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Review

Reuse of Treated Wastewater: Drivers, Regulations, Technologies, Case Studies, and Greater Chicago Area Experiences

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Abstract: Water reuse is a practical solution to augment water supplies in areas where water resources are increasingly scarce. Water reuse technology is versatile and can be used to alleviate the different causes of water scarcity, such as groundwater depletion or increased availability of brackish water. Treatment technologies can be tailored specifically to the end use of recycled water, focusing on these drivers that are region-specific, for a more cost-effective treatment system. This is called a "Fit-for-Purpose" strategy that is commonly implemented in any water reuse project. However, implementing water reuse can be challenging due to infrastructural requirements, economic issues, and social acceptance. To help navigate these challenges, this article provides a comprehensive review of water reuse cases and presents guidelines that can act as a reference framework for future water reuse projects. This article also makes the case for implementing water reuse in the Greater Chicago area as a means of alleviating pressure on withdrawals from Lake Michigan.

Keywords: water reuse; water recycling; wastewater treatment; sustainability; water infrastructure; regulations

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1. Introduction

Currently, freshwater quantity and quality are at risk due to factors such as extreme weather conditions, groundwater depletion, drying lakes, changes in precipitation trends and corresponding runoff, population growth, economic development, increased water demand, and growing water quality concerns (point source pollution and emerging contaminants). Water reuse (also known as water recycling or water reclamation) is a practical, sustainable, and economically beneficial solution to address the future availability of life-sustaining freshwater. Water reuse is a crucial aspect of managing water resources sustainably, especially when it is done to improve local water supplies and lower wastewater production [1].

Although water reuse has been widely researched and put into practice in other countries, it is less common in the United States. No studies have discussed the water reuse challenges and opportunities in the Greater Chicago area. The aim of this study is to review drivers for water reuse worldwide, appraise guidelines and regulations for water reuse in the US, and identify water reuse technologies and associated challenges. This paper also provides case studies where water reuse has been successfully implemented in the US and other parts of the world. Furthermore, an overview of water management, and the feasibility of implementing water reuse in northeastern Illinois including Cook County and its largest municipality, Chicago, is presented in detail. This paper focuses on water reuse in the Greater Chicago area due to the growing constraints in accessing clean water from both surface water and groundwater sources. According to the National Integrated Drought Information System (NIDIS), as of October 2022, 27% of the Midwest Region (where Greater Chicago area is located) is experiencing drought conditions, of which 6% is in severe drought. Without a significant change in our water resource recovery, future generations will face many challenges in obtaining freshwater [2].

2. Drivers for Water Reuse

Scientists widely concur that the Earth is experiencing climate change and warming at a faster pace than anticipated [3]. Although climate change occurs through natural physical processes and the global temperature seems to follow a natural oscillatory cycle, scientific data suggest that manmade causes, such as greenhouse gas emissions, are contributing to climate change [4]. As precipitation patterns change, flooding in some regions and droughts in others may become more common and severe. Approximately 3800 towns and cities globally, with over 2500 residents, are located in floodplains and are at a risk of property damages and loss [4,5]. Climate change is predicted to increase water demand while simultaneously reducing water availability. According to the UN, by 2050, 75% of the world's population will experience drought. This raises awareness of the possibility of reusing treated wastewater as an alternative to freshwater. Jimenez and Asano [1] noted that there are contrasting approaches to water reuse in developed and developing countries. They also provided a summary of the primary factors that motivate water reuse in these two groups of countries, which are outlined in Table 1a. These factors may stem from the physical characteristics of the environment, social considerations, economic conditions, political factors, or water management policies.

Table 1. (**a**) Drivers of water reuse in developed and developing countries. (**b**) Drivers for water reuse in the U.S.

(**a**)

Driver	**Importance in Developed Countries**	**Importance in Developing Countries**
Physical characteristics of the environment		
Insufficient water supply	High	High
Managing drought and securing a reliable water supply	High	Medium
Recycling for meeting agricultural water demand	High	High
Inadequate sanitation resulting from the unintentional reuse of wastewater	-	High
Water management policies		
Recycling is utilized as a means of mitigating the harmful consequences of discharging treated wastewater and safeguarding the environment, particularly in coastal and tourist regions or in ecologically vulnerable aquatic ecosystems	Medium	-
The proper treated wastewater can enhance the ecological conditions in areas with poor water quality	Medium	-
Reusing treated wastewater instead of first-use water for drinking water supply	Medium	-

Table 1. *Cont.*

(**a**)

Driver	**Importance in Developed Countries**	**Importance in Developing Countries**
The rising recognition among water and wastewater authorities of the financial and ecological advantages of utilizing reused water	Low	-
The significant ecological and financial expenses associated with water storage structures, such as dams and reservoirs	Medium	-
The increasing successful water recycling initiatives globally	Low	-
Social considerations		
Implementing water reuse programs rather than increasing the cost of transporting water from external sources or bearing the expenses associated with advanced wastewater treatment	Medium	-
Raising awareness about the ecological consequences connected to excessive consumption of water resources	Low	-
To recover substances present in recycled water, such as nitrogen and phosphorus, without incurring any expenses	Low	High
The eagerness of the community to embrace the idea of water recycling	Low	-
Economic conditions		
As a means of partially covering the expenses of meeting strict standards for wastewater treatment	Medium	-
To utilize recycling as a lower-cost method of waste disposal	Medium	Low
Safeguarding the environment in tourist destinations	Medium	Medium
Physical, social, and economic reasons		
Significant water demands in nearby regions, particularly for urban and industrial purposes	High	High

(**b**)

Driver	Details
Compliance	The Clean Water Acts defines the degree and type of wastewater treatment needed to fulfill effluent requirements. The CWA prohibits pollution discharges into navigable, fishable, and swimming waters, which requires significant water treatment to increase effluent value and usage. Some municipalities prefer to utilize the highly treated effluents instead of discharging them into waterways.
Viable source substitution	For urban irrigation, air conditioning, and toilet flushing, recycled water may be the most cost-effective and practicable alternative. By reusing recycled water, potable water supply is reduced.
Localized water demand increases	Population growth has increased water demand. Reuse is becoming a new water source alternative in areas where population growth has outpaced the availability of conventional water sources.
Societal pressures	Growing recognition of the importance of water sources has led to the development of regulatory frameworks and organizational structures.

Water reuse can also support the 17 Sustainable Development Goals (SDGs) set by the United Nations. Among the 17 SDGs, established by the UN to be achieved by 2030, number six is ensuring universal access to water and sanitation with sustainable management. In order to achieve these goals, water reuse practices are encouraged [6]. Furthermore, the World Water Development Report 2015 stated in the first paragraph that "water is at the core of sustainable development", underlining the importance of water as a component of human growth and ecosystem requirement. Fundamental objectives for drinking water supply, sanitation, and environmental sustainability are included in this goal. Within the purview of goal six is addressing water scarcity, poor sanitation, widespread pollution, rapid decreases in freshwater biodiversity, and the loss of essential ecosystem products and services [7–9].

According to Schramm et al. (2020), nine of the 17 Sustainable Development Goals, as listed below, can be supported by practicing water reuse, including [10]:

- Goal 2: Zero hunger
- Goal 3: Good health and well-being
- Goal 6: Clean water and sanitation
- Goal 8: Decent work and economic growth
- Goal 9: Industry, Innovation, and Infrastructure
- Goal 11: Sustainable cities and communities
- Goal 12: Responsible consumption and production
- Goal 14: Life below water
- Goal 17: Partnerships

Through water recycling, it is possible to adhere to the water supply goals in the U.S. and of the U.N. while accounting for multiple types of water users. The specific drivers for water reuse in the U.S. highlighted in the following sections, with an emphasis on the Greater Chicago area.

2.1. Drivers for Water Reuse in the United States

Currently, 44% of the U.S. is facing moderate to extreme drought conditions [11]. Water availability can be greatly impacted by this, emphasizing the significance of planning for water management and water reuse. Reusing water can be an effective strategy for augmenting existing water supplies and ensuring adequate water availability for urgent needs. In some regions, increased runoff, flooding, and sea level rise pose a greater risk than drought or water scarcity. Nonetheless, these occurrences can degrade water quality and damage the infrastructure utilized to transport and distribute water.

At once, humanitarian and social principles insist that water and sanitation are human rights. For example, the California water code states, "every human being has the right to safe, clean, affordable, and accessible water" despite extreme weather conditions, the current state of water supply resources, or other climate change impacts [12].

Approximately 1.45 to 1.58 trillion gallons of water are expected to be consumed annually by the year 2050, representing a 20 to 30 percent rise in global water demand [13]. Many regions are currently experiencing water scarcity and will not be able to fulfill their water demands. The United States Geologic Survey (USGS) estimates the water use in the United States in 2015 was approximately 322 billion gallons per day (Bgal/day) across eight sectors, i.e., thermoelectric, public supply, irrigation, self-supplied industrial, aquaculture, self-supplied domestic, livestock, and mining. Thermoelectric (133 Bgal/day), irrigation (118 Bgal/day), and public supply (36 Bgal/day) accounts for 90 percent of all water withdrawal [14].

About 74% of the water supply comes from surface water and 26% from groundwater. Among the groundwater resources, The Ogallala and Gulf Coastal Plain aquifers serve states from the high plains (Colorado, Kansas, New Mexico, etc.) to the Gulf States (Texas, Mississippi, and portions of Alabama, Florida, and Louisiana) and have the highest depletion rates of 10.220 km^3/year and 8.430 km^3/year [15].

In 2015, around 88% of the U.S. population relied on public water supply; the remaining 12% relied on self-supplied withdrawals [14]. The United States treats roughly 34 Bgal/day of domestic wastewater that is typically discharged into nearby water bodies. This represents a loss of 34 Bgal/day from a potentially sustainable water supply. The Water Reuse Action Plan (WRAP), a sustainable campaign to reclaim, recycle, and reuse water, was announced in February 2020 by the federal government to alleviate the strain on water sources by harnessing the prospective resource of effluent. WRAP's policies encourage the reuse of treated stormwater and wastewater for agricultural, non-potable, and potable purposes [16].

Although drought-induced water scarcity was the original driver behind water reuse in primarily western states of the U.S., other drivers have also emerged. Asano et al. [17], and the USEPA [18] consider additional drivers in the U.S. such as (1) compliance, (2) viable source substitution, (3) localized water demand increases, and (4) societal pressures (Table 1b).

2.2. Drivers for Water Reuse in Greater Chicago Area

In Illinois, a state bordering both Lake Michigan and the Mississippi River, a growing groundwater crisis suggests that water recycling should be adopted. For example, Joliet, the third largest city in Illinois, has nearly depleted its aquifer which cannot recharge due to the fault line that runs through it. Currently, Joliet's source of water comes from deep wells and deep sandstone aquifer. The water withdrawals have surpassed the sustainable output of the aquifer indicating the overdrawn water pump by the communities, industries, and other water users. The water level of the aquifer has plunged as much as 800 ft because of the excessive water withdrawal with no sign of groundwater recharge. At some point soon, the deep sandstone aquifers of the city of Joliet will no longer be operable [19]. Therefore, Joliet has signed an agreement with the City of Chicago to receive treated Lake Michigan water by pipeline for the next 100 years [20].

As Joliet shifts to Lake Michigan supply, the State of Illinois runs the risk of exceeding its diversion limits set by the U.S. Supreme Court. According to US Army Corps of Engineers (USACE), the running average diversion from the Lake Michigan through Water Year (WY) 1981 to 2015 is 3066 cubic feet per second (cfs), which is just under the 40-year average diversion of 3200 cfs implied under the Lake Michigan Diversion Decree. The yearly average diversion has surpassed the annual limit of 3680 cfs once. In addition, the absolute yearly maximum of 3840 cfs was exceeded during the accounting period of WY 93 [21]. Not only can water reuse help communities experiencing water supply crisis, but it can also help conserve the Lake Michigan Diversion water quota (as some of the potable water is replaced by recycled water) and will help Department of Water to generate revenue from the recycled water sales.

The concept of using recycled water as a solution for water scarcity may not be appealing to some people [22]. However, surveys conducted in drought-prone regions such as Arizona, California, Colorado, and Texas, as well as in areas experiencing significant population and economic growth such as Georgia and Florida, have revealed that the public in many of these states support the use of recycled water for non-potable purposes, as it conserves water, protects the environment, promotes health, and is cost-effective [22]. However, when a project is apparent in their communities and human interaction increases, the opinions change, thus dwindling the support. Although many scientists and engineers think that non-potable reuse is viable, there are arguments when it comes to indirect potable reuse. The technical and scientific difficulties and disagreements among scientists and engineers increase the level of uncertainty around public consumption [22].

According to Lazarova (2022), location and specific local characteristics have a significant impact on the major challenges surrounding the implementation of water reuse projects, their ranking, and some of the predicted obstacles. The main challenges for water reuse are (1) economic viability, (2) social acceptance, (3) policy and regulations, (4) technical feasibility and energy efficiency, and (5) innovation (Table 2) [23].

Table 2. Challenges for water reuse.

Public acceptance (Yuck Factor)	In any water reuse project, having public support is crucial. However, there is a psychological obstacle, commonly referred to as the "yuck factor", that exists among the public regarding wastewater reuse projects. To overcome this obstacle, it is essential to inform and involve the public continuously in water reuse projects, thereby gaining their attention and support for such initiatives.
Economic viability	Water reuse infrastructure and technology require large capital investments, and while sustainable and cost-effective in the long run, the added treatment and monitoring can be more expensive than other sources. Government subsidies may be necessary, and institutional barriers and differing priorities can make large-scale programs challenging.
Policy and regulations	Establishing and implementing guidelines for water reuse is crucial to gain public approval for water recycling. Nevertheless, in certain cases, regulations may impede and create difficulties for the reuse of water.
Technical feasibility and energy efficiency	To avoid overtreatment and energy waste, reuse technologies must be designated specifically to the end use. For example, reverse osmosis should be limited to high-end reuse applications, whereas other technologies may be more efficient for non-potable reuses.
Innovation	To remove the social, political, and economic constraints to the development of water reuse that is cost competitive. The technology innovation for water reuse should be focus-oriented toward developing of reliability, performance, flexibility and robustness of existing technologies, the development of new cost effective and energy efficient technologies, and other tools for water reuse practices.

The most important determinant of the viability of water reuse is water quality. Engineering solutions are needed to achieve the desired water quality for various water reuse practices. For example, the natural wastewater contaminant removal process by the freshwater ecosystem can be replicated with the help of engineered systems. It requires external energy to operate and the construction of engineering infrastructure, but in exchange, it can eliminate contaminants in water with high efficiency. The amount of time for contaminant removal is short in comparison to the process that occurs in a natural ecosystem. To determine the best trade-offs, one might compare how engineering and ecology solutions use resources (including appropriating land) [24].

3. Guidelines and Regulations for Water Reuse

3.1. Federal Policies and Regulations

There are no definite federal regulations governing water reuse in the United States, and the guidelines and regulations implemented by individual states differ significantly, with some states not having any regulations at all. However, the Safe Drinking Water Act (SDWA) and the Clean Water Act (CWA) may play a facilitating or hindering role in water reuse. The USEPA has released guidelines for water reuse, which states can adopt to establish criteria or requirements for different water reuse programs. The guidelines from the USEPA are not legally binding, but they offer recommendations for engineers, stakeholders, and any water reuse programs that are involved in assessing, planning, designing, operating, and managing water reuse facilities [25].

3.1.1. USEPA Water Reuse Categories

Recycled water that has been properly treated can be utilized for potable and non-potable purposes such as industrial processes, and land irrigation. If the treated water is processed further with more advanced treatment technologies or complex wastewater treatment processes, the water can be used as potable water or combined with surface or groundwater to increase the water supply. In this way, the cost of economic and environmental expenses associated with developing additional water sources can be decreased, thus improving the circular water economy. Water reuse categories defined by the USEPA are as follows:

- **Unrestricted urban reuse.** The use of reclaimed water for non-potable applications in municipal settings where public access is not restricted.

- **Restricted urban reuse.** The use of reclaimed water for non-potable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction.
- **Agricultural reuse on food crops.** The use of reclaimed water to irrigate food crops that are intended for human consumption.
- **Agricultural reuse on processed food crops and non-food crops.** The use of reclaimed water to irrigate crops that are either processed before human consumption or not consumed by humans.
- **Unrestricted Impoundments.** The use of reclaimed water in an impoundment in which no limitations are imposed on body-contact water recreation activities (some states categorize snowmaking in this category).
- **Restricted Impoundments.** The use of reclaimed water in an impoundment where body contact is restricted (some states include fishing and boating in this category).
- **Environmental reuse.** The use of reclaimed water to create, enhance, sustain, or augment water bodies, including wetlands, aquatic habitats, or stream flow.
- **Industrial reuse.** The use of reclaimed water in industrial applications and facilities, power production, and extraction of fossil fuels.
- **Groundwater recharge.** The use of reclaimed water to recharge aquifers that are not used as a potable water source.
- **Indirect potable reuse.** Augmentation of a drinking water source (surface or groundwater) with reclaimed water followed by an environmental buffer that precedes normal drinking water treatment.
- **Direct potable reuse.** The introduction of reclaimed water (with or without retention in an engineered storage buffer) directly into a water treatment plant, either collocated or remote from the advanced wastewater treatment system.

According to the USEPA Guidelines, 43 states have created laws, regulations, or guidelines for agricultural reuse to irrigate processed food crops and nonfood crops, 40 states for restricted urban reuse, 32 states for unrestricted urban reuse, and 31 states for industrial reuse.

3.1.2. USEPA Guidelines on Water Quality for Different Reuse Practices

The USEPA established guidelines for each category of reuse. Table 3 shows the recommended guidelines for water reuse based on the reuse category along with treatment degree and quality of recycled water. It is advised that some amount of disinfection must be applied to the wastewater regardless of the category or the reuse applications. Regarding agricultural reuse, the Food and Agriculture Organization (FAO) (1985) established irrigation guidelines for agricultural use of degraded water to assist in determining the salinity of reclaimed water for agricultural use. According to the USEPA, "These guidelines are not intended to be used as definitive water reclamation and reuse criteria. They are intended to provide reasonable guidance for water reuse opportunities, particularly in states that have not developed their own criteria or guidelines." [25]

Table 3. USEPA guidelines for water reuse.

Reuse Category and Description	Treatment	Reclaimed Water Quality
	Urban Reuse	
Unrestricted	Secondary, filtration, disinfection	pH = 6.0–9.0 $\leq$10 mg/L BOD $\leq$2 NTU No detectable fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
The use of reclaimed water in non-potable applications in municipal settings where public access is not restricted.		

Table 3. *Cont.*

Reuse Category and Description	Treatment	Reclaimed Water Quality
Restricted The use of reclaimed water in non-potable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction	Secondary, disinfection	pH = 6.0–9.0 ≤30 mg/L BOD ≤30 mg/L TSS ≤200 fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
Agricultural Reuse		
Food Crops The use of reclaimed water for surface or spray irrigation of food crops which are intended for human consumption, consumed raw.	Secondary, filtration, disinfection	pH = 6.0–9.0 ≤10 mg/L BOD ≤2 NTU No detectable fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
Processed Food Crops The use of reclaimed water for surface irrigation of food crops which are intended for human consumption, commercially processed.	Secondary, disinfection	pH = 6.0–9.0 ≤30 mg/L BOD ≤30 mg/L TSS ≤200 fecal coli/100 mL 1 mg/L Cl_2 residual (min)
Non-Food Crops The use of reclaimed water for irrigation of crops which are not consumed by humans, including fodder, fiber, and seed crops, or to irrigate pastureland, commercial nurseries, and sod farms.		
Impoundments		
Unrestricted The use of reclaimed water in an impoundment in which no limitations are imposed on body-contact.	Secondary, filtration, disinfection	pH = 6.0–9.0 ≤10 mg/L BOD ≤2 NTU No detectable fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
Restricted The use of reclaimed water in an impoundment where body-contact is restricted.	Secondary, disinfection	≤30 mg/L BOD ≤30 mg/L TSS ≤200 fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
Environmental Reuse		
Environmental Reuse The use of reclaimed water to create wetlands, enhance natural wetlands, or sustain stream flows.	Variable, secondary and disinfection (min)	Variable, but not exceed: ≤30 mg/L BOD ≤30 mg/L TSS ≤200 fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
Industrial Reuse		
Once-through Cooling	Secondary	pH = 6.0–9.0 ≤30 mg/L BOD ≤30 mg/L TSS ≤200 fecal coliform/100 mL 1 mg/L Cl_2 residual (min)

Table 3. *Cont.*

Reuse Category and Description	Treatment	Reclaimed Water Quality
Recirculating Cooling Towers	Secondary, disinfection (chemical coagulation and filtration may be needed)	Variable, depends on recirculation ratio: pH = 6.0–9.0 $\leq$30 mg/L BOD $\leq$30 mg/L TSS $\leq$200 fecal coliform/100 mL 1 mg/L Cl_2 residual (min)
Groundwater Recharge—Non-potable Reuse		
The use of reclaimed water to recharge aquifers which are not used as a potable drinking water source.	Site-specific and use-dependent, primary (min.) for spreading, secondary (min.) for injection	Site-specific and use dependent
Indirect Potable Reuse		
Groundwater Recharge by Spreading into Potable Aquifers	Secondary, filtration, disinfection, soil aquifer treatment	Includes, but not limited to, the following: No detectable total coliform/100 mL 1 mg/L Cl_2 residual (min) pH = 6.5–8.5 $\leq$2 NTU $\leq$2 mg/L TOC of wastewater origin Meet drinking water standards after percolation through vadose zone
Groundwater Recharge by Injection into Potable Aquifers	Secondary, filtration, disinfection, advanced wastewater treatment	Includes, but not limited to, the following: No detectable total coliform/100 mL 1 mg/L Cl_2 residual (min) pH = 6.5–8.5 $\leq$2 NTU $\leq$2 mg/L TOC of wastewater origin Meet drinking water standards
Augmentation of Surface Water Supply Reservoirs	Secondary, filtration, disinfection, advanced wastewater treatment	Includes, but not limited to, the following: No detectable total coliform/100 mL 1 mg/L Cl_2 residual (min) pH = 6.5–8.5 $\leq$2 NTU $\leq$2 mg/L TOC of wastewater origin Meet drinking water standards

3.2. State and Local Policies and Regulations

The State of Illinois currently does not have regulations for water reuse [25]. However, there are state regulations that may affect water reuse practices in Illinois.

