2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14175

MULTI-STAGED CONVERSION FROM INTERMITTENT TO CONTINUOUS WATER SUPPLY

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Abstract

About 2.2 billion people worldwide lack access to safely managed drinking water. These include approximately 1.3 billion, mainly in South Asia, Latin America, and Africa, that receive water for domestic purposes through piped networks for only limited durations in a practice known as intermittent water supply (IWS). The complex interactions of demographic (social), technological, economic, environmental, and political factors are the primary causes of IWS. They lead to higher water demand and Non-Revenue Water (NRW) water than supply systems' capacity. Under IWS, the limited water resources are distributed to various zones at different times. In this way, as many consumers as possible can access water and water losses through leakage can be reduced. However, IWS poses high operation costs and NRW to water utilities, coping costs for water storage and treatment facilities to consumers and inequitable water supply, health problems and effects on children's school activities to society. As a result, there is a great interest worldwide in converting from IWS to Continuous Water Supply (CWS). Achieving CWS is challenging for systems that are significantly degraded and require huge investments. Consequently, the conversion to CWS should be gradual and staged. Using the given pilot network, this study proposes an approach for converting from intermittent to continuous water supply by improving the network infrastructure in a phased manner over a period of 5 years according to the limited available financial and water resources. For hydraulic simulations, EPANET 2.2 was used. First, the network input file was modified by placing the leaks to their exact locations. Before starting the rehabilitations, the network operation was assessed. Rehabilitation was phased in five years and the activities involved were leak fixing, pump upgrades, installation of flow control valves (FCVs) at sources, and pipe replacements. These activities were implemented both manually and using codes developed in R and python. Four major indicators were used to assess the effects of the rehabilitation activities each year. The indicators were the proportion of the number of effective hours a subscriber is served (I1), the volume of water leakage (I3), the proportion of volume of water supplied to users(I4) and the level of equity in supply (I9). Through the staged rehabilitation, I1, I4 and I9 increased from 0.907, 0.757 and 0.733 to 0.995, 0.965 and 0.96 respectively while I3 reduced from 0.504 to 0.302.

Keywords
Conversion to continuous water supply, intermittent water supply, non-revenue water, optimisation, water demand

1 INTRODUCTION

One of the traces of climate change and population growth is the limited water resources that people face in some parts of the world [1]. These coupled with economic and political factors are major causes of Intermittent Water Supply (IWS) practices which can be seen, for example, in South Asia, Latin America, and Africa, where people are not guaranteed to get safe and reliable water [2–4], Under IWS, limited water is distributed to consumers for few hours per day, causing an increase in flow rates and thus high-pressure losses associated with contaminant intrusion [5,6]. Maintaining a continuous pressure level throughout the network facilitates customer satisfaction and helps ensure water quality [3,5,7].

The practices around the world show that a transition from the intermittent water supply (IWS) to continuous water supply (CWS) can be accomplished with service adjustments. As an example, one of the zones in Nagpur, India, was converted to CWS, resulting in a decrease in both non-revenue water and consumption demand in addition to improvement in water quality, and customer service [8]. CWS has been achieved in three cities in Karnataka, India (Hubli-Dharwad, Belgaum, and Gulbarga) with 10 % water savings and an increase in revenue[9]. The phased transition was implemented in Badlapur city in India, considering the water availability and future population [10]. The network was divided into new zones, new reservoir construction was planned to meet future demand, leak detection and activities were carried out. The pressure was managed throughout the network to reduce leakage as well [10].

CWS provides numerous benefits to both service providers and users, including reduced coping costs, improved water quality, efficient usage of water resources, and optimal network operation [9]. However, transitioning from IWS to CWS is a complex and difficult to accomplish task. Despite this, there is a limited amount of literature on the transition from IWS to CWS.

Most of the studies suggested the gradual (zone by zone) transition due to financial burden by focusing on different aspects of IWS and adopting different strategies [11]. The sustainable conversion was examined by [12] by understanding IWS causal factors (the indirect and direct drivers of water demand). Various scenarios (business as usual, consumption demand management, non-revenue water (NRW) management, and holistic) were developed to incorporate the uncertainties linked to the evolution of the causal factors. The holistic scenario was found as the most sustainable one. A conceptual approach was proposed by [13], considering IWS systems designed for continuous distribution but operated in intermittent mode. Unlike [12], relevant technical causes of intermittent operation and the need for hydraulic data and network restructuring were considered. Network restructuring was considered with sectorisation, reduction of water losses and pipe replacement. A theoretical model was designed for improving the IWS zone by zone. The study showed no need for additional water resources to achieve CWS because technical rather than economic and absolute water scarcity [11] was experienced by the network studied.

