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Asset Management of WDNs Based on Risk Detection (Case Study)

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Abstract:
Traditionally, the focus of many urban decision-makers has been on the expansion of city infrastructures, while management of valuable assets within the existing aging infrastructure is gaining more attention. Consideration of social developments, conflict criteria, risk management, sustainability, and resiliency has further introduced holistic approaches in Water Distribution Networks (WDN) management. Here in this research, a WDN, aged more than 30 years and serving a population of around 20000 people, comprising three municipal districts in a municipality of Iran, has been selected as the case study. Despite the limitations of comprehensive data, it is evident that the network suffers from two major issues, namely the high rate of leakage and frequent pipe failures. The existing condition of the WDN has been simulated using the EPANET software linked to a designed MATLAB suit. The simulation was based on three main modelling processes: Pressure Dependent Demand for water consumption, Poisson Process for pipe failure, and Integrated Model for pipe water leakage. Based on the calibrated results, risk maps of water leakage and pressure/pipe failure of the WDN were developed, and areas with assets that had high priority for intervention were identified. Multiple practical management methods, such as pressure management, pipe renewal, and designing district metering areas (DMA), are proposed to decrease the severity of the detected problems.
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1. Introduction

Nowadays, the socio-economic life of cities is tied to the water supplied by urban Water Distribution Networks (WDNs) more than ever. These infrastructures are mostly inherited from the past decades and need significant investment for their annual rehabilitation and modification to provide appropriate services. Documented evidence of this issue is hundreds of kilometres of pipes that are upgraded across the world to maintain the uninterrupted transport of water [1]. Based on EPA reports, within the next twenty years, 60% of water infrastructure funds must be allocated to pipe rehabilitation and replacement. Consequently, a new serious challenge called the "rehabilitation and replacement era" is arising for urban managers in which much of water utilities' existing infrastructure has reached to the end of its useful life [2]. In the past, many urban decision-makers focused on the expansion of city infrastructures, but nowadays, this misconception has been changed; aged infrastructures are valuable assets and their management has gained more attention.

Cities have traditionally managed their assets. However, Asset Management (AM) as a new approach was first introduced in the 80s in New Zealand [3]. Not much later, the widespread implementation of this concept in many fields around the world led to many definitions and frameworks for it. The most common point among the proposed frameworks was the main objective of AM, which was to focus on maintaining a desired level of asset services with the lowest life cycle cost [4, 5]. The basis of the proposed frameworks is organized on some similar core steps, which usually start with identifying existing assets and current and desired state while ending with presenting the best-required actions of AM, their priorities, and long-term funding plan.

Literature about implementing AM in WDNs may be chronologically divided into five categories: 1) Condition-based asset management [6-8], 2) Performance-based asset management [9], 3) Service-based or service level-driven asset management [10], 4) Risk-based asset management [1, 11], and finally 5), Sustainable based asset management [12, 13].

The importance of identifying WDNs problems and their emerging risks as the first and most effective step in AM, has led this study to analyse existing condition of a WDN suffering from some detected problems. EPANET software linked to a designed MATLAB suit has been developed to simulate the WDN, find areas with risky assets, and assess some suggested AM measures. In doing so, it is expected that promoting proactive measures with higher priority and

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preventing premature or reactive replacement measures may be identified and minimized without enduring more costs.

2. Problem Description

Governmental legislation to improve WDN performances in various parts of IRAN, which are faced with water scarcity, is the main drive for most water utilities to manage their assets. One of the most troubled WDNs is that of Isfahan Province, located near the southwest of Isfahan City. The existing WDN of the city is more than 30 years old, with an area of 36 km^2 and 100 km of distribution pipes serving a population of around 20000 people, and comprises three municipal districts. The layout of the study network with its pipe diameter ranges in three districts is depicted in Figure 1. Because of the corrosive condition of the soil in the study area, most of the buried pipes are PE and Asbestos. Due to the shallow depth of pipe installations, these pipes are vulnerable to many damages, and consequently, two major issues are apparent, namely, a high rate of water leakage and pipe breakage. Based on field measurements, the average pressure in the distribution network is about 40 m. It is worth noting that despite detected problems in the study network, limitations of comprehensive data and lack of field measurement instruments have exposed water utility to more complicated tasks. This study attempts to prepare risk maps of problems, identify areas with assets that have high priority for intervention, and finally propose some Best Management Practices (BMPs) for AM actions.

