pre-chlorine	21A/BJ ^c	UV reactor 1/2
02J ^{a,b,c}	Wastewater effluent post-chlorine	22J ^{b,c}	RO permeate lagoon
02JB ^b	Wastewater effluent pre-coagulant V/C/G sample	23J ^{a,b}	Source surface water, pre-CIO ₂
03J ^{b,c}	Wastewater effluent pre-coagulant	24J	Source surface water, post-CIO ₂
04J ^a	Wastewater effluent post-coagulant	25J	Source surface water, post-CIO ₂ (400 ft)
05J ^a	MF/RO clarifier influent post-chloramine	26J ^b	Source surface water, post-CIO ₂ (900 ft)
06J ^{a,b}	MF/RO clarifier	27J ^{a,b}	Source surface water, before RO permeate blend
07J ^b	MF/RO clarifier effluent	28J ^{a,b}	RO permeate and surface water blend
08J	MF combined feed	29J	Blend ratio, RO permeate to surface water
09J	MF individual feed	30J ^a	RO permeate blend chlorine and ammonia doses
10J ^{a,b,c}	MF individual filtrate	31J ^a	Rapid mix and coagulant addition
11J ^{a,b}	MF combined filtrate	32J ^{a,b}	Flocculation and clarification
12J ^a	Sodium bisulfite feed system	33J	Post-recarbonation
13J ^a	RO feed break tank	34J	Blended phosphate addition system
14J	Sulfuric acid feed system	35J ^{a,b,c}	After individual granular filtration
15J ^a	Antiscalant feed system	36J ^{a,b}	After combined granular filtration
16J ^a	RO individual feed	37J	Fluoride feed system
17J ^a	First stage RO permeate	38J ^{a,b}	Beginning of clearwell
18J ^a	Second stage RO permeate	39J ^a	After final chloramine dose
19J	Total RO concentrate	40J ^{a,b}	Final effluent to ground storage tanks (GST)
20J ^{a,b,c}	Total RO permeate	41J ^c	Simulated CT beginning at GST
21J	RO percent recovery	42J ^c	Simulated CT ending at High Service Pumps

Note: From the dataset reviewed for this study, codes marked with 'a' were sampled in FSV-1, codes marked with 'b' were sampled in FSV-2, and codes marked with 'c' were sampled during full-scale operations.

Table 3 | Parameters in the wastewater effluent at concentrations above their PMCL/SMCL

Simplified parameter	PMCL/SMCL ^a	Total samples	Samples above MCL	% of samples above MCL	Min	Mean	Max
Nitrate and Nitrite (Total) (mg/L as N)	10	3	3	100	14	15	16
Nitrate (mg/L as N)	10	47	47	100	11	15	20
Turbidity (NTU) ^b	0.3	42,551	42,551	100	0.32	2.97	29.94
Chloride (mg/L)	250, 300 ^{a,c}	3	2	67	230	253	270
Color (Pt-Co)	15 ^a	3	3	100	30	33	35
Odor (TON)	3 ^a	3	3	100	8	8	8
TDS (mg/L)	500, 1,000 ^{a,d}	9	9	100	650	749	900

^aValue is an SMCL.

^bFor systems that use conventional or direct filtration, at no time can the combined filter effluent turbidity go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95% of the samples in any month.

^cThe USEPA SMCL is 250 mg/L, and the TCEQ SMCL is 300 mg/L.

^dThe USEPA SMCL is 500 mg/L, and the TCEQ SMCL is 1,000 mg/L.

These high concentrations required reduction, as elevated nitrate/nitrite levels can pose severe health risks, including methemoglobinemia, particularly in vulnerable populations such as infants and pregnant women (Filer *et al.* 1970). Similarly, TDS levels were 30–80% higher than the USEPA's SMCL but were lower than the TCEQ SMCL of 1,000 mg/L. Note that the TCEQ SMCL for TDS is higher than the USEPA SMCL for TDS due to the naturally high level of dissolved solids in Texas' groundwater sources (TCEQ 2025). Similar logic holds for chlorides, which were at concentrations higher than the

USEPA SMCL but lower than the TCEQ SMCL. Odor and color being at elevated levels suggest the presence of dissolved organic compounds, which would need to be removed by the MF/RO plant. No other regulated contaminants, such as heavy metals, were observed at concentrations higher than their PMCL or SMCL.

Table 4 presents water quality data from the surface water source (sample location 23J) for parameters that were present at concentrations higher than their PMCL or SMCLs from the FSV and FSO periods. Elevated levels of aluminum and iron were observed. Aluminum was detected at concentrations higher than the SMCL 100% of the time, with the aluminum SMCL being an aesthetic water quality criterion set at 0.05–0.2 mg/L to prevent colored water. However, there is no established health-based PMCL for aluminum since there is little indication that orally ingested aluminum is acutely toxic to humans, so concentrations higher than the SMCL are not particularly concerning (WHO 2022). High turbidity levels and elevated TDS further highlight the impact of natural organic material and mineral dissolution in the watershed.

Both the wastewater effluent and the surface water would exceed the PMCL for nitrate if left untreated, which is a health-based concern. While surface water had higher concentrations of iron and aluminum due to the influence of environmental factors, it also had a lower TDS than the wastewater effluent, which demonstrates the different characteristics of both source waters (wastewater effluent vs. surface water).

Finally, the finished water did not have any parameters at concentrations higher than their PMCLs and SMCLs during FSV-1, FSV-2, and FSO. Table 5 provides the specific finished water (sample location 40J) quality data for the parameters noted in Tables 3 and 4. During FSV-2, there was a single isolated 59 mg/L sample of sodium in the finished water that was found at a concentration higher than what is recommended by the USEPA's non-enforceable 2018 Drinking Water Health-Based Advisory guideline of 20 mg/L for individuals on a 500 mg/L restricted sodium diet (USEPA 2018). Note that there was no raw

Table 4 | Parameters in the surface water source at concentrations above their PMCL/SMCL

Simplified parameter	PMCL/SMCL ^a	Total samples	Samples above MCL	% of samples above MCL	Min	Mean	Max
Turbidity (NTU) ^b	0.3	4,176	4,135	99	–	33.9	50.0
Aluminum (mg/L)	0.05–0.2 ^a	3	3	100	0.19	0.68	1.20
Iron (mg/L)	0.3 ^a	3	2	67	0.2	0.7	1.0
Color (Pt-Co)	15 ^a	3	3	100	20	37	60
TDS (mg/L)	500, 1,000 ^{a,c}	47	43	91	420	559	790

^aValue is an SMCL.

^bFor systems that use conventional or direct filtration, at no time can the combined filter effluent turbidity go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95% of the samples in any month.

^cThe USEPA SMCL is 500 mg/L, the TCEQ SMCL is 1,000 mg/L.

Table 5 | Finished water concentrations for parameters that were at concentrations above their PMCL/SMCL in the wastewater effluent and surface water sources

Simplified parameter	PMCL/ SMCL ^a	Total samples	Samples above MCL	% of samples above MCL	Min	Mean	Max
Nitrate and Nitrite (Total) (mg/L as N)	10	3	0	0	0.5	1.0	1.5
Nitrate (mg/L as N)	10	4,210	0	0	0.4	0.7	3.3
Turbidity (NTU) ^b	0.3	4,176	0	0	0.09	0.14	0.27
Aluminum (mg/L)	0.05–0.2 ^a	4	0	0	ND	0.01	0.03
Iron (mg/L)	0.3 ^a	4	0	0	ND	0.01	0.02
Chloride (mg/L)	250, 300 ^{a,c}	4	0	0	79	98	120
Color (Pt-Co)	15 ^a	44	0	0	ND	1.0	8.0
Odor (TON)	3 ^a	48	0	0	ND	0.9	2.0
TDS (mg/L)	500, 1,000 ^{a,c}	4,180	0	0	240	382	462

^aValue is an SMCL.

^bFor systems that use conventional or direct filtration, at no time can the combined filter effluent turbidity go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95% of the samples in any month.

^cThe USEPA SMCL is 500 mg/L, the TCEQ SMCL is 1,000 mg/L.

ND, non-detect.

(wastewater effluent or surface water source) water quality data collected for sodium. The fact that there were no PMCL or SMCL exceedances in the finished water reflects the robustness and integrity of the DPR system, proving its ability to handle varying raw water qualities.

3.2. Process performance observations

The following sections describe detailed observations of key trends observed in each stage of the treatment process. Each process includes a graph of key high-frequency data that shows how the process operated over time. Turbidity was the most frequently sampled parameter in the dataset, so it is included in the graphics for several processes to show how water quality can change across multiple processes in the treatment train. The graphs include vertical lines that indicate when each period (FSV-1, FSV-2, and FSO) occurred, as well as a horizontal red line to indicate NPDWR PMCLs when relevant. For identification of the sample sites, please refer to Table 2.

