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RESEARCH ARTICLE

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Is removal and destruction of perfluoroalkyl and polyfluoroalkyl substances from wastewater effluent affordable?

Alison L. Ling[1] | Rebecca R. Vermace[1] | Andrew J. McCabe[1] | Kathryn M. Wolohan[1] | Scott J. Kyser[2]

[1]Barr Engineering Company, Minneapolis, Minnesota, USA
[2]Minnesota Pollution Control Agency, St. Paul, Minnesota, USA

Correspondence
Rebecca R. Vermace, Barr Engineering Company, 4300 MarketPointe Drive, Suite 200, Minneapolis, MN 55435, USA.
Email: bvermace@barr.com

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Abstract
Several jurisdictions are currently evaluating regulatory standards for perfluoroalkyl and polyfluoroalkyl substances (PFAS) in municipal water resource recovery facility (WRRF) effluent. Effective and responsible implementation of PFAS effluent limits should consider the costs and capabilities of currently available technologies, because the costs of meeting WRRF PFAS limits could disproportionally fall to ratepayers. Cost curves were developed for currently available PFAS separation and destruction options, assuming effluent treatment targets near current analytical detection limits. Removing and destroying PFAS from municipal WRRF effluent is estimated to increase costs per household by a factor of between 2 and 210, using Minnesota-specific data as an example. Estimated costs per household would increase more for residents of smaller communities, averaging 33% of median household income (MHHI) in communities smaller than 1000 people. This exceeds the U.S. Environmental Protection Agency (EPA)-developed affordability index of 2% of MHHI by a factor of 16. Estimated costs per household to remove and destroy PFAS varied among locations, primarily based on WRRF and community size, median income, rural versus urban, and type of wastewater treatment processes currently used.

Alison L. Ling and Rebecca R. Vermace are members of the Water Environment Federation (WEF).

Practitioner Points

- Required tertiary treatment before WRRF effluent PFAS separation, using currently available technologies, is a significant portion (~40–80%) of estimated costs.
- Adding PFAS separation, destruction, and pre-treatment would make Minnesota wastewater rates unaffordable (defined by EPA affordability guidance) without external funding.
- The estimated cost per household is higher for smaller communities and would require substantial external funding to maintain rate affordability.
- Design and operating uncertainties remain for full-scale WRRF retrofits to consistently remove and destroy effluent PFAS with limited full-scale applications.

KEYWORDS

cost burden, perfluoroalkyl and polyfluoroalkyl substances (PFAS), PFAS destruction, PFAS treatment, wastewater affordability, water resource recovery facility (WRRF)

INTRODUCTION

The accumulation and persistence of PFAS in the environment present a global environmental challenge. PFAS are ubiquitous globally in environmental media and continuously distributed through hydrologic and atmospheric processes (Cousins et al., 2022; Evich et al., 2022). In addition, their environmental degradation to non-PFAS end products is limited (Prevedouros et al., 2006; Wang et al., 2017). This environmental persistence, coupled with their ongoing production and widespread use, means that the mass of PFAS present in the global environment continues to grow (Cousins et al., 2022), with potential health impacts for future generations (Sunderland et al., 2019).

The *PFAS Strategic Roadmap* outlines the U.S. Environmental Protection Agency's (EPA's) intention to reduce PFAS loading to surface waters by using the National Pollutant Discharge Elimination System (NPDES) to enforce permit limits on WRRF effluent (U.S. EPA, 2021c). The cost of removing PFAS from water is largely driven by the volume of water treated as opposed to the mass of PFAS present; therefore, treating lower-concentration and higher-volume WRRF effluent is likely to provide less benefit to the environment per dollar spent compared with treating concentrated, low-flow sources found in some industrial wastewater discharges. In many regions, WRRFs that accept concentrated sources of PFAS from industrial facilities are starting to address this disparity by applying PFAS limits in industrial pretreatment agreements (Michigan Department of Environment, Great Lakes, and Energy, 2023; Wisconsin PFAS Action Council, 2020). However, PFAS are widely used in everyday consumer products and are likely to be present in municipal wastewater even in the absence of industrial sources (Choi et al., 2019; Hamid et al., 2018; Roy et al., 2018; Thompson et al., 2022).

This increasing focus on PFAS in WRRF effluent and potential for increased use of NPDES permit limits to restrict them reflect increasing concern around their environmental persistence and potential toxicity. Many studies have focused on the technical feasibility of removing of PFAS from environmental media (Berg et al., 2022; Jin et al., 2021; Liu & Sun, 2021). A few have included detailed cost estimates to remove and destroy PFAS, including recent studies on drinking water (Black & Veatch, 2023) and landfill leachate (Malovanyy et al., 2023). However, none have done so with a focus on WRRF effluent, where economic affordability is a key consideration in permit limit compliance and infrastructure funding availability. The Clean Water Act allows for wastewater dischargers to receive a variance from a permit limit if complying with the limit would result in substantial and widespread economic hardship (i.e., be unaffordable) (40 CFR 131.10, 2023). Additionally, municipal dischargers can receive extra grant funding and subsidized loans if WRRF upgrades would cause economic hardship. Thus, the lack of published cost estimates for removing PFAS from WRRF effluent means that regulators and WRRF operators are lacking critical information about potential economic impacts to states, utilities, and ratepayers that could inform decision-making around NPDES permitting of PFAS.

This study begins to address the literature gap by estimating costs to retrofit existing WRRFs to separate and destroy PFAS from WRRF effluent using effective technologies currently applied at relevant scales. Costs include tertiary treatment retrofits needed to limit fouling of primary PFAS separation technologies. Estimated costs per household served were compared to U.S. EPA affordability metrics, using Minnesota WRRFs as an example case, to inform potential changes in utility rate affordability and impacts to rate payers.

METHODS

Treatment alternative selection and assembly

Treatment alternatives were developed with the goal of producing treated WRRF effluent with PFAS concentrations below current analytical reporting limits (about 5 ng/L) (U.S. EPA, 2021b; MPCA, 2020). Alternatives consisted of multiple technologies that are currently available at the scale of municipal WRRF effluent treatment and that have demonstrated effective PFAS separation or destruction efficacy in the arrangement selected. Technologies demonstrated at scale at the time of screening in late 2022 were granular activated carbon (GAC) adsorption, anion exchange (AIX), reverse osmosis (RO), high-temperature incineration (HTI), and GAC reactivation. The development and demonstration of PFAS separation and destruction technologies is ongoing, and we expect more technologies may be qualified for future consideration soon. Because alternatives were selected to limit the re-introduction of PFAS to the environment, a final PFAS destruction technology was included as part of each alternative.

