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Data-Driven Reliability Assessment of Water Distribution Networks

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Water distribution networks must deliver reliable drinking water service while operating under uncertain demand conditions. Previous operational optimization and reliability studies commonly represent demand uncertainty using parametric probability distributions or ellipsoidal uncertainty. This study investigates whether ellipsoidal uncertainty provides an appropriate representation of short-term operational variability in real water distribution systems. Five years of hourly demand data from a Canadian water distribution network serving approximately 100,000 residents are analyzed to characterize temporal demand structure and deviations from nominal demand profiles. Demand variability is examined, and the statistical properties of hourly demand deviations are evaluated to assess consistency with symmetric ellipsoidal uncertainty assumptions. Results show that demand variability exhibits clear seasonal structure, time-of-day dependence, and asymmetric deviation patterns that are not consistent with ellipsoidal uncertainty representations used in previous studies. These findings point to the need for incorporating empirically derived variability structures into water network reliability assessments.

Keywords: Water distribution networks; Operational reliability; Uncertainty

1 Introduction

Water distribution networks (WDNs) are critical infrastructure that ensure continuous delivery of safe drinking water. Their efficient operation depends on balancing three objectives—maintaining water quality, ensuring hydraulic reliability, and minimizing energy use (Brás et al., 2025; Ramos et al., 2010; Vasconcelos et al., 1997). While utilities rely on scheduling operations to minimize costs under dynamic tariffs, real-time operations are frequently disrupted by stochastic demand fluctuations and infrastructure incidents such as fire flows, pipe bursts, and pump failures. Existing reliability indices, however, typically rely on assumed probability distributions, simplified event representations, or long-term planning horizons (Xu & Goulter, 1999; Filion et al., 2007; Todini, 2000) that fail to capture the empirical likelihood and specific timing of disturbances in real-time operations. As a result, there is a need for a data-driven, dynamic framework to quantify the operational reliability of schedules. However, data-driven reliability assessment is computationally intensive and in practice, operators fall back on predefined uncertainty sets (Goryashko & Nemirovski, 2014) that do not fully reflect actual system variability and disturbances. This motivates the development of tractable uncertainty representations that better reflect observed operational variability

1.1 *WDN Reliability*

Reliable operation of a WDN requires maintaining adequate hydraulic performance and safe water quality under both normal and emergency conditions. In this context, reliability is the ability of the system to deliver potable water in the required quantity and at acceptable pressures over time, despite demand fluctuations, asset faliure, and other disturbances (Farmani et al., 2005; Mays, 2000; Ostfeld et al., 2002; Todini, 2000). Reliability in WDNs is commonly assessed using three broad classes of methods: simulation-based, surrogate (heuristic) indicators, and analytical approaches (Wagner et al., 1988; Mays, 2000). Simulation-based methods represent the system as a whole. While these approaches provide the most comprehensive representation of system behaviour, they remain computationally intensive for operational decision support. Heuristic (surrogate) approaches provide computationally efficient proxies for reliability in WDN. Rather than estimating failure probabilities, they evaluate network attributes whose variation tracks expected service performance, making them useful for screening and embedding reliability considerations within design and operations optimization(Gheisi & Naser, 2014; Mays, 2000; Todini, 2000). Analytical methods estimate WDN reliability directly from network structures and loads, avoiding full hydraulic simulation by leveraging graph-theoretic constructs such as reachability, connectivity, and cut-sets (Yazdani et al., 2011). These graph metrics serve as low-cost structural proxies for reliability (Janet Wagner et al., 1988; Mays, 2000).

Although reliability in WDNs has been widely studied, most existing metrics are still network-level structural or hydraulic-capacity proxies. These indicators are valuable for screening or comparing designs, but they do not yield a clear probabilistic measure of operational reliability. Even in simulation-based studies, uncertainty is often represented using assumed demand or failure distributions and events modeled with fixed or generic magnitudes, durations,

timings, and probabilities, or a limited set of predefined scenarios, rather than being quantified from realistic operational records (Chengchao Xu & Goulter, 1999; Filion et al., 2007; Gomes & Karney, 2005; Tolson et al., 2004). As a result, the literature provides limited evidence on how reliably day-ahead operation can maintain defined levels of service over a day-ahead horizon under realistic, data-derived demand variability and disruptive events (e.g., fire-flows and asset and valve incidents with observed timing patterns). Accordingly, there is a need for a day-ahead, SCADA-based, operational metric that estimates the likelihood of compliance for candidate operational strategies, accounting for the real variability of systems.

