Demand Response Potential of Drinking Water Distribution Networks

Anna Stuhlmacher
Michigan Technological University
annastu@mtu.edu

Johanna L. Mathieu
University of Michigan
jlmath@umich.edu

Abstract

Pumps in drinking water distribution networks can be controlled to participate in demand response programs. In this paper, we estimate the demand response potential of water distribution networks based on actual network data. We calculate the power and energy capacities of community water systems within Wisconsin and Arizona, drawing on publicly available data of consumer water demand, population served, storage tanks, and pump specifications. We then extrapolate this data to get an order-of-magnitude estimate for the entire United States. Overall, we found that water distribution networks are sizable demand response assets with an estimated power capacity of 21 GW and energy capacity of 925 GWh in the United States. We also found that large and very large utilities may be the best demand response candidates. This paper also discusses factors impacting water supply flexibility and future research directions.

Keywords: ancillary services, demand response, flexible loads, water distribution network, water pumping

1. Introduction

Controllable, flexible loads are capable of supporting the electric power grid, for example by participating in ancillary services [1]. Regulatory changes, such as FERC order 2222, have removed barriers for load aggregators to participate in ancillary service markets [2]. Additionally, recent research advances have identified, modeled, and characterized the technical and economic opportunities of different types of flexible loads. Examples include peak load reductions by pre-cooling data centers [3], estimating the flexibility of a distributed energy resource aggregator at the substation level [4], and reducing grid congestion and operation costs with electric vehicle charging strategies [5]. One area of focus is the interconnection of the electric power grid and the drinking water distribution network. Water pumps in the drinking water distribution network can be treated as flexible loads. The power consumption of pumps can be shifted in time while still meeting consumer water demand due to the presence of elevated water storage tanks. Because of this, the water distribution network can be scheduled and controlled to provide services to the grid.

There are a number of papers that focus on leveraging pumps in the water supply network to support the power grid. In [6], an optimization problem is formulated to jointly provide voltage support and frequency regulation. Pumps are scheduled in [7] to consume surplus energy from renewable energy sources. In [8], the authors determine the demand response load shedding capacity and a pilot project of water pumps participating in the Belgium day-ahead market is evaluated in [9]. While there is an established body of literature that examines how to optimally schedule and control water pumps to provide services, the estimated flexibility potential of water distribution networks has not been explored. Several studies have examined the flexibility potential for different types of loads, such as water treatment plants in the United States [10] and residential thermostatically controlled loads in California [11]. However, to the best of our knowledge, no work has estimated the flexibility potential available from controlling pumping assets in drinking water distribution networks.

The goal of this paper is to estimate the potential demand response capacities of water distribution networks under the strategic use of pumps and tanks. The purpose of this work is to determine the viability of leveraging water distribution networks as flexible assets. Here, we estimate energy capacity and power capacity based on publicly available water utility data in the United States. Our case studies develop state-wide estimates given state utility commission databases. The contributions of this work are i) developing energy and power capacity definitions specific to water distribution networks, ii) calculating state-wide power and energy capacities based on Arizona's and Wisconsin's utility commission databases, iii) estimating the resource potential within the United States, and iv) discussing barriers to implementation and opportunities for future research leveraging water pumps as demand response assets. Our analysis found that drinking water network pumping is a sizable flexibility resource within the United States.

The rest of the paper is organized as follows. Section 2 presents the methods and metrics used to estimate the flexibility potential of drinking water distribution networks. Section 3 estimates the energy and power capacity of pumps and tanks within Wisconsin and Arizona water utilities and Section 4 estimates the flexibility potential within the United States. In Section 5, the opportunities and challenges of leveraging water distribution networks as flexible loads are discussed. Concluding remarks are made in Section 6.

2. Methods for estimating water distribution demand response potential

In this paper, we estimate the demand response potential of drinking water distribution networks. We leverage publicly available data for community water systems in Wisconsin and Arizona and extrapolate this data to get an order-of-magnitude flexibility potential estimate of water distribution networks in the United States. Here, we present background on drinking water distribution networks and develop the metrics used to evaluate flexibility potential.

2.1. Background

The purpose of drinking water distribution networks is to safely deliver treated drinking water to consumers. Water distribution networks rely on gravity and pumps to move water through the network. Storage tanks in the water network help hedge against demand uncertainty and periods of high demand. System pressure heads must be maintained in order to reliably supply water and meet emergency fire flow requirements.

