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Abstract
Per- and polyfluoroalkyl substances (PFAS) presents technical challenges in small systems where advanced drinking water treatment implementation is difficult. Publicly available data were used to examine technical treatment capacity for PFAS in the US, using Nebraska as a pilot. Of 1312 PWSs in Nebraska, 441 have technologies capable of removing PFAS from drinking water. Reverse osmosis was the most common treatment technology in Nebraska with 277 total systems using this technology with, 194 PWSs with RO serving populations of <= 100 people. Fifty-two PWSs had granular activated carbon, 47 had ion exchange and 62 had ultraviolet, with UV being primarily used for disinfection. We found PWSs had different technology deployment methods, several systems had "significant deficiencies" reported in management and operation evaluations, and age and previous water quality violations were not correlated to treatment evaluations. The developed methodology models utilizing publicly available data for contaminants across the US.
Key words: technical capacity, drinking water treatment, small water systems, PFAS contamination, data analysis

Impact statement
We developed and tested a model for small drinking water systems contaminant removal that can be used to proactively examine technical capacity for treatment of emerging contaminants of concern.

Introduction
With the introduction of proposed new water quality regulations for per- and polyfluoroalkyl substances (PFAS) by the US EPA in 2023, many states across the United States are now considering how to best regulate, monitor and potentially treat PFAS in public water systems (PWSs). Some states such as Massachusetts, Michigan, Minnesota and Colorado have previously implemented state level maximum contaminant levels and treatment technologies prior to federal regulations (Nelson da Luz, personal communication, 2023). However, most states, Nebraska included, are now starting to consider how to address PFAS in drinking water treatment systems, as many states wait for federal regulatory decisions prior to implementing state-level requirements. Many states such as Nebraska are now monitoring for PFAS under the Unregulated Contaminant Monitoring Rule 5 (UCMR 5) with sampling being completed between 2023 and 2026 (US EPA 2023; US EPA 2021) and have previous data about PFAS presence in large PWSs from Unregulated Contaminant Monitoring Rule 3 (UCMR 3). If and when PFAS compounds are found in drinking water treatment systems, Nebraska and other states will need to have proactively identified which systems will require treatment technologies or alternative solutions to ensure PFAS contaminated water does not reach customers.

PFAS are a class of synthetic compounds with highly polar carbon-fluorine bonds. Their physiochemical properties make them hard to break down using physical and chemical processes, earning them the name "forever chemicals." The difficulty in breaking PFAS down allows these compounds to cycle and persist in the environment (Yadav et al., 2022; Li and Koosaletse-Mswela, 2023). PFAS from industrial products in landfills, fire retardants and foams, and waste infrastructure can leak into lakes, rivers, and ground water, contaminating public water systems. Though PFAS contamination often starts with industrial processes, agricultural regions are seeing PFAS in soil from contaminated irrigation water sources. Other regions with limited industrial infrastructure can still see PFAS contamination from packages containing PFAS breaking down in landfills, the use of fire retardants and foams, and precipitation of contaminated water (Yadav et al., 2022; Li and Koosaletse-Mswela, 2023). Accumulation of PFAS raises environmental and public health concerns. In drinking water specifically, PFAS compounds can enter the human body through the ingestion exposure pathway, leading to documented health impacts such as disrupted endocrine function, poor kidney health, increased risk of cancer, and reduced immune responses (Costello and Lee, 2020; Jha et al., 2021; US EPA 2023). Water treatment to remove PFAS or alternative solutions such as drilling new groundwater wells will therefore be critical to protecting human health in drinking water systems where PFAS is found in the United States.

The urgency created by bioaccumulation of PFAS in aqueous environment has led to extensive research in methods of treating PFAS. PFAS compounds in drinking water have been shown to be difficult to remove with conventional treatment technologies (Yadav et al., 2022; Banks et al., 2020), resulting in extensive research into innovative treatment for PFAS removal (Banks et al., 2020; Kim et al., 2020). Most applied research has been done in the context of large-scale water treatment facilities in high income areas (Pugel et al., 2022), with few studies currently evaluating the real-world technology implementation process for small and rural systems. Previous studies suggest that globally, over a fourth of rural water systems do not function as intended (Valcourt et al., 2020). Water treatment facilities, especially in rural areas, often lack sufficient funds and workers (Grigg, 2023), so there is a larger risk associated with implementing new, untested treatment technologies. Small and rural facilities require an emphasis on appropriate allocation of resources to achieve sustainable solutions (Bereskie et al., 2017; Blanchard & Eberle, 2013; Goodrich et al., 1992; Jones et al., 2019). This includes building upon existing treatment facility infrastructure. Several leading technologies that are commonly used for other pollutants (such as granular activated carbon and ion exchange) are being adapted to include treatment for PFAS (Kim et al., 2020; Yadav et al., 2022). Understanding what water treatment technology capacity already exists preferentially in different states can inform decision-making processes related to technology implementation, both in the implementation of new treatment systems and retrofitting of existing water treatment facilities.

As of summer 2023, the following treatment technologies have been shown to have varying degrees of effectiveness at removing PFAS from drinking water: activated carbon, both granular (Yadav et al., 2022; Banks et al., 2020; Belkouteb et al., 2020; Kim et al., 2020) and powdered (Yadav et al., 2022; Kim et al., 2020), ion exchange, reverse osmosis and advanced oxidation processes combining ultraviolet radiation with oxidants such as peroxide, ozone and different forms of chlorine (Yadav et al., 2022; Banks et al., 2020; Kim et al., 2020). Other specialized technologies (Yadav et al., 2022) have also been shown at lab- or pilot-scale to be effective at removing PFAS. Effective removal rates vary depending on the study conditions, with granular activated carbon (GAC) removing anywhere between 70-80 % of PFOS and PFOA compounds, ion exchange (IX) removing anywhere between 50-90% of long-chain PFAS compounds and <55% of short-chain PFAS compounds and reverse osmosis (RO) removing between 92-99% of compounds (Yadav et al., 2022). Many of these studies have examined technologies at lab-scale or pilot-scale and there is still a need to examine the effectiveness of these treatment technologies in the context of full-scale treatment facilities. Full-scale facilities have additional variables to consider: source water quality variation, managerial and operational treatment capacity, system size (population served), system rurality (considered in this study to be geographic location and degree of remoteness), financial capacity and technical treatment capacity, including the use of multiple treatment barriers available and the appropriateness of the technologies(Bell et al., 2023; Blanchard & Eberle, 2013; Clark, 1987; Logsdon et al., 1990; Maras, 2009; Minnes & Vodden, 2017).

Given the challenges known to exist in small rural drinking water systems it is important to consider the technical, managerial and financial constraints related to implementing, operating and maintaining new technologies (Goodrich et al., 1992; Job, 2009; Logsdon et al., 1990; Minnes & Vodden, 2017; Shanaghan & Beecher, 2001; Soelter & Miller, 1999). Nebraska in particular is a good example of a state with several small systems, with 1312 PWSs serving less than 10,000 people, 1076 of which serve less than 500 people and 666 of which serve less than 100 people (SDWIS, 2023). States that are predominantly rural and small systems often lack data pertaining to the control of PFAS contaminants (Stevie & Clark, 1982; Stoiber et al., 2020) due to challenges associated with sampling. Research on PFAS treatment technology development is creating a growing need to understand how technologies may apply in a practical context (Banks et. al., 2020). Current public national level databases do not provide a comprehensive way of evaluating what PFAS treatment capacity exists, with no current options to specify PFAS violations or treatment objectives related to PFAS, although these elements are slated to be added to the national Safe Drinking Water Information Systems (SDWIS) database in the coming years (ASDWA, personal communication, 2023). This leaves a data gap related to small systems' technical capacities that is important preliminary groundwork in decision-making regarding PFAS treatment solutions.

