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Optimal Scheduling of Rural Water Supply Schemes ⋆

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Abstract: Water Distribution Networks in many rural areas supply water from storage reservoirs at the source of water to a group of villages through gravity or by pumping. Due to poor operational policies, they often fail to meet the demand of the beneficiary villages. This work proposes a rational technique for scheduling the supply in such networks to maximize the water delivered to the villages in an equitable manner. A secondary objective is to minimize the number of valve operations. The problem is formulated as a LP followed by an ILP. The parameters in the optimization problem are obtained by simulations of a well calibrated hydraulic model or experimental data if such a model is not available.

Keywords: Water distribution networks, Equitable distribution, Scheduling algorithms, Linear programming

1. INTRODUCTION

Water distribution systems are key elements of infrastructure crucial for the sustenance of our society while requiring significant investments. The demand for water is expected to double in the next twenty years (Ghaddar et al., 2015) and many Water Distribution Networks (WDNs), especially in the rural areas of developing nations are already inadequate in meeting their demands. Over 35 percentage of treated water is lost as Non Revenue Water and the supply is intermittent with breakdowns often leading to even absence of supply (Mishra, 2008). Hence, it is necessary to utilize the existing infrastructure optimally and deliver the available water equitably at adequate pressure and in the minimum time possible.

Rural areas are usually served by Regional Rural Water Supply Systems (RRWSSs) or Multi Village Schemes (MVS) in which water is supplied from a single source to several villages downstream (Mishra, 2008; Bhave and Gupta, 2006). Bhave and Gupta (2006) have proposed two techniques to ensure adequate supply to the beneficiary villages. In the first method, flow regulating devices are installed in the pipelines to regulate the flow and make it proportional. Unfortunately there are two disadvantages associated with this technique viz. i) Inability of the network to quickly adjust to changes in demand at the villages ii) Further restriction of flow in networks already suffering from network inadequacy. These disadvantages prompt us to explore the second alternative given by Bhave and Gupta, i.e., implementing a scheduled supply. In order to achieve this, a schedule for supply to different villages has to be prepared which is implemented manually using valvemen. In most of systems of this type, the scheduling of water delivered to these villages is heuristically derived or limited by available manpower. In such arrangements, each village receives water once or twice every day and village level storage reservoirs or private storage facilities maintained by individuals may be used for storage. In this work, we propose a novel technique for developing schedules for such water distribution systems based on an LP formulation. Though the case study in this paper make use of of a model to develop the schedule, it is possible to develop a data driven, model free schedule.

WDNS are an active area of interest to engineers and researchers. Network design and reliability (Sherali et al., 1996), optimal pipe selection (Cheng and Mah, 1976), network operations (Bonvin et al., 2017; Nitivattananon et al., 1996) and leak detection and maintenance (Rajeswaran et al., 2018) have all been examined in the past. In network operations, the main thrust area has been the scheduling of pumps because of the savings in energy and hence operational cost. Scheduling of water networks continues to remain a challenging problem. In an early study, Lansey and Awumah (1994) used a dynamic programming approach for pump scheduling which is limited to systems with a relatively small number of pumps or tanks. Subsequently, Genetic Algorithms, Simulated Annealing, Ant Colony Optimization and many other meta heuristics have been used in solving the pump scheduling problem

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(Waterworth and Darbyshire, 2001; López-Ibáñez et al., 2005; López-ibáñez et al., 2008). Recently, Ghaddar et al. (2015) used a Lagrangian decomposition approach along with improved limited discrepancy search to find an optimum pump schedule. A review of literature on operation of WDNs is also available (Mala-Jetmarova et al., 2017).

While most of the above mentioned works considers urban networks with 24/7 water supply, the available studies on intermittent supply, especially for rural areas, are limited. It has to be noted that in case of the rural supply system, even the objective of the scheduling exercise can be entirely different. Modeling of the filling process of an intermittent distribution network was carried out by De Marchis et al. (2010) and a comparative study of continuous and intermittent supply systems was performed by Batish (2003). Equity of distribution, one of the biggest challenges in intermittent supply has also been addressed by few researchers (Ameyaw et al., 2013; Sankar et al., 2015; Solgi et al., 2014). Following their lines, achieving an equitable supply of water is one of the key points addressed in this study as well.

