Potable Water Reuse in Massachusetts

A Major Qualifying Project
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Acronyms

USEPA *United States Environmental Protection Agency*

MassDEP *Massachusettes Department for Environmental Protection*

CDC *Center for Disease Control*

DPR *Direct Potable Reuse*

IPR *Indirect Potable Reuse*

RO *Reverse osmosis*

MF *Microfiltration*

UF Ultrafiltration

NF *Nanofiltration*

CSO *Combined sewage overflow*

SWI *Sea water intrusion*

BOD

N *Nitrogen*

P *Phosphorus*

WWTP *Wastewater Treatment Plant: This treats wastewater before it is discharged.*

WTP *Water Treatment Plant: This treats drinking water before it is delivered to homes*

CECs *Contaminants of Emerging Concern*

PFAS *Per- and Polyfluoroalkyl Substances*

PPCPs *Pharmaceuticals and Personal Care Products*

DBPs *Disinfection By-products*

Abstract

The standard wastewater treatment process in the U.S. comprises of primary, secondary, and tertiary treatments, each targeting different contaminants with the end goal to discharge into the environment. My projects goal was to design a wastewater treatment system for direct or indirect potable water reuse, utilizing reverse osmosis (RO) membranes. Direct potable reuse (DPR) and indirect potable reuse (IPR) both purify wastewater for beneficial use, with IPR using environmental buffers for further purification and DPR storing the treated water until it is transported to a water treatment plant (WTP). Our objectives were to evaluate technologies to remove contaminants (such as CECs, Nitrogen, Phosphorus, and BOD), review state and federal water reuse guidelines, and developing a small-scale design.

The U.S. EPA guidelines and standards for potable reuse outline the importance of risk assessment and management in project development, mitigation concepts to ensure the safety and effectiveness of potable reuse projects, and treatment objectives and processes for groundwater injection. Advanced monitoring techniques are highlighted as crucial for ensuring the effectiveness of potable reuse systems. MassDEP and the U.S. EPA regulate wastewater reclamation. While MassDEP has approved several reuse projects, it only permits the usage of reclaimed water for non-potable purposes like irrigation and industrial use. Despite explicitly stating potable reuse is prohibited, MassDEP allows reclaimed water to be used for aquifer recharge at protected well heads that are or could be considered drinking watersources.

Case studies evaluating operational potable reuse schemes were reviewed to evaluate successful methods used to protect the community and meet federal regulations. We reviewed the IPR plant in Orange County, California, the DPR system that was converted to IPR in Wichita Falls, Texas, and the first-ever operational DPR system in Windhoek, Namibia. These cases highlight the different approaches available and the effectiveness of potable reuse systems when addressing water scarcity, reoccurring contamination, and creating water sustainability. Each strategy is tailored to the specific needs and challenges of the respective regions, showing the importance of adaptable and innovative solutions in water resource management.

Executive Summary

The standard wastewater treatment process in the U.S. comprises primary, secondary, and tertiary treatments, each targeting different contaminants. Despite these treatments, wastewater doesn't meet drinking water standards. My project aimed to design a wastewater filtration system for direct or indirect potable reuse, utilizing reverse osmosis (RO) membranes. My objectives were to evaluate technologies to remove contaminants, reviewing guidelines, and developing a design. Direct potable reuse (DPR) and indirect potable reuse (IPR) both purify wastewater for potable use, with IPR using environmental buffers for further purification and DPR storing water until transported to a water treatment plant (WTP). DPR requires additional disinfection due to a lack of environmental buffers. Both systems require rigorous testing and action plans for process failure. Communities invest in potable reuse due to climate change impacts like droughts, floods, and seawater intrusion (SWI). Massachusetts faces challenges such as drought-induced CSO flooding and SWI due to climate change, prompting policymakers to address these issues through infrastructure upgrades and regulatory measures.

My project discusses the regulations and considerations surrounding water reuse schemes. Wastewater reclamation is regulated through MassDEP and the U.S. EPA. While MassDEP has approved several reuse projects, it currently only permits reclaimed water for non-potable purposes like irrigation and industrial use. Although MassDEP do not allow for potable reuse yet, their regulations allow for reclaimed water to be used for aquifer recharge near protected well heads. Aquifer recharge is regulated under the Underground Injection Control (UIC) program, emphasizing the importance of protecting underground water sources from contamination.

Furthermore, the U.S. EPA guidelines and standards for potable reuse outline the importance of risk assessment and management in reuse project development. Mitigation concepts such as multi-barrier systems, reliability, and system coupling are explored to ensure the safety and effectiveness of potable reuse projects. Treatment objectives and processes for groundwater injection are outlined, including using environmental and engineered buffers to maintain water quality standards. Advanced monitoring techniques are highlighted as crucial for ensuring the effectiveness of potable reuse systems.

All water treatment facilities should address the potentially harmful contaminants in wastewater. This project focuses on Contaminants of Emerging Concern (CECs) such as per- and Polyfluoroalkyl Substances (PFAS), Pharmaceuticals and Personal Care Products (PPCPs), Disinfection By-Products (DBPs), and organic contaminants like nitrogen and phosphorus. It should be noted that most CECs have many potential risks, as their impact is widely uncertain due to limited data from little to no research and other factors. Addressing these contaminants in Wastewater is important to safeguard human and environmental welfare.

PFAS, also known as "forever chemicals," pose risks to human health and the environment due to their persistence and widespread use in various products. They contaminate water supplies through industrial discharge, nonstick pans, and other household items. Studies on the health effects of PFAS exposure indicate potential risks such as developmental issues, reproductive problems, and impacts on Thyroid function and the immune system. Additionally, PFAS bioaccumulate in soil and wildlife, increasing exposure risks.

PPCPs, enter the environment and water supply through many different exposure pathways like, the various uses by humans, animal consumption, and improper disposal methods. The health and environmental risks associated with PPCPs vary depending on the type and dosage. With many falling into the endocrine disruptor compounds (EDC) category, they can potentially affect hormone functions in humans and animals. Research suggests that exposure to these PPCPs can lead to various effects, including changes in estrogen levels and reproductive issues.

DBPs are formed during the disinfection process in water treatment facilities and pose health risks to humans. They are regulated, but some less-known DBPs may be more toxic when exposed to humans. High exposures to DBPs can affect human health, causing diseases in the central and reproductive systems. Additionally, DBPs can have environmental effects, such as altering microbial communities in water bodies.

Organic contaminants like nitrogen and phosphorus enter the environment through fertilizer runoff, sewage discharge, and other sources. Excessive nutrient pollution can severely impact aquatic ecosystems, including algae blooms and oxygen depletion. Algae toxins can harm wildlife and humans, causing stomach issues, memory loss, and other illnesses. Nutrient pollution also has significant economic impacts, affecting industries like tourism and commercial fishing and increasing water treatment costs.

The three cases presented below were reviewed to follow the guidance of professional engineers and their solutions for potable wastewater reuse. These cases highlight the different approaches available and the effectiveness of potable reuse systems when addressing water scarcity and creating water sustainability. Each approach is tailored to the specific needs and challenges of the respective regions, showing the importance of adaptable and innovative solutions in water resource management.

1. Orange County, California IPR:

Context: The Orange County Water District (OCWD) initiated water recycling in 1975 to combat seawater intrusion. Water Factory 21's success led to the expansion of water reuse projects in the early 1990s, and today, it is known as the world's largest water reuse facility. The IPR system has reached a record-breaking clean water production rate of 130 MGD.

Treatment Process: The OCWD's water treatment train involves pre-purification, primary treatment, secondary treatment, microfiltration (MF), reverse osmosis (RO), and UV disinfection. This multi-step process removes suspended solids, microorganisms, dissolved chemicals, and organic compounds.

Regulatory Compliance: The project adheres to regulations regarding minimum retention times, separation distances, and monitoring of Contaminants of Emerging Concern (CECs) such as Endocrine-Disrupting Compounds (EDCs) and Pharmaceuticals and Personal Care Products (PPCPs).

2. Wichita Falls, TX USA:

Context: Facing severe drought, Texas County explored potable reuse options starting in 2012. A Direct Potable Reuse (DPR) system was initially proposed but rejected in favor of an Indirect Potable Reuse (IPR) system. However, the demand for a quick solution led to Governing Officials allowing for the development of a temporary DPR system. Windhoek's DPR system has been operational for decades, providing safe drinking water to its population despite challenging environmental conditions.

Treatment Process: The DPR project involves conventional wastewater treatment followed by MF, RO, and UV disinfection, which was added to ensure the removal of protozoan pathogens.

Regulatory Compliance: Before any treated water can be sent to the conventional WTP, effluent analysis must verify that the treatment train meets drinking water regulations, specifically those focusing on contaminants like nitrate, trihalomethanes (THMs), and microbial pathogens.

3. Windhoek, Namibia:

Context: Windhoek, facing water scarcity magnified by the area's natural desert conditions, implemented a DPR system in 1969, becoming the world's first city in the world to rely on potable reuse. Windhoek's DPR system has been operational for decades, providing safe drinking water to its population despite challenging environmental conditions.

Treatment Process: The DPR system employs a multi-barrier approach, including conventional wastewater treatment, ozonation, enhanced coagulation, flocculation, dissolved air flotation (DAF), dual media filtration, ozonation, biological activated carbon filtration, granular activated carbon (GAC) filtration, ultrafiltration (UF), and chlorination.

Regulatory Compliance: Extensive water quality monitoring ensures the safety of the recycled water, acting as a non-treatment barrier to protect public health.

Each method used in the case studies have advantages and challenges, and the selection depends on factors such as the specific contaminants present in the area, treatment efficiency, cost, and environmental impacts. For this project, we only focused on four types of treatments that we anticipate using for the final treatability apparatus, such as Soil Aquifer Treatment, UF/MF Membranes, RO Membranes, and GAC filters.

Soil Aquifer Treatment (SAT) has been a standard method employed in potable reuse projects. However, emerging contaminants like PFAS and PPCPs have now questioned the safety of using this method. While SAT can temporarily filter some contaminants, concerns arise regarding the potential for aquifer contamination over time; this method runs the risk of these contaminants accumulating in the soil and eventually leaching into the drinking water aquifer, posing risks to water quality. As such, SAT may not be the most suitable method for effectively addressing the removal of specific emerging contaminants.