3.2.1. River Road WWTP effluent

Wastewater effluent quality data were collected at the River Road WWTP after disinfection and prior to its 12.3-mile (19.8 km) journey to the CWTP, as shown in Figure 1. The consistent monochloramine residuals (3.9–5.1 mg/L) observed throughout the system indicate a stable chlorine demand (Figure 2). Additionally, occasional spikes in turbidity (up to 30 NTU) that were present during the FSO period were not observed during the FSV periods. This is most likely due to the turbidity spikes being caused by rain events, which were infrequent during the FSV periods due to the intense drought conditions at the time.

3.2.2. Coagulation and clarification

The first process in the DPR treatment train at the CWTP was ferric sulfate coagulation and clarification. Figure 3 visualizes the impact that coagulation and clarification had on the raw water turbidity and shows how the ferric sulfate dose was paced to match the raw turbidity.

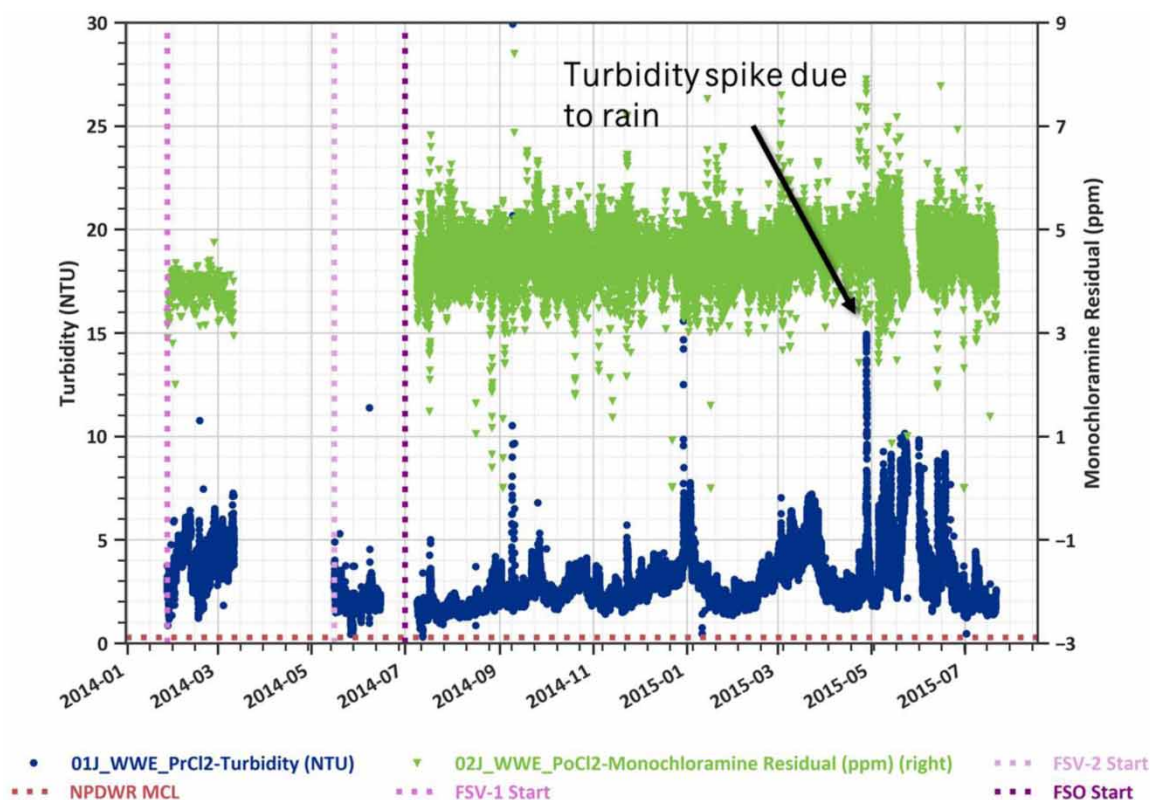


Figure 2 | Turbidity and monochloramine residual in WW feed – FSV and FSO period.

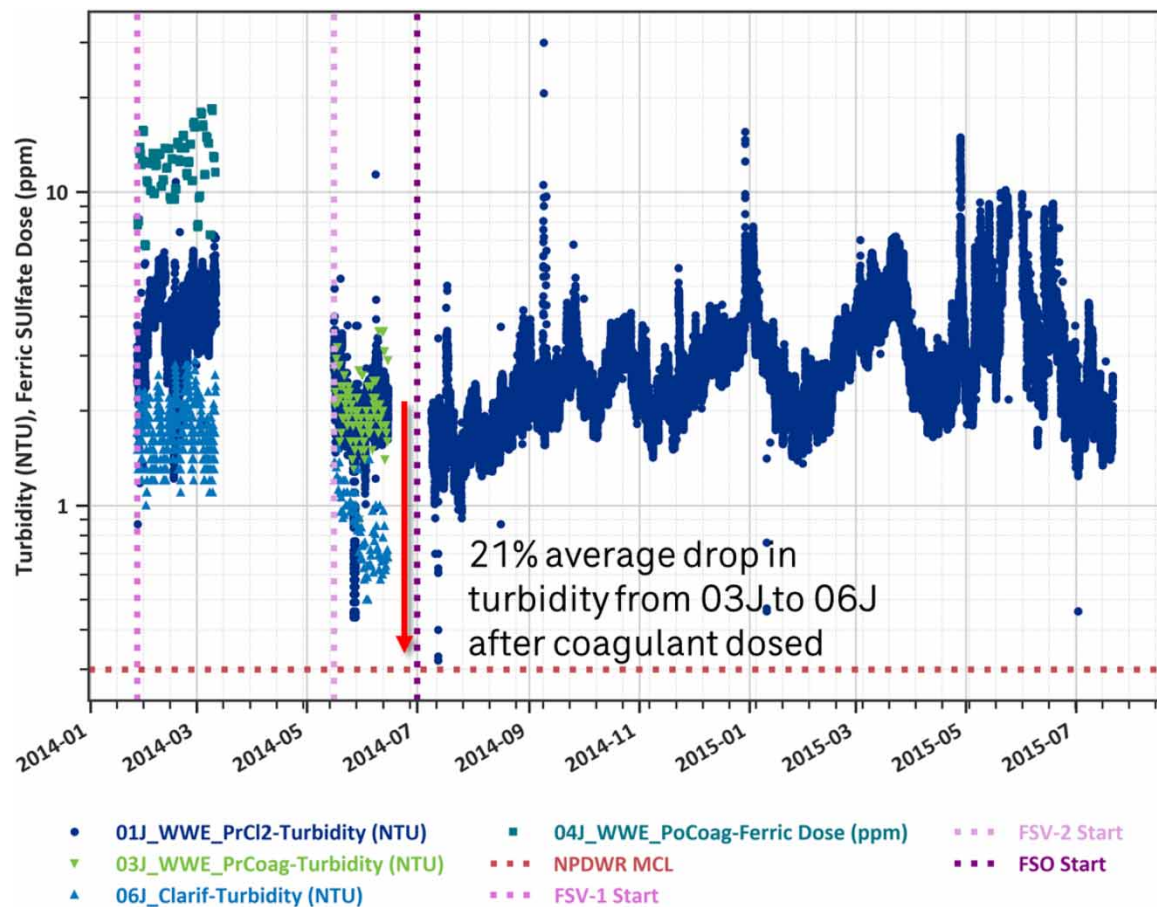


Figure 3 | Turbidity and ferric sulfate dose pre- and post-clarification – FSV and FSO period.

Post-coagulation turbidity levels were, on average, 21% lower compared with pre-coagulation levels after ferric sulfate was dosed. This reduction indicates effective particle aggregation and sedimentation during the coagulation and clarification steps. Note that during the FSO period, there were spikes in raw water turbidity that were not observed during the FSV periods. Post-clarifier turbidity data were not collected during the FSO period, but it appears that the coagulant was still effective based on the trends observed during the FSV periods and the absence of MF turbidity failures and/or membrane fouling.

3.2.3. Microfiltration

Following coagulation, the wastewater effluent was treated by MF membranes. The MF process demonstrated consistent and effective turbidity reduction, maintaining low filtrate turbidity levels even when feed water turbidity exhibited significant variability and spikes, as shown in Figure 4. The graph's logarithmic scale highlights the contrast between the higher turbidity of the MF feed water and the low turbidity of the MF filtrate. The 99.7% average drop in turbidity from the raw water to the post-MF water underscores MF's effectiveness as a barrier for particle and pathogen removal in the overall treatment train. The ability of the MF system to maintain low turbidity levels enhances downstream processes such as RO by reducing fouling potential and ensuring better overall system performance.