In the United States, there are around 50,000 community water systems (i.e., public or private water network utilities that serve 25 or more people year-round) [12]. We characterize the size of the utilities by the population served. We use the definitions in [13], where

- ‘very small’ is 25–500 people,
- ‘small’ is 501–3,300 people,
- ‘medium’ is 3,301–10,000 people,

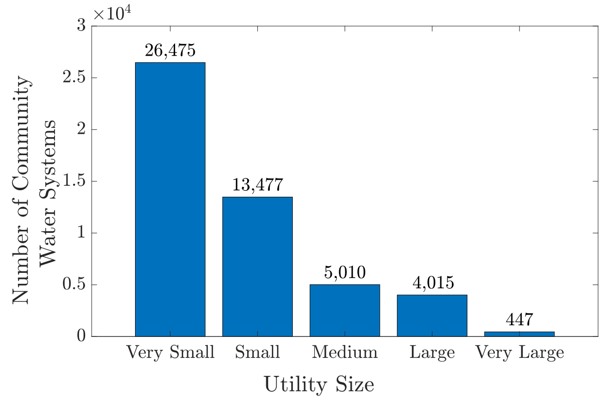

Figure 1. Community water systems in the United States, differentiated by size; 2022 data pulled from [12].

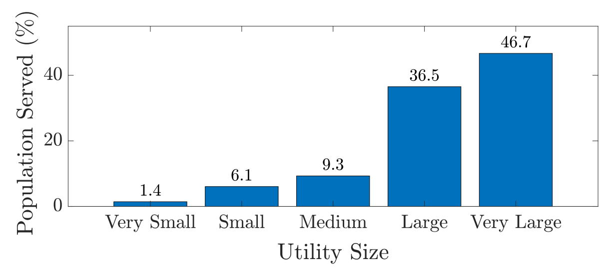

Figure 2. Percentage of U.S. population served by each community water system size classification; 2022 data pulled from [12].

- ‘large’ is 10,001–100,000 people, and
- ‘very large’ is greater than 100,000 people.

Figure 1 depicts the number of community water systems in the United States by size. Despite the large number of very small and small water utilities, the majority of the United States is served by large and very large water networks – around 83% of the population served is supplied by 9% of the water systems (see Figure 2).

Drinking water networks consume around 1% of the electricity use in the United States [13]. Electricity costs are a large portion of a water utility’s costs, where 80% of the electricity consumed is used for pumping [13]. Current best practices for water utilities include reducing demand charge costs by shifting pumping to off-peak times [14].

The energy intensity of utilities depends on a number of factors, such as the size and geographical location of the system as well as the source of the water (i.e., ground or surface water). On average, utilities consume 3.3-3.6 kWh to extract, treat, and deliver 1,000 gallons of drinking water [15]. However, this energy intensity varies significantly by geographical location. For instance, the average energy intensity to supply drinking water in California is 12.7 kWh per 1000 gallons [16]. Additionally, water treatment and distribution benefit from economies of scale, where an increased production of water reduces the marginal energy consumption per volume [17].

Pumps in the water distribution network are loads within the power distribution network. Pumps can be either fixed speed or variable speed. Fixed speed pumps are operated via a binary on/off decision. In contrast, variable speed pumps are also able to adjust the speed setting of the variable frequency drive. Because of this, variable speed pumps can operate more efficiently and are easier to control than fixed speed pumps [18]. Additionally, the finer-grained control of variable speed pumps can be useful for accurately controlling the pump power consumption to provide grid support. Variable speed pumps are also widely accepted in water and wastewater applications [14].

Periods of peak water demand often coincide with high time-of-day electricity rates [13]. Typically, a water utility has elevated water tank(s) and/or ground-level storage tank(s) [19]. Tanks are able to store water for use in other time periods. Because of this, tanks allow pumps to shift their loads in time which is critical for demand response participation. The relative size of the tanks compared to the water demand determines how long the water distribution network can shift its pumping load.

Last, most urban water utilities have Supervisory Control and Data Acquisition (SCADA) systems [17]. SCADA systems i) monitor data from components, including pump status, storage levels, alarms, and energy prices; and ii) format the data to be viewed and analyzed by the system operator [13]. SCADA systems enable the water distribution network to have fast, automated operational control.

2.2. Data sources

We use a number of sources to estimate the flexibility potential of water distribution networks in the United States.