Ultrafiltration (UF) or Microfiltration (MF) as pretreatment is crucial for ensuring the effectiveness, sustainability, and redundancy in potable reuse projects. These membranes can effectively remove suspended solids and particulates, in addition to partial removal of phosphorus, nitrogen, and total organic carbon, depending on the phase. UF membranes have smaller pores (0.1-0.01 microns) than MF membranes (1.0-0.1 microns), but both are equally effective at protecting the RO membrane. However, the difference in pore size offers a slight advantage to the UF membrane when removing finer particles, bacteria, and viruses. This pretreatment helps reduce costs, improve flux rates, and enhance RO effluent quality, making RO systems more efficient and cost-effective.

Reverse Osmosis (RO) is the most common and effective method for potable reuse. RO membranes have exceptionally small pores to remove contaminants from water. It is highly efficient in removing salt ions, particles, organics, bacteria, pathogens, TOCs, and TDSs. RO is particularly effective in treating CECs like PFAS, with removal rates ranging from 83-99.9%. However, one challenge associated with RO is the production of brine, which requires proper disposal to prevent environmental harm. Despite this drawback, RO is mandated by California reuse regulations due to its effectiveness in meeting low TOC contaminate limits.

Granular Activated Carbon (GAC) filtration is mainly used in potable reuse projects in regions like the Eastern U.S. It is known for its effectiveness in removing a broad range of contaminants, including TOC, TDS, PFAS, and PPCPs. GAC has been favored because of its cost-effectiveness, low energy demand, and ability to meet federal discharge limits based on COD testing easily. It should be noted that these limits are higher than California's state regulations. Additionally, minimizing organic matter is crucial to optimize its effectiveness as it will compete with CECs and lower removal rates. Studies show GAC's efficacy in removing PFAS has been relatively low with removal rates ranging from 65% to 99%.

My research suggested that Reverse Osmosis (RO) and Granular Activated Carbon (GAC) are effective methods for potable water reuse, especially if used together. This combination can enhance the removal of contaminants like PFAS and PPCPs. The proposed treatment system involves a treatment train that includes a UF membrane followed by RO and then a GAC filter. The UF membrane is from DuPont's TapTec™ P Ultrafiltration PES Module, which has operational guidelines to prevent membrane damage and ensure effective treatment. The RO process involves DuPont's FilmTec™ TW30-1812-50 HR RO Element, with recommendations to optimize design for efficiency and reliability. Flow rates for both UF and RO processes are calculated for the bench-scale system design. These calculations ensure turbulent flow and proper system operation. Additionally, pump power requirements are estimated based on system parameters provided by DuPont. The materials list includes necessary components such as pumps, pipes, tanks, and valves for the proposed treatment system. Determining the GAC filter and type of disinfection process was outside the scope of the project.

Introduction

Wastewater treatment has standard treatment techniques used across the U.S. to purify water so it can be discharged into nature without adverse health or environmental impacts. There are three stages of treatment for wastewater travel through to meet the U.S. EPA standards before discharge. The first stage, defined as Primary Treatment, removes large objects in the water that could damage the pipes. Secondary treatment is the next stage, which uses biological means to remove the organic materials. In the final stage, the water is disinfected, most commonly executed by chlorine to remove inorganic matter, bacteria, and viruses. Despite these treatment steps, the wastewater is still not up to par with drinking water standards set by the U.S. EPA.

This project aimed to create a conceptual wastewater treatment system designed for direct potable reuse (DPR) or indirect potable reuse (IPR). The system will use a reverse osmosis (RO) membrane, which is assumed to purify water to a quality drinking standard. The main objectives of this project were to:

A. Evaluate the different technologies to use in unison with an RO membrane to remove all concerning contaminates.
B. Review all potable reuse guidelines from U.S. EPA and MassDEP
C. Develop a preliminary reuse design.

A few different membrane technologies can be used with the RO membrane to purify wastewater for potable reuse. This project investigated what treatment processes should be used with the RO membrane to address residual contaminants and protect the membrane from clogging or breaking.

Many communities in the Midwest and West Coast have successfully implemented direct and indirect potable reuse systems to meet their community's water demand. Each project has had to prove risk management and risk mitigation plans to their governing officials and present them to the U.S. EPA. All potential potable reuse projects build pilot-scale systems relative to the full-scale system and test the design's water quality and reliability under normal operating conditions. I investigated four types of contaminants because of their significance in wastewater. These contaminants of concern are PFAS, PPCPs, DBPs, and natural organic matter (NOM) such as Nitrogen (N), phosphorus (P), and

BOD. A detailed contaminate analysis will be outside this project's scope, but it should be conducted if a community wants to move forward with an IPR or DPR project.

What is IPR and DPR?

Figure 1: Indirect Potable Reuse (IPR) process

These two wastewater recovery strategies treat and purify sewage water for potable reuse. Each of the strategies has the same goals for wastewater recovery, but they have different safety precautions. Both IPR and DPR systems undergo a conventional treatment train, advanced filtration methods such as Microfiltration (MF)/Ultrafiltration (UF) membrane and an RO membrane, followed by an advanced disinfection process such as UV or Ozonation (O3). IPR wastewater treatment plants (WWTP) discharge tediously treated wastewater into environmental buffers such as lakes, rivers, dams, and aquifers. Each buffer provides additional purification processes, depending on the buffer. These purification processes include dilution with natural water, filtration, photolysis from sunlight, or biological degradation by native microorganisms (Jeffrey et al., 2022; Rodríguez et al., 2009). WWTP stores freshly treated water at the plant before discharging it to buffers, allowing for final testing to detect treatment failure and either stop the delivery of the water or start corrective measures to protect the community from contaminants. Despite the intensive treatment process of wastewater recovery, once discharged into the environment, it still needs further treatment at a water treatment plant (WTP). **Figures 1** and **2** Show the steps taken in the IPR and DPR treatment processes, respectively.

DPR has a similar approach to IPR, except instead of using an environmental buffer, the water is stored until it is ready to be transported to a WTP. Because DPR processes don't rely on an environmental buffer to continue the purification process, a supplemental process needs to be added (Jeffrey et al., 2022). DPR treatment trains include an additional disinfection process in combination with at least two types of disinfectants, such as UV, Chloride, and O3 (Jeffrey et al., 2022). UV is a powerful disinfectant; however, unlike O3 and Chloride, UV does not leave a residual in the water. For this reason, UV is typically used in sequence with Chloride or O3. Residual disinfectants protect the treated water within the storage tanks while they wait to be transported directly to a WTP. While the treated water waits for the residual disinfectant to do its job before being delivered to a WTP, the facility must test for treatment failure. Like an IPR system, DPR systems require action plans in case of process failure. Local and Federal policymakers have developed regulations and guidelines that will be discussed later on to ensure public welfare while designing water reuse facilities.

Figure 2: Direct Potable Reuse (DPR) Process

Why Have U.S. Communities Invested in Potable Reuse?

Massachusetts has been experiencing erratic climate changes as seasonal droughts increase and summertime temperatures rise. 2023 has been deemed the hottest year on record, with an average temperature increase of 2 degrees F globally. The heat escalated wildfires and contributed to severe rainfall in several countries (NASA, 2023). Recently, 94% of Massachusetts suffered from a level four drought during the summer of 2022 until January of 2023 (Town of Newbury, 2023). Early in August, reservoirs were noted to have decreased water levels, and stream beds had dried up. As the year progressed, the heat waves continued to worsen the state's drought warnings despite rainfall being observed. Although rainfall is hoped for during a drought to relieve the stress on water supplies, it can introduce other issues.

When areas experience long-term extreme heat followed by intense rainfall, the ground's inability to absorb the water creates a risk of flooding. Flooding can cause numerous issues for water supplies, such as runoff contamination and flooding. Flooding has become more frequent in Massachusetts, and overflowing sewer systems have brought a frightening risk to water supplies and public safety. Massachusetts has several combined sewage overflow systems (CSOs) that are exacerbating these concerns. These systems were built over a century ago and are not built to handle the load of recent rainfall and the growing population's wastewater. CSOs were designed to discharge sewage and runoff into the nearest body of water in case the system is overloaded to avoid backups in homes and businesses (BU News Service, 2023). In 2023, 1,943 sewage overflows were reported, not including the sewage water that was released into nearby bodies of water. Some Massachusetts communities face the crisis of sewage flooding whenever it rains (Wasser, 2023). Lawmakers have acknowledged the issues and are working towards replacing the remaining CSOs in Massachusetts. Although bringing these systems to modern standards will be expensive, the reward outweighs the economics (Wasser, 2023; BU News Service, 2023, November).

Another issue many coastal communities are facing due to climate change is Sea Water Intrusion (SWI). SWI is when salt invades and contaminates a community's freshwater aquifer. When this happens, the community suffers from water shortages due to water contamination, and in severe cases, the wells will be shut down entirely. This can sometimes be caused by wells pumping too close to the interface between freshwater and saltwater, sometimes referred to as the transition zone (Water Resource Mission Area, 2019). The rise in sea level can also cause the water table and transition zone to shift, changing the depth of the pump and creating the possibility of saltwater contamination. Another familiar issue that will cause SWI is weather factors such as increased frequency and intensity of rainfall and droughts. These factors affect the aquifer's transition zone, leaving the community with low-quality brackish water (Panthi et al., 2022). MassDEP and state officials are also working with the EPA to develop wastewater discharge strategies and regulations to relieve growing struggles with SWI.

Regulations

State and Federal Regulations can have different requirements for water quality standards. If there is any difference between the regulations, the state regulations typically have more rigid requirements for the health and safety of the communities. Considering there will be some variation in the requirements for a potable reuse scheme, both were reviewed to determine what water quality standards our system will need to meet for an IPR or DPR bench-scale system.

