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A Review of Scenario-Based Approaches in Water Systems Design †

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Abstract: For the design of water distribution networks (WDNs), a multitude of factors must be considered to achieve a resilient and robust system, given the long lifespan of these systems. Designers face challenges such as climate and demographic changes, fluctuating water demand, policy shifts, and evolving stakeholder preferences. Traditional models, including both deterministic and various stochastic approaches, often encounter difficulties when dealing with the profound uncertainties present in these variables. As a result, they frequently fail to predict long-term performance accurately. The recent literature has indicated a shift towards non-deterministic methods that embrace these uncertainties, especially through scenario generation techniques. In this paper, we delve into these alternative methodologies, specifically focusing on scenario generation techniques that effectively incorporate deep uncertainties into the design process of WDNs. We aim to identify, categorize, and analyze these methodologies, highlighting their strengths, limitations, and areas for improvement. Finally, we also suggest new research directions for scenario-based planning in WDNs to improve their adaptability and resilience against uncertain futures.

Keywords: deep uncertainty; long-term planning; scenario generation; water distribution systems

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1. Introduction

Water Distribution Networks (WDNs) represent a critical component of societal infrastructure, necessitating careful design processes to address the uncertainties impacting system performance. Given the significant role of WDNs in enhancing quality of life and development, a designer must consider all possible climate, socio-economic, technological, and political changes when designing the system. Addressing these uncertainties, also referred to as "Deep" in the literature [1], can be quite challenging for the designer.

Traditional deterministic but also many stochastic models commonly cited in the existing literature are typically limited by not handling uncertainty or handling only statistical uncertainty, and they cannot account for long-term system performance under complex and dynamic conditions. The fundamental approach to managing such uncertainties involves exploring multiple plausible futures and then designing a system that is able to perform effectively across a majority of the possible futures. The effectiveness of these systems cannot be measured using traditional reliability indexes, which can be suitable for systems that are designed with probabilistic approaches. Instead, the effectiveness should be focused on robustness, valuing strategies and planning that ensure the optimal performance for a variety of future conditions [2]. The optimization that takes these uncertainties into account in the form of scenarios is called scenario-based robust optimization (RO). The main goal of it is to come up with solutions capable of performing well, even when faced with unforeseen changes. This type of design optimization operates under a framework that can adapt to new information while considering the risks associated with the decision-making process.

In the available literature, RO has been applied to different aspects of WDNs, encompassing design, quality, and operations. This paper aims to consolidate the various methods that have been employed to create plausible future scenarios for WDNs.

2. Literature Review

In the research field of WDNs, the term "scenario" is used differently among different authors, depending on the approach being followed. The most common use for scenarios is to describe future states of the system. In [3], the authors generated water demand scenarios at the node level using a beta probabilistic model. Their methodology was flexible enough to capture small and large demand aggregation in terms of all statistical properties. In [4], nodal demand scenarios were generated by modeling nodes as correlated stochastic variables. This allowed the same model to generate demands at different aggregation levels (in space and time), and the probability of each scenario could be drawn from a multivariate normal distribution. Another bottom-up approach for generating snapshots of water demand is described in [5], which used Latin Hypercube Sampling with a Gamma marginal probability distribution. Similar to the previous approach, the model considered all statistical properties to be dependent on the number of users, thereby allowing the application of scaling laws. A similar approach, which is presented in [6], first generated demand patterns using Monte Carlo sampling. A Normal or Log Normal distribution was then used to create the demand coefficients that were subsequently used to generate water demand scenarios, by multiplying them with the hourly mean of the historical data.

Clearly, the methods that have been mentioned rely on historical data to infer the statistical parameters. The critical question that arises, when pursuing a robust design, is the following: How well can past values help us predict non-stationary events like climate and social changes for the distant future? For this reason, some authors use a different approach when it comes to water demand forecasting. In [7], the authors generated future scenarios for population growth. Each scenario represented a distinct population increase pattern, and each scenario was assigned with an equally likely probability of occurrence. In [8], a decision tree outlined the potential futures, where each branch represented a scenario. These scenarios described changes in the demand, land use, and the introduction of new pumps. The likelihood of each scenario was provided by the best guess of an expert. In [9], scenarios reflecting different drivers of water demand, such as population change, people's behavior, and climate change were generated. These scenarios were then transformed to water demand patterns using a demand simulator.

Another popular use of the term "scenario" is in reference to potential failures, frequently termed as "Failure Scenarios". This term is used when the consequences of an unexpected failure in the system need to be investigated. The type of consequences can vary depending on the study, including economic, resilience, and health impacts. In [10], the authors investigate the economic impact on the pumping costs resulting from system failures and explore how pump relocations can mitigate these economic consequences during a failure. In terms of water quality, failure scenarios can be utilized to explore possible consequences in the quality of the water in the network.