Assembled WRRF effluent management alternatives were evaluated based on technical feasibility, economic feasibility, and byproducts management considerations, and the two most promising were selected for cost estimating. Conceptual designs were developed for three average wet weather design flows (0.1 MGD, 1.0 MGD, and 10 MGD). Influent concentrations for PFAS and general water quality parameters were established as a design basis using typical values reported for WRRF effluent, which are included in Tables S1 and S2 (Coggan et al., 2019; Helmer et al., 2022; Thompson et al., 2022). The WRRF PFAS influent concentrations assumed that industrial loading of PFAS to WRRFs has been minimized through industrial pretreatment agreements. This assumption was chosen because addressing the broad range of industrial PFAS loading scenarios would further complicate this multi-utility analysis. Thus, costs presented here reflect a baseline case and could be augmented with additional estimated costs to treat higher PFAS concentrations resulting from industrial inputs.

Facility-based cost curve development for treating WRRF effluent

Capital cost curves for the two treatment alternatives for three design flow rates were developed within a margin of +50/−30% based on AACE Class V cost estimates for projects at less than 2% of project definition (AACE International, 2020). Equipment costs for removing PFAS from treated WRRF effluent were developed based on vendor budgetary estimates and previous project costs. A treatment building cost of $500 per square foot was assumed based on prior project cost estimates, which included subgrade excavation and preparation, a concrete pad, building materials, heat, power and electrical, mechanical/HVAC/plumbing, and appurtenances. Additional capital costs for mobilization and management, piping and appurtenances, electrical and instrumentation, site work, and installation were calculated as percentages of equipment, building, or construction costs based on relevant project experience and considering the level of preliminary design.

Operation and maintenance (O&M) costs were developed based on process equipment requirements, typical utility costs (U.S. EIA, 2022), and estimated media changeout frequency and are intended to include maintenance allowances, consumables, analytical monitoring, and labor costs. Calculations assumed 365 operating days per year. Costs for HTI or reactivation of sorption media were included based on vendor discussions and U.S. EPA guidance on PFAS destruction (U.S. EPA, 2020) and include estimated trucking costs from Minnesota to out of state incineration and reactivation facilities 760 and 900 miles away, respectively. Allowances for annual process equipment and building maintenance costs were assumed as percentages of equipment purchase price and building footprint, respectively. Monitoring costs assumed monthly PFAS sample collection and analysis to support breakthrough detection and media changeout.

GAC media replacement frequencies were estimated by modeling the estimated bed volumes treated to breakthrough at 5 ng/L, assuming influent perfluorobutanoic acid (PFBA) and perfluorobutanesulfonic acid (PFBS) concentrations of 15 ng/L in WRRF effluent, based on Helmer et al. (2022) and Coggan et al. (2019) (Table S1). Bed volumes treated to breakthrough using GAC (Calgon F400) were estimated using an advection-dispersion model coupled with a homogenous surface diffusion model (HSDM) (Crittenden et al., 1986). Freundlich isotherm parameters for specific PFAS were taken from Burkhardt et al. (2022); water-film mass transfer coefficients and surface diffusivities of PFAS on GAC were taken from Jarvie et al. (2005); and water-phase diffusion coefficients for individual PFAS were taken from Schaefer et al. (2019).

Concentrations of conventional wastewater parameters such as organic matter and solids in secondary WRRF effluent can interfere with PFAS separation unit operations. Pressure vessel and membrane separation vendors recommend pretreatment to achieve total suspended solids (TSS) less than 1 mg/L, total organic carbon (TOC) less than 1 mg/L, and iron and manganese both less than 0.5 mg/L. While multiple tertiary treatment processes are capable of meeting these pretreatment targets, this study assumed that membrane bioreactor (MBR) technology would be installed at all WRRFs prior to PFAS separation. Tertiary retrofit costs were estimated based on full-scale MBR installation costs reported to the Minnesota Pollution Control Agency (MPCA) as well as literature reports on MBR retrofit costs (Brepols et al., 2010; DeCarolis et al., 2007; Lo et al., 2015; Young et al., 2014). Stabilization pond WRRFs were assumed to require investment matching that of a new MBR process, whereas activated sludge WRRFs were assumed to retrofit existing infrastructure with MBR components at a cost approximately 73% of a greenfield installation. Table S2 summarizes assumed WRRF effluent water quality before and after tertiary treatment retrofits, as used to develop conceptual design and cost estimates.

Combined cost curves were developed using 20-year payback timeline and an interest rate of 6.25% to reflect the current prime interest rate as of September 2022 (JPMorgan Chase, 2022). While Minnesota's Public Facility Authority offers financing that discounts the prime rate by 1.5%, the public cash reserve availability to guarantee that rate is unknown given the high potential cost of statewide PFAS treatment needs. Therefore, calculations were developed for this paper assuming that PFAS treatment would be financed completely on the private bond market, using the 6.25% prime rate at the time of analysis.

Affordability analysis for removing PFAS from WRRF effluent

This study estimated average costs per household to add PFAS removal and destruction to WRRF effluent across 232 Minnesota WRRFs that reported wastewater rates to the MPCA in 2021 (Minnesota Pollution Control Agency, 2022). This study does not identify which WRRFs would install PFAS separation and destruction retrofits but instead estimates potential costs if those retrofits were implemented. Small communities without a centralized WRRF were not considered in this study. Costs per household were estimated for WRRF service areas based on 20-year cost curves, reported WRRF design flows, industrial user flows, current wastewater rates, median income, and reported number of households.

This analysis does not include costs to add PFAS destruction for WRRF biosolids. Estimating rate impacts due to biosolids management adjustments involves an economic comparison between existing biosolids management practices and potential future biosolids management options that destroy PFAS. Potential beneficial reuse of biosolids treatment residuals, such as biochar, also complicates the economic evaluation. Because existing biosolids management varies widely between sites, including this economic evaluation in a multi-facility overview analysis like the one conducted here would be subjected to significant uncertainty and was not conducted.

WRRF flow rates and facility type were based on WRRF reports to the MPCA. Monthly average wastewater rates were sourced from the MPCA Water Infrastructure Survey (Minnesota Pollution Control Agency, 2022). Populations, number of households, and MHHI for each service area were based on the 2020 Census (U.S. Census Bureau, 2020), assuming WRRF service area matched municipal boundaries, except in the Minneapolis/St. Paul metropolitan area (metro). Wastewater services for much of the metro area are provided by one utility that operates nine WRRFs. That utility reported the population served for each WRRF (Metropolitan Council Environmental Services, 2023), which was divided by the 2020 census average of 2.55 persons per household in the metro area (U.S. Census Bureau, 2020) to estimate the number of households served by each WRRF in that utility. While Minnesota data were used for this analysis, adding PFAS separation and destruction to WRRF effluent treatment is expected to affect wastewater rates in similar ways elsewhere in the United States.

