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SHORT COMMUNICATION

Epoxy lining influence on recycled water quality during pipeline transit for potable reuse

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Abstract

An epoxy treatment was applied to a pipeline used to convey advanced treated recycled water from a purification facility to a recharge site. The epoxy treatment was applied to prevent further deterioration (corrosion) of the interior cement mortar lining (CML). A soil column study was conducted to evaluate the effect of the epoxy liner on the clogging potential of water before and after conveyance. The clogging potential was represented by differences in the column's relative hydraulic conductivity and water quality, between the treatment plant and injection site, before and after epoxy lining. Hydraulic conductivity of columns at the injection well site declined rapidly before epoxy and improved considerably after epoxy application. Total suspended solids (TSS) and cellular adenosine triphosphate (cATP) median concentrations improved significantly. Before epoxy, TSS increased with pipeline transit from 0.005 to 0.053 (mg/L) compared with 0.009 mg/L after epoxy. Before epoxy, cATP increased from 0.14 to 1.6 pg/ml across pipeline transit compared with 0.37 pg/ml after epoxy. Aluminum and nitrate followed similar trends. Results indicate that epoxy liner reduced the clogging potential of high purity recycled water, likely due to a decrease in particle and biomass load (clogging constituents) accumulated during pipeline transit.

Practitioner Points:

- Clogging potential of advanced treated recycled water increases with pipeline transit.
- Epoxy lining the pipeline used for conveyance reduces the particulate and microbial loading of the highly purified water.
- Applying epoxy to pipelines used to convey advanced treated recycled water has the dual benefit of infrastructure protection and improving water quality.
- Reducing particle and microbial load in the advanced treated recycled water can reduce maintenance frequencies and elongate production periods for MAR applications.

KEYWORDS

advanced treated recycled water, clogging potential, epoxy lining, managed aquifer recharge, pipeline transit, potable reuse

INTRODUCTION

Incorporating recycled water into a region's water supply portfolio is becoming increasingly desirable to meet the demands of population growth in semi-arid regions and may include potable reuse of water, which requires advanced levels of treatment for purification. Conventional wastewater treatment facilities (WWTFs) treat wastewater to a secondary or tertiary level, suitable for safe discharge to the environment. Advanced water purification facilities (AWPFs) use the effluent from WWTF's as source for further treatment using methods such as ultrafiltration, reverse osmosis, and ultraviolet-advanced oxidation processes.

Corrosion control is essential for AWPFs because the treated water, herein referred to as finished product water or FPW, has low alkalinity and aggressive characteristics that can corrode transmission or distribution pipelines. To reduce corrosion, facilities typically add a stabilizer such as sodium hydroxide or calcium hydroxide (lime) prior to conveyance to raise the pH, alkalinity, and mineral concentration (Scott-Roberts & Smith, 2020). Fluctuations in water quality, treatment plant operational variation, and changes in pipeline composition can affect pipeline deterioration (Hokanson et al., 2019). Older pipelines used to convey potable water may be constructed with unlined iron and steel material making them more susceptible to corrosion, whereas newer pipelines usually have cement-mortar lining (CML) applied to the inner walls to reduce corrosion potential (Deb et al., 2007). Recent studies have shown that under specific conditions, certain constituents like heavy metals (e.g., aluminum and lead) can be leached from CML and contaminate drinking water (Bielski et al., 2020; Młyńska et al., 2019; Zielina et al., 2022).

Corrosion and deterioration of CML pipelines may impact the structural integrity of the metal pipeline and the quality of the conveyed water. One mitigation technique is to apply an inner lining to protect the CML and therefore the metal pipe deteriorating. Pipeline coatings or liners may be made from bituminous enamels, polyethylene, polyurethane, or epoxy. Bituminous enamels have been used since the 1920s and are long-lasting, but leaching of trace organics has caused exposure concerns, leading to diminished application (Guan, 2003). The advantage of polyethylene lining is its longevity and ease of application; however, it can be cost prohibitive (United States Environmental Protection Agency, 1984). Polyurethane linings are abrasion resistant but have application complexity (Guan, 2000). Epoxy lining is a cost-effective pipeline rehabilitation technique that can provide a service life of approximately 40 to 60 years if applied correctly (Randtke et al., 2017). Previous studies demonstrated that epoxy has relatively low impacts on drinking water quality, and no significant chemical leaching occurs from the epoxy material into the water (Conroy et al., 1993; Deb et al., 2007; Pierce, 2009). Scott-Roberts and Smith (2020) reported the outcomes of a pipeline rehabilitation project, completed at the same site as the present study, using epoxy lining to protect CML from further corrosion. Physical inspection of the pipeline after several years demonstrated that the rehabilitation project resulted in a significant reduction in solid loading based on water sampling, which indicates that the epoxy liner prevented the CML from further deterioration.

Clogging potential of reclaimed wastewater on aquifer soils during groundwater recharge has been studied using laboratory scale column experiments (Baveye et al., 1998; Okubo & Matsumoto, 1983; Pavelic et al., 2011; Pham et al., 2022; Rinck-Pfeiffer et al., 2013). These studies revealed that clogging is primarily due to physical, biological, and chemical processes. Mechanisms such as the accumulation of total suspended solids (TSS), microbial growth, and chemical precipitation can block pore spaces in soils and lead to rapid decline in percolation rates (Martin, 2013). Additional review of clogging mechanisms is provided by Pham et al. (2022).

