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Critical Review

The Future of Municipal Wastewater Reuse Concentrate Management: Drivers, Challenges, and Opportunities

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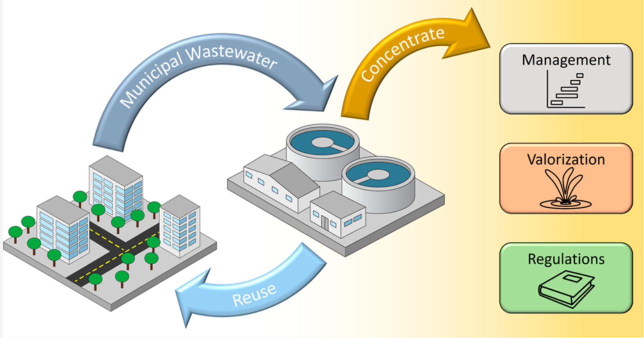
ABSTRACT: Water reuse is rapidly becoming an integral feature of resilient water systems, where municipal wastewater undergoes advanced treatment, typically involving a sequence of ultrafiltration (UF), reverse osmosis (RO), and an advanced oxidation process (AOP). When RO is used, a concentrated waste stream is produced that is elevated in not only total dissolved solids but also metals, nutrients, and micropollutants that have passed through conventional wastewater treatment. Management of this RO concentrate—dubbed municipal wastewater reuse concentrate (MWRC)—will be critical to address, especially as water reuse practices become more widespread. Building on existing brine management practices, this review explores MWRC management options by identifying infrastructural needs and opportunities for multi-beneficial disposal. To safeguard environmental systems from the potential hazards of MWRC, disposal, monitoring, and regulatory techniques are discussed to promote the safety and affordability of implementing MWRC management. Furthermore, opportunities for resource recovery and valorization are differentiated, while economic techniques to revamp cost-benefit analysis for MWRC management are examined. The goal of this critical review is to create a common foundation for researchers, practitioners, and regulators by providing an interdisciplinary set of tools and frameworks to address the impending challenges and emerging opportunities of MWRC management.



KEYWORDS: *municipal wastewater reuse, reverse osmosis, concentrate, brine, infrastructure, management, valorization, regulations, cost-benefit analysis*

INTRODUCTION

To meet ever increasing water demands, utilities are constantly seeking the most cost-effective options to expand their water supplies.[1] While in the recent past this may have involved conveying surface water over greater distances or drilling deeper wells into freshwater aquifers, the onset of climate change has added considerable uncertainty to these cost-benefit calculations.[2,3] As a result, alternatives—especially municipal wastewater reuse—have been gaining traction because of their resiliency to drought.[4] Notably, the planned treatment of municipal wastewater for potable (and non-potable) applications is also being adopted in water-abundant regions to satisfy stricter wastewater disposal regulations, overcome geographic limitations in water storage capacity, protect natural resources, and achieve greater water resource independence.[5,6]

Due to its critical role in legitimizing water reuse, the original treatment train designed by the Orange County Water District (OCWD) in California for Water Factory 21 has informed what has become the gold standard for water reuse.[7] Further validated by Singapore's NEWater program and OCWD's upgraded Groundwater Replenishment System, this three-step, multibarrier process involves pretreatment by microfiltration (MF)—more recently, ultrafiltration (UF)—to remove suspended solids, colloidal matter, and pathogens; reverse osmosis (RO) to remove dissolved solids, metals and chemical pollutants; and advanced oxidation processes (AOP) to remove trace micropollutants.[8] Specifically, the RO step in wastewater reuse operates at moderate pressures (10−20 bar) to filter wastewater effluent through a polymeric membrane

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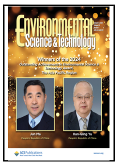

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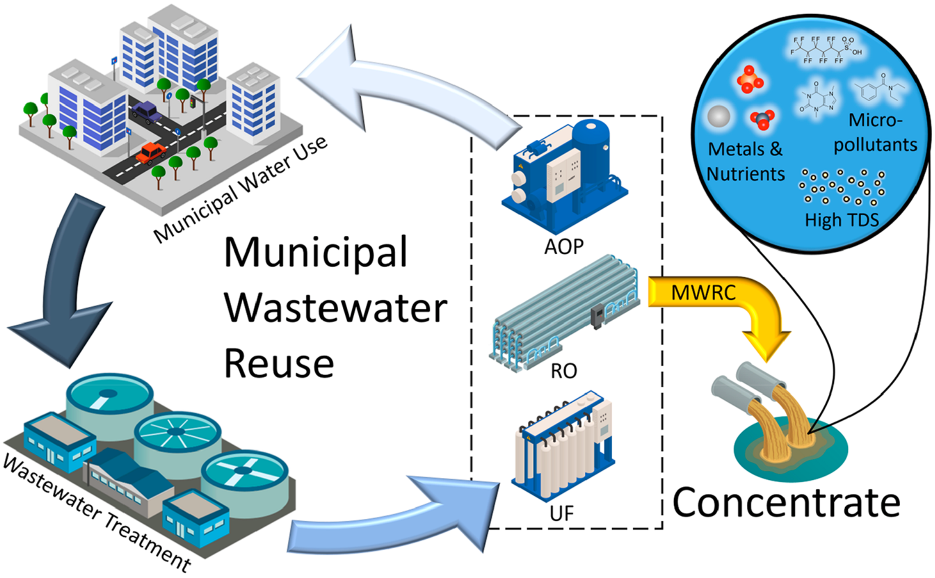

Figure 1. Cycle of municipal wastewater reuse and the corresponding production of municipal wastewater reuse concentrate (MWRC). Today, advanced wastewater treatment for reuse typically involves ultrafiltration (UF), reverse osmosis (RO), and advanced oxidation processes (AOPs). The generation of MWRC is inherent in the operation of RO, which recovers 80−85% of its inflow but concentrates most dissolved contaminants into the MWRC waste stream that comprises the remaining 15−20% of flow. MWRC differs from other reverse osmosis concentrates because it contains elevated concentrations of contaminants specific to municipal wastewater, including total dissolved solids (TDS), metals, nutrients, and micropollutants. As water reuse practices become more widespread, the generation of MWRC will also increase. Therefore, challenges and opportunities for the future management of MWRC need to be explored.

that rejects salt and most dissolved constituents and recovers 80−85% of the inlet flow as permeate.[9]

Municipal wastewater reuse concentrate (MWRC) accounts for the remaining 15−20% of flow and contains all the constituents fed to and rejected by the RO, which have now been concentrated 5−6-fold. In addition to having higher total dissolved solids (TDS) of approximately 3,000 to 8,000 mg/L, and process chemicals (e.g., antiscalants and biocides), MWRC contains elevated concentrations of metals, nutrients, and micropollutants, which include pharmaceuticals and personal care products (PPCPs), endocrine disrupting compounds (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics, and other contaminants of emerging concern (CECs).[10] The rising prevalence of MWRC as a byproduct of water reuse distinguishes it from other reverse osmosis concentrates (ROCs), requiring special consideration for MWRC management (Figure 1).