The studies concerned with hydraulic modelling to achieve continuous supply put stress on different approaches. The provided methods included the rehabilitation of the network's main pipes and optimising pump scheduling [14], optimal scheduling [15] while minimising the valve operations [16], network capacity enhancement with the pipe replacement [17],leakage management [18], gradual transition from IWS to CWS by improving each sector to provide continuous supply at a time until continuous supply is achieved throughout the network. However, there is still a need for a rigorous methodology for converting water distribution systems from intermittent to continuous supply mode .This paper presents a methodology for rehabilitation of a deteriorated network with an intermittent operation originally designed as CWS. The primary objective of this paper is to provide continuous supply to all users and achieve minimum pressure at each demand node. The network was rehabilitated over five years by using a fixed amount for the investment. The actions carried out are leak fixing, pipe replacement, new valve installation, as well as well pump replacement. The effectiveness of the actions taken was ensured with the number of indicators that measure; the volume of water received by each user, pressure levels at demand nodes, the duration of water availability for each user, the leakage volume, and energy consumption. The approach can be applied to improve IWS networks around the world.

The case study and its current problems are presented in the next section, the methodology is then described in detail, and the results are presented with a discussion. Finally, relevant conclusions are drawn in the last section.

2 CASE STUDY AND PROBLEM DESCRIPTION

The network has 3231 pipes and 2859 nodes. The total length of the pipes is approximately 339 km, with the diameters ranging from 20 to 450 mm. The network is fed by six supply sources (natural spring and five wells) with a limited maximum flow rate capacity (300 l/s in total) which remains constant during the simulation. In addition, there are four tanks and seven pumping stations which draw water from the reservoir and wells.

Initially, the network is equipped with several flow and pressure control elements. These are isolation on/off valves, throttle control, pressure reduction, flow control and pressure sustaining valves (TCV, PRV, FCV, PSV, respectively). The existing closed pipes in the initial network is considered to have an isolation valve installed immediately adjacent to the start node in the model.

As with a typical IWS, users have household tanks in this pilot study. Intermittent water supply is caused by uncontrolled consumption, leaks, and reduced capacity. The total average desired demand is 202.77 l/s which varies over the 168 h of a week, but weekly demand remains constant over the simulation. While each node has different desired demand, the weekly demand pattern is the same for all nodes. The peak demand hours are between 08:00 and 15:00, with slight variations each day. The maximum total water demand in terms of flow is 443.17 l/s and takes place during the peak hours. The minimum demand occurs during the night-time (00:00-08:00) with a minimum demand value of 2.29 l/s. This information on the demand variations in the network can help to optimise the network operation and pressure management to reduce the leakage. There are several leaks in the network, and their leakage coefficient ranges from 0.000001 to 0.115240. The volume of leakage in the initial state of the network while all isolation valves are open is 50.4%. The number of leakages remained constant throughout the simulation, but the intensity of non-repaired leakages grew exponentially over the simulation. In terms of water availability and demand, there is sufficient water available to continuously to satisfy the demand imposed on the system. Though, during the peak demand hours, the available flow rate from all sources combined is not enough to cover the momentary peak demand. The gap between total demand flow and available inflow to the network be bridged by utilising the water which is accumulatively stored in the service tanks during low demand periods.

A critical evaluation of the current state of the network was undertaken in order to take action where necessary. The main issues identified in the network are: a) the large elevation differences overall, b) the very high elevations at specific areas which are also further downstream of the main reservoir which feeds the network through gravity, c) the large amount of leakage which is more than 50% in the initial state of the WDN. Figure 1 shows the topography of the network. Hydraulic simulations of the network in its initial state revealed the challenge of maintaining the minimum pressure in certain areas of the network due to the presence of highly elevated nodes. From Figure 1, it can be seen that high-elevation nodes are located around the main source and in the middle of the network around the main distribution pipe. Near the source, high elevated nodes have enough pressure to satisfy user demands. It is difficult, however, to maintain minimum pressure in other high elevated nodes, especially during peak demand periods. In the rehabilitation planning of the 5 years, special attention is given to the areas where there is high leakage and pressure deficiency.