MassDEP

MassDEP has approved nearly a dozen reuse projects. Currently, they are only allowing reclaimed water reuse. MassDEP allows for reuse in toilet and urinal flushing, boiler feeds, industrial purposes, irrigation for landscaping, cooling, wetland creation, and aquifer recharge (CMR 20.06). Under this regulation, it is stated that "*Reclaimed wastewater may be used for aquifer recharge by discharging reclaimed wastewater to the ground within the Zone II or Interim Wellhead Protection Area of a public water system or a Private Water Supply Area.*" Projects that use the highly treated wastewater for aquifer recharge must apply for a permit with the state under the 314 CMR 5.00 permit regulations. Wastewater has been approved to be treated for reuse in communities, but it is not intended to be reused as drinking water (Mass.gov). MassDEP regulates reclaimed water through various regulations through the Division of Water Pollution Control 314 CMR 20.00 - Reclaimed Water Permit Program and Standards outlines the requirements specific to Massachusetts. Regulation 314 CMR 20.04 requires all state-permitted reuse facilities accessible to the public to provide signage that states the water is not intended for potable use.

Although it says that reclaimed wastewater may be used for aquifer recharge, MassDEP has not yet given the green light for potable reuse, nor have they explicitly expressed interest in this potential use for reclaimed wastewater. The 314 CMR 20.06 strictly states that reclaimed wastewater can not be used, discharged, or distributed in any way that could cause any public or private water source to violate Massachusetts Drinking Water Regulations. The regulations also state that reclaimed water can not be discharged into the ground if it violates Surface Water Quality Standards or impacts a potential potable water source. The nearly conflicting regulatory requirements for water reclamation compared to the definition of IPR drive my belief that the Massachusetts government could be open to potable reuse when an effective treatment system is proven. Essentially, Massachusetts Legislators are regulating aquifer recharge under the guise of it not being intended for potable reuse but understanding it will more than likely unintentionally end up in a drinking water source. It should be noted that Massachusetts is regulating wastewater reuse to avoid contaminating drinking water sources with PFAS and PPCPs. Considering these regulations, we investigated some of the Underground Injection Control (UIC) program regulations that all groundwater injection wells must follow.

The UIC program is regulated under 310 CMR 27.00 and authorized by the Safe Water Drinking Act. An aquifer recharge is regulated as a Class V injection well (MassDEP, n.d.-a). The 310 CMR 27.00 regulation aims to protect underground drinking water sources or anything that could become a potable water source from contamination. The regulations strictly prohibit the use of an injection if there is any possibility of it contaminating an aquifer or a portion of the aquifer (310 CMR 27.04). MassDEP holds the right to enter the premises of any injection well or its record facility at any time to ensure the facility is fulfilling all obligations by an inspection, water quality testing, and data analysis. This regulation requires the owner of an injection well to report all construction and operation information and records available to MassDEP. It must have all records up to three years minimum. (310 CMR 27.13). Additionally, **Table 1** includes MassDEP's contaminated discharge limits for a Class V UIC that should be considered for any municipality considering a potable reuse via aquifer recharge.

EPA Guidelines and Standards For Potable Reuse.

For projects being designed for any type of water reclamation, there should be a risk assessment that will develop an understanding of what contaminants will be present in the raw wastewater. A Risk Assessment is a formal process driven by qualitative and quantitative data about the chemicals and pathogens present in raw sewage. The information found will help estimate the probability and severity of potential exposures. Not only should the assessment include all of the information obtained regarding target chemicals and chemicals and pathogens present, but they should also acknowledge missing information that may affect the information provided (EPA Compendium, 2017). The assessment will help project developers design the IPR or DPR system to support the system load capacity, provide system redundancy, and provide effective treatment monitoring for trusted water quality. The EPA is working with other Water environments, nonprofits, and foundations to continue to refine protection procedures for potable and de facto reuse. (EPA Compendium 2017).

Another critical task for potable reuse project development is Risk Management. The management efforts for DPR and IPR systems decide how to address the potential risks best and consider many different factors (e.g., legal, economic, ecological, behavioral factors, and human and environmental welfare). The EPA Risk Characterization Handbook describes the factors for potential risk as follows:

> "*1. Scientific factors provide the basis for the risk assessment, including information drawn from toxicology, chemistry, epidemiology, ecology, and statistics. Factors of age, sex, race, etc. fall into this category.*
>
> *2. Economic factors inform the manager on the cost of risks and the benefits of reducing them, the costs of risk mitigation or remediation options, and the distributional effects.*
>
> *3. Laws and legal decisions are factors that define the basis for the Agency's risk assessments, management decisions, and, in some instances, the schedule, level or methods for risk reduction.*
>
> *4. Social factors, such as income level, ethnic background, community values, land use, zoning, availability of health care, lifestyle, prevalence of underlying health conditions, and psychological condition, may affect exposure to and/or susceptibility of individuals or groups to a particular stressor, leading to greater health risk.*
>
> *5. Technological factors include the feasibility, impacts, and range of risk management options.*
>
> *6. Political factors are based on the interactions among branches of the Federal government, with other Federal, state, and local government entities, and even with foreign governments; these may range from practices defined by Agency policy and political administrations through inquiries from members of Congress, special interest groups, or concerned citizens.*
>
> *7. Public values reflect the broad attitudes of society about environmental risks and risk management.*" (EPA Compendium, 2017)

Considering how a Potable Reuse system would affect social, economic, and environmental factors and address potential concerns in the project's risk management plan shows policymakers and the EPA that an adequate action plan was developed. Furthermore, the EPA has recommended vital concepts for risk mitigation to benefit the development of a potable reuse project.

Mitigation Concepts

Risk mitigation concepts were developed to safeguard consumer and environmental well-being. The first important concept for risk mitigation is the proper use of a **Multi-Barrier System**. It intends to ensure that a single step is not responsible for meeting the target water quality standards (EPA Compendium, 2017). By implementing a multiple barrier system, potable reuse projects can lower the likelihood of treatment failure, protecting public health by adding redundancy. Numerous steps in the treatment train should be able to remove the contamination, and some steps should overlap with other steps to effectively receive the most significant chance for complete removal and inactivation. Not only should several steps in the treatment train work to address the same contaminates, but there must be multiple places in the system to monitor the system's effectiveness.

Regulators use a removal monitoring method referred to as a log removal value (LRV) to verify the proposed treatment process. LRVs are given to individual treatment approaches based on their ability to remove and/or inactive pathogens. Each state may have a different LRV minimum requirement depending on the raw water quality and what is best for their community. Typically, the log removal value is set to the highest degree for a reuse system to ensure that reuse facilities aim for the minimal chance of system process failure. Multibarrier systems and aggressive LRV values give potable reuse projects a reputation of consistency, showing communities and governing parties the system's reliability.

The EPA defines reliability as "*A measurement of the ability of a component or system to perform its designated function without failure.*" **System Reliability** has been an essential requirement for WWTP since 1974 when federal funding became available to update wastewater infrastructure. When discussing potable reuse and WWTPs, it is crucial for the entire system, as well as each step in the treatment train, to be reliable and deliver safe drinking water to consumers. Public and government acceptance will be lost without the knowledge to secure this requirement. The best way to prove the reliability of a treatment process is to constantly monitor the water quality as it goes through the system and once treatment has been completed. Although monitoring various steps will help detect malfunctions or failures, it does not address why a fully functional system has fluctuations in quality.

Some things that influence the reliability of a potable reuse system are the fluctuation in the wastewater effluent, variations of biological and advanced treatment steps, and operator reliability. Fluctuation in the effluent can be managed by creating wastewater effluent control programs. The programs will limit the amount of toxic substances entering the system before treatment, reducing the likelihood of effluent fluctuation. Several factors can cause variations in the biological and advanced treatment processes, but they are specific to the technology used. For example, in pilot-scale models using powdered activated carbon (PAC) as an adsorbent, organic matter in the water competes with the

PPCPs for the binding sites on the PAC. Lowering its ability to remove the expected amount of PPCPs and other organic matter. The efficiency of the removal can also be affected by factors such as the contact time, pH, and the structure of the activated carbon (Wang, J., & Wang, S. 2016). Operator reliability could be detrimental to the effectiveness of a system if not managed properly.

The last concept briefly discussed for safe potable reuse practice is System Coupling, which analyzes the dependency of one treatment step on another. Two types of coupling were described within a treatment project: tight and loose. A tightly coupled system will need help to produce quality water during a process failure or maintenance repair. Consider an RO membrane. If the membrane were the only technology in the system that could remove protozoa, there would be catastrophic repercussions if the membrane broke or whenever the membrane needed to be replaced. For this reason, engineers favor loosely coupled systems because it has the highest probability of the system's success.

Treatment Objectives and Processes for Groundwater Injection

The EPA guidelines outline five main objectives potable reuse projects should address when treating raw wastewater. Each treatment train is unique, designed specifically for the site's influent raw sewage constituents under local and federal regulatory requirements. The treatment train must address removing suspended solids, dissolved chemicals, disinfection, water stabilization, and aesthetics. Each treatment process can earn log removal credits (LRC) depending on how many microorganisms and viruses are removed or inactivated. **Table 2** can be found at the end of this paper to outline what process can accomplish each objective. Potable reuse systems follow a standard WWTP and advanced treatment processes such as MF or UF, RO, and Advanced Oxidation Processes (AOP). UF/MF followed by RO membranes is the generally accepted advanced treatment method in potable reuse treatment trains. RO systems have a significant recovery rate of 85 to 90 percent, especially with detailed source control regulations in place. After the raw wastewater is treated, potable reuse projects have different buffers they can use in between the Advanced Wastewater Treatment Plant (AWWTP) and the conventional WTP.

Environmental buffers are one option for AWWTP because they can remove additional contamination. Aquifer recharge can be an effective natural treatment option if the feed water is high quality. Coastal regions inject the highly treated wastewater into aquifers to reduce SWI as sea levels rise and water tables shift. Considering MassDEP regulations for reclaimed wastewater, we will only explore the EPA's guidance for aquifer recharge. It can also be referred to as Aquifer Storage and

Recovery (ASR) or Soil Aquifer Treatment (SAT) in a potable reuse or water reclamation context. Full LRC for viruses, giardia, and cryptosporidium can be earned from aquifer recharge if the highly treated water is sent through surface spreading. This is a slow process with a minimum of 6 month travel time. In contrast, direct injection projects receive no LRCs for Giardia or cryptosporidium. But it can receive 1 LRC per month for viruses, maxing at 6 LRC. A direct injection approach would need a minimum travel time of 2 months. ASR projects require EPA underground injection control (UIC) permits. **Table 3** in **Appendix A** briefly discusses the techniques and water quality requirements to meet permit standards. Although environmental buffers are beneficial, they are not required for potable reuse projects and can not always guarantee water quality or performance standards.