As we transition our linear water systems into a One Water Cycle—or an integrated planning and implementation approach to managing finite water resources for long-term resilience and reliability, meeting both community and natural ecosystem needs—the ability to implement water reuse is becoming contingent on the ability to manage the MWRC that is generated in the process.[11−13] The goal of this critical review is to create a common foundation for researchers, practitioners, and regulators by providing an interdisciplinary set of tools and frameworks to address the challenges and opportunities of MWRC management. To encourage systems thinking across different water sectors for MWRC management, this review draws on existing wastewater and general brine management practices to inform holistic planning for MWRC management, applies advancements in monitoring and regulatory techniques to ensure the safe and cost-effective implementation of MWRC management, and explores the promises and pitfalls of MWRC valorization while examining the critical role of cost-benefit analysis.

HOLISTIC PLANNING OF MWRC INFRASTRUCTURE

MWRC management strategies for wastewater municipalities implementing reuse ("reuse municipalities") are currently developed case-by-case, depending on geographical considerations, discharge/disposal regulations, proximity to sensitive environments, capacity of existing infrastructure, and other local determinants (Figure 2). Drawing from established brine management practices, current MWRC management options include discharge into surface waters (e.g., seas, estuaries, freshwater systems), sewer disposal, direct use via land application, well injection, evaporation ponds, zero liquid discharge (ZLD), or, in combination with another disposal option, minimal liquid discharge (MLD).[14] Overall, brine management can constitute a significant portion of total costs (up to 33%).[15] Meanwhile, stricter environmental discharge regulations are reducing the options for MWRC disposal.[16,17]

Interconnectedness of MWRC Management Options. Existing MWRC management options can be organized into three categories: conveyance, artificial end points, and environmental end points. Conveyance is the transport of MWRC beyond the jurisdiction of the reuse municipality via brine lines (to artificial or environmental end points) and by sewer disposal. Artificial end points—including evaporation ponds, MLD or ZLD—are "artificial" because highly concentrated or solid waste from the MWRC is produced, requiring disposal to an environmental end point. Environmental end points are the eventual outlet of MWRC from our engineered water system, including surface water outflow, land application, well injection, and landfilling (for solid waste).

Ocean outfall (or discharge to any saline water body) is a critical environmental end point for MWRC, due to the already

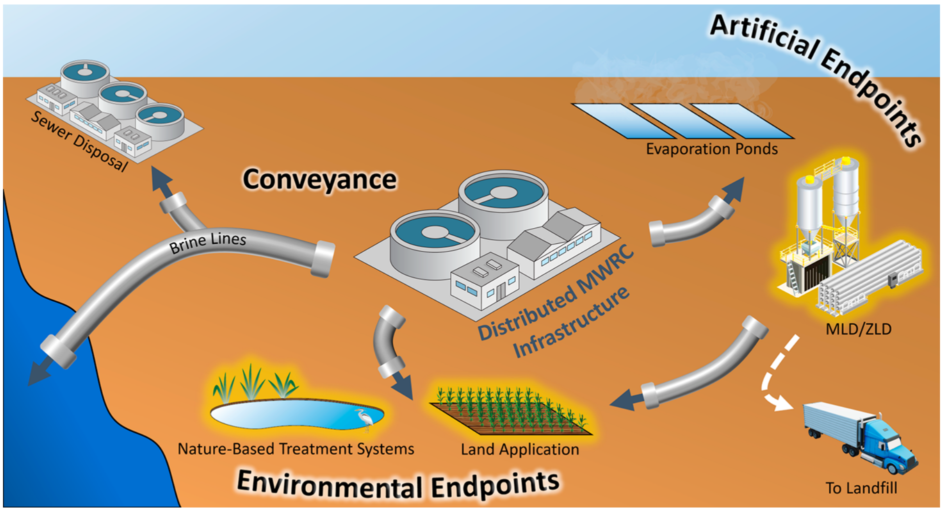

Figure 2. The interconnected categories of MWRC management include conveyance (e.g., brine lines, sewer disposal), artificial end points (e.g., evaporation ponds, MLD, and ZLD), and environmental end points (e.g., surface water outfall, well injection, and land application). Artificial end points are distinct from environmental end points in that they are still engineered systems that do not discharge to the environment until solid waste is produced and typically disposed of by landfill. Nature-based treatment systems, direct use via land application, and MLD/ZLD are highlighted because they offer multibenefits in addition to MWRC disposal.

elevated TDS and vast volumes for dilution of the receiving water body.[18] However, this option is less accessible for inland municipalities that may be considering reuse. As a result, conveyance infrastructure (to both artificial and environmental end points) will play an important role in increasing MWRC management options for inland reuse municipalities. For example, the City of Beaumont in southern California, USA was able to implement reuse due to its proximity to the Inland Empire Brine Line, despite being located more than 70 miles from the coast.[19] Constructing a 23-mile pipeline (or "lateral") to connect to this conveyance infrastructure, the City of Beaumont is able to convey their MWRC an additional 73 miles to Orange County Sanitation District's municipal wastewater treatment facility where it is blended and treated with local wastewater before being discharged to the Pacific Ocean.[20] Although urban development throughout southern California would likely make the construction of this infrastructure cost-prohibitive today, brine lines are still viable in regions where land costs are lower or—alternatively—can be used to convey MWRC to artificial and environmental end points other than the ocean.