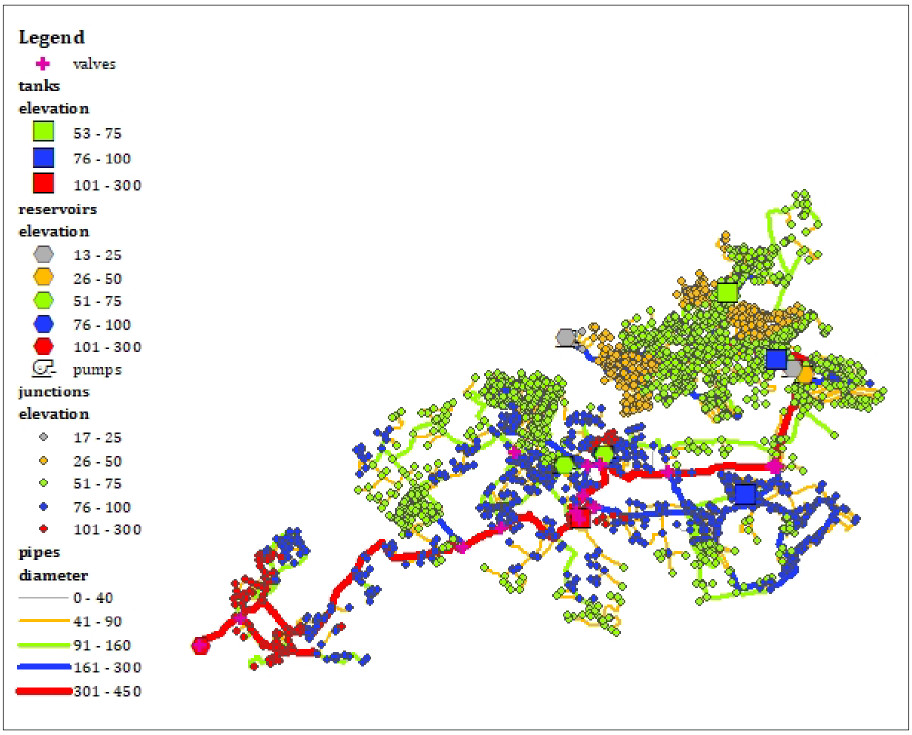

Figure 1 Layout of the case study and elevation of the nodes

Figure 2 shows the average negative pressures in the network. With leaks added to the network, average negative pressures were determined over a simulation period of 168 hours. Figure 2 illustrates the intensity and location of the problems associated with negative pressure.