3.2.1. Illinois Environmental Protection Agency

The Illinois Environmental Protection Agency's (IEPA) existing programs could encourage water reuse. IEPA's Bureau of Water seeks to ensure that Illinois's rivers, streams, and lakes can sustain aquatic life, drinking water supply, recreation, and fish consumption. The Bureau's goal is for all public water systems in Illinois to provide high quality water that meets all regulations. At once, the Bureau endeavors to protect Illinois's groundwater resources [26]. The Illinois water reuse regulation referenced in the 2012 USEPA guidelines [25] is Title 35 Illinois Administrative Code Part 372-Illinois Design Standards for Slow Rate Land Application of Treated Wastewater. This regulation can indirectly discourage water reuse practices in Illinois. For example, Title 35 requires a two-cell lagoon system with tertiary sand filtration and disinfection or a mechanical secondary treatment plant with disinfection for urban areas (urban parks, golf courses, and other areas with public access). Furthermore, the majority of Chicago Area Waterways are exempt from the effluent disinfection requirement since they have relatively low-quality water [27].

Illinois Administrative Code (IAC) Title 35 Subtitle C Chapter 2 Part 378 identifies three types of surface waters; (1) Seasonally Protected Water, (2) Year-Round Protected Waters, and (3) Unprotected Waters. In "seasonally protected water" from May through October, fecal coliform counts should not exceed 200 fecal coliforms per 100 mL. In "year-round protected waters", fecal coliform should not exceed 2000 fecal coliforms per 100 mL. In "unprotected waters", there are no standardized counts for fecal coliforms (Table 4).

Table 4. IPCB regulations on allowable Fecal Coliform counts in surface water.

Type of Surface Water	Fecal Coli./100 mL	Note
Seasonally Protected Water	200	Any waters that support primary contact from May through October.
Year-Round Protected Waters	2000	Applicable to any public and food processing water intake.
Unprotected Waters	Not subjected to Fecal Coli. Standards	When meeting certain characteristic of unprotected waters. - Waters with average depths of 2 feet or less and no summer deep pool; - Waters with physical constraints that impede access or primary contact; - Waters with nearby land uses that discourage primary contact.

Based on data collected from Metropolitan Water Reclamation District of Greater Chicago's (MWRD) seven water reclamation plants (WRPs), Calumet, O'Brien, Egan, Kirie, and Hanover Park are disinfecting their effluent seasonally (Table 5). Therefore, the quality of water at these five WRPs is better from May through October (low fecal coliform counts). Whereas Stickney and Lemont Water Reclamation Plant (WRP) discharge their effluent to the Chicago Sanitary and Ship Canal, under Title 35 III. Adm. Code 302. Subpart D, the fecal coliform counts are not determined and these two treatment plants are not required to meet a certain standard for fecal coliform counts [28].

Table 5. Fecal Coliform counts at MWRD's Water Reclamation Plants from May–October and from November–April.

Water Reclamation Plant	Highest Fecal Coliform Concentration (CFU/100 mL)		Average Fecal Coliform Concentration (CFU/100 mL)	
	May–October	November–April	May–October	November–April
Stickney	48,000	76,000	15,758	12,042
Calumet	150	57,000	45	6827
O'Brien	3500	52,000	113	1817
Egan	200	7500	27	2213
Kirie *	90	10	11	10
Hanover Park *	40	10	13	10
Lemont	220,000	210,000	33,827	20,086

* Many data are not specified from November–April. The 2019 data show a higher concentration between these months.

3.2.2. City of Chicago Ordinances

There are no regulations in Chicago that directly address water reuse, although several local ordinances may affect its implementation. Title 11 of the Chicago Municipal Code discusses Utilities and Environmental Protection. With the intent to keep Lake Michigan as the city's water source, Chapter 8 states, "No groundwater well, cistern or other groundwater collection device installed after 14 May 1997, may be used to supply any potable water supply system, except at points of withdrawal by the City of Chicago or by a unit of local government pursuant to intergovernmental agreement with the City of Chicago". However, groundwater recharge can be possibly applied with the city involvement [28,29].

3.2.3. Chicago Metropolitan Agency for Planning (CMAP)

The Chicago Metropolitan Agency for Planning (CMAP) is the comprehensive regional planning organization for the seven counties of northeastern Illinois. According to state and federal law, the CMAP is responsible for producing the region's official, integrated plan for land use and transportation. The Chicago Metropolitan Agency for Planning (CMAP) is required by federal and state law to evaluate significant wastewater treatment service issues in northeastern Illinois to assure compliance with regional regulations. This includes decreasing pollution in discharges to the region's waterways, using energy-efficient technologies to reduce environmental demands, guaranteeing enough water supply for population growth, and conserving various social and ecological landscapes through green infrastructure techniques [30]. Despite the CMAP's oversight, the Illinois Environmental Protection Agency has the final authority regarding wastewater concerns. In 2010, the CMAP published "Northeastern Illinois Regional Water Supply/Demand Plan", where the possibility of recycled water replacing some potable water uses is discussed. This aspect of planning is vital to analyze in detail in future studies [31].

4. Water Reuse Treatment Technologies

Most residential and industrial activities generate wastewater containing harmful pollutants [32]. Before this wastewater can be safely and sustainably reused, it must undergo treatment to remove these pollutants to an appropriate degree. This plain fact is important to consider since water reuse is increasingly being recognized as a sustainable solution for global water management issues. By addressing the issue of harmful pollutants in wastewater, we can ensure that it can be effectively treated and safely reused. Ensuring water quality is an essential aspect of water reuse, as the suitability of the water for a given purpose can depend on its quality. The challenge rests in implementing water reuse technologies that are cost-effective, robust, and safe for human health and the environment [33].

The goal of water reuse treatment is to produce water that meets the quality of the intended use and is safe for public health and the environment. Producing water viable for particular uses while maintaining safety standards is known as a "Fit-for-Purpose" model that can be customized to a particular purpose. In determining quality thresholds, treatment goals (e.g., salt reduction for irrigation or industrial reuse) are specifically tailored to end user needs, safe for the public and the environment while being cost-effective. This is a frequently used strategy in developing various solutions for water reuse [25].

Treating water for water reuse typically involves treating wastewater in several steps consisting of preliminary treatment, primary treatment, and secondary treatment. Tertiary treatment and advanced treatment may be needed for water reuse purposes. During preliminary treatment, large objects that may damage the treatment process are removed. In primary treatment, some suspended solids and organic matters are removed from wastewater. The removal process is done by sedimentation of floating and settleable matter. In secondary treatment, most of the organic matter is removed using biological and chemical processes. Additionally, tertiary treatment and advanced treatment may be added to the system train for water reuse purposes. In tertiary treatment, disinfection and nutrient removal occurs, and the remaining suspended solids are removed using granular medium filtration or micro screens. Remaining suspended solids and other constituents that are not removed by secondary treatment are then removed by a combination of unit operations and processes in advanced treatment [34].

Wastewater treatment systems can use a variety of different technologies to treat effluent for water reuse. Table 6a,b provide an overview of the various technologies and their applications [17,35]. The various technologies fit under one or more of the following five categories:

- Removal of suspended solids;
- Reducing dissolved chemical concentrations;
- Removal or disinfection of trace organic compounds;
- Stabilization;
- Aesthetics (taste, odor, color correction).

In instances where stringent effluent disposal standards apply, implementing water reuse may require upgrading technologies used at wastewater treatment plants (WWTP) to incorporate tertiary treatment technologies to treat contaminants that remain in the effluent [17,35]. Typical WWTPs use coagulation, flocculation, and sedimentation to remove suspended particles, while medium filtration and micro/ultrafiltration can improve effluent quality by enhancing the removal of solids and microorganisms. Media filtration uses gravity or pressure differentials to pass water through porous mediums, removing solids via adsorption and separation by size. Micro/ultrafiltration use a porous polymer film acting as a selective barrier and operate under size exclusion [35].

Reverse osmosis, electrodialysis, electrodialysis reversal, nanofiltration, granulated activated carbon, ion exchange, and biologically active filtration can be used to degrade dissolved compounds. Typically, a membrane is used to separate dissolved chemical elements such as road salts or pesticides from wastewater influents [35].

Disinfection and removal of trace organic compounds come after the removal of dissolved chemicals to eliminate pathogens in wastewater. This is accomplished through UV, free chlorine/chloramines, peracetic acid, pasteurization, chlorine dioxide, and advanced oxidation processes. These methods neutralize microorganisms through inactivation processes but are dependent on contact time, pH, and temperature [35].

Certain approaches for reducing corrosion, such as reverse osmosis and nanofiltration, must be followed by stabilization. Mineralization may involve decarbonation, or addition of sodium hydroxide, lime, calcium chloride, or mixing. The desired Langelier Saturation Index (LSI) should be close to zero, and thus should produce a final product that will not corrode metal pipelines or concrete tanks [35].

Though aesthetics may appear unimportant, public opinion has a significant impact on the feasibility of wastewater recycling. Therefore, some qualities, such as flavor, odor, and color, must be treated prior to the distribution of water to public systems or agricultural systems. Activated carbon, UV, and chlorination are efficient ways of treating taste and odor. All aesthetic issues are adequately remedied with the help of ozone and biologically activated carbon [35].

Table 7 lists all treatment technologies from various case studies that were collected for this study. As the need for higher water quality increases, the degree of treatment increases. For instance, a more complex treatment process is required when the intended use of the recycled water is for indirect potable reuse (IPR) or direct potable reuse (DPR).

Table 6. (**a**) Unit operations and process used for the removal of different constituents in water reuse applications. (**b**) Treatment technologies and capabilities.

(**a**)

Constituent Class	Secondary Treatment	Secondary with nutrient removal	Depth filtration	Surface filtration	Microfiltration	Ultrafiltration	Dissolved Air Flotation	Nano filtration	Reverse Osmosis	Electro dialysis	Carbon adsorption	Ion exchange	Advanced Oxidation	Disinfection
Suspended Solids	✓	-	✓	✓	✓	✓	✓	-	-	-	-	-	-	-
Colloidal Solids	-	-	-	-	✓	✓	✓	-	-	✓	-	-	-	-
Particulate Organic Matter	-	-	-	✓	✓	✓	✓	✓	-	-	-	-	✓	-
Dissolved Organic Matter	✓	✓	-	-	-	-	-	✓	✓	-	✓	-	✓	✓
Nitrogen	-	✓	-	-	-	-	-	-	✓	-	-	✓	-	-
Phosphorous	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
Trace Constituents	-	-	-	-	-	-	-	✓	✓	-	✓	✓	✓	-
Total Dissolved Solids	-	-	-	-	-	-	-	✓	✓	✓	-	✓	-	-
Bacteria	-	-	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	✓
Protozoan Cysts and Oocysts	-	-	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	✓
Viruses	-	-	-	-	-	✓	✓	✓	✓	-	-	-	✓	✓

Table 6. *Cont.*

(**b**)

Overall Treatment Objective	Unit Processes	TOC	TSS	TDS	Trace Chemical Constituents	Pathogens [3]
Removal of Suspended Solids	Media Filtration, Microfiltration and ultrafiltration	Partial removal	High removal	None	None	High removal [3]
Reducing the Concentration of Dissolved Chemicals	NF/RO	90% removal	High removal	High removal	High removal [1]	High removal
	ED/EDR	None	None	High removal	None	None
	PAC	High removal	None	None	Partial removal	None
	GAC	40–60% removal	High removal	None	40–60% removal	Partial removal
	Ion exchange	None	None	High removal	Partial removal	None
	Biofiltration	High removal, High degradation [2]	High removal	None	High degradation [2]	Partial removal
	Ozone	None	None	None	High degradation *	High degradation
Disinfection and Removal of Trace Organic Compounds	UV	None	None	None	Partial degradation *	High degradation
	Free Chlorine	None	None	None	Partial degradation *	High degradation
	Chloramines [4]	None	None	None	None	Partial degradation *
	PAA [5]	None	None	None	Partial degradation *	High degradation
	Pasteurization [5]	None	None	None	Partial degradation	High degradation
	Ozone	None	None	None	High degradation *	High degradation
	Chlorine dioxide	None	None	None	Partial degradation *	High degradation
	Advanced oxidation processes (UV/H_2O_2, O_3/H_2O_2, UV/Cl_2)	None	None	None	High degradation *	High degradation

Notes: * Contact time and concentration dependencies. [1] Some chemical constituents may have Reverse Osmosis (RO) removal efficiencies less than 90%, such as NDMA, 1,4-dioxane, and flame retardants. Additionally, Reverse Osmosis (RO) likely has greater removal efficiency than Nanofiltration (NF). [2] BAC is effective at removing trace chemical constituents, but BAC will result in higher TOC levels than RO. [3] MF and UF membranes can remove bacteria and protozoa. MF is not considered an effective barrier against viruses, while UF can remove viruses to a certain extent. [4] Extended chloramine contact times are required for virus inactivation, but no Giardia or Cryptosporidium inactivation should be anticipated with chloramine disinfection. [5] Currently used only in wastewater treatment.

Table 7. Treatment technologies used existing water reuse projects.

Category	Tertiary Treatment Process		Reuse Purposes	Location
	Pre-Treatment-Filtration	**Disinfection**		
Urban Reuse	Flocculation Media Filtration	Chlorination	Non-potable irrigation (residential, commercial, industrial)	El Segundo, CA, SUA
Agriculture	Flocculation Multi-media Filters	Chlorination	Raw-eaten vegetables and fruits	Monterey One, CA, USA
	None (Membrane Bioreactor effluent)	Ultraviolet	Vineyards	American Canyon, CA, USA
	Coagulation Flocculation Cloth Media Filter	Ultraviolet	Raw-eaten fruits	Pajaro Valley, CA, USA
Industrial	Microfiltration	Reverse Osmosis (Single Pass) Decarbonation	Industrial—Boiler Feed (BF) water	El Segundo, CA, USA
	Microfiltration	Reverse Osmosis (Single Pass) Ozone Decarbonation	Industrial—Low-Pressured Boiler Feed	El Segundo, CA, USA
	Microfiltration	Reverse Osmosis (Double Pass) Ozone Decarbonation	High-Pressure Boiler Feed	El Segundo, CA, USA
	Sand Filter	Addition of corrosion inhibitors, sodium hypochlorite, acid, and antifoaming agents (at power plant)	Cooling towers	Denver, CO, USA
	Media Filtration	Oxidized Coagulation Disinfected (UV or Chlorine)	Pulp and paper (newspaper)	Los Angeles, CA, USA
	Gravity Filter	Chlorination	Textile (carpet dyeing)	Santa Fe, CA, USA
	Granular Coal	Ultraviolet	Geyser recharge for electricity	Santa Rosa, CA, USA
	Lime Softening Filtration	Chlorination	Cooling towers	Baltimore, MD, USA
Environmental	Automatic Backwash with Sand Media	Chlorination	Wetlands	Orlando, FL, USA

Table 7. *Cont.*

Category	Tertiary Treatment Process		Reuse Purposes	Location
	Pre-Treatment-Filtration	**Disinfection**		
Indirect Potable Reuse	Microfiltration	Reverse Osmosis UV with Hydrogen Peroxide Lime Treatment	Groundwater recharge	Orange County, CA, USA
	Lime Clarification Media Filtration	Granulated Activated Carbon Ion Exchange Chlorination		Fairfax, VA, USA
	Media Filtration	Reverse Osmosis Ultraviolet with Advanced Oxidation Process Chlorination	Groundwater recharge via riverbank filtration	Arapahoe County, CO, USA
Potable Reuse	Flocculation Biologically Active Carbon Filtration Microfiltration Ozonation Granular Activated Carbon	Ultraviolet Chlorination	Drinking Water (preliminary approval)	Castle Rock, CO, USA
	Granular Activated Carbon Filtration	Reverse Osmosis Ultraviolet with Advanced Oxidation Process	Drinking Water (Undergoing regulatory approval)	El Paso, TX, USA
Combination	Granular Coal	Ultraviolet	Farmlands Vineyards Public urban landscaping	Santa Rosa, CA, USA
	None	UV	Agricultural Irrigation (Vineyards) Landscape Irrigation (excludes golf courses) Industrial use Other—Construction site dust control Other—In-plant use at City WRF	American Canyon, CA, USA
	Microfiltration	Chlorine/Dechlorination Reverse Osmosis Ultraviolet	Irrigation Industrial Streamflow Augmentation (future direction) Groundwater Recharge (future direction)	Santa Clara, CA, USA

Table 8. Advantages and disadvantages of various water treatment processes.

Process	Advantages	Disadvantages
Advanced oxidation processes (AOP) Photolysis Heterogeneous and homogeneous photocatalytic reactions non-catalytic wet air oxidation (WAO) Catalytic wet air oxidation (CWAO) Supercritical water gasification	• Local production of reactive radicals; • Chemicals are not necessary; • Pollutant mineralization; • Rapid degradation; • Efficient for color removal; • Efficient in chemical and total oxygen demand reduction; • WAO is efficient for effluent that is too dilute or toxic for biological treatment, phenol removal, and insoluble organic matter conversion.	• Lab-scale technologies; • Economically ineffective for small and medium-sized industries; • Technical issues; • Generate byproducts; • Low production capacity; • WAO is energy-intensive.
Adsorption/filtration Commercial activated carbons (CAC) Commercial activated alumina (CAA) Sand Mixed materials Silica gel	• Simple technologies; • Widely available; • Adsorption targets various contaminants; • Effective with fast kinetics (Adsorption); • Produce high-quality effluent; • Universal elimination depending on adsorbent (CAC); • Efficient in removing chemical oxygen demand; particularly when paired with coagulation to minimize suspended particles, chemical oxygen demand, and color (CAC); • Sand effectively removes turbidity and suspended solids; • Alumina effectively removes fluoride.	• High cost overall (CAC); • High-cost material (CAC, CAA); • Material dependency performance (CAC); • Multiple adsorbents needed; • Derivatization of chemical increases adsorption capacity; • Costly regeneration when clogged; • Complex adsorbent elimination.
Biological methods Bioreactors Biological activated sludge (BAS) Microbiological treatments Enzymatic decomposition Lagoon	• Simple mechanism of removal; • Cost-effective; • Widely accepted; • Eliminates organic materials, NH3, NH4+, iron; • Efficient in color removals; • BAS is effective in biological oxygen demand (BOD) and suspended solids (SS) removal; • Future treatment systems for emerging contaminants removal will rely heavily on microbial activities.	• Required a suited environment; • High maintenance; • Kinetics problems are present; • Poor dyes biodegradability; • Thickening and foaming of sludge (BAS); • Generation of byproducts; • Change of mixed cultures' composition; • Complex mechanisms of microbiology.

Table 8. *Cont.*

Process	Advantages	Disadvantages
Coagulation/flocculation	• Simple process; • Widely available chemicals; • Low capital cost; • Efficient for suspended solids, colloidal particles, and insoluble contaminants removal; • Efficient in chemical oxygen demand, biochemical oxygen demand, and total organic carbon reduction; • Lower precipitation time.	• Arsenic removal rates are low; • Complex dosing; • Requires non-reusable chemicals; • Requires pH monitoring; • High sludge volume generation.
Dialysis Electrodialysis (ED) Electro-electrodialysis (EED) Emulsion liquid membranes (ELM) Supported liquid membranes Membrane filtration Microfiltration (MF) Ultrafiltration (UF) Nanofiltration (NF) Reverse osmosis	• Widely available (with a multitude of applications and module combinations); • Large space is not required; • Efficient even at high concentrations; • Produce a high-quality effluent; • Chemicals are not necessary; • Reduce soil waste production; • Eliminates all salts, mineral concentrations, and colors; • MF, UF, NF, and reverse osmosis are efficient in removing particles, suspended solids and microorganisms; • NF and reverse osmosis are efficient in removing volatile and nonvolatile organics; • ED and EED are efficient for dissolved inorganic matter removal; • ELM is efficient for phenols, cyanide, and zinc removal.	• Requires more energy; • Diverse membrane filtration system design; • High O&M costs; • Frequent clogging problems; • Specific membranes for different applications; • Not as efficient at low solute feed concentrations.
Ion exchange Chelating resins Selective resins Microporous resins Polymeric adsorbents Polymer-based hybrid adsorbents	• Vast selections of products available; • Simple technology; • Easy maintenance; • Integrates well with various methods and is simple to use; • Efficient process; • Generate high-quality effluent; • Considered cost effective for metal removal compared to other technologies; • Effective for recovering valuable metals.	• High columns require for large volumes; • Frequent clogging problems; • Performance is affected by the pH of the effluent; • Removal of certain contaminants are ineffective; • Resins are not selective; • Removal of resins; • Beads are easily damaged by particles and organic matter.

Crini and Lichtfouse (2019) gave an outline of various wastewater treatment processes and analyzed the pros and cons associated with each, considering factors such as cost, effectiveness, practicality, reliability, environmental impact, sludge production, operational complexity, pre-treatment needs, and the potential for generating hazardous byproducts (Tables 3 and 4) [36–56]. Based on the variability of choices, advantages, and disadvantages of wastewater treatment processes and technologies, engineers, stakeholders, and people partaking in water reuse projects can select the most appropriate treatment method and technologies to achieve the desired water quality (Table 8).