- Safe Drinking Water Information System (SDWIS) Federal Reporting Database [12]: The United States Environmental Protection Agency (EPA) reports basic system information (e.g., population served and location) and water quality violations for every community water system in the United States. The data can be queried and downloaded as CSV files.
- Public Service Commission of Wisconsin Database [20]: Within the state of Wisconsin, all municipal and investor-owned utilities are regulated by the Public Service Commission of Wisconsin. The data can be queried and downloaded as Excel files. The Annual Report Data e-portal was used to collect municipal water utility information, including information on pumps, water demand, and water storage capabilities. Wisconsin water utilities are primarily municipally owned; there is only one investor-owned water utility in Wisconsin.
- Arizona Corporation Commission [21]: Within the state of Arizona, all privately owned utilities are regulated by the Utilities Division of the Arizona Corporation Commission. Annual reports for all utilities can be queried and downloaded as scanned PDFs. The reports are used to collect information on private water utilities, including information on pumps, water demand, and water storage capabilities.

2.3. Metrics for demand response potential

We estimate water distribution network flexibility using the terms ‘power capacity’ and ‘energy capacity’, analogous to a battery. We define power capacity P_{cap} as the rated power consumption of the water distribution network’s supply pumps, i.e., the difference in power if all the pumps were switched on or off given a signal. The power consumption of a pump depends upon the pump speed setting and where the pump performance curve intersects with the system curve [18, 22]. Here, we consider the nameplate ratings of the pumps. We define energy capacity E_{cap} as the product of the power capacity and the duration d. The duration d is how long the water demand could be met by the elevated storage tanks if the pumps were forced off, i.e., the total usable tank storage volume divided by the sum of the volumetric water demands.

We use the following data to compute the power and energy capacity.

- *Horsepower of pumps with electric motors.* We only consider pumps that are actively used (i.e., not standby or backup pumps). The horsepower of the pumps within the annual reports is used to estimate the power consumption of the pumps based on their full load rating [22]. Therefore, the power capacity P_{cap} is calculated from the sum of the pumps’ horsepower divided by the pump efficiency

$$P_{\text{cap}} = \sum_{i \in \mathcal{P}} \text{hp}_i \cdot \left(\frac{1}{\eta_i}\right) \cdot (746\,\text{W/hp}), \quad (1)$$

where η_i is the best efficiency point of pump i, $\mathcal{P}$ is the set of active pumps with electric motors, and hp_i is the rated horsepower of pump i. We assume η_i is 75%, which is the pump efficiency default in EPANET, the EPA's open-source water distribution network hydraulic modeling and simulation software [23].

- *Amount of water entering the distribution system.* This is used to calculate the average hourly water demand (AHD), i.e., the sum of the yearly water demand divided by 8760 hours/year.

- *Total capacity of the storage tanks.* The duration d is calculated from the total capacity of available storage divided by the average hourly water demand

$$d = \sum_{i \in \mathcal{S}} v_i / \text{AHD}, \quad (2)$$

where $\mathcal{S}$ is the set of water storage tanks and v_i is the volume of tank i. The energy capacity E_{cap} is then calculated as

$$E_{\text{cap}} = P_{\text{cap}} \times d. \quad (3)$$

3. State-wide estimates

We first analyze the flexibility potential of water utilities in Wisconsin and Arizona using publicly available network specifications. These two states were selected given the availability of sufficient water network data as well as their distinct geographic characteristics. This selection allows us to evaluate the flexibility potential from two different regional areas.

3.1. Case study: Wisconsin

We first use Wisconsin's publicly available data on municipal and investor-owned water utilities to estimate the flexibility potential in Wisconsin. We calculate P_{cap} and E_{cap} for every water network utility in Wisconsin. We collect the pump, storage, and water demand specifications from each utility's 2022 annual report [20]. The water storage volume is calculated from elevated storage tanks, standpipes, and reservoirs that have a positive elevation difference.

One challenge when estimating the flexibility potential is distinguishing between water network treatment and distribution processes. This is due to a lack of standardized terminology in utility reports [13]. Additionally, the treatment and distribution processes complement each other. Especially in smaller networks, pumps in the treatment process can also support the distribution process [13]. How each utility reports their pumps' primary purpose (i.e., primary, booster, or standby) and primary destination (i.e., treatment or distribution) impacts the magnitude of the power capacity estimate if we only consider pumps classified as primarily in the distribution network. Because of this, we calculate the capacity metrics for distribution pumps as well as for distribution and treatment pumps together. We include pumps whose primary destination is either distribution (Case 1) or distribution *and* treatment (Case 2). In both cases, we only consider active pumps with electric motors (not standby pumps or pumps with a diesel fuel source).

