Multi-objective optimization for improving equity and reliability in intermittent water supply systems

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ABSTRACT

Intermittent water systems suffer from several drawbacks such as unfair distribution among users, low reliability and poor water quality. Given limited water and financial resources, making decisions for improving intermittent water supply (IWS) becomes a complex process. The paths to continuous supply are a priori undefined, however, the provision of efficient service is crucial. In the scientific literature, limited research addresses how to improve intermittent systems, to enhance the current service while transitioning to continuous supply. A multi-objective optimization (MOO) tool using a genetic algorithm has been developed to assist in investment decision-making. This approach uses multiple cost-effective intervention options to maximize equity and reliability while minimizing cost implications in an IWS system. The costs in such interventions include expenditure on pipe replacement, booster pump and elevated tank installation. The approach was first tested on a benchmark Hanoi synthetic network, and then applied to the water distribution network of Milagro (Ecuador). The developed tool reveals the extent to which equity and reliability can be driving objectives, and how they can be factored into decision-making. The application of the MOO tool in intermittent systems in order to improve existing distribution networks with strategic infrastructure addition can provide greater equity and reliability.

Key words | equity, genetic algorithm, intermittent water supply, multi-objective optimization, reliability

INTRODUCTION

Over half of the world’s human population currently lives in urbanized areas, and the projections suggest that by 2050, two-thirds of the world’s population will be urbanized (United Nations Department of Economic and Social Affairs Population Division 2018). Rapid increase in population is a major concern in developing countries since they have both financial constraints and infrastructure deficit. Sustainable development of urban infrastructure to cope with increasing demands is critical to ensure that the benefits of urbanization are equitably shared among the residents of that space. In that spirit, the Sustainable Development Goal 6 (SDG 6) of 2014, for instance, buttresses the right to water, and aims to ensure availability of water and sanitation for all. The first target of the SDG6 is achieving universal and equitable access to safe and affordable drinking water by 2030 (United Nations 2015). The aim is to set up ‘safely’ managed drinking water services, where ‘safely’ is defined in terms of accessibility, availability and the quality of the supply service (WHO & UNICEF 2017). Kaminsky & Kumpel (2018) point out that although access to water has improved over the years, there is some indication that the average

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time of water supply is actually declining in many parts of the world.

Historically, the design of water distribution has been demand driven. A water distribution system is required to provide pressurized continuous supply. However, because of limited water resources and/or inadequate infrastructure, water supply systems are unable to support current urban growth in many parts of the world. As a result, the supply in some systems has become intermittent. Intermittent supply means that the water supply service is frequently interrupted in space and time. The Joint Monitoring Report (2017) reflects that 37% of urban populations across the globe who have access to water on their premises have it available at least 12 hours/day or have sufficient supplies from the previous week (WHO & UNICEF 2017). Because of technical and economic challenges, several utilities have embraced Intermittent Water Supply (IWS) systems as a solution to deal with supply-versus-demand deficit. The IWS has gradually turned to an operational norm in some cases. Moreover, infrastructure inadequacy also becomes evident as impacts of reticulation extensions due to urban expansion are rarely tested on the entire network (Galaitisi et al. 2016). For instance, an analysis of the conversion of continuous water supply into intermittent supply in Cyprus revealed the negative impacts on the integrity of the system’s operation and maintenance with the reverse process (i.e. from intermittent to continuous) being rather complex (Charalambous & Laspidou 2017). Due to limited financial support in such cases, it is crucial to investigate optimal resource allocation for maximum benefit in the long run with minimal expenditure.

Multi-objective optimization (MOO) has been used to improve water supply systems while keeping consumer requirement in view (Farmani et al. 2005; Prasad 2010). Genetic algorithms have been instrumental in such optimization processes. Preceding work on intermittent water supply has focused on causes (Simukonda et al. 2018), performance (Andey & Kelkar 2007) and impacts (Agathokleous & Christodoulou 2016; Galaitisi et al. 2016). These authors recommend various structural and non-structural measures to improve intermittent supply. However, implementation of structural interventions is complex since many solutions are possible; therefore, further analysis is required to ensure the most optimal combination(s). How to choose the optimal technical intervention for an individual case has not yet been adequately tackled. However, it must be noted that recent developments have improved the modeling of water systems so as to accommodate not only demand driven simulations but also pressure dependent demand simulations. Optimizing a water distribution network’s ability to equitably provide water according to requirement and ensure reliability in service can be achieved through a combination of a Non-dominant Sorting Genetic Algorithm II (NSGA II) and the Water Network Tool for Resilience (WNTR).