The SDWIS (Safe Drinking Water Information System) database contains several reports relevant to national drinking water regulations available to the public as mandated by the EPA (US EPA 2022a). When evaluated together, the reports can be used to estimate technical treatment capacity for PFAS removal, or another water contaminant of interest, in a given region. However, reports are not currently being leveraged to their full potential, as many studies focus on just violation reports, omitting information about other aspects of PWSs (Pennino et al., 2020; Michielssen et al., 2020, Rubin, 2013, Allaire, 2018). With a mandated effort currently focused on an initial phase of quantifying the magnitude and location of PFAS contamination (NDEE, personal communication, 2023; US EPA, 2023), some PWSs may find PFAS in their area that need to be removed from drinking water. UCMR 5 and UCMR 3 monitoring focuses on community water systems (CWSs) serving more than 3,300 people (as categorized by the USEPA); state efforts in conjunction with researchers at the University of Nebraska-Lincoln will aim to sample small CWSs in 2024-2025 (NDEE, personal communication, 2023). The challenges of PFAS removal combined with added issues that come with being a small system PWS can complicate the process of updating treatment infrastructure (Job, 2009; Ringenberg et al., 2017; Rogers & Louis, 2008) . Using data that is available to evaluate what technical capacity already exists before an infrastructure update is mandated allows for informed decisions and effective allocation of limited resources.

The objective of this study is to develop a methodology for using publicly available data to determine small and rural system technical capacity to meet treatment challenges associated with emerging contaminants of concern. This study aims to use the example of Nebraskan systems and PFAS compounds to establish what technical capacity currently exists for public waters systems. Our study will:

(1) Adapt a definition of technical capacity from literature and identify publicly available data sources that can be used to evaluate technical capacity

(2) Use publicly available data to evaluate technical capacity, with a specific lens of small, rural systems in Nebraska that may require treatment for PFAS once source water monitoring is completed

(3) Use informal stakeholder conversations to contextualize the data in our study, ultimately providing recommendations related to small systems considerations of appropriate technical solutions to PFAS removal.

(4) Generalize the study methodology to develop a model for evaluating technical capacity that is applicable to other regions and water pollutants of concern for additional future modeling efforts.

Methods

This study utilized existing publicly available data to evaluate the technical treatment capacity available in small public water systems to meet the challenge of PFAS contamination. As such, the methods are presented as follows: (1) a description of how technical capacity was defined, (2) the context in which the methods were evaluated in the specific case study of the state of Nebraska, (3) a description of the data sources used in this study and (4) the methodologies used to evaluate technical capacity.

Defining Technical Capacity

A water system's "capacity" can be defined in various ways based on literature (Bell et al., 2023; Blanchard & Eberle, 2013; Jones et al., 2019; Maras, 2009; Minnes & Vodden, 2017; Soelter & Miller, 1999), but is most often defined in terms of technical, managerial and financial (TMF) capacity (Bell et al., 2023; Blanchard & Eberle, 2013). For the purposes of this study, we elected to focus our analyses on technical capacity, as the information necessary to evaluate managerial and financial capacity would need to be acquired through conversations with individual water systems. Acquiring this information is time-consuming and proper data collection would involve ethics reviews and collaboration with several state agencies, all of which was not considered feasible in the timeframe allotted for this project. As a result, we focused our efforts on using existing data about treatment technologies, source water quality and other relevant pieces of data to evaluate technical capacity.

In this study, technical capacity has three components derived from the Nebraska Department of Energy and the Environment (NDEE) definition of capacity (NDEE Capacity Development, 2023a): infrastructure adequacy, system operations and source water adequacy (Figure 1). For each of these three components, we then identified sub-components that could theoretically be evaluated using publicly available data. Infrastructure adequacy was broken into the following sub-components: treatment technology (focused on appropriate technologies for a specific contaminant), the age of the infrastructure and the treatment efficacy. System operations was broken into the following sub-components: management and operations evaluations completed as part of the sanitary surveys completed every three years for CWSs in Nebraska (NDEE, personal communication, July 2023), and stakeholder engagement through informal or formal interviews to contextualize system-specific challenges. Finally, source water adequacy was divided into source water quality and monitoring and source water evaluations again obtained from the sanitary survey program. Each component, corresponding sub-components and identified potential data sources are present in Figure 1.

Context for evaluation

This study was conducted as a 10-week NSF funded REU at University of Nebraska-Lincoln. Due to the limited timeline, the scope of study was kept narrow to emphasize applicability of a model to a specific case study. While Nebraska was first selected because of existing connections to local agencies and because it allowed for a focus on rural, small systems serving less than 10,000 people with the majority of Nebraska systems being small (1312 systems). This is important because small systems are a population that is typically excluded from similar studies, underrepresenting small system challenges such as lack of managerial, operational and financial. The focus on Nebraska was contextualized with a literature review and informal stakeholder conversations with local stakeholders the researchers could easily interface with. Informal conversations included contacting professionals in the field such as state agencies, nonprofit organizations, professional organizations, and academics. This information guided the identification of treatment technologies to focus on as well as what parameters to set when defining capacity

For this study, we examine the combination community water systems (CWSs), transient non-community water systems (TNCWSs) and non-transient non-community water systems (NTNCWSs) as defined by the USEPA (SDWIS, 2023). In the high-level characterization analysis of PWSs in Nebraska, we examine all types of PWSs; in the subset data described below, we examine only CWSs. It is important to note that current monitoring efforts such as UCMR 5 will only characterize CWSs with a population greater than 3,300. However, since PFAS is a public health concern that affects human health even in small doses, we elected to examine all water systems in Nebraska. While initial efforts to treat and remove PFAS will likely focus on water supplies serving larger populations, we include small systems and all types of PWSs (CWS, TNCWS, and NTNCWS) as eventually, any water system with PFAS contamination will need to protect their customers from potential deleterious health risks.

