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Modeling Water Availability during a Blackout under Consideration of Uncertain Demand Response †

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Abstract: Water distribution systems (WDSs) need electric power supply to operate their pumps. Long-lasting power outages (blackouts) can disrupt the availability of water for citizens. If the water supply is limited by constrained pumping capacities caused by the blackout, water demand reduction could help preserve this limited supply, while increased water withdrawal, i.e., stockpiling, could deplete it. This study investigates the effects and subsequent uncertainty of demand response, especially stockpiling, on WDSs in a blackout. Therefore, we (i) model residential water demand reduction, regular water demand, and water stockpiling in a blackout, (ii) simulate the effect of the demand response on the WDS of Darmstadt, Germany, and (iii) investigate uncertainty resulting from the demand response and initial states of the WDS at time of the onset of the blackout. The findings indicate that the demand response and initial tank levels are the main sources of uncertainty and that demand-side management bears the potential to improve water service availability during a blackout.

Keywords: water distribution system; simulation; resilience; demand-side management; WNTR; power outage; critical infrastructure; socio-technical model

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1. Introduction

In cities, the demand for drinking water is primarily covered by water distribution systems (WDSs). WDSs are largescale technical systems consisting of pipe networks, pumps, and water tanks. These systems are considered critical infrastructures (CIs), which means that a disruption to their function can have detrimental effects to society and citizens. Long-lasting power outages (blackouts) can negatively impact WDSs because most of these systems need electric pumps to ensure water availability.

Recent research highlights the impact of human behavior on CIs, e.g., the processes that are needed to build and operate CIs, and the behavior of the users. Models considering these interactions (socio-technical models) are subject to uncertainty from human behavior, especially in uncommon circumstances. In times of disruption, both cooperative and uncooperative behavior is plausible. During a blackout that limits water supply, citizens could choose to either reduce their water demand or to withdraw excess water in order to build personal reserves, i.e., stockpiling water. This choice is called demand response and influences the water remaining in the WDS and therefore introduces uncertainty into the availability of water for all citizens.

In a previous study, we showed that there is a research gap regarding the modeling of socio-technical interactions of users and WDSs; no standard socio-technical approach for modeling WDSs exists, and validation efforts are often limited [1]. Predictions of many models in the literature rely on assumptions to be true without accounting for potential alternative model configurations, which can be considered model and data ignorance [2]. The goal of this paper is to move from ignorance to incertitude, i.e., to identify potential outcome ranges, and move toward stochastic uncertainty, which is the distributional quantification of uncertainty. To achieve this goal, the presented paper explores the uncertain effects of demand response on the performance of a WDS during a blackout. In particular, the following three research questions are addressed:

1. Which responses of residential water demand to a blackout can reasonably be expected, and how can they be modeled?
2. How does the demand response affect the WDS's performance during the blackout?
3. How certain are the results, i.e., what range of effects can be expected?

The model and analysis methods are presented in Section 2; the results are presented in Section 3. The discussion and conclusions can be found in Section 4.

2. Materials and Methods

To investigate the research questions posed above, a socio-technical model was built of the WDS of Darmstadt, Germany. Darmstadt is a medium-sized city housing around 160,000 citizens, with an average demand of 146 L per person [3]. Around 80,000 citizens live within the city's core, which was assumed to be serviced by the WDS in the model. The model was implemented and simulated using Python 3.11.8 and the Water Network Tool for Resilience (WNTR) 1.2.0 [4]. Due to the unavailability of data on the structure of the WDS, the pipe network and the average demands per junction were built according to the procedure described by [5]. This approach utilizes satellite data to estimate the location of pipes based on the parallelism between WDSs and traffic infrastructure and the average demands for each junction by disaggregating the city's total demand according to the volume of the built environment.

The uncertain demand response was implemented by defining demand patterns according to the following seven scenarios, numbered (i) to (vii): Scenario (i), normal demand, was implemented based on a standard load profile for a large city in Germany given in [6]. For scenarios (ii), minor stockpiling, (iii), moderate stockpiling, and (iv), severe stockpiling, the stockpiling was assumed to be limited by the water storage capacities available to the users. Therefore, a demand surge to fill these capacities was added to the first hours of the standard load profile. The capacities in scenarios (ii) and (iii) were implemented based on the recommendations for water rations for one day (2 L per person) and ten days (20 L per person), respectively [7]. The capacities in scenario (iv) were estimated assuming the use of containers typically not considered suitable for drinking water, e.g., bathtubs. An average German household consists of two people [8] and was assumed to have capacities similar to one bathtub holding roughly 150 L, leading to an estimated capacity of 75 L per person. Scenarios (v), minor water demand reduction, (vi), moderate water demand reduction, and (vii), severe water demand reduction, were implemented to represent a proportional reduction of the load profile during the blackout. In scenario (v,) a demand reduction of 33% was estimated, which is equivalent to the average water use for activities that are not personal hygiene or sustenance, e.g., car washing, as reported by the German Association of Energy and Water Industries for 2022 (BDEW) [9]. In scenarios (vi) and (vii), demand reduction was estimated to the minimum water service under restricted supply (50 L per person per day, 65% reduction) and the minimal emergency supply (15 L per person per day, 90 % reduction), respectively, as defined by the Federal Office of Civil Protection and Disaster Assistance [10].

