

Operational and technical performance of a water distribution network in Oman

Ahmed Al Naamani^a and Ahmad Sana^{icb,*}

^aPublic Authority for Water, Muscat, Sultanate of Oman

^bDepartment of Civil and Architectural Engineering, Sultan Qaboos University, P.O. Box 33, Postal Code 123, Al-Khouth, Muscat, Sultanate of Oman

*Corresponding author. E-mail: sana@squ.edu.om

 AS, 0000-0001-7576-1072

ABSTRACT

A water distribution network in an urban area in Muscat region (the capital city of Oman) is assessed for operational performance using the widely accepted methodology proposed by the International Water Association (IWA). The technical performance of this network was assessed using global performance index methods after modifying the performance levels as per local guidelines. A total of 37 operational performance indicators for the network were selected to carry out assessment. Overall operational performance showed high scores whereas some indicators showed unacceptable performance values. The network showed very high technical performance considering nodal pressures. The lower performance for pipe velocity may be attributed to the fact that the network is currently being utilized by 70% of the population for which it was designed. The residual chlorine levels were within the acceptable range of the Public Authority for Water (PAW), showing a very good performance by virtue of water quality. This study will be useful for decision makers to assess the operational, technical and water quality performance of urban networks and take actions for improvements.

Key words: operational performance, technical performance, water age, water distribution network, water quality

HIGHLIGHTS

- A detailed assessment of an urban water supply network in Arabian Peninsula.
- Application of IWA performance indicators in an arid region.
- Synthesis of operational and technical performances of an urban water distribution system.
- Developing new penalty functions using local water distribution guidelines.

INTRODUCTION

The well-being of a modern society strategically relies on an efficient water distribution network among other factors. It is anticipated that the water supply sector will be facing major challenges in the years to come that include keeping pace with a net population growth; closing the gap between coverage and service; ensuring sustainability of existing and new services; and improving the quality of services. The water industry in Oman faces two major challenges: sustainability of the system to meet changes in quantity and quality of water flow in the system due to population growth, and Non-Revenue Water (NRW) or water losses adversely affecting the water utilities.

A regular evaluation of the performance of a water system is imperative to ensure an efficient water supply to the public. There are essentially two main types of performance evaluation methods available to water and wastewater utilities: systems of performance indicators and technical performance assessment tools (Cardoso *et al.* 2004). The performance indicators system developed by the International Water Association (IWA), is used to evaluate the water utility's performance. A performance indicator is defined as a 'quantitative measure of a particular aspect of the water undertaking's performance or standard of service'. Performance indicators are used to assess the performance of the whole service, covering all its sectors of activity (Alegre *et al.* 2000, 2006, WAREG 2017).

Technical performance assessment tools are related to hydraulics of the system. Alegre & Coelho (1995) and Coelho (1997) proposed technical performance indices (TPIs) to evaluate the hydraulic performance. In addition, TPIs have been used for

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

the evaluation of the performance of different pipe materials and an assessment of the operational performance of water treatment plants.

In the present study, an assessment of the performance of an urban water distribution network in Al-Amerat Wilayat of Muscat (the capital city of Oman) is carried out using available data. The water distribution network under consideration is fed from Deem reservoir (25,000 m³ storage capacity) through a transmission line with a nominal diameter of 1,500 mm. It consists of eight district metered areas (DMAs), Al-Amerat storage tank (40,000 m³), three break pressure tanks and two pump stations.

PERFORMANCE OF WATER SUPPLY NETWORKS

The performance evaluation is crucial for sustainability, where performance assessment is defined as ‘any method that allows for the estimation of the competence or the effectiveness of a process or activity through the production of performance measures’ (Alegre & Coelho 2012). Performance assessment is presently a common practice in the water utility sector (Cardoso *et al.* 2004; Kanakoudis *et al.* 2011).

Currently, the Performance Indicators (PI) system developed by IWA is recognized as a well-known industry standard. Since the year 2000, when this system was proposed, it has been adopted in major projects, both for internal assessment of performance, and benchmarking. The performance indicators system can be adopted in any institute irrespective of its dimensions, nature or degree of complication and progress (Alegre *et al.* 2015).

The IWA PIs are grouped in six main categories: water resources, personnel, physical, operational, quality of service and financial. Each of these are divided into subgroups. The purpose of division into subgroups is to facilitate the determination of the use and the manipulator of a specific indicator or indicators. In exceptional cases, subgroups are further divided into smaller units. Some of the indicators are also further broken down into sub-indicators. Generally, sub-indicators are parts of the top indicator, which may or may not be measured separately. It is evident that the data and context information primarily depends upon the quality of inputs of a performance indicators system, and therefore it is highly preferable that they are either measured or obtained from real instances in the utility.