3. Discussion

From the literature that was reviewed, a graph can be drawn that classifies different scenario types.

As shown in Figure 1, scenarios can be categorized based on the followed approach. The two most common types of scenarios, that have already been mentioned above, are as follows: (i) speculative scenarios, which aim to forecast or explore the future, and (ii) failure scenarios, which seek to replicate potential failures in the system. In Figure 1, they are referred to as "Future" and "Failure" scenarios. The biggest difference between these scenario types is the uncertainty that is assigned to them. Failure scenarios are finite in a system while future scenarios are not. This explains why a majority of the authors have the luxury to brute force all possible combinations of failure scenarios when optimizing for failures in a system. For future scenarios, a further distinction is made, separating probabilistic and expert-driven scenarios. Probabilistic scenarios are generated using probability distributions based on past observations, while expert-driven scenarios are developed based on considerations of the external factors of the system, such as population and social changes. This separation helps to address the varying levels of uncertainties these scenarios can capture. Probabilistic scenarios are based on historical data and are therefore incapable of describing phenomena that have never occurred and cannot account for radical PESTEL (political, economic, social, technological, ecological, and legal) changes that can happen in the future. In contrast, scenarios that include PESTEL factors are more likely to anticipate higher levels of uncertainty [2]. However, the ability to anticipate higher levels of uncertainty comes with some challenges, e.g., the designers have to be aware of potential PESTEL changes in the future, which can be tough even for experts.

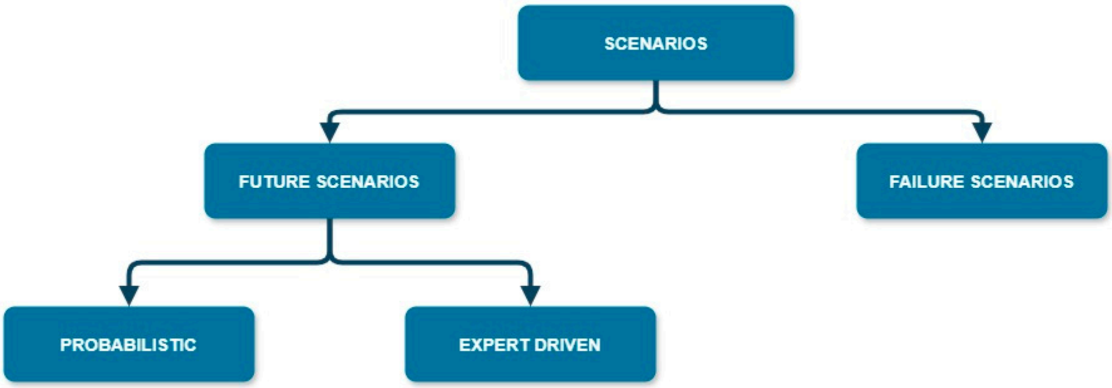

Figure 1. Overview of followed approaches in scenario generation for WDNs.

In the field of foresight studies, there are numerous methodologies for future scenario generation, each being useful in specific areas of interest. A common methodology for scenario generation is Intuitive Logics (IL). The difference between IL and other scenario generating methodologies lies in the search for plausibility. Other methods prioritize different objectives such as preferred or probable futures. According to the literature, several criteria must be met for a described phenomenon to be classified as a scenario in the IL tradition, which the scenario maker must consider. Another requirement for this approach is that a large number of scenarios are needed to fully capture a good representation of possible future states. While this can be carried out very easily with stochastic models, it is very challenging for manual methodologies. Finally, while most of the literature cited in this paper are about water demand, they overlook the other types of uncertainties that designers have to anticipate. Based on this review, there has been limited work performed for human-related uncertainties like stakeholders' preferences. All these facts give space for a framework that can generate plausible scenarios for the uncertainties that a designer has to anticipate during the design process.

4. Conclusions

Scenarios are a crucial tool for exploring uncertainties about the future in a coherent, consistent, and plausible manner. By presenting alternative future states that can affect water distribution systems, managers and decision-makers can develop robust decision and management strategies that are able to cope with a wide range of future conditions. This paper showcases all the possible ways scenarios have been utilized when aiming for robustness. A significant number of articles are utilizing stochastic (probabilistic) methods for generating possible future outcomes. However, stochastic modelling has limitations in describing uncertain systems like WDNs. Conversely, several studies have utilized scenarios that take into account external parameters. The scenarios generated like that can compensate for higher levels of uncertainty as they take into account PESTEL factors. While this method has the potential to generate more appropriate future scenarios, the procedure to generate the scenario is quite complex. The generated scenarios must meet specific requirements like plausibility and distinctiveness. Experts from different areas can help in the crafting procedure, but generating large numbers of scenarios can be time-consuming and expensive. Based on these points, a framework will be developed to automate the process of scenario generation, considering all the PESTEL factors.

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