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Direct Potable Reuse Piloting: Optimizing Chloramination, Operationalizing Ultrafiltration, And Understanding Zero Liquid Discharge Options

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DIRECT POTABLE REUSE PILOTING: OPTIMIZING CHLORAMINATION, OPERATIONALIZING ULTRAFILTRATION, AND UNDERSTANDING ZERO LIQUID DISCHARGE OPTIONS

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Dedication

This thesis is dedicated to Alejandro Servin, thank you for always believing in me.

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by

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Abstract

A pilot study was deployed at the John T. Hickerson Water Reclamation facility to analyze the viability of high recovery direct potable water reuse (DPR), aiming for zero liquid discharge (ZLD). This pilot consists of a chloramination system and ultrafiltration (UF) as pretreatment for reserve osmosis (RO) followed by UV-peroxide, granular activated carbon (GAC), and concentrate-enhanced recovery reverse osmosis (CERRO).

Stabilizing the chloramination and UF system was the first step to ensure efficiency during the downstream processes. The formation of monochloramine is essential for the mitigation of biofouling of the UF membranes. The formation of monochloramine occurs by specific liquid ammonium sulfate (LAS) and sodium hypochlorite (bleach) dosing. However, the varying quality of the influent prevented the constant formation of an exact concentration of monochloramine. The specific flux measured the efficiency of the ultrafiltration system. Since specific flux is affected by flux, biofouling in the membranes negatively impacts its stabilization. Backwashes and chemically enhanced backwashes were performed as needed to mitigate biofouling.

Water quality parameters were analyzed, including pH, conductivity, oxidation-reduction potential, turbidity, alkalinity, ion chronography, and total dissolved solids. Results demonstrate that chloramination and UF are effective pretreatment processes as concentrations of elements and turbidity decreased from influent samples to UF filtrate samples. Future research will include studying the efficacy of the RO, UV-peroxide, GAC, and CERRO systems, which will produce a high salinity concentrate. The power consumption of several systems to further decrease the liquid present (heated screw conveyor, land disposal, and evaporation) in the concentrate are discussed.

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1. Introduction

1.1 Background

As factors such as climate change, water pollution, increasing population, and water scarcity affect the entire world, industries rely on water management strategies and water treatment to manage potable water. The treatment options depend on water availability in local areas, site-specific factors, and different water sources. After treatment, one of the main issues for inland areas is discharging water. It becomes more complex due to the lack of a body of water to receive this water, and deep-well injection can affect surface water or groundwater (Tong & Elimelech, 2016). All these factors are essential to consider as they require different treatments and energy demands. Water reuse is essential in sustainable and resilient water management, especially in the arid and semiarid Southwest.

There are several ways to approach water reuse; one is de facto, the unplanned or incidental presence of treated wastewater in a water supply source (National Research Council, 2012). De facto, however, can negatively affect the environment and human health, as this water contains emerging contaminants (Swana et al., 2020). Purple pipe systems distribute municipally treated reclaimed water for irrigation and industrial purposes. However, this reclaimed water quality may vary depending on the community and regulations in the area (Vandertulip & Weaver, 2010), and this water is not fit for consumption.

Instead of discharging municipal wastewater into a receiving stream or body of water, this flow reuse can occur through indirect or direct potable water reuse. For indirect potable reuse (IPR), after being treated at a water reclamation plant, the effluent is released and now relies on the effectiveness of environmental buffers. These buffers depend on the hydrological conditions of the area where the water was released (e.g., river, lake, or aquifer). After some time, the water will return to a drinking water treatment facility and be considered potable water with additional treatment. Although IPR has been widely researched and generally accepted by the public, direct potable reuse (DPR) could be a more efficient technique for providing potable water. DPR prevents outside sources from affecting the water delivered and traveling a shorter distance, giving greater flexibility for water supply. DPR is also considered less costly than tertiary-treated recycled water for irrigation (Leverenz et al., 2011).

DPR mitigates water quality issues regarding groundwater and surface water sources while avoiding future droughts and climate change. The implementation of DPR can provide a very reliable portion of the water supply and reduce system-wide water age, potentially improving water quality (Liu et al., 2020). For potable consumption, the removal of nutrients, organic materials, pharmaceuticals, and pathogens in the wastewater must occur. In arid and semiarid regions, salinity may also need to decrease for potability purposes. To achieve this, an array of treatment processes is necessary. One of the standard treatment processes used for direct potable reuse involves a sequence of chloramination, membrane filtration, membrane desalination, advanced oxidation, granular activated carbon filtration, chemical disinfections, and clear well storage (Halvorsen et al., 2019).

Chloramination is a disinfection technique that mitigates biofouling of microfiltration and reverse osmosis (RO). Microfiltration (MF) and ultrafiltration (UF) are membrane filtration processes; these processes remove suspended solids and pathogens from the wastewater treatment plant effluent and serve as pretreatment for nanofiltration (NF) or reverse osmosis RO. Nanofiltration and RO require higher hydraulic pressures (proportional to the osmotic pressure of the dissolved constituents) to filter water to pass through membranes. RO is highly effective in removing high molecular weight organic constituents such as humic and fulvic acid (Warsinger et al., 2018). These processes reject salts. Control factors such as pretreatment, flux rate, fouling, and recovery help achieve a stable RO membrane performance.

Some of the main challenges of membrane treatment processes are fouling and scaling, which lead to increasing pressures and operation costs. For reuse applications that do not require desalination for salinity, non-membrane processes, such as adsorption, active biological filtration, and advanced oxidation processes (AOPs), could be options for treatment. The most common AOPs are ozonation and ultraviolet UV light with hydrogen peroxide or hypochlorite. They rely on forming highly reactive radical species (e.g., the hydroxyl radical) and remove taste, odor, color, pharmaceuticals, personal care products, endocrine-disrupting contaminants, and disinfection by-products. Hydrogen peroxide's combination with iron, UV light, and ozone is common (Ksibi, 2006). Achieving high recovery in DPR can decrease brine discharge and reduce negative environmental impact and costs. Multi-stage treatment (e.g., concentrate treatment for volume reduction) is more complex as each downstream process depends on upstream process performance.

In addition to a high-recovery operation, implementing zero liquid discharge (ZLD) eliminates all liquid waste and produces solid residuals. ZLD operation prevents water from being discharged from a system. ZLD also prevents the risk of pollution that comes with wastewater discharge. Typical processes for ZLD systems include wastewater pretreatment, evaporators, and crystallizers. Pretreatment includes filtration, pH adjustment, de-aeration, ultrafiltration, and anti-scaling. Pretreatment is necessary for the removal of contaminants that could affect the following stages and prevents fouling mechanisms that would also affect the performance of the treatment technologies in ZLD. Fouling causes a decrease in permeate flux while increasing filtration resistance, directly causing more frequent physical and chemical cleaning, where all these factors lead to higher operating costs. Pre-adsorption, which is adsorption upstream of membranes, can reduce cake layer fouling, which causes a decrease in UF permeation (J. Wang et al., 2020). Using ozonation as a pretreatment could also help decrease fouling for secondary effluent for both hydrophilic and hydrophobic membranes while enhancing the biodegradability of organic matter (H. Wang et al., 2017).

The main limitation of ZLD is its intensive energy consumption, where energy requirements increase during the crystallization process. Zhang et al. (2021) propose using advanced solar crystallizers paired with a salt crystallization to remove highly concentrated waste brine. Solar-driven water evaporation offers a water removal rate that is only affected by the salt concentration of the source water. However, energy consumption and operation costs are still relevant as they increase proportionally to salt concentration in RO.

1.2 Goal and Objectives

This research was conducted to advance the feasibility of DPR by demonstrating high recovery and ZLD operation.

- The presence of monochloramine results in controlled microbial growth and biofouling mitigation in RO systems (Farhat, Loubineaud, Prest, El-Chakhtoura, Salles, Bucs, Trampé, Van den Broek, et al., 2018). Achieving a specific Cl: N ratio results in the formation of monochloramine; this ratio results from a specific liquid ammonia sulfate (LAS) and sodium hypochlorite (bleach) dosing. The first objective of this work is to characterize the variability of John T. Hickerson effluent and understand the typical operation of LAS and bleach dosing.

- To ensure this system can perform at a high recovery, its specific flux must be stabilized. The stable specific flux will reflect that the flux, flow, and pressure of the system are working accordingly as well as indicating no biofouling in the system. The second objective of this work is to achieve a constant specific flux to achieve high recovery.
- One of the most significant issues with high recovery DPR and ZLD is the disposal of the concentrate, mainly for inland facilities where disposal costs increase by a factor of 2.2 to 3.6 compared to coastal discharge (Sim & Mauter, 2021). The third objective of this work is to analyze options for brine crystal optimization and solid waste disposal.

2. Methodology

2.1 Experimental System

In partnership with El Paso Water and with funding from the U.S Bureau of Reclamation's Desalination and Water Purification Research (DWPR) program (R19AP00115), a direct potable reuse (DPR) pilot system was deployed at the John T. Hickerson Water Reclamation Facility in El Paso, Texas. This plant treats residential and industrial wastewater from the northwest and west parts of El Paso. Part of the effluent of this facility flows to the pilot system, which consists of two trailers, one containing the chloramination and UF system and the other RO, UV-peroxide advanced oxidation process (AOP), granular activated carbon (GAC), and Concentrate Enhanced Recovery Reverse Osmosis (CERRO).

Figure 1. Pilot System Located at the Hickerson Reclamation Facility

2.1.1 Chloramination System

Monochloramine is a disinfectant used to diminish the biofouling of UF and RO. Monochloramine, the most stable form of chloramine, is produced in situ when dosing liquid ammonium sulfate (LAS) and sodium hypochlorite into the feed water. Ideally, achieving a constant mass Cl_2: N ratio (up to 5). Within this range, monochloramine is formed within seconds to minutes, and the total chlorine residual increases by the amount of chlorine added (Crittendenn et al., 2012). For free chlorine to ammonia-nitrogen mass ratios of 5 to 7.5, the chloramines are oxidized, and the total chlorine will decrease to a minimum point, known as the breakpoint. After this breakpoint, free chlorine residual will increase proportionally to the addition of chlorine. While the UF membranes are quite tolerant of free chlorine, RO membranes age rapidly when exposed to free chlorine so it is essential in this application to maintain a Cl_2: NH_3-N mass ratio less than 5.

Although chloramine is a weaker disinfectant than free chlorine and acts slower, chlorine negatively affects the polyamide active layer of RO membranes (Lee, Halali, Sarathy, & De Lannoy, 2020). Free chlorine must not be present before entering an RO system. While determining the optimal conditions of potable reuse, it is crucial to consider the chloramines present, as they contribute to forming disinfection by-product (DBPs). Although monochloramine forms lower THMs, and HAAs, according to (Le Roux et al., 2017), monochloramine could be linked as a source of nitrogen during the formation of nitrogenous disinfection by-products (e.g., nitrosamines).

Factors such as pH can affect the monochloramine formation in the system, as monochloramine is formed at a circumneutral pH (Lee, Halali, Sarathy, & de Lannoy, 2020). A study was conducted where different pH values were tested to analyze mochloramine formation, it was concluded that monochloramine formation ideally occurs at pH value of 8.3 (Farhat, Loubineaud, Prest, El-Chakhtoura, Salles, Bucs, Trampé, van den Broek, et al., 2018). Lee, Halali, Sarathy, & de Lannoy, 2020, also analyzed different pH values for monochloramine formation. Their results stated that the permeability of monochloramine increased from 89% at a pH of 5.5 to 91.5% when the pH value is 7.5. Another study concluded that a Cl_2: N ratio of 5:1 was best achieved at a pH range from 6.5 to 8.5 (Qiang & Adams, 2004).