Permitting and rate setting for WRRF industrial users is a complicated process that can vary widely, including variations in one-time fees, ongoing strength charges, and apportionment of costs based on flow. Using Minnesota's standard permitting practice, industrial flows and rates were considered by adding additional "effective households" for industrial flows based on the ratio of households to non-industrial flows for that WRRF service area (Equation 1). This assumes that the rates for both industrial and municipal users are proportionate to flow, with industrial users paying the same per amount per flow as municipal users.

$$\text{effective households(number)} = \text{reported households(number)} * \left(1+\frac{\text{industrial flow(MGD)}}{(\text{WRRF design flow(MGD)}-\text{industrial flow(MGD)})}\right). \quad (1)$$

According to standard practice in Minnesota wastewater permitting affordability, this study did not consider commercial wastewater users. As a result, the costs of adding PFAS treatment were split between reported industrial users and residential households. WRRFs regulate large commercial users as significant industrial users (SIUs), which would be accounted for under industrial users. However, smaller commercial dischargers not categorized as SIUs would contribute to the overestimation of the costs per residential household in this study, with a magnitude depending on the portion of total wastewater flow and loading sourced from those unaccounted, small commercial users. This overestimation is not expected to change the study conclusions.

Estimated 20-year WRRF costs to add tertiary treatment and PFAS separation and destruction were divided by estimated effective households served to provide an average estimated cost per household for the community served by each WRRF. Estimated additional average costs per household were added to average existing wastewater rates to estimate future average costs per household and then compared with the EPA wastewater rate affordability metric. The U.S. EPA preliminary screening criteria for residential wastewater rate affordability were used. This definition of affordability is wastewater rates comprising less than 2.0% of MHHI to reflect two standard deviations above the average expenditure per household (U.S. EPA, 2021a). If the estimated average annual cost to remove and destroy PFAS per household exceeded 2.0% of annual MHHI for a given WRRF service area, the projected wastewater rates were labeled as "unaffordable" for this study. Only these preliminary screening criteria were used for this high-level analysis across many WRRFs, but EPA recommends additional secondary economic affordability indicators such as localized unemployment, tax collection rates, and bond rating, be used for WRRF-specific affordability analyses.

Affordability estimates are also subjected to the +50%/−30% uncertainty range associated with the cost curves along with additional uncertainty related to the number of households, total and industrial flow rates, current wastewater rates for each WRRF, and site-specific differences between each WRRF and the design basis used for multi-utility cost estimates. The mid-range estimates are presented in this study for simplicity. Estimated average costs per household reflect treatment to less than 5 ng/L in WRRF effluent as well as destruction of PFAS removed from the wastewater stream onto adsorption media, consistent with the facility-based cost estimates.

RESULTS

PFAS treatment alternatives selected for cost estimates

Conceptual design and cost estimating were completed for the two highest ranked alternatives to remove and destroy PFAS from tertiary treated WRRF effluent (Figure 1): lead-lag GAC adsorption vessels (Alternative 1); and RO, followed by lead–lag GAC and AIX treatment of RO concentrate prior to blended discharge (Alternative 2). Costs include both pretreatment using MBR and destruction of PFAS on spent media via HTI or GAC reactivation of sorption media. PFAS removal effectiveness for reactivated GAC is higher when using site-dedicated carbon reused only at a particular site as compared with general pool reactivated carbon (Westreich et al., 2018). Reactivation is expected to be less expensive than HTI, but facilities with under 80,000 pounds of GAC per changeout event (about 1 MGD design flow) are not expected to merit site-dedicated reactivation contracts based on conversations with reactivation vendors. Thus, GAC reactivation was included for WRRFs with flowrates over 1.0 MGD, with HTI included for smaller WRRFs.

Estimated facility costs to treat tertiary WRRF effluent using GAC adsorption with HTI (Alternative 1)

Tertiary-treated WRRF effluent would be routed through lead–lag GAC adsorption pressure vessels. GAC systems for PFAS are commonly operated as pressure vessels in series, in a lead–lag configuration, to improve treatment efficiency and easily monitor breakthrough of PFAS between the lead and lag vessels. Once a treatment threshold has been reached, the GAC media in the lead vessel is replaced, and the flow path for lead and lag vessels are switched such that the former lag vessel becomes the new lead, and the former lead vessel with fresh media becomes the new lag. Based on estimated bed volumes to breakthrough, GAC changeout was estimated to occur about three and a half times per year.

Design basis selections for Alternative 1 are presented in Table 1. The effluent PFAS concentration is dependent on the empty bed contact time (EBCT) of the GAC

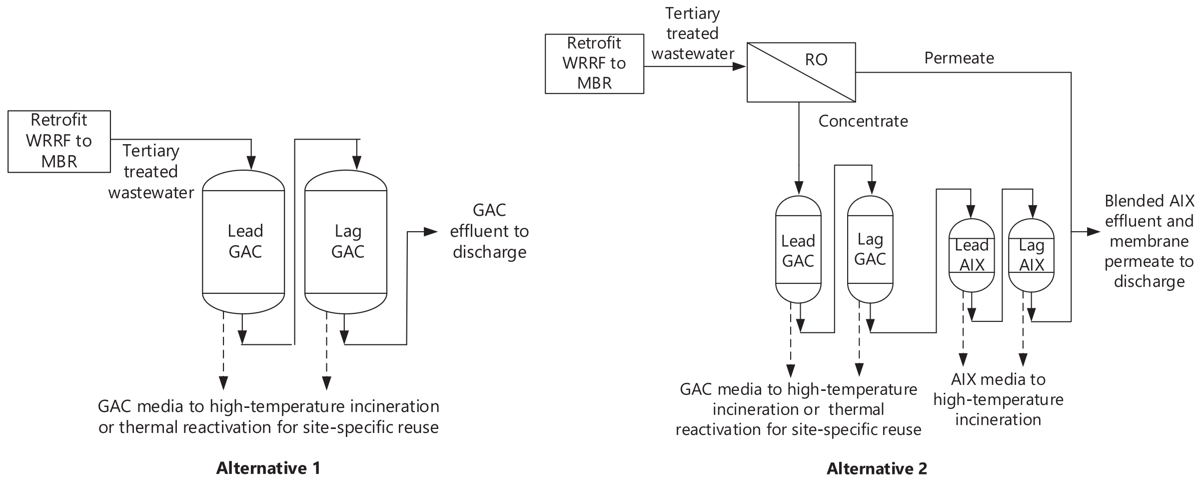

FIGURE 1 Conceptual process flow diagram for granular activated carbon (GAC) for tertiary treated water resource recovery facility (WRRF) effluent (Alternative 1, left) and reverse osmosis (RO) with GAC and anion exchange (AIX) (Alternative 2, right) for tertiary treated WRRF effluent.