Figure 3 plots the non-zero power and energy capacities of the Wisconsin water utilities (Case 2) relative to the population served on a log-log scale. The 572 Wisconsin utilities are depicted as blue circles. We use a log scale since the data covers a wide range of values (i.e., from populations served ranging from 34 people to 647,290 people, power capacities up to 49.76 MW, and energy capacities up to 640.14 MWh) including a small number of very large utilities. As expected, the power capacity increases as the water utility size increases. We found that the correlation between population size and power capacity is statistically significant (Pearson's correlation coefficient of 0.9726 and a p-value of zero). This is because more pumps are generally needed to accommodate larger water volumes for a greater number of customers. We also observe that the energy capacity increases as the size of the water utility increases due to the increase in power capacity (Pearson's correlation coefficient of 0.8685 and a p-value of zero). The duration d is not correlated with the population served (Pearson's correlation coefficient of -0.0261 and a p-value of 0.533).

We also report the total and average power capacity and energy capacity for water utilities in Wisconsin in Table 1. We present a range of estimates based on our calculations for Cases 1 and 2. Despite large and very large water utilities being 13.1% and 0.7% of the total Wisconsin utilities, they make up around 40% and 25% of the total power capacity in Wisconsin, respectively. This indicates that very large and large utilities may be the 'lowest hanging fruit' in terms of water distribution networks participating in demand response programs.

It is important to note that there are only four very large and 75 large utilities in Wisconsin. Particularly

Table 1. Estimated Energy and Power Capacities in Wisconsin's Water Utilities

Utility Size	Number of Utilities	Power Capacity		Energy Capacity	
		Total (GW)	Average (MW)	Total (GWh)	Average (GWh)
Very Small	123	0.005	0.040–0.042	0.677–0.695	0.006
Small	274	0.029–0.031	0.106–0.112	1.590–1.657	0.006
Medium	96	0.035–0.038	0.360–0.401	1.368–1.506	0.014–0.016
Large	75	0.084–0.099	1.120–1.313	2.530–2.906	0.034–0.039
Very Large	4	0.045–0.075	11.271–18.868	0.920–1.389	0.230–0.347
Total	**572**	**0.198–0.248**	0.346–0.434	**7.085–8.153**	0.012–0.014

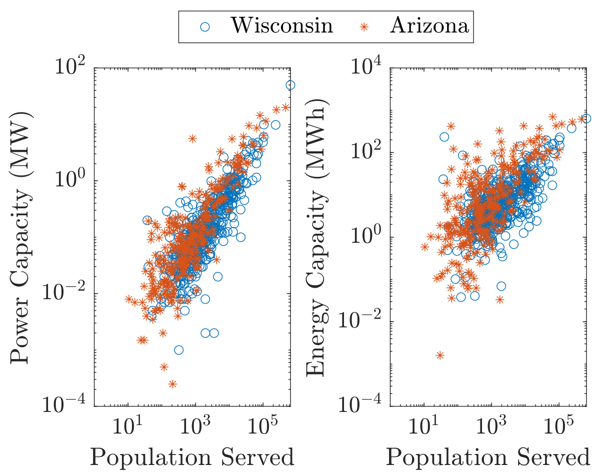

Figure 3. Estimated power capacity (Left) and energy capacity (Right) of Wisconsin (blue circle, Case 2) and Arizona (red asterisk) drinking water utilities as a function of population served on a log-log scale.

for the very large utilities, it is challenging to evaluate if the energy and power capacities are typical for other very large utilities since any one utility annual report can easily skew the data. For example, one of the four large networks in Wisconsin has no pumps or storage tanks since it purchases its water from a different system and is presumably gravity fed. This provides motivation to consider utility data from another state to further improve our estimate.

3.2. Case study: Arizona

We next consider water utilities in Arizona. Arizona is currently facing water-related concerns–such as water scarcity and growing populations–which are anticipated to be exacerbated in the future [24]. Annual reports of privately owned water utilities are posted by the Arizona Corporation Commission [21]. We pulled reports from the year 2019. While a majority of the utilities are privately owned, the largest utilities are municipally owned and sufficient data is not publicly available [24]. For instance, only one of the eleven very large utilities in Arizona is private. We were able to get data on three of the very large municipal utilities from other publicly available reports (e.g., [25]) and email correspondences with the utility system operators. However, data from the city of Phoenix, which is the largest water utility in Arizona, providing water to 1.5 million customers, were not available. In the reports, the primary pump purpose (i.e., treatment or distribution) is not given; therefore, it is most likely that the results here are more in line with Wisconsin's Case 2 estimate which includes distribution and treatment pumps. Another difference between the Wisconsin and Arizona reporting is that Arizona utilities are commonly reported and identified by subsystems of a single company. For example, Arizona Water Company has 19 subsystems each with its own SDWIS water system ID number. While some of those subsystems are geographically isolated, others appear to be connected within divisions, perhaps differentiated by pressure zone. For geographically connected subsystems, this approach (somewhat arbitrarily) splits the energy and power capacity by subsystem. Again, we only consider active pumps.