3. Assessment Materials and Methodology

The existing condition of the WDN has been simulated using the EPANET software linked to a designed MATLAB suit to find areas with high risks of insufficient pressure and water demand, pipe failure, and leakage. The simulation was based on three main modelling processes: the Pressure Dependent Demand for water consumption, the Poisson Process for pipe failure, and the Integrated Model for pipe water leakage. A brief description of each modelling process is explained as follows:

3.1. Pressure Dependent Demand

There are many methods for assessing actual nodal consumption in WDN literature. Among them, PDD modelling is one of the most prevalent methods, supposing the nodal water consumption is a function of the nodal available pressure head. When the nodal pressure head is equal or greater than the reference pressure head, the nodal water demand can be completely supplied. Otherwise, the nodal water consumption will not be acceptable. Herein, the relationship between the nodal pressure and the demand, proposed by Wagner et al. [14], is given below in the form of Equation 1, in which Actual Demand is the actual supplied nodal consumption obtained from PDD modelling, and Nodal Demand is the hourly required demand for nodal consumption. *CPH*, *RPH*, and *MPH* are calculated as EPANET Pressure Head, Local Reference/Desired Pressure Head (18 m), and Minimum Pressure Head (0 m), respectively.

Figure 1. Study network layout with its pipe diameter ranges

$$\begin{cases} Actual\ Demand = Nodal\ Demand & if \quad CPH \geq RPH \\ Actual\ Demand = Nodal\ Demand \times \left(\dfrac{CPH - MPH}{RPH - MPH}\right)^{0.5} & if \quad MPH < CPH < RPH \\ Actual\ Demand = 0 & if \quad CPH \leq MPH \end{cases} \tag{1}$$

3.2. Poisson Process

Without considering why and how many factors are affecting pipe failures, identifying pipes presumed to fail is important. To address this need, many studies have considered different approaches for predicting pipe failures, their consequences, and their effective parameters. A model of pipe failure prediction with high accuracy can lead to better WDN management, higher social approval, lower consequences, etc. Based on St. Clair and Sinha's [6] comprehensive review, these prediction models can be divided into six categories, and each is faced with some limitations.

For the sake of brevity, the study is limited only to the use of the Poisson model proposed by Kleiner and Rajani [15]. It is widely used to describe stochastic processes like pipe failures [16] to allocate a failure probability to each pipe as follows:

$$P_j = 1 - e^{-\beta j} \tag{2}$$

$$\beta_j = BR_j L_j \tag{3}$$

in which βj is the number of failures in a year for pipe j, BR is the break rate of pipe j in the network, L is the length of pipe j, and Pj is the failure probability of pipe j. Due to the lack of sufficient data relating to pipe failure parameters, the same break rate (BR) for all the pipes is used.

3.3. Pipe Leakage

The hydraulic pressure of pipes is one of the main elements of WDN pipe leakage, and it has been taken into consideration many times [17, 18]. In this regard, two questions related to pipe leaks are necessary to reduce non-revenue water (NRW) in WDNs: What is the share of pipe leakage from NRW, and how is this amount distributed in the WDN? To answer these questions, an integrated model for pipe leakage proposed by Tabesh et al. [19] -benefited from integrating nodal and pipe leakage- was used to simulate leakage in the study area.

According to the proposed approach, it is assumed that a number of orifices can cause pipe leakage. The pressure of all orifices in half part of the pipe is equal to the pressure of the upstream node, and the leakage from other orifices is related to the pressure of the downstream node. Having the estimated network leakage rates, the proposed procedure can converge the simulation to the calibrated hydraulic model where the amount of pipe leakage can be determined as Equation 4:

$$Q_{L,ij} = Q_{L,i} \times \frac{L_{fi}}{\sum L_i} \times Q_{L,j} \times \frac{L_{fj}}{\sum L_j} \tag{4}$$

where, $Q_{L,ij}$ is the leakage of pipe ij, $Q_{L,i}$ and $Q_{L,j}$ are the nodal leakage rates, and L_i and L_j are the total pipe lengths connected to nodes i and j, respectively [19].

4. Results and Discussion

4.1. Pressure Dependent Demand

In spite of high daily average pressures, instigating higher potentials for water consumption, in addition to leakage and pipe failure rate, the daily pressure head seems insufficient to satisfy the desired pressure head (18 m) in all areas of districts D and N. Therefore, based on the PDD water consumption model, some nodes within these districts would suffer from pressure deficits and, consequently, water shortages. In the worst nodal condition, there is a node accessing water availability only 14.74 hours during the day. Figure 2 shows the comparison of water demand and supplied water during the day. The map of nodes with the risk of water shortage during the day is shown in Figure 3. Pressure management at the entrance of three reservoirs as the most convenient solution shows that the water shortage can be completely removed without any increase in average pressure head. However, intelligent pressure management within the network, as an effective BMP, requires more detailed analysis.

