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Modeling and Performance Evaluation of Intermittent Water Supply Systems

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Abstract

Water supply systems are made up of various components that work together to collect, store, treat, transport, pump, and distribute water. In this context, pumping and distribution are particularly important for our discussion. Pumping involves the pumps and their supporting equipment, while distribution encompasses reservoirs, pipes, valves, and fire hydrants. Pumping stations are essential to water distribution networks (WDNs), and a significant portion of the operational costs in these networks comes from the energy used by pumps. The specific goals and limitations of each scheduling issue can differ significantly from one situation to another. For instance, when it comes to scheduling, some common objectives might include fairly distributing the available water, cutting down on operational costs, or maximizing social benefits. In areas where water is scarce, ensuring an equitable distribution often takes precedence. On the other hand, energy optimization becomes a key focus in systems that have enough water supply. The constraints involved in these problems generally fall into three main categories. The first category deals with the hydraulic model. The second includes physical limitations, such as the capacities of pumps and reservoirs, as well as the availability of water and workforce. Lastly, the third category encompasses the modelling constraints necessary to translate the scheduling problem into a mathematical framework. Notably, in systems with ample downstream storage, the constraints related to reservoir capacity tend to be less of an issue. However, for systems that rely on manual operation, the availability of manpower can be a significant constraint.

Keywords: Water Supply Systems, Quantity, Supplied, Flexibility, Modeling.

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Introduction

This paper heavily relies on physics-based models, primarily utilizing a public domain software called EPANET, which was developed by the United States Environmental Protection Agency (USEPA) (Mohapatra et al., 2014). While the software accommodates both Hazen-Williams (H-W) and Darcy-Weisbach (D-W) equations for modeling frictional losses, this work predominantly focuses on the widely accepted H-W equation. This particular correlation, tailored specifically for water flow in pipes (as opposed to the more general D-W), provides a reliable model for the network and features a pipe coefficient that remains constant regardless of flow rate. However, it's important to note that using the H-W correlation isn't a critical assumption for the findings of this thesis; similar results could be achieved with any other correlation that the author is familiar with (Ismaeel & Zayed, 2018).

This universal discrete time formulation has also been improved. Instead of monitoring each pump's condition at all times presented a novel method of representing pump schedules by storing the times when pumps turned on and off. To tackle this problem, this work introduces discrete event models for Integrated Water Supply Systems (IWSSs), specifically designed for scheduling tasks. The reason behind creating linear models in this thesis is that scheduling issues only require a limited amount of information from the WDN, rather than the whole model. Additionally, there's an extension that completely bypasses hydraulic models of WDNs, relying solely on field measurements. This aspect is arguably one of the key features that sets this thesis apart from previous research on WDN operations (Taylor et al., 2019).

Review of Literature

The range of values that process variables, such as flow, pressure, and valve positions, can take is known as the state space. Numerous factors, including customer demand, tank levels, and the locations of pumps and valves, affect the flow in a typical Water Distribution Network (WDN). However, in the system we're looking at here, the flow of water in the pipes is solely determined by whether the pumps and valves are turned ON or OFF. No matter the water level, the flow rates into the Overhead Tanks (OHTs) we are talking about are constant because the inlets are located at the top. Additionally, standpipes supply water at a constant, known pressure. Additionally, customer demand has little effect on network flow because there is no direct supply to the point of use. Therefore, the locations of the pumps and valves can adequately explain the system's condition, aside from the water level in the OHTs. For example, even though these occurrences take place at different times during the day, the network's flow rates and pressures will be the same if the same valves are ON during time intervals i and j (Sarisen et al., 2022).

When it comes to the benefits of using discrete event models, one major advantage is the ease of computation. But there's more to it: these models allow us to utilize field data instead of relying solely on hydraulic models. The water supply rate at the end nodes is the only output from a hydraulic simulation that is relevant to the scheduling problem for any given condition. The scheduling algorithm itself doesn't really care about the pressures and flow rates at the intermediate points in the network. Plus, since the data needed from each network setup is quite limited, it makes sense to gather it directly from the field rather than running hydraulic simulations. This implies that rather than using the results of a hydraulic model, we can perform field tests to measure the flow rates that villages receive under various network configurations, and then utilize those real data in the scheduling method (Abdelazeem & Meyer, 2024). Additionally, in Section 5.2.2, we present a heuristic for creating a reduced-order discrete event model based on a small number of measurements. In the research that led to this thesis, we used EPANET, an open-source hydraulic solver, in conjunction with MATLAB to perform hydraulic simulations for all network models. Overhead tanks (OHTs) typically comprise 10–12 in rural water distribution networks, and the processing requirements for these hydraulic models are still rather reasonable.