First, LAS is dosed in this pilot study, followed by a static mixer (Koflo 2-40C-4-6-2 at an approximate mixing intensity 3340/s at a flow of 18 gal/min). Downstream, bleach is then dosed and mixed with a static mixer (Koflo 2-40C-4-6-2 at an approximate mixing intensity 3340/s at a flow of 18 gal/min). The chemical injection pumps used by Stenner Pump Company with the following parameters:

Table 1.Stenner Pump Parameters

	LAS Pump	*Bleach Pump*
Model	E20PHM	E20RHF
Maximum Working Pressure	80PSI/ 5.5 Bar	80 PSI/5.5 Bar
Maximum Flow Rate	1.41 gal/day	4.5 gal/min
Motor Voltage	120V/60Hz	120V/60Hz

2.1.2 ULTRAFILTRATION SYSTEM

Ultrafiltration system is often used as a pretreatment for RO systems to remove particles, colloids, and organic matter and reduce fouling downstream of the system. The eight UF membranes used are iSep MICRODYN iSep 500 Ultrafiltration Module with a membrane area of 27.4 m^2 per module. Typical UF system operational setpoints are:

- Feed Flow: 18.5 gal/min
- Permeate Flow: 16.5 gal/min
- Backwash Frequency: 35 min
- Backwash Duration: 2 min
- Pre-backwash Drain Duration: 15 seconds
- CEB Frequency: 24hrs
- CEB Duration: 4 minutes

Backwashing System

Fouling occurs due to the obstruction of pores and cake layer formation and can be classified as hydraulically reversible or irreversible (Li et al., 2014). Physical cleaning by backwashing helps mitigate reversible fouling. This process entails a flow reversal during a specific duration which should remove the cake layer (Abrahamse et al., 2008). A Chemically-Enhanced Backwash (CEB) reduces hydraulically irreversible fouling, as it could restore the original transmembrane pressure. During CEB, a chemical such as bleach (hypochlorite) enhances the backwash cleaning. Too frequent CEB could alter the chemical and physical properties of the UF membranes (Li et al., 2014).

2.1.3 Reverse Osmosis

RO is a process that requires higher hydraulic pressure (proportional to the osmotic pressure of the dissolved constituents) to allow water to pass through membranes. RO effectively removes high molecular weight organic constituents such as humic and fulvic acid (Warsinger et al., 2018). This process rejects salts, and the salinity of the treated water decreases. Pathogens, trace organic compounds, and RO separates disinfection by-products. Controlling factors such as pretreatment, flux rate, fouling, and recovery, achieve a stable RO performance. Although UF is used as a pretreatment for RO, analyzing the performance of the RO system falls outside the current scope of work.

2.1.4 UV-Peroxide

Some of the main challenges of membrane treatment processes are fouling and scaling, which lead to increasing pressures and operation costs. For reuse applications that do not require desalination for salinity, non-membrane processes, such as adsorption, biologically active filtration, and advanced oxidation processes (AOPs), could be options. The most common AOPs are ozonation and ultraviolet UV light with hydrogen peroxide or hypochlorite. They rely on forming highly reactive radical species (e.g., the hydroxyl radical) and remove taste, odor, color, pharmaceuticals, personal care products, endocrine-disrupting contaminants, and disinfection by-products. UV-Peroxide depends on the plant flow rate (Tow et al., 2021), and the hydroxy radical's efficiency relies on hydrogen peroxide's ability to absorb UV radiation. This absorption depends on the wavelength; as the wavelength decreases, UV adsorption increases (Mierzwa et al., 2018). Analyzing UV-Peroxide performance falls outside the current scope of work.

2.1.6 Granular Activated Carbon

Granular activated carbon (GAC) is an adsorption technique that improves RO performance by eliminating compounds that cause fouling (Warsinger et al., 2018). This physical process is effective for taste and odor control. GAC has sieve sizes which refer to the number of sieves media can pass through before being retained. GAC achieves dichlorination of drinking water. It is a common technique used downstream of a filtration system to control toxic organic compounds, disinfection by-products, and taste and odor (Crittenden et al., 2012). The performance of GAC falls outside the current scope of work.

2.1.7 CERRO

Dr. Tarquin, Dr. Walker along with graduate students from the University of Texas at El Paso (UTEP) developed the Concentrate Enhanced-Recovery Reverse Osmosis CERRO system. This technology helps increase product water and reduces the quantity of brine sent to a downstream unit. CERRO systems have been utilized in El Paso as a cost-effective method to achieve high recovery (Tarquin et al., 2019). The performance of the CERRO system falls out of the current scope of work.

2.1.8 Zero Liquid Discharge

Although the overall system has not reached the state where a ZLD system can be built and tested, several options will be analyzed in consideration for the implementation in the pilot study. The three main options are a) heated screw conveyor, b) evaporation, and c) air drying. It is essential to consider factors such as energy consumption, space available to install or run the system, and climate.

2.2 Methods

The collection of samples occurs at three different points of the system. The first sample occurs from the Reclamation Facility's effluent, considered influent as it enters the system (Facility Effluent/ Plant Process Water), and the second after LAS and bleach have been dosed and mixed. The feed water has settled in the feed tank (Feed Water) after being dosed and mixed with LAS and bleach. The last collection of the sample occurs downstream of the UF membranes (Filtrate Water). All samples were collected ten minutes after the cycle had started.

2.2.1 On-Site (Field) Analyses

Spectrophotometry

Tests such as free chlorine, total chlorine, monochloramine, and free ammonia are measured using the HACH DR1900 Portable Spectrophotometer. Method 10245 measures Free Chlorine, and Method 10250 for Total Chlorine, both within a range of 0.05 to 4.00 mg/L Cl under Program 37. This method includes using DPD Free Chlorine Reagent Powder Pillows (25 mL) and DPD Total Chlorine Reagent Powder Pillows (25 mL) and 10 mL of the sample. Monochloramine is measured using Method 10200; Monochloramine Program 66 is used to measure monochloramine 0.04 to 4.5 mg/L Cl_2. Program 389 measures Free Ammonia, with concentrations ranging from 0.01 to 0.5 mg/L NH_3-N.

Turbidity

Turbidity is the opposite of the clarity of a fluid, which can be affected by suspended particles, dissolved inorganic chemical species, organic matter, and temperature (Kitchener et al., 2017). Turbidity was measured using the Oakton T100WL Turbidity Meter, which uses 90-degree scattering. Its measuring range is from 0 to 1000 Nephelometric Turbidity Unit (NTUs). The higher the number, the higher the turbidity. According to US EPA, the allowable turbidity for drinking water should be lower than 0.3 NTUs in at least 95% of the samples recorded each month and at no time should exceed 5 NTUs. Low turbidity is an indicator that the ultrafiltration system is working properly.

pH, Conductivity, and ORP

The Ultrameter II by Myron L company measures pH, conductivity, and oxidation-reduction potential (ORP) in the field. pH results range from 0-14; lower than seven means that a solution is acidic and results higher than 7 mean that a solution is a basic. Drinking water is typically near a neutral pH of 7. Conductivity results correspond with the salinity present in the water. ORP "indicates the availability of free electrons and water oxidizing or reducing tendency (Siggs et al., 2000). ORP is measured in millivolts (mV), which also helps determine if disinfectants are working correctly. ORP relates to chlorine measurements due to chlorine's reactivity in water which depends on redox conditions; the higher the chlorine concentration, the higher the ORP (James et al., 2004). ThermoScientific ORION Star A323 is used for lab measurements to measure pH and conductivity; the pH probe is calibrated with pH 4, 7, and 10 standards, and the conductivity is calibrated with 1413 µS/cm.

2.2.2 Laboratory Analyses

Total Dissolved Solids and Total Suspended Solids

Total Dissolved Solids (TDS) measures the dissolved solids by baking filtered (0.45µm) water at 180˚ C and weighing the trays before and after the sample. The current TDS standard is 500 mg/L and affects hardness, watercolor, and taste (the United States Environmental Protection Agency, 2022). Total Suspended Solids (TSS) also impact water quality, and a high amount of TSS decreases dissolved oxygen (Verma et al., 2013). To measure TSS, zero weigh a 0.45µm filter before and after filtering water and baking the filter at 103˚ C. The units for the results for both TDS and TSS are in mg/L.

Ion Chromatography

Ion Chromatography (IC) is used to measure ionic species; it analyzes anions and cations. Inorganic cations detected include alkaline earth metals, rare earth metals, and alkali metals. IC is considered a reliable technique for analyzing water. In this case, the Thermo Scientific Dionex Aquion is used to determine the concentrations: Ca, K, Mg, Na, Li, and NH_4 with a Dionex IonPac CS16 (5mm) cation exchange column and an eluent of 47 mM methane sulfuric acid (MSA), and the Anion column used is the Dionex IonPac AS18 (4mm) anion exchange column with a potassium hydroxide from an eluent generator to quantify NO_2, Cl, F, NO_3, SO_4. Chromeleon Beta displays the results in units of mg/L.

Inductive Coupled Plasma

Inductive Coupled Plasma (ICP), a hard ionization method, is used to quantify the concentrations of metals and semi-metals in aqueous solutions. Argon gas is ionized to generate plasma which ionizes elements with high first ionization potentials (Lindon et al., 2017). Perkin Elmer Optima 7300 DV optical emission spectrometer (OES) is used to determine the concentration of the following elements: Ca, Mg, Na, P, As, Ba, Cd, Cr, Cu, Fe, Li, Mn, Ni, Pb, Se, Sn, Sr, U, V, W, Zn, Si, simultaneously.

Alkalinity

Alkalinity is measured using the Microlab FS-522, a titration system that doses 0.02 N Sulfuric Acid. The program counts the drops of acid to lower the pH to approximately 4, then the alkalinity is determined by inspection of the point that the measured pH curve crossed the theoretical titration endpoint pH curve. A standard check with 168 mg/L of $NaHCO_3$ ensures that the results are accurate during calibration. Results are in units of mg/L as $CaCO_3$.

3. Results

The chloramination and UF systems started running in July 2021 with effluent from the Hickerson Reclamation facility. However, from late August 2021 to mid-January 2022, the facility operated at partial capacity, lowering the volume of wastewater. During this period, the Hickerson plant used tap water instead to feed the plant's process water line, which is the influent to the DPR pilot. This project, known as the Frontera Wastewater Replacement Line, allowed the comparison of different analyses between tap water and treated wastewater. Major troubleshooting issues faced during the project's duration, which also delayed the project's progress, are listed in the Table 2 below.

