Improving equity in intermittent water supply systems

Ernest Effah Ameyaw, Fayyaz Ali Memon and Josef Bicik

ABSTRACT

The problems of limited financial resources and water scarcity in urban areas of developing countries are of concern to water managers following growing demand–supply imbalance. As a result, an intermittent supply is widely adopted as a measure for controlling water demand among consumers. However, ensuring equitable water distribution at low cost in intermittent water supply systems becomes a challenge. Most intermittent water supply systems fail to achieve both objectives and how to improve equity remains a complex task for water managers. There is little research in this area and therefore a need to develop more appropriate optimisation techniques that recognise this unique feature of intermittent systems in developing countries. The paper proposes a simple multi-objective optimisation model to measure and improve equity and minimise cost in intermittent distribution networks, under water scarcity condition. A simple network is subjected to intermittent supply to demonstrate the model, in which both locations and capacities of source tanks/reservoirs are subject to optimisation. A simulation model is used to model intermittent systems as pressure-dependent through the use of consumer storage tanks. The paper reveals that equity under intermittent supply conditions is measurable and can be improved through optimal location and sizing of elevated source reservoirs.

Key words | EPANET2, equity, GANetXL, intermittent supply, multi-objective optimisation, tanks

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INTRODUCTION

Following acute financial constraints and water scarcity in urban areas (Arnell 1999; Clarke & King 2004) of many developing countries, intermittent water distribution has widely been adopted as a measure for controlling water demand among consumers (McIntosh & Yniguez 1997; Hardoy *et al.* 2001). Consumers ability to collect water is limited by being physically cut-off for several hours of the day, or even days in some countries. Under water scarcity conditions, efforts are made to distribute the scarce water resource efficiently, dividing the water distribution network into zones (Marchis *et al.* 2010). Each zone is supplied with a percentage of the available amount for a fixed period of time less than 24 hours. Consumers are encouraged by the nature of supply to use over-sized household storage tanks to cope with service intermittency (Criminisi *et al.* 2009), with the intension to store as much water as possible when supply resumes. Hence, node water demand relates to pressure at outlets but not actual user consumption, which is the major difference between continuous and intermittent systems.

Intermittent water supply is prevalent among developing countries, such as south Asia, Latin America and other African countries. In south Asia, for example, it was estimated that at least 350 million people receive water service as little as a few hours daily while 91% of water systems in south-east Asia are intermittent (WHO *et al.* 2000). Vairavamoorthy *et al.* (2008) reported that all Indian cities operate intermittent systems and that two or three hours of water supply a day is considered ‘good’. In Mumbai, for example, water supply is not only intermittent but inequitable: 4% of the population receive water more than 8 hours/day; 33% receive water more than 4 hours/day; 42% receive water

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for just 3 hours/day, and 21% receive water less than 3 hours/day (Vairavamoorthy 2010). This reinforces the argument that service intermittency is a notable management problem: water service providers cannot guarantee customers equal access to limited water resource. Choe & Varley (1997) reported that in Latin America, more than 50 million residents in ten of its major cities receive rationed supplies. A study conducted in four Indian cities to evaluate influence of service intermittency on domestic water consumption revealed that both duration and timing of water supply under intermittent mode have a significant impact on litres per capita per day (lpcd), demand is never satisfied (Subhash & Prakash 2008). In summary, problems of intermittent water supply include (Rajiv 2003; Marchis *et al.* 2010; Vairavamoorthy *et al.* 2010): inability to practise effective supply and demand management; operational inadequacies; customer inconvenience and coping costs; water quality problems; inequitable water distribution.