Another important form of conveyance is sewer disposal or discharging the wastewater generated by one municipality into the sewer network of another (typically larger) municipality. In fact, the previous example could be thought of as a form a sewer disposal as the MWRC eventually made its way to Ocean County Sanitation District before ocean outfall. The benefits of sewer disposal include: (i) unlike new artificial end points, larger sewer networks have already been constructed; (ii) sewer networks can be more readily accessible than environmental end points; (iii) existing wastewater in the sewer network dilutes MWRC, making it easier to discharge; and (iv) eventual disposal falls under existing discharge permits of the larger wastewater municipality.[21] To ensure sewer disposal of MWRC does not impact the larger wastewater municipality's operation or ability to discharge, reuse municipalities would likely be subjected to industrial pretreatment programs.[22] As MWRC is a concentrated form of secondary wastewater effluent, sewer disposal is unlikely to introduce new constituents that would significantly impact the larger municipality's ability to discharge, although this may depend on what industries are upstream of the reuse municipality.[23] A challenging constituent in MWRC for sewer disposal is TDS, which may impact biological wastewater treatment processes. However, these biological processes have been shown to acclimate to TDS as high as 10 g/L after several weeks.[24] As a result, there is still significant capacity for larger wastewater municipalities to assimilate MWRC as reuse becomes more prevalent in the future.

Distributed MWRC Infrastructure. Conveyance is an effective strategy, assuming that MWRC (and its associated TDS content) is eventually purged from the engineered water system. As environmental regulations decrease the availability of environmental end points, there is a need for distributed MWRC infrastructure to provide small-scale, cost-effective options for MWRC management near the point of MWRC generation.[25] One form of distributed MWRC infrastructure is to designate an area to serve as an engineered or natural reservoir that facilitates natural evaporation of the MWRC. Evaporation ponds are shallow pits that promote evaporation by spreading brine over broad swaths of land, and—in some cases—promote natural attenuation of micropollutants.[26] To protect underlying aquifers, evaporation ponds are often required to be constructed with impervious linings, which increases the total cost of this approach to between $\$3.3/\mathrm{m}^3$ and $\$10.0/\mathrm{m}^3$ when coupled with rising land costs.[27,28] While mechanical misting can be used to enhance evaporation by spraying brine into the air to form tiny droplets, this comes at the added cost of $\$0.8/\mathrm{m}^3$.[29]

However, evaporation ponds are restricted to regions where evaporation rates are high (>1 m/year), precipitation rates are low (<0.3 m/year), and flat land is both abundant and cheap.[21,30] Moreover, evaporation ponds run the risk of introducing micropollutants to the environment if there is a breach in the impervious layer or by direct exposure to wildlife.[18,31] In addition to these considerations, natural evaporation rates are often too low to meet the throughput required for MWRC management. Recent research has explored the possibility of using porous, light-absorbing materials to accelerate the evaporation process for ZLD applications.[32−34] Known as interfacial solar vapor generation, this process uses capillary action to spread water into thin films across three-dimensional surfaces to achieve evaporation rates 100 times higher than traditional evaporation ponds.[35] Furthermore, these materials could cover standing bodies of water to mitigate wildlife exposure and can be designed to facilitate the degradation of micropollutants.[36] Although promising, the durability of these materials and their long-term performance on actual brine streams still require further investigation.

ZLD offers another form of a distributed MWRC infrastructure. ZLD refers to the process where the water is completely recovered from a concentrated waste stream, leaving only solid waste for disposal. Conventional ZLD is achieved in two steps: brine concentration through mechanical vapor compression (MVC) to increase TDS to ∼250,000 mg/L, followed by brine crystallization through vapor compression crystallization to remove any remaining water.[37] The trade-off with land-intensive evaporation ponds is that thermal-based ZLD processes are energy-intensive, with brine concentration requiring 20−25 $\mathrm{kWh_e/m^3}$ and brine crystallization requiring 52−66 $\mathrm{kWh_e/m^3}$ of treated water.[38,39] These high energy demands lead to high operating costs, which at an average electricity cost (\$0.15/kWh) corresponds to brine concentration costing \$3.0/$\mathrm{m^3}$ to \$3.8/$\mathrm{m^3}$ and brine crystallization costing \$7.8/$\mathrm{m^3}$ to \$9.9/$\mathrm{m^3}$.[40] To reduce the high operating costs of thermal brine concentration, a wide range of membrane-based technologies have emerged to achieve minimal liquid discharge (MLD), or up to 95% recovery of water from the concentrated stream.[41−43] Not having to induce a phase-change for brine concentration, membrane-based MLD technologies are inherently less energy-intensive, achieving the same level of brine concentration as MVC, but with 75% less energy.[44] Membrane-based MLD technologies that are currently under development include high-pressure reverse osmosis (HPRO), osmotically assisted reverse osmosis (OARO), and low-salt-rejection reverse osmosis (LSRRO).[43,45,46] In conjunction with artificial end points, the goal of MLD is to minimize the amount of MWRC that needs to be managed by evaporation ponds or ZLD.

One final option that is similar to ZLD (in that it does not produce a liquid waste) is the implementation of carbon-based advanced treatment for reuse. As an alternative to the membrane-based advanced treatment train that uses UF-RO-AOP, carbon-based advanced treatment consists of ozone (O_3), biological activated carbon (BAC), granular activated carbon (GAC), and ultraviolet radiation (UV), which follows the nonmembrane treatment scheme of the world's first direct potable reuse plant in Windhoek, Namibia.[47,48] The primary benefit of carbon-based advanced treatment is that—without RO—MWRC is not produced and does not need to be managed. Comparing these two treatment trains by the Sustainable Water Initiative for Tomorrow (SWIFT) program, carbon-based advanced treatment was ultimately selected because of its lower levelized cost of water and improved geochemical compatibility of reclaimed water for groundwater augmentation (with higher TDS effluent reducing metal mobilization).[49−51] Although this is a promising advancement for reuse, more research is needed to compare the advantages and disadvantages between carbon- and membrane-based advanced treatment. For example, the implementation of carbon-based treatment may be less feasible in regions where the TDS of wastewater effluent is higher or supplemental water supplies to dilute the final reclaimed water are limited, which tends to be more common in water scarce regions.[52] Furthermore, the formation of ozonation transformation products or region-specific regulations on contaminant removal (e.g., total organic carbon) can significantly influence whether carbon- or membrane-based advanced treatment is selected.[53,54] As a result, the development of distributed MWRC infrastructure still has a critical role to play in facilitating reuse.