The Orange County Water District (OCWD) in Fountain Valley, California treats (or “purifies”) secondary-treated wastewater using an advanced treatment process that includes ultrafiltration, reverse osmosis (RO), and ultraviolet-advanced oxidation processes prior to groundwater recharge. Because groundwater augmentation using such advanced treated recycled water is a limited practice, few studies have investigated its clogging potential. However, recent research by the present study authors reported that infiltration basins (i.e., percolation ponds) used to recharge high purity water experience clogging over time (i.e., infiltration rate decreases). That study revealed that the clogging potential of high purity water increased with pipeline transit during conveyance from the AWPF to the recharge site and increased further with environmental exposure at the recharge basin (Pham et al., 2022).

The present study investigates the effect of conveyance pipeline and epoxy lining application on the clogging potential of advanced treated recycled water. To address CML corrosion issues, an epoxy liner was applied to a portion of the transmission pipeline that delivers high purity from the treatment water to groundwater recharge sites (both wells and spreading basis). The present study uses small soil columns as analog for recharge basins. Soil column performance was measured before and after the CML pipeline was treated with the epoxy liner. Differences in soil column infiltration rates at the treatment facility and at the recharge site were compared before and after epoxy to infer the clogging potential changes of the water. It has already been established that pipeline transit increases the clogging potential of the purified water (Pham et al., 2022). Here, we hypothesized that the epoxy liner would minimize or eliminate the clogging potential of water conveyed through an epoxy lined pipeline, such that the performance of soil columns before and after a conveyance pipeline which has been lined with epoxy would have comparable performance.

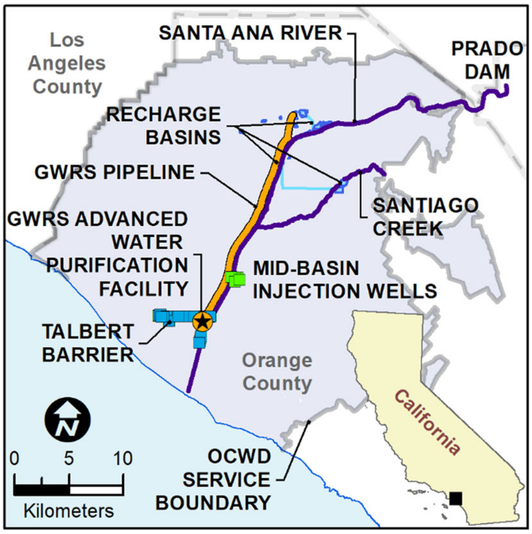

FIGURE 1 Map of advanced water purification facility (AWPF) (★) and Groundwater Replenishment System (GWRS) pipeline (orange) used to convey finished product water to the Mid-Basin Injection well site (green 🟩). Epoxy liner was applied on the inside of the pipeline in the 6 km section from AWPF to the Mid-Basin Injection well site. OCWD, Orange County Water District

MATERIAL AND METHODS

Site description

OCWD manages the Orange County Groundwater Basin (Basin), an aquifer covering approximately 900 square kilometers (km^2) in Southern California (Hutchinson, 2013). Groundwater is the principal drinking water supply for 2.5 million people in north and central Orange County in a region (Southern California) that is largely dependent on imported water. OCWD recharges the groundwater aquifer for potable reuse and to prevent seawater intrusion, using various water sources including recycled water. The Groundwater Replenishment System (GWRS) is a joint project of OCWD and the Orange County Sanitation District, which consists of an AWPF that treats wastewater for indirect potable reuse, groundwater recharge, and seawater intrusion prevention. Approximately, 25% of the water produced from the AWPF is sent to coastal injection wells as a seawater intrusion barrier. Another portion (9%) is sent to groundwater recharge injection wells in the central region of the basin (Mid-Basin Injection [MBI] wells, Figure 1). The remaining water (66%) is sent to the forebay surface water recharge facilities (i.e., spreading ponds) (Burris, 2021). A 22.5 km-long pipeline with diameters ranging between 1.5 m and 2.0 m conveys the water from the AWPF to the MBI wells and forebay facilities (Figure 1). California requires that recycled water used for groundwater recharge via spreading (infiltration ponds) be at least tertiary treated water and recycled water used for groundwater recharge via injection wells receive full advance treatment, which includes RO treatment, due to less soil aquifer treatment experienced with injection. Thus, for a significant volume of treated water (currently approximately 66 million gallons per day [MGD]) that is recharged by spreading, OCWD provides a greater degree of treatment than is strictly necessary to meet state requirements for spreading of recycled water, more information is provided in the Supplementary information (SI).

The high purity and aggressive characteristics of FPW have led to corrosion of the CML inside the pipeline in some sections of the 22.5 km-long pipeline, despite decarbonation and lime addition at the GWRS AWPF prior to conveyance. Inspections between 2010 and 2012 revealed degradation of the pipeline and concrete air gap structures near two recharge basins at the end of the pipeline. Additional inspections between 2012 and 2016 revealed continued CML degradation. In 2018, OCWD rehabilitated 6 km of pipeline by applying an epoxy lining on the interior of the pipeline starting from the AWPF to the MBI injection well site (Figure 1).