Table 2. Troubleshooting Issues faced during duration of the project

	Issue	Date Occurred	Date Resolved
1	System was shut down due to low flow in reclamation facility	8/18/2021	8/26/2021
2	System started running on tap water	8/26/2021	1/18/2022
3	AMIAD Automatic Screening System started faulting	12/13/2021	12/13/2021
4	System was shut down due to leak near permeate pump	12/13/2021	1/4/2022
5	AMIAD Automatic Screening System started leaking	1/24/2022	1/24/2022
6	Leak near AV3 Valve	2/7/2022	2/11/2022
7	System was shut down due to feed pump failure	2/11/2022	2/14/2022
8	System was shut down due to feed tank overflowing	2/18/2022	2/24/2022
9	AMIAD System started faulting	2/25/2022	2/25/2022
10	System was shut down due to no power	3/8/2022	3/8/2022
11	AMIAD System was bypassed	4/13/2022	5/17/2022
12	Flow switch was replaced	4/13/2022	4/13/2022
13	Chemical dosing umps were not working properly	5/5/2022	5/10/2022
14	LAS dosing pump started leaking	5/11/2022	5/17/2022
15	AMIAD System was replaced by static mixer	5/17/2022	5/17/2022
16	UF membranes started fouling	5/17/2022	5/18/2022
17	Pipe near new (Bleach) static mixer started leaking	5/20/2022	5/23/2022
18	Sodium Hypochlorite used for CEB was back ordered	5/23/2022	5/26/2022
19	Both LAS and Bleach dosing pumps were not working properly	5/25/2022	5/31/2022
20	Pipe near new (Bleach) static mixer started leaking	6/17/2022	6/20/2022
21	Pumps were not dosing bleach due it being back ordered	6/29/2022	7/12/2022
22	Automatic valves AV4 and AV6 were not working properly	7/6/2022	7/7/2022
23	Feed pump stopped working	7/7/2022	7/28/2022
24	Due to storm, influent valve broke	7/26/2022	7/29/2022
25	Free Ammonia concentration in influent increased (10 mg/L)	8/4/2022	8/23/2022
26	Backwash drain new valve	8/23/2022	8/23/2022
27	UF membranes started leaking	8/25/2022	10/25/2022

3.1 Field Analyses Water Quality

3.1.1 Hach

As mentioned in the objectives, monochloramine helps to mitigate biofouling. The goal was to achieve a constant concentration of monochloramine and free ammonia with a set dose of

LAS and bleach. Results were very sensitve to the pump set points; as a result, different percentages were tested, shown in Figure 2. When the system ran on tap water, the LAS pump was set to 50% and the bleach pump to 15%; with these settings, monochloramine concentration ranged from 1.6 mg/L Cl_2 to 3.5 mg/L Cl_2 with negligible concentrations of free ammonia.

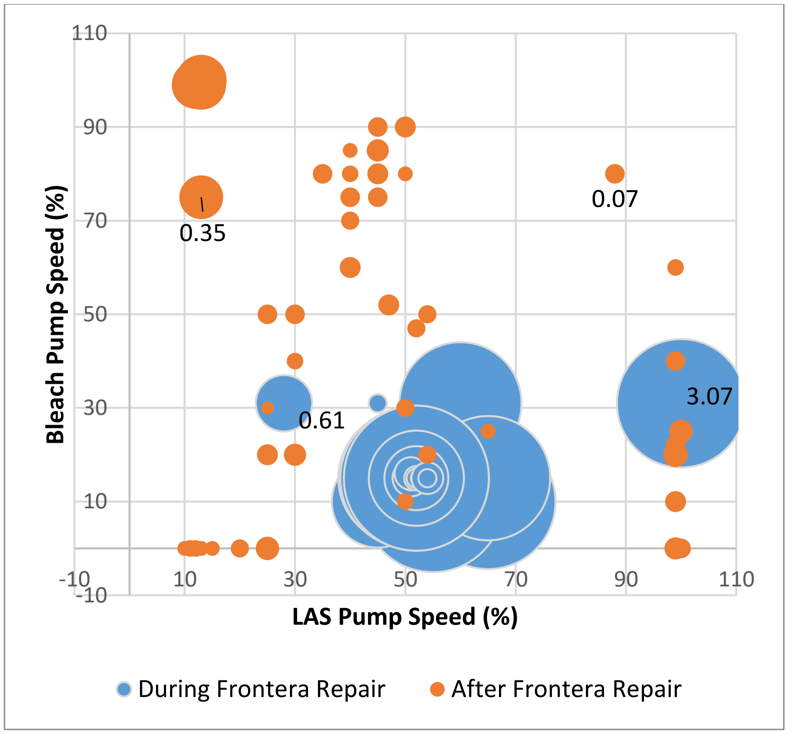

Figure 2. Monochloramine Concentrations (mg/L) in UF Feed Water versus chemical dosing pump speeds (August 2021- August 2022).

Once the influent to the pilot was returned to treated wastewater water (as opposed to tap water), new dosages of LAS and bleach were needed. Set points that showed promising results were LAS pump at 13% and bleach pump at 80%. Results from the month of June, show low concentrations of free ammonia and monochloramine ranging from 1.6 mg/L as Cl_2 to 7.3 mg/L as Cl_2. Although these set points resulted in a monochloramine concentration that could reduce fouling, the wide range concentrations shown in Figure 3b are a result of the variable concentrations of free ammonia in the plant effluent, as shown in Figure 3a.

While the influent free ammonia varies considerably, the LAS and bleach dosing pumps were set such that Cl_2:NH_3-N mass ratio will not exceed 5. Although not ideal, remaining free ammonia will be present but not free chlorine, which can negatively impact processes downstream. This will ensure that the system stays in the monochloramine-predominance region and will not pass the breakpoint nor send free chlorine to the downstream.

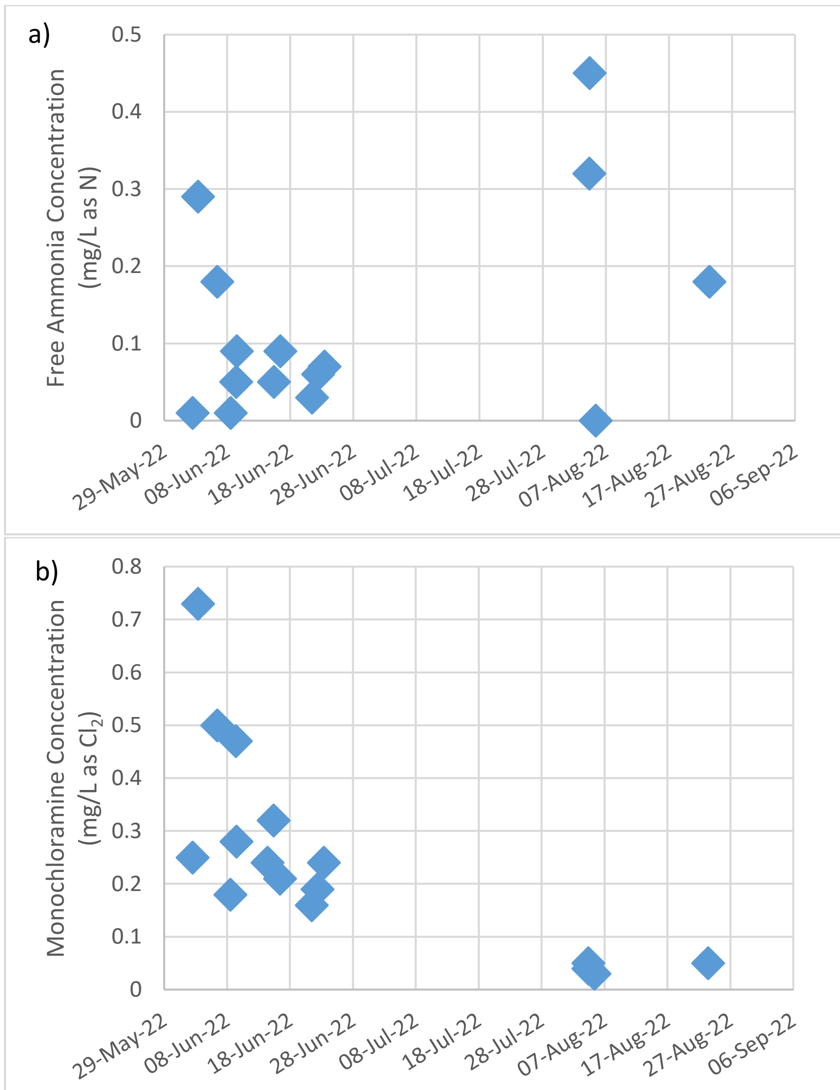

Figure 3 UF Filtrate a) Free Ammonia Concentration and b) Monochloramine Concentration at 13% LAS and 80% Bleach pump (June 2022- August 2022)

3.1.2 ULTRAFILTRATION SYSTEM

Stable flow rates were achieved for most of the piloting (Figure 4a), except for major fouling events in March and April-May 2022. During these fouling events, the permeate vacuum pump significantly increase the transmembrane pressure (Figure 4b) to in response to the PLC ramping up the permeate pump motor speed to try to maintain the permeate flow rate setpoint. As shown in Figure 4c a stable specific flux was not achieved. Fortunately, with several bleach-enhanced backwashes, the specific flux was able to recover.

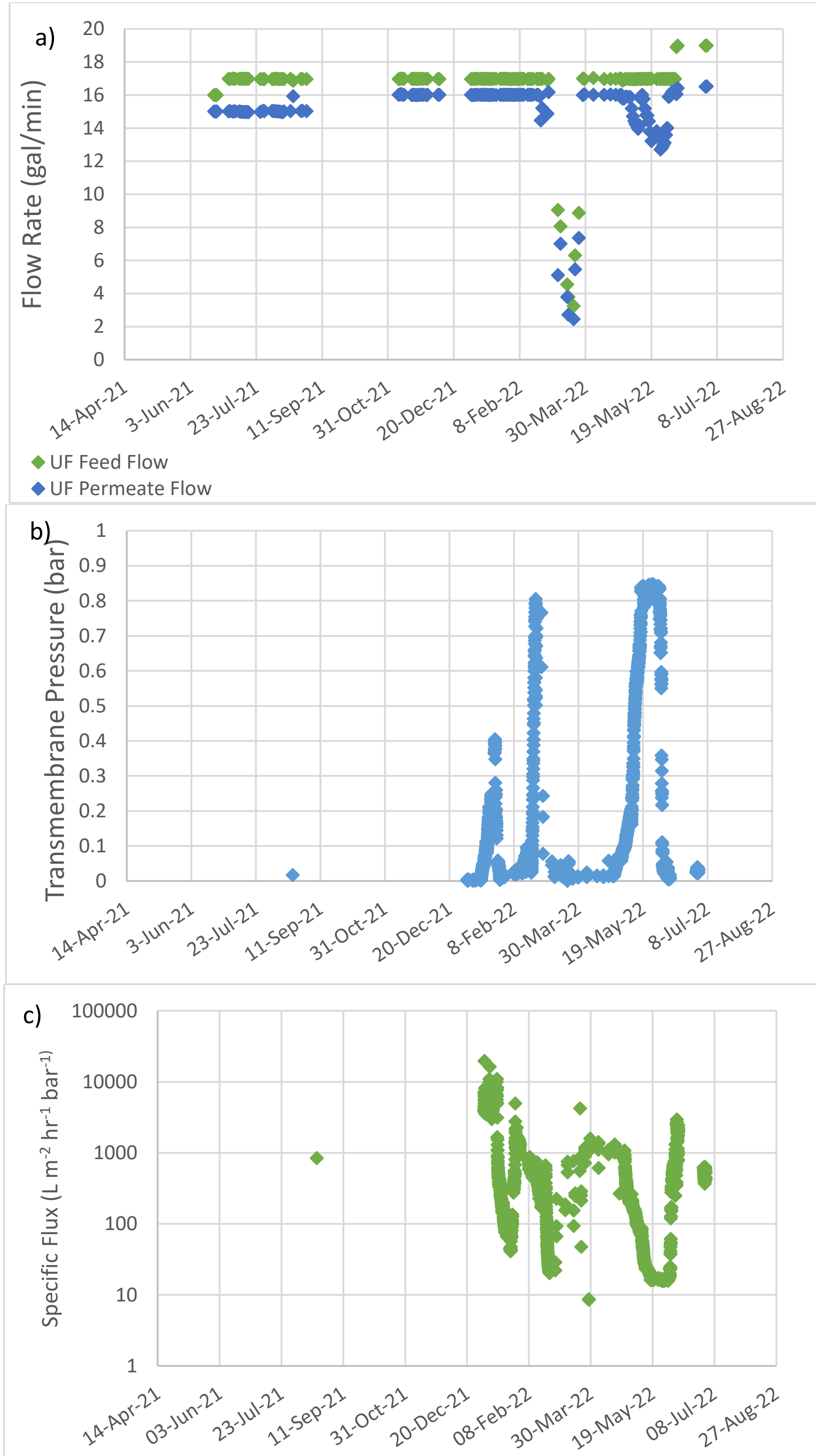

Figure 4. a) Daily Median for UF Feed and Permeate Flow, b) Hourly Median Transmembrane Pressure, and c) Hourly Median Specific Flux.