Recently, a technique for optimal filling of water tanks in drinking networks that employs continuous control valves was proposed by Bonvin et al. (2017). Amrutur et al. (2016) also considered a system installed with continuous control valves in their work on scheduling intermittent water systems. In contrast, we consider systems that are completely controlled by ON/OFF valves, which is in fact a more realistic representation of RRWSSs.

A difficulty while planning the operation of rural networks is the insufficiency and inaccuracy of information regarding the networks. The network configuration might not be up to date in the records and variations might have happened in network parameters over the time. The models generated with such information may show significant deviations from the actual behavior of the network. Therefore, in this study, we propose a scheduling technique for RRWSSs which relies only on sampled data and not on the network configuration and parameters. The technique described here has the objective of delivering water in the minimum time and an equitable manner. Though it is easily applicable on small and medium scale systems (10-12 villages), further improvements are required to successfully apply this technique to large systems.

2. PROBLEM FORMULATION

2.1 System Description

The system in consideration consists of a source supplying water to multiple villages. Water is stored in a master balancing reservoir (MBR) and then supplied to village reservoirs by gravity (Bhave and Gupta, 2006). A sample network of this kind, providing water to seven villages is shown in Fig. 1. Though systems with only a single source are addressed here, the proposed technique can easily be extended to systems with multiple sources as well. The network is provided with valves which are either completely open or closed for each village and these can be operated to open or close the flow of water to the particular village (thus behaving as ON/OFF valves). Generally, these valves are operated manually by valve men and the schedules are decided based on heuristics or practical limitations. Such an operation is not guaranteed to use existing resources optimally or ensure equitable distribution.

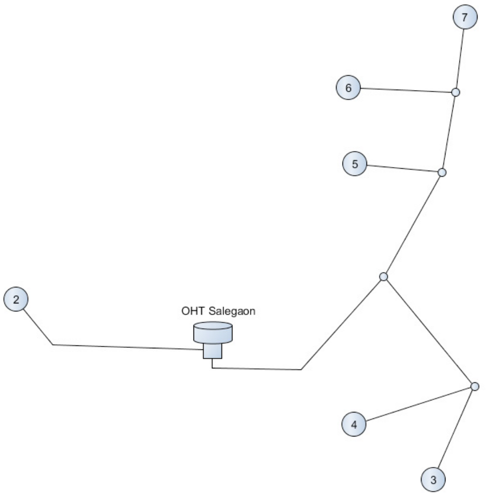


Fig. 1. A sample rural distribution network

The objective of this work is to develop an optimal schedule that ensures that each village is supplied with its corresponding water requirement using the available infrastructure. Also, if it is impossible to meet the daily demand with the available infrastructure, the schedule has to ensure that the water is supplied equitably i.e., every village receives an amount of water that is proportional to their actual demand. In order to achieve this, a schedule has to be prepared which minimizes the time required to supply the water. 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 demands of the villages by a factor equal to the ratio of required minimum time to available time.

2.2 Definitions and Notations

- N denotes the number of villages receiving water from the MBR.
- The term 'State' denotes a configuration of the WDN under consideration. As the only parameters that can change the flow and head characteristics of the system are the valve positions (which in turn can assume only ON or OFF values), the system at any time has to belong to one of the 2^N states. The number 2^N is arrived upon providing two choices (ON/OFF) to every valve in the system. Fig. 2 shows a small network and its possible states are enumerated in Table 1.

- $q_{j,p}$ denotes the flow rate into the j^{th} village while the system is in state p.
- D_j denotes the daily water requirement of the j^{th} village.
- t_p denotes the time for which state p is active in the day.

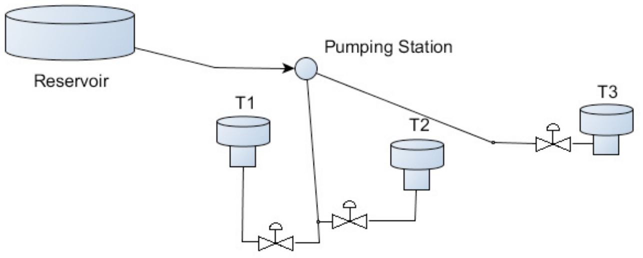


Fig. 2. A small network with three tanks and one source

Table 1. An enumeration of possible states for the network given in Figure 2

State	Status of tanks		
	T1	T2	T3
S1	OFF	OFF	OFF
S2	OFF	OFF	ON
S3	OFF	ON	OFF
S4	ON	OFF	OFF
S5	OFF	ON	ON
S6	ON	OFF	ON
S7	ON	ON	OFF
S8	ON	ON	ON