Although the indicators, data and context information in the IWA system represent universal concepts that may be applied almost anywhere in the world, the system may be modified to accommodate local situations to enable users to develop their own compatible systems (Alegre *et al.* 2006). Before applying the performance indicators, reference values are to be established as per objectives, strategies and anticipated success. The reference value can be based on some standard value, the past value of the indicator, or an internationally observed value of the indicator. A semi-quantitative or qualitative approach had to be adopted in this study, which requires fewer data and information and is easy to apply in the evaluation of water systems in Oman.

According to the collected data and the score of the performance indicator, the performance of water systems in Oman can be evaluated and the resultant indicator score is translated to a level of performance. Either a binary or a subjective assessment of performance can be made. In Binary assessment, two choices are available for assessing the performance: acceptable or unacceptable. Hence, a score of ‘0’ for unacceptable and ‘1’ for acceptable is assigned. In subjective assessment, scores are linked to a subjective assessment of establishment performance; for example, a customer satisfaction rating, such as inferior (0 points), poor (1 point), acceptable (2 points), good (3 points), and excellent (4 points).

Assessment of technical performance

The water supply system is a complex system that consists of pipes, pumps, valves and other electromechanical components installed above and below ground to supply water to the inhabitants. In general, the system is designed to satisfy the domestic, commercial, industrial and firefighting water requirements. The system must always meet the legitimate demands with adequate hydraulic performance, mainly pressure. The system should also be resilient under various scenarios and perform satisfactorily under different demand loads (Gargano & Pianese 2000; Zyoud 2003; Karakouzian *et al.* 2019; Karami *et al.* 2019).

The factors influencing the design and operation of a water supply system include various types of consumer demands, probable failure/absence of assets due to planned (such as maintenance of the pumps) and unplanned events (outage of power, pipe burst, malfunction of instrumentation etc.). Moreover, the quantity of water stored in the elevated tank is required to meet the diurnally fluctuating demand. The quality of water delivered to consumers is to be considered as well.

Hydraulic performance

Hydraulic performance of the system is measured based on an ability of the system to deliver good quality water at all times under a suitable set of operating conditions. It depends on several factors, such as design life of the system, coverage, topographic features to reduce energy costs, predictable population growth, projected industrial and commercial growth, water consumption data and peak flow factors, minimum and maximum acceptable pressures and storage facilities.

The Public Authority for Water (PAW), Oman (PAW 2015) issued guidelines and design criteria for public drinking water systems. These guidelines provide the minimum requirements/standards to be met. The standards for water distribution and transmission systems are also described in the guidelines, including the nodal pressure, pipe velocity, valves, pipeline materials, and so on. The present study concentrated on evaluating the water supply system in the study area based on the PAW, Oman Guidelines (PAW 2015).

Technical Performance Indices (TPIs) were proposed by several researchers to assess the hydraulic performance of a water supply system (Alegre & Coelho 1995; Coelho 1997; Jacob 2006; Sousa 2007). These indices are meant to evaluate the technical performance of a system in terms of pressure, velocity, water losses, reliability, pumping costs and water quality. The performance level is measured from 0% (unacceptable service) to 100% (optimal service). This method is based on the data obtained from the hydraulic simulation models.

The performance evaluation is based on three components (Coelho 1997): (1) state variable; (2) penalty or performance curve; and (3) generalization operator. The state variable is related to the specific aspect (e.g., pressure, velocity, water quality) in consideration. The penalty or performance curve states a relation between the variable values and the performance classification scale (that is, the merit of each element). The generalization operator aggregates the individual performance values to produce the global system performance index. Several performance indices can be combined to obtain the system's overall performance index (Muranho *et al.* 2014).

Figure 1 shows the penalty or performance curves for two state variables: nodal pressure head (h) and pipe flow velocity (V). The performance is based on the relative position of the state variable value to some reference value. Here, h_{\min} and h_{\max} are the minimum required and maximum allowed pressure heads, respectively, and V_{\max} is the maximum allowed pipe flow velocity (Muranho *et al.* 2014).

The performance curve for pressure head is intended to show that nodal pressure head close to the required minimum value (service pressure) is preferable as it represents lower energy costs, the system elements are under less mechanical

