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OPTIMAL TANK DESIGN AND OPERATION TO IMPROVE WATER QUALITY IN DISTRIBUTION SYSTEMS

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Abstract

Water storage tanks or service reservoirs are key components of water distribution systems but often pose water quality problems. This paper assesses the effects of service reservoirs on water quality by comparing two new feasible solutions for the 'Anytown' network that are cheaper than previous solutions in the literature. The recently developed Penalty-Free Multi–Objective Evolutionary Algorithm (PF-MOEA) was used to carry out the optimisation that incorporated tank siting, tank sizing, pipe sizing, rehabilitation, capacity expansion and pump operation seamlessly. More importantly, tank operation was considered explicitly in the optimisation process. The performance of the model is illustrated by application to the benchmark 'Anytown' network that comprises multiple loadings, storage tanks and pumps. The optimization model provided feasible solutions that are cheaper than previous solutions. The results show that the hydraulic performance and water quality in the network can be enhanced by considering the operation cycles of the tanks at the design stage.

Keywords: Penalty-free constrained evolutionary multi-objective optimisation; water distribution system; optimal tank location, design and operation; pressure dependent analysis; water quality; disinfection and disinfection by-products; EU and WHO drinking water standards; optimal pump scheduling

INTRODUCTION

Water storage tanks are crucial components of water distribution networks and are primarily designed and operated to meet demand variations and pressure needs. To achieve this goal, the conventional water distribution network design practice suggests incorporating large storage tanks close to the area of highest water demand (Mays [13]). This approach, however, is conservative and may lead to expensive network designs and more importantly reduce the quality of the supplied water (Basile *et al*. [2]). Improper tank design and inefficient operation can cause long residence time and poor mixing that can lead to water quality issues such as loss of disinfectant, increased formation of disinfection by-products and microbial regrowth (Clark *et al*. [4]; Ghebremichael *et al*.[9]; Grayman and Clark [10]).

Various optimization approaches have been proposed previously to address the water quality concerns in tanks. Kurek and Ostfeld [11] used a multi-objective approach that utilised the Strength Pareto Evolutionary Algorithm (SPEA2) coupled with EPANET. The approach optimised pump operational cost, water quality and tank sizing cost. However, tank location was not considered in the optimisation process. Basile *et al*. [2] presented a multi-criteria decision making tool to optimise tank location, volume and water age. Farmani *et al*. [8] employed evolutionary multi-objective optimisation algorithm to optimise cost, reliability and water age simultaneously, considering the tank operational level as a decision variable.

In this paper, the recently developed genetic algorithm based optimisation model known as Penalty-Free Multi–Objective Evolutionary Algorithm (PF-MOEA) (Siew and Tanyimboh [17]) has been assessed from water quality perspective. The model was developed with the aim of optimising the design, rehabilitation and operation of water distribution networks. PF-MOEA incorporates tank siting, tank sizing, pipe sizing and pump operation seamlessly. Most importantly, the algorithm explicitly considers tank operation that is defined in terms of enhanced depletion and replenishment requirements. PF-MOEA has been applied to the benchmark ‘Anytown’ network that comprises multiple loadings, storage tanks and pumps. The proposed PF-MOEA model provided many feasible solutions that are cheaper than the best previous solutions and satisfy both node pressure and operational constraints for the different loading conditions considered. Two of the best feasible solutions have been assessed herein in terms of water age, disinfection residual and the concentration of disinfection by-products in the entire network.

PENALTY-FREE MULTI–OBJECTIVE EVOLUTIONARY ALGORITHM

PF-MOEA couples a pressure dependent hydraulic simulator with the robust elitist Non-dominated Sorting Genetic Algorithm II (Deb *et al*. [6]). The model considers node pressure constraints effectively using its pressure dependent analysis model that is capable of simulating feasible and infeasible solutions realistically. This enables the optimization algorithm to consider infeasible solutions without the need for penalty functions or other special constraint handling techniques. The pressure dependent model is capable of simulating both hydraulic and water quality of water distribution networks (Seyoum and Tanyimboh [14]).