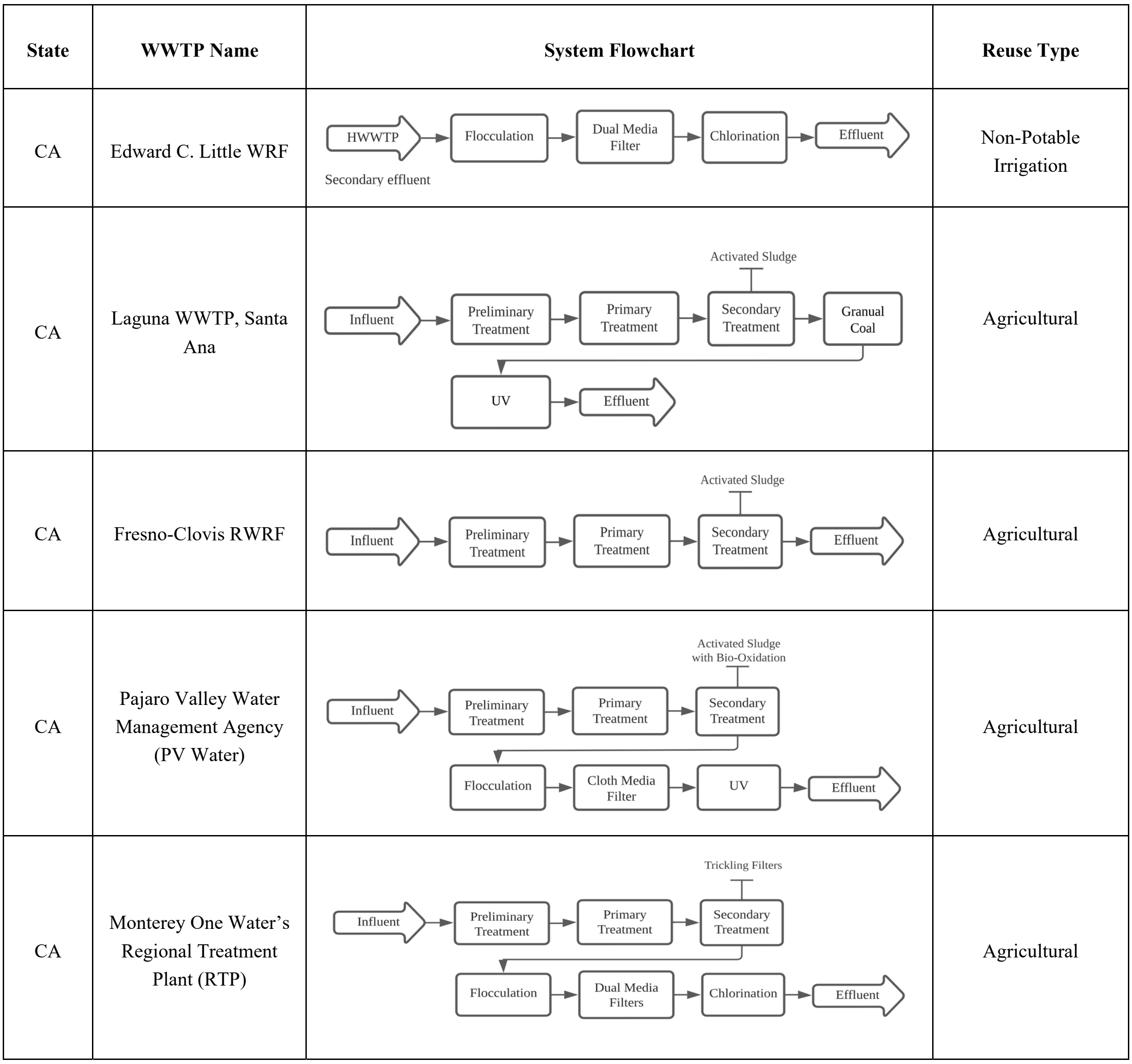
4.1. Non-Potable Reuse Treatment Technologies

The most widely implemented and accepted water reuse practice is non-potable water reuse. It has been successfully implemented in many states in the US, particularly California, Texas, Arizona, and Florida. Due to the variety of non-potable water reuse, treatment goals and processes are based on specified non-potable reuse, and the requirements/guidelines to ensure the protection of public health. Water quality goals for industrial reuse are often site-specific and different from water reuse for irrigation. To achieve industrial water quality standards for cooling and boiler water applications, nutrient (e.g., nitrogen, phosphorus) and ion (e.g., chloride, hardness) removal may be necessary. Typically, tertiary treatment and disinfection are needed for agricultural and crop irrigation reuse. Several filtration technologies may be used to remove suspended particles and pathogens, including granular media filters, moving bed sand filters, cloth filters, and membrane filters. The state of California, California Title 22, maintains a list of permitted filtering methods for non-potable reuse applications. This list is helpful for those designing tertiary filtration [33].

Figure 1 provides some examples of agricultural water reuse and their treatment technologies. Treatment requirements vary depending on the intended use, though water quality restrictions for chloride, TDS, ammonia, TSS, and bacteria are regularly considered for scaling and corrosion in boiler feed and cooling towers. Industrial end-user-specified water quality standards might also alter treatment strategies. Depending on the needs of the system, no extra treatment beyond the tertiary non-potable treatment system may be required, or an independent advanced system may be required to produce higher water quality. If an advanced treatment system is required, it is normally installed by the industrial user at the point of use [33].

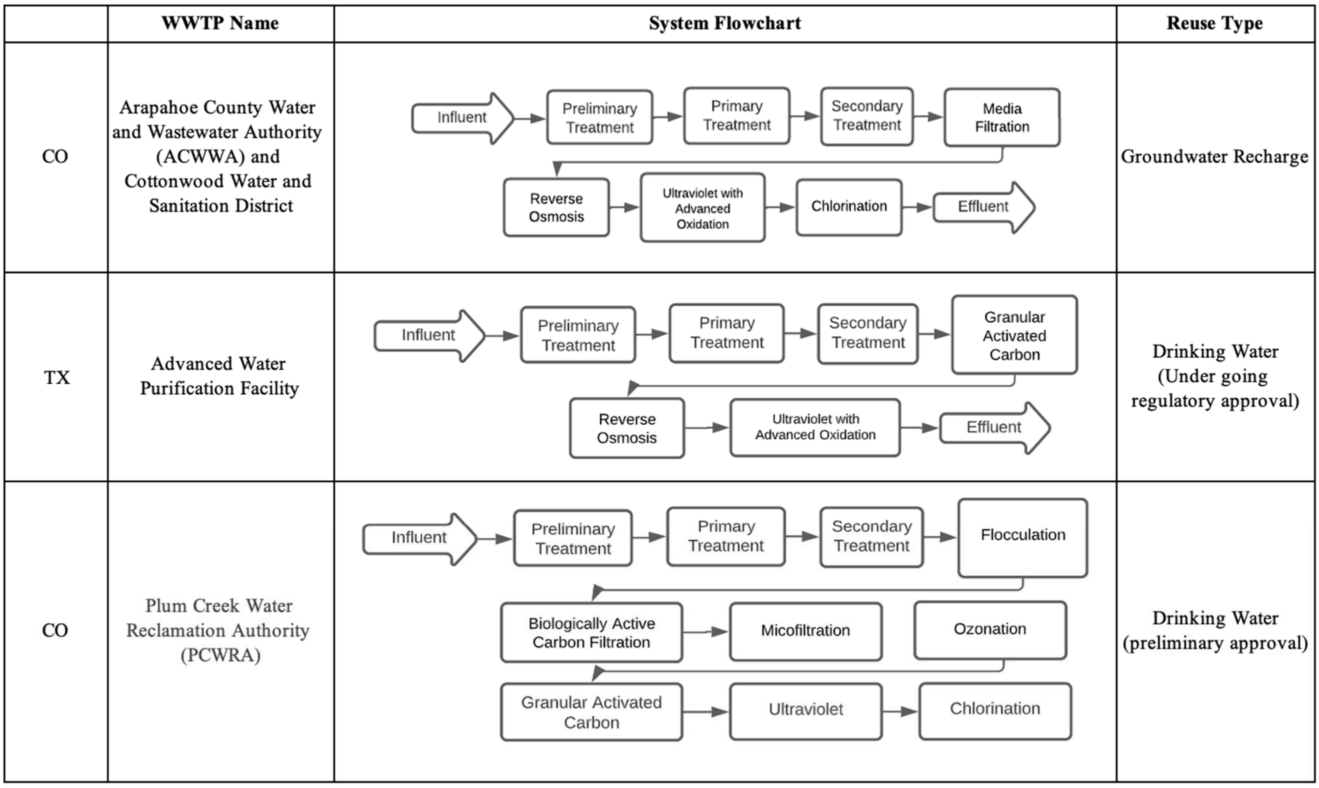
4.2. Potable Reuse Treatment Technologies

Potable reuse can be divided into two categories, which are direct potable reuse (DPR) and indirect potable reuse (IPR). Typically, complex treatment processes are used to remove organics, pathogens, and other impurities to fulfill potable water requirements. IPR refers to a system in which recycled effluent or advanced treated effluent is delivered to an environmental buffer prior to withdrawal for potable uses [57]. Direct potable reuse (DPR) refers to a system in which there is no environmental barrier between recycled effluent and potable water; nevertheless, mixing processes can be employed and still be classified as DPR [33]. Different treatment systems for IPR and DPR are depicted in Figure 2. In 2017, the EPA published the Potable Reuse Compendium which serves as a supplement to the 2012 guidelines and highlights current practices and treatment technologies in potable reuse.



State	WWTP Name	System Flowchart	Reuse Type
CA	Edward C. Little WRF	HWWTP → Flocculation → Dual Media Filter → Chlorination → Effluent Secondary effluent	Non-Potable Irrigation
CA	Laguna WWTP, Santa Ana	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment (Activated Sludge) → Granual Coal → UV → Effluent	Agricultural
CA	Fresno-Clovis RWRF	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment (Activated Sludge) → Effluent	Agricultural
CA	Pajaro Valley Water Management Agency (PV Water)	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment (Activated Sludge with Bio-Oxidation) → Flocculation → Cloth Media Filter → UV → Effluent	Agricultural
CA	Monterey One Water's Regional Treatment Plant (RTP)	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment (Trickling Filters) → Flocculation → Dual Media Filters → Chlorination → Effluent	Agricultural

Figure 1. Wastewater treatment technologies for agricultural purposes based on various case studies in the US.



	WWTP Name	System Flowchart	Reuse Type
CO	Arapahoe County Water and Wastewater Authority (ACWWA) and Cottonwood Water and Sanitation District	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment → Media Filtration → Reverse Osmosis → Ultraviolet with Advanced Oxidation → Chlorination → Effluent	Groundwater Recharge
TX	Advanced Water Purification Facility	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment → Granular Activated Carbon → Reverse Osmosis → Ultraviolet with Advanced Oxidation → Effluent	Drinking Water (Under going regulatory approval)
CO	Plum Creek Water Reclamation Authority (PCWRA)	Influent → Preliminary Treatment → Primary Treatment → Secondary Treatment → Flocculation → Biologically Active Carbon Filtration → Micofiltration → Ozonation → Granular Activated Carbon → Ultraviolet → Chlorination	Drinking Water (preliminary approval)

Figure 2. Wastewater treatment technologies for IPR and DPR purposes based on case studies in the US.

4.3. Costs of Treatment Technologies

As recycled water is a relatively new source of supply, the water sector has not yet adopted a pricing strategy for recycled water. Moreover, the assessment and distribution of costs associated with the production of recycled water are inherently complicated, reflecting both water and wastewater functions and necessitating judgments regarding the optimal management of shared costs [58]. Table 9a provides approximate costs using information from previous water reuse projects in 2009 USD [59], along with a comparison of reclaimed (recycled) water rates for various communities in the US (Table 9b) [25].

Table 9. (**a**) Water reuse projects financial costs. (**b**) Comparison of reclaimed (recycled) water rates [25].

(**a**)

Capacity (Million Gallons per Day, MGD)	**Treatment Technologies**	**Total Capital Cost (USD /kgal per Year)**	**Annualized Capital Cost (USD /kgal)**	**Capital Cost (USD /kgal)**	**Annual Capital Cost + O&M Cost (USD /kgal)**	**End Uses**	**Facility**
5	Secondary treated water–Filtration–UV	5.73	0.5	0.35	0.85	Landscape irrigation	Desert Breeze, NV, USA
10	Secondary treated water–Filtration–UV	4.23	0.37	0.68	1.05	Landscape irrigation	Durango Hills, NV, USA
16.4	Advanced Activated Sludge Treatment	1.14	0.1	0.05	0.15	Landscape irrigation, amenity reservoir	Trinity River Authority, TX, USA
30	Biologically aerated filters–Flocculation–Sedimentation–Filtration–Disinfection	13.57	1.18	1.06	2.24	Landscape irrigation, Industrial cooling, zoo	Denver Water, CO, USA
40	Biological Nutrient Removal (BNR) secondary treated water–Filtration–Chlorine Disinfection	18.75	1.63	1.02	2.65	Irrigation, industrial cooling, laundry, paper processing	West Basin, CA, USA
12.5	Microfiltration-Reverse Osmosis (RO)–Advanced Oxidation	30.72	2.68	2.38	5.6	Indirect Potable Reuse	West Basin, CA, USA
10	Activated Sludge Secondary Treatment with Denitrification–Anaerobic Digestion–Lime Treatment–Sand Filtration-Ozonation-Biologically Active Granular Activated Carbon Filtration–Final Disinfection	23.46	2.05	0.33	2.38	Indirect Potable Reuse	El Paso Water, TX, USA
20	Biological Nutrient Removal (BNR) secondary treated water–Filtration–Chlorine Disinfection–Soil Aquifer Treatment	11.26	0.98	1.18	2.16	Indirect Potable Reuse	Inland Empire, CA, USA

Table 9. *Cont.*

(**a**)

Capacity (Million Gallons per Day, MGD)	Treatment Technologies	Total Capital Cost (USD /kgal per Year)	Annualized Capital Cost (USD /kgal)	Capital Cost (USD /kgal)	Annual Capital Cost + O&M Cost (USD /kgal)	End Uses	Facility
24	Biological Nutrient Removal (BNR) secondary treated water–Sodium Hypochlorite Disinfection–Treatment Wetlands	3.92	0.34	0.35	0.69	Indirect Potable Reuse	Casey WRF/Huie Wetlands Clayton Co., GA, USA
70	Enhanced Primary Treatment–Activated Sludge and Trickling Filter Secondary Treatment–Microfiltration (MF)–Reverse Osmosis (RO)–Advanced Oxidation (ultraviolet light and hydrogen peroxide)	20.0	1.74	1.16	2.90	Indirect Potable Reuse	Orange Co. GWRS, CA, USA

(**b**)

Community	Potable Water Rates (First Tiers Only)		Reclaimed Water Rates	
	Rate per 1000 gal	Use	Rater per 1000 gal	Use
Tucson, AZ, USA	2.19	1–15 ccf	2.45	Variable on all use
	7.82	16–30 ccf		
Dublin San Ramon Services District, CA, USA	3.28	Tier 1 Volume charge, first 22,440 gallons	3.19	Flat rate volume charge
	3.48	Tier 2 Volume Charge over 22,440 gallons		
Eastern Municipal Water District, CA, USA	2.07	Tier 1 Indoor use	0.8	R-452 Non-Ag, Secondary, Disinfected-2009
	3.79	Tier 2 Outdoor use	0.88	R-452 Non-Ag, Tertiary, Disinfected, Filtered-2009
Glendale Water and Power, CA, USA	3.18	Commercial Rate	2.39	Non-potable purposes

Table 9. *Cont.*

(**b**)

Community	**Potable Water Rates (First Tiers Only)**		**Reclaimed Water Rates**	
	Rate per 1000 gal	**Use**	**Rater per 1000 gal**	**Use**
Irvine Ranch Water District, CA [1], USA	1.62	Residential Detached Base Rate 5–9 ccf	1.44	Landscape Irrigation Base Index 41–100% ET
	3.34	Residential Detached Inefficient Rate 10–14 ccf	3.01	Landscape Irrigation Inefficient Index 101–110% ET
	5.78	Residential Detached Excessive Rate 15–19 ccf	5.2	Landscape Irrigation Excessive Index 111–120% ET
Orange Country, FL, USA	1.04	0–3000 gal	0.74	Variable on >4000 gal/month
	1.39	4000–10,000 gal		
St. Petersburg, FL, USA	3.45	0–5600 gal	17.63	Unmetered–First acre
			10.1	Unmetered > 1 acre
			0.5	Metered
El Paso, TX, USA	1.94	Over 4 ccf	1.24	Variable on all use

Notes: ccf = 100 cubic feet; [1] Irvine Ranch Water District employs a steep inclined rate based on watering in excess of the evapotranspiration (ET) rate.

4.4. Water Reuse Distribution Infrastructure

According to Asano and Mills (1990), the network of the reclaimed water distribution system comprises all pipeline routes, storage reservoir locations, sizes, types, and pumping station locations and their capabilities. When elevation changes exist, it may be essential to divide the distribution system into two or more pressure zones; each pressure zone should be able to meet peak water demands. Therefore, redundant infrastructures are needed [60]. Figure 3 depicts a conceptual diagram of several distribution system configurations. Asano et al. (2007) discussed the distribution system types of loop, grid, and tree systems (Table 10). With a grid or loop system, each major reuse area is supplied from multiple directions, ensuring that all demands will be met even if a portion of the distribution system is disrupted. While in a tree system, a failure in the main supply line will interrupt service to all or a portion of the users. A tree system is generally not advised to be used for the distribution of water reuse due to the possibility of odors developing in the dead-end outlets [17].

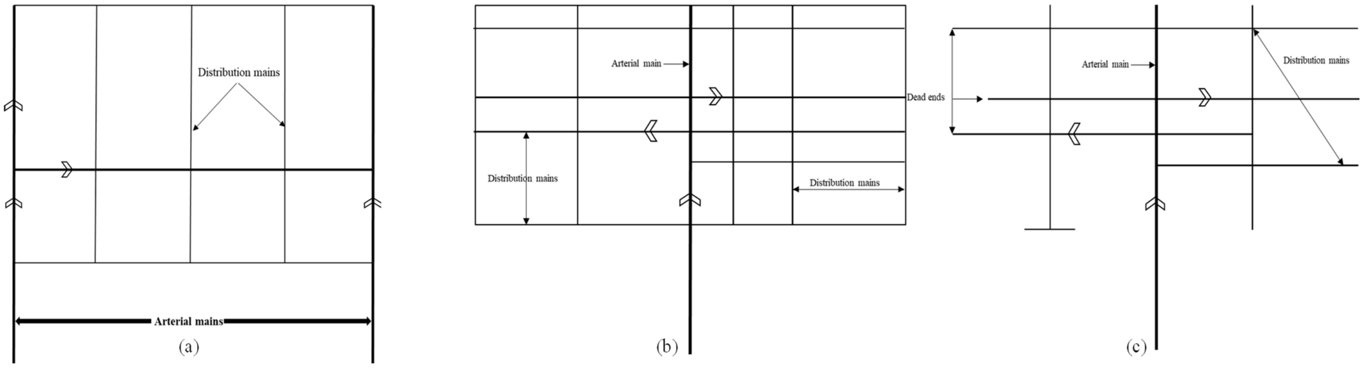


Figure 3. Pipelines distribution configurations: (**a**) loop, (**b**) grid, (**c**) tree.

Table 10. Types of distribution systems.

System Type	Description	Notes
Loop	The areas that are going to be served are surrounded by large feeder mains, and smaller cross feed lines are connected to the main loop.	Reclaimed water is distributed from two directions to the main reuse area. Looped systems have less head loss than tree system.
Grid	The piping is set out in a checkerboard arrangement, and the size of the pipe typically decreases as the distance from the source increases.	Pipe size reduction will reduce material costs and has similar advantages as the loop system.
Tree	It utilizes a single main that decreases in size the further away it is from the source.	Usually used for systems that do not need the higher level of reliability that loop and grid systems offer. The accumulation of build-up in dead ends can be avoided with regular line flushing.

The majority of states mandate that recycled water distribution pipelines to be purple; Pantone 512 or 522 is typically preferred for this purpose. Reclaimed water piping should be identified in accordance with state design guidelines, which may include labeling, tagging, and signs along the piping's alignment. PVC is a popular material for constructing reclaimed water pipes, as it is easy to infuse color during the manufacturing process. Reclaimed water distribution systems will contain all components characteristic of potable water distribution systems. Most standard system components are now available in purple, to facilitate the expanded installation of reclaimed water systems with purple color coding [25].

4.5. Water Reuse Planning Model

Planning a rational project requires well-defined objectives. The conventional framework for analysis begins with determining if a project has a single-purpose or multi-purpose, i.e., designed to serve two or more fundamental functions. The typical wastewater reclamation projects are intended for control or water supply. Water reuse planning generally consists of three stages [60]:

1. Conceptual level planning;
2. Preliminary feasibility investigation;
3. Facilities planning.

According to Asano and Mills (1990), a proposed project is drawn out during conceptual planning, then approximate costs are assessed and a potential market for recovered water is identified. If the conceptual planning seems viable, a preliminary feasibility analysis is conducted. Preliminary feasibility includes the following steps:

- Performing a market evaluation, i.e., identifying a market for recycled water and specifying the criteria that must be met (e.g., user needs for water quality and pricing);
- Evaluating the current water supply and wastewater facilities and creating some preliminary options that might service the entire market, in parts or in full, while meeting its technical and water quality needs;
- Comparing a wastewater reclamation and reuse option with other non-reclamation facilities, such as wastewater treatment for stream discharge or the construction of a reservoir for water supply;
- Considering technical needs, economics, financial advantages, marketability of recovered water, and other restrictions such as health protection of recycled water.

If wastewater reclamation and reuse look feasible, and desired based on the previous preliminary feasibility research, deeper planning may be explored, revised facilities options can be produced, and a final facilities' designs can be suggested [59]. The Water Environment Federation (WEF) also highlights the importance of holistic planning and decision-making frameworks, including but not limited to triple-bottom-line, "one water", and life cycle analysis. The WEF defines three components of water reuse planning, such as establishing a long-term vision for integrated water resource; setting strategic planning goals to create an integrated, reliable, resilient and sustainable water supply; and lastly, mapping the water resource supply/demand and infrastructure capacity [33].

5. Engineering Challenges for Water Reuse

Treatment technologies utilized for water reuse treatment should be more sustainable, energy efficient, and highly effective in treating wastewater. In addition to sustainability, the impacts of extreme weather events on current wastewater treatment systems require immediate attention. Water reuse should consider these changing conditions of the environment. Wastewater treatment technologies should be both sustainable and resilient. Many existing treatment technologies are not built and, therefore, may not be effective to treat emerging contaminants such as Per- and Polyfluoroalkyl Substances (PFAS). This should also be taken into consideration. In addition to that, the development and implementation of technologies can be affected by other non-technical aspects such as social, economic, and policy issues.

5.1. Sustainable Treatment Technologies

Incorporating sustainability in wastewater treatment drives intelligent innovation and efficient treatment. A lifecycle cost analysis tool may be used to examine the full extent of incorporating sustainability into wastewater treatment. The search for a sustainable solution is a multi-objective optimization issue since many indicators must be normalized and weighted in order to be included in a single ultimate objective. To create sustainable wastewater treatment, it is necessary to examine wastewater treatment systems comprehensively from broader environmental, economic, and social perspectives.

A sustainable advanced wastewater treatment in a project can contribute to the accomplishment of the Sustainable Development Goals (SDG). However, site-specific considerations must be considered when selecting wastewater treatment systems with the potential for co-benefits and governments' support. It is also vital to consider economic factors, treatment performance, carbon emissions, recycling, and social concerns. The latest sustainable wastewater treatment technologies are further discussed in Table 11 [61].