Multi-Benefit MWRC Disposal. It should be noted that both evaporation ponds and ZLD produce solid waste from MWRC that is typically disposed of by landfill as an environmental end point. This solid waste may contain micropollutants and requires testing to determine whether the landfill used for disposal should be rated for municipal solid waste or hazardous waste.[29] While the impacts of emerging micropollutants on environmental systems are still being studied, it can be safely assumed that their release to the environment is likely to lead to adverse outcomes that can range from negligible to disastrous. As these micropollutants are at their most concentrated since their initial discharge into the sewer system, the capabilities of ZLD could be expanded to not only enable MWRC management but also facilitate the destruction of these contaminants before their potential introduction to the environment. However, more research is needed to evaluate both the efficacy and cost of micropollutant destruction methods.[55,56]

Alternatively, other benefits can be derived from the direct use of MWRC. Land application is the use of MWRC to irrigate salt-tolerant plants (called halophytes).[21] As land does not need to be purchased, this MWRC management strategy can be less costly (between \$0.74/$\mathrm{m^3}$ and \$1.95/$\mathrm{m^3}$), if a suitable operation is locally available.[27] In addition to land application, the Agua Doce Program in Brazil experimented with using ROC from inland desalination plants to grow tilapia and *Spirulina* as fodder supplements for livestock.[57] Although this program has provided economic benefits to rural regions in northeastern Brazil, the use of ROC for irrigation has been observed to cause progressive soil salinization.[57,58] Furthermore, the suitability of MWRC (as opposed to ROC from groundwater desalination) for these applications is still uncertain due to the presence of micropollutants. Similar to evaporation ponds, aqua- or algaculture can directly expose wildlife to these contaminants, whereas percolation from land application can potentially contaminate drinking water aquifers.[59] As a result, additional precautions or treatments may be necessary before direct use of MWRC.

A final multibenefit option for MWRC disposal is the use of nature-based treatment systems.[60] In the form of engineered wetlands, ponds, or subsurface flow, nature-based treatment systems can reduce MWRC volumes through evapotranspiration and promote the further degradation micropollutants.[61] Like other forms of green infrastructure, nature-based treatment systems can also foster habitats to support biodiversity, prevent soil erosion, provide flood control, reduce the heat island effect, mitigate noise pollution, all while providing aesthetic green spaces for the public to enjoy.[60,62] Serving as the potential backdrop for multiuse public spaces, green infrastructure for MWRC management also brings together a wide range of stakeholders, from community members and conservationists to utility providers and city planners.[63] And it is by integrating these diverse perspectives into decision-making processes that gives rise to holistic solutions for MWRC management.

■ ENABLING REUSE THROUGH MWRC REGULATIONS

MWRC management typically falls under existing disposal programs that cover municipal wastewater treatment plants.[64] As a result, water reuse facilities must obtain permits that specify treatment and monitoring requirements before being able to discharge MWRC to the environment.[65] Depending on the environmental end point (e.g., ocean, surface waters, land application, aquifer), these treatment and monitoring requirements may vary.[64] As previously discussed, the composition of MWRC is comparable to secondary effluent that has (i) undergone UF to remove suspended solids, colloidal matter, and pathogens; (ii) been infused with small concentrations (0.5−2 mg/L) of process chemicals additives, such as residual coagulants or antiscalants; and (iii) been concentrated 5−6-fold by RO (Table 1). The MWRC concentrations presented in Table 1 have been estimated based on values reported for secondary wastewater effluent. However, this composition may vary significantly depending on industrial dischargers and regional regulations.

Table 1. Typical Properties and Composition of Municipal Wastewater Reuse Concentrate[10,66−70]

properties	description	
Physical Properties	Temperature: 15−30 °C	
	Density: ∼1,000 kg/m^3	
	pH: 6.5−8.5	
	Dissolved oxygen: 2−8 mg/L	
	Thermal conductivity: 0.55−0.60 W/mK	
Composition	TDS: 3,000−8,000 mg/L	
	Na^+: 300−3,000 mg/L	Cl^-: 300−4,000 mg/L
	K^+: 20−200 mg/L	Br^-: 0.5−50 mg/L
	Ca^{2+}: 20−200 mg/L	SO_4^{2-}: 20−800 mg/L
	Mg^{2+}: 20−150 mg/L	B: 0.5−20 mg/L
	Cd: 0.1−10 μg/L	Cr: 0.5−120 μg/L
	Cu: 10−200 μg/L	Pb: 0.5−160 μg/L
	Ni: 10 μg/L−2.5 mg/L	Zn: 10 μg/L−1.6 mg/L
	Total N: 0.1−17 mg/L	Total P: 0.1−30 mg/L
	COD: 30−500 mg/L	
	BOD: 15−200 mg/L	
	TOC: 15−400 mg/L	
Process Chemicals	Antiscalants: Polyphosphonates, citric acid, ethylenediaminetetraacetic acid (ETDA)	
	Coagulation: Ferric chloride, aluminum sulfate	
	Cleaning: Anionic surfactants (e.g., alkylbenzenesulfonates)	
	Disinfection: sodium metabisulfite	
Micropollutants	Pharmaceutical and personal care products (PPCPs), endocrine-disrupting compounds (EDCs), disinfection byproducts (DBPs), per- and polyfluoroalkyl substances (PFAS), microplastics	

The Expanding Role of Monitoring. Due to the variable composition and concentrated nature of MWRC, it can be extremely challenging to characterize. However, the expanded monitoring of secondary effluent can be used to develop a basic understanding of the compositional makeup of MWRC, where regulations often require monitoring of bulk parameters such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total organic carbon (TOC), total suspended solids (TSS), nutrients (e.g., nitrogen, phosphorus), and other priority contaminants.[71] As these constituents will be concentrated by RO, a conservative approximation would be to assume complete rejection and multiply the secondary effluent concentrations by the concentrating factor of the RO, where the concentrating factor is the inverse of 100% minus the RO recovery. However, deviations from this approximation are likely to occur because the UF will reduce TSS, BOD, COD, and potentially other dissolved species if a coagulant has been used, and RO may have variable species rejection—especially of small, neutrally charged constituents.[72−74] As larger, biological constituents of concern (e.g., protozoans, bacteria, viruses, and ARGs) are likely to be rejected by UF and recycled upstream of the municipal wastewater treatment plant, the primary MWRC constituents of concern for discharging to the environment are micropollutants (e.g., PPCPs, EDCs, DBPs, PFAS, microplastics), metals (e.g., cadmium, chromium, copper, lead, mercury, nickel, zinc, arsenic, selenium), and nutrients.[75]