PF-MOEA solved several optimisation problems including benchmark as well as real life networks and the model provided superior results in comparison to previously published results. More details can be found in Siew and Tanyimboh [17] and Siew *et al*. [18]. One of the benchmark problems solved by PF-MOEA is Anytown network. The aim of the optimisation problem was to find the most cost effective design to upgrade the existing system to meet future demands. The design options include addition of new pipes, cleaning and lining of existing pipes and construction of new pumping stations and tanks. To address this optimisation problem, PF-MOEA directly incorporates pipe sizing, tank siting, tank sizing and pump operation in the optimisation model. The integrated pressure-dependent hydraulic and water quality model identifies the limits of the tanks’ operational levels during the extended period simulation. PF-MOEA has two primary objectives. The first objective is to minimise total cost (i.e. capital and operation costs). The second objective is to maximise an overall performance measure that also determines the feasibility of the solutions and incorporates the operation of the tanks explicitly.

ANYTOWN NETWORK OPTIMISATION PROBLEM

Anytown network (Figure 1) is supplied from a treatment plant via three identical pumps operating in parallel. There are two existing storage tanks, i.e. Tank 41(E) and Tank 42(E) located at Node 14 and 17, respectively. To help simplify their identification, herein the symbols (E) and (N), e.g. Tank 41(E) above, denote existing and new tanks, respectively. The operating water levels of the tanks range between 68.58 m and 76.20 m. The volume of water below the level of 68.58 m and above 65.53 m is retained for emergency purposes. The network has five loading conditions (i.e. average day demand, instantaneous peak and three fire flows). A minimum pressure of 40 psi or 28.12 m must be provided at all nodes for the average day flow as well as the instantaneous peak flow (i.e. 1.8 times the average day flow). A minimum pressure of at least 20 psi or 14.06 m is required under fire flow conditions. With tanks starting at their low operating levels and one pump being out of service, the storage must be sufficient for the two hours fire flow and at the same time supply peak demand flows (i.e. 1.3 times the average day flow). During fire flow periods only the flow required for fires is assumed to be supplied at the corresponding nodes. Further details including network data and the five loading conditions can be found in CWS [5]. A maximum of two new tanks can be added in the design. An upgrade of the existing pumping station is allowed by adding a maximum of two new pumps with identical characteristics to the existing ones. All nodes are considered as potential sites for new tanks, except those which are already connected directly to the existing tanks.