Characterization of soils packed into columns

Soil was collected at a basin, which exclusively recharges AWPF water. The soil in the basin consists of alluvial sediments ranging from medium to loose dense sandy silt, loose to medium dense silty sand to gravelly sand (Chu et al., 2011). Wet sieve analysis showed that soil is comprised of 5.5% fine gravel, 8.7% very fine gravel, 42.5% very coarse sand, 25.5% coarse sand, 13.0% medium sand, 2.8% fine sand, 0.7% very fine sand, and 1.2% fines (i.e., silt and clays <63 μm) according to the Wentworth grain size classification system (1922) (Figure 2). The median particle size (d_{50}) was 1.1 mm. The bulk density of the soil was 1.6 g/cm^3, with a porosity of 38%, consistent with values for coarse sands (Domenico & Schwartz, 1998; Lewis & Sjöstrom, 2010).

Column design and operation

To evaluate the effect of pipeline transit and epoxy lining on water quality, triplicate soil columns were set-up at each of the two test locations: AWPF and MBI injection well site. The columns are made of acrylic and have a height of 30.5 cm and inner diameter of 3.8 cm. Each column was packed with 450 g of soil, leaving approximately 5.1 cm of saturated headspace for visual observation of surficial clogging layer on the topsoil, for details on soil column packing procedures, see Pham et al. (2022). Columns at the AWPF site, referred to as finished product water (FPW) columns, received FPW before conveyance through the CML pipeline. Columns at the MBI site received FPW after 6 km of conveyance through the CML pipeline. Performance and analysis of MBI columns receiving conveyed FPW before epoxy are denoted as "MBI pre-epoxy" columns, MBI columns receiving conveyed FPW after epoxy lining are denoted as "MBI post-epoxy" columns. FPW columns are treated as the *control*, because they receive water that is not conveyed through the pipeline. A schematic of the soil column set-up at FPW and MBI site is provided in Figure 3. Column effluent flowrates were routinely monitored and used to calculate the hydraulic conductivity (K) using Darcy's Law (see Supplementary information [SI] for details). Hydraulic conductivity over time was normalized by the initial hydraulic conductivity (K/K_0) and expressed as a percentage. For additional reproducibility, trials were repeated sequentially by stopping the columns once their average performance declined to ∼15%–30% of K_0 and replacing them with newly packed soil columns.

Water quality monitoring

To characterize physical, microbiological, and chemical water quality variations and determine any water quality differences between FPW, MBI pre-epoxy, and MBI post-epoxy waters (i.e., across the pipeline, before and after epoxy), feed water samples were routinely analyzed for parameters associated with clogging and pipeline corrosion. Parameters selected as indicators of physical clogging were TSS and particle analyses (size and counts). Biweekly feed water analysis of TSS was performed onsite using a modified version of standard method 2540D, which was adapted for field conditions using a 0.7 μm filter. Biweekly grab samples were collected for particle analyses, which was performed using a Beckman Coulter Multisizer 4 (size ranging between 0.6 and 63 μm). Concurrently, 5-μm polyethylene cartridge filters were operated in parallel to the soil columns, before injection into the MBI-1 well, and scanning electron microscopy/

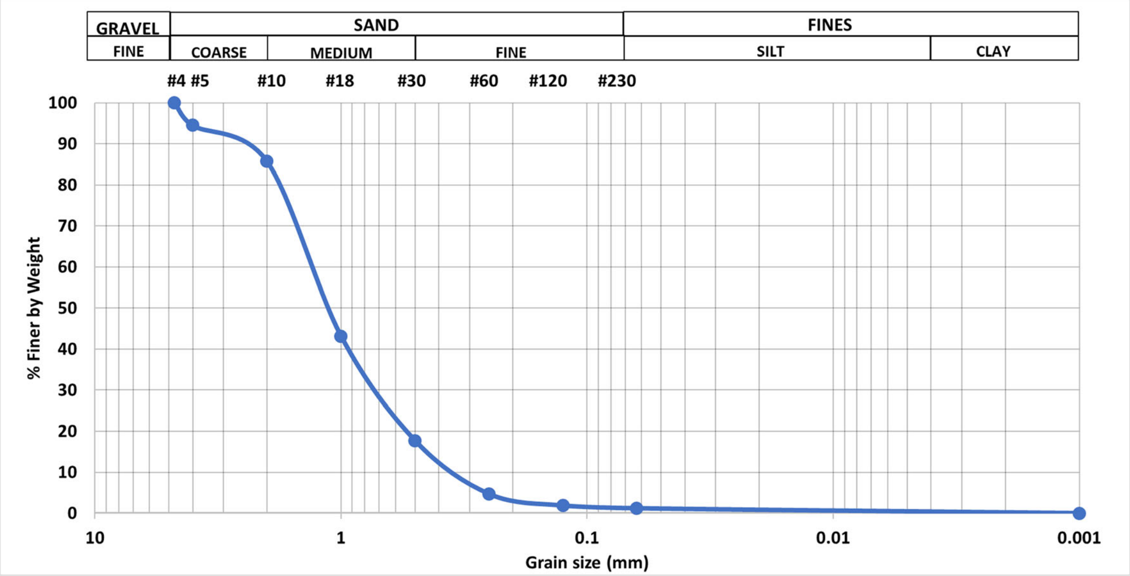

FIGURE 2 Particle size distribution curve of native basin soil used for column packing