Table 11. The latest advanced sustainable wastewater treatment technologies.

Treatment Technology	Description
Scaleban	Scaleban is an innovation that enables industries to accomplish water saving and zero liquid discharge (ZLD). Scaleban solves the following typical issues connected with the use of wastewater treatment in cooling towers: hard water scaling, total suspended solids removal, corrosion, and biofouling. Cooling towers can be operated at greater TDS levels with the Scaleban system.
Forward Osmosis	FO is driven by differential osmotic pressure, and water diffusion occurs from lower (the feed side) to higher concentration (the draw side).
Activated Glass Media Filter	The Activated Glass Media Filter is a filter product produced from an aluminosilicate filter medium, which is subjected to a distinctive three-stage physiochemical activation process to attain an optimal particle size, shape, and charge. This process increases the filter's surface area by up to 300 times, resulting in improved mechanical and electrostatic filtering for enhanced effectiveness.
Vacuum Distillation	Vacuum distillation is a method used to purify substances that cannot be easily distilled under normal atmospheric pressure. This process separates impurities according to their varying boiling points.
Volute	Volute is a sludge dewatering device that continuously removes water and moisture from sludge.
Solar Detoxification	Solar detoxification is a process that utilizes ultraviolet (UV) light and a catalyst to eliminate harmful organic compounds and toxic substances from wastewater.
Sustainable Wastewater Treatment	Effluent is classified into three streams according to their TDS and COD concentration level. Recommendation of sustainable treatment then provided for each stream.

5.2. Resilient Wastewater Treatment

Resiliency in engineering systems may be defined as the capacity to foresee, endure, and recover from climatic effects including sea level rise, extreme flooding, extreme drought, wildfires, and other stressors. Because of the increasing frequency of these extreme events, engineers must design infrastructure systems for unpredictable climate change impacts. However, the ideal resilient infrastructures should be designed to withstand these extreme climate change impacts with the ability to mitigate damage and quickly recover to their full function [5]. A vulnerability assessment should be conducted in resilient infrastructure design for the purpose of (1) identifying the potential negative impacts of climate change on infrastructures; (2) understanding the scope of infrastructure vulnerability to these impacts; (3) developing a process for the project engineers to undertake a more comprehensive and site-specific vulnerability assessment; and (4) informing the operational strategy and adaptative development of resilient infrastructures [5]. Pamidimukkala et al. (2021) classified technical and infrastructure challenges along with the strategies and approaches to mitigate their related challenges (Table 12) [62].

Table 12. Technical and infrastructure challenges along with mitigation approaches for resilient water infrastructure.

Technical and Infrastructure Challenge	Frequency of Occurrence in Previous Studies	Preventive Strategy	Corrective Strategy
Aging infrastructure	51	Geographic Information System (GIS)	Capital Investment
Improper maintenance of water infrastructure	47	Implementing appropriate policies and measures	-
Traditional wastewater treatment methods	39		Protection, accommodation, and retreatment of infrastructure
The interdisciplinary nature of infrastructure systems	32	GIS Awareness of infrastructure resilience and role of media	-
Loss of disinfectant residuals	26	The Environmental Protection Agency Network (EPANET)	-
Escalating physical threats	21	GIS The Water Network Tool for Resilience (WNTR)	-
Redundancy in the water distribution systems	16	-	Examining decisions on management techniques
Interdependencies of water and wastewater infrastructure to electric power	14	Intervention's framework	-
Storage capacity in the wastewater collection system	14	Increasing the storage capacity of wastewater collection system Implementing appropriate policies and measures	-
Backup power and structural stability of drinking and wastewater treatment and pumping facilities	7	-	-
Inefficient pond sand filters	4	Efficient pond sand filters	-
Unauthorized structures	3	Implementing appropriate policies and measures	-

5.3. Treatment of Emerging Contaminants

The majority of municipal wastewater treatment plants (WWTPs) are primarily designed to treat organic nutrients, such as carbonaceous, nitrogenous, and phosphorus substances, and not designed to remove emerging contaminants (ECs), especially persistent and harmful ECs such as antibiotics [63,64]. However, some ECs might be effectively removed with conventional wastewater treatment plants [65]. WWTPs act as primary barriers against the spread of ECs and developing the treatment processes of conventional WWTPs could further reduce the discharge of ECs into the environment.

Numerous countries across the globe are utilizing advanced treatment technologies to construct WWTPs and meet the EC removal objectives [66,67]. In recent years, advanced oxidation processes (AOPs) have been widely researched as an effective technology for removing ECs, but they have yet to be fully implemented at a large scale [68]. Another popular method studied for EC removal is adsorption, with activated carbon (AC) being a commonly used adsorbent due to its high porosity, specific surface area, and strong surface interaction [68,69]. AC treatments are highly effective in removing ECs and seem to be a feasible solution for enhancing WWTPs. However, further investigation is required to assess the practicality of implementing AC adsorption in combination with other treatments, as well as using ACs obtained from different sources and produced in various environmental settings. In contrast, the full-scale use of Granulated Activated Carbon (GAC) and Powdered Activated Carbon (PAC) has been extensively studied and documented [70–72]. Additionally, modeling and simulation studies have been conducted to assess the performance of hybrid systems combining different treatment technologies for the removal of specific pollutants from wastewater. For instance, a recent study proposed a hybrid system of a trickle bed reactor and a multistage reverse osmosis process for the removal of phenol from wastewater [73]. Modeling and simulation studies can provide valuable insights into the design and optimization of hybrid treatment systems for the removal of ECs.

Table 13 summarizes the removal efficiencies of certain ECs by PAC and GAC in full-scale applications [72]. Recently, the detection and treatment of per- and poly-fluoroalkyl substances (known as PFAS) have become a growing concern, receiving the attention of all stakeholders including environmental regulators, researchers, and the water industry.

Table 13. Summary of removal efficiencies by PAC and GAC in specific initial concentration.

Emerging Contaminants	Initial Powdered Activated Carbon (PAC) Concentration	Removal Efficiency Using PAC (%)	Initial Granular Activated Carbon (GAC) Concentration	Removal Efficiency Using GAC (%)
Bezafibrate	1300	90	-	-
17-Alphaethylestradiol	0.24 ± 0.07	83.3	<20	50
17-Beta estradiol	4.68 ± 0.89	99.9	2	>43
Diclofenac	NR	96–98	NR	>98
Propranolol	NR	91–94	-	-
Sulfamethoxazole	NR	58	NR	90
Clarithromycin	NR	88	-	-
Carbamazepine	NR	92	66	23
Iopromide	NR	70	NR	>80
Mecoprop	NR	65	-	-
Bisphenol A	12.60 ± 2.02	53	NR	66
Erythromycin	-	-	300 ± 200	99.9
Ciproflaxacin	-	-	130	82.3
Carbamazepine	-	-	NR	23
Nonylphenol	-	-	NR	84
Triclosan	-	-	NR	95
Galaxolide	-	-	NR	79

5.4. Social, Policy, and Economic Barriers

Lee and Jepson (2020) compile published research on the implementation of water reuse around the world, especially in urban areas. The conceptual framework called PESTLE. PESTLE represents six different considerations that are important for water reuse: Policy, Economic, Social, Technical, Legal/Institutional, and Environmental. Policy barriers include lack of guidelines or policies surrounding water reuse, lack of stakeholder's involvement, lack of public trust in government services, and lack of policy openness. Economic barriers include high capital cost, high operation & maintenance (O&M), restricted market development, and economic concerns including the possibility of financial losses and the fixed price of water rates. Social barriers include public perception of risk, socio-economic, and cultural factors. Technical barriers are poor management, lack of infrastructure availability, the need of additional treatment or infrastructure, and treatment technologies' performance. Environmental barriers are health risks and environmental damage. Legal/Institutional barriers includes lack of institutional support and enforcement challenges [74,75].

Anderson and Meng (2011) recommend (1) educating stakeholders; (2) collecting reliable data on industrial and commercial water consumption patterns and water quality demands; and (3) urging federal, state, regional, and local authorities to implement water reuse regulations [27].

6. Case Studies of Water Reuse

6.1. Selected Case Studies in the U.S.

In this section, we review four case studies of water reuse. These cases represent prominent implementations of water reuse in the U.S. Other than these four mentioned case studies, several significant case studies are also discussed and are summarized in Table 14 [76].

6.1.1. California Case Studies

The Edward C. Little Water Recycling Facility: West Basin Municipal Water District

The Edward C. Little Water Recycling Facility (ECLWRF) in El Segundo, is the first wastewater recycling plant in the world to create five varieties of "designer" water, including Title 22 irrigation water, low pressure boiler feedwater (LPBF), high pressure boiler feedwater (HPBF), cooling tower water, and seawater barrier/ground water recharge for indirect potable reuse (IPR). ECLWRF has produced approximately 634 million m^3 of recycled water since it began operating. Approximately 52% of West Basin's recycled water is provided to refineries, 36% to groundwater seawater barriers, and 12% to irrigation and other purposes. West Basin was also the first U.S. water agency to create indirect potable water utilizing innovative microfiltration, reverse osmosis, advanced oxidation by UV light, and the hydrogen peroxide water purification method.

West Basin implemented water reuse as a solution to address multiple challenges, including a water demand that exceeded the local supply, an unreliable and restricted imported water supply, the necessity for a dependable water supply for local industries, and the support of local authorities in improving the situation [77]. The end users and treatment technologies for West Basin are shown in Table 15.

The West Basin Municipal Water District has been a leader in the application of technology to produce water for indirect potable reuse. The West Basin Municipal Water District adopted microfiltration as a pretreatment step for reverse osmosis and ozone as a pretreatment before microfiltration. West Basin has also effectively performed low-pressure, high-intensity UV disinfection and advanced oxidation for groundwater injection (indirect potable reuse). This technical achievement paves the way for other agencies to pursue similar treatment processes for IPR.

Table 14. Water reuse cases in the United States.

Project/Location	Plant Capacity	Type of Use	Benefits	Cost/Revenue/Funding
Hampton Roads Sanitation	15 MGD	Industrial	Reduce costs to the nearby refinery for process, provide more secure water supply in drought condition, conserve potable water resources, and reduce the nutrient load released to the river	Capital cost: USD 2.6 million O&M cost: USD 135,000–USD 150,000 (fiscal year 2003)
Irvine Ranch Water District	15 MGD and 5.5 MGD	Landscape and agricultural irrigation	Maximize drinking water supply, conserve potable water by switching recycled water for non-potable uses, and minimize the mount of treated wastewater that must be sent to regional wastewater agency for disposal through an ocean outfall	O&M cost for treatment and distribution: USD 6.6 million
Monterey County Water Recycling Project	30 MGD	Agricultural	Conserve potable water for agricultural, reduce sea water intrusion by 40 to 50%	Capital cost: USD 78 million Total cost to treat and deliver to agricultural areas: USD 225/ac-ft Revenue: USD 6 million annually
San Antonio Water System	116 MGD (total from 4 plants)	Industrial and commercial	51% cost saving from potable water rates, reduce dependency on the existing aquifers supply, reduce cost for fertilizer due to nutrients recovered from wastewater	Capital cost: USD 124 million
Water Conserv II	42 MGD	Agricultural, commercial, and rapid infiltration basins (RIB) to recharge aquifer	Elimination of discharge to environmentally sensitive surface waters, demand reduction on aquifer, and enhanced aquifer storage	Capital cost: USD 277 million O&M and distribution cost: USD 4.8 million USEPA funding: USD 100 million
Pinellas County's Reclaimed Water Program	9 MGD and 33 MGD	Irrigation of public access areas	Reduce cost for potable water purchases, and additional potable water savings	Cost to upgrade WTP: USD 150 million Capital cost for water transmission and distribution: USD 140 million Annual O&M cost: USD 1.2 million Revenue: USD 87 million Grants from SWFWMD: USD 28 million

Table 15. West Basin's different types of water reuse and their treatment technologies (Source: West Basin Municipal Water District [WBMWD]).

End Users	Treatment Technologies
Non-potable irrigation (residential, commercial, industrial)—Title 22	HRC, tertiary media filter, Cl disinfection
Groundwater injection for West Coast Basin Seawater Barrier	Ozone, MF, RO, UV-AOP, decarbonation, Cl disinfection
Low Pressure Boiler Feed (LPBF) for Chevron Refinery—Industrial	Ozone, MF, RO (Single Pass), decarbonation
High Pressure Boiler Feed (HPBF) for Chevron Refinery—Industrial	Ozone, MF, RO (Double Pass), decarbonation
Ammonia-free water for cooling towers at Chevron Refinery—Industrial	BAF
Ammonia-free water for cooling towers at Torrance Refinery—Industrial	BAF
BF water for Torrance Refinery—Industrial	MF, RO (Single Pass), decarbonation
Ammonia-free water for cooling towers at Marathon Refinery—Industrial	BAF
BF water for Marathon Refinery—Industrial	MF, RO (Single Pass), decarbonation

Notes: BAF = biologically aerated filter; Cl = chlorine; HRC = high-rate clarifier; MF. microfiltration; RO = reverse osmosis; UV-AOP = ultraviolet advanced oxidation process.

The Groundwater Replenishment System (GWRS): Orange County Water District

The Groundwater Replenishment System (GWRS) is a joint project between the Orange County Water District (OCWD) and the Orange County Sanitation District. It is the biggest water purification facility for indirect potable reuse in the world. GWRS can generate up to 265,000 m^3/d of high-quality water that can fulfill the supply demands of over 600,000 people. The GWRS employs an advanced treatment process comprising three stages: membrane filtration (MF), reverse osmosis (RO), and ultraviolet irradiation using peroxide (UV-A) for advanced oxidation (Figure 4). The GWRS system is capable of reducing the TDS concentration from 1017 mg/L to as low as 55 mg/L [78] and produces water quality that exceeds both state and federal regulations for drinking water.

The main drivers behind GWRS are: (1) to satisfy Orange County's needs for peak demand (2) to expand water recycling and obtain the benefits through reusing highly processed water [17]. Public acceptance of indirect potable reuse (IPR) is the main indicator used by OCWD to evaluate success. The agency managed an active outreach effort to educate and gain support from local, state, and federal policymakers, business and civic leaders, health professionals, academia, and environmental supporters.

OCWD and OCSD collaboration overcome the 'toilet-to-tap" misconception and earned public support [25]. It continues to be a world leader in IPR and sustainability implementation [17]. Singapore designed a smaller-scale IPR project after the GWRS. OCWD is leading the way for others to obtain public acceptance of recycled water by injecting recycled water into the drinking water supply [25].

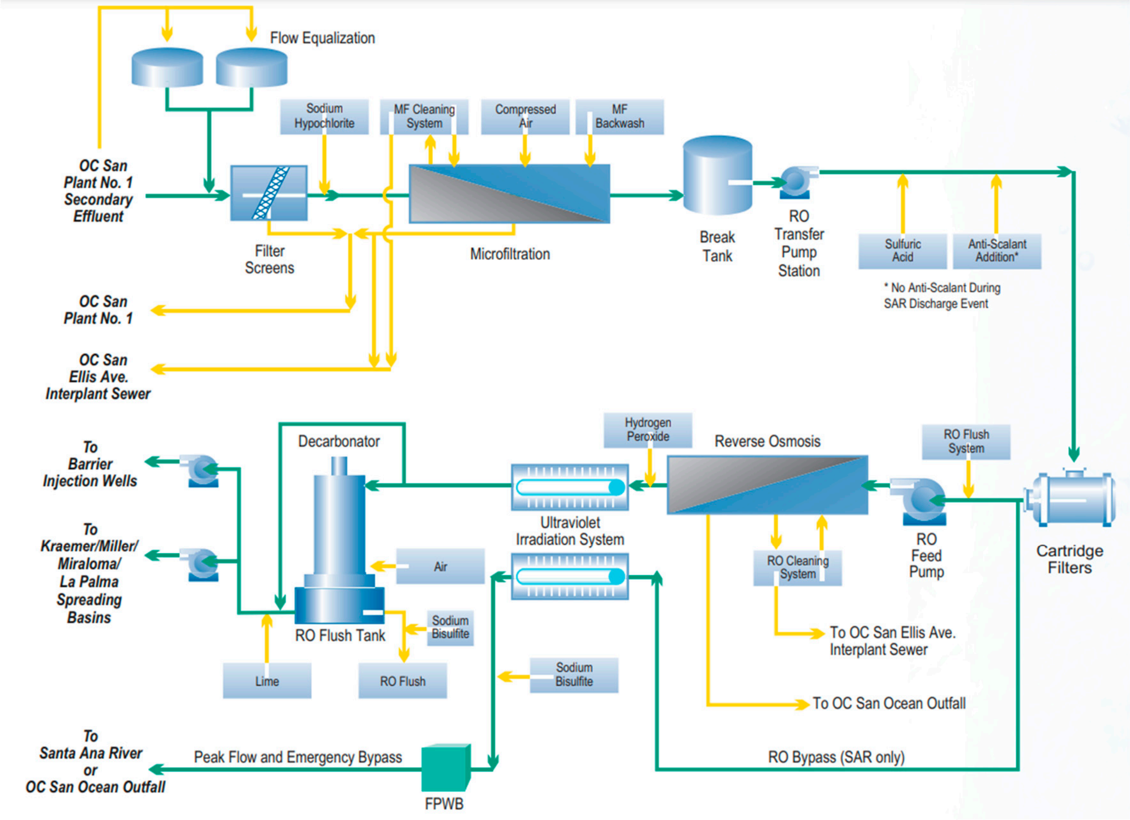


Figure 4. GWRS treatment process flow diagram [78].

6.2. Arizona Case Study

Scottsdale Water Campus: Scottsdale Water Resources Department

According to Freeman et al. [79], the Scottsdale, Arizona water campus is a complex water reclamation facility with updated water treatment technology. The average depth of groundwater in Scottsdale is roughly 150 m (500 feet) [17]. The 141-acre campus consists of a 50 MGD (190,000 m^3/d) conventional water treatment facility, a 12 MGD (45,000 m^3/d) water reclamation plant, and an advanced water treatment plant. Treatment technologies adapted are PPL Microfiltration (MF) membrane (U.S. Filter CMF) and polyamide RO [79]. The treatment process flow diagram is depicted in Figure 5. A total of 27 vadose zone injection wells have been established at the Scottsdale water campus in Scottsdale, Arizona, to recharge 40,000 m^3/d (10 Mgal/d) of RO-treated water [80].

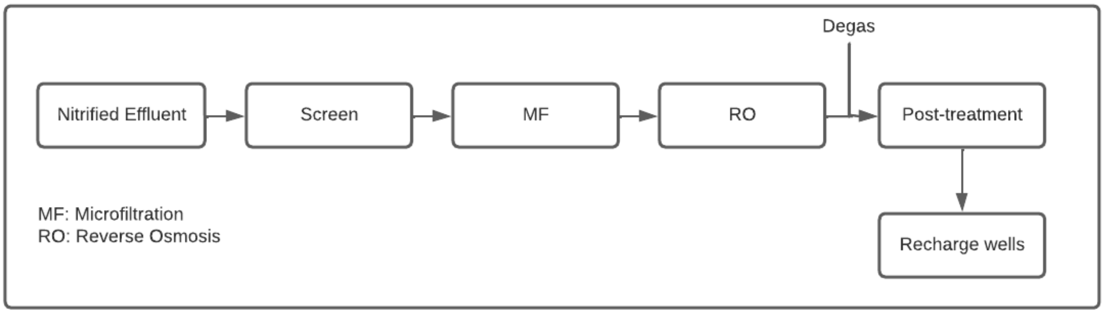


Figure 5. Scottsdale Water Campus treatment process flow diagram.

The Scottsdale water campus was the first to deploy vadose zone injection wells on a wide scale. The facility injects microfiltered surface water into vadose zone wells and claimed that the RO has not experienced clogging difficulties in 10 years. Microbial development can clog a vadose zone injection well; hence, reclaimed water with extra chlorine residuals of 2 mg/L is also recharged into the same vadose zone injection wells to avoid microbiological development. When microbial growth clogs the injection well, chlorine and other cleaning agents will become ineffective in reclaiming the wells [17].

6.3. Florida Case Study

St. Petersburg: St. Petersburg Water Resources Department

According to the Florida Department of Environmental Protection, there are currently 455 wastewater treatment facilities producing effluent that can be reused. These facilities have a capacity of 2779 MGD and treats 1701 MGD of domestic wastewater [81]. One of the successful water reuse cases in Florida is the St. Petersburg water reuse case.

St. Petersburg is a residential community on Florida's west-central coast with a population of 250,000. St. Petersburg has no substantial surface or groundwater resources to supply potable water; therefore, water is sourced from nearby counties. St. Petersburg's condition and demanding wastewater discharge regulations led to one of the world's largest municipal water reuse systems [82]. The plants have a total rated capacity of 260,000 m^3/d, with treatment capacities varying from 47,000 to 76,000 m^3/d (68.4 MGD). The treatment processes include grit removal, activated sludge biological treatment, secondary clarification, chemical coagulation, filtration, and disinfection.

The initial reclaimed water distribution system served golf courses, parks, schools, and significant business districts. Extensive biological studies in the late 1970s and early 1980s led to Florida Department of Environmental Protection (FDEP) and the USEPA approval for expanding the reclaimed water system into residential areas. In 1986, a USD 10 million system was built to serve limited residential and business areas. Expanding the recovered water infrastructure has reduced potable water demands. The demand for potable drinking water has significantly decreased because of the continued expansion of the reclaimed water infrastructure [17]. The excess recycled water and improperly treated wastewater are disposed of through ten deep injection wells at four Water Reclamation Plants (WRPs) [82].

Recovered water demand has played a key role in reducing the consumption of potable water since it was first introduced. The establishment of water reuse infrastructure has resulted in significant economic and environmental benefits. The annual demand for potable water has been stable, whereas the demand for reclaimed water is continuously increasing. Furthermore, water reuse has benefited the city utility customers economically [17].

6.4. International Case Studies

6.4.1. Singapore: NEWater

Singapore is a small dense city-state with a total area of 270 square miles, where approximately 5 million people live. Singapore has a yearly heavy rainfall of 2400 mm. Aside from its heavy rainfall, Singapore is experiencing water scarcity due to the small land area capability to collect and retain the rainfall. On the other hand, poor management of the heavy rainfall can also cause flooding. In 2015, Singapore was declared to be under severe water stress by the year 2040 by World Water Resources.