1.2 *Uncertainty in WDN operations*

In WDNs, uncertainty is the difference between what the model or operator assumes and how the system actually behaves. On short horizons (hours–days), the main drivers of uncertainty are consumer demands, system state (tank levels, pump or valve settings), electricity prices or cost signals, plus imperfect hydraulic and water-quality parameters used by the model (Dandy et al., 2023; Perelman & Ostfeld, 2023). Uncertainty in modeling can be organized into three broad approaches: (1) producing a single forecast from best-available knowledge, (2) quantifying uncertainty with probability distributions and propagating it to outputs and (3) examining multiple plausible futures without assigning probabilities. Probabilistic methods rely on assigning probability distributions to uncertain inputs and optimizing expected outcomes around a most-likely future. This framework becomes unreliable when long-term changes in climate, technology, or society make those probabilities unstable or undefinable (Maier et al., 2016). Khatavkar & Mays (2017) represent demand uncertainty by a chance-constraint in which hourly demands are assumed to follow a normal distribution around their expected values. This probabilistic constraint is reformulated into a deterministic inequality so the model can be solved efficiently while maintaining a specified reliability level for meeting demand. These approaches link energy optimization to probabilistic feasibility but depend on assumed distributions and scenario trees defined by the modeler, and express reliability implicitly via satisfied constraints rather than through a consistent metric that captures how robustly different optimal schedules perform under a wide range of plausible disturbances.

Under deep uncertainty, expected-value optimization often produces unreliable or misleading solutions. A more reliable approach is to evaluate decisions across a range of plausible futures and emphasize robustness and adaptivity (Maier et al., 2016). A complementary approach is robust optimization, which does not require specifying a fixed probability distribution for the uncertainties. Instead, it models them via an uncertainty set. The original problem is then replaced by its robust counterpart, which must satisfy all operational constraints for every realization in uncertainty set while optimizing a guaranteed (worst-case) objective value (Ben-Tal et al., 2009).

Several studies apply robust and adjustable robust optimization to energy-efficient pump scheduling. Goryashko & Nemirovski (2014) introduce linearly adjustable robust policies in which pump flows adapt affinely to observed demands. Perelman & Ostfeld, (2023) generalize this idea using adjustable robust optimization with linear decision rules, distinguishing between “here-and-now” and “wait-and-see” variables so the model remains feasible across plausible demand realizations while preserving tractability. Demand uncertainty is represented with ellipsoidal sets, and the resulting policies achieve costs close to deterministic schedules while remaining feasible under much larger demand variations than deterministic schedules. Perelman et al. (2023) extend the framework to simultaneous uncertainty in both demands and energy prices, using correlated ellipsoidal sets to obtain tractable schedules that secure high level of constraint satisfaction with limited cost increase.

Overall, most operational optimization studies in WDNs rely on deterministic formulations that represent reliability indirectly through operational constraints or surrogate indicators, rather than explicitly evaluating performance under realistic uncertainty conditions. While robust optimization approaches largely represent demand variability using ellipsoidal uncertainty sets to preserve tractability and capture correlated deviations, these assumptions are rarely validated against long-term demand datasets. Accordingly, this study investigates whether ellipsoidal uncertainty provides an appropriate representation of short-term operational variability in real water distribution systems.

2 Material and Methods

The study was conducted using operational demand data from a borough-scale WDN located in a Canadian city. The service area is primarily residential and supplies approximately 100,000 people. Demand data were obtained directly from the supervisory control and data acquisition (SCADA) system and comprise continuous flow measurements at hourly resolution over a five-year period from 2021 to 2025. To evaluate whether commonly assumed ellipsoidal uncertainty structures are consistent with the empirical data, demand variability and its statistical properties were investigated.