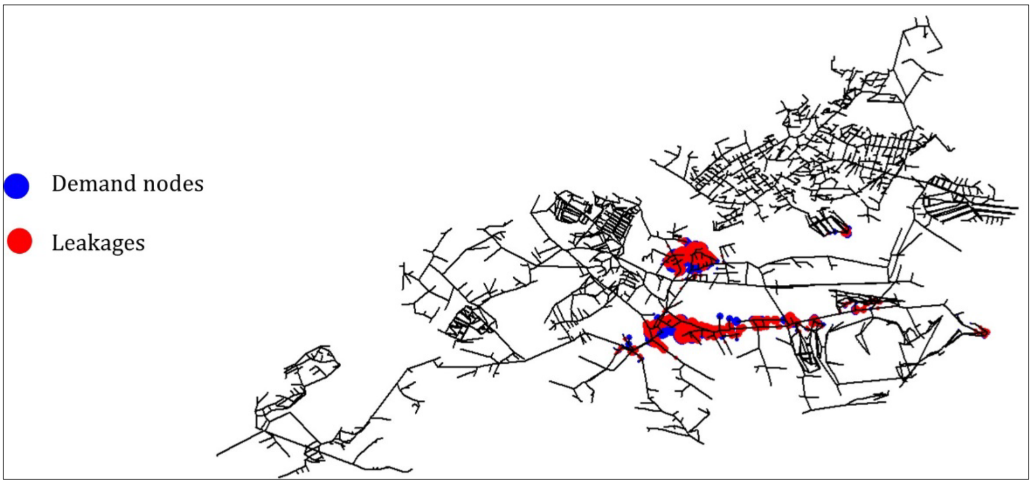

Figure 2 Average negative pressures for 168 hour simulation of the network

3 METHODOLOGY

3.1. Overview

In the first step, the original hydraulic model of the network was modified by inserting leak emitters according to the instructions of the IWS battle. Secondly, the network's initial situation was explored to understand better the current situation of the network and the causes of its water supply deterioration. Finally, the network was gradually rehabilitated every year with a limited budget without changing the network layout for the entire 5-year period.

The cost of the actions was calculated in accordance with the instructions for the Battle of IWS [19]. Actions were taken to improve the service indicators which were provided in the instructions [19]. Figure 3 depicts the entire methodology employed in this study.

Figure 3 The overall methodology employed

The main focus of the methodology is: a) the maximisation of water inflow to the network from all available sources while respecting the maximum threshold set, b) minimisation of leakage and c) headloss reduction across the whole network and especially in disadvantaged areas. The hydraulic model used was adjusted according to the instructions and special care was taken to include leakage nodes in the most realistic way possible. The investments' decisions were focused on improving the supply conditions in the most disadvantaged areas and improvement of the leakage-demand balance. The cost of the investments for each year was calculated in accordance with [19]. For the assessment of the investments' effects, a set of the available service indicators were defined [19]. In the following sections, the hydraulic model is described, and the specific actions taken are discussed.

3.2. Hydraulic Model

The hydraulic model was created based on the information provided by the IWS Battle instructions [19]. To simulate hydraulic behaviour of the network EPANET and the EPANET Toolkit 2.2 were used [20,21]. Simulation time step was 1 hour with the total duration of 168 hours. Leakage was perceived as point events and a new node was created for each leak located along the pipeline. Pipes with leaks were split into subsections and intermediate nodes with emitters were added at the designated positions according to the MS Excel spreadsheet provided. The elevation of these intermediate nodes was calculated via linear interpolation of the start and end node elevations of each leaking pipe. This process was automated using code developed in R and Python programming languages. Leak outflows were simulated by the emitter equation presented below:

$$q = k.p^{a} \tag{1}$$

Where q is the leaked flow, p is the pressure at the location of leakage, α is equal to 1 for all leaks and k is the emitter coefficient indicates the magnitude of the leak

k values were updated each year for the unpaired leaks to represent their growth with time according to the Equation 2:

$$k = k_0 e^{0.25.\frac{w}{260}} \tag{2}$$

Where k_0 is the initial value of k which is provided by [19] for each leak, w is the number of leaks at the beginning of the simulation

However, it was assumed that the intensity of the leaks remained constant throughout the year. Repaired leaks were assumed to remain repaired over the remaining years.

Instead of embedding each household tanks in the model, user behaviours were represented by introducing pressure dependent demand to each node with the expression [22]:

$$q_{D,i} = \begin{cases} D_i & p_i \geq p_f \\ D_i \left(\frac{p_i - p_0}{p_f - p_0}\right)^e & p_0 < p_i < P_f \\ 0 & p_i \leq p_0 \end{cases} \tag{3}$$

Where p_i is available pressure at the node i, Di is the requested demand at node i, $q_{D,i}$ is the actual demand at node i, p_0 is the minimum pressure below which actual demand is zero, p_f is the required pressure to deliver the demand, in this study 0 and 10 m pressure values were used for p_0 and p_f respectively. e is the pressure function exponent which was used 0.5 in this study.

3.3. Multi-staged Rehabilitation of the Network

The available budget for investments each year is fixed at 650,000 €/year. This annual budget should not be exceeded at any time and the total period of analysis and rehabilitation is 5 years. The main types of investments used were leak fixes, pump upgrades, installation of FCVs at sources and pipe replacements. These were decided based on the optimisation of four of the proposed indicators: I1, I3, I4 and I9. While indicators I1, I4 and I9 are to be maximised, indicator I3 (which represents the level of water losses) should be minimised.