Engineered buffers or *DPR* systems are not the most commonly used. However, they allow a reuse project to evaluate the water's quality before discharging to a traditional WTP. Engineered storage buffers (ESB) have the advantages of complete control over the ESB environment, contaminate monitoring, and limiting the natural contaminants that could be found in an environmental buffer. ESB structures are more expensive and require additional treatment methods to compensate for the natural processes lost from lacking an environmental buffer. They need consistent monitoring for quick response times in case of treatment failure. Standard monitoring systems have a failure response time (FRT) of 24 hours minimum, while some advanced monitoring techniques have an FRT for bacteria down to minutes and protozoa to hours. Advanced monitoring tests can increase the log removal credits for RO membrane from 2-log up to 6-log removal. The quicker a DPR system's monitoring is, the more beneficial it is to protect public health and replace the value of an environmental buffer. Additionally, WWTP, WTP, and AWTP must monitor and remove disinfection by products (DBP) and residuals. This will be discussed later in this paper.

Water Contaminants

Engineers, researchers, and governmental protection agencies are concerned about many contaminants infecting urban drinking water. For this project, we will investigate the pollutants assumed to be found in wastewater, their health risks, and where they originate. Many have known health and environmental risks, and others are still being studied to determine their risks. These new contaminants can be called the Contaminants of Emerging Concern (CECs) because they are found in the soil, water, humans, and wildlife. Per- and Polyfluoroalkyl Substances (PFAS) contain unknown health and environmental risks. Studies to determine the dangers of these substances are still ongoing and have suggested some potential risks. Pharmaceuticals and Personal Care Products (PPCPs) are inevitably found in wastewater, and the health and environmental risks depend heavily on the type of medication and dosage in the water. In addition to the CECs, other contaminants can affect the disinfection process or are from the disinfection process itself.

PFAS

PFAS infects the water supply, environment, and humans in various ways. These forever chemicals are "used to make fluoropolymer coating and products that resist heat, oil, stains, grease, and water." (CDC, 2022, May 3). PFAs can be found in firefighting foams, expelled from industrial facilities, and on nonstick pans, leading to contaminated food and wastewater supplies. One of the major concerns for these substances is that the only way to determine the presence of PFAS is through testing because they are tasteless and odorless. The USEPA and MassDEP regulate these substances to reduce the risks of widespread infection. Further specifications on these regulations for these CECs are ever-changing as we learn more about them. Moreover, the health risks associated with persistent exposure to these substances are widely researched and still being investigated.

The current studies regarding the health risks of PFAS exposure show various results due to the discrepancies in the type of exposure, type of PFAS, and groups of people exposed (US EPA, 2021 October 14; ATSDR 2022, November 1). This makes it hard to link the results to other studies. The CDC and ATDSR have developed a short list of possible side effects of persistent PFAS exposure. Some possibly cause changes in the development and growth of children and infants, newborn death, reproduction, and pre-eclampsia in pregnant women. Research on exposure to low levels of PFAS have found it could affect thyroid function, immune systems, risks for high blood pressure, and liver problems. PFAS are often called forever chemicals because they can not decompose in nature and have a chemical attraction to organic matter, leading to a build-up of PFAS in soils and wildlife. Many studies interpolated the build-up of PFAS in wildlife to evaluate the risks to human health.

PPCPs

Pharmaceuticals have an interesting exposure pathway to the environment and water supply. Unlike PFAS, these types of contaminants are not limited by household items. Humans use pharmaceuticals to treat illnesses, and are expelled from the body directly into wastewater. Proper disposal protocols are sometimes ignored, and medications are exposed to the environment by these oversights. Medicines are given to livestock to improve growth and fight diseases linger in the body and the residuals of the medications can become present in the soil when expelled and used for manure. Some cases lead to a direct inflow of PPCPs to a wastewater supply; others can get into a water supply via runoff. Like PFAS, there are various possible health and environmental risks that are inferred from research but are ultimately uncertain. Researchers try to understand the effects of PPCPs on the environment through a regulated approach that extrapolates data from animal studies (e.g., Fish and Rats.) According to Beringer and Brooks (2010) study on fish responses to pharmaceuticals, a toxicology report indicated among the 200 medications in the study, 74% are acutely toxic above 10 mg/L, and “it was predicted that few pharmaceuticals are acutely toxic at concentrations below 10µg/L (0.075%).”

Many PPCPs in wastewater and the environment are Endocrine Disruptors (EDCs). These compounds change hormones in humans and animals, causing various side effects. (US EPA 2015, August 18). The best way to evaluate the long-term low-level side effects of EDCs and other pharmaceuticals on humans is by investigating the impacts experienced by production workers. (Boxell et al., 2012). A case study examining the exposure effects of oral contraceptives for manufacturing workers found that male workers experienced a large increase in oestogen levels and a decrease in testosterone, leaving them with a notably lower sex drive. The study also evaluated postmenopausal women, which showed they also experienced a large increase in oestorgen. (Heron, R. J. L., 2003) Although the research cases examined in Heron R. J. L’s study ranged from the 1970s to the early 2000s, healthcare professionals widely accept the information given. An often overlooked possibility is the effects of having a mixture of low-level medications. It is common knowledge that medications can have adverse reactions to one another. However, with the limited knowledge we can obtain, it remains a question that needs deeper research.

DBP

Disinfection By-Products (DBPs) are chemical compounds that pose health risks to humans. DBPs are found in drinking water and wastewater effluent due to the disinfection process in treatment facilities. They are formed when a disinfecting agent reacts with other compounds referred to as *precursors* (NOM, bromide and iodide, anthropogenic compounds, pharmaceuticals, antibacterial agents, textile dyes, pesticides, etc.) DBP precursors often contaminate water sources because of industrial discharges, agriculture runoffs, and wastewater discharge. DBPs are typically related to chlorine-based disinfectants or Ozonation and are strongly influenced by pH, temperature, ammonium, and metals (Gilca, A., 2020). However, drinking water treatment plants using UV or UV/H2O2 processes can react with PPCPs and form even more DBPs. This is only possible because pharmaceuticals will likely resist traditional drinking water treatment processes (Gilca, A., 2020). The U.S. EPA acknowledges some DBPs, but others go unnoticed. The acknowledged DBPs are regulated and broken up into classes such as trihalomethanes (THMs), Haloacetic Acids (HAA), and Nitrosamines (NDMA), to name a few. The unregulated DBPs are less known and don't get much attention in research or when detected in drinking water, even though they can be more toxic if exposed to humans. Additionally, the enforceable Maximum Contaminant Level (MCL) values for DBPs do not characterize DBPs based on their toxicity, carcinogenicity, and occurrence (Gilca, A., 2020).

The DBPs that are acknowledged and researched are carcinogens that can cause a variety of other health problems in humans. High exposure can cause humans to develop diseases in the central nervous system and reproductive systems. Some of these carcinogens involve mutagenic effects that may or may not become lethal (Gilca, A., 2020). Effects on the reproductive system can cause stillborns, miscarriages, birth defects, or infertility. The environmental impact of Chlorine-Based-Disinfectants (CBDs) was widely investigated during the COVID-19 Pandemic when widespread disinfection, such as bleach and bleaching powder, was considered essential. Chlorine will react with organic and inorganic substances and alter the composition of the microbial communities thriving in the body of water (Parveen et al., 2022). In China residential neighborhoods were disinfected by spreading hypochlorite or sprayed with bleach. The treatment covered roads, sidewalks, roadside plants, open lands, and other vegetation. Plants have a minimum level of chloride recommended at 1g/kg. Nature naturally provides this to plants, and any additional chloride will kill any vegetation it touches. DBPs build up in soil and vegetation over time, shortening their lifespans until they are unable to thrive and die (Parveen et al., 2022). It could be assumed that aquatic wildlife would experience similar effects to humans and vegetation.

Organic Contaminants

Nutrient pollutants such as nitrogen and phosphorus enter the environment through fertilizer runoff, animal manure, sewage treatment discharge, and failing septic tanks (US EPA, March, 2015). It is one of the most costly and challenging environmental problems. Excessive nutrients in the water will substantially impact the economy and cause health problems. Nitrogen is a key nutrient to all life and can live in water in various forms, including ammonia (NH3), Nitrates (NO3), and Nitrites (NO2), which occur naturally in water. Additional nutrients to an aquatic system will throw the aquatic vegetation out of balance, causing overgrowth in aquatic plants and stimulating algae blooms. The excessive plant growth kills aquatic life by depriving the fish, animals, and insects of oxygen. The decomposition of vegetation will require more dissolved oxygen (DO) in the body of water, fueling the decline in the ecosystem. Algae blooms pose an additional risk as some excrete harmful toxins and gasses. The growth and death of algae blooms will block sunlight from penetrating the surface of these bodies of water, killing the plants and organisms that rely on it (US EPA, November, 2015).

Algae blooms not only impact the welfare of wildlife, but it can also impact human health. The aquatic wildlife can absorb algae toxins; if humans consume a tainted animal or drink from the water, they will suffer. The toxins can lead to stomach issues, short-term memory loss, rashes, and even some more serious illnesses. In connection with the topic discussed in the previous section, the chemicals commonly used to treat algae blooms can cause additional health risks when they react. The reactions between the disinfectant and the algae can form DBPs (US EPA, March 2015). To protect the community from these risks, water treatment plants must spend more money to treat the polluted water, raising consumer prices (US EPA, March 2015). Nutrient pollution affects the U.S. Economy every year, impacting many different sectors. The tourism industry loses almost 1 million dollars annually from nutrition-polluted bodies of water. It can cause losses in the commercial fishing and shellfishing industry, amounting to a nearly 10 million dollar loss. Treating contaminated bodies of water can cost billions of dollars to clean. On a local scale, nutrient pollution will also affect waterfront property values.