3.1.3 TURBIDITY

Analyses of Turbidity were conducted at the three different sample points throughout the project. The turbidity from the Hickerson plant effluent ranged from 1.4 NTU to 20.7 NTU in comparison to turbidity present in tap water which was never more than 5 NTU. This comparison, as shown below Figure 5*a*. The UF feed would need subsequent filtration to meet US EPA drinking water standards of 95% less than 0.3 NTU. Figure 6 shows the turbidity removed from both treated water and tap water. Tap water shows a much lower turbidity removed percentage, this is due to the lower turbidity concentration in the influent, which is harder for the system to remove.

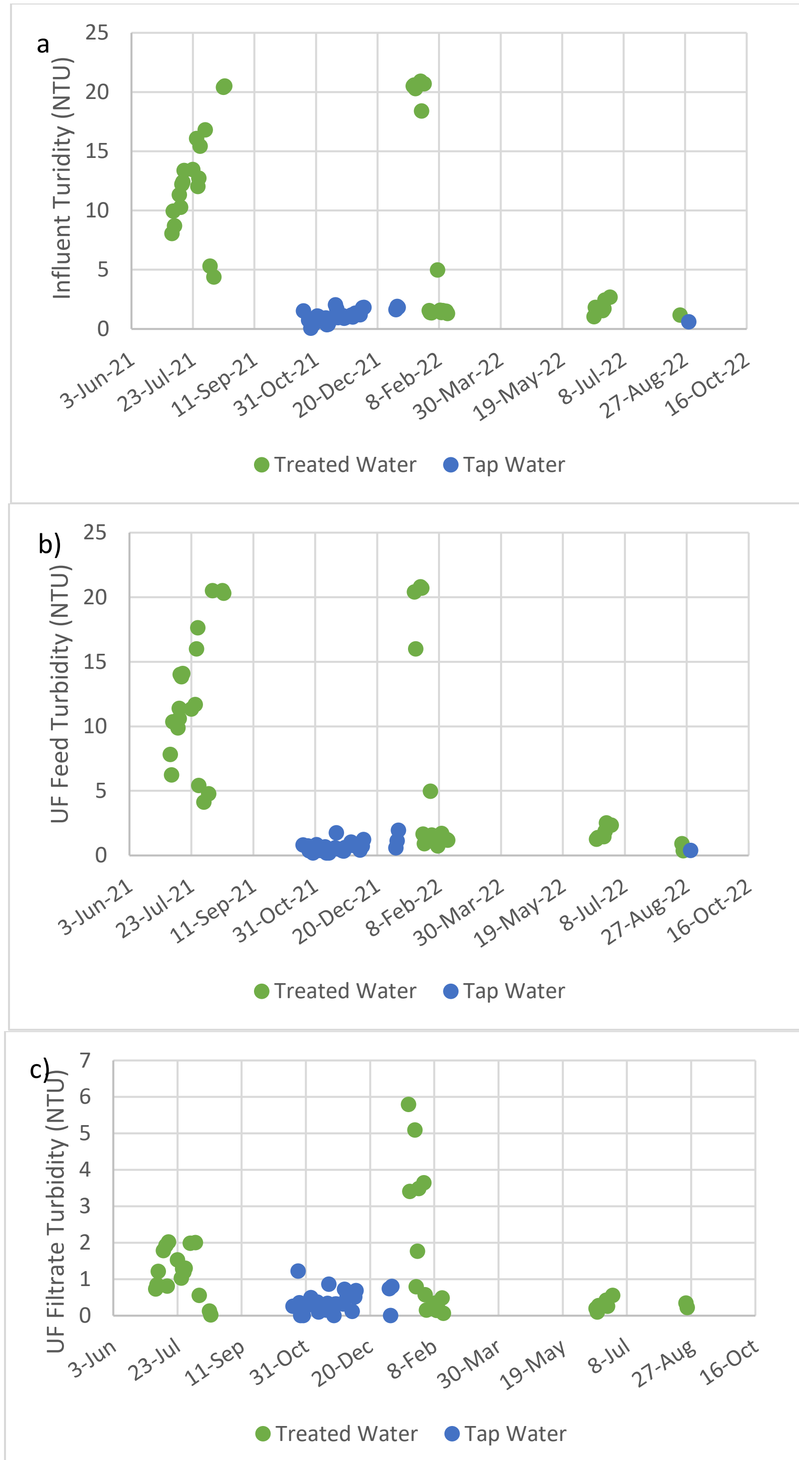

Figure 5. Turbidity of a) Influent Turbidity b) UF Feed Turbidity c) UF Filtrate (June 2021-August 2022)

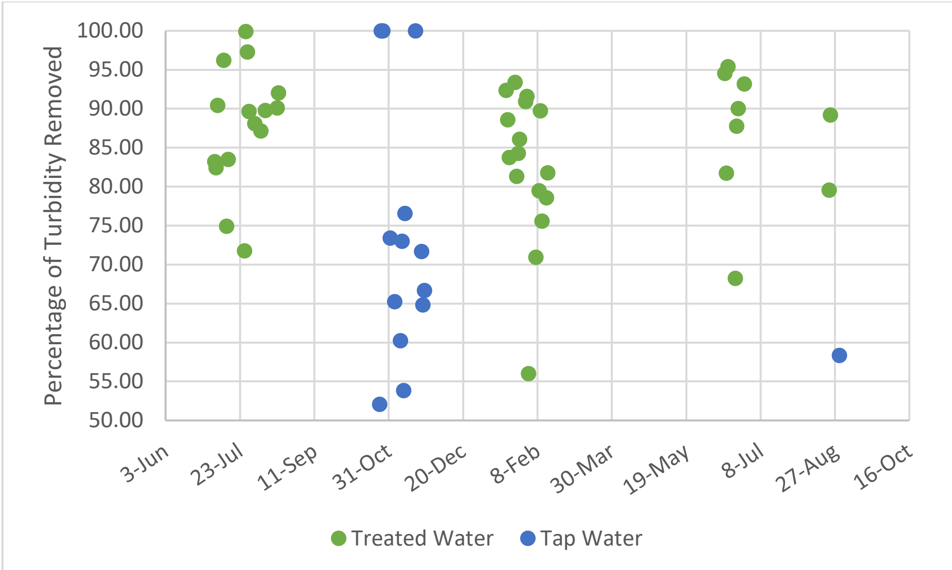

Figure 6. Turbidity removed from influent

3.1.4 pH

Throughout the piloting, pH remained at a neutral range. These expected values are due to the influent being treated before reaching the system, with an average pH of 7.5. The highest pH values were those from tap water at all three different sample points. The US EPA Secondary Drinking Water Standard for pH is 6.5- 8.5, and all the filtrate samples from treated water fall within that range.

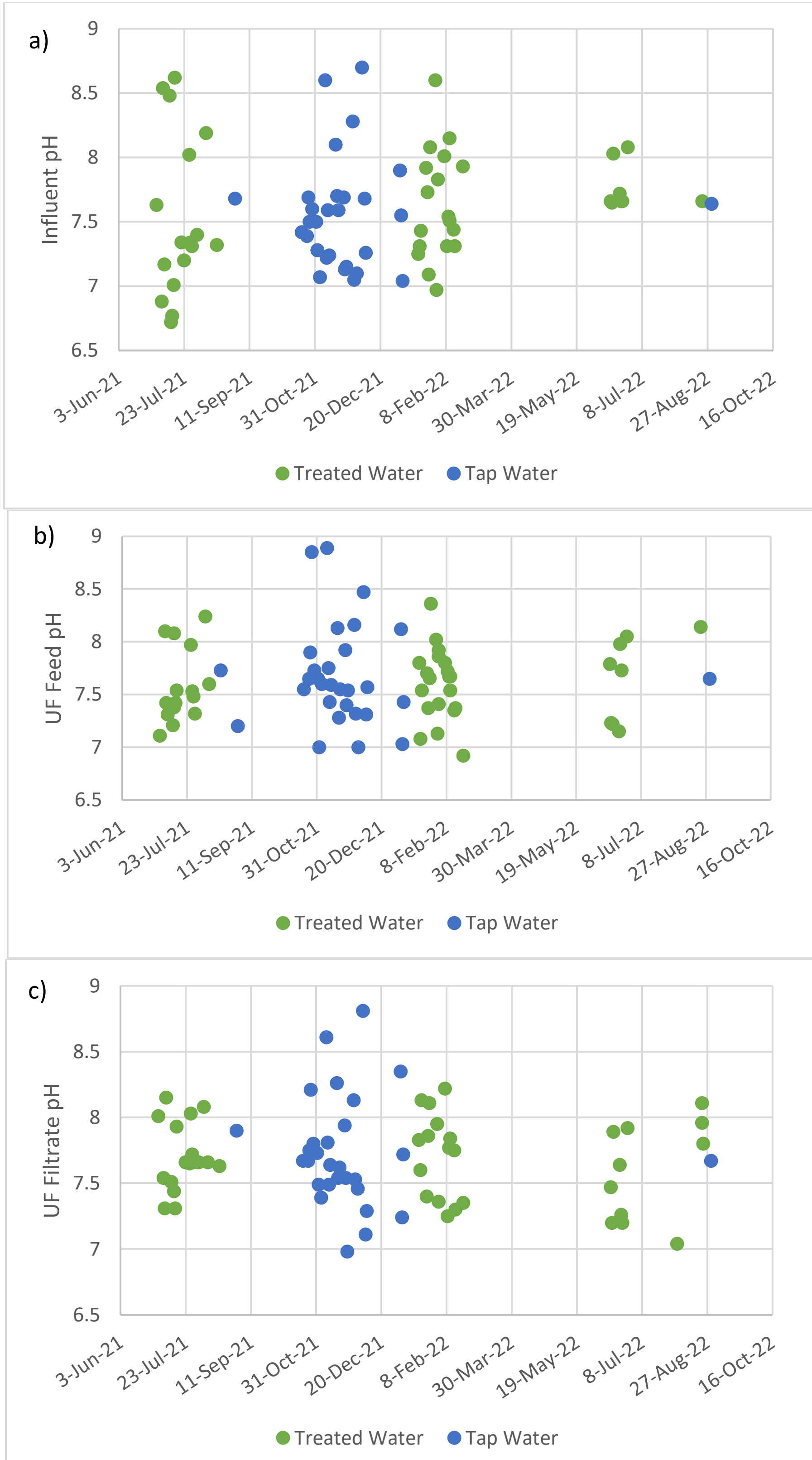

Figure 7. a) Influent pH, b) UF Feed pH, and c) UF Filtrate pH (June 2021-August 2022)

3.1.5 CONDUCTIVITY

Conductivity is correlated with the aggregate concentration of dissolved ions; as the salinity of water increases, conductivity increases. Although both the influents (tap water and treated water) went through water treatment, conductivity levels are lower from tap water due to the lesser ionic content present in the water. Downstream RO will significantly decrease the conductivity of the water for potable reuse.

