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Operation of Intermittent Water Distribution Systems: An Experimental Study

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Abstract

With the demand for water increasing rapidly, optimal operation of Water Distribution Networks (WDNs) is necessary to provide consumers with the maximum amount of water possible in an equitable manner. This paper presents the outcomes of an experimental investigation of supply policies implementable on rural WDNs. Tests conducted on a fully automated lab scale network, configured to represent rural WDNs, shows significant variations in supply time with the operational policy followed. Further, a systematic set of experiments are carried out to determine the flow rates in different network configurations and this data is later used to formulate a linear programming problem that identifies an optimal operational policy for the system.

Keywords: Water distribution networks, intermittent water supply, scheduling, linear programming.

1. Introduction

The global demand for water is increasing rapidly and many Water Distribution Networks (WDNs) are unable to cope with increased demands (Vairavamoorthy et al., 2008). Network operators in developing countries, often resort to demand management through intermittent supply as a temporary solution (Vairavamoorthy et al., 2008). In such intermittent systems, it is common for the supply to be deficient as well as inequitable (Bhave and Gupta, 2006). Even in other networks that normally provide adequate supply, infrastructure becomes a bottleneck for a short time while the system recovers from failures (Chandapillai et al., 2012). These scenarios necessitate an optimal operation of WDNs so that the available water is distributed equitably, in the minimum time possible.

Operation of WDNs has been actively studied in the past few decades and in most of these studies, the objective has been the reduction of operational expenditure (Sankar et al., 2015; Mulholland et al., 2013; Shi and You, 2016). Maintaining the quality of water has also been the objective for few studies (Nichita and Oprea, 2007). As the techniques proposed in the above-mentioned works were mostly intended for urban water networks, availability of sufficient water has been an assumption that is common to all of them. Even though millions of people still receive water for only few hours in a day, the available literature on the operation of WDNs in water deficient scenarios is limited. The method for quantifying the fairness in distributing available water put forth by Solgi et al. (2014) and the model predictive control for water deficient networks proposed by Sankar et al. (2015) are noteworthy efforts in this regard.

In this work, we propose a technique for operating a class of networks with intermittent supply, commonly referred to as Regional Rural Water Supply Systems (RRWSSs). In these systems, one or two sources provide the water required for a group of beneficiary villages with the help of pumps or by gravity. The supply is intermittent and during the supply hours and the objective for the operational policy is to deliver as much water as possible during the day equitably. The control elements available for this are the valves and pumps in the system. Though there have been few recent works that deals with similar networks (Amrutur et al., 2016), the authors have assumed the system to be equipped with continuous control valves. As a feedback loop with flow measurements is necessary for using control valves, they are difficult to implement for rural WDNs and therefore, in this work we limit our scope to networks with only ON/OFF valves. The other important aspect that distinguishes this paper is that it presents the results of an experimental study where experimental data is used instead of a calibrated model. The configuration of the network, experiments carried out on it and results obtained are given in the following sections.

2. Problem description

A typical rural water supply scheme serves several communities or villages in a region. Here, water is stored in a main balancing reservoir and supplied under gravity to village or local tanks using a piped network. The inlet to each tank is fitted with a valve that is either fully open or fully closed and hence behaves like an ON/OFF valve. The basic operation problem of such a WDN is to supply the desired amount of water to each community or village. There are several reasons for poor performance of the network which can be attributed to issues related to design and operation, e.g., mismatch between actual and forecast demand, poor design practices, aged pipes. Even in well designed, relatively new networks, villages at higher elevations or located far away from the source receive lower supplies than those situated near the source or in low-lying areas. The end result is poor performance as defined in terms of limited availability of water, reduced hours of operation, uncertainty and inequity in supply.

The problem we address is the maximal distribution of water to the beneficiary villages maintaining equity. A simple policy is to fill each tank one at a time. An alternative policy is to open all valves simultaneously and close the valves leading to a particular tank when the demand is met. However, these heuristics may not be feasible or guarantee equitable supply. We propose to solve this problem by formulating an optimization problem (P) where the objective is to meet the cumulative demands while minimizing the time required by manipulating the ON/OFF valves in the inlet of the respective tanks. The decision variables are the time span between event points in the day (τ) and the state of the ON/OFF valves (x) during this time. Additionally, the variables Q and h indicate the flow and head in pipes and junctions respectively. Sets E_{pipe}, E_{valve} N_T, N_S and N_I represent the pipes, valves, beneficiary villages (demand points), source nodes and intermediate nodes in the network. I_{max} denotes the number of intervals the available time is divided into. Other parameters used here are the length of pipes (z), diameters (d), Hazen William's coefficients (ϕ) and demand for water at the villages (D). In this Mixed Integer Non-linear Program (MINLP), constraint equations (2) & (3) model the flow across pipes and valves respectively, (4) specifies the head at the source and villages, (5) represents mass balance at intermediate nodes and (6) ensures the demand satisfied at all downstream villages.