2.3 Solution methodology

Typically, variations in the water level in the MBR are negligible and hence it is safe to assume that head at the MBR remains constant as considered in the works of Bhave and Gupta (2006). The number of possible states for the system is not significantly large, given the low complexity of such networks and hence the flow rates of water to each village for every possible valve position can be determined. If the network parameters are available, $q_{j,p}$ can be obtained from a well calibrated model and software such as EPANET. However, it is also possible to use experimental data if such a model is not available. The valves are operated so that each of the possible states are explored and the corresponding $q_{j,p}$ are experimentally recorded. The transients in water networks settle off quickly and this enables the measurements to be obtained without much delay. These experimentally determined values of $q_{j,p}$ are used in place of any hydraulic model for preparing the schedule in this work. The downside here is that the number of experiments required scales up exponentially with the number of villages. Though most of the WDN's does not deal with a large number of villages, an exhaustive experimentation of this type is not possible in large systems and a careful design of experiments is required in such cases.

With the measured data q, a straightforward model P for minimizing the time required for supplying the water can be formulated. Here, the available time is discretized into time slots of length $\tau_i, 1 \leq i \leq I_{max}$ and the indicator variable $y_{i,p}$ decides whether state p is chosen for time slot i. The objective is to minimize the time required for supplying the minimum demands specified in the first constraint. The other two constraints ensures that a maximum of one state is chosen for each time slot and all the inactive slots are aggregated towards the end of the time horizon.

$$
\begin{aligned}
P \quad \min_{y} \; & \sum_{p=1}^{2^N} \sum_{i=1}^{I_{max}} y_{i,p}\tau_i \\
\text{s.t.} \; & \sum_{p=1}^{2^N} \sum_{i=1}^{I_{max}} y_{i,p} q_{j,p} \tau_i \geq D_j \qquad 1 \leq j \leq N \\
& \sum_{p=1}^{2^N} y_{i,p} \leq \sum_{p=1}^{2^N} y_{i-1,p} \qquad 2 \leq i \leq I_{max} \\
& \sum_{p=1}^{2^N} y_{i,p} \leq 1 \qquad 1 \leq i \leq I_{max} \\
& y \in \{0,1\}
\end{aligned}
\tag{1}
$$

In this work, we propose to solve this problem and arrive at the optimal schedule in three simpler steps. The first step involves formulating and solving a Linear Programming Problem (LP) to arrive at the minimum time required to meet the demand of the villages. The time for which each state is active in the day is determined in this step. If the total required time exceeds the daily available limit of 24 hours, in the second step the demands are scaled down proportionally to targets that are realizable. The updated time span of each state in the day is also computed here. The last step is the sequencing of these active states so as to minimize the valve operations in the day.

An optimization problem with the objective of minimizing the time required to deliver the water to the villages is given below ($P1$). This forms the first step in our procedure.

$$
\begin{aligned}
P1 \quad \min_{t} \; & \sum_{p=1}^{2^N} t_p \\
\text{s.t.} \; & \sum_{p=1}^{2^N} q_{j,p} t_p = D_j \quad 1 \leq j \leq N \\
& t_p \geq 0 \quad 1 \leq p \leq 2^N
\end{aligned}
\tag{2}
$$

This problem is designed to calculate the time for which each of the 2^N states is active in the day. The two constraints ensure that the demand of each village is fulfilled and the active time of each state in the the day is non-negative. The objective function tries to minimize the total time required to deliver the water.

This is an LP and can be solved efficiently. As the optimum (or at least one of the multiple optima if it exists) for an LP necessarily happens at a corner point, the solution to this problem will have a maximum of N decision variables take a non-zero value. That is, at most N of the 2^N states would be active in the solution as shown in Fig. 3. The states corresponding to these non zero values (the basic variables) are the only ones that will be required for supplying the water and the system will never be operated at any other state in the optimal schedule.