Focusing on the presence of these constituents in secondary effluents, micropollutants may constitute thousands of different organic compounds that are present at extremely low concentrations. Although organic constituents are traditionally characterized by high performance liquid chromatography (HPLC) and gas chromatography (GC), these techniques need to be coupled with mass spectrometry (MS) and nuclear magnetic resonance spectroscopy (NMR) and may require extensive isolation and enrichment protocols to accurately obtain molecular and structural information.[76] In the presence of these organic compounds, metals form complexes with organic ligands.[77] Although metal concentrations of specific species can be determined by inductively coupled plasma mass spectrometry (ICP-MS), this analysis provides an incomplete picture of how metals will behave in the environment with complexation impacting both mobility and toxicity. Therefore, a similar suite of instruments may be required to further characterize metals in MWRC.[78] In lieu of a high-resolution characterizations of MWRC, it may be more practical to target a diverse set of micropollutants and metals as proxy compounds using established techniques.[79,80] However, the availability of analytical instrumentation and technical expertise in reuse municipalities should not be assumed and is currently a barrier for establishing effective monitoring programs. Fortunately, monitoring nutrients is more straightforward, with well-established procedures to measure nitrogen and phosphorus typically incorporated into preexisting monitoring programs at wastewater treatment plants.[81] To improve the utility of these monitoring techniques, automation and artificial intelligence will likely play a significant role in reducing the cost and increasing the accessibility of many of these analyses, which is why this is an active area of research.[82,83]

Fluorescence spectroscopy is gaining prominence as an inexpensive, noninvasive, and highly sensitive characterization technique that can provide real-time data on the organic constituents for secondary wastewater effluent.[84−86] Fluorescence spectroscopy uses high-energy light to excite electrons and cause fluorescence of specific molecules or moieties.[87] The resulting emissions can be organized into excitation−emission matrices (EEM) or synchronous fluorescence spectra (SFS) that provide information about the composition and structure of organic constituents that may be present in MWRC.[88,89] While fluorescence spectroscopy has been shown to correlate well with bulk measurements like BOD, COD, and TOC, peak overlap of fluorophores makes source apportionment of specific micropollutants difficult.[90] Furthermore, the total analysis of all fluorophores can make it difficult to extract information about specific micropollutants or heavy metal complexes.[91] However, the detection capabilities of fluorescence spectroscopy are improving, especially as this technique is validated alongside other analytical techniques (e.g., LC-MS, GC-MS, NMR). Furthermore, artificial intelligence is even being used to improve data analysis by increasing the accuracy of constituent identification and expanding feature interpretation of the fluorescence spectra.[76,92]

Bioassays to determine the adverse biological effects on living organisms may prove to be useful tools for the direct monitoring of MWRC. Deviating from the methods described thus far, this effect-based approach to monitoring focuses on the outcome of MWRC exposure as opposed to the chemical composition.[93] Relying on *in vitro* (on a culture dish, typically with cells) or *in vivo* (in a biological host, e.g., daphnia, zebrafish) techniques, these bioassays can be used to determine toxicity, mutagenicity, genotoxicity, and physical stress response of living organisms.[94] Bioassays can be run with raw MWRC (demonstrating a worst-case scenario) or diluted MWRC to evaluate ecotoxicity scenarios. Furthermore, effect-directed analysis could be run to probe the relationship between biological responses and the chemical composition of MWRC (or fractionated MWRC).[95] As a result, these analyses may be critical for identifying needs for industrial pretreatment of wastewater or post-treatment of MWRC to protect natural ecosystems. However, bioassays are time-intensive, require expertise, and—due to the variability in MWRC composition, may be difficult to generalize. As a result, research is needed to improve the accuracy and rapidity of these techniques so that they can be more easily implemented in reuse municipalities.

Despite these drawbacks, effect-based methods can form the foundation for an ecological monitoring program and inform MWRC regulations and management.[96] Especially for discharging MWRC into surface water, ecological indicators should be identified that align with uses and values of the water resources (e.g., drinking water source, swimming, fishing, biodiversity). Depending on these values, relevant biological criteria should be identified for monitoring. For example, if the receiving water body is used for fishing, the developmental stages of sentinel fish populations would be a key indicator for monitoring the impact of MWRC discharge.[97] Furthermore, monitoring algae, aquatic plants, benthic organisms, and the presence of stress hormones could provide a more holistic understanding of healthy fish communities.[98] For each of the biological criteria, warning, unacceptable, and severe thresholds should be defined to prompt corrective actions and safeguard the environment receiving MWRC.[99] Although ecological monitoring faces the same hurdles as holistic chemical analyses and effect-based bioassays (i.e., expensive, time-intensive, and requiring specific expertise), these responsibilities could be shared with other governing bodies that manage the same water resources (e.g., fishery oversight board). This underscores the importance of sharing data, not only to ensure the safe discharge of MWRC, but also to help researchers elucidate the connections between chemical composition, biotoxicity, and ecological response (Figure 3).

Easing the Cost of MWRC Regulations. Affordability is a critical consideration when designing regulations that impact MWRC management, especially because of the cost that this may add to implementing reuse. Furthermore, there are many examples around the world of how to reduce or spread these costs while still prioritizing social and environmental outcomes. The first recommendation is to simplify the permitting process through the creation of general permits. Unlike individual permits, where dischargers are approved on a case-by-case basis, general permits allow dischargers to enroll if they satisfy the requirements of the permit. Despite their name, general permits should be adaptable to enable site-specificity. Dilution factors—or the assumed dilution that is applied to regulating brines, typically when discharging to the ocean—provide an example of how to achieve this balance. These dilution factors are typically determined through a mixing study or by use of approved hydrodynamic models, allowing for a more accurate calculation of concentration at the edge of a designated mixing zone.[100] This is an example of how general permits can be site-specific and reflect the physical realities of the receiving water body.[101,102] Moreover, general permits should be designed to foster collaboration between discharging entities to achieve collective goals. The Hunter River Salinity Trading Scheme in Australia provides an example, where various dischargers were provided tradeable credits to discharge TDS into the Hunter River depending on the river's flow.[103] This scheme not only reduced the occurrence of salinity "hot spots" but also encouraged intrabasin collaboration and stakeholder engagement.[104] It should be noted that the Hunter River Salinity Trading Scheme relies on extensive monitoring of this important waterway, underscoring the importance of expanding water monitoring beyond the point of discharge.