TABLE 1 Summary of design basis assumptions for GAC adsorption with HTI (Alternative 1).

	Basis		
Design parameter	**0.1 MGD/70 gpm**	**1 MGD/700 gpm**	**10 MGD/7000 gpm**
Vessel size (lb)	6000	20,000	60,000
Number of trains	1	3	9
Number of vessels	2	6	18
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	2.5	2.1	5.1
Estimated bed volumes to breakthrough[a]	10,000	10,000	10,000
GAC disposal route	Offsite HTI	Offsite HTI	Offsite reactivation

Abbreviations: EBCT, empty bed contact time; GAC, granular activated carbon; HLR, hydraulic loading rate; HTI, high-temperature incineration.
[a]Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L based on previously described Homogeneous Surface Diffusion Model (HSDM) (Barr Engineering Co. & Hazen and Sawyer, 2023); see Appendix D of cited report.

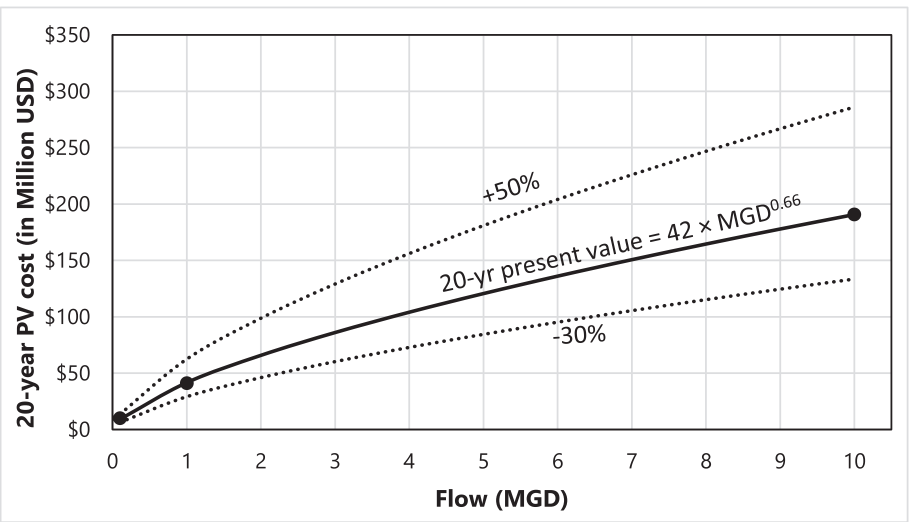

FIGURE 2 Twenty-year present value cost curve for perfluoroalkyl and polyfluoroalkyl substances (PFAS) separation and destruction from water resource recovery facility (WRRF) effluent using granular activated carbon (GAC) adsorption and offsite high-temperature incineration (HTI) (Alternative 1), including membrane bioreactor (MBR) retrofits for pretreatment.

reactor, how frequently the GAC is replaced, and the composition of the matrix being treated. The conceptual design for GAC, for both alternatives, used commercially available vessel sizing with a targeted EBCT of 15 min per vessel and hydraulic loading rate (HLR) range of 1–10 gpm/sq. ft.

The estimated cost curve for Alternative 1 is shown in Figure 2. Estimated 20-year costs for a 10-MGD WRRF range from \$130 million to \$280 million, with a nearly even split between pretreatment costs, PFAS management capital costs, and PFAS treatment O&M costs (32%, 30%, and 37%, respectively). For smaller WRRFs, PFAS management pretreatment costs make up a higher proportion of 20-year costs, at about 46% of total costs for 0.1 MGD systems. O&M costs for a 0.1-MGD system remain about 39% pretreatment costs and PFAS management capital costs make up a smaller percent at about 15%.

Primary uncertainties for Alternative 1 include the degree of pretreatment processes needed and the ability to meet pretreatment targets, actual GAC breakthrough timing and requirements, potential for GAC fouling limiting bed life over PFAS breakthrough, and location and fees of a selected reactivation or HTI facility.

Estimated facility costs to treat tertiary WRRF effluent using RO, GAC adsorption, and AIX (Alternative 2)

Tertiary-treated WRRF effluent would enter an RO membrane separation process, with concentrate routed to lead–lag GAC adsorption pressure vessels, where the majority of PFAS separation from the water phase would occur. GAC effluent would then be routed to a lead–lag AIX system for polishing prior to blending with RO permeate for discharge. GAC serves as the primary PFAS separation process, and GAC changeout would be scheduled to limit PFAS in GAC effluent. Under the design basis used here, we estimated GAC changeout frequency of four and a half times per year. AIX vessels would

TABLE 2 Summary of design basis assumptions for RO/GAC/AIX (Alternative 2).

	Basis		
Design parameter	**0.1 MGD/70 gpm**	**1 MGD/700 gpm**	**10 MGD/7000 gpm**
RO			
Recovery (%)	85	85	85
Flux (gal./sq. ft/day)	16	16	16
GAC			
Vessel capacity (lb)	800	6000	20,000
Number of trains	2	2	4
Number of vessels	4	4	8
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	3.2	1.9	2.4
Estimated bed volumes to breakthrough[a]	8100	8100	8100
GAC disposal route	Offsite HTI	Offsite HTI	Offsite reactivation
AIX			
Vessel capacity (cu. ft)	5	40	200
Number of trains	3	2	3
Number of vessels	6	4	6
EBCT per vessel (min)	4	4	4
HLR (gpm/sq. ft)	3.8	7.8	7.3
Assumed bed volumes to changeout[b]	140,000	140,000	140,000
AIX disposal route	Offsite HTI	Offsite HTI	Offsite HTI

Abbreviations: AIX, anion exchange; EBCT, empty bed contact time; GAC, granular activated carbon; HLR, hydraulic loading rate; HTI, high-temperature incineration; RO, reverse osmosis.

[a]Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L based on previously described HSDM (Barr Engineering Co. & Hazen and Sawyer, 2023); see Appendix D of cited report.

[b]Bed volumes to changeout shown assume one media bed replacement per year, because AIX process will be receiving GAC effluent with limited PFAS loading.