3.2.4. Reverse osmosis

RO followed MF, and the performance of the RO system was a critical component of the CWTP, both for its ability to reject salts and for its role in removing contaminants such as nitrate. The RO elements were replaced in October 2014 due to the elements being at their end of life. They had been in use for 6 years, including the height of the drought, where they had much higher TDS from the drought conditions in the lake water than 'normal'. Pre-changeout the elements were Hydranautics

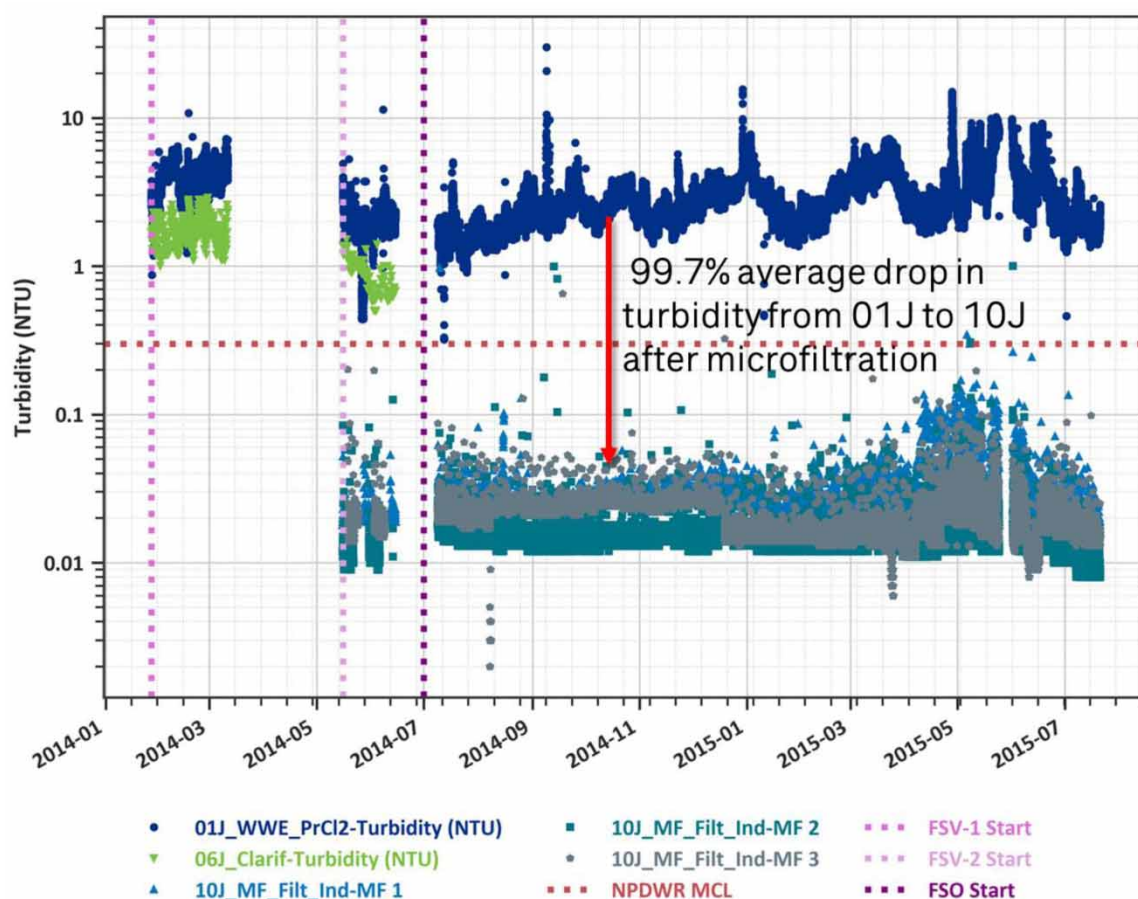


Figure 4 | Turbidity pre- and post-MF – FSV and FSO period.

ESPA2 in the first stage and ESPA4 in the second stage, post-changeout the elements were Hydranautics ESPA2-LD in the first stage and ESPA4-LD in the second stage. Elements were changed to the LD models since the LD models had a wider feed spacer, which allows them to run at a lower pressure/differential pressure.

As shown in Figure 5, the salt rejection efficiency was initially lower during the earlier phases of operation, particularly before membrane replacement. This reduced performance likely reflected the combined influences of membrane fouling and aging, which is common in RO systems over time due to the impacts from scaling, biofouling, and chemical degradation. Following membrane replacement, salt rejection improved significantly, demonstrating the importance of routine maintenance and component replacement to maintain optimal RO performance.

Figure 6 illustrates that nitrate concentrations in the RO permeate were close to the PMCL of 10 mg/L as N during the early operational phases, before the membranes were replaced. This suggests a decline in membrane performance for contaminant rejection over time, consistent with observed salt rejection patterns.

After membrane replacement, nitrate concentrations in the permeate decreased significantly, aligning with the improved salt rejection trends. This correlation supports the idea that salt rejection/conductivity can serve as a surrogate monitor for other contaminants (USEPA 2012a, b; Drewes *et al.* 2018).

Overall, the documented improvements after membrane replacement emphasize the importance of proactive maintenance and system monitoring in ensuring reliability and sustained compliance with water quality standards.

3.2.5. UV disinfection

UV disinfection was introduced as a polishing step following RO during the FSO period, with the system coming online on 11 February 2015. The addition of UV disinfection was a requirement by TCEQ if the emergency DPR system ran longer than 6

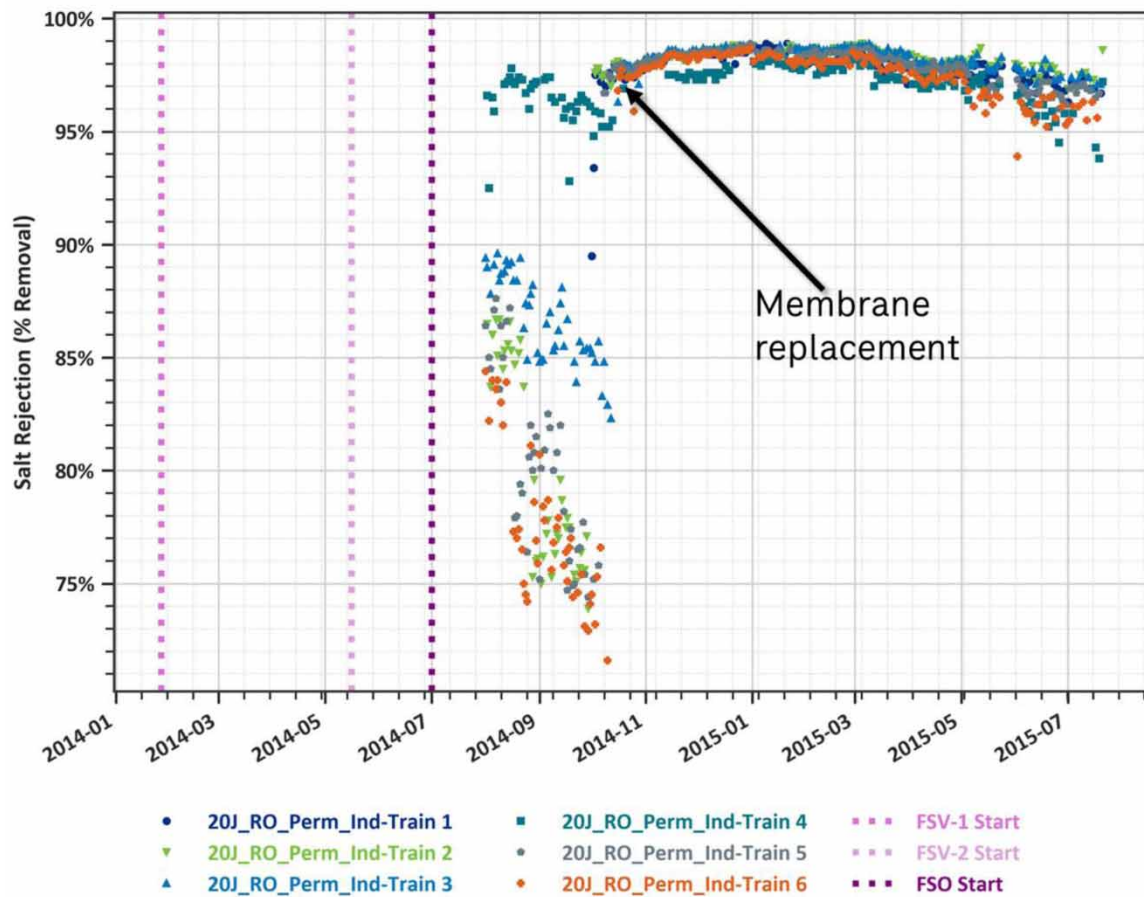


Figure 5 | RO salt rejection – FSV and FSO period.

months and aimed to supply an additional 3.0 LRV barrier against *Cryptosporidium* and *Giardia*, providing redundancy and safety in the treatment train.