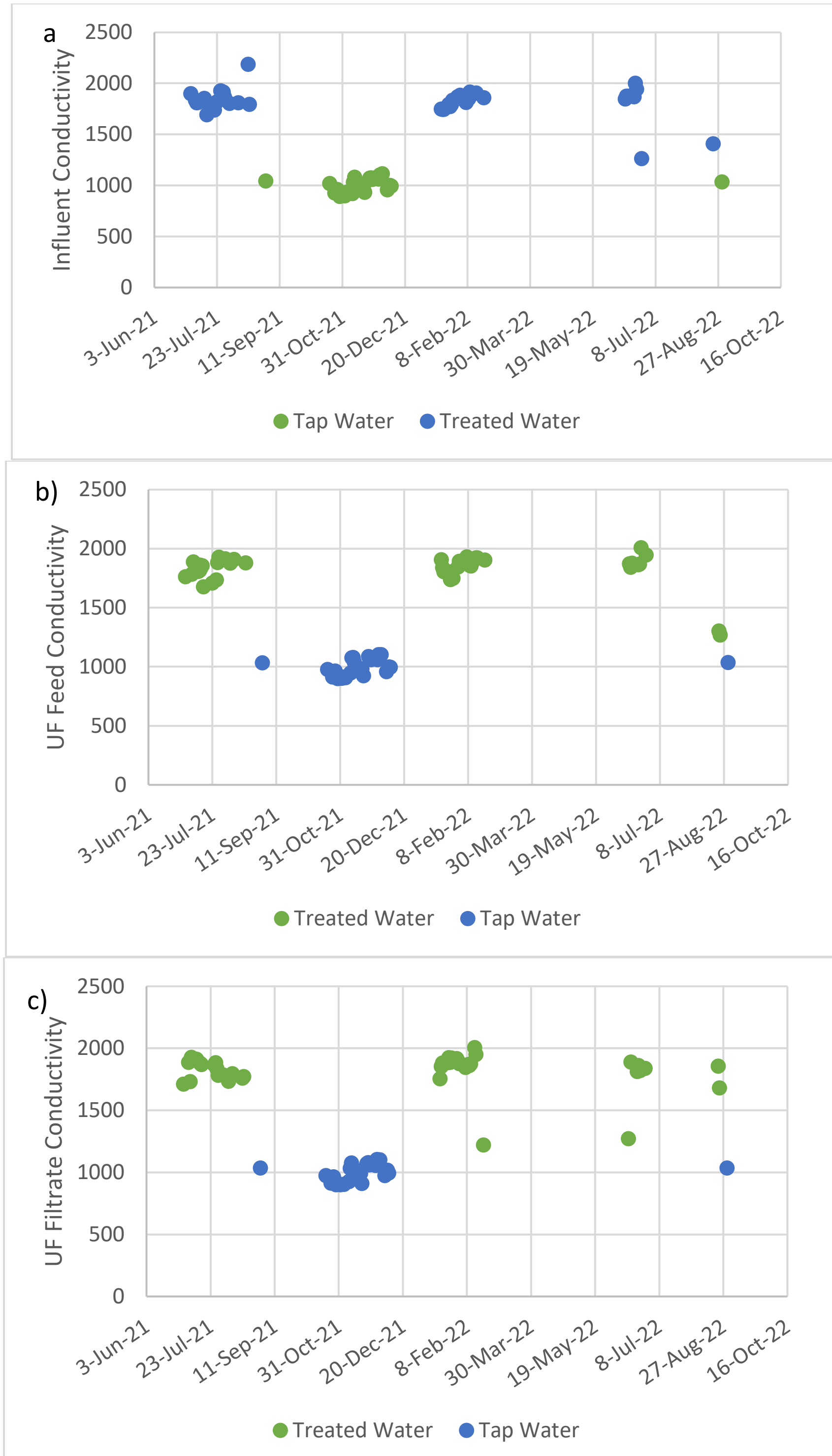

Figure 8. a) Influent Conductivity, b) UF Feed Conductivity, and c) UF Filtrate Conductivity (June 2021-August 2022)

3.1.6 ORP

As previously mentioned, ORP is an indicator of the oxidation-reduction condition of the water. A lower ORP can indicate the presence of organic compounds in the water (Vasquez et al., 2006). The higher ORP in tap water (Figure 10) could be linked to the chlorine presence of the free chlorine, as free chlorine produces a higher ORP. The sensor logged in ORP measurements in the UF trailer after chemical treatment, results are shown in Figure 9. A negative ORP was measured from November 2021 through May 2022, resulting from the low concentrations of chlorine. The ORP for treated water was significantly lower than tap water at all stages. Although insignificant, there is an increase in ORP from the influent to UF filtrate, where the average ORP for treated wastewater was 170mV and 211 mV, respectively. Although ORP measured by the Ultrameter II by Myron L and the ORP sensor do not match specifically, the negative ORP values reflected by the sensor correlate with the timeframe where chemical dosing was not stable. The differences between both types of measurements could be due to the sensors or probe being uncalibrated or human error with the Ultrameter II by Myron L.

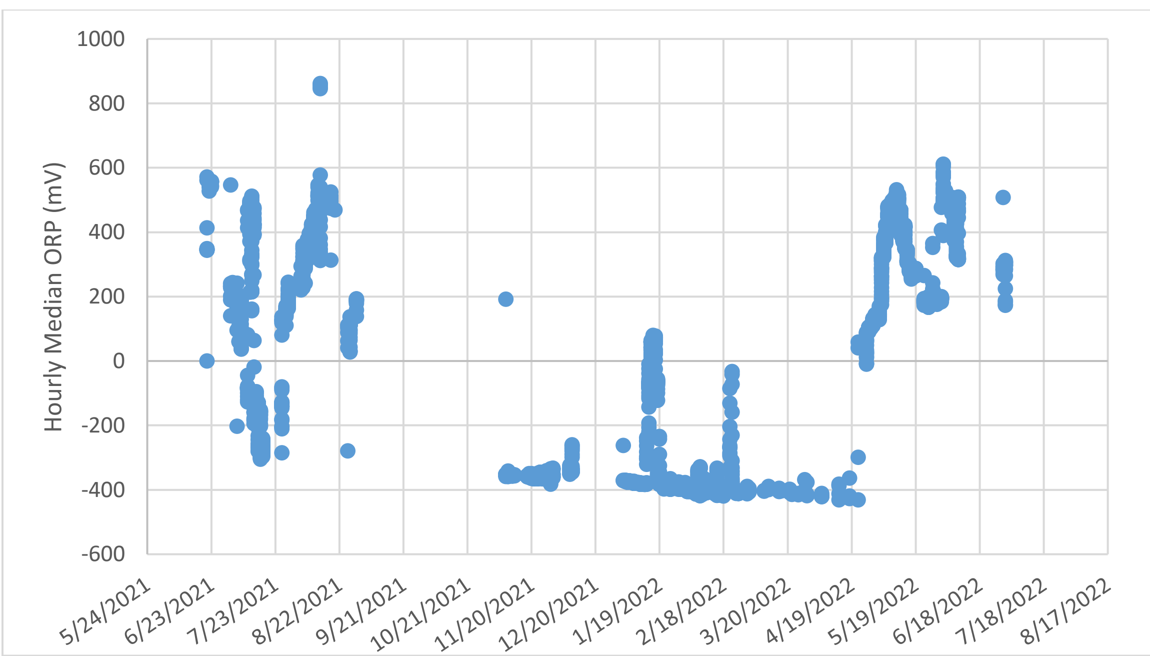

Figure 9. ORP logged by the system.

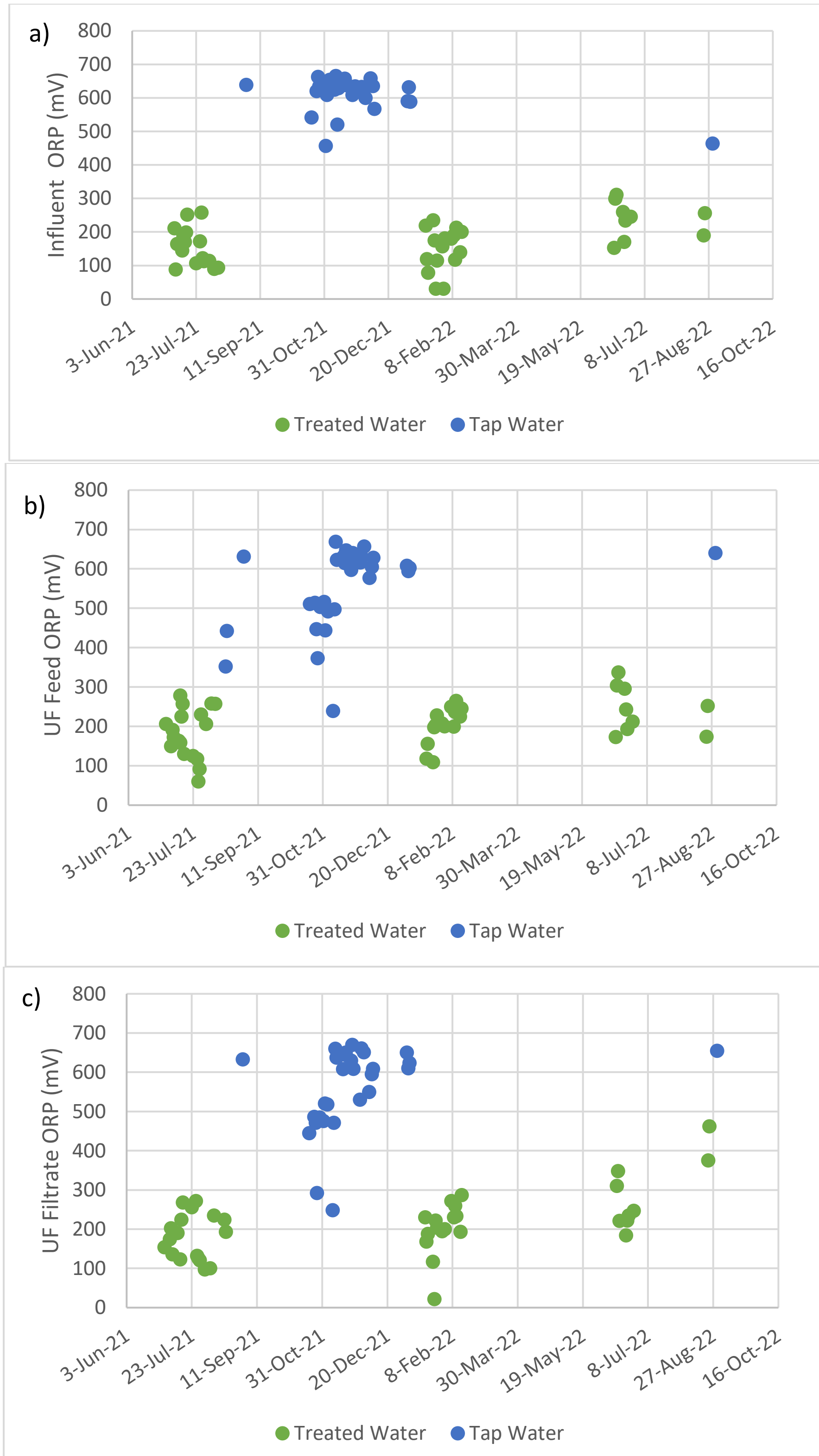

Figure 10. a) Influent ORP, b) UF Feed ORP, and c) UF Filtrate ORP (June 2021-August 2022)

3.2 Laboratory Analyses

3.2.1 Total Dissolved Solids and Total Suspended Solids.

TDS is correlated with conductivity; as conductivity increases, TDS also increases. The TDS results below correlate to the conductivity section, where treated water contains a higher conductivity than tap water. However, there was no significant decrease in values from the influent water TDS (average of 1139 mg/L) to the feed water TDS (average of 1130 mg/L). With a TDS of less than 1000 mg/L, water is considered freshwater, while anything above that limit is brackish water, not recommendable for potable use (Crittendenn et al., 2012). Although UF did not achieve high TDS removal, combining it with the downstream systems, such as RO and disinfection, would significantly improve its performance.