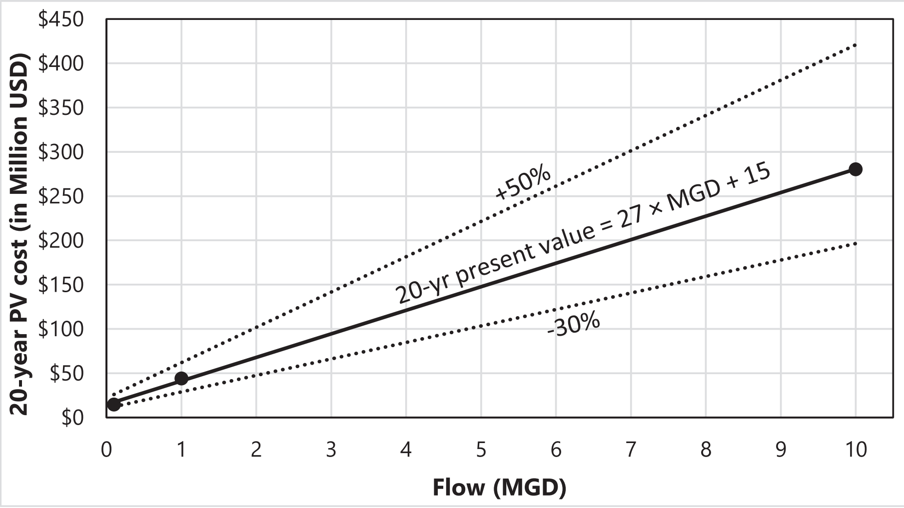

FIGURE 3 Twenty-year present value cost curve for perfluoroalkyl and polyfluoroalkyl substances (PFAS) removal and destruction from tertiary treated water resource recovery facility (WRRF) effluent using reverse osmosis (RO), granular activated carbon (GAC) adsorption, polishing anion exchange (AIX), and offsite high-temperature incineration (HTI) (Alternative 2), including membrane bioreactor (MBR) retrofits for pretreatment.

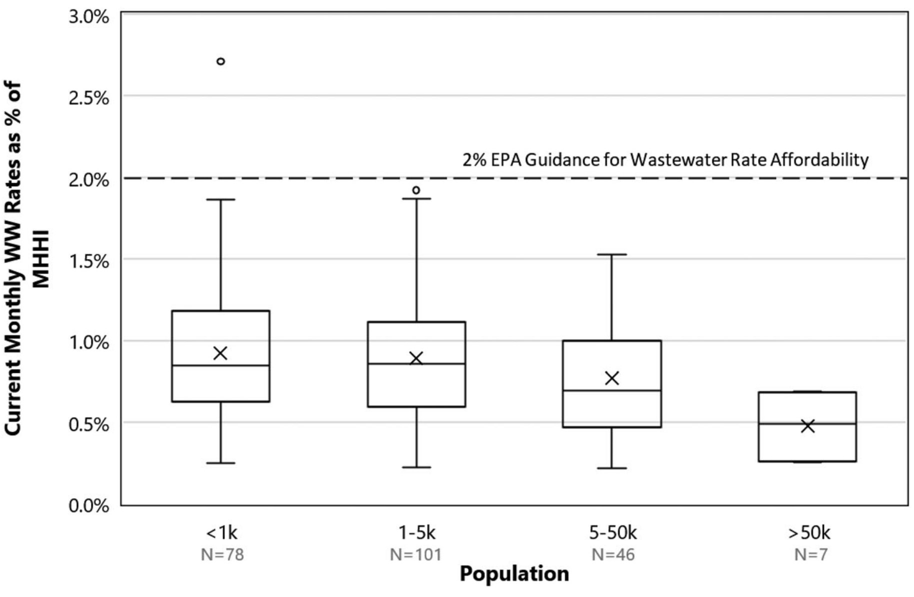

FIGURE 4 Current reported wastewater rates as percent of median household income (MHHI) for Minnesota water resource recovery facilities (WRRFs), by population served.

receive minimal PFAS loading, and thus, changeout could be infrequent, assumed to be once annually for this study. GAC would be sent to site-dedicated reactivation for facilities larger than 1.0 MGD. GAC from smaller facilities and AIX from all facilities were assumed to be sent to HTI. Design basis selections for Alternative 2 are presented in Table 2. Conceptual design for AIX vessels used commercially available vessel sizing with a targeted EBCT of 4 min per vessel and HLR range of 5–18 gpm/sq. ft.

The estimated cost curve for Alternative 2 is shown in Figure 3. Total 20-year costs for a 10-MGD facility under Alternative 2 range from $200 to $420 million, about 50% higher than for Alternative 1. The makeup of total costs is 22% pretreatment, 33% PFAS management capital, and 45% PFAS management O&M for a 10-MGD system and 33% pretreatment, 16% PFAS management capital, and 51% PFAS management O&M for a 0.1-MGD system. While the RO membrane equipment adds additional capital costs, the sorption media vessel sizing can be much smaller because the media influent flow is the membrane concentrate, which is lower than the total flow routed to sorption media for a dual-media system without RO pre-concentration. O&M costs for the system with RO are higher due to similar media use rates but added energy and consumables costs for RO operation.

Primary uncertainties for Alternative 2 include those from Alternative 1 as well as the achievable recovery, associated energy usage, and potential fouling of RO membranes; fouling potential and actual changeout frequency needs of AIX media; and relative balancing of changeout priority for GAC versus AIX media.

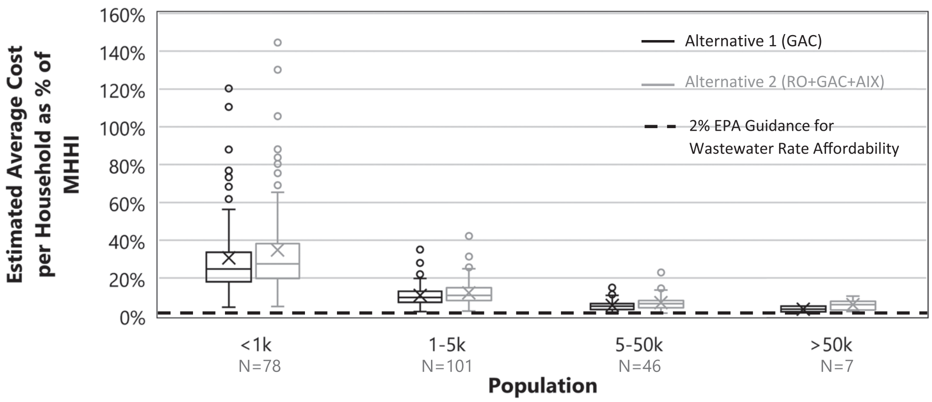

FIGURE 5 Estimated average costs per household, as percent of median household income (MHHI) for retrofits to separate and destroy perfluoroalkyl and polyfluoroalkyl substances (PFAS) from Minnesota water resource recovery facility (WRRF) effluent, by population served.

Current wastewater rate affordability

Of the 232 WRRFs evaluated, 34 are located in the metro area, and 198 are located outside the metro. The WRRFs included serve between approximately 20 and 700,000 residential households, with design flows from 0.01 MGD to 310 MGD. The proportion of flow from industrial sources ranged from 0% to 79%, up to 20 MGD, with the majority receiving no industrial flows. Seventy percent of the WRRFs studied discharge continuously and have activated sludge processes for cost retrofit estimating purposes. The remaining 30% are stabilization ponds with 180-day hydraulic residence times that are only permitted to discharge during fall and spring.