The second recommendation is for industries connected to the sewer system upstream of a reuse municipality to share the burden of treatment (and cost), especially for recalcitrant micropollutants that they are responsible for introducing into the sewer system. Treating these contaminants at the source of production is likely to achieve higher treatment efficacy as the target contaminants are most concentrated and isolated before mixing with other sewage. Typically regulated through industrial pretreatment programs, an enhanced sewer source (or "sewershed") protection entreats industries to pretreat their wastewater before discharging into the sewer.[105,106] Although past applications of sewershed protection have focused on protecting drinking water quality from reuse, enhanced sewershed protection has the expanded goal of reducing the cost of MWRC management. Furthermore, the stewardship of recalcitrant micropollutants should also extend beyond the parent compound to transformation products that are likely to arise in wastewater treatment and the natural environment.[107−109]

In addition to enacting at the industrial level, enhanced sewershed protection should also be applied to consumer products. A key limitation of industrial pretreatment programs is an inability to regulate nonpoint-source introduction of chemicals (i.e., from residential households). This was the case in Israel in the late 1990s, where 80% of municipal wastewater was being reuse for agriculture and other nonpotable applications.[110] As TDS (especially boron) can have an adverse effect on crop growth, the Israeli government regulated the amount of boron, sodium, and chloride that could be in domestic and industrial detergents.[111,112] While this may be challenging for some dischargers (e.g., pharmaceuticals and hospitals) where active ingredients may be difficult to substitute, industries should still partner with wastewater and reuse municipalities to identify opportunities to facilitate

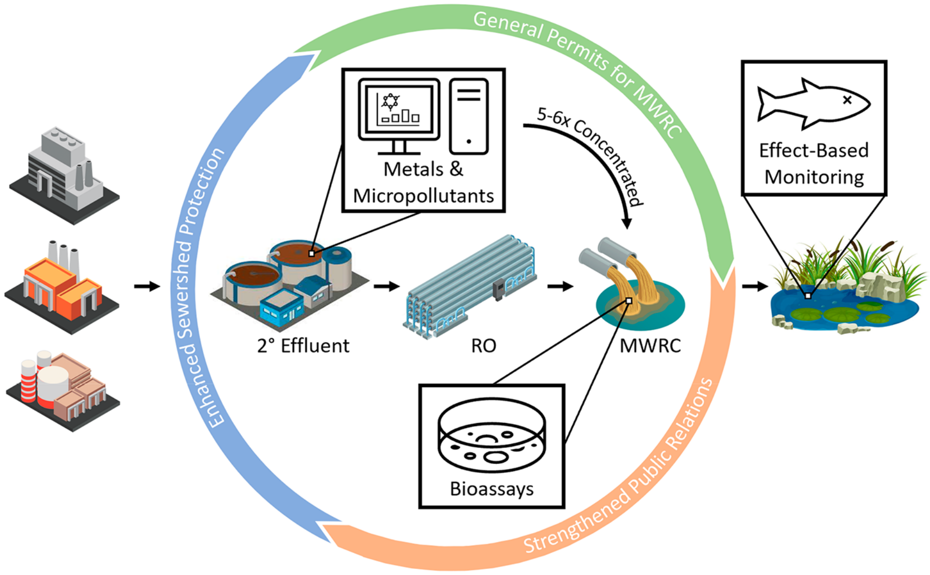

Figure 3. Composition of MWRC can be extrapolated from the composition of the secondary effluent, which is likely being monitored in compliance with water reuse programs. In secondary effluent, it is especially important to analyze for metals and micropollutants due to the elevate risk they pose to environmental systems. Meanwhile, MWRC should be evaluated using bioassays to identify any adverse biological effects on living organisms, whereas effect-based monitoring should be used to monitor ecosystem health of the MWRC-receiving environment. In conjunction with MWRC monitoring, effective MWRC regulations begin with enhanced sewershed protection, facilitated by general permits, and empowered by strengthened public relations.

enhanced sewershed protection. However, there is currently little incentive to do this. A key challenge with industrial pretreatment programs is that the responsibility of enforcement falls on the wastewater municipality, which may lack the resources and legal authority needed to ensure sufficient compliance, particularly in the case of unregulated or emerging contaminants.[113] To aid municipalities, research is needed to develop forensic methods for tracing the source of micropollutants that are accurate, timely, and affordable.[114]

The third recommendation to reduce the costs for reused municipalities is strengthening relations with the public they serve. Water resources may hold significance for people for a wide range of reasons, including water supply, recreation, wildlife habitat, and cultural.[71] Therefore, the optimal MWRC management strategy may depend on how well that strategy aligns with the values held by their constituents. For example, in Switzerland, concerns about pharmaceuticals in drinking water and the environment prompted government action to upgrade wastewater treatment plants to reduce the discharge of micropollutants in 2014. In addition to government funding, these upgrades were also supported by increases in the cost of wastewater services of 10−50%.[115] Although traditionally a source of public tension, these rate increases were determined after extensive public consultation and passed due to alignment with held values.[116,117] This public outreach can also be considered a form of institutional work that contributed to this project achieving legitimacy.[118] According to institutional theory, various forms of institutional work—including advocacy, political work, changing normative associations, constructing normative networks, mimicry, theorizing, educating, valorizing and demonizing, mythologizing, and imagery—are required at different phases of the legitimation process (i.e., innovation and local validation, diffusion, general validation).[119,120] This legitimacy framework has been applied to study a variety of systems from the influence of water scarcity on fluctuating demand for seawater desalination in Australia to the proliferation of water reuse in California.[118,121] However, more research is needed to identify opportunities for institutional work that can inform actionable strategies for reuse municipalities to legitimize emerging MWRC management approaches.