Singapore's main source of water comes from the local catchment process, water desalination process, and NEWater process to fulfill the water demand in the country [83]. Singapore utilized combined technologies of Microfiltration, Ultrafiltration, Reverse Osmosis, and Ultraviolet disinfection (Figure 6) to produce NEWater. Currently, four NEWater facilities provide an average of 30% of Singapore's water consumption; by 2060, this amount is projected to climb to 55%, at which point NEWater output might reach 440 million imperial gallons per day (MGD) [84]. Singapore water reuse products are divided into two categories: industrial water and NEWater. Industrial water is considered a lower-grade water that was first introduced in 1996 and used to replace potable water resources for non-potable use in industries. The term for higher-grade water in Singapore is NEWater. NEWater is utilized for direct non-potable use (NPDU) and indirect potable use (IPU). The quality of NEWater surpasses the drinking quality standard set by WHO and U.S EPA [85].

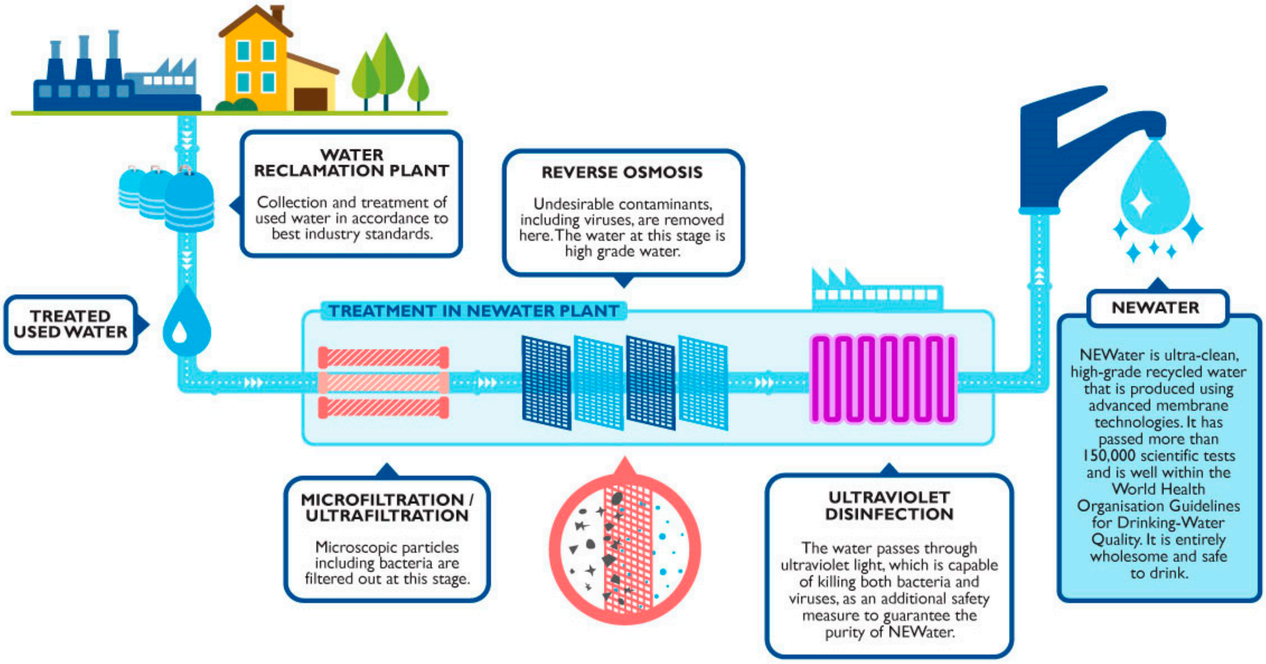


Figure 6. Singapore NEWater treatment process diagram [86].

Technologies used to produce NEWater are Reverse Osmosis (RO) and Ultraviolet (UV) disinfection. In 1998, PUB initiated a study to determine if NEWater could be used to supplement Singapore's water supply through planned IPU [86]. The study consisted of three main components: (1) a demonstration plant that used microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) technologies to produce 10,000 m^3/day of NEWater; (2) a Sampling and Monitoring Program to evaluate the quality of the water; and (3) a Health Effects Testing Programme to assess the safety of NEWater. Public perception was also taken into consideration. From 2000 to 2002, the demonstration plant was constructed, and a team of experts examined its results. According to PUB, it was concluded that NEWater met or exceeded the WHO Drinking Water Quality Guidelines and USEPA National Primary Drinking Water Regulations and was deemed safe for human consumption [85].

6.4.2. Cyprus: Suwanu Europe

Cyprus is an island country located in the eastern Mediterranean Sea and currently facing drought conditions and water scarcity. The annual inflow of water to Cypriot dams decreased from 79 million cubic meters (MCM) in 1987 to 48.9 MCM in 2017. Water consumption in Cyprus is mostly for agriculture and domestic use. The agricultural sector will be most likely affected by water scarcity challenge [87] since the water demand for irrigation (agricultural and landscape) is roughly 160 MCM or 59% of the total water demand. Consumption of domestic use is 29% of the overall water, 5% for tourism, 3.3% for livestock farming, and 3% for industrial use. Dams and desalination supply 85–90 percent of total drinking water, and up to 40 percent of agriculture water provided by dams and reclaimed water combined [88].

Reclaimed water in Cyprus is utilized for irrigation, enrichment of aquifers, infiltration in dry riverbeds, and discharge into the sea. Treatment technologies used in Cyprus are mostly chlorination/dechlorination disinfection (Table 16). Currently, reclaimed water supplies existing and new irrigation networks of 5000 acres. Since 2004, recycled water has been utilized to recharge artificial aquifers. This water is pumped back up from the aquifers and distributed to water-stressed agricultural areas via irrigation pipelines. Artificial recharge controls seawater intrusion, stores effluent water for later reuse, serves as an eventual natural distribution system, purifying effluent water (reducing biological load), and saving freshwater [89].

Table 16. Capacity of the main UWTPs in Cyprus and technologies applied [90]. (Source: Water Development Department).

WWTP	Capacity (m^3/day)	Capacity (Person Equivalent (PE))	Biological Treatment Process Applied	Tertiary Treatment Process Applied
Anthoupoli	13,000	130,000	Membrane Bioreactor (UF)	-
Vathia Gonia (NSB)	22,000	202,000	Membrane Bioreactor (MF)	UV disinfection
Larnaca	18,000	100,000	Membrane Bioreactor	Sand filtration—Chlorination
Moni Limassol	40,000	272,000	Conventional Activated Sludge	Sand filtration—Chlorination
Paphos	19,500	160,000	Conventional Activated Sludge	Sand filtration—Chlorination
Paralimni-Ayia Napa	21,000	125,000	Conventional Activated Sludge	Chlorination
Total	133,500		UF: Ultrafiltration; MF: Microfiltration	

The Water Development Department (WDD) and the Cyprus Urban Sewerage Boards (Public Utility Organizations) are responsible for the construction of water reclamation facilities and the sewerage networks, while the Urban Sewerage Boards are responsible for their operation and maintenance. A total of 80% of the capital cost is covered by the European Community, while 20% of the capital cost and 100% of O&M cost are covered by the Urban Sewage Boards (through taxation). Cyprus is able to sell the reclaimed water 33–40% cheaper than the freshwater price. This is one strong reason for the end-users to accept reclaimed water [91].

Despite the critical need for alternative water supplies to address water security issues, public acceptability of recycled water programs remains a major issue [92]. There are psychological barriers such as fear of the "yuck factor", health hazards, and lack of trust in authorities to handle risks [93].

6.4.3. China: Tianjin Megacity Water Reuse

Tianjin, a megacity located in northeastern China, owes its existence and development to the Haihe River, which has nourished its people for generations. The Haihe basin is the general name for the many basins of the river and its tributaries, and it is the historical natural river that has shaped the life of Tianjin. However, with the population growth, city expansion, and water source exploitation, Tianjin has become a water scarce city [94]. The overexploitation of water resources has significantly lowered the water table, resulting in land subsidence [95]. The per capita water capacity is only 1/15 of the national per capita and 1/60 of the global per capita water availability, making this region extremely water scarce. Tianjin is one of the most significant industrial cities in China and 80% of Tianjin water consumption is allocated to industrial activities. The challenges for water reuse in Tianjin are: (1) there are not enough pipes, (2) large clients using low water volume, and (3) public acceptance [91]. To address the issue of water scarcity, various approaches have emerged as the most prominent solutions, such as water conveyance from southern China, desalination, and wastewater reclamation. Comparing the three approaches, Tianjin decided to implement wastewater reclamation as the main solution for water scarcity considering the project cost and long-term investment in wastewater reclamation [94]. The first water reclamation plant was built in 2002, Ji Zhuangzi WTP, which has a total capacity of 50,000 m^3/d. Ji Zhuangzi WTP has two treatment process systems. The first one consists of coagulation, sand filtration, and disinfection producing 30,000 m^3/d of recycled water for industrial activities. The second system consists of coagulation, ozone, and continuous external pressure microfiltration (CMF) providing water for landscaping and urban miscellaneous or (residential areas) [91]. With the growing population and growing demands, the Ji Zhuangzi WTP has upgraded its treatment technologies and capacity. The sand filter was replaced by a submerged microfiltration (SMF) unit and the treatment capacity was increased to 40,000 m^3/d.

As a coastal city, Tianjin's wastewater has a significant salt content, requiring reverse osmosis (RO) to control salinity. Currently, Tianjin's four water reclamation plants use the core treatment train, shown in Figure 7, which includes coagulation, micro- or ultrafiltration, reverse osmosis, ozonation, and chlorination. In 2020, Tianjin recycled 11% of its wastewater mainly for the scenic environment, industrial (cooling water), and municipal (toilet flushing, landscape irrigation). The government of Tianjin has expressed interest in turning wastewater into a substitute for tap water [94]. Toward this goal, the city approved an investment mode for building water reclamation infrastructure, supported the development of main pipelines, and enforced a set of rules for reclaimed water development. In the meantime, people have become more open to using recycled water [94].

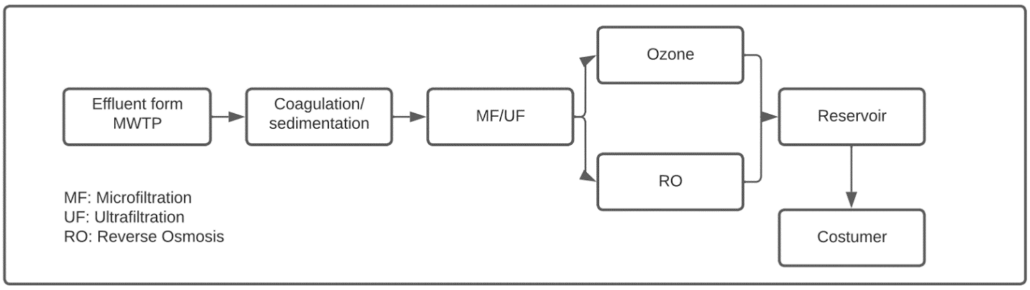


Figure 7. Wastewater treatment process at Tianjin Wastewater Treatment Plant.

As illustrated by this case study, government endorsement and promotion are very important in any water reuse projects. It is beneficial for water treatment plants and water reuse infrastructure development. Public acceptance of water reuse projects may also be positively influenced if projects had the support of the government [94].

6.4.4. Israel–Jordan: Advanced Wastewater Treatment Technology for Crop Irrigation

Israel is a semiarid nation with inadequate natural water supplies and this condition is expected to worsen the future. To mitigate water crisis and increased water demand, treated wastewater reuse and desalination have become Israel's primary sources of water. As of 2016, Israel recycles 86% of its sewage, and provides 50% of the country's irrigation water [96]. As stated in EPA's 2012 Guideline for Water Reuse, most wastewater use comes from secondary treatment plants or other lower-quality sources, which typically contain pathogens, organic compounds, and salts that can harm soils and crops if used for short- or long-term irrigation [25].

Higher water quality is needed for agricultural use. Considering this matter, the Technion–Israel Institute of Technology, Al-Quds University and the National Center for Agricultural Research and Extension in Jordan collaborated to investigate membrane treatment approach for removing polluting agents and reusing the wastewater [25,97–99]. Advanced membrane treatment technologies are expected to produce effluents with higher quality that are essentially suitable for unrestricted irrigation. These treatments will be based on ultrafiltration (UF) and two-stage reverse osmosis (RO). The operation of the UF was regularly monitored as the UF required weekly NaOH cleaning, periodic acidic (HCl) cleaning, and backwash cycles. To prevent damage, the UF feed was chlorinated as a biofouling preventative, followed by dechlorination before entering the RO membranes. Up to 88% of the UF system's water was recovered. UF permeate is conveyed to the initial RO stage (RO1). The RO1 brine was then conveyed to the RO2 stage. Soil salinity, shown in Table 17, is expressed as electrical conductivity (EC) induced by irrigation water from UF permeate, UF-RO permeate, and RO permeate compared to irrigation water from secondary treated effluent after two seasons at a Jordanian site and after six years at the Arad site in Israel [25].

Table 17. Electric conductivity in soil induced by secondary treated effluent, UF permeate, and mix UF-RO, and RO permeate after 2 seasons at Jordanian site and 6 years at Arad site, Israel [25].

Irrigation Water Quality		**Jordan (after 2 Seasons)**		**Israel (after 6 Years)**	
		EC (dS/m)		**EC(dS/m)**	**Sodium Adsorption Ratio (SAR)**
Depth (cm)		0–20	20–40	-	-
Effluent from Secondary Treatment		3.24	3.01	16	25
UF Permeate		2.83	2.71	9	20
RO Permeate		-	-	2	3
UF-RO mix	30–70	-	-	6	16
	50–50	1.14	0.99	-	-
	70–30	-	-	5	12

The research results provide guidance for the regional and global operation of large-scale wastewater treatment facilities that are economically and technically possible. They show the possibility of adding up to 600,000 m^3 of high-quality water to the regional resources for irrigation and aquifer recharge. The general conclusion and advice to water authorities for keeping an adequate water supply for agriculture and ensuring the sustainability of production is to establish large-scale membrane systems at secondary treatment facilities over the entire region [25]. The development of large-scale desalination makes it possible to significantly increase the amount of freshwater available. Moreover, allowing for greater wastewater recycling since the water salinity is reduced. Desalination combined with higher-quality wastewater minimize Israel's vulnerability to the impacts of climate change and extreme weather conditions [100,101].

6.4.5. Germany: MULTI-ReUse Project

The use of treated wastewater is crucial in the water cycle, although it is typically discharged into rivers which is considered acceptable from an environmental standpoint. However, the water is not suitable for agricultural or industrial use. The goal of the MULTI-primary ReUse project is to create a modular water treatment system that can provide different grades and volumes of service water for various applications at reasonable costs. This project was developed to evaluate and demonstrate the reuse of water from a wastewater treatment facility located in the northern coastal region of Germany, as part of a German research program on water reuse. Despite the success of water reuse projects worldwide, the implementation of such projects in Germany is still a topic of critical and defensive debate, according to the Umwelt Bundesamt (UBA) in 2017 [102].

Based on climate projections, it is expected that summers in central Europe will be warmer and drier in the future. The effects of this trend on groundwater levels and surface water reservoirs have already been observed in several regions of Germany during 2018 and 2019, as reported by Hellwig et al. [103]. Considering these climate-related impacts, a regional water board in Lower Saxony, Germany, agreed to examine municipal wastewater reuse for industrial applications. Nordenham is a city in the Wesermarsch region of northwest Germany, where water-intensive industries are located. However, the district does not have access to its own source of potable water. Therefore, drinking water is extracted from groundwater sources in neighboring districts, purified, and transported over long distances to meet the needs of the industrialized area.

This study was an integral part of a German multicenter research consortium's MULTI-ReUse project. The technological investigations centered on the membrane processes ultrafiltration (UF) and reverse osmosis (RO) with additional treatment phases included. Depending on the intended use, the processes may be arranged in various treatment chains (Fit-for-Purpose). Reliable wastewater treatment technologies were required to maintain the desired water quality. There is lack of data to evaluate how extreme events (e.g., drought or extreme precipitation) affect membrane operations at the reclamation plant. Chemicals present in WWTP effluent may potentially disturb the in/out UF process. High in situ monochloramine production before the RO membrane prevented biofouling and maintained performance. Passing the membrane and stabilizing the water reduces bacterial proliferation in RO permeate. Biofouling is common in hot summers and droughts. Energy and maintenance expenses for rigorous cleaning of membrane pipes can be minimized, increasing treatment efficiency. High in situ formation of monochloramine before the RO membrane was a very effective way to prevent biofouling and keep the performance of the RO membrane.

Membrane processes provide several advantages, but a major drawback is the generation of concentrates and residues during treatment, and their proper disposal or post-treatment. When UF and RO membranes are in use, chemically contaminated water is generated, which must be disposed of appropriately.

There are three types of water ReUse considered. ReUse Water 1 has high neutral salt content (chloride, sulphate, and nitrate). ReUse Water 2 is similar to ReUse Water 1. In ReUse Water 3, neutral salt concentrations have been reduced and alkalinity is almost gone. It was found that polymeric materials (e.g., PE pipes) are suitable for all three types of ReUse Water. Due to the high neutral salt concentration of ReUse Waters 1 and 2, metallic items can only be used under specific network construction and service circumstances, and corrosion inhibitors may be required [104].

7. Appraisal of Water Reuse in Greater Chicago Area

Northeastern Illinois's sources of water are Lake Michigan, the Fox and Kankakee Rivers, and the groundwater. In 2005, Lake Michigan contributed around 69% of the water used for all purposes excluding power generation and approximately 85% of the public water supply. Most of the water withdrawn for power generation is returned straight to its source, with a tiny portion lost to evaporation after being circulated once for cooling [105].

The groundwater sources available to northeastern Illinois include the Ancell Unit, Ironton-Galesville Unit, and Mt. Simon Unit. In most of northeastern Illinois, shallow and deep aquifers are divided by a large, somewhat impermeable confining unit that significantly restricts vertical water leakage to the deep aquifers. In practice, wells bored into deep units are sometimes left open to all overlying units, so water from both shallow and deep units can be withdrawn [102]. However, withdrawals from such wells (deep wells open to shallow aquifers) accounted for less than three percent of the region's total groundwater withdrawals. Time and financial constraints limited the ability to demonstrate potential future water supply networks. Current supply concerns are the southwest suburbs where the source of water is from groundwater, especially the city of Joliet. Withdrawals from deep, confined sandstone aquifers for more than a century have resulted in unprecedented decreasing water levels. A model created by the Illinois Water Survey indicates that certain wells might collapse as early as 2030 and the future of water supply for communities with groundwater as their main source of water is uncertain [106].

After the completion of the three canals (CSSC, North Shore Canal, and Cal-Sag Channel) by the early 1920s, the Illinois diversion from Lake Michigan presented a problem for the Great Lake basin. The United States Supreme Court issued a decree in 1967 addressing these concerns. The decree restricted the amount of water that Illinois could divert from the Mississippi River to 3200 cfs for a 5-year running average and gave the state of Illinois the authority to decide how this limit should be distributed. This decree was later amended in 1980 because the Illinois diversion was consistently exceeding the annual limit. This amendment restricted the amount of water diverted from Lake Michigan by the state of Illinois to 3200 cfs yearly over a period of forty years [27].

A study conducted by Dziegielewski and Chowdhury [107] depicted three scenarios of water demand in Northern Illinois (Figure 8).

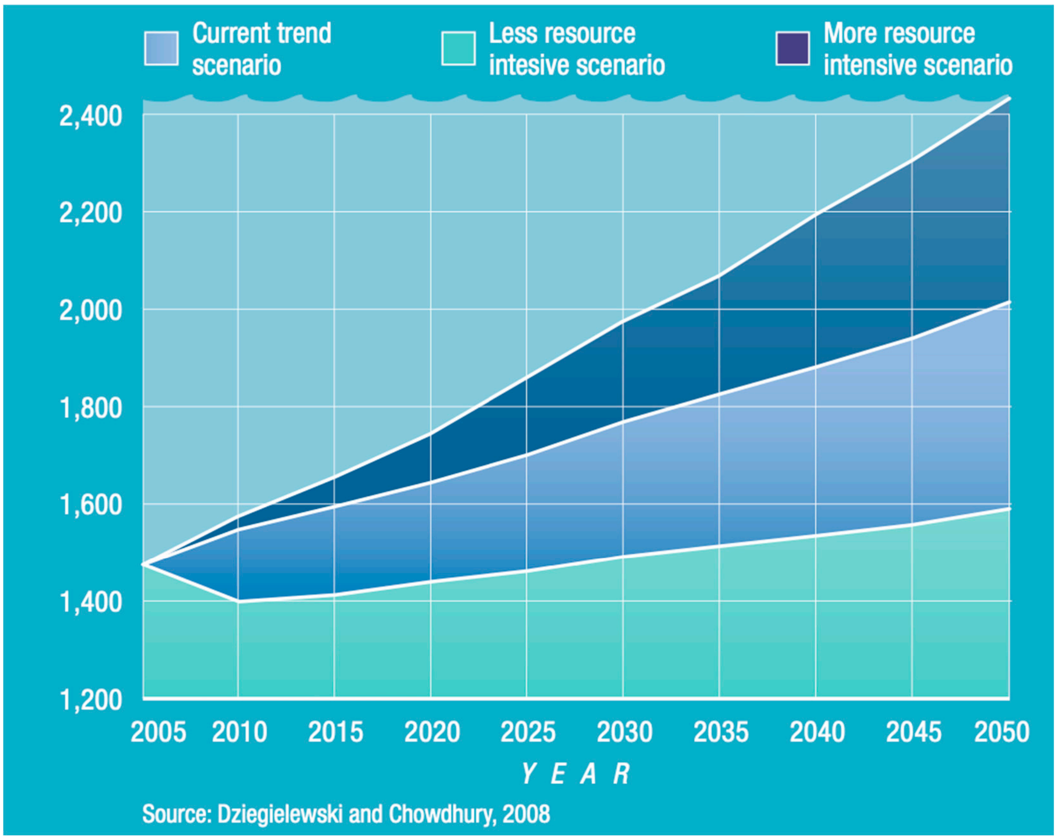


Figure 8. Projected Water Demand in NE Illinois 2005–2050 in million gallons per day [107].

- **Current trend scenario (CT):** assumptions include that the population growth and urban development trends from the past 10–20 years continue, income and price follow historical patterns, geographical distribution of growth based on market forces and expected public policies implementations and increased water efficiency.
- **Less resource-intensive scenario (LRI):** assumptions include water conservation, decrease in water-intensive activities, lower income and higher water prices in the future, some population shifts to a more urbanized area (Cook and DuPage).
- **More resource-intensive scenario (MRI):** assumption include less water conservation than indicated by the current trend scenario, increase in water-intensive activities, and some population shifts to western collar counties (Kane, Kendall, and McHenry).