First, to analyze variability across different temporal resolutions, representative demand profiles were constructed. Average yearly demand profiles by week were developed to evaluate seasonal structure, while average weekly demand profiles by hour were used to examine intra-week variability and typical diurnal demand patterns. Next, to compare the observed data with the assumption of an ellipsoidal uncertainty distribution, deviations from nominal demand values were computed by subtracting the mean hourly demand profile from observed demand values. This approach follows the deviation-based uncertainty representation commonly used in adjustable robust optimization formulations

for pump scheduling (Perelman & Ostfeld, 2023). The resulting deviation structure was analyzed to assess the magnitude and temporal dependence of short-term demand variability relative to nominal operating conditions. Finally, the distributional properties of hourly demand deviations were evaluated using skewness analysis to determine whether they exhibit symmetric behavior around nominal values, as expected under an ellipsoidal uncertainty representation.

3 Results

3.1 *Demand profiles*

The analysis of 5 years of hourly demand data brings insights into the variability of demands at different scales. By analyzing yearly demands, shown in Figure 1, the results indicate that seasonal variation is a dominant driver of demand uncertainty. Demand is relatively stable between January and April, followed by a pronounced increase beginning in late spring and reaching peak values during the summer months. This increase is accompanied by greater variability, shown by a widening of the percentile envelope. After September, demand gradually declines toward winter baseline levels. A secondary localized increase in variability is observed toward the end of the year, which may reflect a short-duration consumption event.

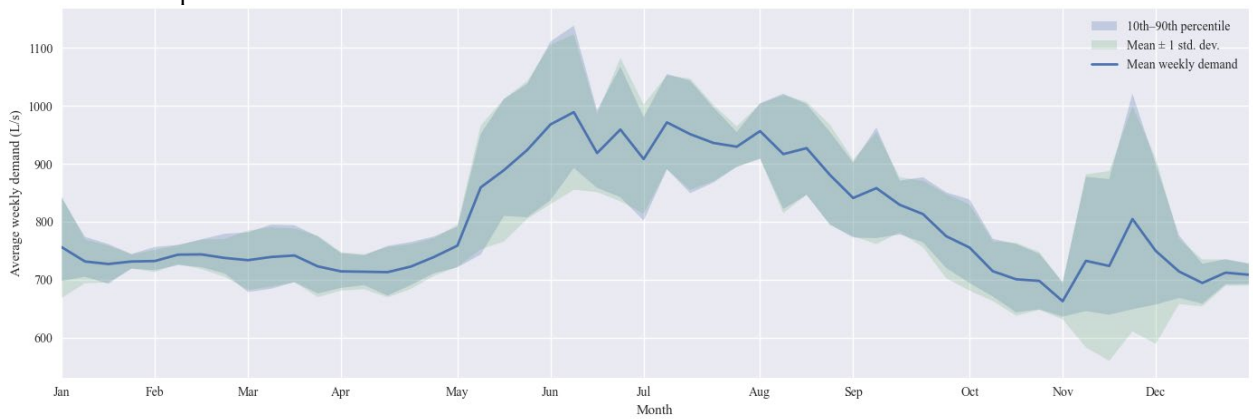

Figure 1. Average yearly demand profile by week

At a weekly scale, results presented in Figure 2 show that demand variability follows a diurnal structure. Within each weekday there is generally a peak in the morning and another in the evening. Weekend demands have a more pronounced peak in the late morning, and greater variability, suggesting that consumption patterns during these periods are less predictable. Together, these results show that uncertainty evolves systematically within the weekly operating cycle and is tied to the timing of peak consumption periods. This further supports the need for uncertainty representations that account for time-of-day-dependent variability rather than relying on a single aggregated demand distribution.