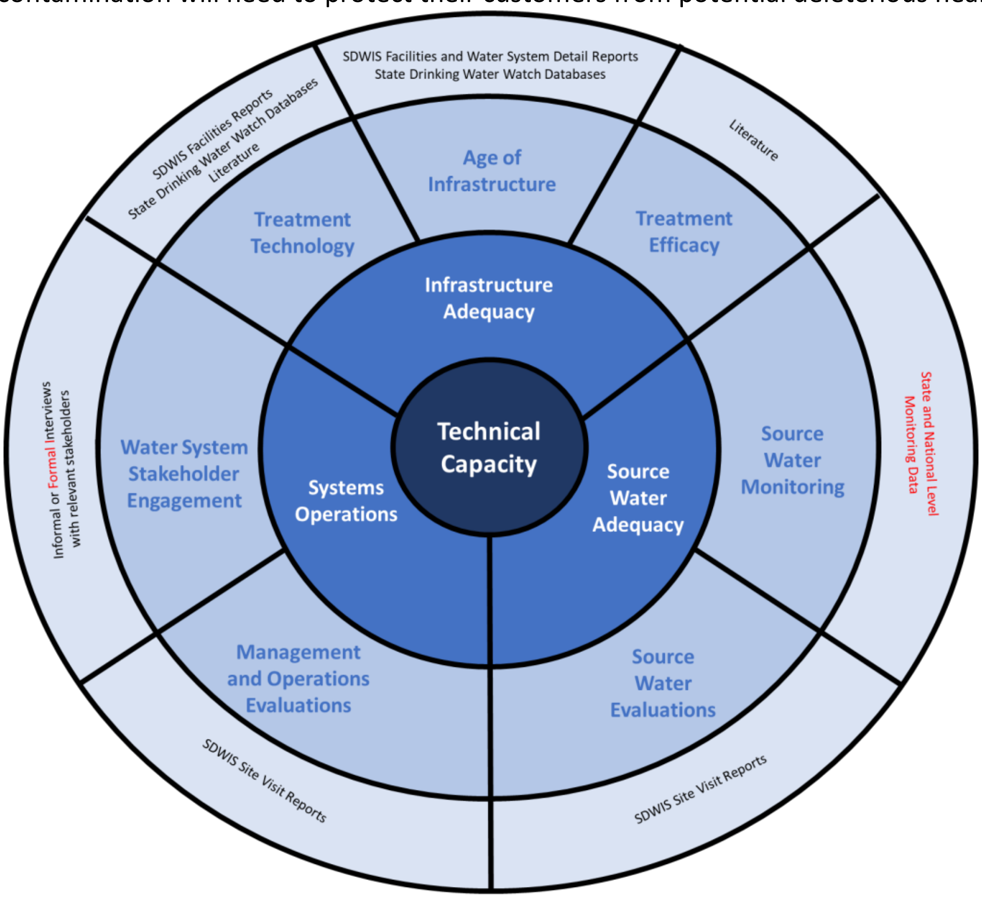

Figure 1: Definitions of technical capacity used in this study, including sources of data used to evaluate each element. Text in red represents data that was unavailable at the time this study was completed.

Data Inputs

This study used several publicly available data reports which came from the US EPA Safe Drinking Water Information System (SDWIS) and the Nebraska Drinking Water Watch (DWW) database. SDWIS contains a Facility, Water System Detail, and Site Visits report among the ten reports available on the database platform. The Facility report contains information related to the treatment process used by each facility, activity status of the public water system overall, activity status of each facility within the PWS, and the PWS type (community water system, transient non-community water system, etc.). The Water System Detail report contains the contact information for each facility as well as a population category which is set by the EPA as <=100, 101-500, 501-1,000, 1,001-3,300, 3,301-10,000 for systems serving less than

10,000 people. The Site Visits Report contains various types of evaluations that are conducted as part of the sanitary survey program (US EPA Office of Water, 2019) including treatment evaluation, source water evaluation, management operation evaluation, and finished water evaluation and the result of each of these evaluations. All three reports have a unique PWS ID, and name used for system identification in federal registers. The PWS ID was used to search for more information about each PWS in the Drinking Water Watch database throughout the study. The Nebraska DWW database contains additional information about when the treatment technology was first installed in the facility and state specific records about each PWS and can be searched by specific PWS ID numbers.

Data Analysis

The evaluation of each component of technical capacity is described below in detail in relation to the publicly available databases described in Figure 1.

Infrastructure Adequacy

Infrastructure adequacy was evaluated by examining both the treatment technologies available in PWSs and the age of the infrastructure within each system. Appropriate treatment technologies for PFAS were identified using literature and informal conversations with stakeholders and were then used as filtering criteria in the data analysis of SDWIS Facility reports. PWS specific characteristics such as source water type, PWS type, population category, system activity status and other identifying information was extracted from the System Detail reports to contextualize the analysis and to provide additional information for the calculation of infrastructure age. Only active water systems and active facilities were included in this analysis to avoid making conclusions about treatment technologies that may have been deactivated in the PWSs.

First, the facilities and system detail reports were joined by the PWS ID. The data was filtered for only active facilities and systems serving a population of 10,000 or less. This created a sample size of 1312 PWSs. Of the active small systems, we filtered for the following treatment processes: reverse osmosis, granular activated carbon, powdered activated carbon, ion exchange, peroxide, and ultraviolet radiation. These water treatment facilities were grouped and counted by PWS type, type of treatment process, and population category to examine commonalities and potential observable trends, maxima and minima in the data.

A subset of 16 unique public water systems for further analysis was created by filtering for only community water systems, ground water systems, and facilities that utilize reverse osmosis, granular activated carbon, powdered activated carbon, or ion exchange. In the full data set of 441 systems, there is too much variation between PWSs to make meaningful conclusions about specific treatment types, source waters, etc.; as a result, this subset was created specifically to allow researchers to conduct a more detailed analysis of a specific subset of systems with common characteristics. For this subset, the Nebraska Drinking Water Watch database was used to find the first reported date of when the treatment technology was first installed, verify the population data reported in SDWIS and provide additional information about the PWS.

The first reported data was subtracted from 2023 to calculate the age of each water treatment technology. Age of treatment systems is sometimes used as a metric in the water industry as a proxy for when treatment technologies have reached the end of their useful lives although a systematic use of age is not well represented in peer review literature. Older technologies may be expected to have more repairs or maintenance needs. For example, GAC has been found to be less effective in removing short chain PFAS as it gets older (Belkouteb et.al., 2020). Following the industry's lead in predicting quality of treatment technology, we examined age versus number of violations, treatment technology and whether the treatment was centralized or decentralized. Violations reports from SDWIS for the subset systems were also added to the subset dataset to expand the amount of information available for the detailed analysis.

System Operations

In the Site Visits report, the treatment evaluation, source water evaluation, management operation evaluation, and finished water evaluation and their results were examined. We examined only the three most recently completed sanitary surveys conducted in each of the subset systems. This report was joined with the same subset data frame used to evaluate infrastructure adequacy by PWS ID. We compared the results of each type of evaluation for each CWS of the subset data frame based on the population size of the PWS. These evaluations are conducted every three years in Nebraska by a designated inspector from the NDEE (NDEE, personal communication, July 2023) and use information from the EPA Sanitary Survey handbook (US EPA Office of Water, 2019) to evaluate whether components of the PWS are performing well, or if there are identifiable deficiencies (minor or major). These evaluations were used to examine existing information about management and operational procedures. Informal or formal stakeholder interviews with water systems would help to verify management and operational practices; however, due to the timeline of this study, this was not considered feasible. However, future studies looking to apply the methodology presented here should consider at least informal interviews to properly contextualize database data using mixed methods research methodologies (Creswell, 2006).

Source Water Adequacy

We examined source water adequacy using a combination of source water evaluations from the SDWIS Water System Detail Report and source water quality data specifically relating to PFAS. Source water evaluations were extracted from the site visit reports. However, PFAS monitoring data did not currently exist in publicly available resources at the time of the study. USEPA is currently collecting PFAS data under the Unregulated Contaminant Monitoring Rule 5 (UCMR 5) and NDEE is conducting state-led sampling, both of which will be available once monitoring is complete. PFAS monitoring data from source waters helps to identify potential systems at risk to PFAS contamination and would have provided another metric to use to evaluate source water adequacy. However, because this quantitative data was not available for small systems at the time of this study for Nebraska, we focused our analysis on the source water evaluations from the sanitary survey. These surveys contain more qualitative questions, examples of which can be found in Supplemental Information. It should be noted that monitoring data exists for other states currently on the US EPA PFAS Analytic Tool website to evaluate the presence or absence of PFAS (US EPA, 2022c), but that data is still being collected across the United States under UCMR 5 based on the proposed primary drinking water regulations for PFAS (US EPA, 2023b, US EPA, 2021). Source water data through the USEPA ECHO database has since become available and can be used in future studies.