(RE)DEFINING VALORIZATION FOR MWRC

The economic viability of any infrastructure project is often evaluated using cost-benefit analysis (CBA), where the costs of investing in a water project are compared with the monetary benefits. As costs and benefits are incurred at different points in time, the net present value (NPV) is often used to compare the current value of these future monetary streams.[122] NPV is calculated by

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{B(t) - C(t)}{(1+i)^n}$$

where $B(t)$ and $C(t)$ are the annual rates of benefits and costs as a function of time, respectively, i is the discount rate (typically set to between 5% and 7%), and n is the projected lifespan of the project (typically 30−50 years for new projects and 10−25 years for retrofits). The present value for both benefits and costs accounts for the fact that fixed monetary streams generally decrease in value over time due to positive interest rates. The net present value, therefore, is the difference between benefit and cost monetary streams over the lifespan of the project, which should be greater than 0 for projects to be deemed net beneficial. To help tip the scales of CBA, there is growing interest in augmenting benefits through resource recovery from wastewater.[123,124]

Which "Resources" are Worth Recovering from MWRC? Wastewater valorization is the process of deriving additional value from wastewater, its constituents, or its properties. Based on this definition, resource recovery is a form of wastewater valorization that focuses on recovering and

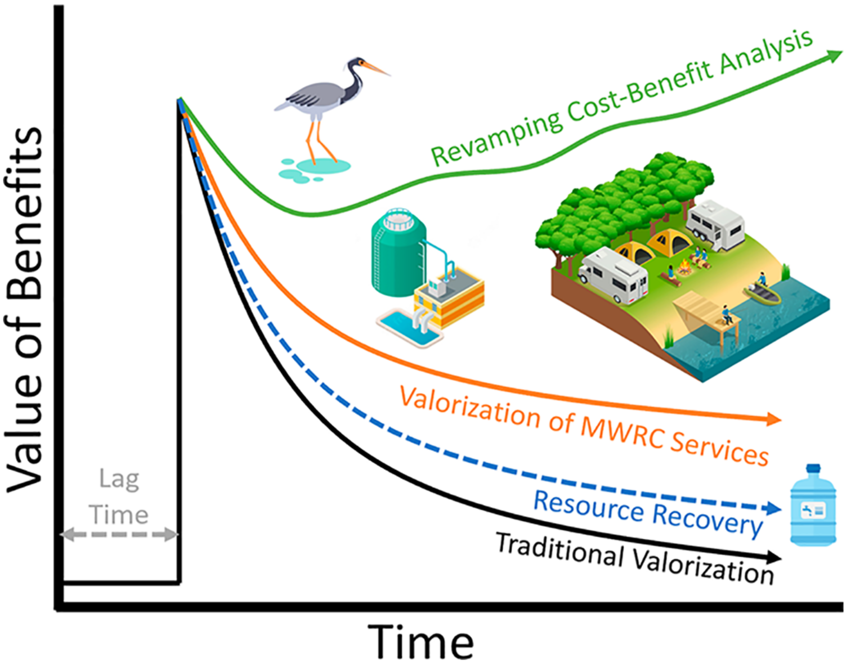

Figure 4. As observed by the "traditional valorization", discount rates used in cost-benefit analysis (CBA) cause the value of benefits to decrease over time (i.e., years). While resource recovery and, to a greater extent, the valorization of MWRC management services can increase the stream of benefits in CBA, the underlying mechanics of how CBAs are conducted (specifically discount rates and time horizons) need to be revamped to improve the CBA prospects of MWRC management.

selling specific constituents from wastewater or products derived from those constituents. Resource recovery from municipal wastewater streams has the potential to remove pollutants that would otherwise be discharged into the environment as well as expand benefit streams to improve CBA prospects. Importantly, resource recovery would displace more environmentally damaging mining, petrochemical, or chemical-processing industries associated with conventional practices for obtaining these resources.

MWRC—with potentially recoverable constituents from secondary effluent having been concentrated 5−6-fold—would appear to be a logical wastewater stream for resource recovery. However, the MWRC has undergone ultrafiltration, removing coagulated nutrients and particulate organic matter. Furthermore, all aqueous species—including interfering constituents like dissolved organics that chelate to metals and antiscalants that prevent precipitation of minerals—have also been concentrated, which can significantly reduce the recovery efficiency for extracting a specific constituent of interest. As a result, without the reconfiguration of upstream wastewater treatment processes or specialized pretreatment, the prospects of resource recovery from MWRC are like to be low.[125−127]

While the prospects of resource recovery from MWRC are like to be low, this does not mean that there is nothing to be valorized from MWRC. As previously discussed, the direct use of MWRC for irrigation, aquaculture, or algaculture can serve as a multibeneficial form of MWRC disposal.[57] Furthermore, the advent of MLD technologies are lowering the cost associated with achieving higher water recoveries from MWRC. Although municipal reuse might not justify the cost of implementing MLD, additional postprocessing of this high-purity water could be used to meet water quality criteria for specific industries. Known as "fit-for-purpose" this water can be sold at a premium, while reducing the volume of MWRC that needs to be managed.[128] However, it is essential to ensure that fit-for-purpose water meets an actual demand in an accessible market and that MLD and postprocessing technologies are designed to be agile enough to meet constantly changing market demands.

Valorizing MWRC Management Services. Beyond resource recovery, there are a wide range of ancillary benefits to the proper management of the MWRC that have already been discussed. Nature-based treatment systems for MWRC disposal not only support habitats for biodiversity but can also provide aesthetic spaces for recreation.[60,62] Additionally, expanding ZLD to facilitate the destruction of micropollutants in MWRC can result in significant damages avoided in the future.[129] Lastly, the data generated both from wastewater and natural ecosystem monitoring programs can have important implications for public and environmental health.[108] Another benefit of MWRC management is enabling the adoption of reuse into new regions where MWRC disposal is the cost-limiting factor. Depending on how water reuse is implemented, reclaimed water has been used to prevent seawater intrusion, impede land subsidence, and disrupt the formation of harmful algal blooms.[8,130,131] Most of all, water reuse can be a reliable, decentralized water source that has been viewed as a form of "drought insurance" and offers reuse municipalities flexibility, resiliency, and independence to adapt to climate change.[132,133]

However, many of these benefits (and costs) go unaccounted for in CBA because they are either "incommensurable" or "intangible". Incommensurable benefits can be physically measured but it is difficult to assign these benefits a monetary value (e.g., water scarcity, pollution), whereas intangible benefits cannot be physically measured or assigned a monetary value (e.g., aesthetic beauty, resilience).[134] Although physical measurements or qualitative assessments of these benefits can be included in CBA, a lack of comparable monetary quantities cause these nonmarket services to be undervalued.[135]

To help bridge this gap, contingent valuation has been used to ascertain monetary values of social and environmental benefits.[136] This surveying method uses hypothetical scenarios to probe the willingness to pay for specific benefits or willingness to accept compensation for specific losses.[137] However, by relying on stated preference to assign values to these nonmarket services, this technique is susceptible to biases (e.g., hypothetical bias, social desirability, lack of familiarity bias).[138] Alternatively, revealed preference methods infer the value of nonmarket services by monitoring the behavior of related market transactions. Examples of revealed preference methods include "hedonic pricing", where changes in the price of a market good are correlated to an underlying nonmarket service (e.g., using differences in housing prices to infer air quality), and the "travel cost method" where the distance traveled to experience a nonmarket service is correlated to its value (e.g., traveling to a MWRC-fed wetland for birdwatching).[139] However, revealed preference methods are limited by the availability of relevant data and the confounding factors that impact behavior.[140] Although these methods are imperfect (and tend to be human-centric), any attempt to more holistically account for benefits is better than disregarding them from CBA altogether, which is why research is still needed on applying these methods to the valuation of MWRC management services. Moreover, increasing the value of benefits for MWRC management can have only a limited impact unless the other fundamental aspects of CBA are addressed.