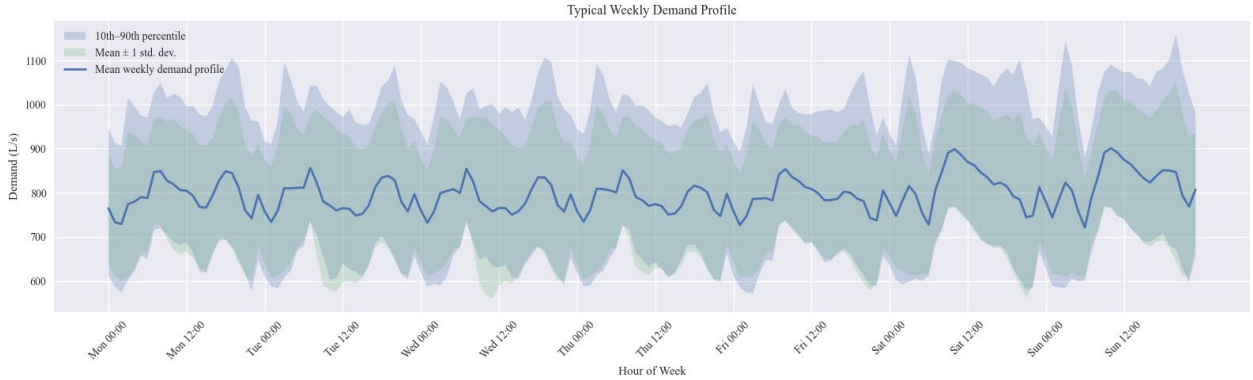

Figure 2. Average weekly demand profile by hour

3.2 *Uncertainty analysis*

3.2.1 *Deviation from nominal demand*

To characterize short-term operational uncertainty, deviations from nominal hourly demand values were plotted, as shown in Figure 3. The deviations show that the spread of possible realizations varies across the day, with larger deviations observed during peak-demand periods. Different from previous studies, the empirical results presented here demonstrate that the spread and orientation of deviations vary systematically with time of day, indicating that a single uncertainty structure may not fully represent the range of disturbances encountered in practice.