For the first year of investments it was decided to try withdrawing the maximum of the available water from all sources in the most efficient way with sufficient head to service the surrounding area. Pump replacements and FCV installations were done to achieve that. The rest of the remaining budget was allocated to fixing leaks. In general, during all investments, leaks with the highest outflow volume during the 168 simulation hours were prioritised.

These changes are described in detail below:

1. <u>Changing pump capacity:</u> Some pumps' curves were decided to be changed according to: the maximum available flow withdrawal and the increase of available pressure in the surrounding area. For that reason, B_SM and B_SA pump curves were changed to C60/40 and C_70/10 respectively. Flow control valves were also added after each well pump to limit the inflow from each source to the maximum allowed withdrawal.
2. <u>Valve additions and pipes replacement:</u> A FCV was added before pipe 'L1720' (immediately downstream of the FCV of well W3_AB) and its setting is 10.5l/s. This change was done to allow more flow into pipe L1718 which supplies a disadvantaged cluster of demand nodes. In the surrounding area of W2_SA, an isolation valve was added in pipe 'L1762' and to restrict the well's water flow into the downstream southwest area which is disadvantaged. Pipes 'L1762' and 'L1759' were also replaced with larger diameter pipes (200mm and 125mm respectively) as they had a lot of leaks. Isolation valves were placed in pipes L1217 and L2242 in order to restrict flow to the surrounding area of W4_SM. In order to increase the capacity of the network in the northeast part of the network, pipe 'L1134' was replaced with a larger pipe diameter of 200mm. Also, isolation valves were added to pipes 'L1024' and 'L1019' to allow the isolation of the most north-eastern part of the network which is disadvantaged. Finally, to isolate the part of the network starting from well 'W1_R1' and leading to the area around node 'N2255' which is disadvantaged, a series of isolation valves were added to pipes: 'L157', 'L185', 'L226', 'L2060' and 'L2057'.
3. <u>Leaks repairing:</u> About 263 leaks were repaired during the first year.

After regulating the inflow in the network and repairing a large amount of leaks during the first year, the need to further reducing the leakage was identified. Thus, the whole investment budget in the second year was used to repair leaks (about 265 leaks were repaired).

The main focus on rehabilitation in the third year was to replace pipes with high head losses and bigger length (e.g. more than 30m/km head loss). This resulted in replacing about 67 pipes with larger diameters. Also, during the yearly investments it was noted that the inflow from the main source was up to approximately 88% (175 l/s). In order to take advantage of all available water resources, it was decided to gradually upgrade the main distribution pipe that goes through the whole area (see Figure 1) from the diameter of 400 mm to 450 in the initial part and 350 mm to 400mm for the rest of the stretch up to tank T1_CO. A part of it was upgraded in the third year and the rest was partially upgraded during the fourth and fifth years. Meanwhile, the remaining investment budget of these years was used to repair leaks and replace pipes according to the principles already discussed. This is because if all leaks were left untreated, leakage would increase considerably again after the initial reduction.

For the fourth year, after upgrading a part of the main pipe, the remaining budget was used to fix 11 leaks. For the fifth year of investment, several leaks were repaired (about 96 leaks), some pipes from the main supply line were replaced and other pipes with direct hydraulic influence to pressure deficient areas were replaced too.

While it was initially planned to apply optimisation techniques for optimising the operation of available valves and pumps of the network, the task was abandoned after a few attempts due to the high computational cost and the limited time available. As a result, manual changes in the operation of valves and pumps were explored. For the whole period of analysis, valve V_PE1 was closed completely to separate the zone supplied by reservoir W3_AB from the main distribution network. This way, all available flow from W3_AB was directed to the surrounding area which is disadvantaged and has pressure deficiencies.

4 RESULTS AND DISCUSSION

As seen from Figure 4, Table 1 coupled with Figure 5, during the first 2 years of interventions where pump upgrades and major leak fixes ere applied, the indicators for leakage, service pressure, and equity were significantly improved. In the next three years of investments, the discharge from the main reservoir (R1) was almost maximised by the main pipe replacement as the comparison for the flows before and after is showing (Figure 6).