Generating a systematic approach for technical capacity

Through the course of performing the analyses described above, we generated a replicable methodology that can be used by a wider audience than Nebraska stakeholders alone. Because SDWIS is a publicly available database, this data can be accessed, downloaded and analyzed by a multitude of potential different stakeholders to replicate the methods presented here in other states or at the national level. Therefore, one objective of this study is to summarize the process of data collection and analysis so other stakeholders can use our methodology to examine technical capacity to treat not only PFAS in drinking water, but other potential emerging contaminants of concern as well. In presenting this generalized methodology in the results, we summarized data sources (both those used in this study and other potential data sources), identified strengths and gaps in the available data and presented a flowchart stakeholders can use to aid the process of data analysis.

Results

Infrastructure Adequacy

Filtering the SDWIS facility reports revealed a total of 441 PWSs meeting the criteria described above. Table 1 gives a detailed summary of what treatment technology exists in Nebraska that could be used to remove PFAS. Of the PWSs examined, reverse osmosis is the most common treatment technology in Nebraska with 277 total systems using this technology. Of these, 194 PWSs serve populations of <= 100 people. We noted that many Non-Transient Non-Community Systems and Transient Non-Community Systems use reverse osmosis, especially the very small systems serving less than 100 people. Through conversations with NDEE (NDEE, personal communication, 2023) and verification using the Nebraska Drinking Water Watch database, we learned that many of these systems are point-of-use or point-of-entry systems being used to treat specific contaminants. Reverse osmosis is predominantly used for inorganics removal in 211 of the 277 systems, for organics removal in 53 systems, iron removal in four systems, Radionuclides removal in four systems, softening and hardness removal in four systems and disinfection by-product control in only one system.

There are 52 systems with granular activated carbon (GAC) treatment technology. These are also predominantly present in transient non-community systems serving populations of <=100 (43 systems). It is interesting to note that GAC is not currently a common approach in these systems, as it is a leading technology for PFAS removal. We found GAC being used for the following treatment objectives: organics removal (48 systems, 92%), taste and odor control (two systems, 0.4%), de-chlorination (one system, 2%) and inorganics removal (one system, 2%). There are 47 systems with ion exchange treatment technology. These are also predominantly present in transient non-community systems serving populations of <=100 (18 systems), though there are 11 non-transient, non-community systems using ion exchange, and 13 community water system using ion exchange. Ion exchange is used by 23 systems (49%) for inorganics removal, 18 systems for softening and hardness removal (38%) and by six systems radionuclides removal (13%).

There are 62 systems with ultraviolet radiation treatment technology. These are predominantly present in transient non-community systems serving populations of <=100 (50 systems). The treatment objective for all 62 of these ultraviolet systems is either disinfection or disinfection by-product control. There are only two systems that use peroxide treatment, one for iron removal and one for taste and odor control. There is only one system that uses powdered activated carbon for taste and odor control.

Table 1: Summary table of what PFAS removal technology currently exists in Nebraska, group by population size and PWS type. This was taken from a dataset size of 1312 PWSs, 441 of which are shown in this table.

PWS Type	Population	Activated Carbon, Granular	Activated Carbon, Powdered	Ion Exchange	Reverse Osmosis	Ultraviolet Radiation	Peroxide
Community Water System	3,301-10,000	-	-	1	1	-	-
	1,001-3,300	-	1	6	1	-	-

	501-1,000	-	-	-	1	-	-
	101-500	1	-	6	23	-	-
	<=100	-	-	-	44	-	-
Non-Transient Non-Community System	3,301-10,000	-	-	-	1	-	-
	501-1,000	1	-	-	1	1	-
	101-500	-	-	6	40	-	-
	<=100	-	-	5	53	2	-
Transient Non-Community System	501-1,000	-	-	1	1	1	-
	101-500	7	-	4	14	8	1
	<=100	43	-	18	97	50	1

Table 2 provides a detailed summary of the PWSs within the subset data, showing the treatment technology, age of the technology, the treatment objective, if a violation is present, and when that violation occurred. Most of the technologies in place are currently being used for inorganics removal. Involving contaminants like nitrates, uranium, and arsenic. The ages of the technology ranged from 3-24 years old. The PWSs are also grouped by the deployment method, either centralized or decentralized through the use of POU/POE devices. Four of the PWSs in the subset were point of use/point of entry (POU/POE) and 13 PWSs had centralized treatment in place.

Only System 01, serving between 101-500 people, is using a 19 year-old GAC system for organics removal. No violations have been present in System 01 in the existing dataset, so it is difficult to determine which specific organics are of concern in this system. Systems 02-10 use ion exchange (IX), with Systems 02-07 using IX for inorganics removal and System 08-10 using IX for radionuclide removal. If violation data is present, for systems treating for inorganics removal, the contaminant rule violated was the nitrate-nitrite rule in System 03, System 06 and System 04 which additionally had violations for combined uranium. Systems using IX for radionuclides removal had contaminant violations for combined radium and combined uranium. In Systems 11-17, reverse osmosis is used to removal inorganics, with only System 14 using RO for iron removal in addition to inorganics removal. Contaminant rules in violation in the past have included arsenic, combined uranium and nitrate-nitrite. It is important to note that although we were able to look at violations for specific contaminant rules in these systems, we cannot verify with precision if the specific technologies are intended to treat for these *specific* contaminants, only that the treatment objective relates to a *class* of contaminants. We included the contaminant violations to get a better understanding of what types of other contaminants may be present in this subset of systems, contaminants which may have an impact on these technologies if the technology is also employed to treat PFAS.

Table 2: Subset of CWS with ground water sources, only community water systems, serving less than 10,000 people.

	System	Population Category	Treatment Technology	Age of Treatment (years)	Treatment Objective	Has there been a violation related to the treatment objective?	Violations (if present)	
							When	What Parameters
Centralized	System 01	101-500	Activated Carbon, Granular	19	Organics Removal	No	NA	NA
	System 02	1,001-3,300	Ion Exchange	5	Inorganics Removal	No	NA	NA
	System 03	1,001-3,300	Ion Exchange	18	Inorganics Removal	Yes	2022, 2006, 2005	Nitrate-Nitrite
	System 04	3,301-10,000	Ion Exchange	17	Inorganics Removal	Yes	2006	Nitrate-Nitrite, Combined Uranium
	System 05	101-500	Ion Exchange	18	Inorganics Removal	No	NA	NA
	System 06	101-500	Ion Exchange	19	Inorganics Removal	Yes	2009, 2021	Nitrate-Nitrite
	System 07	101-500	Ion Exchange	5	Inorganics Removal	No	NA	NA
	System 08	101-500	Ion Exchange	10	Radionuclides removal	Yes	2016	Combined Radium (-226 and -228)
	System 09	101-500	Ion Exchange	11	Radionuclides removal	No	NA	NA
	System 10	1,001-3,300	Ion Exchange	13	Radionuclides removal	Yes	2010	Combined Uranium
	System 11	1,001-3,300	Reverse Osmosis	24	Inorganics Removal	No	NA	NA
	System 12	3,301-10,000	Reverse Osmosis	13	Inorganics Removal	No	NA	NA
	System 13	501 - 1,000	Reverse Osmosis	19	Inorganics Removal	No	NA	NA
POU/POE	System 14	101-500	Ion Exchange	3	Inorganics Removal	Yes	2022	Arsenic
			Reverse Osmosis	3	Iron removal	Yes	2022	Arsenic
					Inorganics Removal	Yes	2022	Arsenic
	System 15	101-500	Reverse Osmosis	11	Inorganics Removal	Yes	2021,2020, 2019, 2018	Arsenic
	System 16	<= 100	Reverse Osmosis	7	Inorganics Removal	Yes	2022, 2021, 2019, 2017	Nitrate-Nitrite
	System 17	<= 100	Reverse Osmosis	16	Inorganics Removal	Yes	2019,2008	Combined Uranium