TSS testing occurred only for treated water. There was not a specific trend shown by the results, as in some samples, filtrate TSS increased from their respective influent TSS, and in other samples, it decreased. This depletion could be due to a lack of precision with oven temperature or human error. One possible factor affecting results is the low concentration of suspended solids in the water. For each test, only 20 mL of sample was used.

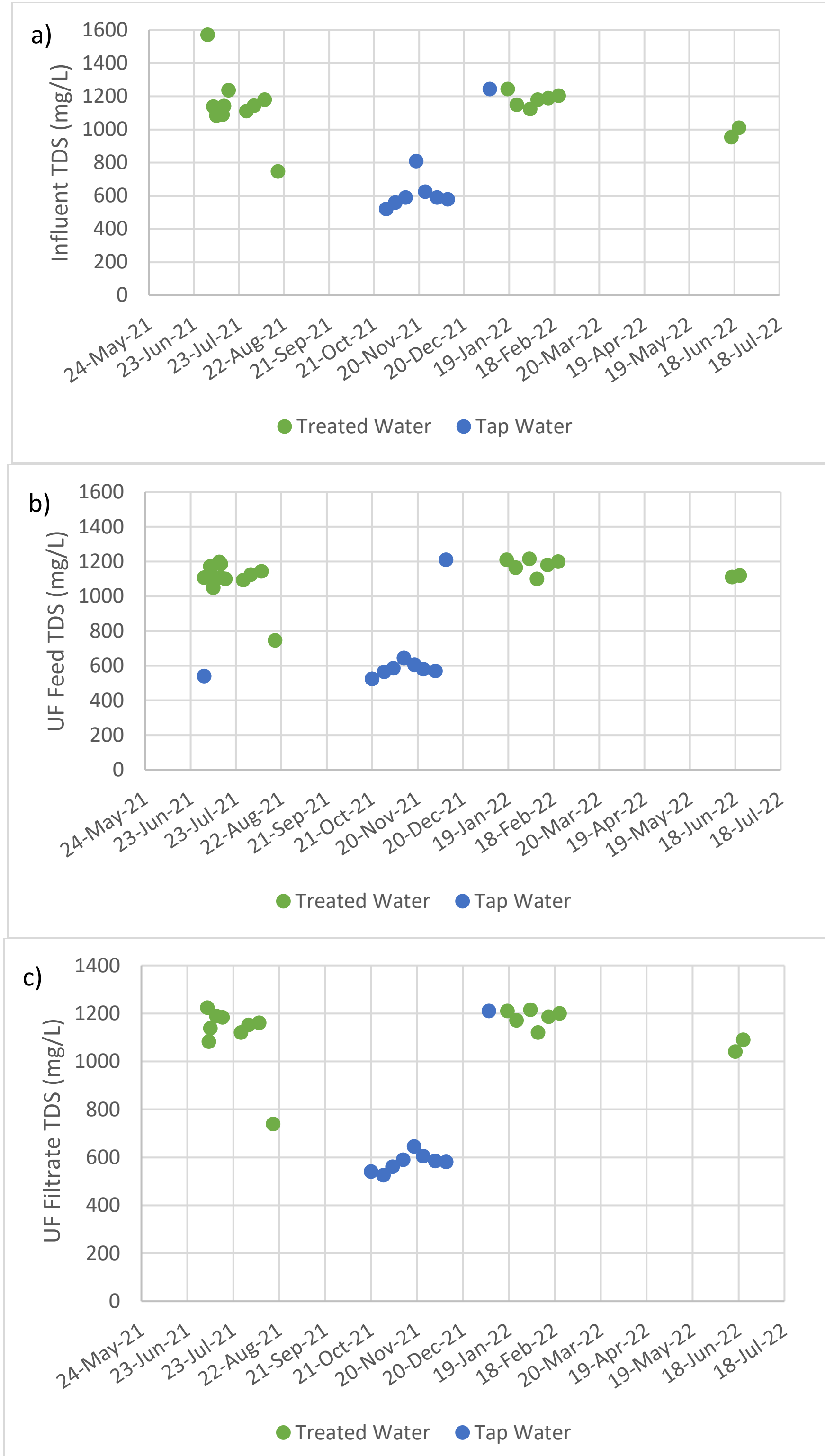

Figure 11. a) Influent TDS, b) UF Feed TDS, and c) Filtrate TDS (June 2021-June 2022)

3.2.3 Ion Chromatography

IC results show concentrations of anions chloride, fluoride, nitrate, nitrite, and sulfate and cations calcium, potassium, magnesium, sodium, lithium, and ammonium. For comparison, Figure 12a shows that the potassium and magnesium concentrations decrease as the water travels downstream. Figure 12b shows the difference and decrease in concentrations between Cl^-, SO_4^-, NO_3^-, and NO_2^-.

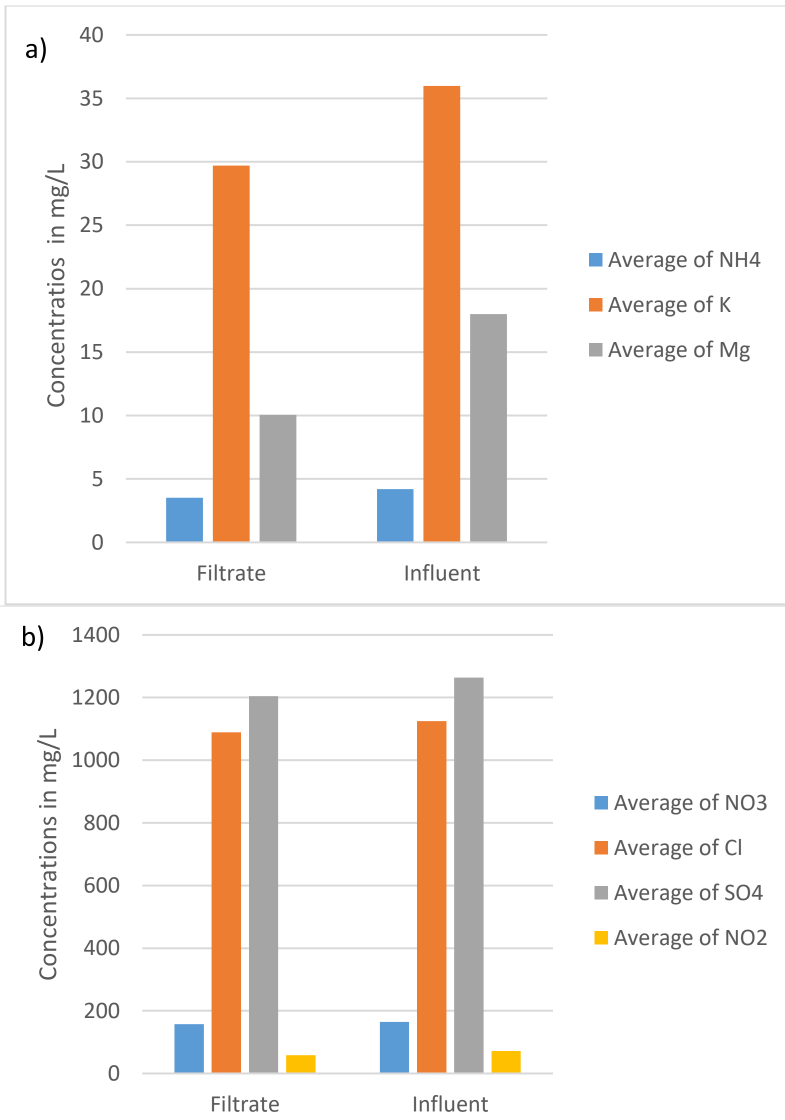

Figure 12. a) Average Concentrations of K, NH_4 and Mg b) Average Concentrations of Cl, SO_4, NO_3 and NO_2.

3.2.4 INDUCTIVE COUPLED PLASMA

ICP results show concentrations of certain elements. For several elements, such as copper (Cu), manganese (Mn), and iron (Fe), the results showed undetectable concentrations. Concentrations of other elements listed previously in the Inductive Coupled Plasma section are standard in wastewater and do not show potential risk due to their low concentrations. For comparison, the arsenic (As) and barium (Ba) concentrations are shown in Figure 12 in mg/l. The average of barium remains constant regardless of the type of water, while the average for arsenic increases for filtrate. This result could be due to low concentrations being more challenging to remove than concentrations greater than 1 mg/L. Figure 12b shows these two elements' minimum and maximum concentrations, which show a consistent trend throughout the different water types.