As shown in Figure 7, UV transmittance (UVT) remained consistent throughout the FSO period as long as the system was online. There was a period when measured UVT decreased, but that was when the system was taken offline. Consistent UVT is indicative of the RO system's effectiveness in removing organic matter and other UV-absorbing substances such as chloramines (Beauchamp *et al.* 2018). Overall, the absence of significant UVT fluctuations suggests that few organic spikes passed through the RO system. In addition, consistently high UVT levels (>90%) indicate that the feedwater to the UV system was free of significant turbidity or organic loads that could inhibit UV disinfection efficacy.

The system delivered a mean calculated UV dose of 18.8 mJ/cm², as shown in Figure 8. According to the USEPA UV Disinfection Guidance Manual (USEPA 2006), this dose corresponds to a 3.5-log (99.97%) inactivation of *Giardia lamblia* cysts and *Cryptosporidium parvum* oocysts, which was 0.5 log above the 3.0-log inactivation (representative of a dose of 11–12 mJ/cm²) required by the TCEQ.

Occasional spikes in UV dose were observed, likely corresponding to fluctuations in flow rate or UV intensity, which could potentially have been caused by an issue with the UV intensity sensor. These spikes demonstrate the system's capacity to adjust to varying operational conditions, maintaining adequate pathogen inactivation even under transient flow changes.

Overall, the UV disinfection system provided an additional layer of protection downstream of the RO. This setup was intended to address residual *Giardia* and *Cryptosporidium* that might pass through or bypass the RO with an additional treatment barrier, enhancing the overall reliability and safety of the treatment process.

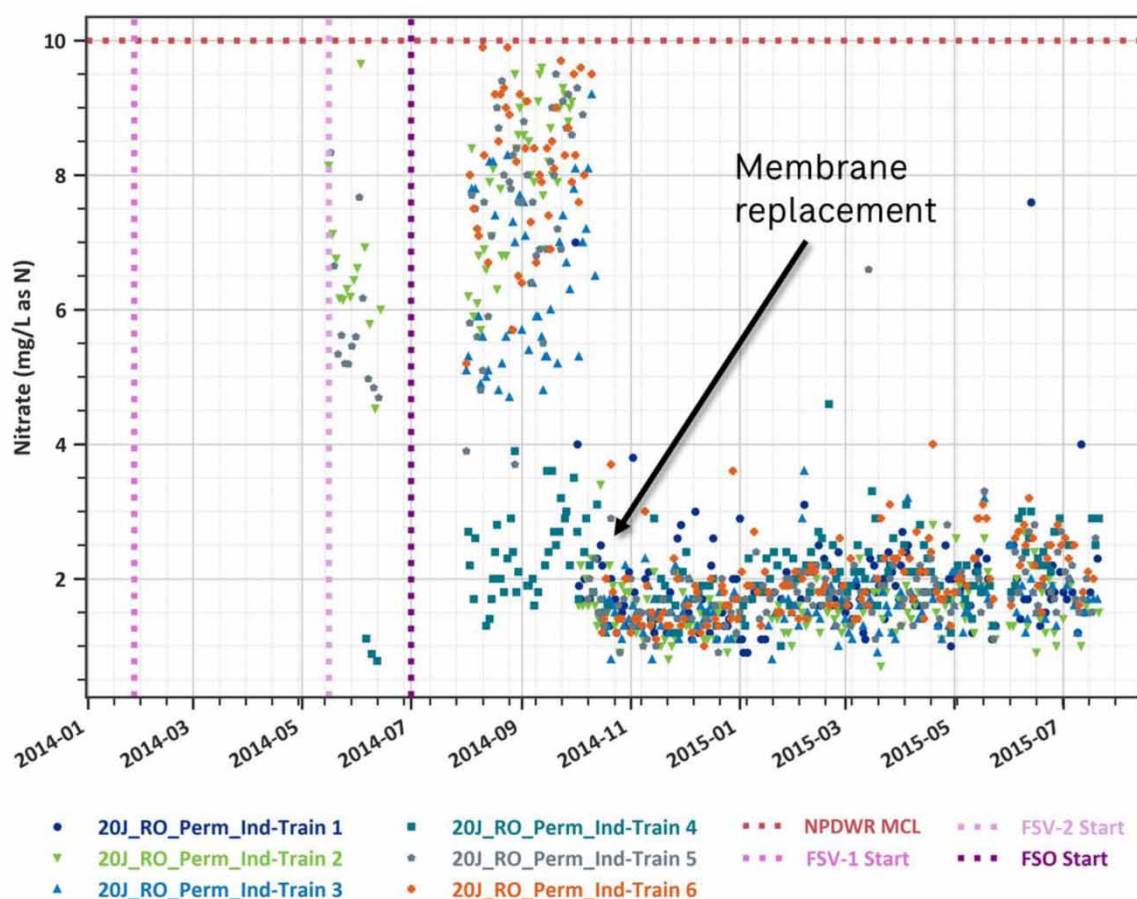


Figure 6 | RO permeate nitrate concentration – FSV and FSO period.

3.2.6. RO permeate lagoon and surface water source

After the RO permeate passed through the MF/RO/UV process at the CWTP, the water was then discharged to the 3-million-gallon (11,400 m³) permeate lagoon. After passing through the permeate lagoon, the RO permeate was blended with water from Lake Arrowhead and/or Lake Kickapoo in the splitter box before being sent for additional treatment at the CWTP conventional surface water treatment plant. As shown in Figure 9, at times the RO permeate exceeded 50% of the total surface water plant influent blend (up to 54%), but when it happened, it was only for short periods of time. It is important that the blend percentage remains consistent since varying blend percentages have been found to impact the performance of downstream unit processes (Upadhyaya *et al.* 2023).

The blending of RO permeate with surface water from the lakes had a direct effect on the turbidity of the combined water. The presence of surface water increased turbidity relative to the RO permeate, which is generally very low in turbidity. Figure 10 demonstrates the turbidity levels before and after the blending process during the FSV and FSO periods.

The turbidity from the surface water showed a noticeable increase as FSV-1 progressed, highlighting potential issues with the lake's water quality during this period, which was most likely due to the impact of declining lake levels decreasing the volume of water that could dilute the suspended solids in the lake water. To manage the increased turbidity and potential microbial risks associated with higher turbidity in the blended water, chloramine dosing was employed. This dosing helped to reduce turbidity, likely by promoting coagulation, killing biofilms/bacteria, and facilitating particle removal in subsequent treatment stages.