Water distribution should be equitable and efficient (Chambers 1980; Molden & Gates 1990). However, under intermittent supply conditions many difficulties arise, and achieving equitable water distribution in a cost effective manner becomes difficult, if not impossible. Traditionally, water distribution system design has focused on continuous water supply for 24 hours a day. Yet, in many developing countries, existing continuous water distribution systems are operated as intermittent systems. Therefore, the network pressure often becomes inadequate and unable to provide a satisfactory level of service to all consumers (Marchis *et al.* 2010). The resulting effect is that water distribution is inequitable, affecting temporal and spatial distribution (Fontanazza *et al.* 2007). Given pressure variations in distributing water, distant consumers do not receive a sufficient amount of water, as supply is limited to consumers close to the supply nodes. Limiting distribution to nearby users could reduce distribution losses, particularly in networks with high leakage rates, but such a distribution is not equitable (Indra *et al.* 1995).

Intermittent water distribution has been analysed by many researchers (McIntosh & Yniguez 1997; Vairavamoorthy *et al.* 2001; Tokajian & Hashwa 2003; Fontanazza *et al.* 2007; Rosenberg *et al.* 2008; Andey & Kelkar 2009; Marchis *et al.* 2010), but how to measure and improve equity in existing intermittent water distribution networks has been less investigated. Typically, the operation of intermittent systems is based on experience of a water utility, analysis of supply and demand, and the search for a compromise (Twort *et al.* 2000) rather than on equity issues. In the literature, very few models have been proposed considering equity issues in intermittent water systems. Vairavamoorthy and co-authors (Vairavamoorthy & Lumbers 1994; Vairavamoorthy & Elango 2002; Vairavamoorthy *et al.* 2000, 2007) have proposed models for the design and control of intermittent water systems. However, the models have been found to be flawed by some authors. Tzatchkov & Cabrera-Bejar (2009) argued that the models are more academic than practical and that water distribution models must be functional and practical to be able to produce reliable results to guide decision-makers. Moreover, the models proposed by Vairavamoorthy and co-authors are more sophisticated and require specialised software (Ingeduld *et al.* 2006). Ease of use of water distribution network models is fundamental in developing countries (Tzatchkov & Cabrera-Bejar 2009). A simple two-objective optimisation model for measuring and improving equity and minimising cost in intermittent distribution networks is described.

THE CONCEPT OF EQUITY IN WATER SUPPLY SYSTEMS

The 'concept of equity' is both very simple and complex: it is simple because everybody is aware of it and complex because there is no single best measure of equity (Sampath 1988; Indra *et al.* 1995). Equity of water distribution refers to the '*delivery of a fair share of water to users throughout a system*' (Molden & Gates 1990, p. 806). They further argued that equity is a complex objective to measure given that many factors determine the meaning of a 'fair share', and because authors often interpret a fair share in a subjective manner.

In intermittent water systems in developing countries, the issue of inequity (in terms of water quantity) among consumers is a well known problem, but, as mentioned earlier, the academic literature on equity in intermittent water supply systems is scarce. This seems to be due to the fact that drinking water systems are designed for a 24/7 supply. However, most of these systems are later operated as intermittent systems following various challenges. At the distribution level, inequity among users results from the two transitional phases of intermittent systems (Marchis *et al.* 2010); first, network filling up – where the quantity of water entering the network does not reach users at the same time, which can last for several hours in large networks. Consumers located far away from supplying sources (nodes) become disadvantaged. Second, emptying process – the generation of peak flows greater than anticipated in intermittent supply pipelines creates increasing pressure losses denying users located faraway adequate supply. Overall, the issue of inequity at distribution level is mostly associated with water scarcity; when water supply is limited, competition is generated among users.

Different ways of measuring equity (or inequity) of water distribution have been suggested in the water management literature, where many of these studies focused on irrigation water systems (e.g., Garces 1983; Sampath 1988; Elawad 1991; Indra *et al.* 1995). Range, relative mean deviation, variance, coefficient of variation (CV), Gini coefficient (based on economic literature on equity in income) and Theil's information measure are some useful positive measures of equity measures (for irrigation system performance evaluation) reported by some authors (Sampath 1988; Fuard *et al.* 1992). These statistical measures are fairly easy to determine and could be used by decision or policy makers. The CV of spatial distribution of water to farm plots was employed as a measure of inequity in irrigation systems (Molden & Gates 1990). By this measure, the target value is 0.00 and a small (minimised) value of CV indicates an improved water distribution to all farm plots. Indra *et al.* (1995) also evaluated 1 – CV as a measure of equity in irrigation systems, in which a value close to 1.00 represents improved water distribution. Both approaches produced good results.