Current average Minnesota wastewater rates for Minnesota WRRFs range from 0.22% to 2.7% of the MHHI, reflecting affordable rates per the EPA's 2% guidance. Only one of the 232 facilities evaluated exceeded the 2% of MHHI affordability metric at 2.7% of MHHI. Although current wastewater rates are considered affordable for most facilities in Minnesota, rates are higher for WRRFs serving fewer people. The current average percent of MHHI spent on wastewater rates for WRRFs serving over 50,000 people (0.5%) is about half that for WRRFs serving less than 1000 people (0.9%) (Figure 4).

Estimated costs per household and affordability with PFAS removal and destruction

Installing tertiary treatment and PFAS removal unit operations is estimated to increase cost per household by a factor of 2–210 over current wastewater rates across the 232 WRRFs evaluated. About half of that cost increase is attributed to retrofitting WRRFs with tertiary treatment upstream of PFAS removal unit operations.

The estimated future costs per household as a percent of MHHI are higher and increase more in smaller communities, reflecting both economy of scale of treatment processes and typical lower incomes in smaller communities (Figure 5). For some of the smallest communities, the estimated wastewater costs per household would be greater than the MHHI for that community, as reflected by predicted future monthly wastewater rates above 100% of MHHI. Only the four largest WRRFs in the state had costs per household below the affordability threshold of 2% of MHHI for Alternative 1 (1.1% to 1.7% of the MHHI). Only the second largest WRRF in the state was below the 2% threshold for Alternative 2 (1.5% of the MHHI). Costs per household presented here reflect the average within a given community and do not reflect income disparities within each community. The high count of users served by these large WRRFs statistically diffuses the costs and does not consider affordability for financially insecure households; localized consideration of poverty and inequity could make these "affordable" costs "unaffordable" for many residents (Cardoso & Wichman, 2022; Raucher et al., 2019).

Estimated costs per household as a percent of MHHI are significantly higher outside the metro area, reflecting compounding factors of both lower MHHI in rural areas and higher cost per household for the smaller WRRF sizes predominant in rural areas (Figure 6). Estimated costs per household as a percent of MHHI are also greater for WRRFs that currently operate seasonal or intermittent pond treatment, reflecting both increased tertiary retrofit costs and smaller sizes of these facilities. WRRFs outside the metro area typically had lower influent flow rates than those within the metro area, and WRRF using pond treatment typically had lower influent flow rates than activated sludge WRRFs.

Implementing PFAS separation and destruction from WRRF effluent could create additional cost inequities borne disproportionately by lower-income communities. If estimated household costs were to fall exclusively on residential rate payers, rates would be a larger percent of MHHI for WRRFs serving poorer communities, as

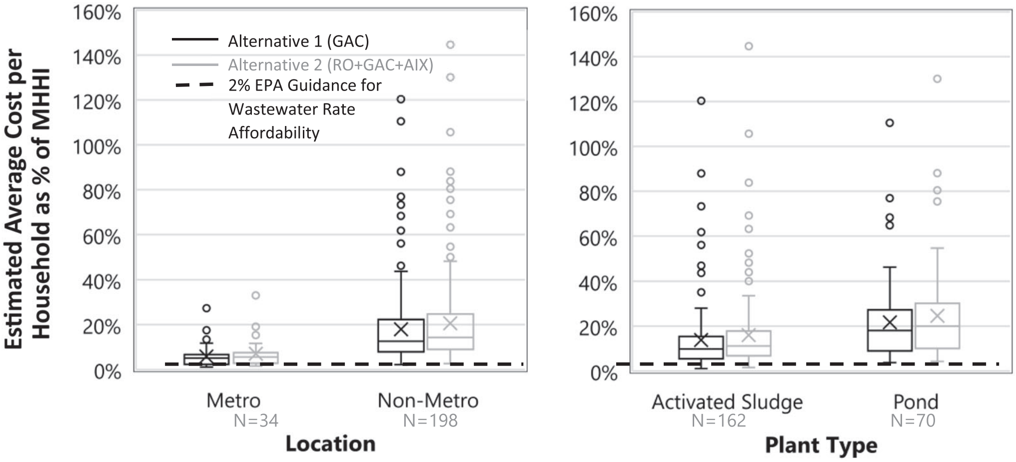

FIGURE 6 Estimated average costs per household, as percent of median household income (MHHI) for retrofits to separate and destroy perfluoroalkyl and polyfluoroalkyl substances (PFAS) from Minnesota water resource recovery facility (WRRF) effluent, by location and plant type.

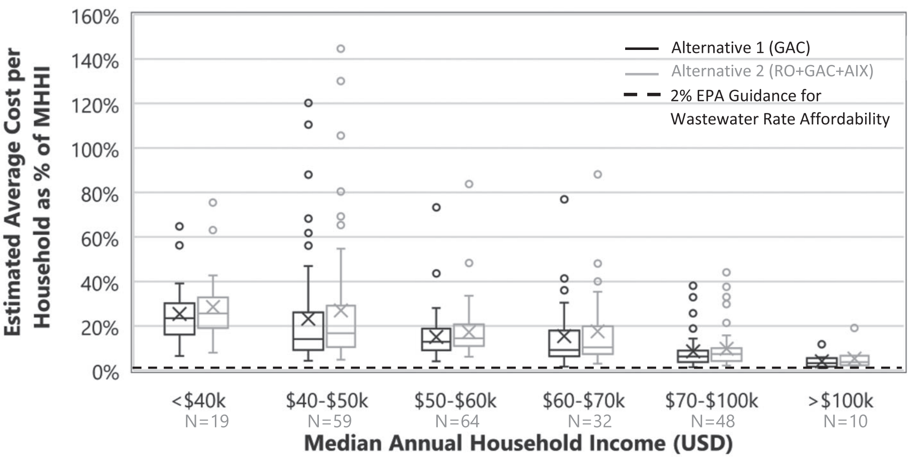

FIGURE 7 Estimated average costs per household, as percent of median household income (MHHI) for retrofits to separate and destroy PFAS from Minnesota water resource recovery facility (WRRF) effluent, by MHHI.