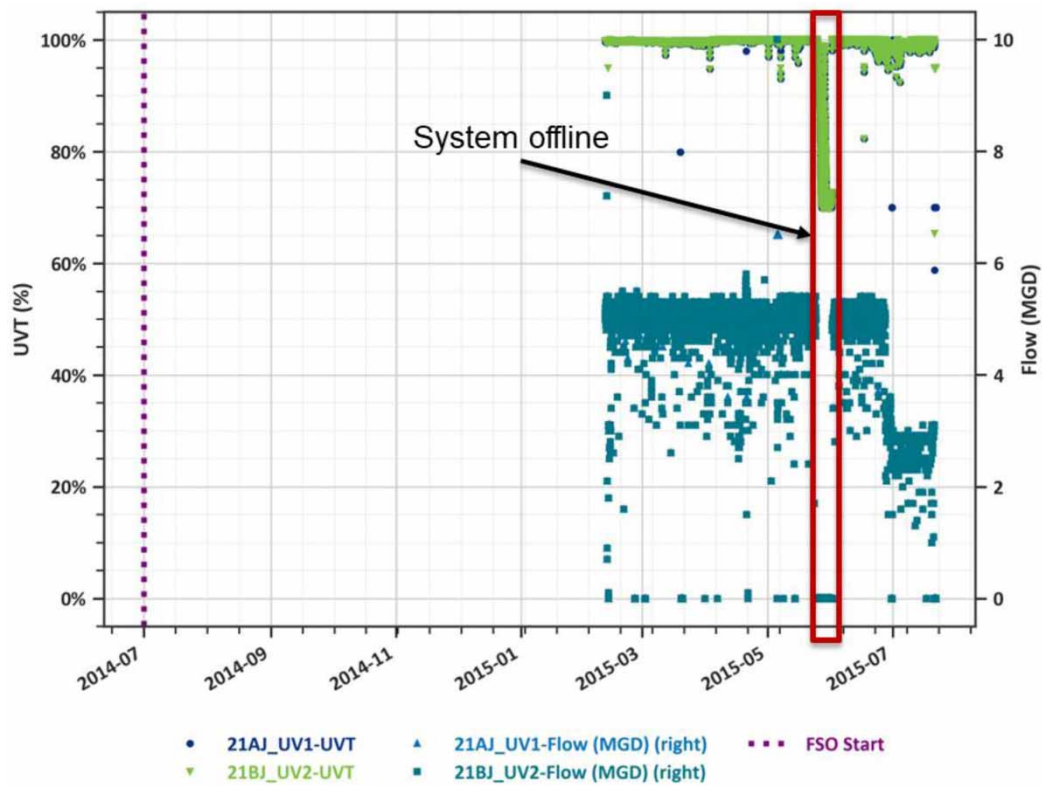


Figure 7 | UVT vs. UV flow – FSV and FSO period.

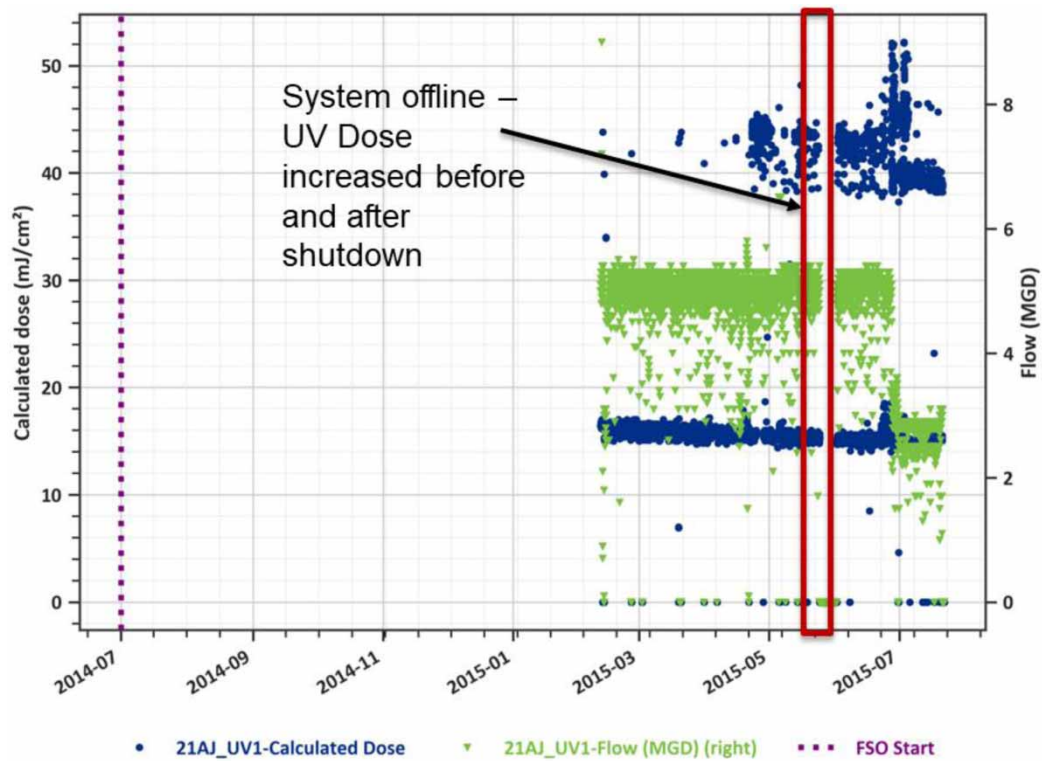


Figure 8 | UV dose vs. flow – FSV and FSO period.

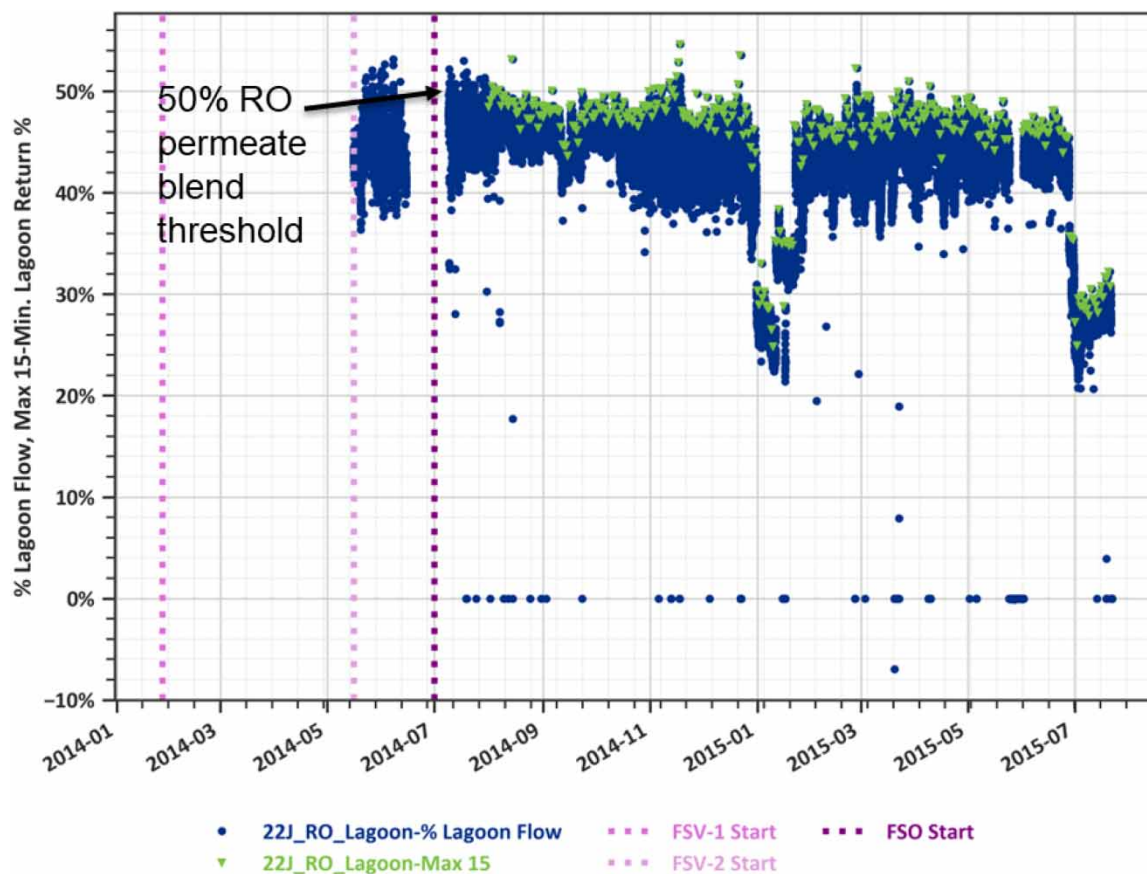


Figure 9 | RO permeate lagoon blend % – FSV and FSO period.

3.2.7. Coagulation/rapid mix/clarification/restabilization

The coagulation, rapid mix, and clarification processes at the beginning of the surface water treatment plant were essential for further reducing turbidity after the water was blended in the splitter box. These processes aim to remove suspended particles and other impurities, ensuring that the treated water meets required quality standards before being sent to GMF. As seen in Figure 11, turbidity decreased significantly after clarification, indicating the effectiveness of these treatment stages in removing particulates. However, despite the turbidity reduction, there were still instances where the turbidity exceeded the treatment technique limit of 0.3 NTU for the PMCL, which underscores the need for a robust filtration process downstream of clarification because filtration removes particles that may remain after coagulation and clarification.

3.2.8. Granular media filtration

As shown in Figure 12, turbidity levels decreased by an average of 96% following GMF treatment during both the FSV and FSO periods, consistently bringing the GMF effluent turbidity to be compliant with the PMCL, which states that turbidity must be less than or equal to 0.3 NTUs in at least 95% of the samples in any given month. As expected, this significant reduction of turbidity demonstrates the ability of GMF to act as a critical polishing step in the treatment process, removing suspended particles, including fine particulates or poorly aggregated flocs, before the water undergoes final disinfection.