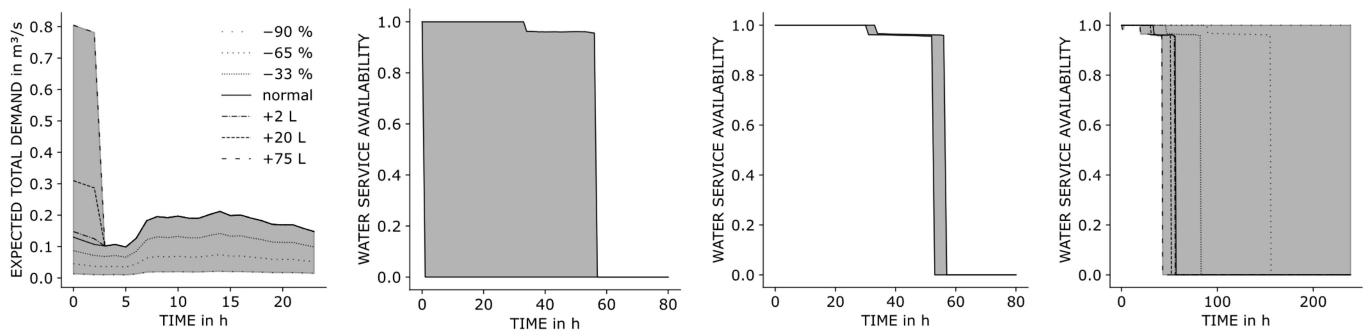
The results were evaluated using the metric water service availability (WSA) for each hour, as defined in the WNTR, and compared based on the time of full service (WSA = 100%) and the complete collapse of service (WSA ='0%). To separately analyze the impact of the sources of uncertainty, a one-at-a-time sensitivity analysis (OATSA) was performed. Given the fixed structure of the WDS, the following three sources of uncertainty were investigated: the initial tank levels, the time of day at the onset of the blackout, and the demand response by users, i.e., the demand scenario. Each source of uncertainty was analyzed in the OATSA by instantiating the other sources as full initial tank levels, blackout onset at 12 a.m., and the normal demand pattern, respectively.

3. Results

The results are summarized in Table 1, and the associated time series are presented in Figure 1. The area shaded in gray indicates the incertitude range. The time series subject to uncertain initial tank levels, presented in Figure 1b, and demand response, presented in Figure 1d, show a wide range of outcomes; the onset time presented in Figure 1c shows a smaller variation in outcomes. The time of full WSA for scenarios (v)–(vii) of water demand reduction is prolonged, not reaching zero in the simulated duration under severe demand reduction (vii). Scenario (iv) of severe stockpiling shows an immediate drop followed by a short recovery of WSA. Furthermore, the WSA reaches zero earlier than it does without stockpiling. The scenario of minor stockpiling shows no noticeable difference from the scenario of normal demand (i).

Table 1. Evaluated sources of uncertainty, assessed input incertitude, and observed output incertitude. [] indicates a range of values, and {} indicates that the complete set of assessed values is reported.

Source of Uncertainty	Input Incertitude	Output Incertitude	
		WSA = 100 %	**WSA = 0 %**
Initial tank levels	[0%, 100%]	[1 h, 34 h]	[1 h, 57 h]
Time of day at blackout onset	[0 h, 24 h] in hourly intervals	[31 h, 34 h]	[53 h, 57 h]
Excess blackout onset demand	{0, +2 L, +20 L, +75 L}	{34 h, 34 h, 31 h, 0 h}	{57 h, 56 h, 52 h, 43 h}
Demand reduction	{0, −33 %, −65 %, −90 %}	{34 h, 47 h, 90 h, -}	{57 h, 83 h, 156 h, -}



(**a**) (**b**) (**c**) (**d**)

Figure 1. (**a**) Aggregated water demand for the first day of all demand response scenarios; (**b**–**d**) WSA subject to uncertain (**b**) initial tank levels, (**c**) blackout onset time, and (**d**) demand response. The lines represent the investigated scenarios and the shaded area highlights the plausible incertitude range.

4. Discussion and Conclusions

In this paper, the effect of demand response on a water distribution system (WDS) during a blackout was investigated. As many models of socio-technical interactions on infrastructures ignore parts of socio-technical model uncertainty, the focus of this study was to investigate the range of predictions given by such models.

The presented results indicate that the initial tank levels and the water demand behavior are the main drivers for the uncertainty. The onset time of the blackout has a less pronounced effect. Additionally, the results show that water demand reduction can increase the duration of full WSA through the WDS, and demand surges can decrease this duration. These results indicate the potential for demand-side management. However, planning actual interventions requires precise data about the WDS, as factors like the topology of the WDS, water quality, and existing crisis management measures like emergency generators were excluded from the investigation. The results illustrate how ignorance of socio-technical uncertainty can impact socio-technical models. To achieve a quantified (stochastic) model uncertainty, it is necessary to gain additional prior information like the probabilities of initial conditions and parameters. Specifically, relationships between the onset time, initial tank levels, and dynamics of demand response should be investigated.

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