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DATA DRIVEN APPROACH FOR EQUITABLE SUPPLY IN WATER DISTRIBUTION NETWORKS

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***Abstract*— In the localities where there is a limitation on water availability, water supply will be available only for a certain period in a day and in rural areas water collection will be possible only during these limited periods. In this type of networks, inefficient operational methods leads to inequity in water supply. This paper uses data driven method to schedule the supply of available water. A scheduling problem is formulated and solved using the flow measurements from a scaled real time network. A heuristic is developed using Epsilon greedy algorithm to limit the number of state measurements. This approach was tested on a lab scale Water Distribution Networks (WDN) and optimal scheduling was found with minimal measurements.**

I. INTRODUCTION

Water Distribution Networks (WDN) are used to transport water from source to consumers using reservoirs, pumps, pipes and additional instrumentation. These WDN are classified as Continuous Water Supply Systems (CWSS) and Intermittent Water Supply Systems (IWSS). In CWSS, the network is always pressurized and consumers can withdraw water at any time. In case of IWSS water is supplied only for a limited period. The reason for limited period supply is the water scarcity and limitation of infrastructure. A typical Regional Rural Water Supply System's (RRWSS) is operated intermittently. Withdrawals at the demand nodes may not always be proportional to the demand. As long as there is supply, demand nodes might try to withdraw water, which can cause inequity in supply. In such cases, it is important to control the valves and pumps in the system in a scheduled manner in order to ensure equitable supply. In these WDN problems, equity is defined as the uniformity in demand satisfaction through out the network. Equitable supply here means if the villages are supplied with less amount than the required demand, it is ideal for each village to have similar fractional reduction in demand. This fractional deviation from the desired demand will be considered as the measure of equity and minimizing this deviation becomes the main objective of scheduling problem. A model based optimization requires detailed and well calibrated hydraulic models which may not be available. On the other hand, a data driven approach can used to schedule the water supply as it does not depend on a detailed hydraulic model. In this work, we show the application of a data driven method for equitable supply in a scaled down laboratory water distribution network.

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II. METHODS

Typically in WDN, if sufficient water is available, the objective is to meet consumer demands while preventing wastage. Utility operators resort to intermittent operation in order to cope with inadequate supply. On the other hand, if the available water is insufficient or inadequate to meet consumer demands at the required pressures (which is the case in many Indian water supply schemes), equitable distribution of the available resource is of primary importance. Equitable and or efficient supply in a water distribution network can be formulated as an optimization problem, given network details, available water, demands at the villages and operational constraints and a well calibrated hydraulic model. The decision variables for this mixed integer non-linear programming (MINLP) problem are the valve position (ON/OFF) which is a binary variable(1/0), flow rates, head level at different times, and the relative deviation between demand and supply. The scheduling horizon is discretized into certain equal time intervals. The operational objective is to minimize the deviation, leading us to define this as Problem (P). But this problem is difficult to solve due to the non linearities resulting from hydrualic models and integer variables . Hydraulic equations, typically head loss equations and continuity equations used for modelling and simulating WDN to find flow rate and pressure drop at different nodes. When these hydraulic equations are part of the optimization problem, it becomes difficult to solve. In order to overcome this we will convert this MINLP problem to integer linear programming problem (ILP) problem by decoupling hydualic models from the problem using a Discrete Event Model (Kurian et al., 2023).

A. Optimization problem

Minimize:

$$P_1 = \sum_{j \in NT} \left(\frac{\sum_{i=1}^{I_{\max}} \sum_{k \in U} q_{j,k} y_{i,k} \tau}{D_j} - 1 \right)^2 \qquad (1)$$

Subject to:

$$\sum_{k\in U} y_{i,k} = 1, \quad 1 \le i \le I_{\max} \tag{1}$$

$$x_{j,1} \ge \sum_{k\in K} y_{i,k} v_{j,k} - v_{j,0}, \quad j \in NT \tag{2}$$

$$x_{j,1} \ge -\sum_{k\in U} y_{i,k} v_{j,k} + v_{j,0}, \quad j \in NT \tag{3}$$

$$x_{i,j} \ge \sum_{k\in U} (y_{i,k} - y_{i-1,k}) v_{j,k}, \quad 2 \le i \le I_{\max}, \quad j \in NT \tag{4}$$

$$x_{i,j} \ge -\sum_{k\in U} (y_{i,k} - y_{i-1,k}) v_{j,k}, \quad 2 \le i \le I_{\max}, \quad j \in NT \tag{5}$$

$$\sum_{j\in G_l} x_{i,j} \le 1, \quad 1 \le i \le I_{\max}, \quad G_l \in G \tag{6}$$

$$\sum_{i=1}^{I_{\max}} x_{i,j} \le 4, \quad j \in NT \tag{7}$$

$$\sum_{k\in U} y_{i,k} v_{j,k} = 0, \quad i \in S_j, \quad j \in NT \tag{8}$$

The objective function minimizes the relative deviation between demand and supply for villages, accounting for significant demand variations. Key constraints ensure only one state is selected per interval, limit valve operations per operator, and restrict daily valve operations to four or less, as large number of switches to the valve can be inconvenient if the valve is being operated manually and might result in wear and tear. While the above problem is linear, it contains a large number of decision variables, associated with the set of achievable flow rates.