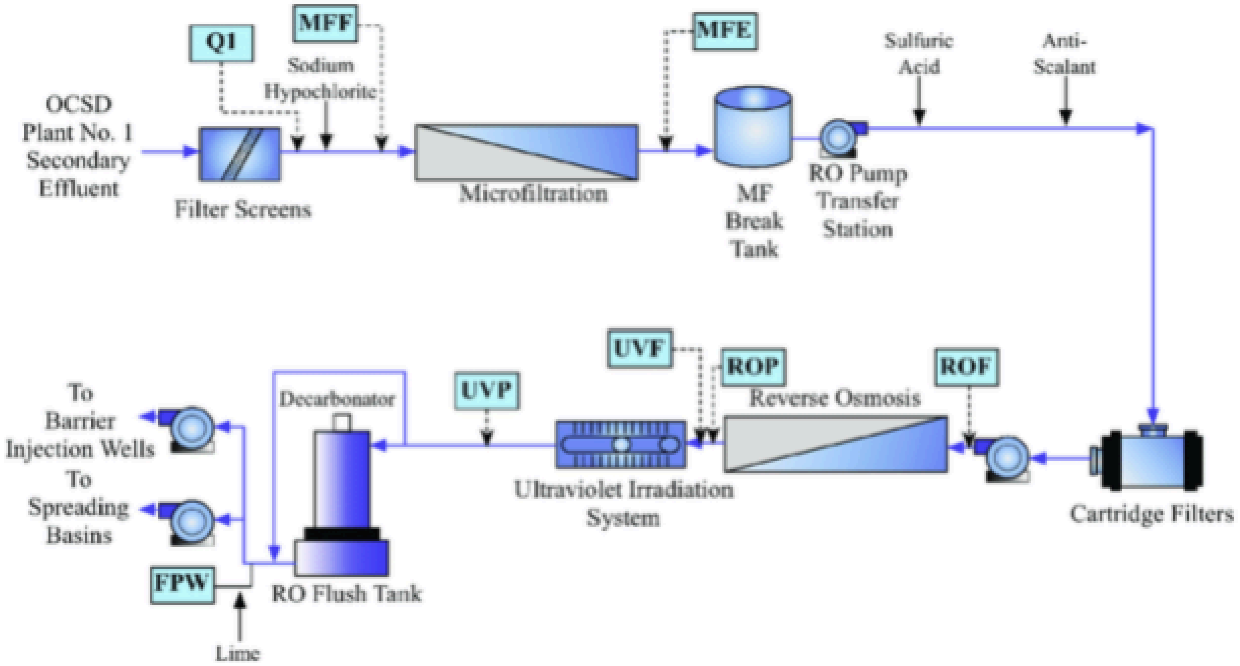
Case Studies

Orange County, California IPR

The Orange County Water District (OCWD) oversees three of Southern California's major water supplies. OCWD began practicing water recycling systems in 1975 at Water Factory 21 (WF 21) to combat seawater intrusion contaminating the Orange County groundwater basin (Markus and Torres, n.d.; Orange County Water District, 2023a). The success of this project led the OCWD and Orange County Sanitation District (OCSD) to expand the water reuse project in the early 1990s to address the need for the OCSD and fulfill Orange County’s water demands to eliminate the task of needing to import water to the county (Markus and Torres n.d.). Early in 2023, OCWD expanded its IPR system from producing 100 MGD to 130 MGD. Making this IPR project the largest water reuse facility in the world, being awarded “Most wastewater recycled to drinking water in 24 hours” (Guinness World Records 2018, April 20). In this case, the process required to treat wastewater for drinking water has proven successful.

The OCWD water treatment train has four steps, with the main objective to clarify, desalinate, and disinfect the secondary effluent. The first step in this treatment is pre-purification, which removes impurities such as suspended solids and some microorganisms. During the primary treatment, the water flows into settling tanks with a residence time of 2 hours, allowing the suspended solids to settle and be easily removed. Next is the secondary treatment, which uses screen bars, grit chambers, trickling filters, and activated sludge to remove the remaining particles, including the aerobic microorganisms. The second step uses a microfiltration membrane (MF) made of hollow polypropylene fibers to remove solids larger than 0.2 microns, protozoa, bacteria, and certain viruses. Step three implements a semi-permeable reverse osmosis (RO) polyamide polymer membrane to remove dissolved chemicals and any remaining viruses and PPCPs.The final step before delivery is disinfection by UV light coupled with hydrogen peroxide to destroy any remaining organic compounds. Half the water produced is injected into the seawater barrier, while the rest is sent to the groundwater basins (Orange County Water District, 2023).

Figure 3: Advanced treatment process for IPR System in Orange County Water District, Califonia (Jeffery et al., 2022)



According to Jeffery et al., (2022) research, some of the important conditions required by the governing officials to mitigate the risk of contamination of the treated water:

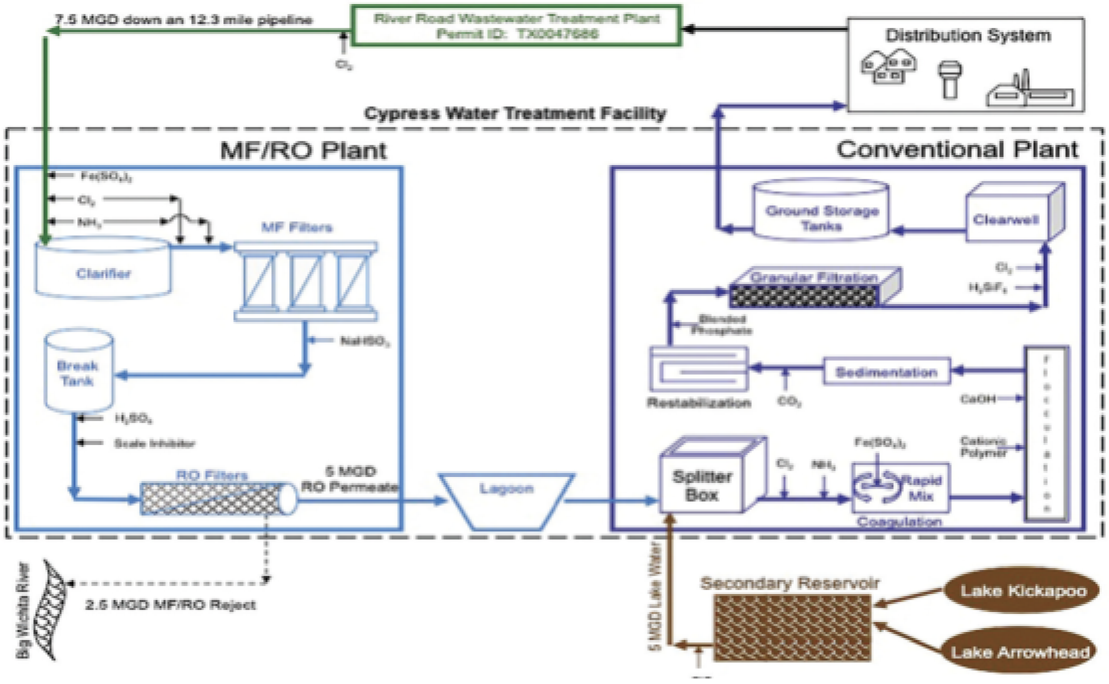
A. “Minimum retention times and separation distances between both the surface spreading basins and the barrier injection point to the nearest down-gradient drinking water production well;
B. A Maximum contribution of 75% from the recycled water stream to the total water stream at the surface spreading basin;
C. The requirement to monitor CECs such as (EDCs and PPCPs)and, subject to advice from an independent advisory panel, specific CECs based on health impact or as an indicator of process performance.”

Wichita Falls, TX, USA

Texas County began looking for potable reuse options in early 2012 because of a severe drought from 2010 - 2015. The city’s calculations indicated that the water supply would dry by 2013 (Nix et al., 2021). A Direct Potable Reuse (DPR) system was proposed but was rejected by the Texas Commission on Environmental Quality because they preferred an Indirect Potable Reuse (IPR) system. Building projection for the IPR system proposal estimated that the project would be operational in 2017. This would leave a 4-year gap, limiting the water available to the public from 2013 - 2017. This estimate obligated TCEQ to approve a Temporary Emergency DPR Project." The effluent was analyzed and compared with the U.S. EPA's primary and secondary drinking water regulations to design the system and address the contamination of the community's wastewater. to address any contaminants that do not meet the MCL. As a result of the wastewater effluent analysis, it was determined that the contaminants of concern were nitrate (N), trihalomethanes (THMs), and microbial. (Nix et al., 2021)

In 2014, the DPR project began operations that included a series of treatment processes and multiple treatment steps. First, the wastewater was treated at a conventional Wastewater Treatment Plant (WWTP) consisting of aeration basins and secondary clarifiers before being dosed with linear alkyl benzene sulfonate (LAS) to react with chlorine at another contact basin. Disinfection by LAS and chlorine addressed the removal of total trihalomethane (TTHM). The WWTP's effluent was then transported to the MF and RO treatment facility, which would remove protozoan (MF), nitrate (N), and viruses (RO). TCEQ also required that a UV light system was added to this process after the MF and RO treatment to ensure a higher log removal of protozoan pathogens. Additionally, the treated effluent was delivered to the local raw water supplies and blended with a 50% ratio before being delivered to a conventional water treatment plan (*Coagulation, Softening, Flocculation, Clarification, Filtration, and Chloramine Disinfection)* (Nix et al., 2021; Aleksić, Natalija 2022) After all these treatment steps were completed the treated potable water was stored in a ground storage tank with a 24 hour detention time allowing for a final check to ensure the water was safe to consume.

Figure 4: Advanced treatment process for DPR system in Wichita Falls, Texas



Windhoek, Namibia

Namibia is a small African nation; the continent is known for its endless deserts, prone to drought (Sysop, 2022). The heat alone causes 83% of rainfall to evaporate. The desert ground only allows 1% of the rain into the soil (Aleksić, Natalija 2022). In 1968, Windhoek, the capital of Namibia and hub for its industrial sector, faced an extreme water crisis. It was estimated that within six months, the city's water supply would be dry, depriving more than 400,000 citizens of drinking water. Although potable reuse is not widely accepted, many are inclined to take this solution when the unrelenting environment gives no other options (Sysop, 2022). In 1969, Windhoek became the first city in the world to use a DPR system for its population (Aleksić, Natalija 2022). Windhoek was initially designed for 5.9 MGD, but today it produces around 9 MGD. Windhoek extensively monitors the quality of the purified and recycled water to ensure its safety. They refer to the monitoring process as a non-treatment barrier that can protect the citizens in case of treatment failure. The newly established DPR plant was designed to imitate natural water cycles to eliminate health risks (Aleksić, Natalija 2022).