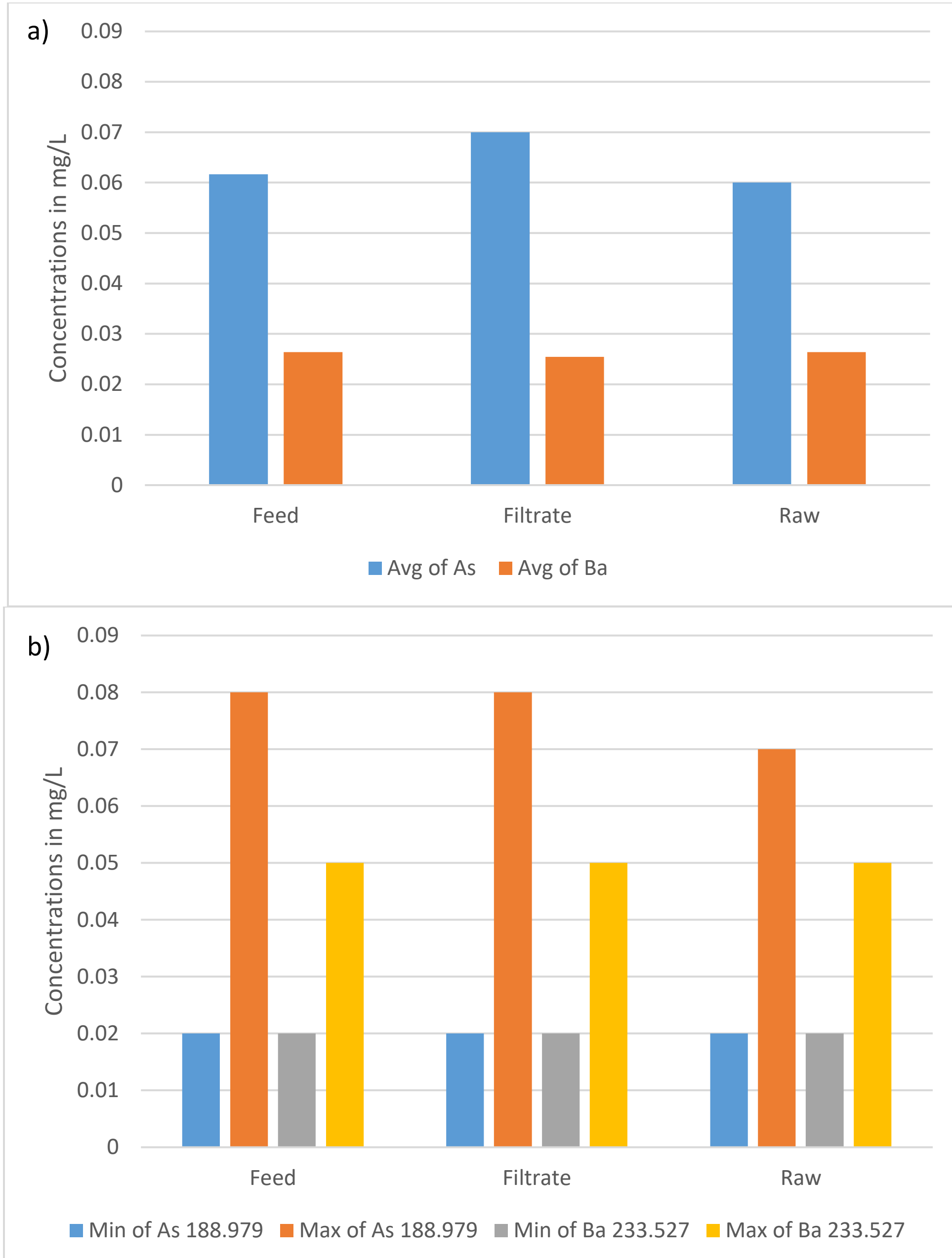

Figure 13. a) Average concentrations of As and Ba. b) Maximum and Minimum Concentrations of As and Ba

3.2.5 ALKALINITY

Alkalinity is affected by weak acids, carbonate systems, phosphates, silicates, and borates (Crittenden et al., 2012), meaning that the varying quality in the influent will affect alkalinity at all sample points. pH and alkalinity are correlated as both shall increase when the other does. Alkalinity is a result of a weak acid. Knowing and maintaining specific alkalinity helps better understand how susceptible water is to acidity. As seen below in Figure 14, although there is a slight increase between each sample point, all are within the same range. Treated water having similar alkalinity as tap water could mean that these results are within reasonable concentrations.

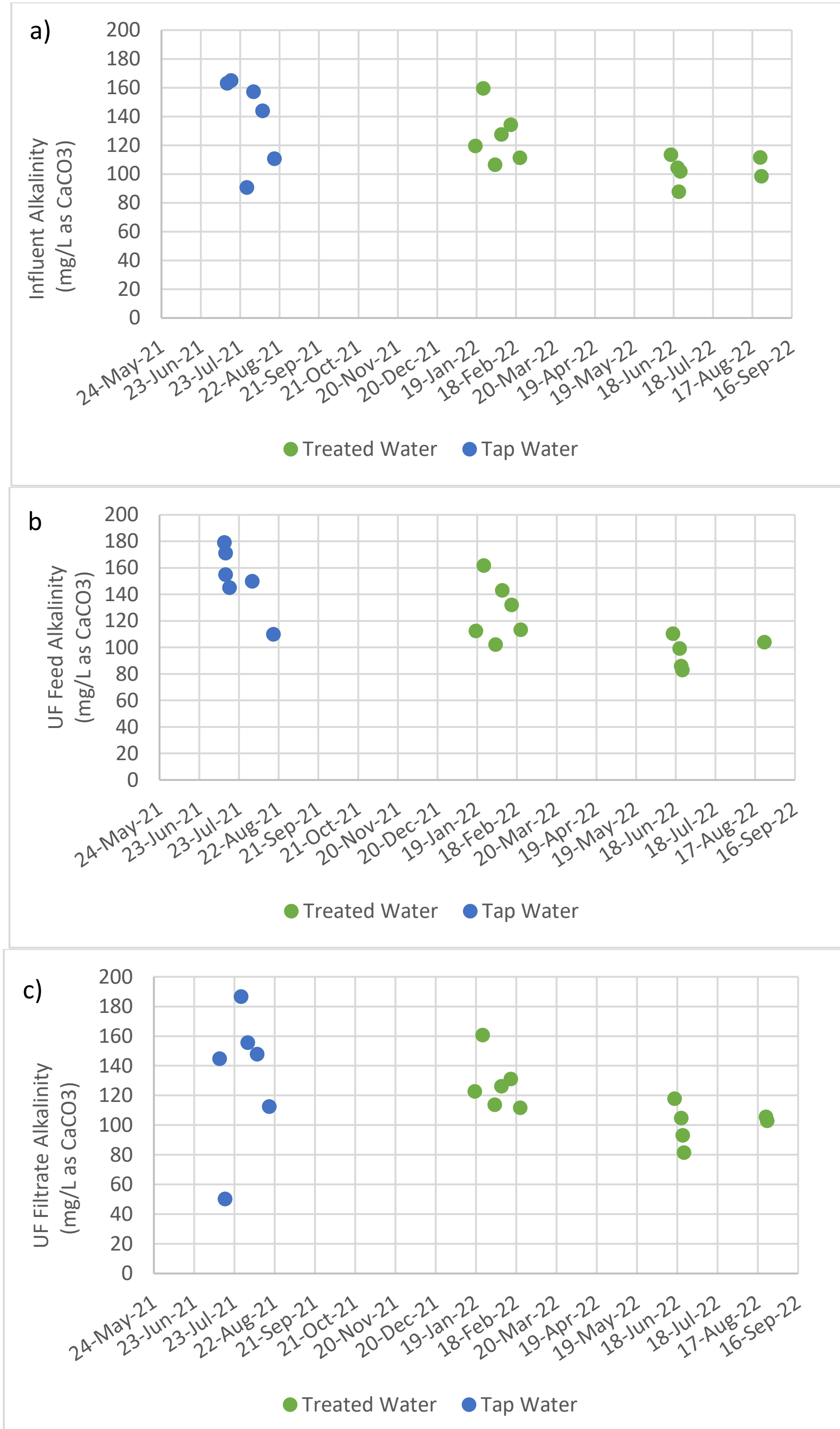

Figure 14. a) Influent Alkalinity, b) UF Feed Alkalinity, and c) UF Filtrate Alkalinity (June 2021-August 2022)

3.3 Achieving Zero Liquid Discharge

Ideally, with ZLD, the salt produced could be sold, reused, or disposed of in an eco-friendly manner. However, the solid waste produced by high-recovery DPR and ZLD is not reusable (without additional treatment) since this concentrate (brine) is a saline reject stream that contains dissolved salts, organic matter, metals, nutrients, and pathogenic substances (Panagopoulos & Haralambous, 2020). Although these contaminants are found in concentrations of µg/L, they can lead to adverse effects on the environment in the long term (Pramanik et al., 2017). \Brine disposal can be especially difficult for inland communities as water bodies are not available for discharge. Deep-well injection is not available everywhere, nor is it typically suitable for smaller communities (due to high costs of well drilling), and it is not ideal for areas with intense seismic activity. Sewer discharge and land use are not feasible as they apply to limited quantities of brine.

The current regulations around land disposal and DPR do not follow a particular framework (Scruggs & Thomson, 2017). Even though the EPA and the state of Texas regulate the disposal of solid waste, the definition of solid waste, sludge from a treatment facility, is broad. Overall, States regulate waste disposal, and it is the state's responsibility to comply by the rules and regulations provided by EPA. Regulations will depend on the framework available in the specific region. Stricter requirements to protect environmental species and ecosystems might be implemented in the future, but the question of brine disposal still needs to be answered. A thorough analysis of the contaminants present in the brine is required to establish if which disposal method complies with proper standards and regulations of concentrate disposal, especially when it comes to concentrating disposal from wastewater.

Beyond environmental regulations, technical feasibility and economic viability also constrain ZLD options. Three systems were conceptually analyzed for thickening and/or dewatering the CERRO superconcentrate, and factors such as energy consumption, solar panels, cost, and overall feasibility were accounted for. However, the actual implementation of any system is part of future research. Table 3 summarizes the three different options mentioned and shows the footprint, energy consumption and maintenance needed for each.

Table 3. Summary of three different options to achieve zero liquid discharge.

	Footprint	**Energy**	**Maintenance**
Screw Conveyor	6 to 100 ft	164kW	• Service life from 5 to 10 years • Proper and constant lubrication is needed • Screw damage, wear and material building must be monitored
Landfill	1,155 ft^2	**-**	• Constant monitoring for leakage • Pollution analysis • Solids must be measured by volume every five years
Evaporation	2.7 to 4.6 meters in depth	162 kW	• Constant monitoring due to change in water conditions such as temperature and pH

3.3.1 Heated Screw Conveyor

Heated screw/auger conveyors are commonly used to heat or dry liquids or slurries by a rotating screw that moves the material linearly. There are different configurations- vertical, horizontal, or inclined - depending on the goal. Screw conveyors include key design components such as the pitch and the axial distance between each crest, which can vary based on the desired outcome. A shorter pitch is mostly used for both inclined and vertical screw conveyors, while a longer pitch creates desired agitation of the liquid media and is used for rapid material conveying processes (*Screw Conveyors*, n.d.). Screw conveyors with jacketed trough are typically used for cooling or heating materials. As for materials, stainless steel is recommended as it is resistant to corrosion.

Using an inclined screw conveyor is a good option in this case as the inclined screw could convey a slurry or solids into a container for disposal, in addition to thickening/dewatering. The angle can range from 0 to 45 degrees, the higher the angle, the efficiency and load capacity decreases. Use of an inclined screw conveyor also decreases material fallback. A vertical screw conveyor offers a decrease in footprint needed and lifts materials, but the feed concentration must be matched with appropriate motor power. An inclined screw conveyor was preferred for this application and it was assumed that the CERRO super concentrate would enter the bottom of the screw, and air could be blown countercurrent from the top of the screw conveyor. At the top of the screw conveyor. the thickened/dewatered material would be released into a container for disposal.

Different companies were contacted and analyzed to ensure that their products were able to perform the desired results. S. Howes provided the most thorough information about their products. S.Howes conveyors transfer heat through contact with an external jacket or through transfer auger. Their products claim to be cost saving, have accurate control of temperature, can be used for high pressure applications, and have an effective heat transfer surface per unit. These conveyors can be used for processes such as cooling, heating, and drying. The auger can be customized to provide different types of augers, seal, jackets.

Regarding heating, the parameters are the following:

- Heating Capacity: 100/lbs/hr to 2 tons/hr
- Temperature: 50 F in to 1000 F out
- Diameter Range: 4” to 36”
- Thermal Transfer Contact Area: up to 300 sq. ft

Given this information and considering a flow (Q) of 1 gal/min, density (ρ) of 8.34 lbs/gal, and a change of temperature (Δt) of 80˚C (*i.e.*, from 20˚C to 100˚C), the following calculations were performed to determine the viability of using a heated screw conveyor to obtain zero liquid discharge. The mass flow ($\dot{m}$) is calculated in Eq. (1), and the required heat flow ($\dot{q}$) is calculated for water with a specific heat capacity (c) in Eq. (2).