This paper proposes that, in addition to investment costs, equity and reliability be treated as the primary objectives in improving intermittent systems. Equitable distribution refers to delivery of fair shares throughout the system (Ameyaw et al. 2013; Ilaya-Ayza et al. 2017). Fairness can be viewed from different perspectives, i.e. in terms of volume or time of supply as alluded to by Molden & Gates (1990). Reliability refers to the ability of the network to provide consumers with adequate quantity and quality of water supply under normal and abnormal conditions (Xu & Goulter 1998; Farmani et al. 2006). Ameyaw et al. (2013) and Gottipati & Nanduri (2014) outline the challenge to equitable distribution in IWS as low pressures affect the temporal and spatial distribution of the water. Distribution is often impacted by network configuration, customer location, volume of supply, duration and schedule, among other factors (Ilaya-Ayza et al. 2018). As Shamir & Howard (1981) have suggested, in order to improve reliability, the considered resilience factor is positively impacted by introducing additional redundancy. The resilience index introduced by Todini (2000) considers hydraulic reliability and water availability when a system fails. Investment costs are critical for decision-making; if solutions are expensive, they may not be executed. The possible investment costs in the networks considered in the study include costs for pipe replacement, pump installation and tank construction.

**METHODOLOGY**

MOO is computer-based solving by mathematical programming. It can be employed to improve the performance of a physical system by adjusting the system’s components based on certain performance objectives. The resulting
solutions can be divided into two stages, objective function satisfaction and the trade-offs appropriate for the decision-maker (Chiandussi et al. 2012). NSGA II was developed by Deb et al. (2002). One of its main advantages is a reduction in computational time in solving MOO because of relatively low computational complexity. In other words, NSGA II is a fast-non-dominated solution ranking method. Other advantages include a good diversity of solutions and uniform distribution of Pareto solutions. However, there are some disadvantages as well: the algorithm can suffer premature or stretched time convergence, there may not be a guaranteed optimum and there is a probable loss of good solutions. A multi-objective approach was therefore used in this case to find the optimal solution given the following objectives: equity and reliability versus cost of improving the distribution network.

Three intervention options were used to improve the set’s optimization objectives. The first option is to replace old pipes with newer pipes of either the same or larger size in order to improve flow. New pipes have improved roughness. Option two combines pipe replacement with a booster pump to enhance pressure. The third option includes option two with the addition of an elevated tank targeting steadier pressure.

The Uniformity Coefficient of a water network is an indicator of fairness, and its value lies between 0 and 1. Gottipati & Nanduri (2014) introduced the formulation derived from a nodal supply–demand ratio. Ilaya-Ayza et al. (2018) further expanded the equation as shown in Equation (1):

$$ UC = 1 - \frac{\sum |S_p - S_{av}|}{S_{av} \times n_e} $$

where $S_p$ is the supply–demand ratio obtained by dividing $Q_s$ which is the supplied flow and $Q_d$ which is the demand on the node. $S_{av}$ is the average supply ratio and $n_e$ is the total number of nodes. Zero indicates no equity and an increase to 1 indicates improvement to the best possible value. The reliability surrogate is presented in Equation (2), where the resilience index ($I_r$) is expressed as:

$$ I_r = \frac{\sum_{i=1}^{n} node q_i (h_{ava, i} - h_{req, i})}{\sum_{j=1}^{n} reservoirs Q_j H_j + \sum_{k=1}^{n} pump (P_k / \gamma) - \sum_{i=1}^{n} node q_i h_{req, i}} $$

where $q_i$ is the nodal demand, $h_{ava, i}$ is the average head at the node $i$, $h_{req, i}$ is the minimum allowable hydraulic head, $Q_i$ and $H_i$ are the discharge and head (respectively) at each reservoir, $\gamma$ is the specific weight of water (1,000 kg/m$^3$) and $P_k$ is the power supplied by the pumps in the network (Todini 2000; Farmani et al. 2006). The continuous range for the equation is from 0 to 1. Zero represents a poor performance while 1 is the most ideal performance value. Since both the objectives are crucial in a network functioning with intermittent supply, the two objectives have been combined. The Weighted Sum Method (WSM), used here, allows for the flexibility to maximize one objective over the other, depending on need, and each with a weighting factor ($w_1$ and $w_2$) to form a single objective function, as is shown in Equation (3):