Figure 3 depicts the non-zero energy and power capacities of water utilities evaluated in Arizona and Wisconsin. We observe similar patterns for both Arizona and Wisconsin power and energy capacity estimates, where the power and energy capacity increases with increasing population served. In Table 2, the power and energy capacities are estimated for the Arizona water utilities for which we have data. Comparing Tables 1 and 2, we observe that the average energy and power capacity by water utility size is higher for Arizona utilities compared to Wisconsin utilities. This is likely due to regional variations (e.g., in topology, climate, and distance between water sources and consumers), where community water systems in the western United States are generally more energy-intensive [26]. Furthermore, energy intensity

Table 2. Estimated Energy and Power Capacities in Arizona's Water Utilities

Utility Size	Number of Utilities	Power Capacity Total (GW)	Power Capacity Average (MW)	Energy Capacity Total (GWh)	Energy Capacity Average (GWh)
Very Small	153	0.009	0.058	1.697	0.011
Small	90	0.023	0.257	1.688	0.019
Medium	24	0.020	0.820	1.525	0.064
Large	26	0.095	3.640	3.939	0.151
Very Large	4	0.056	13.940	1.728	0.432
Total	**297**	**0.202**	0.680	**10.578**	0.036

Table 3. Estimated Energy and Power Capacities for Water Utilities in the United States

Utility Size	Number of Utilities	Total Power Capacity (GW)	Total Energy Capacity (GWh)
Very Small	26,686	1.35	231.33
Small	13,288	1.96	122.10
Medium	5,002	2.42	126.35
Large	4,001	7.65	271.16
Very Large	447	7.33	174.21
Total	**49,424**	**20.72**	**925.16**

is expected to continue increasing for water-stressed regions [27].

4. Estimating the water distribution network flexibility potential in the U.S.

We then extrapolate this data to the United States, where there are around 50,000 year-round water utilities [13]. We do not consider the non-transient non-community water systems (e.g., schools and hospitals) or transient non-community water systems (e.g., campgrounds or gas stations) because they are not open year-round. From [12], we create a list of all of the utilities in the U.S. and their population served; the number of utilities by size classification is summarized in the first two columns of Table 3. We calculate the average power capacities and energy capacities for each of the five utility size classifications from the combined Wisconsin and Arizona data. We then estimate the total power and energy capacities by multiplying the average power and energy capacities by the number of utilities for each utility size classification in the United States. The U.S. power and energy capacity estimates are given in Table 3. The results are order-of-magnitude estimates of the entire nation's water distribution network flexibility potential. While these numbers are approximate, they do indicate that drinking water network pumping is a sizable flexibility resource. For comparison, Nevada's and New Jersey's energy storage mandate aims for 1 GW and 2 GW capacity by 2030, respectively [28].

To determine if extrapolating U.S. estimates from Arizona and Wisconsin data is reasonable, in Figure 4, we compare utility sizes across our case studies and nation-wide data. We have numerous very small, small, and medium utilities to inform our power and energy capacity estimates. However, we have a smaller number of large and very large utilities. To evaluate how representative the sampled utility sizes are for the entire U.S., we plot the distribution of large and very large water utilities by population served within our sampled utility data and within the entire United States in Figure 4. For very large utilities, we exclude the two largest water supply networks within the United States from Figure 4 since their inclusion makes the rest of the data difficult to interpret at that scale. These networks, the New York City Water Supply and the City of Los Angeles, serve 8,271,000 and 4,041,284 customers, respectively [12]. These two water systems are significantly bigger than all other utilities (e.g., the NYC water utility serves three times more people than the third largest utility). The left figure displays a histogram of population served for large utilities and the right figure displays a histogram of population served for very large utilities. For large utilities, we observe that the histogram using Arizona and Wisconsin data roughly follows the nation-wide histogram. Very large utilities in the United States have a longer tail compared to the very large Wisconsin and Arizona utilities. This indicates that the demand response potential estimate for the entire nation may be an underestimate since utilities with more consumers typically have higher power and