Figure 2 shows the age of the treatment process with respect to the population size, type of treatment technology, deployment method, and if the PWS is in violation for the contaminants it is currently treating. There is no correlation that supports that age of infrastructure is a strong predictor of if a PWS is in violation or not. For example, System 05 and System 06 are nearly the same age, in the same population category, and are systems using ion exchange, but one is in violation, and one is not. The same scenario is seen with System 08 and System 09. Looking at different technologies, System 10 and System 12 have the exact same age of 13 years, but again, System 10 is in violation and System 12 is not.

Technology types and violations also lack a strong correlation. Ion exchange and reverse osmosis both contain a mix of violation statuses. Ion exchange has six systems with violations and four systems without violations. Reverse osmosis has four systems with violations and three systems without violations. There is only one system in the subset using granular activated carbon (System 01), and though it is not in violation, there are no other systems to compare it to.

There is a trend with deployment methods and violations. All of six systems (100%) using point of use/point of entry (POU/POE) as a deployment method have violations. Five out of 13 (38%) systems using centralized treatment have violations. However, POU/POE is a decentralized deployment method, meaning that there are several locations being evaluated within each system. If one location is in violation, then the entire system is documented as in violation. The specifics of the violations within POU/POE systems were not publicly available at the time of the study.

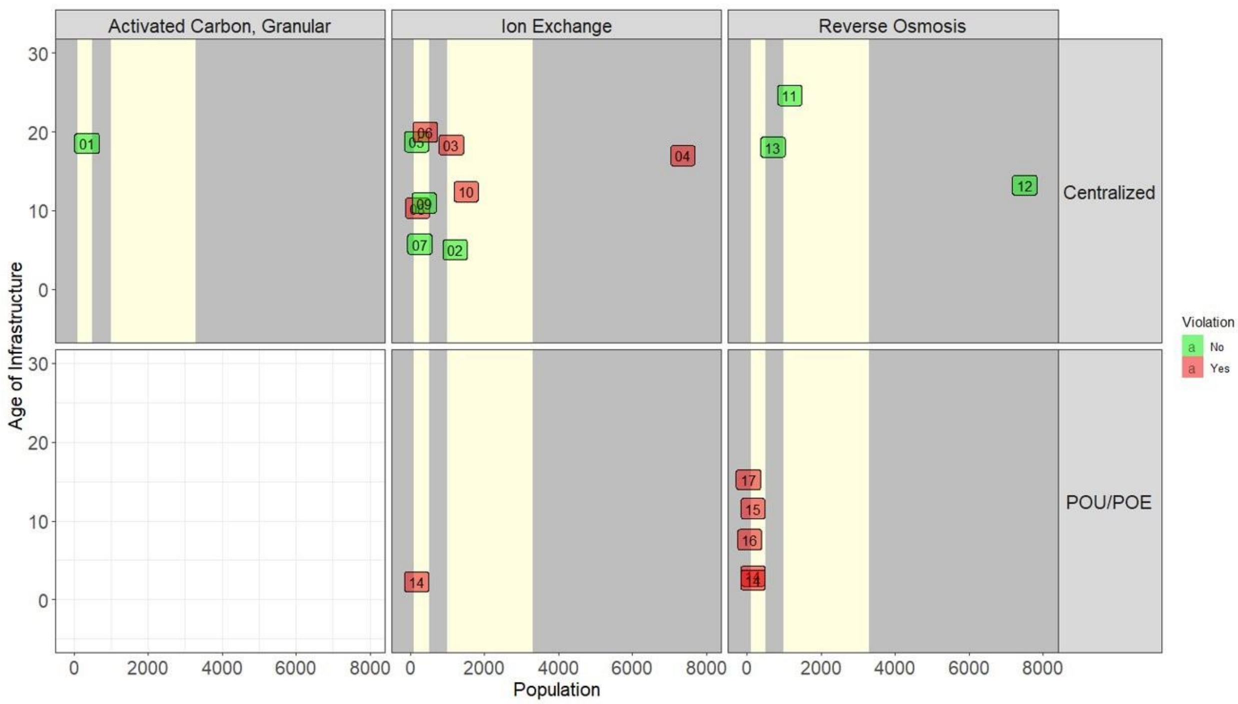

Figure 2: The age of treatment process with respect to type of treatment technology, population size, deployment method, and if the PWS is in violation for the contaminants it is currently treating. The points are numbered 1-17 to represent each system in the subset. Shading in the graph background was used to visually show population category divisions.

System Operations

Figure 3 shows the three most recent management and operation, finished water, and treatment evaluations for the subset data. These are a part of sanitary surveys that are conducted at each PWS every three years (NDEE, personal communication, 2023US EPA Office of Water, 2019). The most recent sanitary survey is labeled "current", the second most recent survey is labeled "Previous SS #1", and the third most recent survey is labeled "Previous SS #2." Which year the survey was conducted varies between systems as each system is on a different 3-year cycle of sanitary surveys. The general trend found was that there are significant deficiencies in management and operations and no deficiencies in finished water or treatment evaluations; however, there are results for specific groups and systems of note.

System 01 is a system serving a population of less than 100 people with 19-year-old GAC technology. It has had no reported deficiencies in all four evaluations for the last three sanitary surveys conducted. It is the only GAC system in the subset, so there is no other system to compare it to. System 12, a 13-year-old RO system is the only other system in the subset with the same result; however, this is not the trend with the other RO systems in the subset. Six out of seven RO systems have reported significant deficiencies in at least 2/3 of their management evaluations, and five of them have current deficiencies.

Four of the RO systems are also POU/POE. All the POU/POE systems (Systems 14, 15, 16, and 17) have reported significant deficiencies in at least two out of the three most recent management operation evaluations. System 16 is of particular note because it is missing a reported treatment evaluation for the past three evaluations. It also had violations for nitrate-nitrite in four years, has management deficiencies reported for the past three sanitary surveys, and serves a population <= 100 people. On top of all of these factors, the finished water quality evaluation has no deficiencies for the past three evaluations.

There are several situations presented in the subset regarding management deficiencies over time (examples of possible deficiencies are presented in the SI). Four out of 11 systems with management deficiencies reported in the third most recent evaluation had no deficiencies reported in the next two evaluations. Two out of the same 11 systems have reported deficiencies in the third and second most recent evaluations but do not currently have deficiencies. Five out of the same 11 systems have had management deficiencies reported for the past three evaluations.