$$ \text{maximize Equity & Reliability} = w_1(UC) + w_2(I_r) $$

The total cost is the sum of the cost of pipe replacement, civil and equipment cost for the pump station and the cost of the elevated tank. To the cost objective, a penalty is added as a constraint (see Equation (4)) to assist the NSGA II in solving the problem. The objective function for the cost is expressed in Equation (4):

$$ \text{minimize Cost} = C_{pipes} + C_{pump} + C_{tank} + \text{Penalty Constraint} $$

where $C_{pipes}$ is the cost of pipe replacement, $C_{pump}$ is the cost of the pump and $C_{tank}$ is the cost of the elevated tank. The penalty function is expressed in Equation (5):

$$ P = \begin{cases} \infty (|h_i - h_{\text{max/min}}|) + \beta, & (if: \ h_i > h_{\text{min}}, \ h_i < h_{\text{max}}) \\ 0, & \text{otherwise} \end{cases} $$

where $P$ is the penalty constraint, $h_i$ is the nodal pressure, $h_{\text{min}}$ and $h_{\text{max}}$ are the minimum and maximum pressure head thresholds, and $\alpha$ and $\beta$ are penalty parameters (Kim et al. 2017). As nodal pressure is the major challenge in intermittent supply, a consideration of the level of deviation to the required range, as defined by the penalty factors, is
critical. Pressure dependent demand simulations enable the identification of nodes with undesirable pressure deficit.

The optimization tool is comprised of the NSGA II coupled with an EPANET hydraulic engine embedded in the WNTR. WNTR, developed by Klise et al. (2017), is a Python package that has the ability to create, simulate and analyse water distribution networks. One of its abilities is the calculation of the Water Service Availability (WSA). This is the ratio of the actual water supplied to the node versus the expected nodal demand. WSA can be both in space and time. In the current case, the WSA in space is used to calculate the supply ratio for each node after a pressure dependent demand simulation. The results obtained aided in deriving the UC of the chosen distribution network. An additional ability is the calculation of the hydraulic reliability of the network using the resilience index.

**Optimization parameters**

Various parameters were used to test the performance of the optimization approach. Initial seed population and the number of generations are primary parameters. These and other parameters are listed in Tables 1 and 2.

**The Hanoi network**

There are several benchmark networks available in the literature that have been used for optimization. Among them is the Hanoi water distribution network, proposed by Fujiwara & Khang (1990), and it has been employed by many researchers (Vairavamoorthy & Ali 2000; Chandapillai et al. 2012; Soltanjalili et al. 2013; Sivakumar et al. 2013). The network, as illustrated in Figure 1, is three-looped and has 32 nodes linked with 34 pipes. The Hazen–Williams coefficient for all the links is 130. The diameters of the pipes in this network are between 12 inches (305 mm) and 40 inches (1,016 mm). The minimum flow requirement in this network is 5 m³/h.

The initial characteristics of the network resemble nodal supply deficiency. Optimization works towards fulfilling the nodal demand using the available resources. Equation (6) is used to calculate the pipe replacement cost, and is built on values provided by Iglesias-Rey et al. (2007). The cost of the Hanoi initial network is based on the pipes’ diameters (m) as:

\[
\text{Cost}_{\text{pipe}} = 271.71 \times \text{Diameter}^{1.5}
\] (6)

Marchionni et al. (2016) have proposed the following Equations (7)–(10) for calculating the cost of the pumping station and elevated tank:

\[
C_{\text{cwp}} = 11603 \times P_k^{-0.53}
\] (7)
where $C_{\text{cwp}}$ is the civil works cost, and $P_k$ is the hydraulic power (kW) used. Equation (7) considers pump wattage raised to a negative power of a factor. Other equipment cost, which includes the pump, is expressed in Equation (8):

$$C_{\text{ep}} = \frac{42853}{P_k^{0.59}}$$

where $C_{\text{ep}}$ is the equipment cost while $P_k$ is the same as for Equation (7). The sum of the two equations is the pump cost. The investment cost for the elevated tank also has two components. The cost of civil works ($C_{\text{cwt}}$) is expressed as:

$$C_{\text{cwt}} = \frac{358.45}{V^{0.72}} \times h^{0.58}$$

where $V$ is the tank volume (m$^3$), which is applicable to a range of volumes from 100 m$^3$ to 500 m$^3$, as shown in Table 2, and $h$ is the height of the tank (m). The equipment cost for the elevated tank $C_{\text{et}}$, which uses similar parameters, is as shown below:

$$C_{\text{et}} = 78.01 \times V^{0.46} \times h^{0.18}$$

The Milagro network

San Francisco de Milagro is the second largest city located in the Guayas province, Ecuador. The city's urban area is about 23 km$^2$, but the water coverage is only 16 km$^2$. The population of the city is 147,000, based on current statistics and the number is projected to reach 193,000 in next 25 years. The main source of water is groundwater, extracted from wells that dot the city. The water supply system operates intermittently due to low or no pressure during the day. The lack of pressure is caused by the network's topology and limited distribution pipe sizes that cannot support the current demand. Other possible causes may include untested network expansions, leakage and illegal
connections. In this study, the network was sectorized into four supply areas and the most affected area was selected for further study. The simplified network of the chosen sector is presented in Figure 2. It is composed of 63 pipes, 62 junctions, six reservoirs (water wells), two pumps, two tanks, and seven flow control valves. The flow control valves regulate the volume of water to mimic groundwater well yields. The simplification of the network is conducted using a WaterGEMS skeletonization tool.

Three intervention options were evaluated as part of the optimization process, and are as follows.

**Intervention option 1: pipe replacement**

The growth of water distribution systems over several decades and centuries is guided by population growth and economic development. Such developments may often result in continual untested network expansion and also limited pipe rehabilitation programmes. The pipe replacement approach aims at improving the current network in terms of equity and reliability. If head loss is reduced, the flow could be improved.

**Intervention option 2: pipe replacement and inline booster pump**

One of the factors causing equity and reliability challenges in a water system is the lack of adequate pressure, which results in the limited (often deficient) volume of the supplied water. Therefore, the addition of a pump can aid in increasing the available pressure in the system. The Todini Index is used to test the reliability of the additional pressure made available to the system. Pump selection is based on the expected normal flows and the required head in the network. In the current case, the head requirement in Hanoi is 30 m; therefore, the lowest pump was set at +50 m.

**Intervention option 3: pipe replacement, inline booster pump and elevated tank**

In addition to the interventions outlined in options 1 and 2, an elevated tank is added in option 3. The pressure factor is considered in the second scenario and an elevated tank can provide buffer capacity and a steadier pressure head. However, a pump is still required to fill the tank. There is a
difference between the pump used for the elevated tank and the pump used with option 2 since the former has a lower head and is only required to satisfy a single tank junction. To ensure that the elevated tank has an impact in the Hanoi network, in which all the nodes are at the same level, the minimum elevation was set at 35 m.

NSGA II can be applied for water system optimization despite some disadvantages. The identification of the objectives, functions and other parameters is critical to the optimization process. The validation of a developed tool on a benchmark network measures the performance of the approach on a known system. Several approaches have to be considered to test the extent of the performance of a tool. Application in a case study gives insight into possible intervention solutions.

RESULTS AND DISCUSSION

The main objective of this study was to develop an MOO approach for the improvement of intermittent water supply. Equity and reliability were a combined objective and minimal cost was the second objective. A penalty function was added to the actual infrastructure cost to enhance the identification of optimal solutions. The three approaches presented in the preceding section were applied to both the Hanoi network and the selected section of Milagro.

The results for each of the approaches, considering the same optimization setup (cf. Table 1), are presented below.

Method verification: Hanoi network

A graphical representation of cost versus equity and reliability for pipe replacement at the end of the optimization process is presented in Figure 3. The figure also reflects the individual results for the equity indicator, UC and the Todini Index.

Figure 3 shows the combined objective functions of equity and reliability yield to be just above 0.5. However, a closer look shows values of 0.8 to 1.0 for UC, and below 0.1 for the Todini Index. The cost value is within the appropriate value for the Hanoi network at $6,081,000 (Iglesias-Rey et al. 2007). The second approach (pipe replacement in the seed population along with a booster pump) was also evaluated. The results for this approach are shown in Figure 4.

Figure 4 shows a slight increase in the function for equity and reliability when a booster pump is included in the solution. UC continues to be high and an improvement in the Todini Index can be observed. Total cost values increase significantly.

The third approach includes initial pipe replacement with an additional booster pump and an elevated tank being fed by the pump as well. The results are presented in Figure 5.

Figure 5 shows a continued increase in the total cost while most of the solutions indicate high UC. A clear improvement in reliability is reflected by the Todini Index, with the values above 0.2. There is a reduction in the combined cost with the additional infrastructure, which
indicates that fewer nodes are deviating from the set threshold pressure range.