3.3. Pathogen removal/inactivation

Pathogen removal (filtration) and inactivation (disinfection) are critical steps in water treatment that are especially important for DPR. Besides *Escherichia coli*, the three primary microorganisms that were tested during the emergency DPR project were enteric viruses, *Cryptosporidium* oocysts, and *Giardia* cysts. Samples were collected for all three

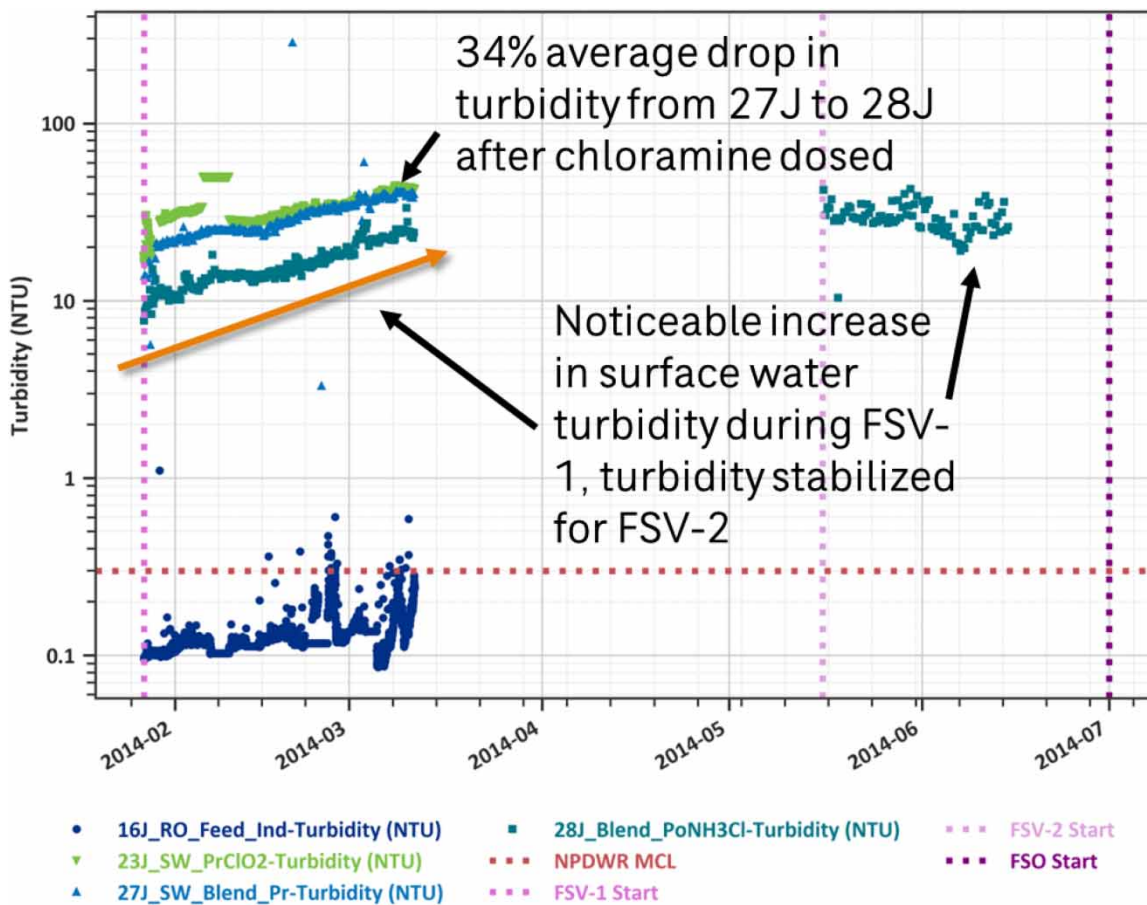


Figure 10 | Turbidity pre- and post-blend – FSV and FSO period.

pathogenic indicators from the surface water, the WWTP effluent, and the DPR effluent to assess the effectiveness of pathogen removal across the treatment train. The treatment process was required to meet regulatory Virus/*Giardia*/*Cryptosporidium* LRVs of 9/8/5.5, and was credited by TCEQ with LRVs of 9.2/12.3/9.3 (Table 6). LRVs for *E. coli* could not be calculated because *E. coli* was always non-detect after chloramination of the wastewater effluent, as described in Section 3.2.1.

As shown in Figure 13, there were detectable concentrations of *Giardia* cysts and *Cryptosporidium* oocysts in the wastewater effluent source that were removed to non-detect levels by the time the water had passed through the DPR treatment process. Note that viruses are not included in Figure 13 since viruses were not detected in any of the samples collected. Several pathogen detections were observed in the wastewater effluent after the first round of disinfection, suggesting that the initial disinfection did not fully eliminate these microorganisms. This is expected since chloramines were used as the disinfectant, which are not effective at removing *Giardia* cysts and *Cryptosporidium* oocysts but instead are used primarily for virus reduction (Drogui & Daghrir 2015).

The absence of any detectable pathogens in the DPR effluent demonstrated the effectiveness of the DPR process in achieving comprehensive pathogen removal. Viruses were sampled for using USEPA Method 1615, which provides culture and molecular procedures for detecting human enteroviruses and noroviruses using RT-qPCR, and mammalian orthoreoviruses using a culture procedure in water (USEPA 2012a, b). There were no detections of any of those virus types in the dataset. The absence of virus detections in both the wastewater effluent source and the DPR effluent product makes it difficult to ascertain the effectiveness of the treatment process for viruses, but it is assumed that viruses were removed to the same degree that other DPR/IPR treatment trains have achieved, especially given that the treatment process contained multiple rounds of physical filtration and chemical disinfection (Pyper *et al.* 2016; Ge *et al.* 2021).

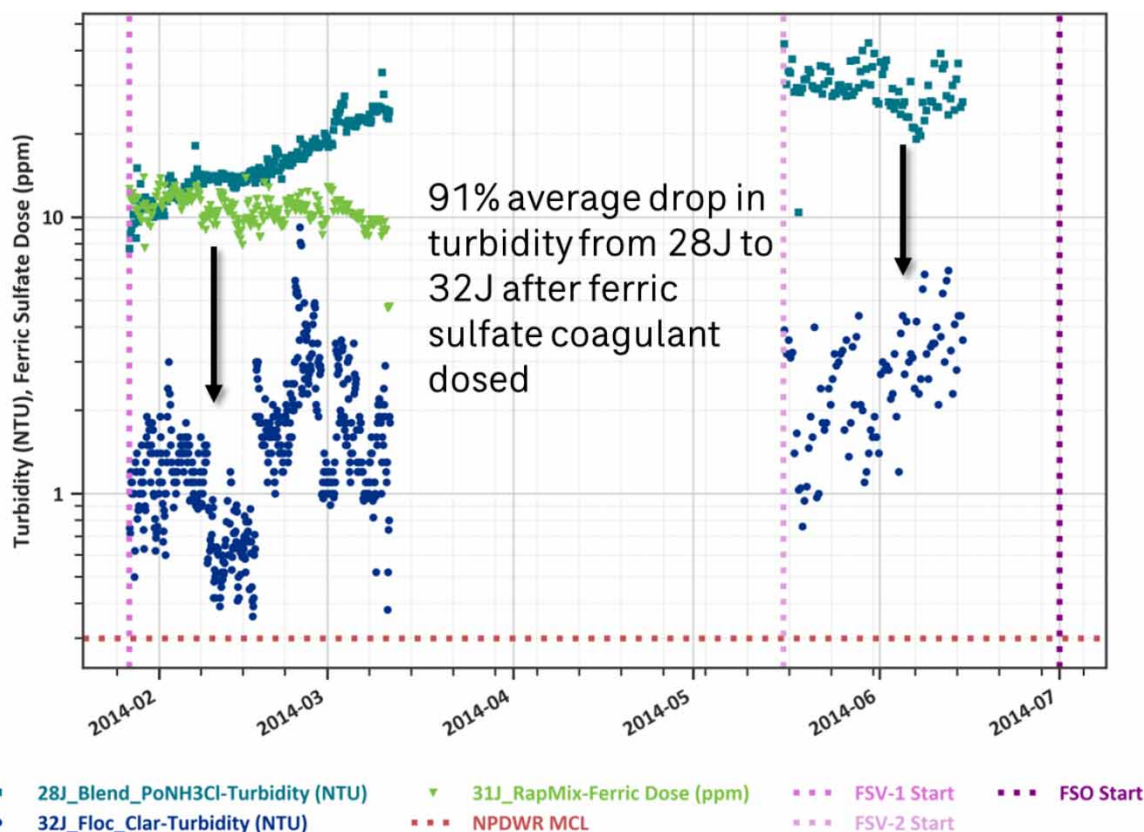


Figure 11 | Turbidity and ferric sulfate dose pre- and post-blend clarification – FSV and FSO period.