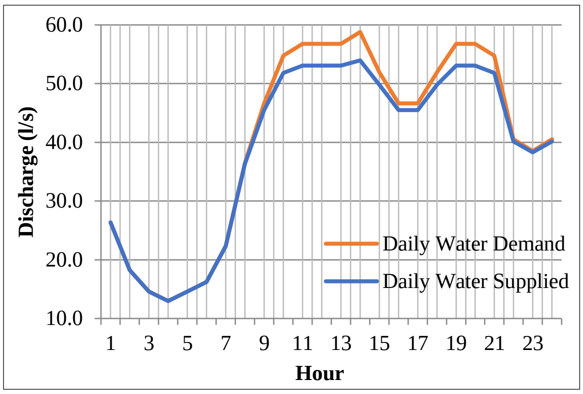

Figure 2. Comparison of daily water demand and supplied

4.2. Poisson Process

Based on statistical analysis of pipe break in WDN utilities, the same BR for all the pipes in the network is calculated as Equation 5:

$$\text{BR} = \frac{Number\ of\ Pipe\ Break\ (per\ year)}{Total\ Lenght\ of\ Pipes\ (km)} = 3.65 \tag{5}$$

According to the assumptions made in the Poisson Process model, the break probability of each pipe is related to the length of the pipe, but the consequences of pipe break are only related to the hydraulic performance of the corresponding pipe. The consequence of a pipe break is evaluated here by addressing the issue of the inability of the network to meet the desired demand in the case of the corresponding pipe failure. The maps of the break probability and the failure risk for each pipe are shown in Figures 4 and 5, respectively. A comparison of these figures shows that having a higher pipe break probability does not necessarily correspond to a higher pipe failure risk. Proactive pipe renewal can be nominated as one of the BMPs to reduce the calculated risk of pipe assets. Conducting a detailed-scheduled annual rehabilitation plan based on facilitated financial support may serve as a practical means of implementing asset management in which each asset will be replaced at its minimum life cycle cost. This proactive task is usually overlooked in WDN management practices as water utilities/disciplines would primarily respond to failures.

4.3. Pipe leakage

While the Minimum Night Flow (MNF) and the leakage rate from the network are estimated, the map of risk for pipe leakage from applying the Integrated Model is depicted in

Figure 6. The amount of the hourly leakage and average pressure in the study network is condensed in Table 1. As shown in this table, the maximum leakage occurs when the average pressure head is maximum, while during the peak hour of water consumption, the hourly leakage and average pressure head have their lowest values. Thus, creating District Metering Areas (DMAs) and pressure management in these DMAs and pipe renewals may be proposed as selected BMPs.

Figure 3. **Map of nodes with water shortage risk**

Figure 4. **Map of Poisson probability of break for pipes**

Figure 5. **Map of failure risk for pipes**

Figure 6. **Map of pipes with water leakage risk**

Table 1. **Hourly pipe leakage and average pressure during the day**

Hour	Q_{leak} (l/s)	$P_{average}$ (m)	Hour	Q_{leak} (l/s)	$P_{average}$ (m)	Hour	Q_{leak} (l/s)	$P_{average}$ (m)
1	10.10	43.09	9	9.42	39.89	17	9.42	39.89
2	10.29	43.95	10	9.05	38.21	18	9.18	38.82
3	10.35	44.25	11	8.95	37.75	19	8.95	37.75
4	10.38	44.36	12	8.95	37.75	20	8.95	37.75

5	10.35	44.25	13	8.95	37.75	21	9.05	38.21
6	10.32	44.12	14	8.85	37.29	22	9.66	41.00
7	10.20	43.55	15	9.19	38.82	23	9.73	41.34
8	9.80	41.67	16	9.42	39.89	24	9.65	41.00

5. Summary and Conclusion

This paper deals with the importance of identifying problems and quantifying their risks for WDNs with an asset management perspective. The approach is further examined in the case of a WDN in the Isfahan province, Iran, which is suffering from various aging problems. The current condition of the network was simulated based on three key modelling processes: 1) Pressure Dependent Demand for nodal water consumption, 2) Poisson Process for the pipe break, and 3) Integrated model of Pipe leakage for the water pipe losses. Based on calibrated simulation results, the areas with assets exposed to high risks were identified and presented as risk maps. It was found that while the districts of D and N are faced with more pressure deficit and water shortage problems, the assets of these districts have a higher rate of leakage and failure risks. These results may attract more attention and investments in these districts rather that District W, which was initially perceived to be in need of rehabilitation for domestic reasons. Pipe renewal, pressure management, and DMA zoning of WDNs can be proposed as BMPs to solve identified problems. Further achievements in the asset management approach may be gained by presenting a scheduled plan of activities and investigating their priorities based on the current proposed approach.

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