Eq. (1) $$\dot{m} = Q\,\rho = \left(1\,{}^{\mathrm{gal}}/_{\mathrm{min}}\right)\left(8.34\,{}^{\mathrm{lb_m}}/_{\mathrm{gal}}\right) \div \left(2.2\,{}^{\mathrm{lb_m}}/_{\mathrm{kg}}\right) = 3.79\,{}^{\mathrm{kg}}/_{\mathrm{min}}$$

Eq. (2) $$\dot{q} = \dot{m}\,c\,\Delta t = \left(3.79\,{}^{\mathrm{kg}}/_{\mathrm{min}}\right)\left(4.18\,{}^{\mathrm{kJ}}/_{\mathrm{kg}}\right)(80\ ^{\circ}\mathrm{C}) \div \left(60\,{}^{\mathrm{s}}/_{\mathrm{min}}\right) = 21\ \mathrm{kW}$$

$$\dot{m} = Q\rho = (1\,{}^{gal}/_{min}\,)(8.34\,lb_m)(2.2\,{}^{lb_m}/_{kg})$$

The value for heat flow only accounts for the change of temperature to 100˚C, not the total heat required to evaporate. The heat flow ($\dot{q_{vap}}$) needed for heat of vaporization (H_{vap}) can be determined by the following:

Eq. (3) $$\dot{q_{vap}} = \dot{m}H_{vap} = \left(3.79\,{}^{\mathrm{kg}}/_{\mathrm{min}}\right)\left(2260\,{}^{\mathrm{kJ}}/_{\mathrm{kg}}\right) \div \left(60\,{}^{\mathrm{s}}/_{\mathrm{min}}\right) = 143\ \mathrm{kW}$$

Thus, the total heat flow required would be approximately 164 kW, which can be converted to ${}^{\mathrm{kWh}}/_{\mathrm{kgal}}$ by the following conversion:

$$\left(\frac{164\ \mathrm{kW}}{1\,{}^{\mathrm{gal}}/_{\mathrm{min}}}\right)\left(\frac{1000\ \mathrm{gallons}}{\mathrm{kgal}}\right)\left({}^{\mathrm{hr}}/_{60\ \mathrm{min}}\right) = 2{,}733\ {}^{\mathrm{kWh}}/_{\mathrm{kgal}}$$

3.3.2 Landfill Disposal and Evaporation Ponds

Regardless of the area needed, regulations provided by the EPA Resource Conservation and Recovery Act Regulations (RCRA) must be followed. Under Subtitle D of RCRA, it is stated that each state is responsible for meeting these requisites and could incorporate its criteria. The location of a landfill must be away from any wetlands, faults, or flood plains. Two feet of compacted clay soil overlaying the landfill's bottom and sides to protect the underlying soil and groundwater is required. Any leachate collection must be removed for proper disposal, and once the landfill is ready for closure, it must be covered. For environmental protection, funding must be available for monitoring and clean-up during and after landfill closure.

For evaporation ponds, the Texas Land Application Permit program regulates discharges that affect waters indirectly. This permit requires test results, dimensions, leak detection, outfall information, engineering report, pollutant analysis, and other site-specific information. The Texas Commission on Environmental Quality (TCEQ) expects additional requirements on environmental quality. Determining the size of the pond should consider the rainfall and evaporation rates. According to the Water Data for Texas, the minimum monthly evaporation rate (v_{evap}) for El Paso over the period of 1954-2021 is approximately $2\,\frac{in}{month}$ (*Water Data for Texas: Lake Evaporation and Precipitation*, n.d.). Following the formula below, an area of 1,155 ft^2 would be required to manage the concentrate flow from the RO system. Evaporation ponds are also affected by relative humidity, water pressure, wind velocity, barometric pressure, and the salt content present (Crittendenn et al., 2012).

Eq. (3) $$A = \frac{Q}{v_{evap}} = \frac{\left(1\,{}^{\mathrm{gal}}/_{\mathrm{min}}\right)\left(1440\,{}^{\mathrm{min}}/_{\mathrm{day}}\right)\left(31\,{}^{\mathrm{day}}/_{\mathrm{month}}\right)\left(12\,{}^{\mathrm{in}}/_{\mathrm{ft}}\right)}{\left(2\,{}^{\mathrm{in}}/_{\mathrm{month}}\right)\left(7.48\,{}^{\mathrm{gal}}/_{\mathrm{ft^3}}\right)} = 1{,}155\ \mathrm{ft}^2$$

The acceptable liners are clay thickness (in situ or constructed) which must be at least three feet thick or synthetic liner (plastic or rubber). The location must be at least 100 feet from the state's surface water. It must be 500 feet from a public water supply well and 150 away from a private one. A report regarding soil sampling, the quantity of solid and liquid waste removed, and quality control should be provided for closure.

Every five years, solids must be measured by volume and recorded. Any solids removed from the evaporation ponds must abide by the Industrial Solid Waste and Municipal Hazardous

Waste. If the criteria are not applicable, it must follow the Texas Health and Safety Code, Solid Waste Disposal. (Texas Commission on Environmental Quality, 2022).

3.3.3 EVAPORATION

As previously mentioned, ponds are used for evaporation. However, there are different processes to increase evaporation rates. Aeration and air stripping affect evaporation. Aeration consists of adding air into water by diffusion in a pipe or basins, cascading water, or surface turbines (Crittenden et al., 2012). Air stripping is the removal of gases from water through towers or aerators. Increasing air-water contact makes volatile chemicals move faster from the water to air or gas. Although aeration and air stripping can improve evaporation rates, other factors can affect it. Evaporation increases as relative humidity decreases, temperature increases, and the amount of salt in the brine decreases (Qu et al., 2020). Relative humidity refers to the amount of water vapor in the air and affects a substance's chemical and physical properties. Temperature affects relative humidity, the lower the temperature, the higher the relative humidity. For this scenario, 20% and 90% relative humidity were considered due to the range of temperature experienced in El Paso. A 70˚ F (21˚C) was considered for the air density to measure the amount of power needed for the brine evaporation.

Eq. (2) $$\dot{m} = Q\,\rho = \frac{8.34\,{}^{\mathrm{lb_m}}/_{\mathrm{gal}}}{(.014\,{}^{\mathrm{lb_{H_2O}}}/_{\mathrm{lb_{air}}} - .003\,{}^{\mathrm{lb_{H_2O}}}/_{\mathrm{lb_{air}}}} = 758\ {}^{\mathrm{lb_{air}}}/_{\mathrm{min}}$$

Eq. (4) $$Q_{air} = \frac{m_{air}}{\rho_{air}} = \frac{758\ \mathrm{lb}\ {}^{\mathrm{air}}/_{\mathrm{min}}}{.075\,{}^{lb}/_{ft^3}} = 10{,}110\ {}^{\mathrm{ft}^3}/_{\mathrm{min}}$$

At 20% relative humidity: $\frac{0.003\ lb\ H_2O}{lb\ dry\ air}$

At 90% relative humidity: $\frac{0.014\ lb\ H_2O}{lb\ dry\ air}$

Assuming a P= of 5psi

$$P = Q * \ Press = 162 \text{ kW}$$

Which can be converted to $\text{kWh}/_{\text{kgal}}$ by the following conversion:

$$\left(\frac{162 \text{ kW}}{1 \ \text{gal}/_{\text{min}}}\right)\left(\frac{1000 \text{ gallons}}{\text{kgal}}\right)\left(\text{hr}/_{60 \text{ min}}\right) = 2{,}700 \ \text{kWh}/_{\text{kgal}}$$

4. Conclusion

Due to the current water scarcity affecting the world, finding alternatives to provide clean and safe water for all becomes increasingly important. Direct potable water reuse (DPR), where municipal wastewater is treated for potable purposes, provides water supply flexibility as water travels a shorter distance and is not affected by outside sources. Implementing DPR in inland communities mitigates future drought and climate change issues. This research intended to analyze DPR's feasibility by demonstrating high recovery and ZLD operations. In the pilot study, located at the John T. Hickerson Water Reclamation facility in El Paso TX. The objectives of this study were to optimize the chloramination dosing, operationalize the ultrafiltration (UF) system and backwashing, and to explore zero liquid discharge (ZLD) options.

Although a set of LAS and bleach dosing would typically result in a specific Cl: N ratio to form monochloramine, this was not achieved due to the varying concentration of free ammonia present in the influent. With set points of LAS pump at 13% and the bleach pump at 80%, monochloramines will form, total chlorine residual will increase, and a negligible amount of free chlorine will be present with low concentrations of free ammonia.

When comparing tap water and treated water, it is evident to see the difference in dosing set points due to the difference in water type. However, it is essential to understand that the variation of free ammonia present in the treated wastewater will affect monochloramine formation. However, for future research, it is important to log the incoming free ammonia to help adjust these doses as needed.

Due to the issues faced during the project duration, the ultrafiltration system could not run at steady specific flux. Several significant fouling events were observed, but backwashed and chemical cleaning were sufficient to recover flux. In future research, to achieve a better specific flux, starting at lower flux and increasing it by smaller intervals as the system could be effective.

With the samples gathered at three different points of the system (influent, UF feed, and UF filtrate), water quality analyses were performed on-site and at the laboratory. Although several results were not within EPA limits, no elements of concern were present in the water. It is important to note that the UF effluent is pretreatment, and RO, UV-Peroxide, GAC, and CERRO will enhance the water quality.

Consequently, decreasing the amount of brine is essential for simplified management. While the system has not reached a testing stage for ZLD, three different options were analyzed last steps of achieving ZLD: heated screw conveyor, landfill disposal and evaporation ponds, or pneumatic evaporation. Energy estimates for the heated screw conveyor pneumatic evaporation options were similar at approximately 160 kW for evaporating 1 gal/min of CERRO superconcentrate, and the area estimated for the evaporation ponds was approximately 1160 ft^2.

Although DPR is a promising way to mitigate water scarcity, more research at a pilot scale is needed. This research presented many issues, most from troubleshooting and outside factors; however, as the data presented is only for pretreatment for RO the viability of achieving high recovery is still possible. Future research for this project scope includes the stabilizing specific flux in the UF system and once achieved, running of the RO, UV-Peroxide, GAC, CERRO system, and ZLD.

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Vita

Marcela C. Herrera Alvarez was born in Cd. Juarez and grew up in the El Paso-Juarez area. She earned her Bachelor of Science degree in Geological Sciences in December 2019 at the University of Texas at El Paso (UTEP). During her undergraduate, Marcela maintained a student assistant job on campus and conducted research with Dr. Jason Ricketts on the "Petrographic Analysis of a Clastic Dike Cutting the Castner Marble, Franklin Mountains" research project. During the 2020 Spring semester, Marcela began pursuing her master's in science degree in Environmental Engineering and working at the Center for Inland Desalination Systems (CIDS). She became the lead student in the research project "All of the Above and Kitchen: Sink Zero Liquid Discharge Desalination for Direct Potable Reuse" funded by the U.S Bureau of Reclamation, under Dr. Shane Walker's and Joe Feuille's supervision. Marcela is currently working as an Engineer Intern with Garver in El Paso, Texas where she is expected to take a full-time position upon graduation.