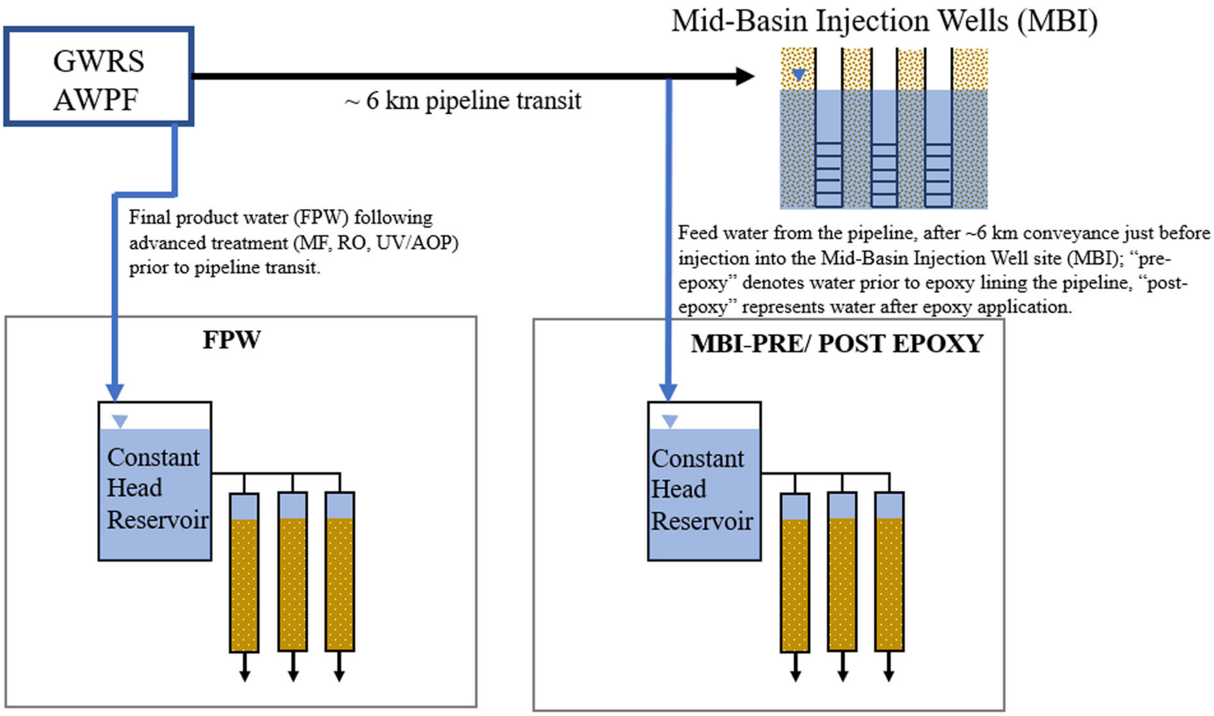

FIGURE 3 Schematic of triplicate constant-head soil column set-up at each site. Feed water is pumped into the constant-head reservoir, and then gravity fed into the columns. Overflow from the constant-head reservoir and column effluent was conveyed to a drainage pipeline. AWPF, advanced water purification facility; GWRS, Groundwater Replenishment System; MF, microfiltration; RO, reverse osmosis; UV/AOP, ultraviolet light/ advanced oxidation processes.

energy dispersive x-ray spectroscopy (SEM/EDS) analyses using a Tescan GAIA-3 GMH FIB-SEM imaging instrument were performed on the filters to visualize the composition of the fouling material. All samples were sputter coated with gold of palladium or platinum (Pd/Pt [4 nm]) before analysis.

Parameters used as indicators of microbial growth or relevant to microbial activity were nitrate (NO_3) and nitrite (NO_2), total organic carbon (TOC), and cellular adenosine triphosphate (cATP) (a direct measure of total living biomass) using the benchtop Luminultra® QGA Test Kit. Monthly grab samples of aluminum (Al), iron (Fe), calcium (Ca), and magnesium (Mg) (major constituents found in CML) were analyzed to determine pipeline shedding; pH, electrical conductivity (EC), total dissolved solids (TDS), and alkalinity were collected and analyzed at OCWD's Philip L. Anthony Water Quality Laboratory using EPA standard methods.

RESULTS AND DISCUSSION

Columns' hydraulic performance

Percolation rates were collected from the triplicate columns and averaged to monitor column performance over time. Average initial hydraulic conductivity (K_0) for all soil columns, ranged from 42 to 132 m/d, these values are within the expected range for coarse sand (Freeze & Cherry, 1979). Variability is commonly observed in soil packing and mixing protocols (Lewis & Sjöstrom, 2010); therefore, relative hydraulic conductivity (K/K_0) is used to show clogging as indicated by percolation rate decline. Decline in K/K_0 was observed for soil columns across all trials, irrespective of water quality (Figure 4). The fastest hydraulic conductivity decline occurred for columns fed with MBI pre-epoxy water, for example, water conveyed through the pipeline prior to epoxy application. The rate of decline is slower for the columns fed with MBI post-epoxy water (after the epoxy application), and slowest for the columns receiving FPW (Figure 4).