Equity and reliability were equally weighted and the impacts they have on each other are evident. Both are highly vital in an intermittent system because consumers perceive the service to be unreliable as well as unfair. The combination of equity and reliability ensures that as UC checks if the nodal demand is satisfied, the resilience index considers the availability of excess energy in case of any changes in the flow regime that cause a failure of service. Attaining equity of one is possible using the approach; however, the improvement of reliability requires an additional pressure head to be introduced into the system. Improving reliability with pressure-boosting systems can only work to a certain extent, since pipe redundancy plays an important role as well.

The Milagro network

The case study network was divided into sectors from which Las Pinas (cf. Figure 2) was selected for optimization. The hydraulic simulation yielded the objective values listed in Table 3 before intervention.

The reliability indicator in Table 3 reflects the optimum figure which can be attributed to the system having multiple sources; however, the equity component stays below 50%.
As seen in Figure 6, a marginal improvement of the Equity and Reliability function by 0.01 can be attributed to pipe replacement. It can also be observed that there is a greater improvement by 0.4 in the UC. This improvement of UC, however, reduces the Todini Index values to below 0.7. Total Cost with Penalty indicates there are several nodes not meeting the 30 m minimum pressure threshold.

There is a considerable decrease in the Equity and Reliability function with this option. This can be attributed to lower reliability, as reflected in Figure 7. The improvement in UC to over 0.8 causes a reduction in the Todini Index value to 0.17. The cost function increases with the addition of the pump, which also impacts the acceptable pipeline design.

Figure 8 shows further reduction in the combined objective function and an increase in the total cost. The costs of the pump and the elevated tank have a major effect on the overall cost, as can be calculated using the investment Table 3 | Output values for the base Las Pinas sector

| Description          | Values |
|----------------------|--------|
| Equity & Reliability | 0.71   |
| Uniformity Coefficient | 0.39 |
| Todini Index         | 1.02   |

Figure 6 | Las Pinas population 50 generation 150 pipe replacement only.

Figure 7 | Las Pinas population 50 generation 150 pipe replacement and booster pump.
equations mentioned above. Up to 70% of the investment cost is related to additional infrastructure but excludes pipe replacement. Reliability seems to suffer more as additional power is added in the network, and improvement of nodes in parts reduces the head in others. Alternatively, if a lower threshold of pressure ($P_{\text{min}}$) is required for the optimization, reliability can be improved.

Although a marked reduction in the equity and reliability was observed, there is improvement in the overall distribution of water as UC has increased considerably. Investment in pipe replacement is lower with the inclusion of pressure-boosting infrastructure when pipes with smaller diameters are utilized. The location and the capacity of the pump and the elevated tank have an impact on network reliability, as they (the pump and tank) affect the flow’s direction. The reliability indicator’s results for the Las Pinas network are negatively affected with the optimization process. This could be because excess energy from the pressure-boosting infrastructure is concentrated on a few nodes and not redistributed because of the partial looped configuration. The network nodes, which had previously lower head, show significant improvement when pumps and tanks are included.

**CONCLUSIONS**

The approach presented enables the optimization of intermittent water distribution systems considering equity, reliability and cost. Fair distribution of available water can be improved with pipe replacement in both the Hanoi and Las Pinas networks. However, in the benchmark network (i.e. Hanoi), additional pressure-aiding infrastructure may not be necessary due to its flat topography. In the application case (Las Pinas), on the other hand, such additional infrastructure improves the furthest nodal pressures as its topography is different. Equity improvement impacts the overall reliability of the network; therefore, a combined analysis is critical to reveal the extent to which they affect each other. Engineering expertise is essential to ensure the right interpretation of the optimization results, which will eventually lead to a feasible design being identified and implemented.

The results show the consistency of the method when applied to a looped network, since reliability improves when flows are rerouted. However, for weakly looped networks there is a lower level of reliability, which reveals the limitations of the application of the resilience index in the partially looped Las Pinas network. The parameters for the pipe, pump, and the elevated tank have to be carefully selected, considering a priori knowledge of the network. The location of the pumps and tank is complex; therefore, further analysis of the optimization mechanisms needs to be carried out to find the most suitable approach for a particular system. This process is also deeply dependent on the information provided by the water service provider.

Further research in developing solutions for locating and sizing the optimization of booster pumps, which can

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*Figure 8* | Las Pinas population 50 generation 150 pipe replacement, booster pump and elevated tank.
be included in the initialization of the seed population in a
distribution system, is required. The optimized solutions
from one intervention option may be used as seed popu-
lation for the following options. The researcher also needs
to consider an alternative reliability indicator besides
excess energy. This may include other factors such as mul-
tiple sources and/or pipe uniformity, which can provide
more insight into the overall improvement of the distri-
bution network.

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