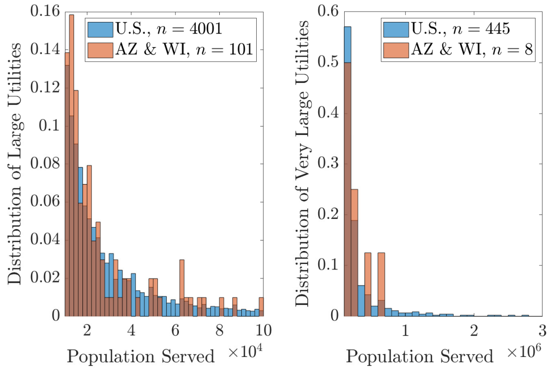

Figure 4. Distribution of large (Left) and very large (Right) water utilities by population served across the entire U.S. (blue) and within Arizona and Wisconsin (red). The two biggest water utilities in the U.S. are excluded from the distribution for data clarity since their inclusion compresses the rest of the data. Data pulled from [12, 20, 21].

energy capacities.

5. Discussion

5.1. Factors impacting flexibility potential

This work provides an order-of-magnitude estimate of the flexibility potential of water distribution networks within the United States. For a specific utility at a specific time, there are several considerations to factor in when determining flexibility potential.

- *Variable water demand:* The actual energy capacity is highly dependent upon current water demand. During peak water demands, the energy capacity would be smaller because the tanks would be able to supply the network for a shorter amount of time before being depleted and vice versa for low demand times.

- *Economies of scale:* While we calculated the flexibility potential for all water distribution networks, prioritizing the use of larger utilities (e.g., large to very large) to provide power system services may make more sense economically. This is because larger utilities generally have more pumps and tanks and have relatively larger power and energy capacities. Therefore, these utilities would be able to provide more demand response services.

- *Spatial flexibility:* The estimate in this paper only captures the temporal flexibility (i.e., the water distribution network shifting power consumption in time by storing water in elevated storage tanks) and not the spatial flexibility (i.e., shifting pumping load between different pumps) in the water distribution network. This feature may be useful if providing local grid support, e.g., voltage regulation [29]. Additionally, the pump power consumption depends on the pump's operating point, which is determined by the pump performance curve and system curve. Consequently, shifting pumping in time or between pumping stations can impact the pump efficiencies for better or worse.

- *Operational storage capacity:* The volume of a tank that can be used for demand response is less than the physical storage capacity of the tank. This is because tanks are also needed to maintain system pressure as well as provide sufficient amounts of water for firefighting. The specific volume that can be used during operation can vary based on state-wide regulatory constraints and utility-specific requirements. For instance, there may be a required amount of 'dead storage' needed to meet minimum pressure requirements for all consumers [30]. It can be unclear in utility reports whether the tank capacity includes the volume of stored water designated as dead storage.

- *Regional network differences:* Drinking water systems are influenced by topography, water availability, climate, population, and regulations. These differences have several notable impacts on water supply system management and operation.

  First, the energy intensity of water networks vary significantly by region. For example, while drinking water systems consume around 1% of the electricity in the U.S., 3% of the electricity consumption in California goes toward drinking water distribution [16, 31]. This increase in energy consumption is primarily from the State Water Project transporting water over very long distances. The State Water Project delivers water from Northern California to Central and Southern California and is the single largest electricity consumer in California [32]. Additionally, energy intensity varies by water source. Water supply systems with groundwater sources consume around 30% more energy than surface water sources due to increased pumping needs [31].

  Second, the significance of issues–such as water scarcity or lead contamination–vary across the United States. Water management and regulation is decentralized, with jurisdiction mainly falling on states [24]. Because of this, issues, regulations, and policies that impact water supply system operation vary across states and local utilities. For example, in Arizona, the 1980 Groundwater Management Act put in place water conservation monitoring and requirements for areas with severe groundwater depletion [24]. This Act limits the amount of water that can be drawn from groundwater sources, which may further limit the operation and flexibility of water utilities.

- *Water quality and dynamics:* U.S. water utilities typically use chlorine during the water treatment process. Water entering the distribution network contains a minimal residual disinfectant concentration to prevent bacterial regrowth [33]. In the distribution network, water continues to age (i.e., chlorine decays). Changes to operation may impact water quality. For instance, low water flow rates may lead to water stagnation, and storing more water in tanks can reduce water turnover, which can lead to disinfection byproduct formation and biological regrowth [33].