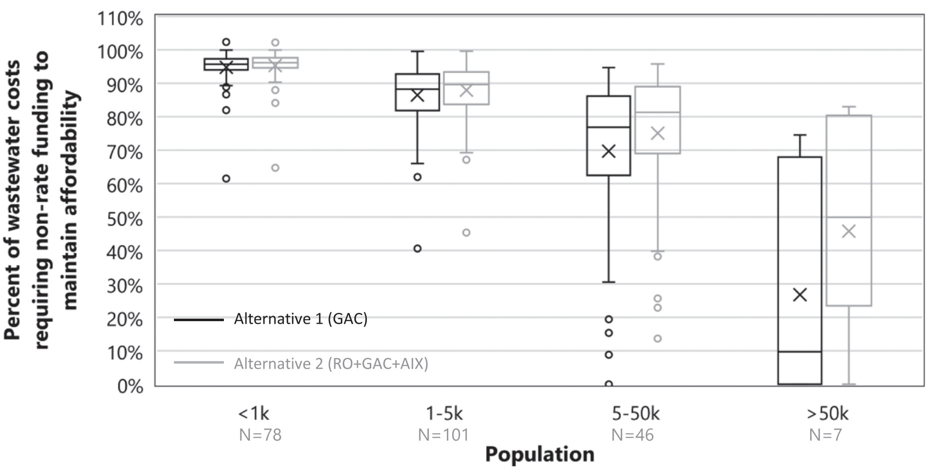

FIGURE 8 Percent of 20-year perfluoroalkyl and polyfluoroalkyl substances (PFAS) separation and destruction costs that would require external funding other than wastewater rates to maintain rate affordability (using Environmental Protection Agency [EPA] threshold of 2% of median household income [MHHI]).

reflected in Figure 7. Service area income correlated strongly with location of a WRRF. Metro area communities had higher MHHI with 80% of communities above $100,000 MHHI within the metro area and none of the metro communities below $60,000 MHHI.

Estimated additional investment needs to maintain wastewater rate affordability

Because populations served by most WRRFs would experience estimated wastewater rates exceeding the EPA affordability metric, the amount of external funding needed to maintain wastewater rate affordability was also evaluated. Figure 8 presents estimated percent of 20-year costs for PFAS-related WRRF retrofits that would need to be funded by a source other than ratepayers to maintain rate affordability. For WRRFs serving less than 1000 people, the average community would need external, non-ratepayer grant funding for about 95% of estimated retrofit costs to maintain rate affordability for both treatment alternatives. This study did not evaluate savings related to subsidized low interest loans. For WRRFs serving more than 50,000 people, an average of 27% for Alternative 1 to 46% for Alternative 2 of estimated retrofit costs would need external funding to maintain rate affordability, depending on WRRF-specific conditions and the PFAS treatment alternative selected.

DISCUSSION

Factors most influencing affordability

While Alternative 2 was consistently more expensive that Alternative 1, projected rate affordability was much more influenced by facility size, type, location, and population served than by treatment process selection. Selection between Alternatives 1 and 2 could be based on permit requirements, with more stringent permit conditions using the more reliable and more expensive Alternative 2.

Because all the options evaluated here were unaffordable based on the EPA affordability metric, widespread implementation of PFAS treatment at WRRFs is expected to require external funding outside of rate increases. WRRFs that are smaller, more rural, non-mechanical, and serving smaller communities are expected to incur higher costs per household and require more external funding to maintain rate availability. Because those factors frequently co-occur, special consideration should be made when implementing NPDES permits for small WRRFs.

Media changeout frequency complexities

Permitted WRRF effluent limit levels, as well as limit averaging period, can impact both capital and operating costs to separate and destroy PFAS. For example, higher effluent limits or a longer averaging period may mean that lead media vessels can be operated past breakthrough without exceeding permit limits, which decreases media changeout frequency and associated O&M costs.

In this study, media changeout frequency was estimated with a level of accuracy appropriate for a statewide analysis, but individual WRRFs would need to tailor changeout frequency to their individual water quality and PFAS loading. PFAS loading to WRRFs can be so variable that appropriately characterizing daily PFAS WRRF loading required up to nine randomly collected grab samples per day to accurately capture instantaneous PFAS peaks (Szabo et al., 2023). These temporal fluctuations in concentrations of PFAS, as well as other water quality parameters, limit the accuracy of media changeout frequency predictions, making it difficult to guarantee compliance with low-level PFAS effluent limits for individual WRRFs. WRRFs could offset uncertainty associated with early breakthrough by adding polishing media vessels in series, imparting additional capital costs.

Breakthrough of PFAS into adsorption media vessel effluent can happen suddenly, within hours, but PFAS analytical results can take days to weeks to receive (U.S. EPA, 2021b). These long lead times, paired with high costs of commercial PFAS testing, mean that PFAS monitoring to maintain non-detectable concentrations in GAC vessel effluent will be logistically challenging for WRRFs. WRRFs could decrease PFAS analytical lead times by operating their own PFAS analytical instrumentation, but the instrumentation requires specialized operators and can cost more than $500,000 (Saravia, 2023), which is likely beyond the resources of all but the largest WRRFs. More research is needed on the real-world and long-term performance of PFAS adsorption in municipal wastewater, and regulatory agencies should consider flexible permitting strategies to address PFAS design uncertainties.

Effect of permitted WRRF effluent PFAS chemistry (short-chain vs. long-chain) on costs

Which individual PFAS are assigned discharge permit limits can also affect treatment costs. While eight-carbon perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) have received the most regulatory

TABLE 3 Comparison of breakthrough times and O&M cost multiplier for removal of short-chain PFAS relative to C8 PFAS.

Compound	Difference in time to breakthrough relative to PFOA and PFOS (C8s), from previous literature[a]	O&M cost multiplier relative to PFOA and PFOS (C8s), from this study[b]
PFBA (C4)	2–12 times faster than PFOA[c,d]	1.2–1.7 relative to PFOA
PFHxA (C6)	1.0–2.4 Similar to PFOA[e,f,c,d]	Similar to PFOA
PFBS (C4)	1.2–9 times faster than PFOS[e,c]	1.4–2.9 relative to PFOS
PFHxS (C6)	0.75–2 times faster than PFOS[e,c]	1.2–1.5 relative to PFOS

Abbreviations: O&M, operation and maintenance; PFAS, polyfluoroalkyl substances; PFBA, perfluorobutanoic acid; PFBS, perfluorobutanesulfonic acid; PFOA, perfluorooctanoic acid; PFOS, perfluorooctanesulfonic acid.
[a]Difference in breakthrough times reported varied based on what loss of removal efficiency constitutes breakthrough. Generally, time to 50% breakthrough (i.e., removal efficiency decrease to 50% for a particular compound) was used here.
[b]Cost multipliers are estimated based on HSDM bed volumes to breakthrough (Barr Engineering Co. & Hazen and Sawyer, 2023); see Appendix D of cited report. Ranges of cost multipliers are based on the three flowrates evaluated, 0.1, 1, and 10 MGD, with higher multipliers for larger flow ranges reflecting a higher proportion of O&M costs dedicated to media changeout at larger sites.
[c]For GAC removal of PFOA, PFOS, PFBA, and PFBS from raw groundwater as reported in (Woodard et al., 2017). Sulfonate values reflect time to 10% breakthrough, because 50% breakthrough not observed for PFOS.
[d]For GAC removal of PFOA and PFBA from raw groundwater as reported in (Riegel et al., 2023). Values reflect time to 10% breakthrough, because 50% breakthrough not observed for PFOA.
[e]For GAC removal of PFOA, PFOA, PFHxA, PFBS, and PFHxS from raw groundwater and NF concentrate as reported in (Franke et al., 2021).
[f]For GAC removal of PFOA, PFHxA, PFHxS, and PFBS from raw groundwater as reported in (Westreich et al., 2018).