Projections indicate that water demand (water withdrawal) will increase approximately 530 MGD or 36% under the CT scenario, and 949 MGD or 64% under the MRI scenario [31,107].

The Department of Water Management provides drinking water supply to the City of Chicago and 126 suburb communities, removes wastewater and storm runoff through the sewer system, and maintains the public sewage system. The public sewage system collects and conveys sanitary and industrial wastes as well as surface-water drainage to the Metropolitan Water Reclamation District of Greater Chicago (MWRD) interceptors. The Department of Water Management manages and maintains two water purification plants and ensures the potability of the water through monitoring. The Safe Drinking Water Act specifies stringent requirements for all aspects of potable water. The US Environmental Protection Agency, the Illinois Environmental Protection Agency, and the Illinois Department of Natural Resources enforce the standards that the Department of Water Management need to meet [108,109].

There are two water purification plants that serve the Greater Chicago Area, the Jardine Water Purification Plant and Eugene Sawyer Purification Plant. The two-water treatment plants involve similar water treatment processes. According to the City of Chicago, the treatment processes are as follows:

1. Lake Michigan water enters the intake crib at depths between 20 and 30 feet.
2. The water reaches the intake basin of the purification plant through a tunnel beneath the lakebed.
3. The water is filtered by eight moving screens to remove debris.
4. For the initial chemical treatment, water is pumped up to 25 feet using low-lift pumps.
5. Water is then transferred.
6. Water is circulated through mixing basins to initiate the flocculation process.
7. Flocculated water is transferred to settling basins, where it sits for hours to allow floc settling.
8. Water is filtered through finely graded sand and gravel to provide "natural polishing."
9. The filtered water then flows for final chemical application in a clear well.
10. Water flows from water reservoirs to the distribution system.

Chemicals used in the treatment processes are chlorine (as water disinfections), aluminum sulfate or alum and polymer (for coagulation), blended polyphosphate (for pipes coating and lead leaching prevention), activated carbon (to remove unpleasant odors and tastes), and fluoride (to help fight cavities in children's teeth) [109].

To further understand the quality of treated wastewater and municipal water in Chicago, the comparison of municipal water quality from South Water (now Eugene Sawyer) Purification Plant (ESPP) and the Metropolitan Water Reclamation District (MWRD) treated effluent from Stickney Water Reclamation Plant (SWRP) was studied by Anderson and Meng in 2011. The studied data was the average water quality data of ESPP for November 2001, February, May, and August 2002 compared to the effluent quality of SWRP in 2002. The greatest increases in contaminants include nitrogen compounds, chloride, potassium, and sodium. Nitrogen compounds increased about 20 to 30 times, while chloride, potassium, and sodium increased by about 12 times. A new data comparison study between Eugene Sawyer Purification Plant, Jardine Purification Plant, and Stickney Water Reclamation Plant was conducted. Based on 2021 chemical analysis data of the three water treatment plants, a significant increase of 28 times can be seen in the concentration of chloride, about four times in suspended solids, as well as total dissolved solids (Table 18). These changes are expected, considering the state of water before it undergoes treatment. At ESPP, freshwater is treated to drinking water quality complying with the Safe Drinking Water Act (SDWA). At Stickney Water Reclamation Plant, wastewater is treated to comply with the National Pollutant Discharge Elimination System (NPDES), a part of Clean Water Act (CWA), where the quality of water does not have to be the quality of drinking water but must be sufficient treated as to not harm the nation's water resources.

The Metropolitan Water Reclamation District of Greater Chicago (MWRD) is a wastewater treatment and stormwater agency that owns and operates seven water reclamation plants in Cook County. The Chicago area sewers consists of a network of combined sewer systems. In a combined sewer system, sanitary sewage and stormwater flow into the same pipes which can lead to backups and overflows. After flowing into municipal drains, water is diverted by MWRD intercepting sewers to seven water reclamation plants for treatment before being released into waterways. The MWRD runs 560 miles of intercepting sewers and force mains, which are pumps that transfer water under pressure by using compressors. The seven water reclamation plants owned by MWRD treat about 500 billion gallons of wastewater every year [110].

Table 18. Municipal water quality from South (Eugene Sawyer) Water Purification Plant and Jardine Water Purification Plant (from March to September 2021) compared to Stickney Water Reclamation Plant Effluent (from January to September 2021).

Parameter	**Unit**	**Municipal Water**			**Treated Water**
		South Water Purification Plant	**Jardine Water Purification Plant (Central)**	**Jardine Water Purification Plant (North)**	**Stickney**
Temperature	°C	14	13.7	13.7	17.3
Turbidity	N.T.U.	0.167	0.3	0.1	-
pH		7.87	7.9	7.9	7.1
Dissolved Oxygen	mg/L	-	-	-	8.3
BOD5	mg/L	-	-	-	<6
Total Solids	mg/L	189.3	184.0	187.3	697
Total Dissolved Solids	mg/L	157.3	156.0	156.3	692
Hardness	mg as $CaCO_3$/L	138.3	138.3	139.0	246
Total Alkalinity	mg as $CaCO_3$/L	101.8	102.2	101.1	-
Calcium	mg/L	35.0	35.1	35.3	63.6
Magnesium	mg/L	12.2	12.3	12.5	21.1
Sodium	mg/L	8.8	8.8	8.8	-
Potassium	mg/L	1.4	1.4	1.4	-
Ammonia	N mg/L	<0.1	<0.1	<0.1	<0.7
Nitrite	N mg/L	<0.25	<0.25	<0.25	-
Nitrate	N mg/L	0.316	0.309	0.307	-
Total Phosphate	mg/L	1.2	1.2	1.2	0.76
Chloride	mg/L	16.0	15.9	16.0	450
Fluoride	mg/L	0.7	0.7	0.7	0.5

The sewer system in Cook County is divided into a combined sewer system, a separate sewer system, and a combined and separate sewer system. Since it was first built, the majority of local sewers convey water exceeding their capacity, resulting in backups and overflows at some point in the sewage system due to insufficient flow capacity. When a large amount of rain falls rapidly in a small region, stormwater may reach sewers quicker than they can flow through them, surpassing their flow capacity. When this occurs, a portion of the combined sewer cannot reach the MWRD's tunnels, reservoirs, or canals and it may overflow onto streets and unprotected basements. The MWRD advises the public to restrict water consumption before and during storms to avoid sewage overflow [107]. Sewer backup prevention action taken by MWRD includes the Tunnel and Reservoir Program (TARP) reservoir, and implementation of green infrastructure. Stormwater may be absorbed in the ground instead of flowing to the sewer system by utilizing porous pavement, rain gardens, native plant landscaping, bioswales, green roofs, and greenways. This will minimize the chance of sewer overflows and backups.

Raw influent from seven MWRD's water reclamation was studied. The compiled data of raw influent water quality is then compared to the quality of final effluents from each of the seven WRPs. Table 19a–d show raw influent quality in 2021 from Stickney, O'Brien, Kirie, Hanover Park, Calumet, Lemont, and Egan WRPs.

Table 19. (**a**) Raw influent data of Stickney WRP (Monitoring period of January–September 2021). (**b**) Raw influents quality data of Calumet, and O'Brien WRPs (Monitoring period of January–September 2021). (**c**) Raw influents quality data of Egan, and Kirie WRPs (Monitoring period of January–September 2021). (**d**) Raw influents quality data of Hanover Park, and Lemont WRPs (Monitoring period of January–September 2021).

(**a**)

Parameter	Symbol	Unit	Stickney (South West)			Stickney (West)		
			Min	Avg	Max	Min	Avg	Max
Flow		MGD	136	302	794	64	302	582
Acidity	pH		Not Reported			Not Reported		
Biological Oxygen Demand	BOD5	mg/L	83	373	2691	51	183	912
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	Data Not Available			Data Not Available		
Fat, Oil, and Grease	FOG	mg/L	<5	<12	40	6	18	38
Suspended Solids	SS	mg/L	68	655	8320	45	256	1480
Volatile SS	VSS	mg/L	64	458	6280	39	194	1060
Total Solids	TS	mg/L	544	1220	5360	636	880	1280
Total Volatile Solids	VTS	mg/L	136	506	2390	140	344	608
Total Kjeldahl Nitrogen	TKN	mg/L	13	46	213	11	37	85
Ammonia	NH_3-N	mg/L	3.5	20.0	60.2	7.6	22.8	46.8
Nitrite Nitrate	NO_2-N + NO_3-N	mg/L	<0.25	<0.20	1.25	<0.25	<0.28	2.73
Phosphorous	P-TOT	mg/L	2.72	11.49	56.39	2.23	7.16	18.38
Flow		MGD	136	302	794	64	302	582
Cyanides	CN	mg/L	<0.005	<0.012	0.031	<0.005	<0.008	0.018
Amenable, Cyanide	CN AM	mg/L	<0.005	<0.004	0.007	<0.005	<0.004	0.009
Phosphorous	P-SOL	mg/L	Data Not Available			Data Not Available		
Phenol	Phenol	ug/L	<0.005	<0.012	0.031	<5	<26	138
Fluoride	F	mg/L	0.3	0.6	0.8	0.4	0.7	0.8
Total Organic Carbon	TOC	mg/L	Data Not Available			Data Not Available		
Arsenic	As	mg/L	0.002	0.005	0.020	<0.002	<0.003	0.007
Barium	Ba	mg/L	0.044	0.117	0.632	0.040	0.067	0.121
Cadmium	Cd	mg/L	<0.002	<0.002	0.009	<0.002	<0.002	0.003
Chromium	Cr	mg/L	<0.003	<0.022	0.184	<0.003	<0.016	0.036
Copper	Cu	mg/L	0.033	0.125	1.053	0.027	0.072	0.158

Table 19. *Cont.*

(**a**)

Parameter	Symbol	Unit	Stickney (South West)			Stickney (West)		
			Min	Avg	Max	Min	Avg	Max
Iron	Fe	mg/L	1.14	4.07	24.89	0.75	1.78	4.03
Soluble Iron	Sol Fe	mg/L	0.06	0.23	1.87	0.03	0.11	0.16
Lead	Pb	mg/L	0.004	0.021	0.136	0.003	0.010	0.024
Manganese	Mn	mg/L	0.089	0.203	1.089	0.049	0.094	0.213
Mercury	Hg	ug/L	<0.5	<0.4	0.6	<0.5	<0.4	<0.5
Nickel	Ni	mg/L	0.006	0.030	0.292	0.005	0.013	0.024
Selenium	Se	mg/L	<0.004	<0.003	0.009	<0.004	<0.003	0.004
Silver	Ag	mg/L	<0.004	<0.003	0.014	<0.004	<0.003	<0.004
Zinc	Zn	mg/l	0.081	0.285	1.573	0.065	0.156	0.337
Antimony	Sb	mg/L	<0.002	<0.002	0.005	<0.002	<0.002	0.003
Beryllium	Be	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium(6+)	Cr^6	ug/L	<3	<2	<3	<3	<2	8
Sulphate	SO_4	mg/L	Data Not Available			42	61	86
Chloride	Cl	mg/L	Data Not Available			Data Not Available		

(**b**)

Parameter	Symbol	Unit	Calumet			O'Brien		
			Min	Avg	Max	Min	Avg	Max
Flow		MGD	Not Reported			Not Reported		
Acidity	pH		6.9	7.4	8.0	Not Reported		
Biological Oxygen Demand	BOD5	mg/L	41	189	2084	30	108	289
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	27	139	2662	13	73	135
Fat, Oil, and Grease	FOG	mg/L	8	23	66	8	26	54
Suspended Solids	SS	mg/L	18	267	2388	37	126	417
Volatile SS	VSS	mg/L	12	211	2200	Data Not Available		
Total Solids	TS	mg/L	592	1119	2959	478	687	982
Total Volatile Solids	VTS	mg/L	138	358	1232	Data Not Available		
Total Kjeldahl Nitrogen	TKN	mg/L	11	26	77	6	24	36
Ammonia	NH_3-N	mg/L	3.6	14.0	26.9	5.1	16.0	23.7
Nitrite Nitrate	NO_2-N + NO_3-N	mg/L	<0.25	<0.26	2.39	<0.25	<0.30	2.69

Table 19. *Cont.*

(**b**)

Parameter	Symbol	Unit	Calumet			O'Brien		
			Min	Avg	Max	Min	Avg	Max
Phosphorous	P-TOT	mg/L	1.74	7.18	21.50	0.99	3.71	7.58
Phosphorous	P-SOL	mg/L	0.70	3.95	17.00	0.84	2.00	2.72
Cyanides	CN	mg/L	<0.005	<0.010	0.051	<0.005	<0.007	0.020
Amenable, Cyanide	CN AM	mg/L	<0.005	<0.004	<0.010	<0.005	<0.004	0.008
Phenol	Phenol	ug/L	<5	<22	105	<5	<21	52
Fluoride	F	mg/L	0.4	0.5	0.7	0.4	0.6	0.9
Total Organic Carbon	TOC	mg/L	34	103	771	25	73	113
Arsenic	As	mg/L	<0.002	<0.004	0.009	<0.002	<0.002	0.003
Barium	Ba	mg/L	0.036	0.095	0.244	0.033	0.048	0.076
Cadmium	Cd	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium	Cr	mg/L	<0.004	<0.006	0.025	<0.004	<0.003	0.004
Copper	Cu	mg/L	0.017	0.061	0.229	0.025	0.042	0.106
Iron	Fe	mg/L	0.86	3.32	12.01	0.43	0.88	3.01
Soluble Iron	Sol Fe	mg/L	0.06	0.48	3.57	0.09	0.15	0.19
Lead	Pb	mg/L	<0.002	<0.008	0.040	<0.002	<0.004	0.016
Manganese	Mn	mg/L	0.082	0.185	0.536	0.037	0.057	0.126
Mercury	Hg	ug/L	<0.5	<0.4	<0.5	<0.5	<0.4	<0.5
Nickel	Ni	mg/L	0.004	0.009	0.030	0.004	0.010	0.087
Selenium	Se	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Silver	Ag	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Zinc	Zn	mg/l	0.052	0.197	0.917	0.047	0.091	0.189
Antimony	Sb	mg/L	<0.002	<0.002	0.004	<0.002	<0.002	0.002
Beryllium	Be	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium(6+)	Cr^6	ug/L	<3	<2	<3	<3	<2	<3
Sulphate	SO_4	mg/L	Data Not Available			Data Not Available		
Chloride	Cl	mg/L	Data Not Available			100.98	277.24	2019.7

(**c**)

Parameter	Symbol	Unit	Egan			Kirie		
			Min	Avg	Max	Min	Avg	Max
Flow		MGD	Data Not Available			Data Not Available		
Acidity	pH		6.6	7.4	7.7	Data Not Available		
Biological Oxygen Demand	BOD5	mg/L	86	176	441	26	138	260
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	69	119	252	Data Not Available		
Fat, Oil, and Grease	FOG	mg/L	9	35	70	<5	<21	65

Table 19. *Cont.*

(**b**)

Parameter	Symbol	Unit	Calumet			O'Brien		
			Min	Avg	Max	Min	Avg	Max
Suspended Solids	SS	mg/L	80	186	721	474	922	2070
Volatile SS	VSS	mg/L	Data Not Available			Data Not Available		
Total Solids	TS	mg/L	672	932	1894	22	157	1180
Total Volatile Solids	VTS	mg/L	Data Not Available			Data Not Available		
Total Kjeldahl Nitrogen	TKN	mg/L	15	30	56	4	28	93
Ammonia	NH_3-N	mg/L	6.0	17.1	27.4	2.5	17.4	32.7
Nitrite Nitrate	NO_2-N + NO_3-N	mg/L	<0.25	<2.19	5.08	<0.25	<0.87	2.75
Phosphorous	P-TOT	mg/L	2.43	6.37	11.20	0.93	4.35	19.15
Phosphorous	P-SOL	mg/L	1.12	3.98	5.17	0.37	2.11	3.88
Cyanides	CN	mg/L	<0.005	<0.006	0.017	<0.005	<0.005	0.014
Amenable, Cyanide	CN AM	mg/L	Data Not Available			<0.001	<0.001	0.001
Phenol	Phenol	ug/L	0.4	0.6	0.7	<5	<26	67
Fluoride	F	mg/L	6	26	46	0.3	0.6	0.8
Total Organic Carbon	TOC	mg/L	43	95	180	67	97	126
Arsenic	As	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	0.002
Barium	Ba	mg/L	0.037	0.053	0.135	0.039	0.061	0.104
Cadmium	Cd	mg/L	<0.002	<0.001	<0.002	<0.002	<0.002	0.008

(**c**)

Parameter	Symbol	Unit	Egan			Kirie		
			Min	Avg	Max	Min	Avg	Max
Chromium	Cr	mg/L	<0.004	<0.004	0.015	<0.004	<0.004	0.011
Copper	Cu	mg/L	0.027	0.067	0.288	0.016	0.068	0.116
Iron	Fe	mg/L	0.40	0.93	4.17	0.36	1.02	3.32
Soluble Iron	Sol Fe	mg/L	0.08	0.17	0.31	0.09	0.19	0.29
Lead	Pb	mg/L	<0.002	<0.002	0.010	<0.002	<0.003	0.010
Manganese	Mn	mg/L	0.050	0.073	0.113	0.041	0.069	0.126
Mercury	Hg	ug/L	<0.5	<0.4	<0.5	<0.5	<0.4	<0.5
Nickel	Ni	mg/L	0.004	0.009	0.022	0.004	0.014	0.038
Selenium	Se	mg/L	<0.004	<0.003	0.004	<0.004	<0.003	0.004
Silver	Ag	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	0.006
Zinc	Zn	mg/L	0.043	0.109	0.436	0.031	0.112	0.251
Antimony	Sb	mg/L	<0.002	<0.002	0.002	<0.002	<0.002	0.002
Beryllium	Be	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002

Table 19. *Cont.*

(**c**)

Parameter	Symbol	Unit	Egan			Kirie		
			Min	Avg	Max	Min	Avg	Max
Chromium(6+)	Cr^6	ug/L	<3	<2	<3	<3	<2	<3
Sulphate	SO_4	mg/L	Data Not Available			35	78	93
Chloride	Cl	mg/L	128.28	209.12	476.71	106.24	236.11	1084.30

(**d**)

Parameter	Symbol	Unit	Hanover Park			Lemont		
			Min	Avg	Max	Min	Avg	Max
Flow		MGD	Data Not Available			Data Not Available		
Acidity	pH		6.3	7.0	7.7	6.9	7.4	7.8
Biological Oxygen Demand	BOD5	mg/L	27	187	916	41	176	379
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	Not Reported			22	103	242
Fat, Oil, and Grease	FOG	mg/L	14	42	71	<5	<15	34
Suspended Solids	SS	mg/L	30	145	729	35	298	9300
Volatile SS	VSS	mg/L	Data Not Available			25	220	1832
Total Solids	TS	mg/L	598	796	1474	674	1423	9678
Total Volatile Solids	VTS	mg/L	Data Not Available			136	401	7722
Total Kjeldahl Nitrogen	TKN	mg/L	12	40	83	11	36	66
Ammonia	NH_3-N	mg/L	7.2	27.0	36.9	5.7	18.5	31.7
Nitrite Nitrate	NO_2-N + NO_3-N	mg/L	<0.25	<0.27	4.74	<0.25	<0.63	4.14
Phosphorous	P-TOT	mg/L	1.85	5.85	13.24	1.45	5.53	11.91
Phosphorous	P-SOL	mg/L	2.07	3.73	4.79	Data Not Available		
Cyanides	CN	mg/L	<0.005	<0.006	0.015	<0.005	<0.010	0.031
Amenable, Cyanide	CN AM	mg/L	<0.001	<0.001	0.001	Data Not Available		
Phenol	Phenol	ug/L	7	37	64	<5	<11	19
Fluoride	F	mg/L	0.3	0.6	0.7	0.5	0.9	1.0
Total Organic Carbon	TOC	mg/L	32	128	314	Data Not Available		
Arsenic	As	mg/L	<0.002	<0.001	0.002	<0.002	<0.001	0.003
Barium	Ba	mg/L	0.035	0.049	0.084	0.042	0.064	0.138
Cadmium	Cd	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium	Cr	mg/L	<0.004	<0.003	0.004	<0.004	<0.003	0.009
Copper	Cu	mg/L	0.018	0.049	0.122	0.023	0.084	0.310
Iron	Fe	mg/L	0.32	0.66	1.99	0.27	1.09	3.52
Soluble Iron	Sol Fe	mg/L	0.09	0.16	0.22	0.05	0.13	0.18

Table 19. *Cont.*

(**d**)

Parameter	Symbol	Unit	Hanover Park			Lemont		
			Min	Avg	Max	Min	Avg	Max
Lead	Pb	mg/L	<0.002	<0.002	0.005	<0.002	<0.003	0.009
Manganese	Mn	mg/L	0.040	0.071	0.128	0.020	0.066	0.148
Mercury	Hg	ug/L	<0.5	<0.4	<0.5	<0.5	<0.4	0.7
Nickel	Ni	mg/L	0.002	0.003	0.005	0.002	0.003	0.009
Selenium	Se	mg/L	<0.004	<0.003	0.004	<0.004	<0.003	<0.004
Silver	Ag	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Zinc	Zn	mg/l	0.035	0.090	0.235	0.031	0.148	0.558
Antimony	Sb	mg/L	<0.002	<0.002	0.003	<0.002	<0.002	0.002
Beryllium	Be	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium(6+)	Cr^6	ug/L	<3	<2	<3	<3	<2	<3
Sulphate	SO_4	mg/L	Data Not Available			Data Not Available		
Chloride	Cl	mg/L	90.93	169.40	474.69	Data Not Available		

As previously discussed, the wastewater treatment process typically consists of preliminary, primary, and secondary treatment processes. These processes are characterized by physical, chemical, and biological processes. Shown in Table 20 is the wastewater treatment processes found in seven water reclamation plants operated by MWRD. All seven WRPs do have the basic wastewater treatment systems which are preliminary treatment, primary treatment, and secondary treatment. Most of the treatment plants (Calumet, O'Brien, Egan, Kirie, and Hanover Park) include filtration and disinfection in addition to primary and secondary treatment processes. Chlorination and dechlorination along with filtration are added into the treatment process as tertiary treatment at Egan, Kirie, and Hanover Park WRPs. Chlorination and dechlorination are also found at Calumet WRP, although without filtration. Lastly, Kirie WRP utilizes Ultraviolet (UV) disinfection.