Similarly, the above measures of dispersion could be adapted to evaluate equity issues in intermittent water supply systems. Equity measures for intermittent systems should be designed with the kind of situation at hand (e.g., water-deficient system). The objective of any equity measure for intermittent systems must seek to determine the deviations in actual quantities of water delivered to users throughout a distribution network.

METHODOLOGY

Example distribution network and model formulation

The example network (Figure 1) is from the literature and its data can be found in Gupta & Bhave (1996) and Ang & Jowitt (2005). The network has been used by researchers to demonstrate pressure-dependent demands in water distribution. The network consists of a source tank, four demand nodes at 1,000 m apart and four pipes in series, and total length of 4,000 m. The source tank has an elevation of 100 m above ground level. In this study, the network is modelled as an intermittent system using a

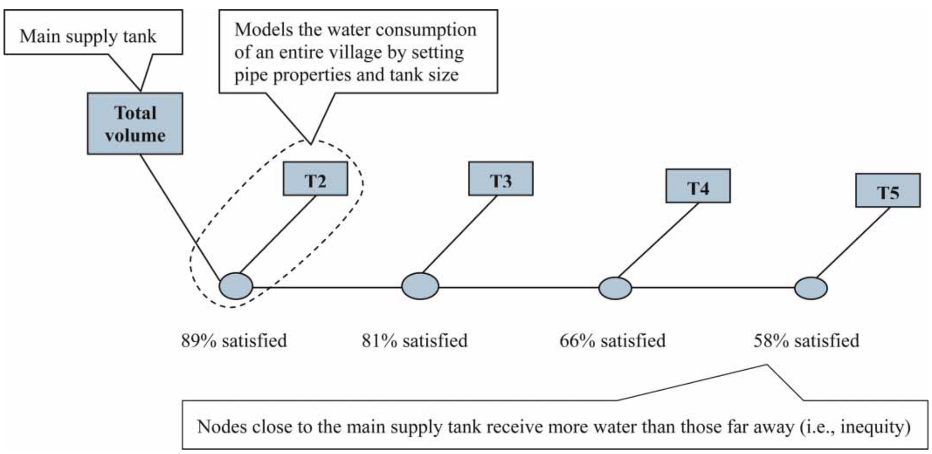

Figure 1 | The baseline scenario.

simulation tool. Node demands are modelled through the use of 'equivalent tanks' (discussed later), where T2, T3, T4 and T5 represent original node demands of 2,877.12, 2,885.76, 4,320.00 and 1,442.88 m^3, respectively. As shown in Figure 1, T2–T5 refers to consumer (or private) tanks. Water is supplied from the main supply tank to all four nodes, each representing a group of consumers of specified population with a demand allocation of 100 L h^{-1} d^{-1} for a fixed supply.

The required amount of water to satisfy daily demands is 11,525.76 m^3, but a fixed volume of 8,640 m^3 (i.e., 74.963% of 11,525.76 m^3) is assumed to be available for supply, causing a deficit of 2,885.76 m^3. This assumption is applicable for this study because the emphasis is on supplying limited water under a water scarcity scenario. Therefore, water is supplied intermittently, creating problems of competition and inequitable delivery. Figure 1, the base scenario, shows the percentage of 'demand satisfaction' at each node. Demand satisfaction in this context is the quantity of water delivered to each consumer node, expressed as a percentage of 8,640 m^3. A value of 100% means that demand at a node is fully satisfied and a lower percentage indicates a poor satisfaction level. The need for strategies to improve the situation and ensure equitable supply therefore arises, which is an optimisation problem.