$$(\text{P}) \min_{\tau,x,Q,h} \sum_{i} \tau_i \tag{1}$$

$$\text{s.t.} \quad h_{i,l} - h_{i,m} = sgn(Q_{i,(l,m)}) \frac{10.67\,|Q_{\{i,(l,m)\}}|^{1.85} z_{(l,m)}}{\phi_{(l,m)}^{1.85} d_{(l,m)}^{4.87}} \qquad (l,m) \in E_{pipe},\ 1 \le i \le I_{max} \tag{2}$$

$$(h_{i,l} - h_{i,m}) x_{i,(l,m)} = 0 \qquad (l,m) \in E_{valve}, 1 \le i \le I_{max} \tag{3}$$

$$h_{i,j} = h_{i,j0} \qquad j \in N_T \cup N_S, 1 \le i \le I_{max} \tag{4}$$

$$\sum_{(l,m)\in E} Q_{i,(l,m)} = 0 \qquad m \in N_I, 1 \le i \le I_{max}, E \in E_{pipe} \cup E_{valve} \tag{5}$$

$$\sum_{i} Q_{i,(l,m)} \tau_i = D_m \qquad j \in N_T \tag{6}$$

Upon solving the problem P, if the minimum time is less than the maximum time of operation (e.g., 24 hours if daily demand is specified), the solution is feasible. However, if the minimum required time is greater than the available time, the solution is infeasible. In such a case, we reduce the supply time for every community by the same factor and such a policy would distribute the maximum amount of water equitably.

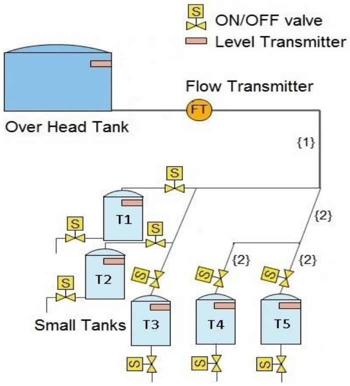
The above problem is a computationally challenging MINLP and requires a well calibrated hydraulic model to be solved. We address both these issues and present an efficient technique for solving the same. To this end, we propose to decouple the optimization from the hydraulic modeling completely. Each of the valve configurations results in a unique set of flow rates in the network. Given n tanks in the network, each inlet valve can be either in the ON or OFF state and hence the number of states is $N=2^n$. Hence, the network state space is finite and the flow rates in the pipes and the tank inlets are uniquely determined by the state of the valves. The problem would determine the time for which the system had to be operated in each of the above-mentioned valve configurations to meet the demand requirements. The objective is to minimize the time required for supplying the water. The decision variables t_p are the time intervals for which valve configuration p had to be active. $q_{j,p}$ denotes the flow rate into tank j in valve configuration p.

$$(P1) \min_{t\ge 0} \sum_{p=1}^{N} t_p \qquad s.t \quad \sum_{p=1}^{N} q_{j,p}\, t_p = D_j \;, 1 \le j \le N_T \tag{7}$$

The flow rates q_{jp} can be determined using a hydraulic solver. However, if the number of tanks is small, the flow rates can be determined experimentally by recording flow rates into the tank in all the N valve configurations. Thus, the decomposition approach allows us to solve a Linear Program (*P1*) to be solved instead of a challenging MINLP and obviating the need for a well calibrated hydraulic model.

3. Experimental setup

This study was conducted on a lab scale WDN indicating a RRWSS with a single source supplying water to five downstream villages. A schematic of the setup is given in Fig.1. It consisted of one Over Head Tank (OHT) representing the source and five Small Tanks (STs - numbered T1 to T5) representing the storage at the villages. The OHT was made of PVC with 75 cm height and 45 cm diameter and had a capacity of 100 litres. It



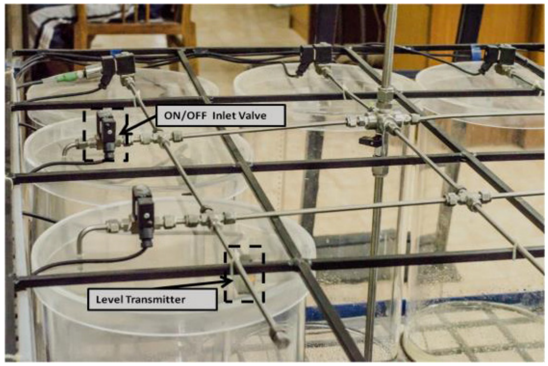


Figure 1 a) Schematic of network b) Lab scale water distribution network

was placed at an elevation of 4 m from the ground. The STs were made of acrylic glass with 50 cm height, 30 cm diameter and 25 litres capacity. The main pipe denoted as 1 in Fig.1(a) had 300 cm length and 1.27 cm diameter and smaller pipes denoted as 2 were of 30 cm length and 0.32 cm diameter. All pipes were made of stainless steel and the complete setup was supported on a 4 × 2.5 × 2 m steel structure.