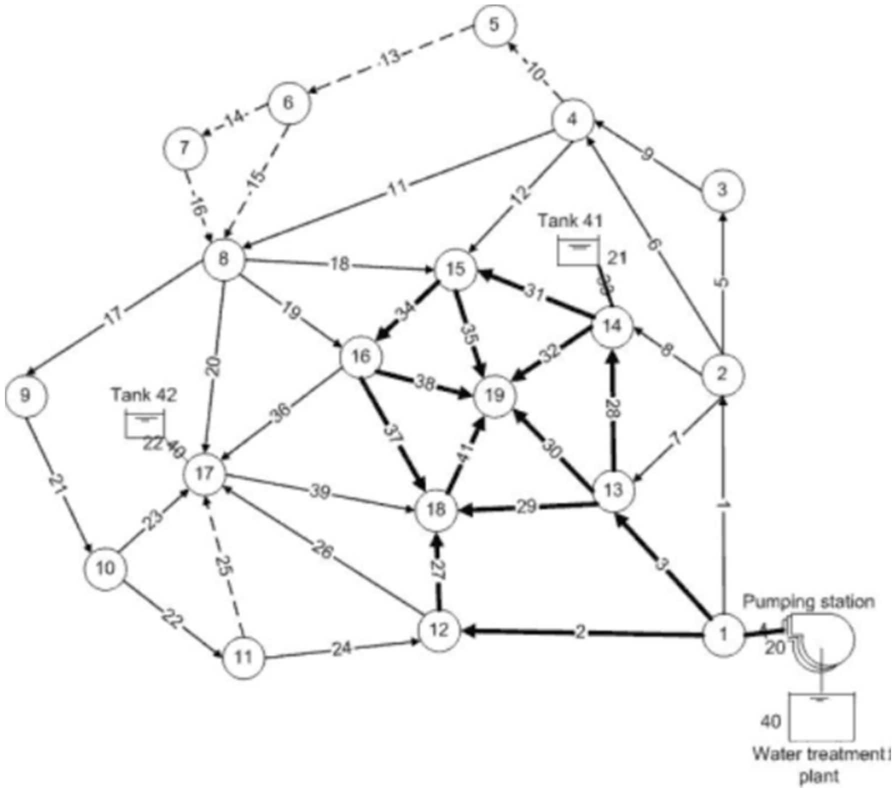


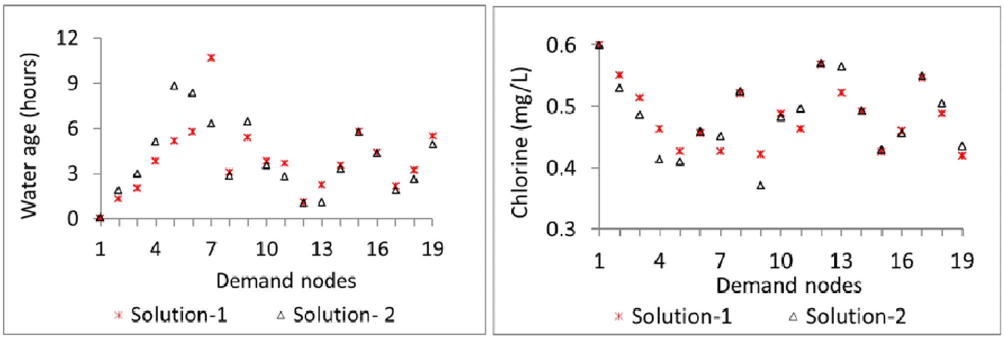
Figure 1. Anytown Network

RESULTS AND DISCUSSIONS

Two alternative design options for the tanks were considered: (a) with enhanced tank operation requirement; and (b) without enhanced tank operation requirement. In both cases, the proposed PF-MOEA optimization model provided many feasible solutions that do not violate any node pressure constraints for all the five loading conditions. One of the solutions obtained is 2.6 % cheaper than the least cost solution published in literature; the details are available in Siew and Tanyimboh [16]. Two near-optimal solutions of PF-MOEA are evaluated herein in terms of water quality. For simplicity the solutions with and without the enhanced tank operation requirement are named as "Solution 1" and "Solution 2" respectively. A single new tank with diameter 18.67 m was added at Node 7 for Solution 1 (Tank 7(N)) and at Node 6 for Solution 2 (Tank 6(N)). The maximum operating water level for both tanks is 72.98 m while the minimum operating level is 67.18 m for Tank 7(N) and 66.56 m for Tank 6(N). The bottom level for both tanks is 60.96 m. It is interesting to note that Tanks 6(N) and 7(N) are not centrally located within the network. Both tanks are on the opposite side in relation to the water treatment plant and pumping station. No new pumps were added to the pumping station for both solutions. Among the three existing pumps, one operates for only 9 hours when demands are high while the other two operate for the entire 24 hours. All pumps operate consistently near their best efficiency point (Siew [15]). Except for Tank 42(E) of Solution 1, the operational volume of all the new and existing tanks of Solutions 1 and 2 are effectively utilised during the 24-hour operation cycle and recover fully by the end of the day. Tank 42(E) of Solution 1 does not fully empty during the day and only approximately 40% of the total operational volume is utilised; several researchers have discussed this issue previously (Vamvakeridou-Lyroudia1*et al.* [18]*)*. The water level fluctuates as the tank fills and drains partially several times over the operation cycle of 24 hours.