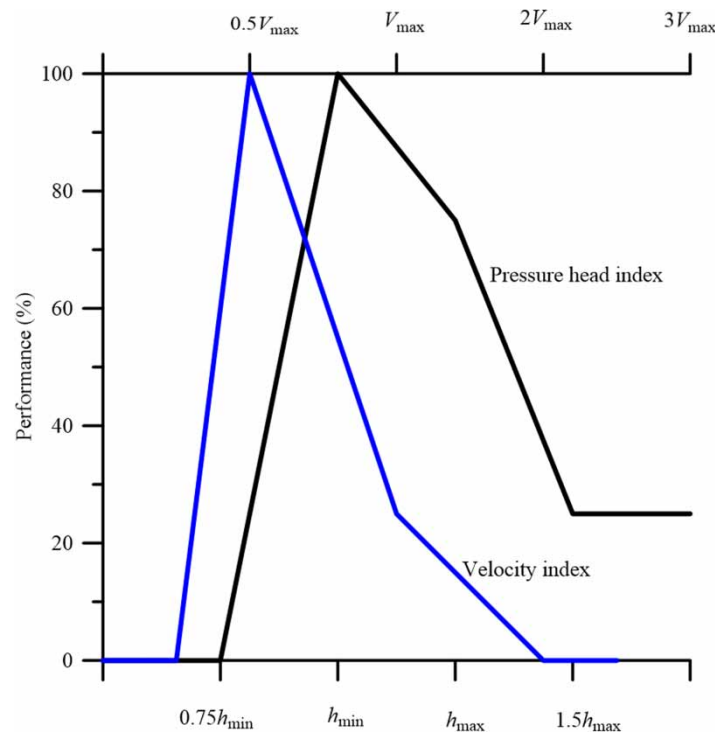


Figure 1 | Performance curves for pressure head h and velocity V (data from Muranho *et al.* 2014).

stress, and indeed, could cause lower water losses. The performance curve for the pipe flow velocity depicts that the values above some maximum recommended are undesirable (increased pipe abrasion, higher head loss, noise, and hydraulic transients) (Muranho *et al.* 2014).

The global system performance *TPI* for the pressure and velocity (major state variables in a water distribution network) can be computed using weighted averages, considering weights for the nodes proportional to their demands and for the pipes proportional to the water volume contained therein. The global performance index for pressure (TPI_p) is defined using the following relationship (Sousa 2007; Muranho *et al.* 2014):

$$TPI_p = \sum_{i=1}^{NN} W_i P_i \quad (1)$$

$$W_i = \frac{Q_i}{Q_T} \quad (2)$$

where NN is the number of nodes in the network, P_i is the performance value, W_i is the weight assigned to the i th node, Q_i is the water demand at node i and $Q_T = \sum_{i=1}^{NN} Q_i$.

For velocity, the global performance index and the respective weighting factor are defined by:

$$TPI_v = \sum_{j=1}^{NP} W_j P_j \quad (3)$$

$$W_j = \frac{L_j D_j^2}{(LD^2)_T} \quad (4)$$

NP is the total number of pipes in the network, P_j is the performance value, W_j is the weight, L_j and D_j are the length and diameter of pipe j and $(LD^2)_T = \sum_{j=1}^{NP} L_j D_j^2$.

Water quality

Two approaches can be used for water quality assessment of a water distribution network: direct sampling and computational predictions. The first approach is straightforward but needs considerable time and financial resources. It is suitable and practical for monitoring the water quality based on predefined standards. The computational predictions are based on mathematical modelling. The mathematical models can be of assistance in obtaining a reasonably accurate representation of the water quality across the system, which can later be verified or confirmed through limited sampling (Jalal 2008; Nazari-Sharabian *et al.* 2019a, 2019b).

The hydraulic models mainly consider advection and decay while calculating the water quality in the water distribution system. The modeling of chlorine decay in a distribution system requires the combined effects of the liquid bulk and pipe wall. Generally, a first-order reaction is considered when modeling chlorine decay (Newbold 2009):

$$C_t = C_0 e^{-kt} \quad (5)$$

where: C_t = Concentration at time t (mg/l), C_0 = Initial Concentration (at time zero) (mg/l), and k = reaction rate constant (1/time units).

The reaction rate constant (k) in Equation (5) is the composite reaction rate constant, such that it incorporates both the bulk and wall reaction rate constants. The bulk reaction rate constant can be determined experimentally by obtaining measurements in the distribution network. The wall reaction constant must be evaluated considering the mass transfer rate of chlorine between the liquid bulk and pipe wall. The reaction rate constant is given as:

$$k = k_b + k_w \quad (6)$$

$$k_b = -\frac{1}{t} \ln\left(\frac{C}{C_0}\right) \quad (7)$$

where: k_b is the bulk reaction rate coefficient (1/time units) and k_w is the wall reaction rate coefficient (1/time units).

For residual chlorine and water age, the performance assessment is based on Figure 2 (Tabesh & Dolatkhahi 2006). For an optimum range of 0.2–0.5 mg/l (recommended by WHO), the performance is 100% (excellent). Values from 0.5 mg/l to 0.6 mg/l are considered as ‘good performance’ (75%) and values from 0.6 mg/l to 0.7 mg/l correspond to ‘acceptable’ performance (50%). Residual chlorine values more than 0.8 mg/l are considered ‘unacceptable’ (25%). Finally, any situation with less than 0.1 mg/l chlorine concentration corresponds to ‘no service’ (0%).

Any travel time below the concentration-time limit (T_{limit}) is considered as an excellent performance (100%). From T_{limit} to maximum time (T_{max}) the performance is acceptable (50%), and travel time longer than T_{max} is considered as ‘no service’ (0%). Water quality performance index for the entire network is defined as:

$$TPI_{WQ} = \sum_{i=1}^{NN} W_i \cdot WQ_i \quad (8)$$

where TPI_{WQ} is the water quality performance index of the entire network, WQ_i is the performance index for node i , and W_i is the weight of each node as given by Equation (2).