A matter of concern here is that the LP can return a solution that requires more time than the allowable time (typically 24 hours) in order to meet the demands of the villages. The implication of this is that the demand of the villages cannot be completely met by the given infrastructure. In such a situation, the active time of all the states have to be scaled down proportionally such

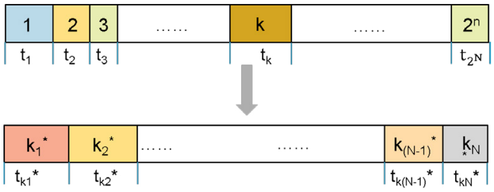


Fig. 3. LP solution with only N states active

that the total time equals the maximum allowable time as shown in Fig. 4. This schedule would ensure that the ratio of supplied water to actual demand is the same for all villages. In fact this ratio would also be equal to the ratio of the available time to the time required according to the original LP solution.

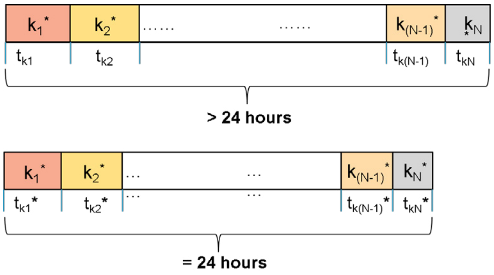


Fig. 4. Proportionally scaling down the active time of states

Once the time for which each state is active is finalized, the next task is to sequence the states so as to minimize the valve operations in the day. That is, we sequence the states such that once the valve to a village is opened, all other states supplying water to the particular village occurs in continuation to this. Besides reducing the burden on the valve-men, this procedure also tries to agglomerate together the periods in which each village receives water and thereby makes the collection easier for villagers. The problem can be mapped into a Traveling Salesman Problem (TSP) and solved using one of the standard ILP solution techniques as described by (Kurian et al., 2018).

For mapping the problem into a TSP, we begin by constructing the equivalent graph. For this purpose, each active state in the schedule is treated as a node in the graph. If the state in which none of the consumers receive water is also active in the day, that is also treated as node. The distance between each pair of nodes is the number of valve switches required to move between them. Here, the term 'switch' denotes a change in position (ON/OFF) of the valve. For example, consider the case in which four states of the network given in Figure 2, viz. S1, S2, S3, S7 are active. The number of switches required to move between a pair of these states vary from one to three. An equivalent graph can be constructed as shown in Figure 5. The numbers on the edges denote the switches required to move between the states.

Now, we need to start with a state, traverse through all other states and return back to the initial using minimum switches. This is analogous to starting at one of the nodes, moving through all other nodes and returning to the initial one travelling a minimum distance, i.e. the Travelling Salesman Problem (TSP). TSPs are generally not easy to solve (Harsha and Srinivasan, 2010). But for a system with not many villages, this can be solved in reasonable time using one of the standard solution procedures such as the branch and bound technique.

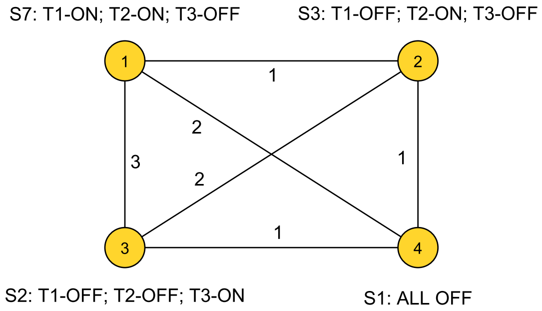


Fig. 5. Graph representing four active states of the network given in Figure 2

Having discussed the technique in detail, we proceed to demonstrate the applicability of the technique on a system that is reported to have been constantly delivering insufficient quantities of water. The insufficient delivery may not necessarily because of deficiency at the source but also because of the incapability to distribute the available water with the existing infrastructure.

3. CASE STUDY: SUGAVE MULTI VILLAGE SCHEME

The Sugave regional rural scheme was proposed some years back for supplying water to few villages in the the state of Maharashtra in India. However the scheme remained incomplete for a long time due to various reasons and few of the villages later opted out of the scheme. CTARA at IIT Bombay has published a detailed report of the case (Prasad and Sohoni, 2011). A schematic of the network with its beneficiary villages considered for this work is given in Fig. 6.