Model formulation

Analytical procedures comprising simulation (EPANET2), optimisation (GANetXL), and visual basic (VBA) programming are applied to select desired solution(s) regarding two objectives: equity and cost. GANetXL is used with EPANET2 to evaluate the fitness of solutions for a given set of decision variables and EPANET2 exposes its application programme interface (API) in the form of a dynamic link library (DLL) to invoke its functions from the VBA. GANetXL is a decision support system (DSS) generator for multi-objective optimisation of spreadsheet-based models, which addresses some of the difficulties associated with the development and application of model-based DSS in water engineering practice (Savić *et al.* 2011). The relevance of GANetXL and EPANET2 to the modelling is discussed in the sections 'Simulation model' and 'Multi-objective optimisation', respectively.

Optimisation model

Equity of water distribution

Equity refers to a measure of spatial distribution of (drinking) water over a distribution network (Elawad 1991). Equity must be well defined to enable existing intermittent systems to be rehabilitated well. This study defines equity as being quantification of actual volume of water delivered at specific locations (i.e., nodes that represent consumers), and any deviation among the nodes measures the level of equity. This is a measure of spatial uniformity, describing the extent of variability in relative water delivery from node to node over a water distribution network. To ensure equitable water delivery, minimisation of variation (inequity) among consumer nodes which is equivalent to maximisation of equity is a main objective function. The proposed equity measure is expressed as:

$$D_E = \text{Min} \sum_{i=1}^{n} |(\%Qav - \%Qs)| \qquad (1)$$

where D_E (%) = deviation of equity. It represents the absolute value of summation of deviations (variations in water delivery) of percentage of total water supplied to each consumer node from the percentage average. This sum represents inequity among consumer nodes in the distribution of the 8,640 m^3 of water. Therefore, the closer the value of D_E is to zero, the greater the level of equity in water distribution. n is the number of consumer nodes in the water distribution network. Qs(%) is the volume (m^3) of water delivered to each consumer node expressed as a percentage. It is the ratio of actual amount of water received to the amount required. Qs is a supply indicator which is computed for each consumer node.

Qav (%) is the percentage average volume of water delivered to all consumer nodes in the network. Thus, Qav is expressed as the average of $\%Qs$ for all consumer nodes. Qav is what every consumer node should be getting for the fixed supply. Thus, as a good level of equity is achieved (say $D_E = 0\%$), consumers receive the same level of demand satisfaction and vice versa (see Table 2).

Cost

The cost of each feasible solution includes the capital and installation costs of elevated source tank(s). The cost of a tank is expressed as a function of volume and is from Centre for Water Systems (2004). Intermediate tank sizes are considered in this approach, and corresponding costs can be interpolated from tank sizes and costs. To generate affordable solutions, minimisation of cost which is expressed as a non-linear function, is considered as the second objective function:

$$C = \text{Min}[164377\ln(v) - 789739] + n \tag{2}$$

where C = total cost of tank(s) in US dollars ($); ln = natural log; v = size (m^3) of tank; n = cost of transportation and installation, and is likely to be variable and site specific.

The proposed multi-objective optimisation model considers both objective functions: minimise D_E and minimise C.

Constraints to the model

The above model is limited by the two following constraints, supply constraint and tank status constraint.

Supply constraint

The quantity of water distributed to the consumer nodes in the network cannot exceed the total quantity of water available for supply. The constraint is a mass balance which must be satisfied for any feasible solution:

$$\sum_{i=1}^{n} V_i = A_w \tag{3}$$

where n = number of source tanks optimised; V_i = total volume (m^3) of n for any solution; A_w = major constraint: maximum availability of water for daily supply (m^3).