METHODOLOGY

Selection of performance indicators

Selection of key performance indicators needs time and consideration of many factors. Some of the indicators are easy to measure where one indicator may be sufficient to capture the underlying result. But for critical links, there may be several possible indicators measuring different dimensions, or even one dimension, of the underlying results. The IWA Performance Indicator System has been widely used in numerous water projects for internal performance assessment. To assess the performance of water operation in the present study area six factors were selected as follows:

1. Inspection and maintenance
2. Calibration of the instruments
3. Rehabilitation
4. Operational water losses
5. Failure
6. Water quality metering

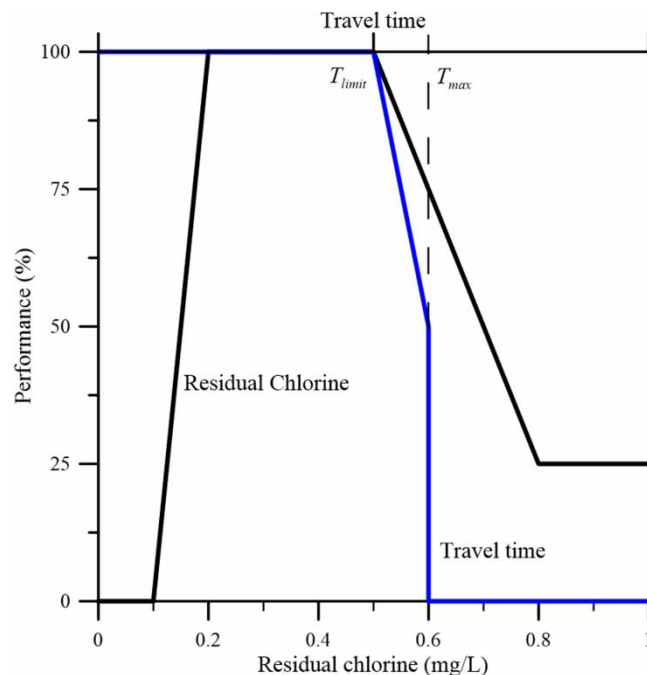


Figure 2 | Performance curves for residual chlorine and water age (data from Tabesh & Dolatkhahi 2006).

Data collection

To carry out the performance assessment of operation and maintenance of the water distribution network in the present study, data collection was extremely critical and challenging. The assessment of operational performance indicators was carried out using the semi-quantitative method. A set of principles and indicators of operation was first explored. The indicators were examined, using evidence from public documents. The main sources of data were Computerized Maintenance Management System (CMMS), Geographical Information System (GIS), contractor reports on operation and maintenance that included plans and completed tasks, E-service programming system for water leakage and pipe shutdown, water quality reports from the water quality department, discussions with the staff in operations and customer service, and field visits and observations.

Finally, a simple scoring method was used against each of these indicators. The purpose of this assessment is to enable the decision makers to draw conclusions on the resilience of a particular system and take actions to improve the water services and systems under PAW management.

Operational performance indicators

The operational performance of the water service in the study area was evaluated based on the performance scores for all the indicators used in the present study. To measure the operational performance, a scoring method was developed. In the beginning, the percentage of the indicator was calculated using the relationship developed for each indicator, then a score was allocated according to its percentage, which corresponds to the level of performance. Two types of scoring systems were used for the performance indicators. In Type-1, high scores represent good performance while low scores represent poor performance as illustrated in Table 1. Whereas in the Type-2 scoring system a low score represents high performance while high scores represent poor performance. The total or overall performance score for each group of indicators was produced by taking the sum of all scores divided by the number of indicators.

Assessment of technical performance

Hydraulic performance

The data for general evaluation of the hydraulic performance of the present network were obtained from SCADA, PAW reports and information systems, and from the hydraulic modelling of the water system. The as-built information, such as characteristics of transmission pipes (length, diameter, and material), nodal elevations, storage reservoirs, tanker filling stations and pump details were collected from PAW archives to set up a real scale hydraulic model.

The current consumptions of each customer were obtained from the customer service department in PAW to allocate the real demand as an input for the hydraulic model. The population and water demand data were taken from the consultants' reports.

Hydraulic modeling using WaterGEMS

The hydraulic modeling was carried out using Water GEMS software (Bentley Inc.). The hydraulic model was calibrated using the observations from Supervisory Control and Data Acquisition (SCADA) with the computed values at selected locations.

All the required data (bulk flow meter readings, pressure records, GIS drawings, customer connection points with consumption, water quality test results, tanker filling, pump details etc.) were collected from various departments of PAW and analyzed. The hydraulic model was set up and calibration was done using observed data.