The FPW soil columns are used as the ideal (control) performance scenario to compare against columns fed with water conveyed through the pipeline and assess whether pipeline transit increases clogging potential of the source water. The FPW-fed columns exhibited variable, yet slow rates of decline, falling between 80% and 100% of K/K_0 within 90 to 240 days, except for the first trial, which declined to 40% within 100 days and stabilized thereafter (Figure 4). This column performance for the first trial could be due to stochastic differences in soil column performance due to variability in soil packing, or

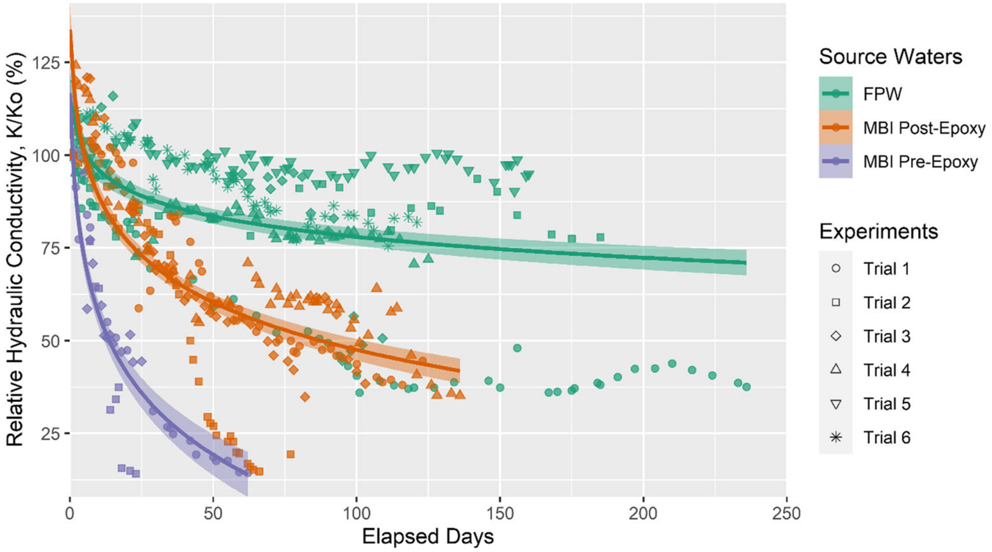

FIGURE 4 Average relative hydraulic conductivity (K/K_0) of soil columns showing decline over time for each sequential replicate trial; bold lines represent the 2nd polynomial exponential decay curve fit to the data. The shaded areas surrounding the bold lines represent the 95% confidence interval. Finished product water (FPW) column trials (green) ranged from 90 to 240 days ($n = 6$), Mid-Basin Injection (MBI) pre-epoxy column trials (purple) ranged between 25 and 60 days ($n = 3$), and MBI post-epoxy column trials (orange) ranged between 80 and 140 days ($n = 4$). Relative hydraulic conductivity curves for each trial represent the average of the triplicate soil column.

mobilization of fine particles across the packed soil when the columns are upfilled with water to expel entrained air bubbles, prior to starting the experiment. The MBI pre-epoxy columns receiving water that traveled through 6 km of pipeline prior to epoxy exhibited the fastest decline, decreasing between 20 to 40% K/K_0 within 25 to 60 days. MBI post-epoxy columns were installed after epoxy was applied to the pipeline. The MBI post-epoxy columns decreased between 20 to 40% K/K_0 within 80 to 140 days. MBI post-epoxy columns operated approximately twice as long as the MBI pre-epoxy before reaching a hydraulic conductivity decline comparable to the MBI pre-epoxy columns (Figure 4).

Clogging potential of product water from the AWPF increases across pipeline transit, as shown from these results. The moderate decline in K/K_0 over time in the MBI post-epoxy columns suggests that the epoxy application improved water quality and reduced its clogging potential. While the primary driver for epoxy application in this case was pipeline asset protection to prevent corrosion related failure of infrastructure, this study demonstrates that a secondary benefit is the potential improvement in percolation rate during groundwater recharge via spreading ponds and potential reduction in injection well clogging. Soil column performance after epoxy lining was significantly better than column performance pre-epoxy; however, the post-epoxy performance was still inferior to the column performance of FPW columns at the plant. These differences suggest that pipeline transit increases clogging potential, even through a freshly epoxied pipeline.

Physical and chemical water qualities

The observed decline in soil column hydraulic performance correlates with specific water quality parameters. Overall, water quality deteriorated across the pipeline but improved after the epoxy lining was applied. Particle and some chemical concentrations increased from the FPW to the MBI site prior to epoxy application, consistent with increasing exposure of purified water to CML and earlier observations from interior pipeline inspections (Ishida, 2015; Scott-Roberts & Smith, 2020). Constituents that increased with pipeline transit were TSS, particles, and Al. These constituents then decreased once epoxy was applied, suggesting that these water quality changes were a direct result of the water being exposed to the CML. Other water quality constituents measured (Fe, pH, EC, TDS, alkalinity, Ca, NO_3, and TOC) appeared stable and showed no significant changes with pipeline transit or after epoxy application (Table 1).