Tank status constraint

The status of all the source tanks (T6–T9) cannot be off (0) during the genetic algorithm (GA) runs (Figure 2). The status of the source tanks are simulated using a binary variable, an integer taking the values 1 (on – tank is used) or 0 (off – tank not used). Both values (1, 0) refer to the same node (location); a tank is either on or off during the GA run. A GA generates a population of potential solutions to the optimisation problem via iterative randomised processes of selection, crossover and mutation (see Goldberg 1989; Savić et al. 2011). In this way, a GA optimises the objective functions.

The formulated model is a multi-objective nonlinear optimisation model, which can be solved using a GA. GAs have poor ability to handle constraints when applied to water distribution networks (Prasad & Park 2004). Constraints such as mass balance equations are best handled externally by a hydraulic solver. For this reason, the hydraulic analysis of the network is performed using EPANET2, by linking it to GANetXL.

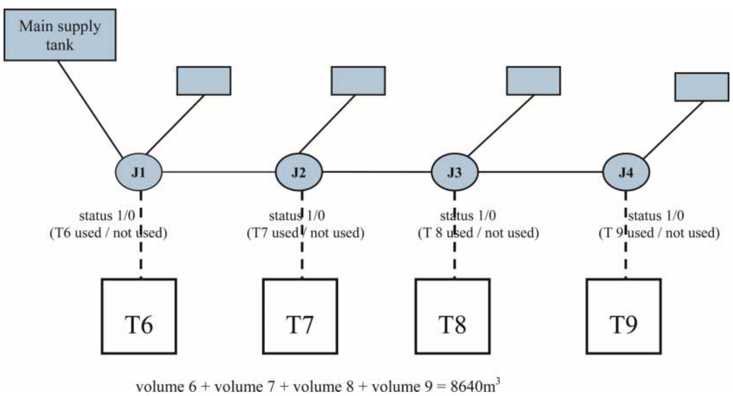

Figure 2 | Optimisation scenario.

Simulation model

The simulation model models the simple serial network (Figure 1) for intermittent supply.

Modelling demand

EPANET2 is a complex hydraulic solver with powerful functions which is adjusted to function as pressure-dependent to model demands under intermittent supply (Ingeduld *et al.* 2006). The hydraulic solver has specified demands at junction nodes. In this study, the approach employed to model node demands is based on an 'equivalent tank' which represents the total demands at a node to ensure pressure-dependency at nodes of the network. A tank will fill up based on the existing pressure at the tank and it is possible to visualise tank fill levels and the development of pressure (and hence the amount of water delivered) at each consumer tank. As tanks of shallow depths offer good results (Trifunovic & Abu-Madi 1999), all consumer tanks are therefore limited in height to 2 m, giving large surface areas. EPANET2 scales pressure between 0 and 2 m. Tank capacities (in m^3) are estimated based on the total demand (i.e. population to be served) at each node. For a cylindrical tank with a varying diameter but a constant height of 2 m:

$$V = \pi r^2 h \tag{4}$$

$$V = \frac{\pi d^2}{4} h \tag{5}$$

$$d = \sqrt{\frac{V4}{h.\pi}} \tag{6}$$

where d = tank diameter (m); V = volume of consumer tank (m^3); h = tank height (m).

Decision variables and coding

There are three types of decision variables for water distribution network models of fixed layout: pumps, pipes, and tanks (Vamvakeridou-Lyroudia *et al.* 2005). In this study, source tanks are the only decision variables considered. To achieve reliable results, the following approach is used to model and optimise the problem. Up to four elevated source tanks are considered by the model and the height (depth) and diameter are defined to determine a tank's capacity. Therefore, all nodes are potential locations for new source tanks. The decision variables for tanks are: status and diameter of each tank, giving a total of eight decision variables for the problem.

New source tanks that are introduced into the water distribution network are simulated and optimised with the use of integer numbers, referring to status and diameters of tanks. As explained earlier, the status of tanks are simulated using binary variables of 1 and 0. The nodes and tanks are defined by their respective indices using EPANET2 programmers toolkit. Tank diameters are simulated using integer values, between 2 and 20, which are scaled to correspond to the supply constraint. This helps to obtain the realistic diameter for each tank, and avoid infeasible solutions. In summary, the optimisation applies to the number, location and capacities of elevated source tanks in the network.