The flow rates at the end nodes are affected only by pump status and valve positions, which means the network will have only finite number of possible configurations or states. e.g., if the network contains 3 demand nodes valves, then the number of states for which flow rate data should be computed or estimated is 2^3. However, if the number of valves in the network increases, for example, if there are 13 valves, then flow rates corresponding to 2^{13} = 8192 valve combinations need to be computed or estimated, which may be difficult. Moreover, a detailed and well calibrated hydraulic model may not be available. In such situation, the flow rates for different valve states (position of valves in the network) can be measured and sent as parameters in the optimization problem. While this results in a linear problem and a detailed hydraulic model can be dispensed with, the number of parameters and decision variables grows exponentially with the number of demand nodes. To overcome this, a heuristic is proposed using Epsilon Greedy algorithm, which uses a probabilistic approach to get the near optimal schedule using only a small set of valve states which are determined experimentally without use of a detailed model.

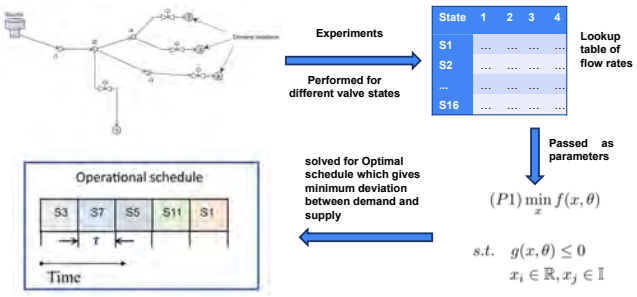


Fig. 1. Procedure for finding the optimal schedule

The result is an optimal schedule for operating valves and pumps that the utility provider can implement.

III. Experimental Setup and Procedure

The Re-configurable Test bed for the Control and Operation of Water Distribution Networks (RTCOP-WDN) set-up is used to create a lab-scale WDN system with eight demand tanks of diameter 0.3 meter and height of 0.5 meter which are connected to one Over Head Tank (OHT) placed at an elevation of 4 meters above the ground. Ultrasonic sensors (HCSR04) are used to measure the level of demand tanks. Each tank is equivalent to a typical village reservoir in an RRWSS as described above. Continuous control valves (Burkert Motorized Proportional valve-3280) are fixed at the inlet of demand nodes which are used as binary valves in this case. As there is significant elevation and head between OHT and demand tanks, flow is by gravity-driven which is similar to a typical RRWSS. Level data is collected from all the tanks for different valve states, and using level vs time data, flow rate can be calculated. LabVIEW software is used to control the valve openings of the demand tanks. Flow data was measured first for 8 random valve states as there are 8 demand nodes in the network. This flow data is used to solve the optimization problem and get the optimal schedule. A new state will be chosen in a way that it provides water to the demand nodes with higher relative deviation from the previous state. This is an iterative process, iterations will carried out till the deviation in demand for all tanks reaches an acceptable value. Stochastic selection ise used to balance between exploiting known states and exploring new states with a small probability to avoid getting stuck in sub-optimal states, which is done using epsilon greedy algorithm.



Fig. 2. Three-dimensional model of RTCOP-WDN setup



Fig. 3. A fully functional RTCOP-WDN

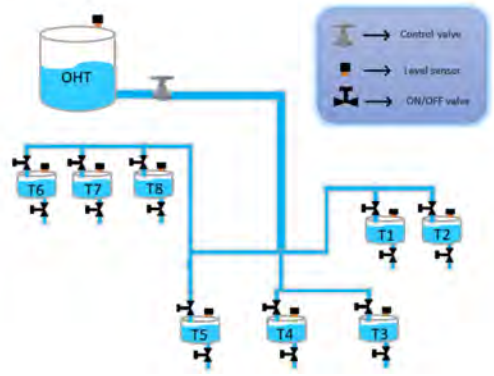


Fig. 4. The schematic diagram of experimental network

IV. Results

The results obtained using the proposed method with a maximum number of 4 valve switches are summarized in Table 1 and illustrated in Fig 1.

The Gantt chart below presents the 24-hour operational schedule for an 8-tank water supply system, with each hour indicating the status of various valves. Different flow rates corresponding to specific valve states are represented using distinct colors.