3.4. Emerging contaminants/regulatory changes

Since the implementation of the Wichita Falls emergency DPR project in 2014–2015, potable reuse regulations have evolved significantly in the United States, particularly at the state level. At the time, the facility's treatment train, which consisted of MF, RO, and UV disinfection, followed by blending with surface water and conventional treatment (Figure 1), was rigorously monitored for key water quality parameters, including turbidity, nitrate–nitrite, UV transmission, salt rejection, and microbial contaminants. All measured parameters complied with the NPDWRs and NSDWRs, as described in the previous sections. However, if a similar DPR project were undertaken today, additional monitoring and treatment requirements would need to be considered to align with current regulatory expectations.

For instance, California's DPR regulations mandate continuous online monitoring of total organic carbon (TOC), nitrite, and nitrate to provide real-time data to ensure stable treatment performance (SWRCB 2024). Weekly sampling for perchlorate and lead, as well as quarterly monitoring of emerging contaminants such as pharmaceuticals and personal care products, *N*-nitrosodimethylamine (NDMA), lithium, and microplastics, is also required. Additionally, the removal of 1,4-dioxane through advanced oxidation processes (AOP) is explicitly regulated.

Aside from California, other states that have successfully passed DPR regulations as of 2025 include Florida (FDEP 2025), Colorado (CDPHE 2024), and Arizona (ADEQ 2025), which shows that DPR is gaining traction in the United States. While Texas has not implemented formal DPR regulations, a guideline document titled 'Direct Potable Reuse for Public Water Systems' that specifies general requirements for pathogen and chemical treatment, water quality monitoring, and treatment performance monitoring was released by TCEQ in December 2022 (TCEQ 2022). In addition, compliance with evolving national standards, such as the recent inclusion of some per- and polyfluoroalkyl substances (PFAS) in the NPDWR, would be necessary. These emerging regulatory trends highlight the growing emphasis on online and frequent grab-sample monitoring, as well as enhanced treatment requirements that could influence the design and operation of future DPR projects.

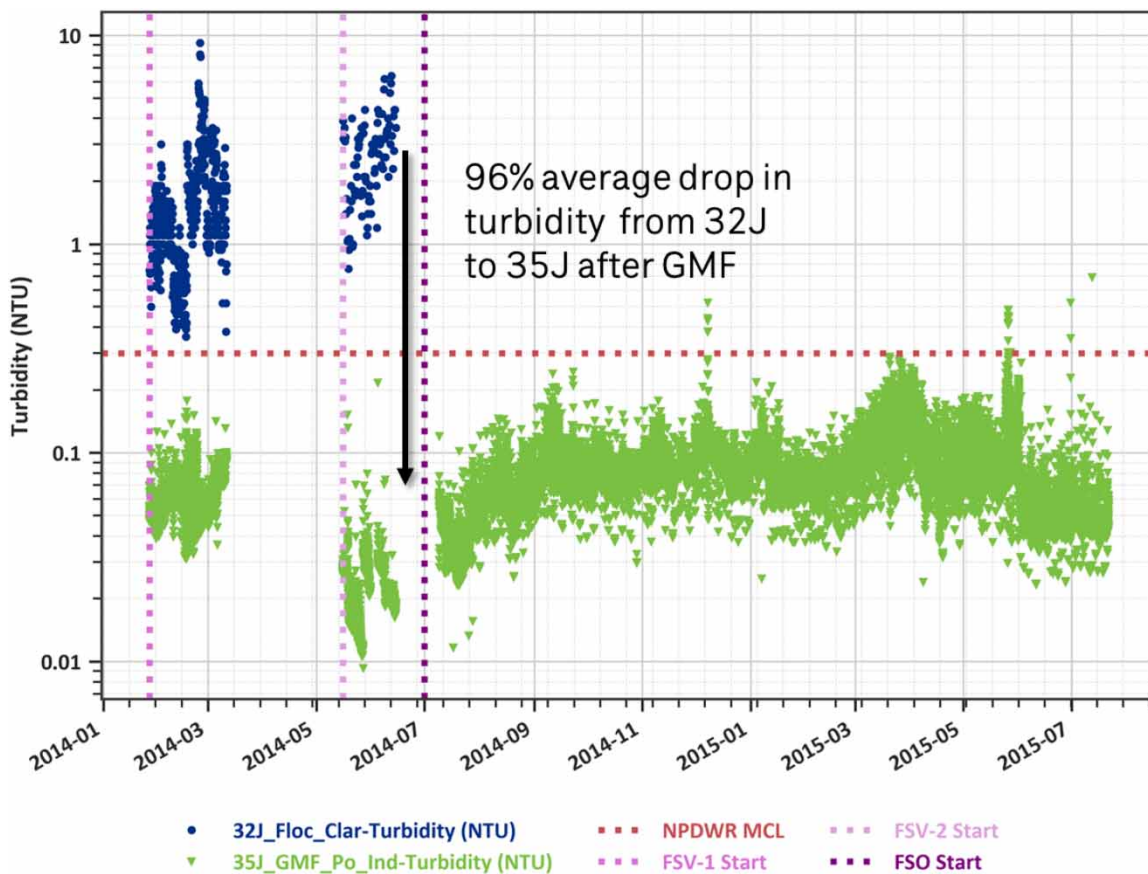


Figure 12 | Turbidity pre- and post-GMF – FSV and FSO period.

Table 6 | Wichita falls DPR project Log removal value (LRV) summary^a

Process	Virus LRV	Giardia LRV	Cryptosporidium LRV
Chloramines (D1) ^b	1.11	0.64	0
MF/RO clarifier	0.5	0.5	0.5
Chloramines (D2 and D3) ^c	0.72	0.41	0
MF	1.5 ^d	2.8	2.8
RO	0	0	0
UV	0	3.0	3.0
Conventional ^e	0.5	0.5	0.5
Gravity filters	1.5	2.5	2.5
Chloramines (D4 and D5) ^f	3.37	1.95	0
Total	9.2	12.3	9.3
Site-specific goals	9	8	5.5

^aLRVs determined by TCEQ.

^bLRVs are based on contact time in the pipeline from the River Road WWTP to the Cypress WTP.

^cAdditional disinfection zones in the Cypress WTP MF/RO Plant side.

^dLRVs are awarded based on a combination of prior conventional treatment with MF. MF alone would not retain virus particles.

^eConventional water treatment consists of rapid mix, coagulation, flocculation, and sedimentation.

^fAdditional disinfection zones in the Cypress WTP Conventional Plant side.

D stands for disinfection zone.

Table modified from [Steinle-Darling \(2015\)](#).