TSS concentrations revealed a trend of increasing suspended solids with pipeline transit, followed by a decrease after epoxy was applied. Figure 5a shows the median TSS concentrations in FPW, MBI pre-epoxy and MBI post-epoxy feedwaters (0.005, 0.053, and 0.009 mg/L, respectively). Median TSS values of MBI pre-epoxy fell within the range of previously collected data from Pham et al. (2022) showing increasing TSS at the end of the 22.5-km long GWRS pipeline, affirming that particle sloughing increases with pipeline distance as the aggressive AWPF water contacts more CML material through longer distance. Previous researchers have found that

TABLE 1 Averages (± SDs) of feed water quality constituents measured monthly

Parameter	Units	FPW ($n = 20$)	MBI pre-epoxy ($n = 5$)	MBI post-epoxy ($n = 15$)
Al	µg/L	1.20 (± 0.86)	4.50 (± 2.9)	1.46 (± 1.16)
Calcium	mg/L	13.6 (± 1.02)	13.0 (± 1.34)	13.8 (± 1.04)
EC	µS/cm	95.7 (± 5.8)	103.5 (± 6.43)	93.0 (± 3.56)
Fe	µg/L	0.50 (± 0.15)	0.50 (± 0.00)	0.50 (± 0.00)
Mg	mg/L	0.05 (± 0.01)	0.05 (± 0.00)	0.05 (± 0.00)
NO_2	mg/L	0.04 (± 0.01)	0.12 (± 0.03)	0.03 (± 0.00)
NO_3	mg/L	0.70 (± 0.20)	0.98 (± 0.17)	0.61 (± 0.12)
pH		7.94 (± 0.25)	8.22 (± 0.47)	7.95 (± 0.21)
TDS	mg/L	48.5 (± 9.58)	64.9 (± 14.58)	43.9 (± 12.35)
TOC	mg/L	0.10 (± 0.05)	0.11 (± 0.05)	0.09 (± 0.02)
Total alkalinity	mg/L	37.5 (± 2.21)	36.9 (± 2.30)	37.6 (± 1.50)

Abbreviations: EC, electrical conductivity; FPW, finished product water; MBI, Mid-Basin Injection; TDSs, total dissolved solids; TOC, total organic carbon.

significant clogging can still occur in alluvial soils used for recharge with TSS concentrations as low as 0.5 mg/L (Pitt & Magenheimer, 1997; Pyne, 2005), yet this study shows that hydraulic conductivity of soils can decline with concentrations much lower than that, suggesting that other types of clogging (i.e., biological or chemical) may be contributing to the rapid decay in performance.

The TSS data follow a similar trend observed in column hydraulic performance where after pipeline conveyance, pre-epoxy columns experienced a faster decline compared with the columns after epoxy application. The median TSS values were higher in the pre-epoxy water and decreased after epoxy application on the pipeline, yet not as low as the water at the AWPF. Higher TSS concentrations measured after pipeline conveyance mean a higher particle load on the columns, which may block pore spaces of soil inside the columns, therefore, decreasing the hydraulic conductivity of these columns more rapidly. The measured increase in particle loading is supported by visual (qualitative) evidence of particles and fine sand grain deposits within the constant head tank fed with MBI pre-epoxy water, and a subsequent reduction of particle deposition after epoxy was applied (Figure 6). Scott-Roberts and Smith (2020) observed that as CML deteriorates, aggregate sand particles are released and settle at the bottom of the pipeline. When flow velocities change, they can agitate the pipeline inner walls, slowly scouring off more CML. Hydraulic disturbances and flow variations impact the shear stress (the perpendicular force) on pipeline walls, leading to mobilization of material bound within them and result in particle deposition and resuspension (Husband & Boxall, 2011; Prest et al., 2021). The visual observation of the particles settled at the bottom of the reservoirs prior to epoxy application affirms this, and additional particle data from Scott-Roberts and Smith (2020) found that before epoxy application, particle loading onto 5 µm cartridge filters ranged between 0.013 and 0.054 mg/L, whereas the rate of deposition ranged between 0.001 and 0.016 mg/L after epoxy application. This represents a reduction of 75% in particle loading after epoxy lining; however, 25% of the particles are still being accumulated across the pipeline post-epoxy. SEM and EDS analyses on these cartridge filters support this general trend of CML sloughing particles from the pipeline prior to epoxy lining and water quality improvement after epoxy application (Figure S1). The reduction in particulate load after epoxy lining demonstrates the resin's properties of having a harder and smoother surface, and higher durability and hydraulic capacity than CML, which protects it from corrosion and particle sloughing (Deb et al., 2007).

Aluminum concentrations in the water can be used as an indicator of CML sloughing because Al is a constituent in CML. Aluminum concentrations increased from FPW (1.20 µg/L) to MBI pre-epoxy (4.50 µg/L) and then decreased after epoxy application at MBI post-epoxy (1.46 µg/L); however, standard deviations indicate that the differences between the three sites were not statistically significant (Table 1). This trend of increasing aluminum with pipeline transit and decreasing after epoxy suggests particle shedding from the pipeline and is consistent with the scouring of the CML observed in previous investigations (Ishida, 2015; Scott-Roberts & Smith, 2020). After the epoxy is applied, the reduction in particles and Al may be a result of reduced pipeline shedding and sloughing because the epoxy seals in the CML and protects it from scouring associated with water velocity changes during operation. Ca and Mg are also constituents found in CML, and concentrations detected in conveyed water are indicative of pipeline sloughing.