  Furthermore, hydraulic transients may need to be considered during water system operation and expansion, further impacting water distribution network flexibility [30]. Inefficient operation or sudden changes can cause issues such as water hammer and cavitation [22].

5.2. Future research directions

Given the opportunities and barriers to leveraging pumps as flexible loads, we suggest several future research directions:

- *Water quality:* The impact of adjusting pump and tank operation to provide grid services on water quality is largely unexplored. However, it is common practice by water system operators to shift pumping to off-peak hours to reduce operational costs. Incorporating water quality modeling requires smaller time steps and complex mixing models. We refer the reader to [34], and the references therein, for more details.

- *Wear and tear of equipment:* Another consideration is whether operation choices lead to higher-than-normal equipment wear and tear. Frequent pump starts/stops or variations away from the designed operating range can lead to additional equipment damage [22]. Wear and tear on the valves, pump bearings, and pipes can lead to reduced efficiency and increased maintenance costs. The effect of incorporating these maintenance costs into pump demand response problems is an open question. Several ways to address this is to penalize frequent pump starts/stops or include the maintenance cost of pump adjustments in the cost function.

- *Regional policy differences:* Given that water management falls to state and local jurisdiction, identifying the best candidates for providing demand response is a compelling research question. This involves determining the power and energy capacity along with regulatory processes. Future directions include developing control strategies and gaining a better understanding of the costs and incentives of demand response participation based on specific characteristics of water distribution networks.

6. Conclusion

In this paper, we estimated the flexibility potential of water distribution networks. Through a case study, we analyzed publicly available water distribution network data from Wisconsin and Arizona and then extrapolated the data to get a rough estimate of the flexibility potential of water distribution networks in the United States. We found that water distribution networks appear to be a sizable flexibility resource. However, aspects–such as regional differences, water quality, and seasonal/daily variations–are not fully captured in these estimates. Future work may consider how these aspects impact the demand response opportunities and the spatial/temporal flexibility of water distribution networks.

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References

[1] O. Ma, N. Alkadi, P. Cappers, P. Denholm, J. Dudley, S. Goli, M. Hummon, S. Kiliccote, J. MacDonald, N. Matson, D. Olsen, C. Rose, M. D. Sohn, M. Starke, B. Kirby, and M. O'Malley, "Demand response for ancillary services," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 1988–1995, 2013.

[2] "FERC Order No. 2222: Fact Sheet – Federal Energy Regulatory Commission," https://www.ferc.gov/media/ferc-order-no-2222-fact-sheet.

[3] M. Lukawski, J. W. Tester, M. C. Moore, P. Krol, and C. L. Anderson, "Demand response for reducing coincident peak loads in data centers," in *Hawaii International Conference on System Sciences (HICSS)*, 2019.

[4] Q. Li, J. Liu, B. Cui, W. Song, and J. Ye, "Distribution system flexibility characterization: A network-informed data-driven approach," *IEEE Transactions on Smart Grid*, vol. 15, no. 1, pp. 1188–1191, 2024.

[5] A.-P. Surani, T. Wu, and A. Scaglione, "Competitive reinforcement learning for real-time pricing and scheduling control in coupled EV charging stations and power networks," in *Hawaii International Conference on System Sciences (HICSS)*, 2024.

[6] A. Stuhlmacher and J. L. Mathieu, "Flexible drinking water pumping to provide multiple grid services," *Electric Power Systems Research*, vol. 212, p. 108491, 2022.

[7] D. Fooladivanda, A. D. Dominguez-Garcia, and P. Sauer, "Utilization of water supply networks for harvesting renewable energy," *IEEE Transactions on Control of Network Systems*, vol. 6, no. 2, pp. 763 – 774, 2019.

[8] Y. Liu, C. Barrows, J. Macknick, and M. Mauter, "Optimization framework to assess the demand response capacity of a water distribution system," *Journal of Water Resources Planning and Management*, vol. 146, no. 8, p. 04020063, 2020.

[9] I. Boukas, E. Burtin, A. Sutera, Q. Gemine, B. Pevee, and D. Ernst, "Exploiting the flexibility potential of water distribution networks: A pilot project in Belgium," *IEEE Transactions on Smart Grid*, vol. 15, no. 1, pp. 394–404, 2024.

[10] Y. Liu and M. S. Mauter, "Assessing the demand response capacity of U.S. drinking water treatment plants," *Applied Energy*, vol. 267, p. 114899, 2020.

[11] J. L. Mathieu, M. E. H. Dyson, and D. S. Callaway, "Resource and revenue potential of California residential load participation in ancillary services," *Energy Policy*, vol. 80, pp. 76–87, 2015.