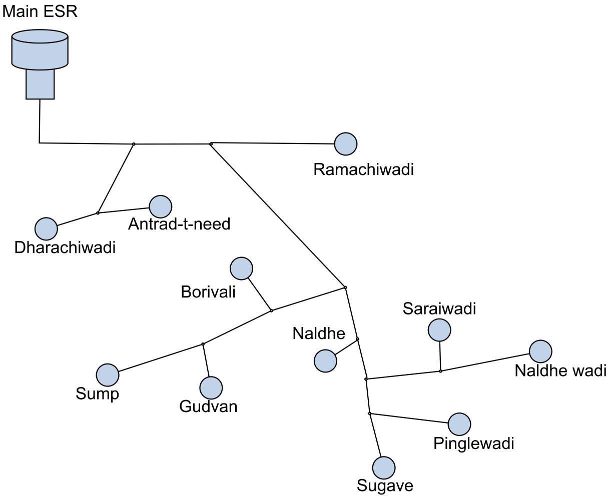
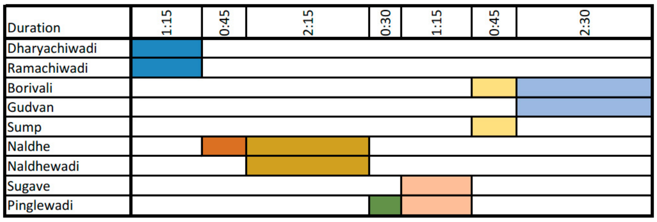


Fig. 6. Schematic of the Sugave network (ESR: Elevated Storage Reservoir)

Based on the data provided by CTARA, a hydraulic model for the system was developed using EPANET (Rossman, 2000) and it was configured to carry out a pressure driven analysis of the system. The operational schedule for one particular day was reported by CTARA and the net water delivered to the villages following this scheme was estimated using the hydraulic model. The obtained data is given in table 2. The total operational time was 9 hour 15 minutes and the schedule is given in Fig. 7.

Table 2. Water supplied to villages in Sugave following the reported schedule

Settlement	Water supplied (m^3)
Dharyachiwadi	28.62
Ramachiwadi	12.09
Borivali	41.84
Gudvan	87.50
Sump	5.76
Naldhe	121.11
Naldhewadi	30.46
Sugave	40.08
Pinglewadi	16.06

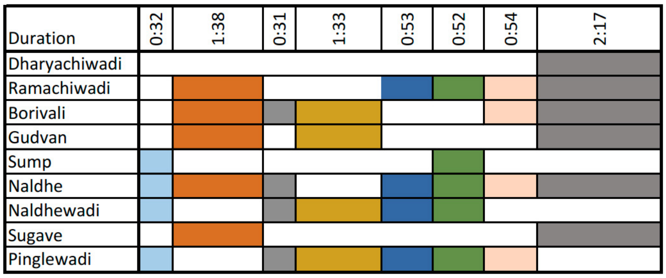


Duration	1:15	0:45	2:15	0:30	1:15	0:45	2:30
Dharyachiwadi	■						
Ramachiwadi	■						
Borivali						■	■
Gudvan							■
Sump						■	
Naldhe		■	■				
Naldhewadi			■				
Sugave					■		
Pinglewadi				■	■		

Fig. 7. An operational schedule of the Sugave network

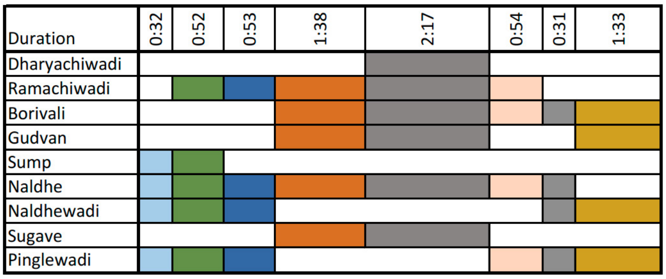
Following this, the flow information for all possible states of the system was obtained from the hydraulic model. It has to be noted that, in case field measurements are possible, the flow information provided by the hydraulic model can completely be substituted by field measurements as the volume of data required is finite. Using the data, the optimization problem $P1$ was formulated and solved using MATLAB to identify the minimum time required to supply the same amount of water following the 'optimal' supply policy. $P1$ being a small LP, the solution time was insignificant. The returned minimum time required for supplying the water was little less than 5 hours. As this was much less than the earlier required time of $9\frac{1}{4}$ hours, the remaining time was used to supply more water to the beneficiary villages. This was achieved by proportionally scaling up the active time for every state so that the total time equalled $9\frac{1}{4}$ hours. The resultant active times for different states is given in Fig. 8. This optimal policy provided about 80 % increment in the amount of water supplied to the villages.