The DPR system uses a multiple barrier approach to treat the city's domestic secondary effluent (Aleksić, Natalija 2022). Because the capital is the country's industrial hub, the nation has strictly separated the domestic and industrial wastewater to ensure the public's welfare. As of 2002, Windhoek's DPR systems have operated through treatment barriers and purification systems to ensure safe consumption. The domestic wastewater undergoes a sewage treatment plant that targets nutrient removal before it is sent to maturation ponds (Aleksić, Natalija 2022). The effluent comes from 2 different wastewater plants blended, and PAC is added to remove dissolved organic compounds. Next, the waste undergoes a pre-treatment of ozonation, and then an enhanced coagulation and flocculation process takes place to remove the solids within the water. After flocculating, the water goes into a dissolved air flotation (DAF) tank to separate the flocs by raising them to the top of the tank for removal. DAF effluent is sent to the dual media filtration consisting of anthracite and sand to remove any straggler suspended solids that were not removed in the previous step; this process is followed by the main ozonation process which will address all remaining viruses, bacteria, and parasites. Additionally, Ozone oxidation will enable the biological degradation of organic compounds and pharmaceuticals. After the ozonation process, a biologically activated carbon filtration process removes the biodegradable dissolved organics remaining in the water. Next, the water is sent to a granular activated carbon (GAC) filter to remove the organic compounds and pharmaceuticals. UF is the final barrier to removing the system's suspended solids, microorganisms, and viruses. The last step is to disinfect with chlorine and stabilize with caustic soda to protect the consumers and maintain the pH level. (Lahnsteiner et al., 2018; Aleksić, Natalija 2022; Wingco, 2024). The result of the highly treated wastewater is blended with the reservoir's water supply so that no more than 35% of the reservoir water is recycled water (Lahnsteiner et al., 2018).

Treatment Options

This section discusses the benefits of the different treatment options in a typical potable reuse project. A stakeholder for a reuse project should look to develop a triple-bottom-line analysis for the system they intend to enact in their community. The wastewater must be socially, environmentally, and economically conscientious. Social and environmental considerations should revolve around human and wildlife health and quality of life. Economic considerations should evaluate the energy demand, capital, and maintenance costs. Traditionally, most potable reuse schemes rely on either soil aquifer treatment (SAT), granular activated carbon (GAC), or RO coupled with supporting clarifying treatment processes (Schimmoller et al., 2015.). All can be considered acceptable methods; however, with CECs such as PFAS and PPCPs, using soils to address remaining contaminants in water is no longer feasible. The soil may be able to filter PFAS temporarily, but with an excessive inflow of PFAS, the soil will have a build-up that will eventually leach into the drinking water aquifer. Additionally, PPCPs, even in low concentrations, can resist conventional drinking water treatment processes (Gilca, A., 2020). DPR systems are often considered to avoid contaminating the highly treated recycled water with the PFAS that may already exist in the soil.

Ultrafiltration (UF) & Microfiltration (MF)

UF and MF membranes are generally similar as they can effectively remove suspended solids and particles, typically causing treatment systems to use one or the other. The major difference between these two membranes is that a UF membrane has a pore size between 0.1 and 0.01 microns, and MF membranes have a pore size between 1.0 and 0.1 microns. Because of the different sizes, a UF membrane has a slight advantage over an MF membrane. Unlike a UF membrane, MF membranes can only remove limited amounts of bacteria and even fewer viruses (depending on the pore size). Virus removal during pretreatment is desired in water reuse schemes because RO membranes receive little credit for pathogen removal. (Warsinger, D. M., 2018). Both membranes can partially remove Phosphorus, nitrogen, and total organic carbon depending on the phase. The UF membrane has a higher removal rate for nutrient contaminates than the MF membrane but can not remove the nutrient contaminates if dissolved (Das, P. P., & Mondal, P. 2023). These benefits play into the redundancy requirements a reuse facility must follow but are not the only benefit the system will gain. Although UF membranes have their advantages in their removal efficiency, the benefits an RO membrane would receive from MF/UF are nearly equivalent.

UF/MF membranes are essential in potable reuse systems to protect the RO membrane from fouling and breakage. RO membranes have much smaller pores and are more selective. The higher the water quality they are treating can help avoid clogging. The benefits of pretreatment would include reducing the cost of the reuse project, improving flux rates, and improving the RO's effluent quality. Pretreatment can reduce costs by enabling a smaller system size, decreasing the need for RO replacements by 33%, and reducing the frequency of cleanings. The flux rates can be increased with the higher water quality, depending on the salinity of the feed water (Pearce, G. K. 2007). All RO systems must consider forms of pretreatment to protect the membrane, as it is a costly piece of equipment.

Reverse Osmosis (RO)

RO-based potable reuse is the most common and effective purification method. The Membrane has a pore size of 0.0001 microns, effectively rejecting nearly all salt ions, particles, organics, bacteria, and pathogens. In addition to these contaminants, RO can also remove TOCs and TDSs. California State regulations require all Potable reuse projects to have an RO followed by AOP. The state has made RO the standard requirement because California has very low limits for TOC and TDS contaminants (Schimmoller et al., 2015). For instance, the EPA conducted studies and created a database outlining the efficiency of various treatment methods for all contaminants in the database. RO membranes bench scale and full-scale treatment processes are highly effective for treating PFAS. The removal rate for the various types of PFAS ranged from 83-99.9% removal (TDB, EPA, n.d.). A drawback for RO that concerns potable reuse project developers is the rejected RO water referred to as Brine.

Reuse projects *appear* to have three methods for RO brine streams: discharge to coastal waters, evaporation ponds, or mechanical evaporation and salt disposal. California state tries to regulate what is discharged into coastal waters because studies have shown brine is denser than seawater. It settles at the bottom of the ocean, likely causing harm to marine organisms and elevating salinity. As of 2018, the California Ocean Plan did not have any regulations surrounding elevated salinity levels in the ocean, leading to discharge permits only being approved on a case-by-case basis (California State Water Quality Control Board 2018, July 5). Additionally, by discharging brine into ocean water, WWTP risks aquatic habitats further by polluting the environment with the CECs the RO membrane removed. RO proves to be a valuable option for potable reuse projects, but the disposal of brine must be considered.

All WWTPs are designed and built to be site-specific, and any municipality looking to introduce a potable reuse project must weigh the benefits and drawbacks of RO and GAC and determine the plant's best treatment option.

Granulated Activated Carbon (GAC)

GAC is an option predominantly used in potable reuse schemes in the Eastern U.S. Like RO membrane, GAC is used for the removal of TOC and TDS, in addition to PFAS and PPCPs (Schimmoller et al., 2015; TDB, EPA, n.d.; Wang, J., & Wang, S. 2016). In practice, a GAC filtration process can easily meet the limits set by federal regulators. This is partially due to the higher discharge limits allowed federally compared to California's State regulations for organics based on the COD tests (Schimmoller et al., 2015). GAC is cheaper and has a low energy demand compared to RO. If a Potable reuse scheme intends to use GAC instead of an RO membrane to Address PFAS and some PPCPs, the project planners should ensure the absolute minimum amount of organic matter. Any organic matter remaining in the system will compete with the PFAS and PPCPs to bind to the GAC (Wang, J., & Wang, S. 2016). Studies conducted by the EPA in bench-scale and full-scale applications found that GAC is most effective at removing longer-chain PFAS. For PFAS removal, the rate for various types of PFAS ranged from 65 - 99% removal (TDB, EPA, n.d.). Additionally, perfluorinated sulfonates are easier for GAC to adsorb than perfluoroalkyl acids.

Bench Scale Treatability Apparatus

The research conducted for the contaminants, case studies, and treatment options found that RO and GAC are the two practical and commonly applied methods for potable reuse. Using RO and GAC together can create an extra barrier to removing PFAS, PPCPs, and other contaminants. By using these two processes one after another, an engineered system can be designed to target CECs affecting today's environment and communities and reduce the risk of exposure via reclaimed water. GAC is a generally inexpensive and low-energy purification process that will easily add to the potable reuse installment. **Figure 5** shows the proposed treatment system that will be adequate for any Municipality looking to implement a small-scale potable reuse system. **Table 8** shows the materials required to build the designed bench scale treatability apparatus. The following sections discuss the operating parameters for the UF and RO membranes according to the manufacturer's operating limits and our benchsacle design needs.