There are trends of note in the results of evaluations across evaluation type. Five of six times there was a finished water deficiency, there was also a management deficiency reported. Seven out of 10 times there was a source water deficiency there was a management deficiency reported. Five out of Five times there was a treatment evaluation deficiency there was a management deficiency reported.

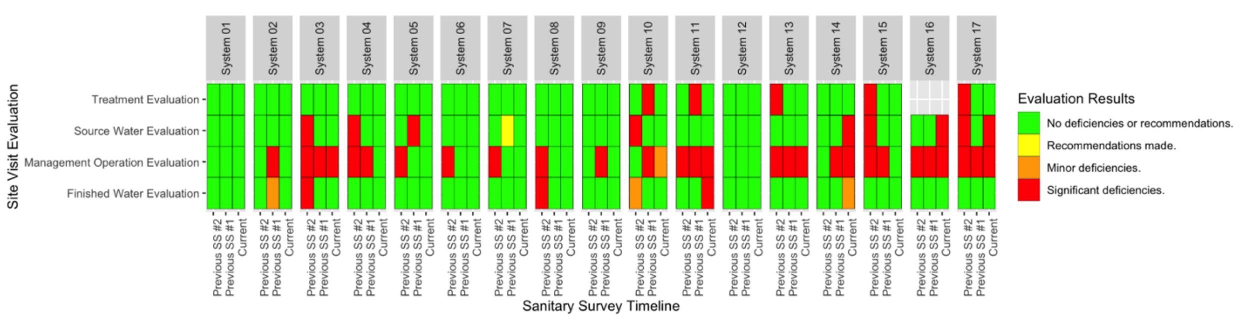

Figure 3: The 3 most recent treatment, source water, management operation, and finished water evaluation results for subset data derived from complete sanitary surveys in each CWS. An alternative red-green color-blind version of this figure is presented in the Supplemental Information.

Source Water Adequacy

Though there is not yet publicly available data regarding PFAS monitoring in source water in Nebraska in small systems, Figure 3 does show the three most recent source water evaluations for each system in the subset data. Like the management operations and finished water evaluations, the source water evaluation is a part of a scheduled sanitary survey conducted every three years (US EPA Office of Water, 2019). However, at the time of this analysis, no PFAS monitoring data was publicly available in Nebraska (NDEE personal communication, 2023), so this source water evaluation does not include PFAS contamination. For the evaluation that was available, the general trend found was that there are no deficiencies in the source water. Nine out of 17 systems in the subset have had either no deficiencies or had recommendations made for their past three source water evaluations. In Systems 03, 04, and 05, there were significant deficiencies found in the third recent source water evaluation but has improved no deficiencies in the two most recent evaluations. System 16 and 17 have reported significant deficiencies in their source water in the most recent source water evaluation.

System Approach

Figure 4 illustrates three key columns in the general methodology generated from this study: data inputs on the left, how the data informs each analysis in the middle column and the data analysis output on the right. Each data element is color-coded with its corresponding analysis. In Figure 4, any time multiple data elements from different data sources are fed to a single data analysis, this represents a “join” in the data. To join data together using a software programming platform, a unique identifier is needed; in this study the unique identifier used as “PWS ID”, a string consisting of the state abbreviation letters first, followed by an eight-digit identifier. “PWS ID” is present in all SDWIS reports and also in state drinking water watch databases, making it an ideal parameter to join large datasets together for analysis.

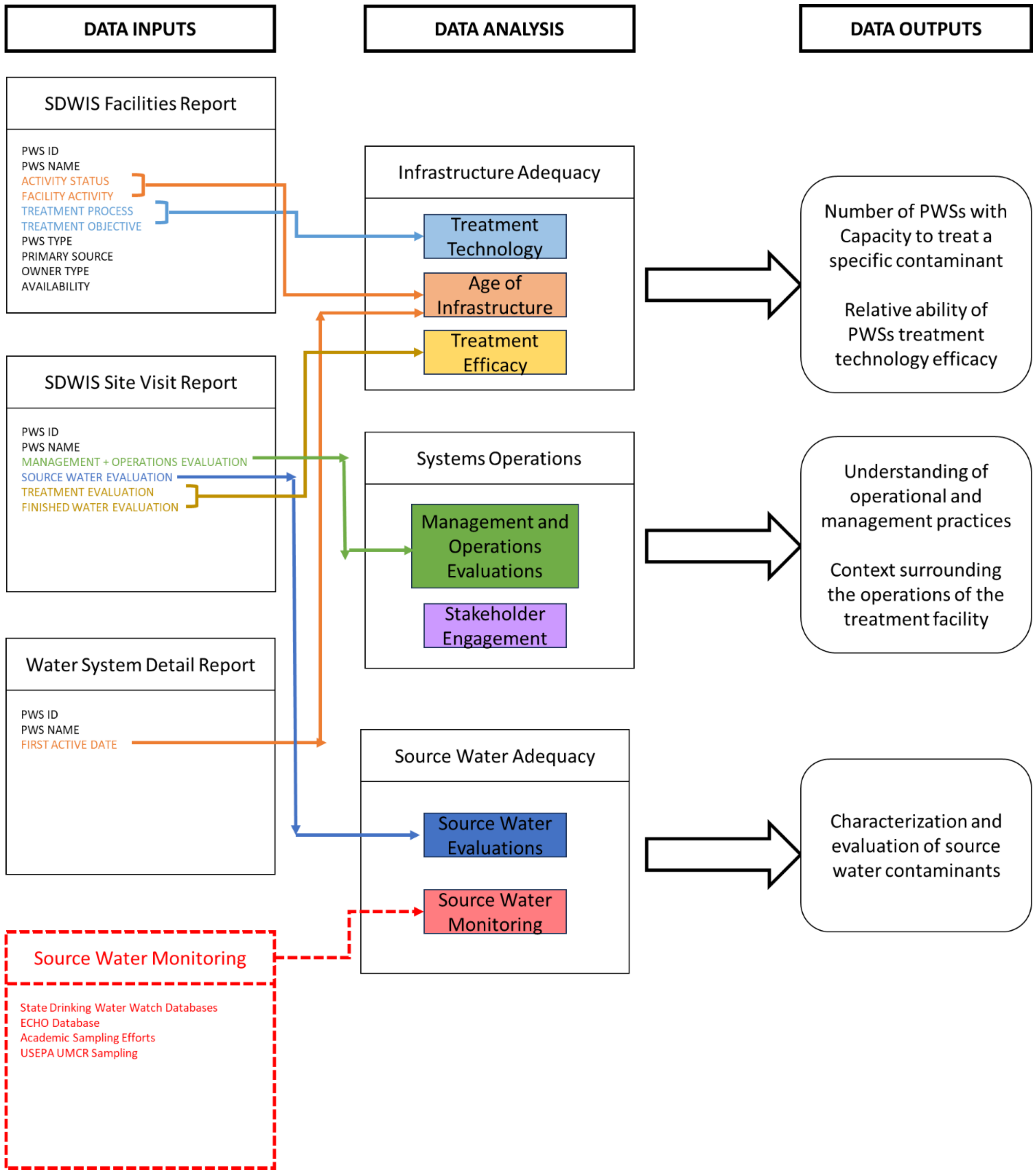

Figure 4: Generalized methodology used to evaluate technical capacity using existing publicly available databases.