attention, they are also two of the easier PFAS to remove from water because they are relatively hydrophobic. In contrast, short-chain PFAS, such as PFBA, PFBS, and perfluorohexanoic acid (PFHxA), prefer to stay in the water phase and are harder to remove through media sorption with GAC and AIX (J. Burkhardt et al., 2019; Franke et al., 2021; Riegel et al., 2023; Westreich et al., 2018).

The difference in duration between the time to GAC breakthrough for different PFAS varies by water quality and influent concentrations but has been observed to be between 2 and 9 times more rapid for four-carbon PFAS compared with the most similar eight-carbon PFAS (J. Burkhardt et al., 2019; Franke et al., 2021; Westreich et al., 2018; Woodard et al., 2017) (Table 3) These more rapid breakthrough times reflect higher GAC usage by a similar margin. Therefore, alternatives relying on GAC sorption or AIX media to separate PFAS from the water phase will require more frequent sorption media changeout to consistently remove short-chain compounds. This results in higher O&M costs for facilities using GAC or AIX media to remove short-chain PFAS, (Table 3) especially at higher flow rates, high influent PFAS concentrations, and a high ratio of short-chain to long-chain PFAS concentrations.

While 28 states have water phase guidelines (including drinking water, groundwater, surface water, and wastewater) for PFOA or PFOS, only 14 states currently have water phase guidelines for PFBA or PFBS (ITRC, 2023) as of January 2023. The U.S. EPA's recently proposed National Primary Drinking Water Regulation for PFAS includes PFOA, PFOS, perfluorononanoic acide (PFNA), perfluorohexanesulfonic acid (PFHxS), PFBS, and hexafluoropropylene oxide dimer acid (HFPO-DA or GenX) (U.S. EPA, 2023). This list also favors long-chain compounds over short-chain compounds and more sorbable sulfonates over alkyl acids. The availability of appropriate water treatment and environmental remediation technologies should be considered as the types of PFAS in use evolve and regulations around use and environmental discharge are updated.

Site-specific variation

Preliminary designs and costs were developed for a range of facility sizes to address design basis influent water quality established for this project (Tables S1 and S2). The costs presented here are intended to be useful for high-level, regional, and economic evaluations and are not appropriate for site-specific facility planning. Existing effluent water quality from specific WRRFs will differ from the representative values assumed as design basis here and can significantly affect GAC and AIX changeout frequency needs. Other site-specific factors include influent PFAS concentration and speciation, treatment goals, existing infrastructure and space constraints, and distance to reactivation or HTI facilities. These site-specific variations will result in compounding variations affecting equipment sizing, efficacy and changeout frequency of GAC and AIX resin, level of tertiary treatment needed, and degree of fouling and associated maintenance needs relative to those estimated here. Any of these factors could push site-specific capital and O&M costs outside the range estimated in this study for WRRFs conforming to the stated design basis. Because this analysis reflects a baseline with minimal industrial PFAS inputs, WRRFs with significant industrial PFAS loading could require additional investment, likely through costs of more frequent media changeout and/or additional media vessels.

CONCLUSIONS

Effective and responsible implementation of PFAS regulations for WRRFs should consider the costs and limitations of current technologies. This study developed the following conclusions related to the cost of removing and destroying PFAS from WRRF effluent:

- Advanced tertiary pre-treatment is needed for secondary WRRF effluent upstream of PFAS separation to prevent media or membrane fouling and to preserve adsorption capacity. MBRs are one option for this high level of pre-treatment and were included in costs presented here. Upgrading existing pond and conventional secondary WRRFs to MBRs is a significant capital investment and large portion (about 40–80%) of estimated costs.
- Current residential wastewater rates in Minnesota are affordable, but adding PFAS separation and destruction as well as tertiary pre-treatment retrofits is expected to make them unaffordable, as defined by EPA guidance. The estimated average cost per household is expected to be higher for smaller communities, communities with lower income, and communities outside the Twin Cities metropolitan area. Substantial external funding would be needed to maintain affordable rates.
- PFAS sorbed to media must be destroyed to prevent future releases to the environment, and destruction was included in the cost estimates presented here. However, only two destruction technologies currently have infrastructure in place to accept spent media at the scale of WRRF effluent: GAC reactivation and HTI. Alternate PFAS destruction technologies may be available at relevant scales in future years, potentially with lower capital or O&M costs.
- Substantial design uncertainties remain to enable retrofit of a full-scale WRRF to consistently remove and destroy PFAS from WRRF effluent. Resolving these uncertainties would require substantial full-scale testing and engineering design as well as flexible permitting strategies on the part of regulatory agencies when evaluating testing outcomes and developing permit conditions. Costs for a specific WRRF will depend on the degree of pretreatment needed, the PFAS targeted, permit conditions, and other site specifics.

AUTHOR CONTRIBUTIONS

Alison L. Ling: Conceptualization; methodology; formal analysis; writing—original draft; writing—review and editing; investigation; validation; data curation; visualization. **Rebecca R. Vermace:** Methodology; formal analysis; writing—review and editing; investigation; validation; data curation; visualization. **Andrew J. McCabe:** Investigation; methodology; formal analysis. **Kathryn M. Wolohan:** Supervision; investigation; funding acquisition; project administration; writing—review and editing. **Scott J. Kyser:** Funding acquisition; supervision; writing—review and editing; conceptualization; data curation.

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CONFLICT OF INTEREST STATEMENT

In submitting this manuscript, the authors do not have any conflicts of interest or other considerations that would limit the publication of the manuscript. Alison Ling, Rebecca Vermace, Andrew McCabe, and Kathryn Wolohan are consultants to the Minnesota Pollution Control Agency and served in that role while assisting with the preparation of this manuscript.

DATA AVAILABILITY STATEMENT

The data used in this manuscript were publicly available, with the exception of vendor budgetary estimates.

ORCID

Rebecca R. Vermace https://orcid.org/0000-0002-0676-9270

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SUPPORTING INFORMATION

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

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