Methodology

The scheduling problem can be approached as a mixed integer linear program. To do this, we simply swap out the cost coefficients (C 0) in problem P1 with the power consumption for each state, which we'll refer to as c from now on. However, this problem remains quite challenging to tackle because of the numerous integer variables involved. To address this, we introduce a new technique that reformulates the issue into two sequential sub-problems for more efficient solving. We address a softer version of the problem in the first stage, concentrating just on the overall demand for each OHT and ignoring the immediate demands for each OHT. This method turns the problem into a linear program (LP), which is technically equivalent to ignoring the binary variables. Finding the energetically optimal system states and outlining the operating time intervals for each selected system state are made easier by solving this LP (Zyoud, 2022).

It is commonly assumed that by carefully selecting the values for the binary variables, we may make the solution to the relaxed problem work for the original problem. In the next sections, we will explore the meaning of this relaxation and the logic of this assumption. Finding a workable timetable that satisfies the time-varying demands

while adhering to the OHTs' capacity limitations is the next stage. Using the previously determined system states and their operating time intervals as well as additional limitations, we will construct a mixed integer linear program with the goal of determining that workable schedule. Since the LP relaxation provides us with a lower constraint on the possible optimal value, finding a workable solution for the ILP also indicates that we have discovered the best answer for the original problem. The algorithm will reformulate the LP in the first step and iterate from there to find a sub-optimal solution to the original problem if we are unable to discover a workable solution for the ILP. The next sections will provide a detailed explanation of each of these three steps. Next, we'll demonstrate the method with a Municipal WDN model (Sashikumar et al., 2003).

It is well acknowledged that by carefully selecting the values for the binary variables, we may make the solution to the relaxed problem work for the original problem. The importance of this relaxation and the logic behind this assumption will be covered in more detail in the following sections. Finding a workable plan that satisfies the evolving demands while adhering to the OHTs' capacity restrictions is the next stage. A mixed integer linear program will be created using the previously determined system states and associated operating time intervals, as well as other limitations, to assist us in determining that workable timetable. Since the LP relaxation provides us with a lower constraint on the possible optimal value, finding a workable solution for the ILP also indicates that we have discovered the best answer for the original problem. The algorithm will reformulate the LP in the first step and iterate from there to find a sub-optimal solution to the original problem if we are unable to discover a workable solution for the ILP. The sections that follow will provide a detailed explanation of each of these three steps. Next, we'll demonstrate the method with a Municipal WDN model.

Results and Discussion

In the selection process we talked about earlier, there's a chance we might end up measuring a state that's already in the database, which could cause some cycles in the algorithm. To prevent this from happening, we make the selection process probabilistic. This means that the nodes we choose might not include all the nodes that received insufficient supply in the last round. Instead, it could just be a subset of those nodes, based on a certain probability (Fig. 1).

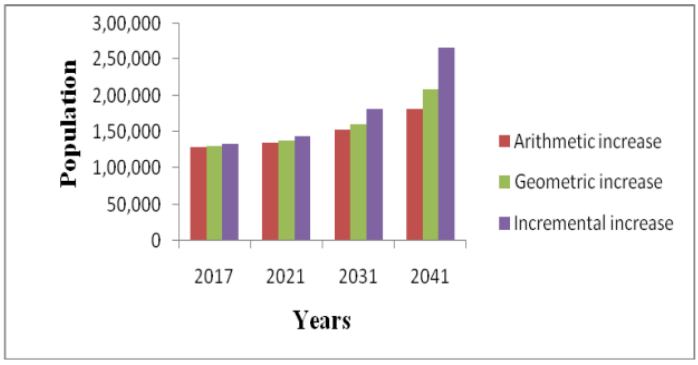


Fig. 1: Graphical Representation of Population Projection Method

To make this work, we need to go through a few steps in each round. First, we identify the demand points that aren't getting enough supply—those with a negative deviation. Next, we normalize their relative deviations and sort them from highest to lowest based on how significant those deviations are. After that, we select a portion of these demand points to receive supply in the next phase (Marsili et al., 2023).