Table 1 | Performance scoring

Performance score	Performance level	Type-1 Indicator (%)	Type-2 Indicator (%)
4	Very high	89–100	0–15
3	High	71–88	16–25
2	Moderate	61–70	26–35
1	Low	51–60	36–50
0	Very low	≤50	≥50

Technical performance indices

The hydraulic performance of water distribution network for the study area was also evaluated using the concept of technical performance indices. The estimates of technical performance indices are based on the data obtained in the hydraulic simulation model.

In the present study, the hydraulic performance of the water distribution network was evaluated using the concept of TPIs by comparing the values of pressure head in the junctions and the values of velocities in the pipes (state variables) with reference values as given in PAW design guidelines (pressure head: 15–60 mH₂O and velocity: 0.5–2.0 m/s). The penalty or performance curves for the state variables, nodal pressure and pipe flow velocity, were developed as presented in Figure 3. The performance is based on the relative position of the state variable values to reference values; that is, the minimum required (1.5 bar) and maximum (6 bar) allowable pressures, and the minimum (0.5 m/s) and maximum (2 m/s) pipe flow velocities allowed as per PAW guidelines. The global performance indices for pressure (TPI_p) and velocity (TPI_v) were calculated using Equations (1) and (3), respectively.

Water quality performance assessment

The assessment of water quality for the network was carried out using model predictions by calibrated hydraulic model. The reaction rate constant (k) incorporates both the bulk and wall reaction rate constants as described before. The wall reaction constant is considered to be zero because most of the water network pipes in Oman are ductile Iron (DI) and high-density polyethylene (HDPE) pipes. The bulk reaction rate constant (k_b) was determined experimentally by obtaining measurements of the initial concentration (C_0) and the concentration at time t in mg/l (C_t) in the distribution network, and then the value of k_b was calculated using Equation (7). For the assessment of water quality performance, Figure 4 was developed for residual chlorine and water age. The water quality performance index of different elements of the entire network was calculated using Equation (8).

RESULTS

Assessment of operational performance

A total of 37 operational performance indicators were considered in the present study covering six main operational criteria listed in the previous section. The scores for all the indicators were calculated based on the criteria shown in Table 2. For

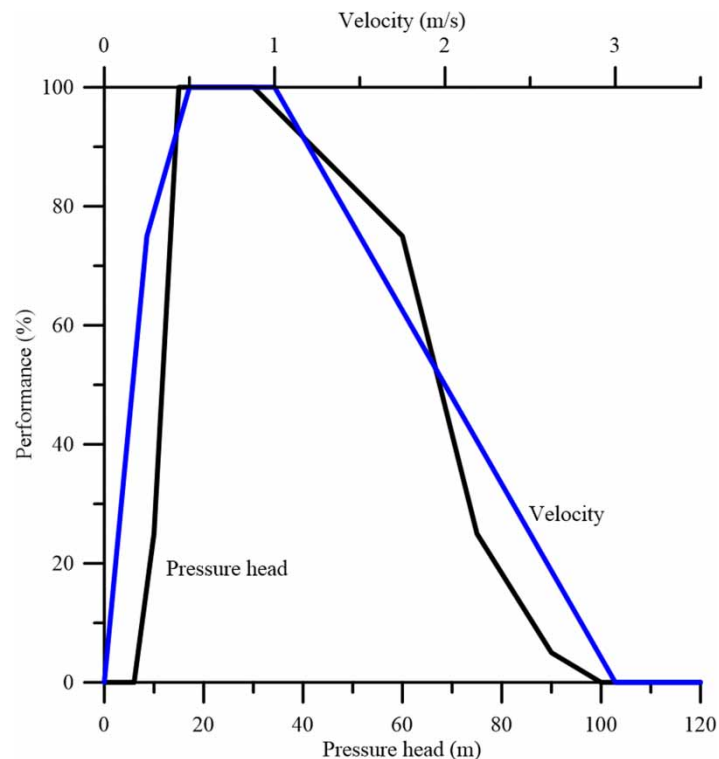


Figure 3 | Performance curves for pressure head and velocity.

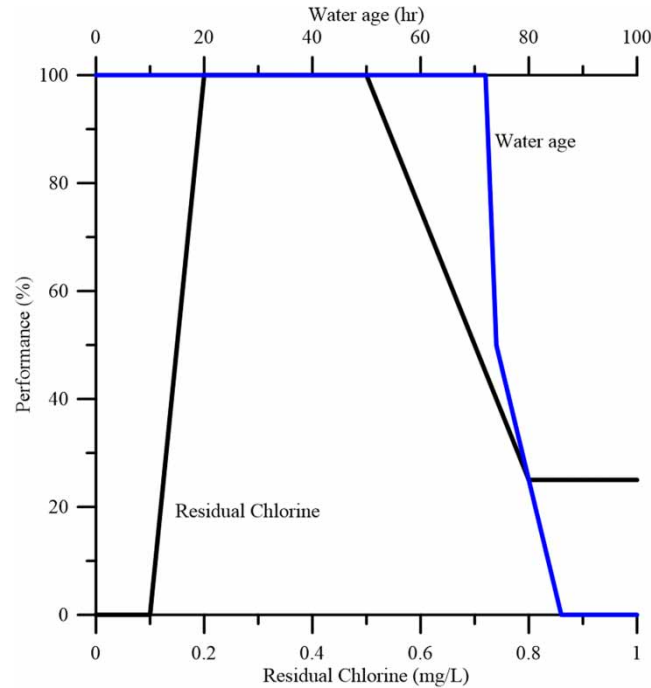


Figure 4 | Performance curves for residual chlorine and water age.