As discussed in the previous section, a secondary objective that has to be considered is the reduction of the valve operations. This can be achieved by properly sequencing the active states. For this, a travelling salesman problem was formulated with the active states representing the cities and the number of valve operations representing the distance between the cities. The problem was solved using a TSP solver (TSPG, 2017) to obtain the optimal schedule given in Fig. 9. The solution time for this step was also negligible. The total number of valve operations required for implementing the optimal schedule was 24 and this was slightly higher in comparison to the 18 switches required in the current practice given in Fig. 7.



Duration	0:32	1:38	0:31	1:33	0:53	0:52	0:54	2:17
Dharyachiwadi								■
Ramachiwadi		■			■	■	■	■
Borivali		■	■	■			■	■
Gudvan		■		■				■
Sump	■					■		
Naldhe	■	■	■		■	■	■	■
Naldhewadi	■		■	■	■	■		
Sugave		■						■
Pinglewadi	■		■	■	■	■	■	

Fig. 8. The active states and their respective time span for maximal supply in the Sugave case



Duration	0:32	0:52	0:53	1:38	2:17	0:54	0:31	1:33
Dharyachiwadi					■			
Ramachiwadi		■	■	■	■	■		
Borivali				■	■	■	■	■
Gudvan				■	■			■
Sump	■	■						
Naldhe	■	■	■	■	■	■	■	
Naldhewadi	■	■	■				■	■
Sugave				■	■			
Pinglewadi	■	■	■			■	■	■

Fig. 9. The optimal schedule for the Sugave system after minimization of valve operations

The time minimization ILP, P was also formulated and solved for this WDN. The model was formulated using PuLP (Mitchell and Dunning, 2011) and solved using CBC (2017). The time horizon for the scheduling problem was set to 10 hours and the the discrete intervals in this horizon were given equal length of half hour. A maximum time limit of 1000s and fractional gap of 0.05 was specified while solving the problem on an Intel® Core^{TM} 2 Duo CPU E7400 @ 2.80 GHz system. The solver exited on reaching the maximum time and the best objective was 5.5 hours with an MIP gap of 9.09 %.

The benefits seen in this case might not be fully realizable in practice as there can be model inaccuracies and other system specific restrictions that are unknown to us. Such a shortcoming, if it exists, can be overcome by incorporating field measurements and thereby removing any model inaccuracies that might have crept in. Also, the current operational policy might be different from the reported policy. Nonetheless, the technique does not lose its significance and the example considered here does make a strong case towards affirming the importance of scheduling in water distribution systems. The proposed schedule is easy to implement but may require existing manually operated valves to be retrofitted so that they can be remotely activated. Furthermore, the schedule can be published online to enable consumers to plan their daily activities better.

4. CONCLUSION

This paper discussed a novel formulation with an LP followed by an ILP for scheduling RRWSSs. In contrast to existing formulations, the objective considered here tries to distribute the maximum amount of water possible in the given time. Equitability of distribution was also considered while preparing the schedule. The technique allows for incorporating field measurements in place of hydraulic simulations and thereby avoids any model inaccuracies. However, in the present form, for large systems, the number of measurements required for preparing the schedule is very high. Therefore, efforts are being made to considerably reduce the number of field measurements required. In this context, it is encouraging to be reminded that, in the final schedule, we do not use most of the measured states and a careful design of experiments can reduce the burden of sampling significantly. Also, further improvements in the technique are required to ensure that the schedule is realizable with the available team of valve men in case the system cannot be automated.

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REFERENCES

Ameyaw, E.E., Memon, F.A., and Bicik, J. (2013). Improving equity in intermittent water supply systems. *Journal of Water Supply: Research and Technology - AQUA*, 62(8), 552–562. doi:10.2166/aqua.2013.065.

Amrutur, B., Kumar, M.M., Kumar, K.S., Patel, L., Sundaresan, R., and Vaidhiyan, N.K. (2016). Wateropt: a method for checking near-feasibility of continuous water supply. In *Proceedings of the 2^{nd} International Workshop on Cyber-Physical Systems for Smart Water Networks*, 7–12. IEEE.

Batish, R. (2003). A New Approach to the Design of Intermittent Water Supply Networks. *World Water Environmental Resources Congress*, 1–11.

Bhave, P. and Gupta, R. (2006). *Analysis of water distribution networks*. Narosa Publishing House Pvt. Ltd.

Bonvin, G., Demassey, S., Le Pape, C., Maïzi, N., Mazauric, V., and Samperio, A. (2017). A convex mathematical program for pump scheduling in a class of branched water networks. *Applied Energy*, 185, 1702–1711.