Multi-objective optimisation

A multi-objective optimisation is performed for equity and total cost. In most instances, water engineering decision-making problems – water system designs, rehabilitation/improvement, and operation – need to achieve multiple objectives. This usually involves conflicting objectives such as maximisation of benefits, minimisation of cost, minimisation of risks, maximisation of reliability, etc., which should be optimimised simultaneously (Haimes 1998; Walters *et al.* 1999; Farmani *et al.* 2006).

Many multi-objective optimisation models and tools for treating water engineering/management problems have been developed and applied (Farmani *et al.* 2003). GANetXL is one of these models (Savić *et al.* 2011).

GANetXL combines the power of single objective and multi-objective optimisation using a GA with a graphical user interface that allows users to easily create a DSS application that employs a GA to define water engineering optimisation problems, configure, and execute optimisation runs and analyse generated results through visualisation of Pareto-optimal solutions (Savić *et al.* 2011). For multi-objective problems, GANetXL supports NSGA-II algorithm (Savić *et al.* 2011). The concept of GANetXL is to produce a set of optimal solutions in a Pareto front – largely called Pareto-optimal solutions – in objective and decision spaces. Detailed discussion of GANetXL and its application is provided by Savić *et al.* (2011). The necessary installation package can be downloaded from the Centre for Water Systems' website: http://cws/ganetxl/. In this case, the optimisation scenario entails the possibility of supplying water from up to four source tank(s) – T6, T7, T8 and T9. Thus, a tank is used or not used based on its status and that of the connection pipes, as illustrated in Figure 2. It is worth noting that the main supply tank is not open to optimisation.

APPLICATION OF THE MODEL

The above methodology is applied to measure and to select equity levels for water distribution in a simple water distribution network (Figure 1). The degree of equity among the consumer nodes is calculated based on the amount of water delivered to each node and the locations and capacities of source tanks. Simulation of source tanks for optimisation within a GA is complex, involving several decision variables (Walters *et al.* 1999), which have effect on the objective function value (Vamvakeridou-Lyroudia *et al.* 2005). In order to simplify the optimisation problem the following assumptions are made: (1) the source tanks (T6–T9) are cylindrical in shape; (2) the height (depth) of each tank is fixed at 5 m; (3) the volume of each new (elevated) source tank is effective storage, which provides acceptable pressure in the network; and (4) each source tank empties its contents within a 24-hour extended period simulation.

These assumptions are applicable for this methodology because the emphasis of the study is on equity in water delivery with respect to optimal location and capacities of source tanks. However, the model will work fine with an increased number of decision variables without a need for complex coding.

The methodology for the optimisation problem defines the objective functions, decision variables, constraints and any relationships among these variables. An Excel spreadsheet file with a worksheet named 'Problem' (referred to as Excel spreadsheet model) defines the optimisation problem, stating cell locations of the decision variables, the objective functions and the constraint of the problem. Microsoft Excel spreadsheet, as used in this study, offers various chart options to enable visualisation of the decision space. During the optimisation run(s), visualisation of the decision space is by an optimisation progress form which displays generated solutions in the form of a chat containing values of objective functions, penalty functions, and decision variables. The simulation tab of GANetXL calls EPANET2 to evaluate fitness of organisms through a VBA macro. The water distribution network is simulated using EPANET2 which determines the water levels (tank filling) in the four consumer tanks. These water levels (equivalent to pressures) are read into the 'Problem' sheet of the excel file during the optimisation process. From these water levels, the amount of water delivered to each consumer node is calculated, from which the equity objective is computed automatically. Results from the optimisation run(s) are automatically saved in a separate worksheet of the same spreadsheet file at the end of each run.