each operational indicator, the assessment criterion is shown, based on which the collected data was used to calculate the performance value in percentage. Then, a performance score was assigned based on the type of indicator, as per Table 1. The performance indicators relevant to losses are scored using Type 2 scoring as a lower percentage of losses represent better performance. Some of the operational PIs have zero scores (e.g., OP-8, OP-9 and OP-10) because inline water quality sensors are not installed in this network.

The operational water losses depicted by the performance indicators OP-19, OP-20 and OP-21 are scored as per the classification given by Liemberger & McKenzie (2005) for developing countries in Table 3 (considering Oman among the developing countries). The average pressure in the present pipe network is 25 m, approximately. Accordingly, the values of OP-19 and OP-21 correspond to the lowest leakage performance category D; so, using the Type-2 indicator, a score of 1 is assigned. For OP-20, the network falls in category A and, therefore, a score of 4 is assigned.

The Unavoidable Annual Real Losses (*UARL*) are calculated as (Lambert *et al.* 1999):

$$UARL(\text{m}^3/\text{year}) = (6.57L_m + 0.292N_s + 9.132L_p)P \quad (9)$$

L_m = mains length (km),

N_s = number of service connections (main to property line),

L_p = total length of underground pipes, property line to meter (km),

P = average pressure (meters).

The Infrastructure Leakage Index (*ILI*) is the ratio of Current Annual Real Losses (*CARL*) to *UARL*.

In the present water distribution network, in general, the meters are located at the property line ($L_p = 0$). Total number of service connections is 22,101, mains length is 615.9 km and average pressure is 37.5 m. So, *UARL* is estimated to be 0.394 Mm^3/year and using *CARL* as 6.1 Mm^3 , the value of *ILI* is 15.5. As per the Leakage Performance Classification (LPC) shown in Table 3, the present network falls in category C. In the LPC classification, having four categories (A to D), the present system falls at rank 3 and therefore, according to the scoring system adopted in this study, a score of 2 is assigned to Op-23.

Assessment of hydraulic performance

In the present study, WaterGEMS was used as the hydraulic network model. The model was set up using the available information from the water distribution network. The model was calibrated using the observed data from SCADA and some field

Table 2 | Assessment results of operational performance indicators

Performance criterion	Indicator code	Performance indicator	Assessment criterion	Assessment data	Value of PI	Indicator type	Score
Inspection and maintenance	Op-1	Pumping inspection and maintenance	No. of inspections done/required number of pump inspections	11/12	92%	1	4
	Op-2	Storage tank cleaning	Number of cleaned/total number of storage tanks	0/5	0	1	0
	Op-3	Network inspection	Inspected/total number of district metering zones	5/8	63%	1	2
	Op-4	Gate valve inspection	Inspected/total number of gate valves	581/1,120	52%	1	1
	Op-5	Leakage control repair	Surveyed (km)/total main pipe length(km)	200/620	65%	1	2
	Op-6	Hydrant inspection	Inspected/total number of fire hydrants	850/1,532	55%	1	1
Calibration of the instruments	Op-7	System flowmeter calibration	Number of calibrated/total number of flowmeters	37/37	100%	1	4
	Op-8	Water level sensor calibration	Number of calibrated/total number of water-level sensors	0/0	0%	1	0
	Op-9	Inline water quality monitoring equipment calibration	Calibrated/total number of inline water quality sensors	0/0	0	1	0
	Op-10	Water quality equipment's calibration	Calibration/total number of water quality equipment	0/0	0	1	0
	Op-11	Pressure meter calibration	Calibrated/total number of pressure meters	2/15	13%	1	0
Rehabilitation	Op-12	Mains rehabilitation	Pipe length rehabilitated/rehabilitation required	17 m/17 m	100%	1	4
	Op-13	Mains renovation	Pipe length renovated/pipe length requiring renovation	101 m/123 m	82%	1	3
	Op-14	Mains replacement	Pipe length replaced/pipe length requiring replacement	39 m/42 m	93%	1	4
	Op-15	Meter replacement	Number of meters replaced/meters requiring replacement	902/983	92%	1	4
	Op-16	Replaced valves	Number of valves replaced/valves requiring replacement	25/25	100%	1	4
	Op-17	Service connection rehabilitation	Number of service connections rehabilitated/ service connections requiring rehabilitation	891/1,183	75%	1	3
	Op-18	Pump replacement	Pump capacity replaced/pump capacity requiring replacement	30 kW/45 kW	67%	1	2
Operational water losses	Op-19	Water losses (unaccounted-for water) per connection per day	Water losses (m ³ per day)/no. of connections	17,836/22,101/	800 L/day/ connection	2	1
	Op-20	Apparent or commercial losses per connection per day	Apparent losses (m ³ per day)/no. of connections	1,151/22,101	52 L/day/ connection	2	4
	Op-21	Real or physical losses per connection per day	Real losses (m ³ per day)/no. of connections	16,712/22,101	756 L/day/ connection	2	1
	Op-22	Residential customer reading efficiency	Number of residential meters read/total number of residential meters	18,568/22,101	84%	1	3
	Op-23	Infrastructure leakage index	CARL (Mm ³ /year)/UARL (Mm ³ /year)	6.1/0.394	15.5	2	2