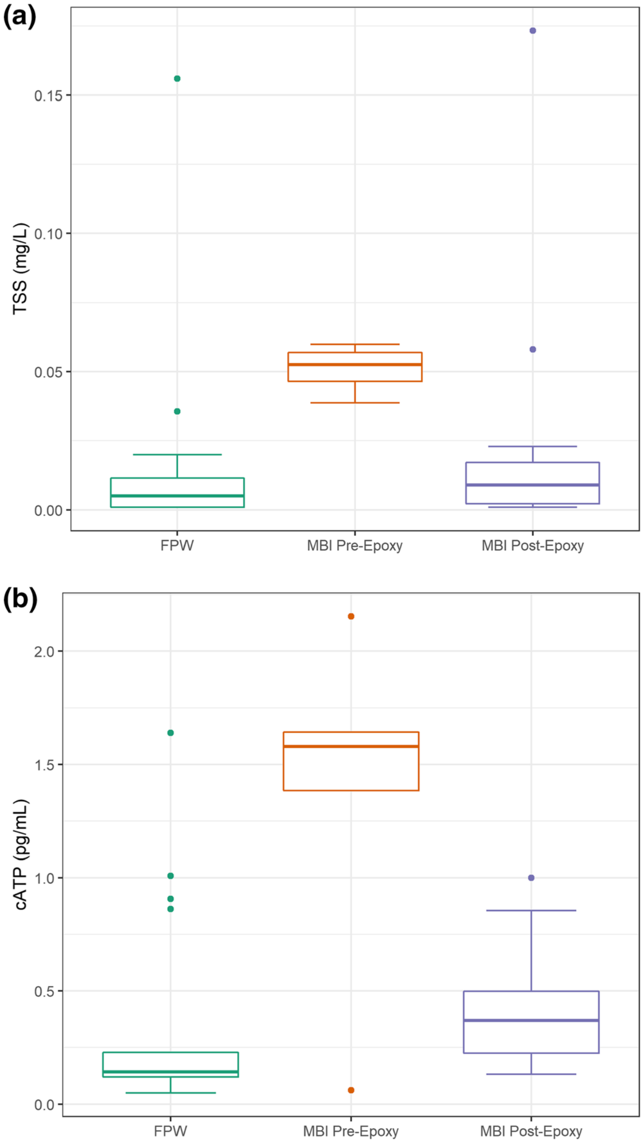

FIGURE 5 Median (a) total suspended solids (TSS) and (b) cellular adenosine triphosphate (cATP) concentrations for finished product water (FPW) feeding the columns at the advanced water purification facility (AWPF) ($n = 18$ for TSS and $n = 19$ for cATP), after 6-km pipeline conveyance to the Mid-Basin Injection well site prior to epoxy application to the pipeline (MBI pre-epoxy) ($n = 4$ for TSS and $n = 5$ for cATP), and after epoxy application to the pipeline (MBI post-epoxy) ($n = 14$ for TSS and $n = 14$ for cATP)

Although concentrations of Ca and Mg appeared stable in the feedwater samples (Table 1), the evidence above and the increase in TSS and Al suggest that slight particle loading still occurs after epoxy lining the pipeline, depositing foulants within pore spaces of cartridge filters and likely within the soil columns as well.

Though SEM and EDS analysis of the columns could provide a better and more direct understanding of the foulant seen by the soil, performing this analysis on the soil was not possible. Instead, an SEM and EDS analysis was conducted on the cartridge filters as indirect evidence of CML fouling, because it is expected that the fouling seen on the cartridge filters would be the same as that observed by the soil columns. The SEM and EDS show foulant from the pipeline on cartridges before and after epoxy application. Furthermore, the foulant seen on the SEM/EDS on the post-epoxy cartridges explains why the hydraulic performance of the MBI post-epoxy columns was not as high as the FPW columns; additional information is provided in the Supporting information, Figure S1. EDS results follow the same trend, where some elements were detected at higher concentrations after pipeline transit, prior to epoxy, but decreased once epoxy was applied (see Table S1). It was expected that the soil column performance at MBI after epoxy would be similar to that of FPW (Figure 2); however, MBI post-epoxy still features greater TSS (and other water quality indicators) and a slight decrease in relative hydraulic conductivity of soil columns compared with FPW. This suggests that epoxy-lined CML pipelines improve water quality and filtration rate (column performance); however, clogging potential of purified water increases with pipeline transit irrespective of pipeline treatment (no epoxy liner vs. epoxy liner on CML pipeline).

Parameters associated with chemical precipitation of post-treatment lime addition to the FPW, or free lime leaching from the CML (i.e., Ca, total alkalinity, pH, EC, and TDS), remained stable and did not correlate with the hydraulic conductivity decline observed in the columns before or after epoxy lining. Despite the increases in TSS and Al prior to epoxy lining, concentrations of other constituents found in CML (i.e., Ca, Mg, and Fe) were stable across the pipeline and after epoxy (Table 1), suggesting that these were not added to the total load in the water by sloughing off from the pipeline during the duration of the experiment and that chemical clogging caused by loading and precipitation of these constituents within soil column pore spaces was not a significant factor in hydraulic performance decline.