Water quality analysis

Solutions 1 and 2 have been assessed by simulating water age and, for illustration purposes, indicative chlorine residual and trihalomethane (THM) concentrations using the EPANET 2 model based on the average loading condition. Complete mixing was assumed in all tanks. All water quality simulations were run for a total duration of 72 hours to enable the results to stabilize and exhibit a clear periodic pattern. Results for the last 24 hours are presented herein. Hydraulic and water quality time steps of *one minute* were used for all the extended period simulations. Bulk and wall reaction rate constants of 0.5/day and 0.1m/day, respectively, were assumed (Carrico and Singer [3]). To ensure that the chlorine residual at all demand nodes and tanks is not below the mandatory minimum of 0.2 mg/L (WHO [20]), the chlorine concentration at the treatment plant was assumed constant at 0.6 mg/L. A maximum total THM concentration of 100 μg/L was adopted based on EU and UK drinking water standards (EC [7]; HMG [11]). During simulations of water age and THM, initial values of zero were assumed at all nodes and tanks. To complete the 72 hour extended period simulation, EPANET 2 required an average time of 1.6 seconds for water age, 1.3 seconds for chlorine and 2 seconds for THM on an Intel Xeon work station (2 processors of CPU 2.4 GHz; and RAM of 16 GB). Figure 2 shows the average hourly water age and chlorine residual values at all demand nodes over the 24-hour cycle for the two solutions. The maximum *average hourly-water-age* is 10.63 hours at Node 7 and 8.81 hours at Node 5 for Solution 1 and 2 respectively. The minimum *average hourly-chlorine-residual* is 0.42 mg/L at Node 19 and 0.37 mg/L at Node 9 for Solution 1 and 2 respectively. Results for THM (not shown herein) indicate a maximum *average hourly-concentration* of 17.35 μg/L at Node 7 for Solution 1 and 16.38 μg/L at Node 5 for Solution 2.



(a) Water age (b) Chlorine residual

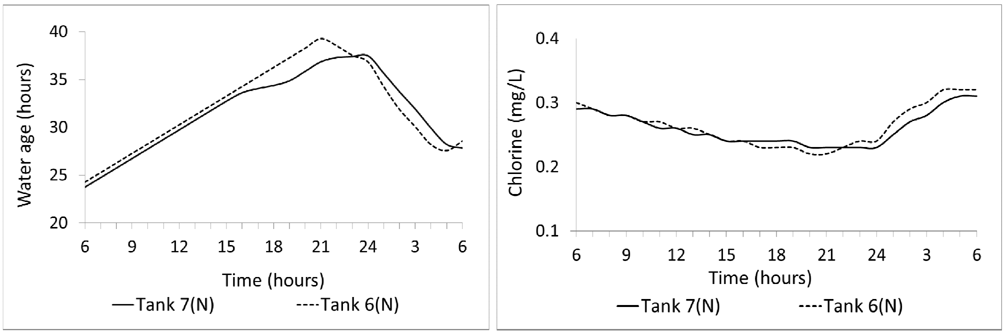
Figure 2. Average hourly water age and chlorine residual at demand nodes over 24-hour cycle

The water quality results for the two solutions in general appear to suggest that all nodes would meet the required water quality standards. The chlorine residual values at all demand nodes and tanks are above the minimum required concentration of 0.2 mg/L and the THM concentrations are below the maximum concentration limit of 100 μg/L. The maximum water age limit is not specified in drinking water standards. However, based on a survey of more than 800 U.S. utilities, the water industry database (AWWA and AwwaRF [1]) indicates an average distribution system retention time of 1.3 days (31.20 hours) and a maximum retention time of 3.0 days (72 hours). Also, Farmani *et al.* [8] solved Anytown network considering water age as one of the objectives and presented different solutions each of which has a single new tank. The maximum water age values of these solutions range from 1.4 to 1.7 days. Table 1 summarises the lowest hourly water quality values over the 24-hour cycle while Figure 3 shows the distribution of water age and chlorine at the new tanks 6(N) and 7(N). The two tanks have comparable results for water age, chlorine and THM.