One of the critical components missing from technical capacity in this study was the inclusion of source water monitoring information. In this study specifically, PFAS was the contaminant of concern; data available was sparse, generally from academic studies or sampling efforts by the US EPA (UMCR program, etc.) (US EPA, 2021; US EPA Office of Water, 2019), and did not cover the public water systems included in this study. UCMR data from UCMR 3 or UCMR 5 does not cover small systems and at the time of the study, the ECHO PFAS State database had not yet been made publicly available. Figure 4 illustrates the concern with availability of source water data by outlining this data input in red. Part of the definition of technical capacity in this study is related to source water adequacy; the reason this parameter is important is because source water quality determine what types of treatment may be best suited for each facility. In this study, we were unable to comment on whether the subset of systems found even needed PFAS treatment due to a lack of data available. As a result, while our model to determine technical capacity includes source water adequacy, we identified a key gap in data, specifically for PFAS, but more holistically as well as there are few publicly available data sources. While this data may be obtained from state agencies or other institutions to round out the source water adequacy component of this model, the lack of easily identifiable data is a gap that could be filled by increased database transparency.

In the model shown in Figure 4, there are several key characteristics to be aware of when utilizing this framework. First, in our study, age was calculated by taking the current year and subtracting the first active date from the state drinking water watch database. However, state databases report several different dates, related to individual facilities such as treatment units, new wells, etc. and also to violations, sampling dates, etc. In addition, using the current year can underestimate or overestimate the age of the system by one year depending on the month in which the facility was activated, although this discrepancy is a smaller concern that using the incorrect activation date.

Discussion

Our data analysis revealed that few systems in Nebraska currently have treatment technologies that could feasibly remove PFAS from drinking water, and even if the system has an appropriate technology, there are both technical and non-technical factors that influence whether that technology will be efficacious for PFAS removal. While we do not currently have source water data from Nebraska to verify whether any of the 441 identified systems need to remove PFAS from drinking water, we do have enough data and stakeholder input to remark on considerations these systems should account for should PFAS treatment be necessary. Our discussion therefore presents considerations for (1) verification of appropriate treatment technologies, (2) selection of appropriate technology deployment mechanisms and (3) examines the technical and non-technical factors we identified through analysis, literature and stakeholder input that impact successful implementation of a PFAS removal strategy.

Verification of appropriate treatment technologies

Our analysis revealed 441 systems in Nebraska with technologies that can potentially remove PFAS from drinking water. However, while there is a wealth of information about the type of technology, treatment objective, etc. in SDWIS, there are still questions raised about whether the technology would be appropriate for PFAS removal in a real-world setting. While literature was instrumental in identifying possibly technologies, the reality of operating these technologies for PFAS removal in small PWSs involves several additional factors highlighted by stakeholder conversations. Potential concerns include how to “scale-down” proven technologies to a small system size (ASDWA, personal communication, 2023), how treatment systems will be operated and maintained including economic cost over time and how treatment technologies will be integrated into existing infrastructure. Below we discuss several considerations brought to our attention by our literature review and stakeholder engagement sessions that we can explore based on our data analysis.

1. Consideration of co-contaminants

Current studies of PFAS removal technologies are primarily lab-based (Banks et al., 2020; Belkouteb, 2020) with many studies testing technologies in "best-case" laboratory settings where real-world co-contaminants and other water quality parameters are not present (Banks et al., 2020). Treatment technologies that have been identified often work specifically for only PFOS and/or PFOA, only short-chain or long-chain PFAS and not all six of the PFAS compounds in the proposed EPA drinking water regulation (Banks et al., 2020; Kim et al., 2020; Belkouteb, 2020; Yadav et al., 2022). Subsequently, while treatment technologies may be appropriate for PFAS removal in theory, the reality of treating PFAS in small systems is complicated by other co-contaminants, ultimately leading to the implementation of additional treatment instead of using existing infrastructure. Table 2 was instrumental in demonstrating what the treatment objective of treatment technologies were and shedding light on possible other co-contaminants present in each PWSs' water system. We noted that systems using IX, which can remove PFAS (Yadav et al., 2022; Banks et al., 2020; Kim et al., 2020), primarily use IX for inorganics removal. IX systems are designed to be ion specific, removing anions from drinking water preferentially by charge (Yadav et al., 2022). This preferential removal of anions is often accomplished by ion specific resins, such as nitrate removing resins (USEPA, 2023a, Yadav et al., 2022). In three of the IX systems we identified, there have been violations of nitrate-nitrite. While we cannot verify that these systems use IX specifically for nitrate-nitrite removal, the presence of nitrate-nitrite in source waters would introduce an anion that would potentially compete with PFAS for removal sites on the resin. This example demonstrates that while a *technology* can be appropriate for PFAS removal based on laboratory studies, the reality of choosing specific *features of the technology* such as resin in an IX system, is also critical to address any concerns with co-contaminants in the drinking water source.

2. Consideration of maintenance and operational factors

Verifying an existing technology is appropriate for PFAS removal also requires an evaluation of whether additional maintenance will be required and whether operational changes need to be made to the system to ensure PFAS removal. Several previous studies have noted management and operational challenges in general are larger and more difficult to manage in small systems (Bell et al., 2023; Blanchard & Eberle, 2013; Maras, 2009), a sentiment that was echoed by stakeholder conversations (NDEE, personal communication, 2023). Our results do indicate that there have been "significant deficiencies" in the management and operation evaluation for our subset of systems (Figure 3), but we did not compare to larger systems and so cannot comment on whether or not small systems have more or fewer operational issues. Indeed, we cannot also determine specifically what types of management concerns were reported in the management evaluation as there was no additional information in Nebraska's drinking water watch database that could be used to determine a reason for a significant deficiency. We accessed publicly available records on sanitary survey results contained in consumer confidence reports, compliance reports and other documentation and correspondence between NDEE and individual CWSs. However, public records in the NDEE database only date back to 2019 on the current platform (NDEE, 2023b) and while we were able to locate information for three of the systems related to management and operation evaluations, we did not want to make substantial conclusions about causes of "significant deficiencies" without more information from individual system stakeholders in a subset of only 17 systems. Conversations with ASDWA revealed that some states do report the reasons for deficiencies (ASDWA, personal communication, 2023), but without more specific information, it was difficult to make conclusions about why management deficiencies were present. We have included a selection of questions found in the EPA Sanitary Survey Handbook (US EPA Office of Water, 2019) in the Supplemental Information to inform readers of some of the components included in each of evaluations presented in Figure 3.

While we cannot identify specific management and operational concerns, literature does suggest that adequate and regular procedures extend the life of treatment technologies (Bereskie et al., 2017; Garvin, 2003; Goodrich et al., 1992), help to prevent repeat violations of water quality parameters and maintain public health protection of customers. PFAS in particular has unique chemistry that may be new to water operators in small PWSs, and if co-contaminants are present, changes in operational procedures may be necessary (ASDWA, personal communication, 2023). Adding a new technology instead of retrofitting an existing technology may also add additional work for operators that already have multiple responsibilities, both regulatory and in their community (Ernest et al., 2009; Job, 2009; Shanaghan & Beecher, 2002). A deeper understanding of management and operational practices could be achieved through informal stakeholder interviews, similar to those conducted in this research to contextualize concerns. While we cannot identify trends in management and operational deficiencies, their presence alone signifies the need for additional data collection.