Biological water quality

The evidence of water quality deterioration across the pipeline is further supported by comparing the concentrations of cATP and NO_2. Despite the low TOC concentration across the pipeline, viable microbial growth was evident from occurrence of cATP. Comparing the median concentrations, values were lowest at FPW, increased with pipeline transit, then decreased after epoxy application (0.14, 1.58, and 0.37 pg/mL, respectively) (Figure 5b). For NO_2 concentrations, the same trend of increasing across

FIGURE 6 Particulates were not observed settled at the bottom of the constant-head reservoir by the end of the column trials at the advanced water purification facility (AWPF) site where the columns were fed with finished product water (FPW). For columns fed with water from the end of the 6-km pipeline at Mid-Basin Injection (MBI pre-epoxy) well site prior to epoxy application, brownish, fine, sand-like particulates were observed settled at bottom of the constant-head reservoir after each trial. After epoxy was applied, subsequent column trials at the MBI site (MBI post-epoxy) did not show fine particle matter settled at the bottom of the constant-head reservoir. The colored ring surrounding the edges of the reservoir is discolored glue residual, not biological growth.

the pipeline and then decreasing post epoxy application is observed with average concentrations of 0.04, 0.12, and 0.03 mg/L at FPW, MBI pre-epoxy, and MBI post-epoxy, respectively (Table 1). The average concentrations of NO_3 also increased across the pipeline and decreased post-epoxy; however, these changes are not significant, as indicated by their standard deviations (Table 1).

The increasing trends of cATP and NO_2 suggest that microbial growth occurs across the pipeline and shows the water quality improvement (decrease in constituent concentrations) after the pipeline is coated with epoxy. The slight increase in NO_2 suggests the growth of ammonia oxidizing bacteria prior to epoxy application, with concentrations similar to those found in past observations (Pham et al., 2022). Applying epoxy to the CML may have reduced the surface adhesion of biofilms, decreasing microbial growth along the pipeline.

The increase in microbiological parameters (e.g., cATP and NO_2) correlating with rapid decline of the MBI pre-epoxy columns also supports the hypothesis that clogging potential increases with pipeline transit. As microbial growth develops across the pipeline, biofilms are produced, comprised of microbial cells and extracellular polymeric substances. These are major contributing factors of biological clogging (Ragusa et al., 1994; Rinck-Pfeiffer et al., 2000). There is potential for this biofilm and microbial growth to have sloughed off the pipeline and loaded onto the soil columns, resulting in their rapid decline in performance prior to epoxy lining. Despite the high purity water produced at the AWPF, biofilm formation has been found to increase across drinking water distribution systems, undermining FPW quality at the point of use (Makris et al., 2014). It is possible that the added particles from the pipeline loaded into the soil columns, providing additional surface area that fostered microbial growth and subsequent biological clogging within the soil columns, as was observed in previous studies by Rinck-Pfeiffer et al. (2000) and Pavelic et al. (2011). Epoxy application of the pipeline appeared to reduce the clogging potential of advanced treated recycled water, as evidenced by the reduction in these parameters and the improvement in column performance after epoxy application. These observations affirm findings from previous researchers (Pierce, 2009; Randtke et al., 2017; Whelton et al., 2013) who demonstrated improvement in water quality after epoxy application.

CONCLUSIONS

Field observations of pipeline corrosion caused by conveyance of soft, aggressive advanced treated recycled water led to the application of an epoxy lining along the interior of a 6 km section of the 22.5-km long pipeline used to convey the high purity water to groundwater recharge sites. While costly, the epoxy lining will protect the CML from further deterioration. The objective of this study was to determine the degree to which the epoxy lining may, as a secondary benefit, improve (reduce) the clogging potential of the AWPF product water. Using triplicate soil column sets packed with native material from a recharge basin, it was observed that before epoxy lining the CML pipeline, pipeline transit increased the clogging potential of this highly purified water. After epoxy lining of the CML, the clogging potential of water reduced significantly, but not to the level of the (pristine) water originating from the AWPF.

This study demonstrates that applying epoxy to pipelines transporting high purity water has the dual purpose of infrastructure protection and reducing clogging potential. The reduction in clogging potential (or improved column hydraulic conductivity) after epoxy application was supported by a reduction of particle loads and microbial loads, which are indicators and contributors of physical and biological clogging, respectively. Improved water quality may result in longer sustained recharge intervals, for example, higher volume of water being recharged to the groundwater aquifer, while minimizing maintenance frequency of the well or recharge basins. Recycled water facilities utilizing advanced treatment should consider the materials of infrastructure used to convey FPW to avoid corrosion issues and maintain water quality.

Though this study focused on investigating the effect of using epoxy lining on the clogging potential of water, more research is needed to investigate other potential benefits or effects of epoxy lining CML pipelines, such as to investigate whether epoxy liner can prevent or reduce heavy metal leaching from the CML. Despite the high purity water produced from AWPFs, recharge performance in the field is highly dependent on site-specific variables, and more investigation is needed to ensure appropriate conditions to avoid unintended mobilization of clogging constituents (i.e. particles) in the surface and subsurface that may impact water quality or recharge capacity. Future research investigations using columns to understand and predict clogging issues is needed to inform data and models that can improve field operations and maintenance of MAR sites receiving advanced treated recycled water.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization, investigation, writing—original draft, methodology, validation, visualization, project administration, formal analysis, data curation, resources, and software: Christine Pham. *Investigation, writing—review and editing, methodology, validation, data curation, resources, conceptualization, and formal analysis*: Ricardo Medina. *Supervision, resources, investigation, funding acquisition, conceptualization, methodology, validation, writing—review and editing, and formal analysis*: Megan H. Plumlee.

DATA AVAILABILITY STATEMENT

Data supporting the research findings are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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