(Continued)

Table 2 | Continued

Performance criterion	Indicator code	Performance indicator	Assessment criterion	Assessment data	Value of PI	Indicator type	Score
Failure	Op-24	Operational meters	Number of operational meters/number of direct customer meters	18,668/22,101	84%	1	3
	Op-25	Unbilled unmetered water	Free tankers (Mm ³)/system input volume (Mm ³)	0.266/21.30	1%	2	4
	Op-26	Pump failures (days/pump/year)	No. of pump failure/no. of pumps	1/4	25%	2	3
	Op-27	Mains failures (km/year)	Length of mains with failures (km)/total mains length(km)	66/620	11%	2	4
	Op-28	Service connection failures (no./ year)	No. of service connection failures/no. of service connections	2,369/22,101	11%	2	4
	Op-29	Hydrant failures (no./ year)	No. of hydrant failures/total no. of hydrants	821/1,532	54%	2	0
	Op-30	Power failures (hours/ year)	Power failure hours/total working hours	0/24	0%	2	4
	Op-31	Water-point failures (tanker filling station) (no./ year)	No. of water point failures/no. of water points	2/15	13%	2	4
Water quality metering	Op-32	Water quality tests carried out	No. of tests carried out/no. of tests required	345/408	85%	1	3
	Op-33	Physical-chemical tests carried out	No. of tests carried out/no. of tests required	173/204	85%	1	3
	Op-34	Chlorine tests carried out	No. of tests carried out/no. of tests required	173/204	85%	1	3
	Op-35	Microbiological (E-coli and total coliform) tests carried out	No. of tests carried out/no. of tests required	172/204	84%	1	3
	Op-36	E-coli tests carried out	No. of tests carried out/no. of tests required	172/204	84%	1	3
	Op-37	Coliform tests carried out	No. of tests carried out/no. of tests required	172/204	84%	1	3

Table 3 | Leakage performance categories (LPCs) based on Infrastructure Leakage Index (ILI) and water losses under various system pressures for developing countries (Liemberger & McKenzie 2005)

LPC	ILI	Water loss in liters/connection/day when the system is pressurized at an average pressure of:				
		10 m	20 m	30 m	40 m	50 m
A	1–4	<50	<100	<150	<200	<250
B	4–8	50–100	100–200	150–300	200–400	250–500
C	8–16	100–200	200–400	300–600	400–800	500–1,000
D	>16	>200	>400	>600	>800	>1,000

Explanation of LPC categories: A: Further loss reduction may be uneconomic unless there are shortages, B: Possibilities for further improvement, C: Poor leakage management, tolerable only if resources are plentiful and cheap, D: Very inefficient use of resources, indicative of poor maintenance and system condition in general.

measurements. The calibrated model was employed to assess the technical performance of the network. Moreover, water quality performance was evaluated in terms of chlorine decay and water age using the model.

Hydraulic model calibration

The data of network was imported in the hydraulic model from GIS and the customer demands were allocated to the nearest node. Extended Period Simulations (EPS) were run by the model to simulate an operation of 24 hours duration and to calibrate and validate the model. In order to ensure that the model computations agree well with the actual readings and field measurements, some parameters were adjusted, for instance demand patterns, pump curves, control valve settings, the position of isolation valves and pipe roughness coefficients.

The comparisons between observations and model predictions (after calibration) of nodal pressure and flowrate for selected DMAs are shown in Figures 5 and 6, respectively. The model predictions agree well with the measurements over a 24-hour period qualitatively. During some hours at a few DMAs the model underestimates or overpredicts the nodal pressures and flowrate. However, overall agreement between the computed values and observations is reasonably good for all the DMAs.

Technical performance indices

To evaluate the hydraulic performance of water distribution networks, nodal pressure heads and pipe-flow velocity were calculated from WaterGEMS. The total number of nodes and pipes in the present water distribution network model are 10,460 and 11,467, respectively. The weightage of each node was calculated according to the demand at each node divided by the demand of the network (Equation (2)), whereas, the volume of water in each pipe was used to calculate its weightage (Equation (4)). Then, the global technical performance index of the system for pressure (TPI_p) and velocity (TPI_v) were calculated at every hour for 24 hours using Equations (1) and (3), respectively.