Final effluent quality data from the seven WRPs were also studied. These data were utilized to measure the feasibility of current wastewater treatment processes, the final quality of the treatment, and the possibility of water reuse applications. Table 21a–d show the final effluent quality data of Stickney, Calumet, O'Brien, Egan, Kirie, Hanover Park, and Lemont WRPs. The final effluent quality from these seven WRPs are then compared to the 2012 USEPA guidelines (Table 3).

Currently, the final effluents from all seven WRPs are being discharged into the Illinois waterways after the final treatment process. MWRD must ensure the quality of the treated water meeting all the regulations before releasing the water to waterways. According to MWRD, the seven wastewater treatment facilities can purify sewage water into clean water in 12 h. Sludge from wastewater during primary and secondary treatment is collected and transformed into fertilizer for golf courses, parks and recreational facilities, athletic fields, agricultural fields, forests, and for restoration of strip mines and other disturbed lands [110].

Table 20. Existing wastewater treatment technology at Stickney, O'Brien, Calumet, Egan, Kirie, Hanover Park, and Lemont Water Reclamation Plants.

Water Reclamation Plant	**Primary**	**Secondary**	**Filtration**	**Disinfection**
Stickney	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	×	×
O'Brien	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	×	UV Disinfection
Calumet	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	×	Chlorination/ Dechlorination
Egan	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	Sand and Anthracite	Chlorination/ Dechlorination
Kirie	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	Sand and Anthracite	Chlorination/ Dechlorination
Hanover Park	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	Sand and Anthracite	Chlorination/ Dechlorination
Lemont	Coarse Screen Aerated Grit Tanks Preliminary Settling Tanks	Activated Sludge Aeration Tanks Final Settling Tanks	×	×

Table 21. (**a**) Quality of treated effluent quality data of Stickney WRP (Monitoring period of January–September 2021). (**b**) Quality of treated effluent quality data of Calumet, and O'Brien WRPs (Monitoring period of January–September 2021). (**c**) Quality of treated effluent quality data of Egan, and Kirie WRPs (Monitoring period of January–September 2021). (**d**) Quality of treated effluent quality data of Hanover Park, and Lemont WRPs (Monitoring period of January–September 2021).

(**a**)

Parameter	Symbol	Unit	Stickney		
			Min	Mean	Max
Flow		MGD	260	595	1267
Acidity	pH		6.7	7.1	7.4
Dissolved Oxygen	DO	mg/L	5.3	8.3	10.5
Temperature	Temp.	°C	8.5	17.3	25.3
Biological Oxygen Demand	BOD5	mg/L	<2	<6	16

Table 21. *Cont.*

(**a**)

Parameter	Symbol	Unit	Stickney		
			Min	Mean	Max
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	<2	<2	6
Total Solids	TS	mg/L	480	697	1031
Total Volatile Solids	TVS	mg/L	28	189	540
Suspended Solids	SS	mg/L	<4	<5	15
Total Kjeldahl Nitrogen	TKN	mg/L	1	2	6
Ammonia	NH_3-N	mg/L	<0.3	<0.7	4.5
Unionized Ammonia	Un-ionNH3-N	mg/L	0	0	0
Nitrite Nitrate	NO_2 + NO_3-N	mg/L	2.21	7.64	13.48
Phosphorous	P-Tot	mg/L	0.16	0.76	4.53
Phosphorous	P-Sol	mg/L	Data Not Available		
Chloride	Cl	mg/L	112.41	450.21	1967.00
Fluoride	F	mg/L	0.3	0.5	0.6
Fats, Oils, and Greases	FOG	mg/L	<5	<4	<5
Phenol	Phenol	ug/L	<5	<4	12
Fecal Coliform	Fecal col.	cfu/100 mL	1100	GM = 7790	37,000
Sulphate	SO_4	mg/L	48	89	113
Cyanides	CN	mg/L	<0.005	<0.006	0.019
Arsenic	As-Tot	mg/L	<0.002	<0.002	0.002
Barium	Ba-Tot	mg/L	0.009	0.020	0.046
Cadmium	Cd-Tot	mg/L	<0.002	<0.001	<0.002
Chromium	Cr-Tot	mg/L	<0.004	<0.003	<0.004
Copper	Cu-Tot	mg/L	<0.002	<0.003	0.022
Iron	Fe-Tot	mg/L	0.04	0.07	0.13
Lead	Pb-Tot	mg/L	<0.002	<0.001	<0.002
Manganese	Mn-Tot	mg/L	0.004	0.015	0.032
Iron	Fe-Sol	mg/L	0.02	0.03	0.04
Mercury	Hg	mg/L	<0.5	<1.1	3.0
Mercury LL	HgLL	mg/L	Data Not Available		
Nickel	Ni-Tot	mg/L	0.003	0.008	0.019
Selenium	Se-Tot	mg/L	<0.004	<0.003	<0.004
Silver	Ag-Tot	mg/L	<0.004	<0.003	<0.004
Zinc	Zn-Tot	mg/L	<0.010	<0.021	0.050
Antimony	Sb-Tot	mg/L	<0.002	<0.001	0.002
Beryllium	Be-Tot	mg/L	<0.002	<0.001	<0.002

Table 21. *Cont.*

(**a**)

Parameter	Symbol	Unit	Stickney		
			Min	Mean	Max
Thallium	Tl-Tot	mg/L	<0.002	<0.001	<0.002
Chromium(6+)	Cr+6-Tot	ug/L	<3	<2	<3
Calcium	Ca-Tot	mg/L	38.01	63.63	101.60
Magnesium	Mg-Tot	mg/L	11.59	21.11	33.73
Hardness	Hardness	mg/L	143	246	387
Amenable, Cyanide	AMENCN	mg/L	<0.005	<0.004	<0.005
Total Organic Carbon	TOC	mg/L	Data Not Available		
Total Nitrogen	Tot_N	mg/L	4	9	14

(**b**)

Parameter	Symbol	Unit	Calumet			O'Brien		
			Min	Mean	Max	Min	Mean	Max
Flow		MGD	105	239	452	98	199	427
Acidity	pH		6.8	7.2	7.5	6.8	7.1	7.2
Dissolved Oxygen	DO	mg/L	5.5	7.8	9.9	7.5	9.2	11.5
Temperature	Temp.	°C	8	15	22	Data Not Available		
Biological Oxygen Demand	BOD5	mg/L	<2	<7	21	<2	<6	29
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	<2	<3	7	<2	<2	13
Total Solids	TS	mg/L	520	864	2512	Data Not Available		
Total Volatile Solids	TVS	mg/L	46	148	414	Data Not Available		
Suspended Solids	SS	mg/L	<4	<5	11	2	4	13
Total Kjeldahl Nitrogen	TKN	mg/L	<1	<1	4	<1	<1	<4
Ammonia	NH_3-N	mg/L	<0.3	<0.4	2.8	<0.3	<0.5	2.3
Unionized Ammonia	Un-ionNH3-N	mg/L	Data Not Available			Data Not Available		
Nitrite Nitrate	$NO_2 + NO_3$-N	mg/L	3.91	8.14	17.06	4.72	9.44	14.15
Phosphorous	P-Tot	mg/L	1.16	3.64	7.39	0.49	1.80	2.90
Phosphorous	P-Sol	mg/L	1.05	3.52	7.14	1.01	1.97	2.55
Chloride	Cl	mg/L	115.18	352.50	1273.03	100.95	346.85	2014.83
Fluoride	F	mg/L	0.4	0.5	0.6	0.3	0.5	0.6
Fats, Oils, and Greases	FOG	mg/L	<5	<4	<5	<5	<4	5
Phenol	Phenol	ug/L	<5	<4	9	<5	<4	5
Fecal Coliform	Fecalcol.	cfu/100 mL	<10	GM $\leq$ 15	57,000	<10	GM $\leq$ 66	52,000

Table 21. *Cont.*

(**b**)

Parameter	Symbol	Unit	Calumet			O’Brien		
			Min	Mean	Max	Min	Mean	Max
Sulphate	SO4	mg/L	Data Not Available			Data Not Available		
Cyanides	CN	mg/L	<0.005	<0.006	0.023	<0.005	<0.005	0.025
Arsenic	As-Tot	mg/L	0.002	0.003	0.004	<0.002	<0.001	<0.002
Barium	Ba-Tot	mg/L	0.011	0.021	0.040	0.018	0.027	0.052
Cadmium	Cd-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium	Cr-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Copper	Cu-Tot	mg/L	0.002	0.003	0.008	0.003	0.005	0.008
Iron	Fe-Tot	mg/L	0.06	0.10	0.13	0.04	0.05	0.09
Lead	Pb-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Manganese	Mn-Tot	mg/L	0.010	0.031	0.091	0.005	0.010	0.044
Iron	Fe-Sol	mg/L	0.03	0.04	0.08	0.02	0.03	0.04
Mercury	Hg	mg/L	Data Not Available			Data Not Available		
Mercury LL	HgLL	mg/L	<0.5	<4.4	20.8	<0.5	<21.7	624.3
Nickel	Ni-Tot	mg/L	0.002	0.004	0.009	0.002	0.009	0.144
Selenium	Se-Tot	mg/L	<0.004	<0.003	0.004	<0.004	<0.003	0.004
Silver	Ag-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Zinc	Zn-Tot	mg/L	0.011	0.018	0.027	0.017	0.028	0.047
Antimony	Sb-Tot	mg/L	<0.002	<0.001	0.002	<0.002	<0.001	0.002
Beryllium	Be-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium(6+)	Cr+6-Tot	ug/L	<3	<2	<3	<3	<2	<3
Calcium	Ca-Tot	mg/L	45.72	73.22	106.22	38.32	59.78	99.34
Magnesium	Mg-Tot	mg/L	14.90	25.24	40.73	12.48	20.87	33.37
Hardness	Hardness	mg/L	179	287	411	147	235	381
Amenable, Cyanide	AMENCN	mg/L	<0.005	<0.004	<0.005	<0.005	<0.004	<0.005
Total Organic Carbon	TOC	mg/L	6	9	12	5	7	24
Total Nitrogen	Tot_N	mg/L	5	9	23	<8	<11	<17

(**c**)

Parameter	Symbol	Unit	Egan			Kirie		
			Min	Mean	Max	Min	Mean	Max
Flow		MGD	16.3	21.8	50.7	14.32	32.35	116.93
Acidity	pH		7.0	7.2	7.4	7.0	7.4	7.8
Dissolved Oxygen	DO	mg/L	6.3	6.9	8.5	6.6	8.0	9.1
Temperature	Temp.	°C				46	61	73

Table 21. *Cont.*

(**c**)								
Parameter	Symbol	Unit	Egan			Kirie		
			Min	Mean	Max	Min	Mean	Max
Biological Oxygen Demand	BOD5	mg/L	4	5	12	<2	<3	9
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	<2	<2	6	<2	<2	4
Total Solids	TS	mg/L	Data Not Available			Data Not Available		
Total Volatile Solids	TVS	mg/L	Data Not Available			Data Not Available		
Suspended Solids	SS	mg/L	2	3	6	<2	<2	24
Total Kjeldahl Nitrogen	TKN	mg/L	<1	<2	<5	<1	<1	4
Ammonia	NH_3-N	mg/L	<0.3	<0.3	1.9	<0.3	<0.3	3.4
Unionized Ammonia	Un-ionNH3-N	mg/L	Data Not Available			Data Not Available		
Nitrite Nitrate	NO_2 + NO_3-N	mg/L	5.86	17.37	22.76	3.50	8.13	12.20
Phosphorous	P-Tot	mg/L	0.42	3.42	5.10	0.16	0.67	2.13
Phosphorous	P-Sol	mg/L	0.60	3.17	4.34	<0.15	<0.72	2.09
Chloride	Cl	mg/L	133.59	207.08	478.00	107.28	248.75	695.32
Fluoride	F	mg/L	0.3	0.5	0.6	0.3	0.5	0.8
Fats, Oils, and Greases	FOG	mg/L	<5	<4	<5	<5	<4	<5
Phenol	Phenol	ug/L	<5	<4	7	<5	<4	23
Fecal Coliform	Fecal col.	cfu/100 mL	<10	GM $\leq$ 15	7500	<10	GM $\leq$ 7	90
Sulphate	SO_4	mg/L	Data Not Available			42	77	92
Cyanides	CN	mg/L	<0.005	<0.005	0.011	<0.005	<0.004	0.012
Arsenic	As-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Barium	Ba-Tot	mg/L	0.018	0.024	0.048	0.015	0.027	0.053
Cadmium	Cd-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium	Cr-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Copper	Cu-Tot	mg/L	0.004	0.008	0.013	0.002	0.004	0.008
Iron	Fe-Tot	mg/L	0.05	0.07	0.09	0.04	0.05	0.08
Lead	Pb-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Manganese	Mn-Tot	mg/L	0.007	0.015	0.049	0.010	0.015	0.038
Iron	Fe-Sol	mg/L	0.04	0.06	0.10	0.03	0.04	0.05
Mercury	Hg	mg/L	0.6	1.1	5.3	Data Not Available		
Mercury	HgLL	mg/L	Data Not Available			<0.5	<8.6	170.2
Nickel	Ni-Tot	mg/L	0.002	0.004	0.008	0.003	0.006	0.012
Selenium	Se-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	0.004
Silver	Ag-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Zinc	Zn-Tot	mg/L	0.016	0.025	0.031	0.011	0.029	0.058
Antimony	Sb-Tot	mg/L	<0.002	<0.001	0.002	<0.002	<0.001	0.002
Beryllium	Be-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002

Table 21. *Cont.*

(**c**)

Parameter	Symbol	Unit	Egan			Kirie		
			Min	Mean	Max	Min	Mean	Max
Chromium(6+)	Cr+6-Tot	ug/L	<3	<2	<3	<3	<2	<3
Calcium	Ca-Tot	mg/L	55.00	67.85	102.80	38.53	74.97	107.17
Magnesium	Mg-Tot	mg/L	20.72	25.76	37.09	13.12	27.70	39.42
Hardness	Hardness	mg/L	223	275	409	150	301	430
Amenable, Cyanide	AMEN CN	mg/L	Data Not Available			Data Not Available		
Total Organic Carbon	TOC	mg/L	7	10	19	6	7	10
Total Nitrogen	Tot_N	mg/L	Data Not Available			Data Not Available		

(**d**)

Parameter	Symbol	Unit	Hanover Park			Lemont		
			Min	Mean	Max	Min	Mean	Max
Flow		MGD	3.59	6.44	13.64	1.33	2.43	4.21
Acidity	pH		6.5	6.8	7.2	7	7.3	7.6
Dissolved Oxygen	DO	mg/L	7.4	9.7	12.3	2	5.2	8.5
Temperature	Temp.	°C	11	45	74			
Biological Oxygen Demand	BOD5	mg/L	<2	<6	20	<2	<9	57
Five-day Carbonaceous Biochemical Oxygen Demand	CBOD5	mg/L	<2	<3	7	<2	<4	16
Total Solids	TS	mg/L	Data Not Available			672	1179	2584
Total Volatile Solids	TVS	mg/L	Data Not Available			86	198	428
Suspended Solids	SS	mg/L	<2	<4	18	<4	<6	38
Total Kjeldahl Nitrogen	TKN	mg/L	<1	<2	<5	<1	<2	6
Ammonia	NH_3-N	mg/L	<0.3	<0.3	1.6	<1.5	<0.6	3.7
Unionized Ammonia	Un-ionNH3-N	mg/L	Data Not Available			Data Not Available		
Nitrite Nitrate	NO_2 + NO_3-N	mg/L	7.4	18.89	25.5	5.12	16.75	25.07
Phosphorous	P-Tot	mg/L	1.08	3.58	4.9	<0.15	<3.01	4.3
Phosphorous	P-Sol	mg/L	1.01	3.53	4.72			
Chloride	Cl	mg/L	96.06	165.4	393.84	156.09	409.62	1263.34
Fluoride	F	mg/L	0.3	0.5	0.6	0.4	0.8	1
Fats, Oils, and Greases	FOG	mg/L	<5	<4	5	<5	<4	<5
Phenol	Phenol	ug/L	<5	<4	7	<5	<4	12
Fecal Coliform	Fecal col.	cfu/100 mL	<10	GM ≤ 9	40	910	GM ≤ 11,805	220,000
Sulphate	SO_4	mg/L	Data Not Available			Data Not Available		
Cyanides	CN	mg/L	<0.005	<0.005	0.01	<0.005	<0.006	0.016

Table 21. *Cont.*

(d)

Parameter	Symbol	Unit	Hanover Park			Lemont		
			Min	Mean	Max	Min	Mean	Max
Arsenic	As-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Barium	Ba-Tot	mg/L	0.022	0.03	0.056	0.03	0.039	0.059
Cadmium	Cd-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium	Cr-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Copper	Cu-Tot	mg/L	0.004	0.007	0.011	0.004	0.009	0.026
Iron	Fe-Tot	mg/L	0.04	0.05	0.12	0.05	0.08	0.28
Lead	Pb-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Manganese	Mn-Tot	mg/L	0.005	0.018	0.053	0.005	0.015	0.056
Iron	Fe-Sol	mg/L	0.03	0.04	0.05	0.04	0.05	0.06
Mercury	Hg	mg/L	Data Not Available			Data Not Available		
Mercury	HgLL	mg/L	<0.5	<1.0	2.4	<0.5	<1.0	2.5
Nickel	Ni-Tot	mg/L	<0.002	<0.002	0.004	<0.002	<0.001	0.002
Selenium	Se-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	0.005
Silver	Ag-Tot	mg/L	<0.004	<0.003	<0.004	<0.004	<0.003	<0.004
Zinc	Zn-Tot	mg/L	0.026	0.044	0.061	0.017	0.033	0.066
Antimony	Sb-Tot	mg/L	<0.002	<0.001	0.002	<0.002	<0.001	<0.002
Beryllium	Be-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Thallium	Tl-Tot	mg/L	<0.002	<0.001	<0.002	<0.002	<0.001	<0.002
Chromium(6+)	Cr+6-Tot	ug/L	<3	<2	<3	<3	<2	<3
Calcium	Ca-Tot	mg/L	49.99	64.66	102.82	65.65	91.57	120.32
Magnesium	Mg-Tot	mg/L	17.83	24.46	38.17	25.15	32.49	38.38
Hardness	Hardness	mg/L	199	262	412	267	362	458
Amenable, Cyanide	AMEN CN	mg/L	Data Not Available			Data Not Available		
Total Organic Carbon	TOC	mg/L	9	12	17	Data Not Available		
Total Nitrogen	Tot_N	mg/L	Data Not Available			Data Not Available		

7.1. Water Reuse Tools and Strategies

The Public Building Commission of Chicago (PBC) published a Water Reuse Handbook listing the following tools and strategies for water reuse in Chicago and Cook County [108].

- *Reducing Fresh Water Usage:* The most basic strategy to reduce freshwater usage is to utilize high-efficiency fixtures and appliances wherever practical. Some of accepted toilet/urinal strategies by USEPA are as follows, high-efficiency toilets (HETs), dual flush toilets, and high-efficiency urinals (HEU) [111].
- *Rainwater Harvesting System Design*: Rainwater harvesting systems can be used on the exterior and/or interior of buildings for irrigation, toilet or urinal flushing, and other non-potable applications. This will significantly reduce potable water utilization and help assist stormwater management. Rainwater harvesting system utilization in offices and institutional buildings can have a significant impact on water conservation since flush fixtures are the main source of potable water demand. The Illinois Plumbing Code does not specify regulations for rainwater harvesting systems (the State has jurisdiction over plumbing issues in Chicago). Therefore, the rainwater

harvesting systems should essentially follow some rigorous process to get city and state approvals [111].

- *Greywater System Design*: The basic strategy of a greywater system for interior building relies on harvesting greywater from the shower, lavatory, and laundry water, filtering and treating the water, and storing it until it is needed to flush toilets and/or urinals. Greywater systems are an excellent fit for buildings with showers, such as residential buildings, because one shower requires nearly the same amount of water as one person's daily flushing [111].
- *Blackwater Systems*: Blackwater systems treat wastewater from flush fixtures, which often contain feces and urine, and repurpose it for toilet flushing, irrigation, or fertilization of gardens or farmland. Although blackwater systems may be a feasible option for wastewater treatment, the State of Illinois does not have any aerated or wetland-based blackwater treatment facilities [111].

As mentioned before, there are few case studies or attempts for water reuse implementations that have been conducted around Cook County. There is potential for water reuse in Cook County based on MWRD's seven waste reclamation plants' effluent data. Shown in Table 22 is the quality of final effluent in 2021 (average value between January through September) compared to USEPA Guidelines for water reuse. It is shown that effluent from Calumet, O'Brien, Egan, Kirie, and Hanover Park WRPs has the potential to be reused for urban reuse (restricted), agricultural reuse (processed food crops and non-food crops), impoundments (restricted), environmental reuse, and industrial reuse (Table 23) with or without minimum additional treatment. From the effluent data, it was also found that the TDS concentration at Stickney, Calumet, and Lemont WRPs fall into the "Slight to Moderate" and "severe" degree of restrictions for irrigation reuse (Table 24). The TDS data are not provided for the other WRPs. Additional treatment for TDS removal may be required at these seven WRPs if water reuse projects are considered in the future. The fecal coliform counts were also higher at Stickney and Lemont compared to other plants with disinfection technologies. Treatment technologies to address this matter can be tailored specifically to the need of water reuse end users. Shown in Figure 9a,b are the possible treatment technologies to treat TDS and Fecal Coliform according to Asano et al. (2007) [17] and Tricas (2018) [35].

Table 22. Final effluent of seven WRPs (monitoring period of January–September 2021) in comparison with the USEPA guidelines.