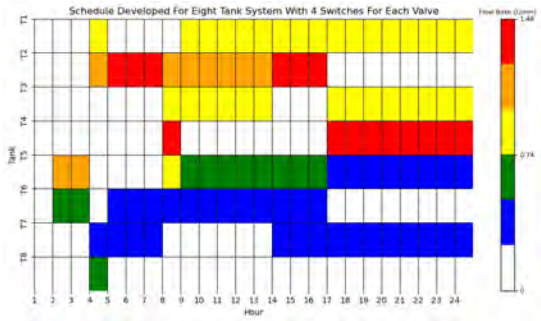


Fig. 5. 24-Hour Schedule of Valve Operations and Flow Rates in an 8-Tank System

TABLE I

Relative Deviation for different tanks: 4 switches

Tank (T)	1^{st} iteration	31^{st} iteration
T1	-0.47	0.0017
T2	-1.00	-0.0028
T3	-0.01	-0.0023
T4	-1.00	-0.0390
T5	-0.33	0.0155
T6	0.02	0.0022
T7	-0.05	-0.0047
T8	0.01	0.0004

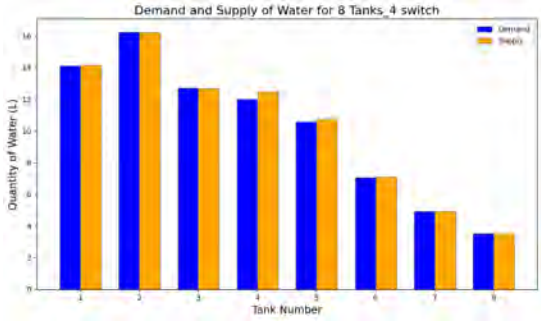


Fig. 6. Demand vs supply

The results of the proposed method with a maximum number of 3 valve switches are as described below in Table II and Fig 6:

Here is the youtube link of demonstrating collection of level vs time data `https://youtu.be/ZUFe0LKd30Q`

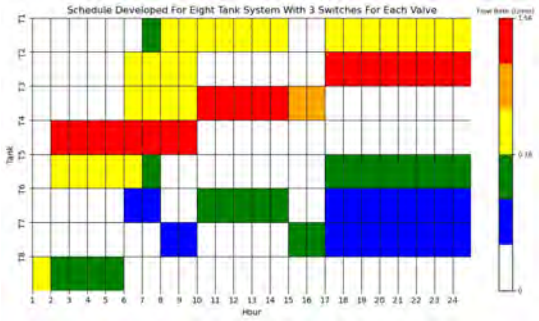


Fig. 7. 24-Hour Schedule of Valve Operations and Flow Rates in an 8-Tank System

TABLE II

RELATIVE DEVIATION FOR DIFFERENT TANKS: 3 SWITCHES

Tank (T)	1^{st} iteration	37^{th} iteration
T1	-0.467	-0.015
T2	-1.00	-0.041
T3	-0.008	-0.009
T4	-1.00	-0.021
T5	-0.334	-0.037
T6	0.023	-0.0034
T7	-0.054	-0.014
T8	0.013	-0.033

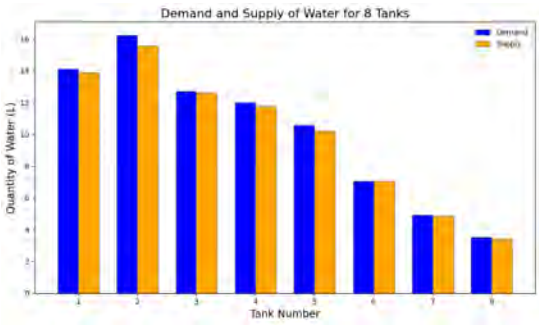


Fig. 8. Demand vs supply

V. CONCLUSION

In the previously discussed 8-tank system, the total state space encompasses 256 possible states. Through our analysis, we discovered for four switch cases,We were able to derive a near-optimal scheduling solution by examining just 31 valve states, with the optimal schedule depending on only 8 of these states. When we reduced the system to three switches, the number of required valve states increased slightly to 37, while the optimal schedule was determined by just 7 of these states. Remarkably, in both scenarios, the relative deviation between demand and supply across all tanks remained consistently below 0.5 percent, ensuring efficient and balanced operation. From the results, the advantage of using this approach is clear in finding suboptimal schedules with fewer states, even for large networks.

VI. AKNOWLEDGEMENT

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VII. APPENDIX

In the optimization problem discussed above, we define the following sets and parameters:

Sets:

- NT: The collection of beneficiary villages within the system.
- U: The set of operational states for which flow rate data is available.
- S_j: Identifies the set of time intervals during which supply should be restricted for village j (where $j \in NT$).

Parameters:

- $q_{j,k}$: Indicates the flow rate entering village j under system state k.
- $v_{j,k}$: Represents the status of the valve leading to village j in state k; it takes a value of 1 if the valve is open and 0 otherwise.
- $v_{j,0}$: Describes the state of the valve leading to village j just before the scheduling horizon commences.
- D_j: Demand of village j for the duration of the scheduling horizon.

Decision Variables:

- $y_{i,k}$: A binary variable that indicates whether state k is active during time interval i, with a value of 1 if active and 0 if not.
- $x_{i,j}$: A binary variable that signifies whether the valve for village j is operated (either turned ON or OFF) at the beginning of time interval i, taking a value of 1 if operated and 0 otherwise.

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