Steps for model application

The steps for applying the proposed methodology to multi-objective intermittent water distribution optimisation are suggested as follows:

1. A number of solutions are produced at each generation by the DSS generator, GANetXL.
2. For each solution, the water distribution network is solved using EPANET2 in order to select the number of source tanks, compute the capacity of each source tank, and compute the amount of water in the consumer tanks.
3. From step 2, the objectives of equity and total cost are automatically calculated, using Equations (1) and (2), respectively.
4. Steps 1, 2, and 3 are repeated for all solutions in any single generation.
5. All solutions (say X) together with their respective total cost (C) and equity (D_E) values enter the trade-off procedure of the GA. This is to ascertain the Pareto-optimal curve and selection for reproduction to the next generation.

6. Recombination and mutation occur, and a new generation of solutions is produced. GANetXL offers the flexibility of selecting different mutation and crossover operators and probabilities.
7. Start from step 1 for the next generation of solutions, until termination criteria for GANetXL are met.

During the optimisation process, it must be noted that, the worst case occurs when the water is distributed to only three consumer/private tanks. In that case, those tanks will be fully satisfied while the disadvantaged tank will receive zero percent supply, giving the worst equity value of 150%. For example, if the limited water (8,640 m^3) is supplied to only T2, T4 and T5, the worst equity value of 150% is generated. This is undesirable. The optimisation methodology, therefore, tries to avoid this situation by minimising this maximum value, as demonstrated in this study.

RESULTS AND DISCUSSION

Different equity measures and total costs are generated by applying the above methodology. By optimising source tanks' locations and capacities, some control is imposed on the amount of water delivered to each consumer tank (node), hence the determination of equity levels. Percentages of water demand satisfaction of the four demand nodes (T2–T5) of the water distribution network are shown in Table 2 under both base and optimised scenarios. Under the base scenario, when no control was imposed on water distribution, the water delivery favoured consumer nodes close to the main supply tank (Figure 1). But when water distribution control is imposed in the application of this methodology as in Figure 2, the distribution of the scarce water resource (8,640 m^3) tends to be more equitable (see Tables 1 and 2).

Solutions of different values of equity and cost are shown in the generated Pareto trade-off curve in Figure 3. They are extracted from the Pareto-optimal curve generated by the twin-objective optimisation. The details of the total costs, equity values, and number of optimised tanks and their respective capacities and locations of the solutions are presented in Table 1. The 'best' Pareto-optimal front in Figure 3 is chosen following several test runs. It is produced

Table 1 | Proposed solutions

Solution	Tank(s)/ capacities (m^3)	Tank(s) location	Equity (%)	Total cost ($)
1	T7 – 8640	J2	25.56	705,200
2	T7 – 8273 T9 – 367	J2 J4	21.59	883,897
3	T7 – 7776 T9 – 864	J2 J4	16.48	1,014,589
4	T7 – 6912 T9 – 1728	J2 J4	11.83	1,109,166
5	T6 – 5530 T9 – 3110	J1 J4	4.19	1,169,105
6	T6 – 5359 T7 – 371 T9 – 2910	J1 J2 J4	3.68	1,344,598
7	T6 – 5031 T7 – 125 T8 – 1129 T9 – 2355	J1 J2 J3 J4	2.85	1,487,233

Table 2 | Demand satisfaction: optimised solution vs. base scenario

		Optimised solutions (%)			
Consumer tank	Base scenario (%)	1	5	6	7
T2	89	76.90	75.47	75.31	75.16
T3	81	85.21	75.97	76.11	76.52
T4	66	69.45	73.31	73.50	73.74
T5	58	67.11	76.87	76.38	75.09
Qav	73.5	74.67	75.41	75.32	75.13