Water Parameter	Limit	Stickney	Calumet	O'Brien	Egan	Kirie	Hanover Park	Lemont
Urban Reuse (Unrestricted): The use of reclaimed water for non-potable applications in municipal settings where public access is not restricted (toilet flushing, air conditioning, irrigation of parks, residential landscaping, school yards, etc.)								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤10	<6	<7	<6	5	<3	<6	<9
NTU	≤2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fecal Coli (cfu/100 mL)	None	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Urban Reuse (Restricted): The use of reclaimed water where public exposure is controlled. Irrigation of areas such as highway median, and subsurface irrigation								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤30	<6	<7	<6	5	<3	<6	<9
TSS (mg/L)	≤30	<5	<5	4.0	3.0	<2	<4	<6

Table 22. *Cont.*

Water Parameter	Limit	Stickney	Calumet	O'Brien	Egan	Kirie	Hanover Park	Lemont
Fecal Coli (cfu/100 mL)	≤200	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Agricultural Reuse (Food Crops): The use of reclaimed water to irrigate food crops that are intended to be eaten raw								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤10	<6	<7	<6	5	<3	<6	<9
NTU	≤2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fecal Coli (cfu/100 mL)	None	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Agricultural Reuse (Processed Food Crops and Non-Food Crops): The use of reclaimed water to irrigate crops that are processed before consumed, and irrigation of non-food crops (seed crops, industrial crops, processed food crops, fodder crops, orchard crops, etc.								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤30	<6	<7	<6	5	<3	<6	<9
TSS (mg/L)	≤30	<5	<5	4.0	3.0	<2	<4	<6
Fecal Coli (cfu/100 mL)	≤200	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Impoundments (Unrestricted): The use of reclaimed water in an impoundment in which no limitations are imposed on body-contact water recreation activities (some states categorize snowmaking)								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤10	<6	<7	<6	5	<3	<6	<9
NTU	≤2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fecal Coli (cfu/100 mL)	None	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Impoundments (Restricted): The use of reclaimed water in an impoundment where body contact is restricted (some states include fishing and boating)								
BOD (mg/L)	≤30	<6	<7	<6	5	<3	<6	<9
TSS (mg/L)	≤30	<5	<5	4.0	3.0	<2	<4	<6
Fecal Coli (cfu/100 mL)	≤200	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Environmental Reuse: The use of reclaimed water to create, enhance, sustain, or augment water bodies, including wetlands, aquatic habitats, or stream flow								
Variable but not exceed:								
BOD (mg/L)	≤30	<6	<7	<6	5	<3	<6	<9
TSS (mg/L)	≤30	<5	<5	4.0	3.0	<2	<4	<6
Fecal Coli (cfu/100 mL)	≤200	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 22. *Cont.*

Water Parameter	Limit	Stickney	Calumet	O'Brien	Egan	Kirie	Hanover Park	Lemont
Industrial Reuse: The use of reclaimed water in industrial applications and facilities, power production, and extraction of fossil fuels								
Industrial Reuse (Once-through Cooling)								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤30	<6	<7	<6	5	<3	<6	<9
TSS (mg/L)	≤30	<5	<5	4.0	3.0	<2	<4	<6
Fecal Coli (cfu/100 mL)	≤200	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Industrial Reuse (Recirculating Cooling Towers)								
pH	6.0–9.0	7.1	7.2	7.1	7.2	7.4	6.8	7.3
BOD (mg/L)	≤30	<6	<7	<6	5	<3	<6	<9
TSS (mg/L)	≤30	<5	<5	4.0	3.0	<2	<4	<6
Fecal Coli (cfu/100 mL)	≤200	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Groundwater Recharge (Non-potable Reuse):								
Site Specific								
Groundwater Recharge (Indirect Potable Reuse)								
pH	6.5–8.5	7.1	7.2	7.1	7.2	7.4	6.8	7.3
TOC (mg/L)	≤2	N/A	9	7	10	7	12	N/A
NTU	≤2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fecal Coli (cfu/100 mL)	None	GM = 7790	GM ≤ 15	GM ≤ 66	GM ≤ 15	GM ≤ 7	GM ≤ 9	GM ≤ 11,805
Chlorine (mg/L)	1 (min)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Meet Drinking Water Standards								

Note: GM = Geometric Mean.

Table 23. Potential water reuse applications for Calumet, O'Brien, Egan, Kirie, and Hanover Park WRPs based on 2021 average effluent data in comparison with USEPA water reuse guidelines.

Reuse Category	Stickney	Calumet	O'Brien	Egan	Kirie	Hanover Park	Lemont
Urban Reuse (Unrestricted)							
Urban Reuse (Restricted)		♦	♦	♦	♦	♦	
Agricultural Reuse (Food Crops)							

Table 23. *Cont.*

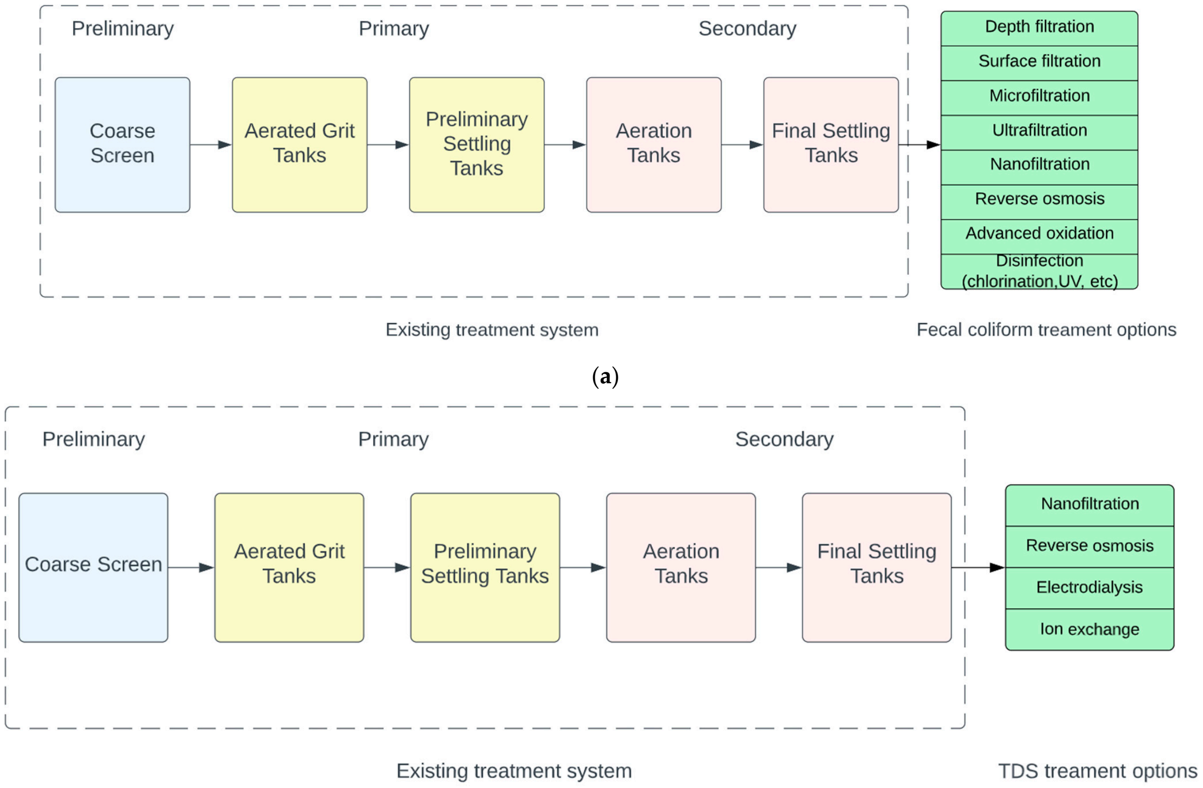
Reuse Category	Stickney	Calumet	O'Brien	Egan	Kirie	Hanover Park	Lemont
Agricultural Reuse (Processed Food Crops and Non-Food Crops)		♦	♦	♦	♦	♦	
Impoundments (Unrestricted)							
Impoundments (Restricted)		♦	♦	♦	♦	♦	
Environmental Reuse		♦	♦	♦	♦	♦	
Industrial Reuse (Once-through Cooling)		♦	♦	♦	♦	♦	
Industrial Reuse (Recirculating Cooling Towers)		♦	♦	♦	♦	♦	
Groundwater Recharge (Non-potable Reuse)	Site Specific						
Groundwater Recharge (Potable Reuse)	Meet Drinking Water Standards						

Table 24. TDS concentration from Stickney, Calumet, and Lemont WRPs in comparison with USEPA water reuse guidelines for irrigation water (Monitoring period January–December 2021).

Facility	Unit	Min	Avg.	Max
Stickney WRP	mg/L	476	692	1016
Calumet WRP		440	793	2501
Lemont WRP		624	1147	2546

Note: TDS (mg/L) < 450—None, 450–2000—Slight to Moderate, >2000—Severe.

Students at the University of Illinois at Chicago conducted a study for water reuse at Stickney WRP. Considering the end use of non-potable irrigation and toilet flushing, six parks and 34 institutional buildings were plotted within a 2-mile radius of Stickney WRP, and a distribution pipeline configuration was constructed (Figure 10). Following the USEPA guidelines for urban reuse (restricted), this study indicates that further treatment will be needed for water reuse application in Stickney WRP. Currently, there is no tertiary treatment at Stickney WRP; although some industrial water reuse applications may be possible, the existing treatment process limits the possibility for various options of water reuse applications.



(**a**)

(**b**)

Figure 9. (**a**) Stickney WRP current treatment processes combined with treatment options for fecal coliform removal. (**b**) Stickney WRP current treatment processes combined with treatment options for TDS removal.

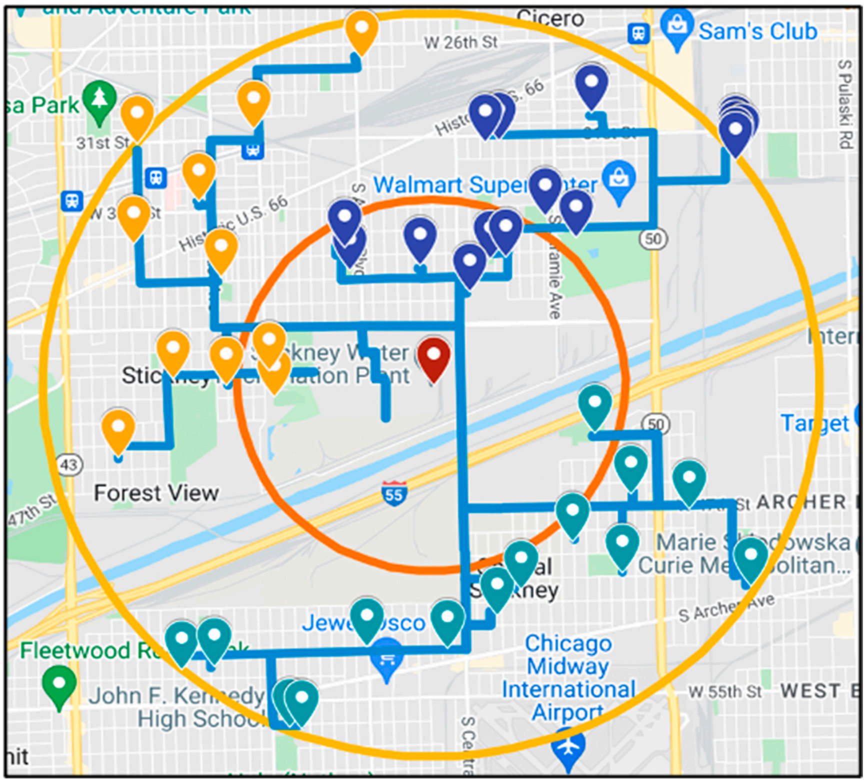


Figure 10. Stickney WRP and potential water reuse users within 2-mile radius.

7.2. Illinois and Greater Chicago Water Reuse Experience

According to the IEPA, there are 103 facilities that are licensed to reuse some or all of their treated effluent for land irrigation in Illinois. All WWTPs that reuse their effluent for irrigation are regulated by the IEPA. The capacities range from 0.01 MGD to 1.0 MGD, with Pingree Groove having the highest capacity of 1.0 MGD. The total amount of water reused per day is approximately 8.1 million gallons from all WWTPs. Pingree Groove's treated effluent was intended to irrigate all green spaces in the village (golf course, highway, sports fields, etc.). However, due to the limitations on how much water they can apply to the area, they changed their license to allow them to discharge some of its effluent. Currently, the Kirie WRP provides irrigation water to Majewski Park. A study conducted in 1991 indicated that MWRD reused some of its treated wastewater internally. The estimated volume is approximately 8 MGD at Stickney, 0.56 MGD at Calumet, 0.26 MGD at O'Brien, 0.31 MGD at Kirie, 0.98 MGD at Egan, 0.95 MGD at Hanover Park, and less than 0.01 MGD at Lemont. This is about 11.05 MGD (0.8%) of MWRD's total effluent across seven WRPs.

7.3. Three Water Reuse Case Studies in Cook County

7.3.1. Kirie Water Reclamation Plant

A study conducted by Yi Meng in 2009 found that there are 28 industries nearby Kirie WRP with a total water discharge of 1.09 MGD. Based on a previous study of industrial water reuse demand, Meng defined 50% of the total water discharge (0.58 MGD) can be satisfied with water reuse. These industries are categorized according to their distance from Kirie WRP and from there, the pipeline distribution system map was constructed with the possibility of expansion considered (Figure 11a). After setting up the pipeline system, it is possible to calculate the costs of each component at the Kirie WWTP reuse site by using the overall flow rate and pipeline length. In this particular study, the use of treated effluent from a tertiary WWTP throughout the year was analyzed, including the costs for constructing and operating the pipeline and pumping systems for 12 months, as well as the disinfection costs for 6 months. The pipeline development at Kirie makes up 91% of the total yearly expenses, as shown in Figure 11b [112].

7.3.2. O'Brien Water Reclamation Plant

There are 11 industries surrounding the O'Brien WRP with a total amount of water discharge of 92.6103 gallon per day. Similar to the Kirie case study, assuming a ratio of 50%, the demand for treated wastewater would be 463,103 gpd. The pipelines configuration was constructed with a total length of 5.07 miles for water reuse distribution (Figure 12). Compared to Kirie WRP, water reuse at O'Brien would be less favorable because of the existing slope surrounding the O'Brien WRP. The slope value (cumulative value, QL) indicates that for every mile of n pipeline created at the North Side WWTP site, 5000 gallons of water will be supplied daily [109].

7.3.3. Calumet Water Reclamation Plant

In 2016, a water reuse study was conducted for Calumet Water Reclamation Plant. During the conceptual planning, pipeline distribution configurations were established (Figure 13). The Illinois-American Water Company (ILAWC) pursued partnership with MWRD on the development of a project for the beneficial reuse of effluent water at Calumet Water Reclamation Plant. Cost-effective systems that can effectively conserve water and fulfill daily water demands are needed by municipalities, businesses, schools, and urban areas. This is indeed a challenge, given the nation's aged and inefficient infrastructure and growing water demand [113].

(**a**)

(**b**)

Figure 11. (**a**) Kirie WRP proposed water reuse pipelines configurations [112]. (**b**) Annualized cost contribution for Kirie WRP water reuse case study.

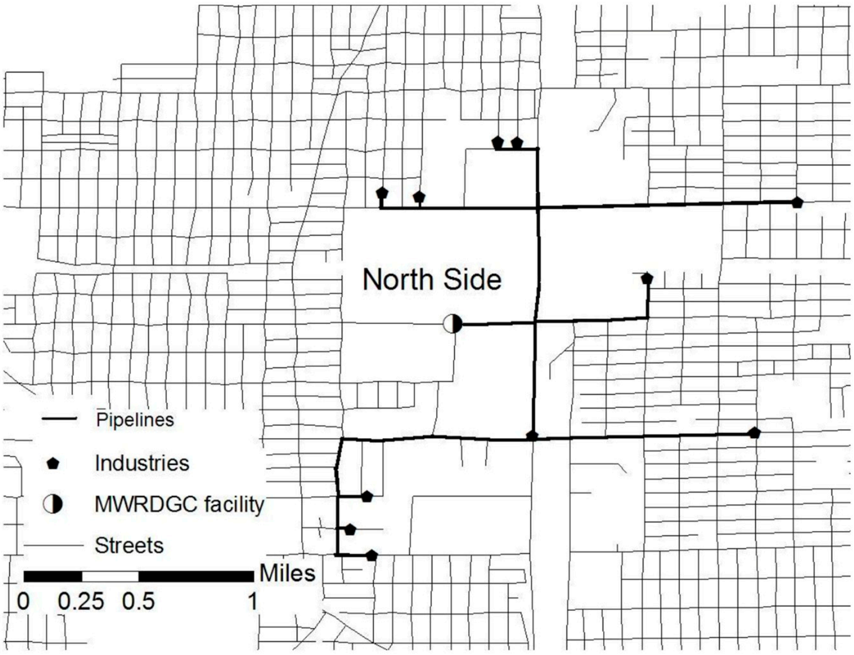


Figure 12. O'Brien WRP proposed water reuse pipelines configurations [112].

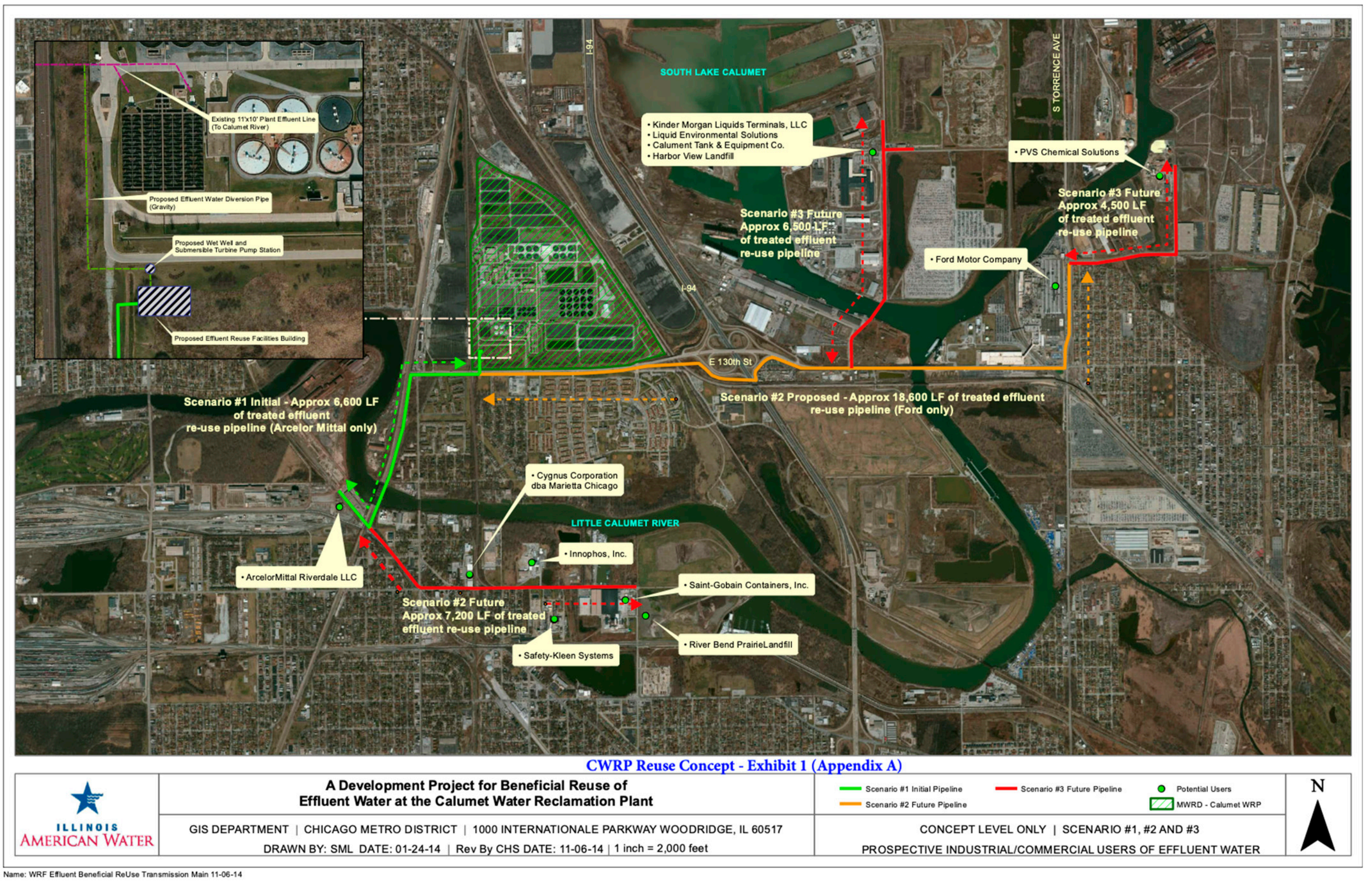


Figure 13. Calumet WRP conceptual planning for water reuse pipeline layout and potential end users [113].

8. Conclusions and Future Studies

Water reuse (water recycling) seems to be a practical and reasonable solution to augment water supply to meet growing water demand and address current depletion of freshwater sources. In the case of the Cook County, the Lake Michigan water withdrawal limit has been exceeded three times, and the yearly water withdrawal quota has always been close to the limit. This paper summarizes the drivers for water reuse, guidelines and regulations for water reuse, water reuse treatment technologies, engineering challenges for water reuse, and case studies of water reuse in the US including the Greater Chicago area and internationally.

The USEPA has extensive guidelines for water reuse including the quality of water and the degree of treatment. Non-potable reuse is widely used and accepted globally in comparison to potable reuse. This is due to people's perception of consuming treated "wastewater" or yuck factor. However, indirect potable reuse (IPR), where treated water is injected into the groundwater, has been successfully implemented in many places around the world, California, and Singapore for example. Knowing the intended use of the treated water and the water quality goal, treatment technologies can be selected. Case studies presented in this paper show that different types and combinations of treatment technologies can be used for various water reuse categories (e.g., membrane filtration combined with reverse osmosis treatment system is commonly used for IPR).

The global interest in safe water reuse is on the rise, but there are several challenges hindering its adoption. These challenges include economic feasibility, lack of public acceptance, insufficient understanding of technological advantages, and inadequate coordination among industry, government, and water agencies. Moreover, decisions regarding the implementation of innovative technologies and concepts for water reuse and desalination are often marked by conflicting economic, technical, environmental, and sociopolitical objectives. In order to encourage decision-makers to embrace new technologies and convince doubters of the benefits of water reuse, it is essential to establish transparent and robust decision-making criteria.

Infrastructure is another barrier that must be overcome to successfully implement water reuse. With the long-established water distribution infrastructure in place, building new water reuse infrastructure is challenging. There are possibilities for water reuse in Cook County, considering the effluent quality of MWRD's seven water reclamation plants. First, the end users and the intended use of the water needs to be identified, then the biggest challenge of constructing water distribution infrastructure needs to be considered and evaluated. The support of federal and local governments is an important factor for the implementation of water reuse projects and the installation of water reuse infrastructures.

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