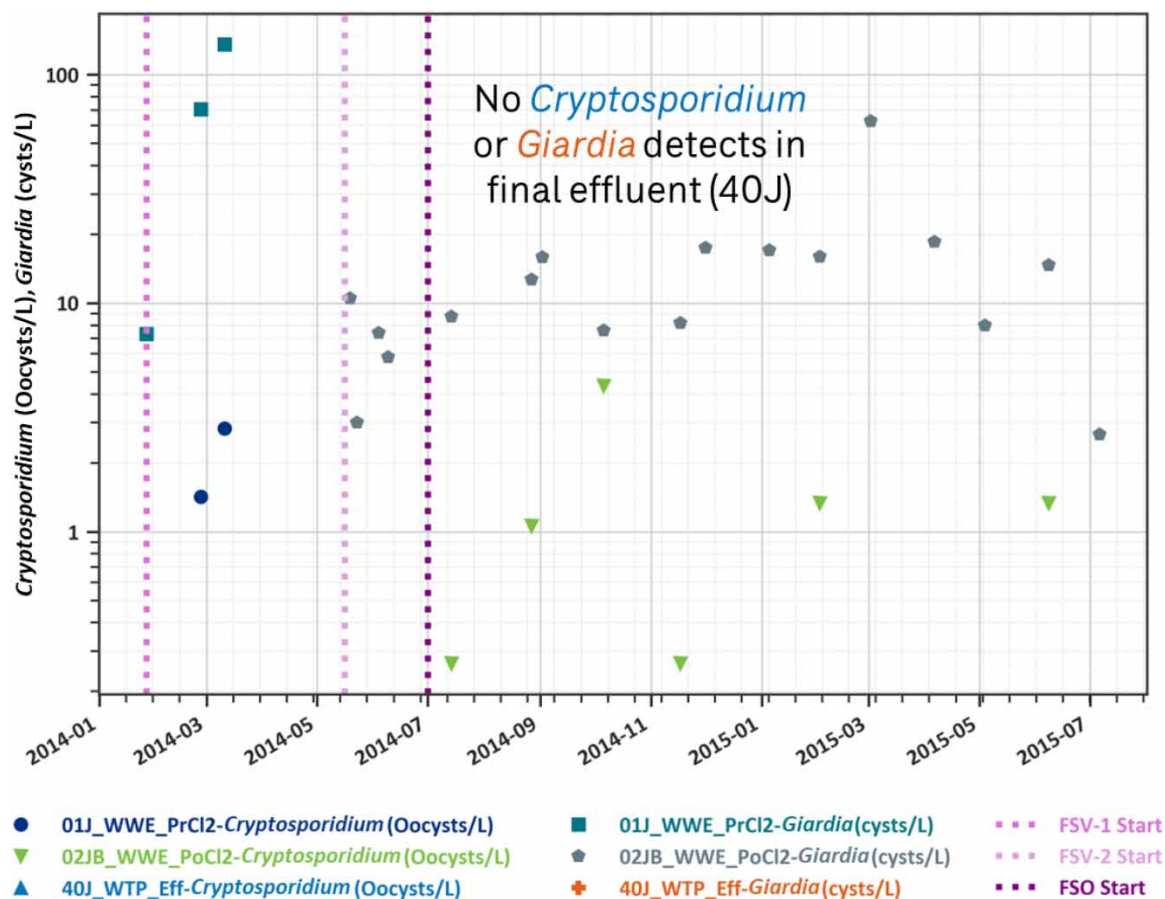


Figure 13 | *Cryptosporidium* oocysts and *Giardia* cysts removal – FSV and FSO period.

If the Wichita Falls DPR treatment facility were designed today, integrating continuous monitoring systems for key water quality indicators, such as TOC and nitrate, and incorporating additional treatment steps, such as UV AOP and granular activated carbon (GAC) filtration, for specific contaminants would likely be necessary. For example, the new DPR project in El Paso, TX, will incorporate GAC filtration after the UV AOP to remove low molecular weight compounds that can pass through RO, including chloroform and other disinfection byproducts, and deliver the purified water directly to the drinking water distribution system (El Paso Water and Arcadis 2024). The El Paso DPR project is under construction at the time of publishing this article, with an estimated completion date of 2028. The regulatory emphasis on emerging contaminants suggests that utilities pursuing DPR must adopt more comprehensive water quality monitoring strategies to meet current and future standards. This underscores the need for further research and data collection to refine the best practices for DPR system design and operation.

4. CONCLUSION

CWF's implementation of an emergency DPR system in response to the severe drought from 2011 to 2015 serves as a pioneering example of innovative water management. The successful design, construction, and operation of the DPR treatment facility, which ran continuously for 454 days (77 days of testing, 377 days of distributing water to the public), underscores the city's adaptability and commitment to ensuring a safe, reliable water supply. The DPR system met all NPDWRs and NSDWRs as well as all state-required drinking water requirements.

During its operation, the DPR system treated over 2 billion gallons of high-quality wastewater effluent, transforming it into potable water that played a crucial role in providing a safe water supply to Wichita Falls and 13 surrounding communities during a time of crisis. The system ran until historic rains occurred in May 2015 that refilled the reservoir (Figure 14), allowing

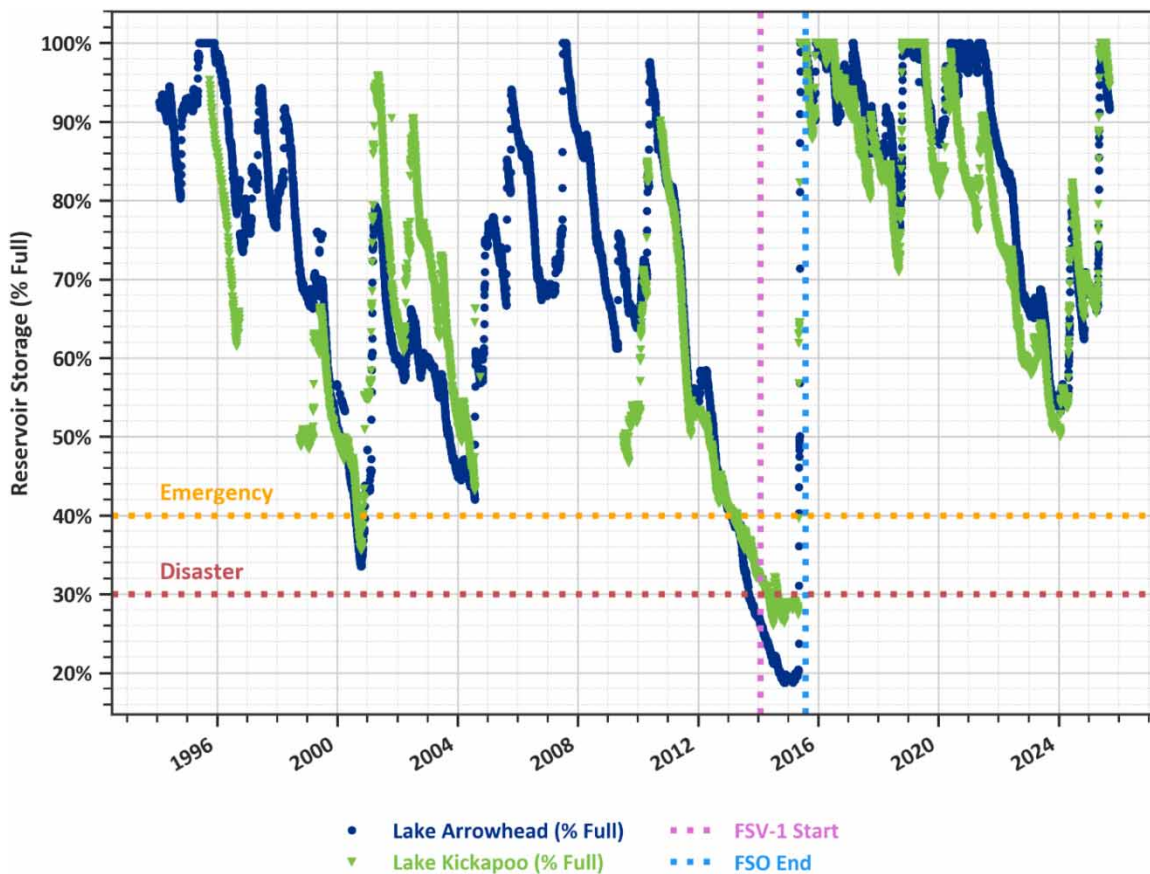


Figure 14 | Wichita Falls reservoir capacity from 1994 to 2025.

the city to shut down the DPR system on 21 July 2015 and transition the CWTP back to treating water from Lake Kemp. Note that even if the drought did not end with historic rainfall, the DPR system was always meant to be a temporary emergency measure since the 12.3-mile (19.8 km) long HDPE pipeline connecting the River Road WWTP to the CWTP was needed for the permanent IPR facility that began construction after the DPR system was decommissioned.

Public perception and acceptance of DPR were notably positive, with many residents preferring the taste of DPR water over the traditional lake water (Force 2016; Ikehata *et al.* 2024). This acceptance was a key factor in the system's success and demonstrated the potential for public support in future potable reuse projects.

The experiences and data collected during the City's operation of the DPR system offer valuable lessons for other municipalities considering similar reuse strategies. Of note is the dramatic increase in nitrate removal efficiency that occurred after the RO elements were replaced, demonstrating the key importance of regular operation and maintenance of RO systems. The CWF has demonstrated that with careful planning, rigorous testing, and adherence to regulatory standards, potable reuse systems can be a viable solution to water scarcity challenges. The performance of potable reuse processes is influenced by factors such as source water quality, equipment selection, and operational practices.

In conclusion, the Wichita Falls case study exemplifies the effectiveness of potable reuse systems in addressing water shortages and provides a model for other cities facing similar challenges. The transition from DPR to IPR further illustrates the flexibility and long-term sustainability of reuse systems in urban water management.

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emergency period, the staff of CDM Smith, Corlett Probst, and Boyd for developing the plan that led to the DPR implementation, and Greg Wetterau and Susan Crawford for reviewing this work prior to publication.

IMPACT STATEMENT

This case study highlights the successful deployment of DPR in Wichita Falls, TX, providing critical insights for utilities planning potable reuse implementation.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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