The out flow of the OHT was controlled by a flow control valve connected to its outlet. The flow into the STs were controlled by ON/OFF valves (Burkert 6011, solenoid valve) placed at their inlet and out flow from them were controlled by ON/OFF valves connected to their outlet. All tanks were equipped with ultrasonic level transmitter (Baumer U500) to measure the water level online. Additionally, there was an ultrasonic flow transmitter (Burkert 8081) connected downstream of the control valve to measure the flow inline. All the instruments were interfaced to a computer through National Instruments DAQ card and LabVIEW was used to program and control the devices. The water level in the OHT was maintained at a constant level of 42.5±2.5 cm.

Here, the problem of supplying water to beneficiary villages translates into the problem of supplying water to the STs from the OHT. For this, the water requirements at the STs were decided as given in Table 1. The problem at hand was to satisfy the water requirement of the STs in the minimum time possible. As in the RRWSS discussed by Bhave and Gupta (2006), the control elements available for our experiments were the ON/OFF valves at the inlet of the STs. The outlet of these tanks was kept closed and therefore, the amount of water supplied could easily be inferred from the level measurements. Levels were measured at a rate of 5 Hz and filtered within LabVIEW. The control valve immediate downstream of the OHT was always kept fully open.

4. Operational policies

Two heuristic supply policies were tested for the case. In the first case (HEURISTIC-I), the inlet valves to all the five STs were opened simultaneously. The supply to each tank was stopped as when its respective demand was satisfied. This mode of operation required 2284 s to meet the requirements as shown in Figure 2. A colored cell indicates that the valve is open and white cell indicates that the valve is closed. In the next policy tested (HEURISTIC-II), the inlet to only one tank was opened initially. Once the requirement for the tank was satisfied, it was closed and the next was opened. Continuing likewise for all tanks, it took 3712 s to provide the water. The actual amount of water supplied following each of the above-mentioned control policies is given in Table 1.

The optimal operation here is the one which meets the requirements of the STs in the minimum time. The setup involved five tanks with ON/OFF valves connected at their inlet, there were a total of 2^5 valve configurations possible. Therefore, 32 different experiments were conducted to determine the flow rates into each tank at different valve configurations. The optimal supply scheme (OPT) obtained by solving $P1$ required 2197 s to supply the water. The Gantt chart depicting this is shown in Fig. 3. The actual amounts of water supplied (last column of Table 1) are almost equal to the demands. The slight deviations between them is due to flow measurement errors and marginal variation in the head within operating range set for OHT. While the heuristic supply schemes have only one downstream tank receiving supply for all or some of its operational time, the optimal scheme provides supply to at least two tanks always. In this way, it makes a better use of the pipes in the network and delivers water in the minimum time.

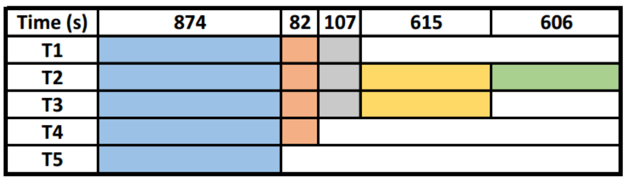


Figure 2: The heuristic supply policy beginning with all tanks open (HEURISTIC-I)

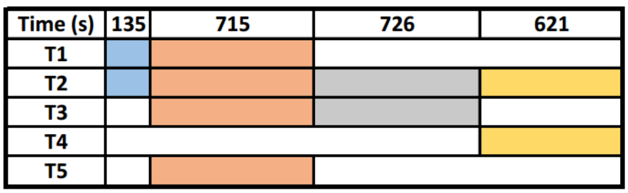


Figure 3: Gantt chart showing optimal supply policy (OPT)

Now if in the real scenario, we have only 1750 s to complete the supply, even the optimal supply policy would not meet the requirement in the given time. In such a case, the active time of every network configuration in the optimal operational policy has to be brought down by a factor of 1750/2197. Such a scheme of operation would reduce the supply to every ST by the same factor i.e.~ 0.8 and ensure equitable operation.

Table 1: Water supplied to the STs

Tank Number	**Demand (l)**	**Supplied (l)**		
		HEURISTIC-I	HEURISTIC-II	OPT
T1	6.40	6.44	6.27	6.37
T2	18.70	18.81	18.58	18.82
T3	11.35	11.39	11.41	11.33
T4	7.48	7.53	7.43	7.50
T5	7.48	7.45	7.41	7.51

5. Conclusions

The paper presented the determination of supply time in WDNs with operational policies with the help of experiments conducted on a lab scale network. The optimal supply scheme required 4 - 69 % less time in comparison to heuristic supply strategies. Also, on implementing the operational policies developed from measured flow rates, the actual water supplied met the demands for all consumers. The results are encouraging for implementing the operational scheme on intermittent WDNs retrofitted with automated ON/OFF valves.

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