Table 1. The nodes and times with the least favourable water quality parameters

Water quality parameters		PF-MOEA solutions	Times	Nodes
Water age (hours)	37.48	1	24:00	Tank 7(N)
	39.28	2	15:00	Tank 6(N)
Chlorine residual (mg/L)	0.22	1	13:00	Node 7
	0.22	2	20:00 and 21:00	Tank 6(N)
THM (μg/L)	50.71	1	22:00	Tank 7(N)
	53.15	2	21:00	Tank 6(N)

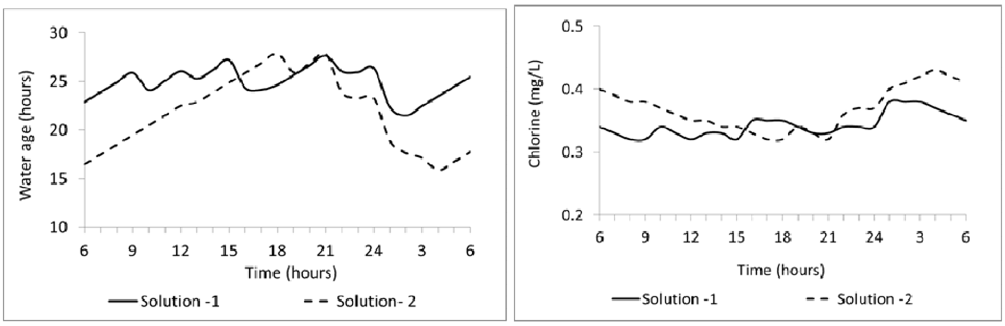
As described earlier, the water level of Tank 42(E) of Solution 1 fluctuates and the tank does not fully empty during the day. The water level variation in the tank is about 4.2 m; approximately 60% of the balancing storage is not utilised as indicated previously. By contrast, Tank 42(E) of Solution 2 is efficiently used with the tank emptying and filling gradually throughout the day. The water level variation in the tank is 7.4 m. As can be seen in Figure 4, Tank 42(E) of Solution 2 provides significantly better water quality than Solution 1.



(a) Water age (b) Chlorine residual

Figure 3. Variation of water age and chlorine residual at Tank 6(N) and Tank 7(N)

Tank 42(E) of Solution 2 reaches its minimum level that is 0.21 m above the minimum operating level at the 18^{th} hour (Figure 4). It was noted that during tank filling the water age is getting smaller as the fresh water enters into the tank while during tank emptying or draining, the water is ageing until the minimum operating level is reached. Thus at Tank 42(E) of Solution 2, around the end of the drain cycle water age reaches its maximum value while chlorine residual is at its minimum value. The reverse occurs at the end of the fill cycle. Overall, these results indicate that increasing the tank's water level variation improves the rate of turnover or entry of fresh water in the tank that results in improved water quality.



(a) Water age (b) Chlorine residual

Figure 4. Variation of water age and chlorine residual at Tank 42(E)

CONCLUSIONS

In this work, solutions from the Penalty-Free Multi-Objective Evolutionary Algorithm (PF-MOEA) have been assessed based on the benchmark 'Anytown' network from the perspective of tank operation. The model provides near-optimal feasible solutions that meet hydraulic as well as indicative water quality requirements. The solution with optimized tank operation in particular enhances the water quality of the network by improving the operation cycles of tanks. The results demonstrate that explicit incorporation of tank operation in the optimisation problem coupled with efficient tank location, tank sizing, pipe sizing and pump operation leads to improved water quality in general. Finally, it may be worth considering an extension to the Anytown network specifications to include operational data for water quality together with reaction rate constants that could contribute to the development of integrated optimisation approaches that include water quality.

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