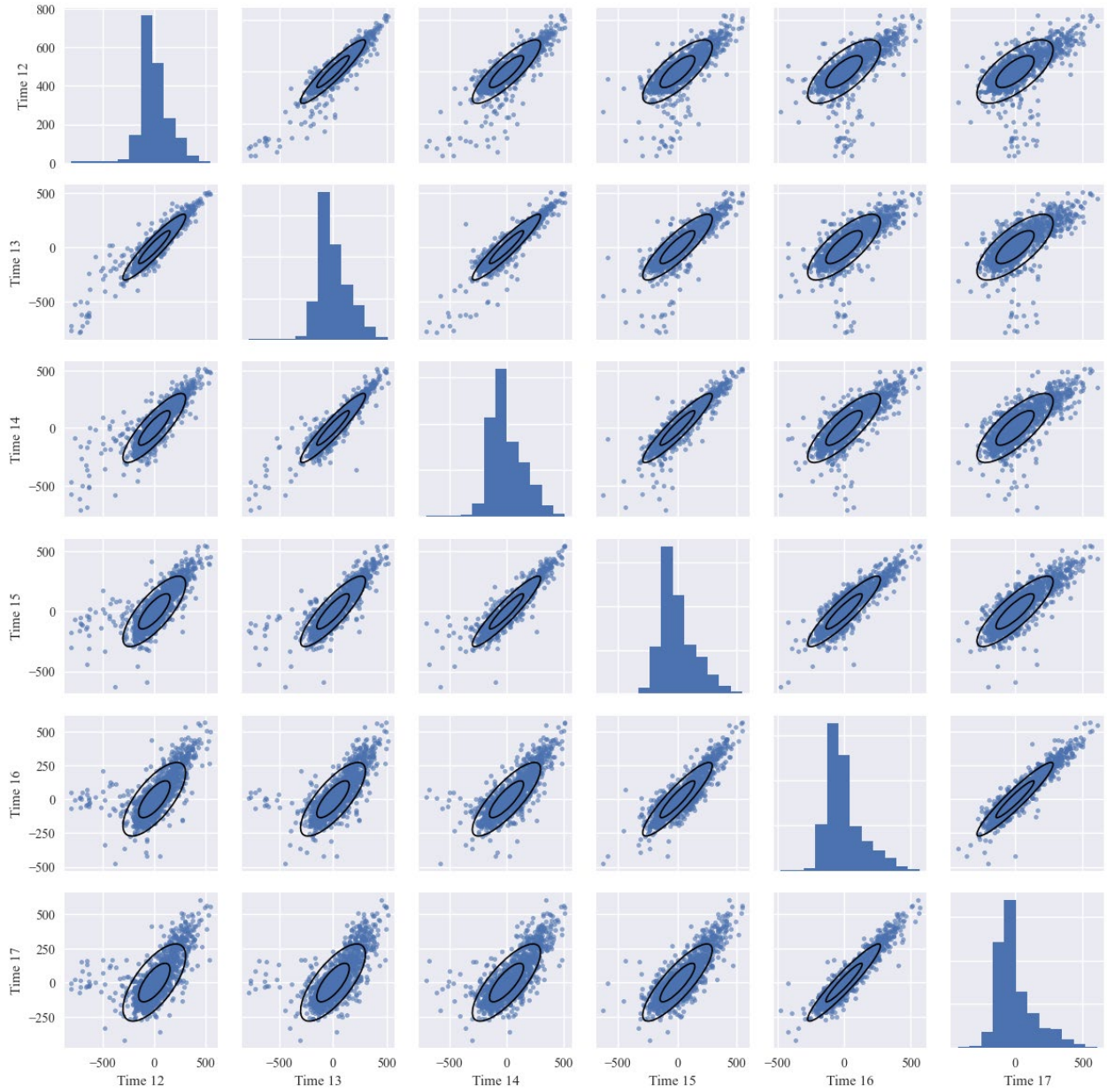

Figure 3. Deviation from nominal demand values

3.2.2 *Distribution shape of hourly demand deviations*

Further analysis of skewness indicate that the distribution of deviations is not symmetric and varies substantially with time of day. The strongest asymmetry is observed during late afternoon and evening hours, as shown in Figure 4, where skewness values increase significantly and indicate a pronounced tendency toward positive deviations. Thus, the uncertainty structure is both asymmetric and time-dependent. Since ellipsoidal uncertainty sets assume symmetric deviation structure around a nominal operating point, the observed skewness patterns suggest that such representations may only approximate the true geometry of demand uncertainty. In particular, the systematic variation of skewness throughout the day indicates that uncertainty cannot be fully characterized by a single symmetric distribution applied uniformly across all operating conditions.

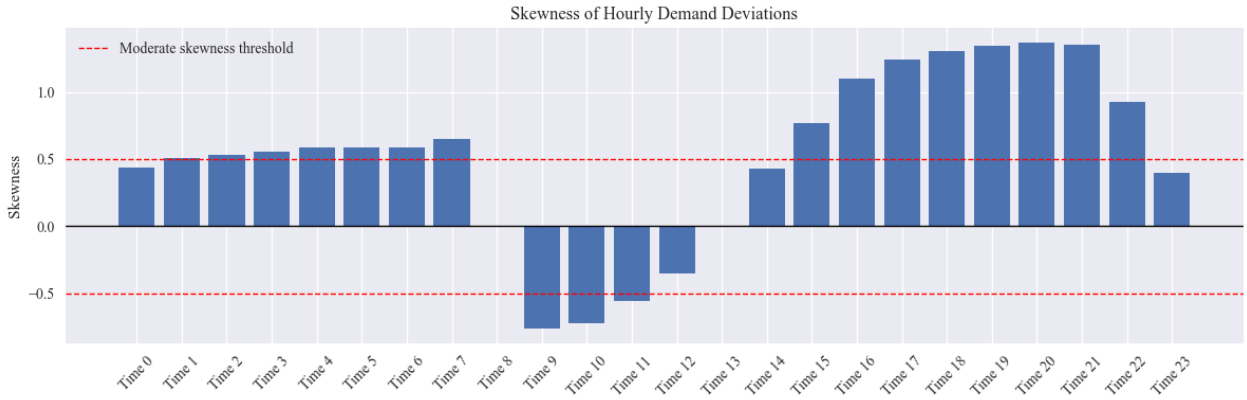

Figure 4. Deviation from nominal demand values

4 Conclusions

Previous WDN operational optimization and reliability studies represent demand uncertainty using parametric probability distributions or ellipsoidal uncertainty sets. Ellipsoidal uncertainty sets are frequently used because they are computationally efficient and represent uncertainty using correlations between demand variations. However, the analysis herein of a 5-year hourly demand dataset shows that demand variability exhibits a seasonal structure, time-of-day dependence, and asymmetric deviation patterns that are not consistent with previous ellipsoidal uncertainty representations. Future research will seek to incorporate empirically derived variability structures into WDN reliability assessment to improve the realism evaluations.

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