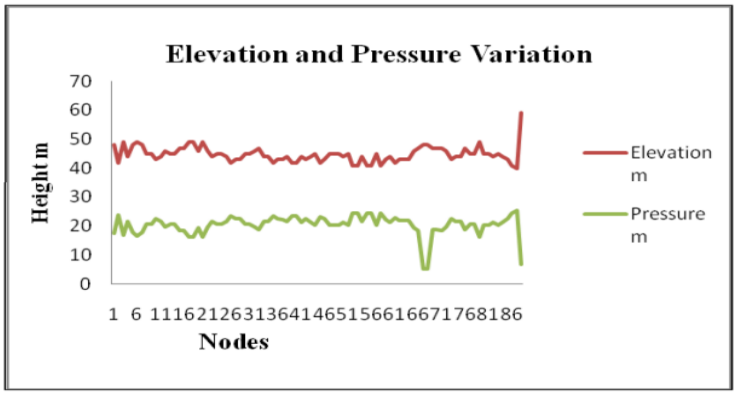


Fig. 2: Graph Representing Elevation and Pressure

The items at the top of the list show the greatest difference from their demand, making them the best candidates for supply with a high likelihood of success. Those further down the list can be selected with less certainty since they are in a much stronger position regarding meeting demand. We begin our selection from the top and continue down the list until we hit a specific 'stopping point.' For P4, we set the minimum duration for time slots to be half an hour. We are unable to execute this if the total active time for any state determined from P3 is less than 30 minutes. In those situations, state K must be removed from the schedule after transferring the demand it was meeting to the other states that were in operation. Essentially, we can eliminate that particular state and allocate extra time to the others to ensure that all demands at the OHTs are met. Adjusting this distribution using states already deemed 'efficient' likely won't lead to a significant increase in overall energy consumption (Fig. 2).

Deciding on this 'stopping node' needs to be done using a probabilistic approach. When we tested the scheduling techniques on actual water network models, we discovered they could lead to impressive savings in both energy and operational time (Fig. 3).

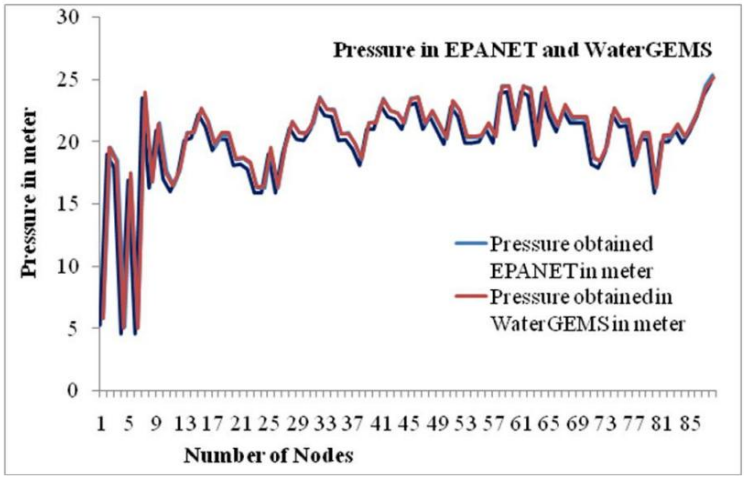


Fig. 3: Pressure Variations in EPANET and WaterGEMS

Achieving fairness in how water is distributed can be accomplished by establishing the right goals for the scheduling challenge. Research on actual networks has demonstrated that even basic strategies created with minimal resources can lead to significant operational enhancements. Additionally, sharing the schedule with the public or posting it online can help consumers organize their daily routines more effectively.

Conclusion

In this paper, we explored techniques for optimizing the operation and scheduling of a specific type of water network known as Intermittent Water Supply Systems. Plus, they can be generated from either a complete hydraulic model or from field measurements, depending on what's available. We also introduced a systematic approach to distribute water fairly using just a few measurements from the system. This method can be adapted for the efficient operation of the system, as the scheduling technique allows users to manage it even with an incomplete model. Beyond the linear models for Water Distribution Networks (WDNs), we've developed innovative solution techniques to further reduce the computational load when tackling the scheduling problem. Our strategy involves breaking down the larger problem into a series of simpler subproblems, which is informed by insights from real-world systems. Additionally, we've extended this work to incorporate time-varying tariffs into the overall formulation.

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