[12] U.S. Environmental Protection Agency, "Safe drinking water information system (SDWIS) federal reporting services," data retrieved from SDWIS Search, https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/200.

[13] S. Pabi, A. Amarnath, R. Goldstein, and L. Reekie, "Electricity use and management in the municipal water supply and wastewater industries," Electric Power Research Institute, Tech. Rep. 3002001433, 2013.

[14] Malcolm Pirnie, Inc., "Water and wastewater energy management: Best practices handbook," New York State Energy Research and Development Authority (NYSERDA), Tech. Rep., 2010.

[15] C. Copeland and N. T. Carter, "Energy water nexus: The water sector's energy use," Congressional Research Service, Tech. Rep. R43199, 2017.

[16] G. Klein, M. Krebs, V. Hall, T. O'Brien, and B. B. Blevins, "California's water-energy relationship, final staff report," California Energy Commission, Tech. Rep. CEC-700-2005-011-SF, 2005.

[17] D. Denig-Chakroff, "Reducing electricity used for water production: questions state commissions should ask regulated utilities," Water Research and Policy, Tech. Rep., 2008.

[18] "Pump life cycle costs: A guide to LCC analysis for pumping systems," Hydraulic Institute, Europump, and U.S. Department of Energy, Tech. Rep. DOE/GO-102001-1190, 2001.

[19] B. Sparn and R. Hunsberger, "Opportunities and challenges for water and wastewater industries to provide exchangeable services," NREL, Tech. Rep. NREL/TP-5500-63931, 2015.

[20] Public Service Commission of Wisconsin, "Municipal annual report data," data retrieved from E-Services Portal, https://apps.psc.wi.gov/ARS/WEGSqueries/default.aspx.

[21] Arizona Corporation Commission, "Utilities division," data retrieved from Water Company Annual Reports, https://www.azcc.gov/utilities/water.

[22] Office of Energy Efficiency and Renewable Energy, *Improving Pumping System Performance: A Sourcebook for Industry (2nd edition)*. United States Department of Energy, 2006.

[23] L. A. Rossman, H. Woo, M. Trybyand, F. Shang, R. Janke, and T. Haxton, "EPANET 2.2 user manual," Environmental Protection Agency, Tech. Rep. EPA/600/R-20/133, 2020.

[24] S. B. Megdal, "The role of the public and private sectors in water provision in Arizona, USA," *Water International*, vol. 37, no. 2, pp. 156–168, 2012.

[25] City of Mesa Water Resources Department, "2018 water master plan," City of Mesa, Arizona, Tech. Rep., 2018.

[26] R. B. Sowby and S. J. Burian, "Survey of energy requirements for public water supply in the United States," *Journal-American Water Works Association*, vol. 109, no. 7, pp. E320–E330, 2017.

[27] K. T. Sanders and M. E. Webber, "Evaluating the energy consumed for water use in the United States," *Environmental Research Letters*, vol. 7, no. 3, p. 034034, 2012.

[28] Pacific Northwest National Laboratory (PNNL), "Energy storage policy database," https://energystorage.pnnl.gov/regulatoryactivities.asp.

[29] A. Stuhlmacher and J. L. Mathieu, "Chance-constrained water pumping to manage water and power demand uncertainty in distribution networks," *Proc. IEEE*, vol. 108, no. 9, pp. 1640 – 1655, 2020.

[30] A. Anderson, J. Johnson, N. Feagin, S. Mallery, D. Pell, S. Perry, S. Torpie, and L. Waring, "Water system design manual," Washington State Department of Health, Tech. Rep. 331-123, 2020.

[31] "Water and sustainability (volume 4): U.S. electricity consumption for water supply and treatment—the next half century," EPRI, Tech. Rep. 1006787, 2002.

[32] California Department of Water Resources, "State water project," https://water.ca.gov/programs/state-water-project.

[33] M. Badruzzaman, C. Cherchi, J. Oppenheimer, C. Bros, J. Jacangelo, S. Bunn, M. Gordon, V. Pencheva, C. Jay, and I. Darcazallie, "Optimization of energy and water quality management systems for drinking water utilities," Water Research Foundation and California Energy Commission, Tech. Rep. CEC-500-2015-088, 2015.

[34] H. Mala-Jetmarova, N. Sultanova, and D. Savic, "Lost in optimisation of water distribution systems? A literature review of system operation," *Environmental modelling & software*, vol. 93, pp. 209–254, 2017.