CBC (2017). Coin-or branch and cut. url https://projects.coin-or.org/Cbc. Accessed: 2017-12-19.

Cheng, W.b. and Mah, R.S. (1976). Optimal design of pressure relieving piping networks by discrete merging. *AIChE Journal*, 22(3), 471–476.

De Marchis, M., Fontanazza, C.M., Freni, G., La Loggia, G., Napoli, E., and Notaro, V. (2010). A model of the filling process of an intermittent distribution network. *Urban Water Journal*, 7(6), 321–333. doi:10.1080/1573062X.2010.519776.

Ghaddar, B., Naoum-sawaya, J., Kishimoto, A., Taheri, N., and Eck, B. (2015). A Lagrangian decomposition approach for the pump scheduling problem in water networks. *European Journal of Operational Research*, 241(2), 490–501. doi:10.1016/j.ejor.2014.08.033.

Harsha, P. and Srinivasan, S. (2010). Approximation Algorithms for NP-hard problems. url http://www.tcs.tifr.res.in/ prahladh/teaching/2009-10/limits/lectures/lec01.pdf. Accessed: 2017-12-19.

Kurian, V., Narasimhan, S., and Narasimhan, S. (2018). Optimal Operation of RRWSS. *Journal of Indian Water Works Association*. In press.

Lansey, K.E. and Awumah, K. (1994). Optimal pump operations considering pump switches. *Journal of Water Resources Planning and Management*, 120(1), 17–35.

López-Ibáñez, M., Prasad, T.D., and Paechter, B. (2005). Optimal pump scheduling: Representation and multiple objectives. In *Conference on Computing and Control for the Water Industry*.

López-ibáñez, M., Prasad, T.D., and Paechter, B. (2008). Ant colony optimization for optimal control of pumps in water distribution networks. *Journal of Water Resources Planning and Management*, (August), 337–346.

Mala-Jetmarova, H., Sultanova, N., and Savic, D. (2017). Lost in optimisation of water distribution systems? a literature review of system operation. *Environmental Modelling & Software*, 93, 209–254.

Mishra, S. (2008). Review of Effectiveness of Rural Water Supply Schemes in India. Technical report, The World Bank. URL `https://openknowledge.worldbank.org/handle/10986/19488`.

Mitchell, S. and Dunning, I. (2011). Pulp: a linear programming toolkit for python.

Nitivattananon, V., Sadowski, E.C., and Quimpo, R.G. (1996). Optimization of Water Suppy System Operation. *Journal of Water Resources Planning and Management*, 22, 249–254.

Prasad, P. and Sohoni, M. (2011). Sugave Water Scheme, Multi-village drinking water scheme analysis. Technical report, CTARA, IIT Bombay. URL `https://www.cse.iitb.ac.in/~sohoni/mvs.pdf`.

Rajeswaran, A., Narasimhan, S., and Narasimhan, S. (2018). A graph partitioning algorithm for leak detection in water distribution networks. *Computers & Chemical Engineering*, 108(Supplement C), 11 – 23. doi: https://doi.org/10.1016/j.compchemeng.2017.08.007.

Rossman, L.A. (2000). Epanet 2: users manual.

Sankar, G.S., Kumar, S.M., Narasimhan, S., Narasimhan, S., and Bhallamudi, S.M. (2015). Optimal control of water distribution networks with storage facilities. *Journal of Process Control*, 32, 127–137.

Sherali, H.D., Smith, E.P., and Kim, S.i. (1996). A Pipe Reliability and Cost Model for an Integrated Approach Toward Designing Water Distribution Systems. In *Global Optimization in Engineering Design*, 333–354. doi:10.1007/978-1-4757-5331-8.

Solgi, M., Haddad, O.B., Seifollahi-aghmiuni, S., and Loáiciga, H.A. (2014). Intermittent Operation of Water Distribution Networks Considering Equanimity and Justice Principles. *Journal of Pipeline Systems Engineering and Practice*, 6(4), 1–11. doi: 10.1061/(ASCE)PS.1949-1204.0000198.

TSPG (2017). TSP Solver and Generator. url https://tspsg.info/. Accessed: 2017-12-19.

Waterworth, G. and Darbyshire, K. (2001). Comparison of methods of pump scheduling in water supply systems. In *European Simulation Multiconference*.