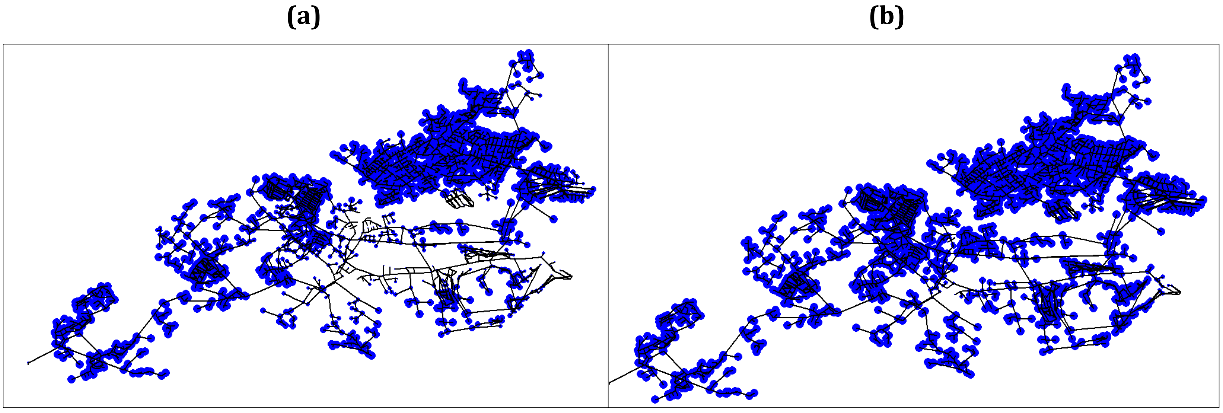

Figure 4 Demand satisfaction ratio for all the nodes a)initial situation before any changes b)final situation after the 5th year

Table 1 Reference indicators for each year

Year	Indicator1	Indicator 3	Indicator 4	Indicator 9
Initial year	0.907	0.504	0.757	0.733
Initial year after operational changes	0.908	0.5	0.753	0.743
1st year	0958	0.316	0.864	0.851
2nd year	0.972	0.272	0.898	0.89
3rd year	0.973	0.29	0.903	0.895
4th year	0.982	0.307	0.927	0.921
5th year	0.995	0.302	0.965	0.96

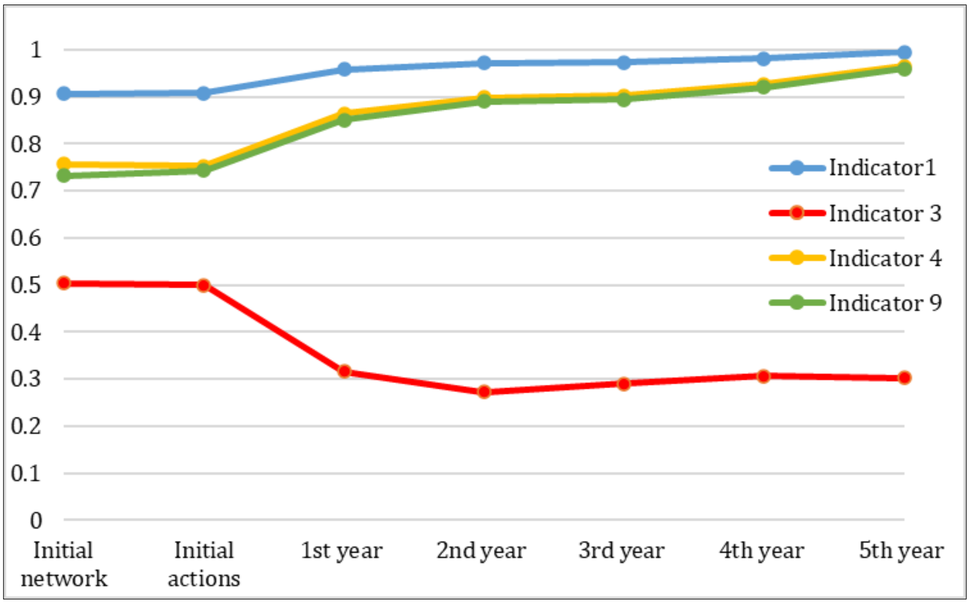

Figure 5 The improvement in the selected indicators after the rehabilitation of the network in each year