Suggested Design: UF ➡ RO ➡ GAC

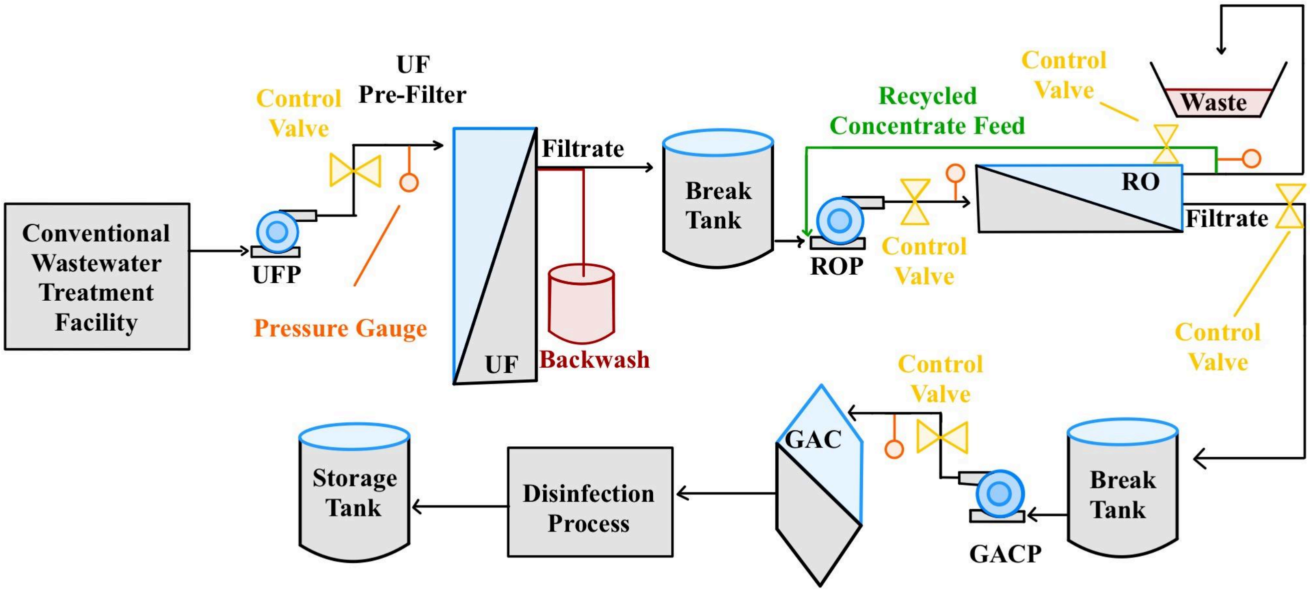


Figure 5: Water reuse Schematic: UFP *Ultrafiltration Pump;* UF *Ultrafiltration membrane;* ROP *Reverse Osmosis Pump;* RO *Reverse Osmosis Membrane;* GACP *Granular Activated Carbon Pump;* GAC *Granular Activated Carbon Module*

DuPont™ TapTec™ P Ultrafiltration PES Module

TapTec™ P Ultrafiltration PES Module Product Datasheet provides the following parameters in **Table 4**. The TapTec UF membrane may be an option for the bench-scale study because it meets the operational needs and size requirements. This is a dead-end flow membrane, meaning there is only an inflow and a permeate flow, and a backwash system is used to handle the rejected water. DuPont stated that 100% of the wastewater feed can be recovered from a dead-end UF treatment process. With this UF membrane, there will be no need to plan for any treatment or disposal of the rejected wastewater (*FilmTec™ Reverse Osmosis Membranes Technical Manual*, pg. 58, 2023). A dead-end membrane is not an ideal treatment practice, but it was one of the only small-scale membranes with the ability to run at low flow rates that was found. We designed a system to treat 30 GPD of wastewater for the small-scale treatability study. The Product Data Sheet did not provide any energy consumption values, so we evaluated the system based on a generalized assumption given by Tow et al., 2021. the energy consumption for a UF membrane is typically around 0.2 $\frac{kWh}{m^3}$ kWh of water treated. Using this assumption, the approximate energy requirement for the system will be about 0.023 kW per day.

Table 4: TapTec Multibore PES Module Product Parameters.

Pore Size	Membrane Area	Filtrate Flow Rate	Filtration Flux	Pressure Limit
0.02 micron	5.4 ft^2	0.4 - 4.76 (max)	106 gfd	44 psi

DUPONT's TapTec UF membrane is designed for point of use treatment. The Product Data Sheet ties the care guidelines with DuPont's IntegraTec™ UF In - Out P Series Process and Design Guidelines (Form No. 45-2234-en) for operating parameters. For this study, the TapTec PES module guidelines will be gathered from the previously mentioned document [1]. The operating parameters for membranes are important to follow to avoid irreversible damage to the membrane and achieve acceptable water quality after treatment. The assumed guidelines that would go across the board for all membranes during the design process are as follows:

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[1] NOTES: Additional requirements for the UF membrane could not be included because the technical manual was not readily available.

- The system should be designed to avoid any pneumatic and/or hydraulic pressure surges or siphoning effects.
- The system must include means to control the feed and backwash volume flow rates. (via frequency control pumps or control valves with PID controllers). Ensuring the set point value for the flow rate is reached within 5 - 7 seconds is essential for the backwash controller; *this time is dependent on pump capacity and valve dimension.*
- All butterfly valve actuators should have air-throttling valves to control the opening and closing procedure.
- The switching circuits for the pumps and valves must be designed to confirm that no pressure surges are produced within the system.
- When designing a UF system, there must be no dead spaces, especially on the filtrate side, as it can stimulate microbial growth.
- Avoid corrosive matter within the UF module.
- Only air-release valves may be used to prevent air from entering the system.
- Gap-type/ edge filters are not recommended for the pre-filter protection stage. The pre-filters should have a maximum mesh size of 230 microns with an inner diameter of 0.7 mm for Multibore membranes. Additionally, the pre-filter should be automatically backwashable
- Sealed filtrate/ backwash tanks with air filters are required to prevent microbiological contamination.

DuPont™ FilmTec™ TW30-1812-50 HR RO Element

DuPont's FilmTec TW30-1812-50 HR RO Element Product Data Sheet provides operational parameters in **Table 5**. A deeper investigation of FilmTec's Reverse Osmosis Technical Manual gives more information that will help to calculate the missing parameters needed for the design of the bench scale treatment system. Because the membrane appears much smaller than the UF membrane, a second membrane could be added to the system. Like the UF data sheet, the RO data sheet did not include any energy requirements for running the system. Using the information researched, we assume an RO system will require between 0.54 $\frac{kWh}{m^3}$ and 0.64 $\frac{kWh}{m^3}$ of water treated (Tow et al., 2021). Therefore, the estimated energy demand for the RO process will range between 0.06 and 0.7 kW per day.

Additionally, the technical manual states that a 30% recovery rate will be expected for a single-module element. This means that 21 gallons of brine and 9 gallons of clean water will be produced daily; this is not an accurate estimate as the water quality is uncertain and will affect this value. Additionally, DuPont mentions ways to improve the recovery rate, which is discussed further in this section.

Table 5: FilmTec TW30-1812-50 HR Element Product Parameters.

Membrane Area	Filtrate Flow Rate	Target Flux Rate	Feed Flow	Recovery Rate	Pressure Limit
2 sq. ft	50 GPD (max)	30 gfd	2 gpm (max)	30 %	49 psi

DuPont included some recommendations for users to consider when designing an RO system with any of their Filmtec Membranes. A quality design for an RO membrane system should have apparent goals for the treatment process. Adhering to operating limits to minimize fouling rate and/or mechanical damage. Dupont noted that any water with an expected poor quality should be designed at a low flux rate for their elements. The design must be limited by:

- Maximum recovery
- Maximum permeate flow rate
- Minimum Concentrate flow rate
- Maximum feed flow rate

RO systems are primarily designed for continuous operations. However, when smaller volumes are treated, they can be designed for batch treatments. Batch treatments have some advantages and disadvantages compared to continuous treatment systems, as shown in **Table 6**. Testing the elements removal capabilities for CEC and other contaminants through a batch treatment would benefit our study. However, as the study progresses toward implementing an RO system into a large-scale WWTP, testing the system design with a continuous flow rate will be required.

Table 6: The Advantages and Disadvantages of a RO Batch Treatment Process

Advantages of Batch Treatment	Disadvantages of a Batch Treatment
1. Flexibility when feeding water quality changes 2. System recovery can be maximized 3. Cleaning is easily implemented 4. Simple automatic controls 5. Permeate quality can be controlled and improved by termination of the process and by total or partial second-pass treatment, respectively. 6. Favorable operating conditions because the membranes are only in contact with the final concentrate for a short time 7. Easily expandable 8. Lower investment cost	1. No continuous permeate flow 2. No constant permeate quality 3. A larger feed tank could be required 4. Larger pumps could be required 5. Higher power consumption 6. Longer residence time for feed/concentrate 7. Higher total running costs

As previously discussed, a single module is expected to have only a 30% recovery rate. DuPont has noted that the more modules or stages a system has, the higher the system's recovery will be. **Table 7** shows the recovery values for a multi-element system treating brackish water. DuPont did not include any data for wastewater systems. Treatment facilities should consider this as they size up the system designs. Another way to increase the amount of clean water produced is to recycle part of the concentrate (*brine*) leaving the system. In single-module systems, concentrate recycling is required to comply with element recovery. To recover more than 50% of its flow rate, part of the concentrate exiting the system should return to the suction side of the feed pump. During the design stage, the amount of recycled brine must be factored into your system's flow rate. Brine recycling comes with a few disadvantages that should be considered and evaluated, such as:

- Larger, more expensive feed pumps
- Higher energy consumption
- A Decrease in Permeate Quality

Table 7: DuPont's "recovery" values for multi-element systems treating brackish water

Brine Produced (%)	Number of Elements in Series	Number of Stages
40 – 60	6	1
70 – 80	7 – 12	2
85 – 90	12 – 14	3

UF Process

A 35-gallon tank holding the wastewater effluent collected from a WWTP will feed the UF membrane. The flowrate and velocity of the water traveling from the tank to the (UFP) and from the pump to the membrane (UF) were determined by using the Reynolds number for turbulent flow (3500), the diameter of the pipe (0.75 in), and the kinematic viscosity of water at room temperature. The flow rate for the UF membrane was determined to be 0.9 gpm, which is on the low end of the membrane's flow parameters. The velocity of the water traveling through the pipe was calculated to be $36.25\frac{ft}{min}$. As previously mentioned, the designated volume of water that will be treated in a day is 30 gallons. Therefore, the UF process will only need 34 minutes to treat the collected wastewater. Per Dupont's recommendations, the pressure from the pump to the UF membrane should be between 22 – 44 psi. We chose to run the pump with an applied pressure of 30 psi, giving the UFP a size requirement of 0.02 hp.