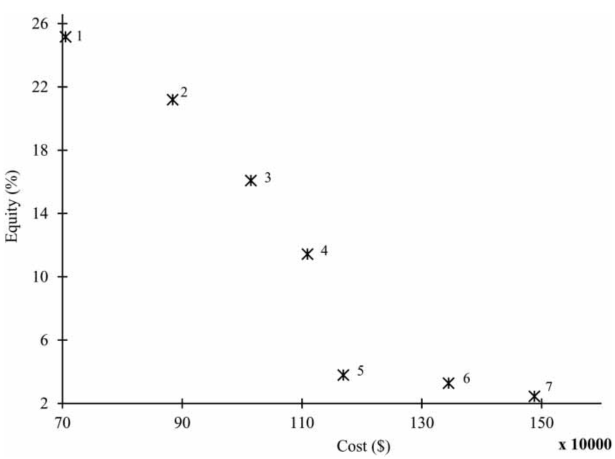

Figure 3 | Equity vs. cost pareto-optimal.

from 2,000 generation runs, a population size of 100, simple multi-point recombination operator with probability of 0.9, and a simple gene mutation operator with probability of 0.125 (see Goldberg 1989 for discussion of terms).

Inspection of the solutions along the proposed Pareto-optimal front reveals that each potential solution has a different number and location of new source tanks. This is due to the competing objectives of equity and cost. Solution 1 is the best in terms of cost and solution 7 provides the best equity function value. There is a sharper change in equity function values from 25.56% in solution 1 to 4.19% in solution 5 (see Figure 3 and Table 1), indicating a good level of equity. However, there is a marginal improvement between solutions 5 and 7. Layouts of selected solutions are shown in Appendix A (available online at http://www.iwaponline.com/jws/062/065.pdf). 'J' refers to junction node as used in EPANET2.

Solutions 1, 5, 6 and 7 representing solutions on the extremities and centre of the Pareto front are compared with the base scenario and among themselves, in Table 2. The table shows the percentage of demand satisfaction, indicating the degree of variation among the demand nodes represented by private/consumer tanks. It also suggests that water delivery becomes more equitable as equity values near zero.

It must be noted that the optimisation problem is solved assuming that the decision variables are discrete (i.e. integer bounded). This limits the number of optimal solutions in the Pareto-optimal set, allowing easy analysis of compromise solutions in the set. Furthermore, the application of GANetXL generates a set of optimal solutions to aid the decision-maker to analyse and select the most optimal solution based on equity and budget allocation in this case. In developing countries, cost is a major consideration, the decision-maker may be interested in solutions that do not offer maximum equity, however, meet the budget constraint. The main differences in total costs of the solutions relate to the level of equity and number of source tanks. Thus, improved equity implies the use of more than one new source tank which increases the cost of the solutions. A tank's cost is primarily a function of its capacity.

However, the emphasis is the ability of the methodology to improve equity rather than putting too much emphasis on cost in this case. This is because the costs of elevated tanks (and tanks in general) are highly site-specific and the comparison must be made on a case-by-case basis. In a practical situation, the choice of a solution must be balanced with social concerns. Given that high inequity is a recipe for social conflict (Indra *et al.* 1995), public anger and non-payment of bills, the choice of a solution must guarantee a good level of equity. In this model, the choice of a solution means that the decision-maker becomes aware of the amount of water to be delivered to each demand node (four nodes in this case) and the number and capacities of source tanks from the spreadsheet model or the simulation model.

CONCLUSION AND FUTURE WORK

The paper describes an optimisation methodology for measuring and improving equitable water distribution under intermittent supply. A spreadsheet-based multi-objective optimisation model, GANetXL, for minimising inequity and cost is illustrated. The paper also shows that EPANET2 can be adjusted to model intermittent water systems successfully. The applied methodology in this case suggests that equity among water consumers (inter-consumer equity) can be improved through optimal location and capacities of elevated source tanks in an existing intermittent water system. This methodology offers a set of solutions to enable the decision-maker to arrive at a final decision based on economic or social factors. In this case, the best equity level is associated with the highest total cost and vice versa. A balance must be made between consumer concerns on equity and the water utility's financial strength.

Future research would focus on application of the methodology to a large and typical intermittent water supply system, while adding other performance measures, including reliability and efficiency of supply, water quality and individual costs.

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