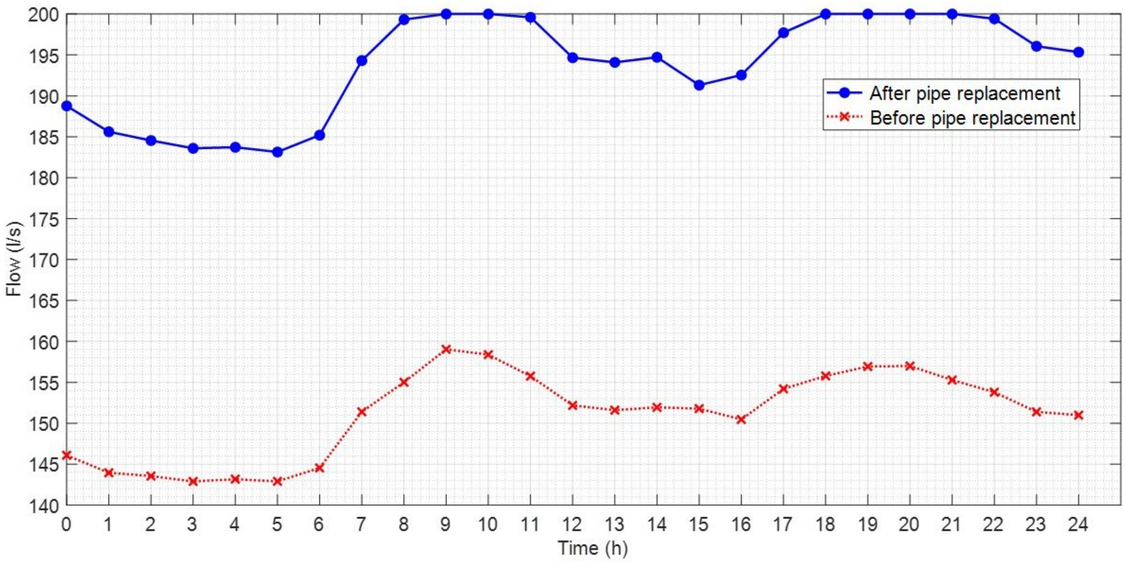

Figure 6: Discharge from R1 before and after main pipe replacements

At the end of all the investments, negative pressures were almost completely minimised and thus, indicator 7 was considerably improved. Energy consumption was not considered during the analysis and for this reason, the related indicator was disregarded. It was considered that the rest of the indicators were more important, and these gathered the focus of study.

Utilisation of the tanks of the network was not considered in the specific study due to the fact that some of them were not completely filling while one (Tank T3_MO) is positioned where its elevation is effectively lover than the surrounding areas for it to provide adequate head. Efficient use of tanks would include expansions and control actions based on time and/or surface level. Ideally, in order for the weekly simulations to provide identical results, the levels of all tanks at the beginning and at the end of the 168 simulation hours should be the same.

The network can be further improved by optimisation of schedules of valves and pumps. Some of the valves that were installed at early years of investments are not utilised but could be important for further improvement of the network.

5 CONCLUSIONS

This paper presented a methodology for staged conversion for a deteriorated network from intermittent to continuous supply over a period of 5 years with limited budget (650 000 € for each year). Multiple actions were taken to improve the network condition after the problem of high elevation and leakage were identified. Particularly, in the first year, a number of pumps with higher discharge heads were replaced, different new valves were installed, and high leaks were repaired. A large number of leaks were repaired in the second year to supply the users with as much water as possible and to prevent the increase in water loss due to the expansion of leaks and increase in pressure within the network in the upcoming years. For the other three years, pipe replacement was prioritised in addition to repairing some leaks. To do this, pipes with high head loss and with small diameters were targeted. Also, pipes from the main source were replaced to utilise the water source efficiently.

The performance of the network was evaluated with the key indicators (I1, I3, I4 and I9) following the investment made each year. Through the staged rehabilitation, I1, I4 and I9 increased from 0.907, 0.757 and 0.733 to 0.995, 0.965 and 0.96 respectively while I3 reduced from 0.504 to 0.302. These improvements in the key indicators show that it is possible to ensure that each customer has as much water as possible with longer supply duration. Following all of these investments over the past five years, the network now appears to have better performance in respect of pressure levels at nodes, volume of leakage, and the balance between supply and demand for customers.

For future work, the performance of the network could be improved with the optimisation of valve and pump schedule and/or with the pump installation to the specific parts of the network to increase the pressure at nodes.

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