RO Process

We aimed to design a socially and economically feasible system for potable reuse that will recover an ideal amount of clean water. To accomplish a higher recovery rate than what was estimated by the manufacturer, we designed to recycle 70% of the brine produced by the RO membrane (14.7 gallons); this will raise our recovery rate and flow rate for the RO membrane to 44% and 44.7 GPD, respectively; this will theoretically produce 13.4 gallons of clean water daily. A 35-gallon tank holding the UF membrane effluent will feed the RO membrane. The required flow rate from the tank to the RO Pump (ROP) and from the pump to the membrane (RO) was determined using the Reynolds number for turbulent flow, the pipe diameter [2] (1.5 in), and the kinematic viscosity of water. The flow the RO

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[2] NOTE: The membrane feed inlet is between 2.0 and 2.05 inches, and a pipe coupler must be included in the design.

membrane will operate at is 1.75 gpm, and the velocity in the pipe will be 18.2 $\frac{ft}{min}$. Using these parameters, we can determine that the RO process will take 25 minutes to treat the 44.7 gallons of water. DuPont stated that the *RO module's feed inlet* *pressure should not exceed 41 psi* *over atmospheric pressure. Pressure drops across the module typically occur between 5- 30 psi from the feed inlet to the concentrate outlet.* With this in mind, we will design the RO process to run at an applied pressure of 30 psi, giving our pump a size requirement of 0.04 hp to meet the system's operating conditions.

Table 8: Materials list for bench scale treatability apparatus

Item	Type	membrane
Pumps	Positive Displacement Pump	3
0.75 inch Pipe	PVC	3
RO Backwash Pipe *(Size Not Disclosed)*	PVC	1
1.5 inch Pipe	PVC	3
Pipe Coupler	PVC	2
RO Brine Pipe *(Size Not Disclosed)*	PVC	1
35 gallon tank (UF Feed and UF Effluent)	Polyethylene	2
20 gallon tank (RO Effluent and Storage)	Polyethylene	2
Control Valves	PVC Ball Valves	5
Pressure gauges	PVC Pressure Gauge	4
RO Membrane	FilmTec™ TW30-1812-50 HR RO Element	1
UF Membrane	TapTec™ P Ultrafiltration PES Module	1

Conclusion

Federal regulations from the U.S. EPA Guidelines for Potable Reuse stress the importance of risk assessment, management, and mitigation techniques to protect public safety. This paper assessed the possible contaminates that could be found in a typical wastewater treatment plant and evaluated the risks they would impose on the public welfare discussed in the Water Contaminates section of this paper. The bench sale design would be the first step into testing the reliability of a potable reuse system's ability to protect communities against CECs that would otherwise travel into the environment and WTP. The proposed treatment processes will address the multiple-barrier system requirements in place by the U.S. EPA, ensuring that a single step is not responsible for removing a contaminate, lowering the odds of treatment failure.

MassDEP regulations are stricter than the U.S. EPA regulations because MassDEP is currently not allowing potable reuse. Despite the regulations strictly prohibiting potable reuse, its water reclamation regulations allow aquifer recharge near wellheads that are or could become drinking water sources, with the limitation that the treated wastewater must meet all drinking water and surface water quality standards. This allows for an IPR system without actually allowing it. MassDEP is interested in considering potable reuse but needs local studies using potable reuse techniques to ensure public safety from PFAS and other CEC contaminants. In conclusion, the bench-scale potable reuse system designed in this project could be the first step to helping state policymakers change the regulations that limit the beneficial uses for reclaimed wastewater.

My Project designed a bench-scale system to treat 30 GPD of wastewater for direct or indirect potable reuse for any municipality that can be added to the existing infrastructure. Its objectives were to investigate the state and federal regulations for potable reuse water quality standards, evaluate the treatment options available to treat wastewater contaminants such as nutrients (nitrogen, phosphorus, BOD, and CECs,) and conduct case studies on operational potable reuse schemes. It was concluded that a UF → RO → GAC treatment train would be the best method to address state and federal water quality standards and the federal guidelines for any potable reuse scheme. Using RO and GAC in series to treat wastewater will address the PFAS and other CEC removal. Neither RO or GAC are 100% effective in removing PFAS. Coupling these two methods will limit the amount of NOM and PFAS competing to bind to the activated carbon.

The UF membrane was designed to run at 0.9 gpm to treat the 30 gallons of wastewater within 34 minutes. The designed flow rate was chosen to maintain a turbulent flow throughout the process and is within the operating parameters specified by the manufacturer. The UF membrane needs a 0.02 hp pump to run effectively within these parameters. Our RO membrane must run at a flow rate of 1.75 gpm to treat the UF effluent and 14.7 gallons of the RO's concentrate. The RO membrane will need a 0.04 hp pump to run effectively and meet the operating conditions and parameters for the membrane. Additional methods should be reviewed to increase the system's total recovery rate.

Recommendations

1. Review the TapTec PES UF membrane

The TapTec™ P Ultrafiltration PES Module operating parameters are ideal for the bench-scale operating conditions discussed for the potable reuse treatment study. We chose the TapTec membrane based on its compatibility with our system design. However, operating a potable reuse system with a dead-end membrane will pose some risks for fouling and water quality. The membrane may have the ability to be set up as a cross-flow membrane, but this is uncertain as the assembly manual is not readily accessible, and the manufacturer's website stated we needed to contact a sales representative to receive the document. Additionally, the membrane was designed for point-of-use treatment, not wastewater treatment. This may increase the risk of fouling and breakage in the system because it will treat much lower-quality water than intended. Keeping the system's operating conditions and the membrane's limitations in mind, we recommend further investigation of the TapTec membrane and other UF or MF membranes for this study to continue.

1. Choose a GAC Filter and Disinfection Process.

We recommend finding an engineered GAC filter to follow the RO treatment process for this study to continue. Finding a GAC filter was not within this project's scope and was not investigated. The benefits of having a GAC filter in the treatment process would be an increase in the effluent's water quality and an additional barrier to protect the public and environment for CECs such as PFAS. GAC filtration is a well-known standard practice for wastewater treatment worldwide and would not entail as much research to implement in our system. Additionally, the GAC filter should be sized to the bench-scales system's operating conditions, and a pump should be sized to meet the filter's operating parameters.

We also recommend choosing a disinfection process that will work best for the wastewater being treated. Disinfection processes should be selected based on a municipality's water quality and goals. The U.S. EPA has recommended AOP for DPR systems because of its strong ability to disinfect and break down trace contaminates (e.g., organics and chemicals); however, AOPs are expensive and may over-treat the water. There are other acceptable disinfection methods, but the chosen process should consider how to protect the highly treated water from DPBs. Ultimately, the decision-makers need to assess the municipality's needs, whether the system will be a DPR or IPR system, and the risks each process could pose to the water quality.

2. Build and Examine Systems Operations

The designed system should be built for this project to continue, and extensive testing should be conducted to evaluate its effectiveness. Small-scale testing will enable the design team to ensure the membranes are running optimally and assess the potential risks for fouling and system failure. Different configurations for the RO and UF membranes can also be tested. Each configuration has its benefits that should be considered to optimize the system's production rate and water quality. We recommend monitoring operating conditions throughout the system and testing the water quality after each treatment step. The water quality is currently unknown, so the recovery rate could be higher or lower than anticipated. Testing the quality after each step will help make an educated decision for improving the system and evaluating the potential of treatment failure. After the bench-scale system has shown to be successful, pilot testing would be the next step for a treatment facility to proceed to a full-scale design. Pilot testing is the most crucial test a municipality should conduct to help adjust the system design to meet the needs and minimize the risk for the final product.

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Appendix A

Table 1: MassDEP MCL for direct injection of recycled wastewater.

	Outside Zone II	Within Zone II and 2 year ToT	Within Zone II, Outside 2 year ToT	Within Zone II Outside 5 year ToT
BOD5	30 mg/L	10 mg/L	30 mg/L	30 mg/L
TSS	30 mg/L	5mg/L	10 mg/L	10 mg/L
Turbidity	n/a	2 NTU	5 NTU	5 NTU
TOC	n/a	1 mg/L	3 mg/L	n/a
Oil and Grease	15 mg/L	15 mg/L	15 mg/L	15 mg/L
Nitrate-Nitrogen	10 mg/L	5 mg/L	10 mg/L	10 mg/L
Total Nitrogen	10 mg/L	5 mg/L	10 mg/L	10 mg/L
TDS	1,000 mg/L	1,000 mg/L	1,000 mg/L	1,000 mg/L
Fecal Coliform	200 counts/100 mL	Non-detected over 7 day period, 14 colonies/100 mL max	200 counts/100 mL	200 counts/100 mL
Total Residual Chlorine (if disinfection is by chlorine)	1 mg/L	1 mg/L	1 mg/L	1 mg/L
Notes:	Reg requires "enhanced secondary treatment"	Filtration and disinfection required; demonstrate 5-log disinfection of MS-2 or poliovirus	Filtration and disinfection required	Filtration and disinfection are required. Anticipated limits based on DEP internal guidance (not in CMR 5.00)

Table 2: Processes used to accomplish drinking water treatment objectives included in the EPA 2017 guidelines.

Overall Treatment Objectives	Process to Achieve Objectives
Suspended Solids	● Coagulation ● Flocculation ● Sedimentation ● Media Filtration ● MF/UF
Dissolved Chemicals	● RO ● NF ● Granular Activated Carbon (GAC) ● Biologically Active Filtration
Disinfect and Remove Trace Organics	● UV ● Chlorine/Chloramines ● Ozone ● Chlorine Dioxide ● Advanced Oxidation Processes (AOP)
Stabilization	● Sodium Hydroxide ● Lime ● Calcium Chloride ● Blending
Aesthetics (Taste, Odor, and Color)	● Ozone/biologically Activated Carbon (BAC) ● MF/RO

Table 3: Based on Massachusetts regulations, the table includes the quality regulations that must be met and the treatment train recommended.

	Treatment Steps	Water Quality Parameters
Groundwater Recharge (potable aquifers) by Injection	**1. Secondary** **2. Filtration** **3. Disinfection** **4. Advanced Water Treatment**	● No detectable total coliform /100 mL ● Minimum of 1mg/L Cl2 residual ● pH between 6.5 and 8.5 ● Less than 2 nephelometric turbidity units (NTU) ● Less than 2 mg/L TOC originating from wastewater ● Must meet drinking water standards.

(1) Conventional treatment processes such as activated sludge, trickling filters, etc. BOD and TSS should be less than 30 mg/L

(2)Filtration through media filters such as sand, anthracite, or membrane filtration.

(3) Disinfection through chemical, physical, or biological processes. Pathogen inactivation must be accomplished.

(4)AWT includes chemical clarification, carbon adsorption, RO, Membrane filtration, advanced oxidation processes (AOP), and ultrafiltration.