Revamping Cost-Benefit Analysis. The formulation previously discussed for CBA presents several challenges for many infrastructure projects including MWRC management. The first challenge is the "lag time" associated with permitting and construction before the streams of benefits begin to incur. As a result, discount rates disproportionately reduce the value of these delayed benefit streams over cost streams, which favor retrofits over new constructions to reduce the lag time. The second challenge is that the time horizon used for cost-benefit analyses is often too short for long-term benefits to materialize. For example, a 6% discount rate causes the present value of benefits to decrease to less than 20% of their original value after 30 years, rendering long-term benefits effectively negligible.[141] This incentivizes near-sighted cost-saving (or cost-externalizing) measures, like the use of carbon-intensive or environmentally damaging practices where the full costs may be unknown and difficult to measure.[142] The third challenge is that publicly owned reuse municipalities are oftentimes prohibited from making a profit and have to provide their services at-cost. While this regulation safeguards affordable water prices, it hinders the ability of reuse municipalities to generate revenue and can undermine long-term solvency.[143−145]

As a result, revamping how discount rates and time horizons are used is potentially more impactful to CBA determinations (Figure 4).[142,146] Higher discount rates (5−7%) have been traditionally used in CBA for reasons ranging from uncertainty about long-term benefits to priority of immediate social needs. As previously discussed, these high discount rates render long-term benefits beyond 30 years effectively negligible. This is often the justification for using shorter time horizons, despite the projected lifespan of infrastructure projects (30−50 years) and even longer implications this infrastructure may have on the environment.[142] Furthermore, high discount rates carry an ethical implication that the welfare of people alive today is more important than the welfare of people in the future.[146] As a result, CBA favors projects that produce benefits in the short term and externalize costs that manifest in the long term.

Many of the benefits of proper MWRC management that have been discussed begin to accrue in the long term or support complex ecosystems services that grow nonlinearly with time.[147] To better capture the value of the benefits in CBA, the use of longer time horizons with lower discount rates are recommended. Prioritizing intergenerational equity, strong cases have been made to use low (and even zero) discount rates. However, to balance short-term costs with long-term benefits, the use of time-dependent discount rates is recommended. These include declining or hyperbolic discount rates that preserve the value of long-term benefits by reducing the discount rate over an appropriate time scale. For example, the United Kingdom uses a discount rate of 3.5% for the short- and medium-term, but a discount rate of 1% after 300 years.[148] Another technique is differential discounting, where distinct discount rates are applied to different costs and benefits independently. Similarly, the time horizon for analysis can also be varied to look at the financial analysis period (~30 years), the technically useful or physical lifetime of the project (30−100 years), and the welfare impact horizon (100 years and beyond).[142] Although this makes the CBA more complicated, it can also allow for a more targeted sensitivity analysis, where the effect of discount rates and time horizons on specific costs and benefits can be evaluated.[149] Further research is needed to demonstrate the effect of modifying discount rates and time horizons on the CBA prospects of various MWRC management options. While these techniques can be applied to all kinds of infrastructure projects, it is particularly important to incorporate them into how we evaluate MWRC management because of the critical role water reuse will play in creating resilient water systems.

■ OUTLOOK FOR MWRC MANAGEMENT

As the water infrastructure built in the 20th century reaches the end of its operational lifespan, there is an opportunity to build something better. Treatment technologies have improved to enhance the mitigation of pollutants while lowering energy requirements. Analytical techniques have deepened our understanding not only about the chemical and biological composition of wastewaters but also the impact on human and environmental health. Additionally, policy tools can enable cost-effective decisions that prioritize both resilience and equity. While these advancements will aid in the transition to a One Water Cycle—where improved water supplies and reduced environmental burden can be simultaneously achieved through expansion of water reuse—ultimately the ability to implement reuse is contingent on options for MWRC management.[12]

Essential to the development and implementation of MWRC management practices is collaboration. This review attempted to bring together insights, tools, and frameworks from a wide range of disciplines, including engineering, chemistry, microbiology, ecology, economics, public policy, and other fields of social science. Furthermore, MWRC management lies at the intersection of multiple sectors including municipalities, regulators, industries, and the environment. Fortunately, there is already a thriving intellectual ecosystem for water reuse, supported by institutional actors that fund research, formalize expertise, and organize annual conferences.[118] These activities have been successful in legitimizing water reuse (especially in the United States), but as water reuse practices become more widespread, greater attention should be paid to advancing MWRC management. As there are currently only a few examples of MWRC management, data sharing and case studies are needed that showcase how context-specific factors inform MWRC management and monitoring strategies. Not only can this information be used to build frameworks to assist municipalities considering water reuse weigh different MWRC management options, but this would also help generalize MWRC management practices to be more broadly applicable for different international contexts.

Although MWRC management focuses on the wastewater specifically from water reuse activities, as our water infrastructure evolves into the One Water Cycle, MWRC management becomes the future of all wastewater management. As a result, the future of MWRC management is not just an opportunity but a fundamental obligation to take full responsibility over the wastewater we produce. Building on ideas presented in this review, MWRC management can serve as the first steps toward the comprehensive treatment of micropollutants and harmonizing of our built infrastructure with natural ecosystems. Moreover, MWRC management has a pivotal role in increasing climate resilience and ensuring equitable outcomes for our water infrastructure. To realize this potential, it is imperative that we harness the collective insights and diverse perspectives of researchers, practitioners, and stakeholders from all sectors into the development of the emerging field of MWRC management.

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Notes

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