Selection of appropriate technology deployment strategy

The subset analysis presented in Table 2 and Figure 2 revealed many of the reverse osmosis systems identified in this study are decentralized POU/POE systems. Conversations with ASDWA and other stakeholders (NDEE, personal communication, 2023; ASDWA, personal communication, 2023; Nelson da Luz, personal communication, 2023), and PFAS guidance documentation from the US EPA (US EPA, 2023b) revealed that there are several other methods besides centralized treatment being considered to address PFAS contamination. Other strategies include identifying and verifying alternative source waters, considering interconnection or consolidation with other PWSs and decentralizing treatment using POU/POE devices. Of these alternatives, there is evidence from the subset data in Table 2 that at least four community water systems use POU reverse osmosis devices to removal inorganics and iron from drinking water. POU/POE devices represent a potential decentralized option and can be used to bring PWSs into compliance with the Safe Drinking Water Act (SDWA) (USEPA, 2006), a method which requires the use of certified devices, a rigorous sampling schedule to ensure treatment efficacy and operational and maintenance activities completed by the PWS.

Data from our study suggests POU devices are used in Nebraska as a solution in very small systems serving less than 100 people (Table 2), but that these systems have had past violations (Figure 2), reported management and operational concerns (Figure 3) and that POU devices present a difficult management and operational regime since a device is located in each home (NDEE, personal communication, 2023). RO devices specifically will produce a concentrated wastewater with high levels of PFAS compounds as noted previously (Banks et al., 2020; Goodrich et al., 1992; Speth et al., n.d.; Yadav et al., 2022), which further increases the cost and management challenges posed by POU devices as a decentralized solution. However, in very small systems, POU devices may represent a temporary solution to PFAS contamination where a long-term solution is needed but cannot be implemented in a timely manner. POU devices also have the added benefits of requiring fewer upfront capital costs (Bixler et al., 2021; Lane et al., 2023; Speth et al., n.d.), being certified for targeted contaminant removal and treating only water used for drinking and cooking purposes, which removes PFAS from the oral ingestion exposure route (Lane et al., 2023; Speth et al., n.d.). While our results cannot support a recommendation of centralized versus POU/POE devices, we can demonstrate that POU devices are currently being used as a solution in Nebraska and should at least be considered as an alternative strategy to increase the technical treatment capacity of a small system in the event that PFAS contamination is present.

Verifying data accuracy through stakeholder engagement

This study highlights the presence of extensive data about various components of technical capacity publicly available to be leveraged; however, due to missing data, in both quality and quantity, there are gaps in the story it tells, limiting the definitive conclusions that can be pulled from the data analysis. In general, very small systems in particular are known to have inaccurate data reporting, and similar SDWIS studies remove small systems from the analysis (Allaire et al., 2018).

The largest limiting factor in the model developed in this study is the source water monitoring data specifically for PFAS as it was in the process of being collected in Nebraska. During the time of the data analysis, PFAS monitoring was in its initial data collection phase following UCMR5 guidelines (NDEE, personal communication, 2023; US EPA 2023b). These guidelines require a 5% representative sample of Nebraska and do not include small systems of populations less than 3,300 people (US EPA, 2021). The NDEE will also include some small systems of Nebraska, in addition to what is required by USEPA, but many systems will still be excluded (NDEE, personal communication, 2023). We therefore had to rely on the source water evaluation component of sanitary surveys for an evaluation of source water adequacy in this study. These evaluations do not yet include PFAS, and do not have specific regulations attached to the result reporting. The violations found could be an issue in water quality or quantity of source water (US EPA, 2019). Without knowing what regulation was violated, we do not know what type of source water issue is present.

There are also limitations regarding treatment data. For example, in the facility report there is an option to report “innovative” for the type of treatment technology being used (SDWIS, 2023). This term is ambiguous and could be defined differently from state to state. GAC and nanofiltration, both of which can remove PFAS from drinking water (Banks et al., 2020; Yadav et al., 2022), could be considered innovative in Nebraska, so some PWSs with infrastructure to remove PFAS could have been excluded from the results. In SDWIS, there is also a treatment objective listed for each infrastructure in place (SDWIS, 2023), but it is not known if the violations reported for each system are because of the violated contaminant is within the treatment objective category. Without this information we could not evaluate if the technology was working for its intended purpose.

There are many reported sanitary survey evaluations and their results in SDWIS, but there is no information linking regulations or corrective action timelines with each violation reported (SDWIS, 2023). We attempted to link SDWIS data to the Nebraska DWW database but found even with 17 systems in our subset that there was a large amount of uncertainty in the data, both due to its sparseness and the variations in reporting. Ambiguity in violation reporting made it difficult to generate a generalizable method to evaluate sanitary survey data in our overall model. The deficiencies reported from year to year in Figure 3 could have been the same regulation violation multiple years in a row, causal of each other, or separate issues. The lack of timeline of corrective actions with the evaluation also limits the ability to see a recovery time for each system. Will consumer confidence reports are available for this type of data, it took extensive time and effort to review each report in detail to locate potential causes of deficiencies; this type of qualitative thematic analysis could be added to the model we propose in this study, but does not lend itself well to a consistent methodology across states. Consistently reported information, such as a format for entering reasons for significant deficiencies in DWW or SDWIS, would be valuable in evaluating infrastructure resiliency, allowing stakeholders to draw stronger conclusions between sanitary survey results, not only within a state, but nationally as well. Trends could be more defensibly explained with a deeper understanding of how deficiencies in various aspects of technical capacity in public water systems relate to each other.

Publicly available data can be leveraged to a high potential, but the current data gaps that arise when applying the model developed in this study call for a need to contextualize results with a thorough literature review and stakeholder engagement. There are extra variables that impact what components of technical capacity are most relevant that vary based on region or state. Stakeholders in the region where the model is applied may have important insight as to what technology will be accepted and where particular deficiencies in capacity may exist that need further exploration. Informal conversations with stakeholders were a critical part of the model to contextualize the real-world challenges associated with increasing the technical capacity of small systems.

Conclusions

Analyses of publicly available national- and state-level databases revealed very few systems in Nebraska had technical capacity to sustainably remove PFAS from drinking water in the coming years. Furthermore, a full evaluation of technical capacity to treat PFAS in drinking water in Nebraska was restricted by data availability, a scenario likely not uncommon across states who have only started considering PFAS regulations and monitoring. It was found that 441 of 1312 PWSs in Nebraska have treatment technologies theoretically capable of removing PFAS, but that differences in management and operation, deployment methods and treatment process objective will influence the efficacy of these technologies if PFAS is detected in these water systems. A deeper look at a subset of 17 systems revealed that neither age nor past violations were useful in examining differences in technical capacity and that a system-specific approach to examining technical capacity is likely to be more beneficial to systems once contaminants of concern have been identified in source waters. In the process of analyzing technical capacity for treating PFAS in Nebraska, a model for evaluating technical capacity in any region was developed. This study identified gaps in available information about water systems facilities, gaps that if filled, would be instrumental in not only identifying PFAS technical capacity in other states, but could be used in the model developed in this study to evaluate other emerging contaminants of concern. Other emerging contaminants of concern will require treatment in the long-term, and the model developed in this study provides stakeholders with a way to evaluate existing data and be more proactive about treatment technology choice and implementation.

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Author contributions

Chloe Yoder - Data collection, data analysis, informal stakeholder engagement, manuscript writing
Kaycie Lane - Conceptualization of study, manuscript writing, editing

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