The global performance index of nodal pressure for the present network varies between 69 and 85% (Figure 7). Whereas, the pipe velocity performance index ranges from 19.6% to 20.1%. In general, the present network performs well by virtue of pressure. However, the performance in case of pipe velocity is quite low. From 22:00 hrs to 04:00 hrs, a high-performance index of pressure is depicted. While, in the case of velocity, a rather constant performance (approximately 20%) prevails during 24 hours.

The occurrence of overall low velocities in the network implies that the pipe diameters are larger than the required considering the current demands. This is due to the fact that many houses are not connected to the PAW system yet. Moreover, a number of plots are vacant, which would eventually be constructed in future. At present the total water coverage of the present network is 70%. In other words, the pipes in the network are designed to cater for the future growth.

Water quality performance

There is only one chlorine dosing system for the present network, which is located at the water source (a desalination plant in Quriyat 82 km away from the network). Water quality performance of the network has been assessed using the calibrated model in WaterGEMS. Hydraulic analysis indicated that for most of the nodes the range of residual chlorine is between 0.2 and 0.5 mg/l, which is within Omani specifications. The overall percentage score for the system is 96.89%, which was obtained from the data collected from water quality department of PAW as shown in Table 4. Only DMA-1 showed a residual chlorine value slightly above 0.5 mg/L, which is specified as the maximum allowable value in PAW guidelines.

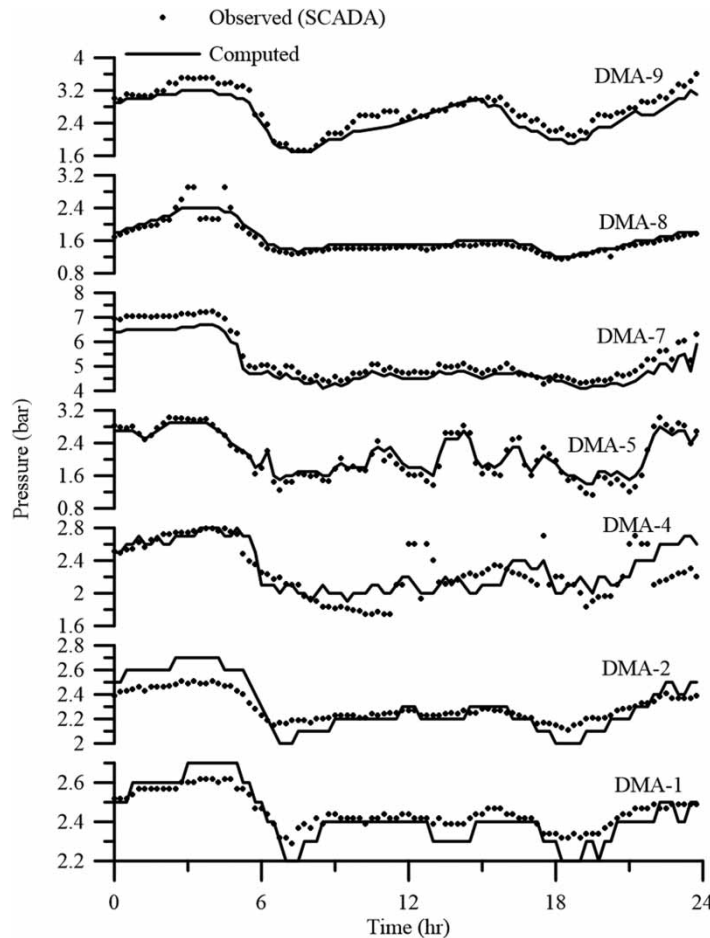


Figure 5 | Pressure at selected DMAs after calibration of the hydraulic model.

Hydraulic analysis also indicated that the water needs 72 hours to reach the stable condition of the network by virtue of water age. Therefore, the analysis was carried out for 288 hours (12 days) in order to achieve stable conditions. The water age performance for the network was found to be 84% (Figure 8).

CONCLUSIONS

An urban water distribution network located in Muscat region (Oman) was evaluated using IWA performance indicators. The evaluation was carried out using measured data or a WaterGEMS model. Most of the 37 performance indicators for the system showed good results. Some of the indicators scored very low; for instance, storage tank cleaning, fire hydrant damage, instrument calibration and some water loss-related indicators. These network components are essential and require an action plan to improve the performance levels. The water losses require special attention and appropriate actions must be taken to reduce them. The indicators for rehabilitation, water quality and failure score higher than 3, depicting a high level of performance.

The global technical performance indices (TPIs) indicated that the network under considerations has high technical performance levels by virtue of pressure. The lower values of performance of velocity in the pipes can be attributed to the fact that 70% of the population is connected to the network as yet. Therefore, the future demands would be adequately fulfilled by the network. However, this conclusion would require running the hydraulic model with full water demand to check the system performance under design conditions. The water quality performance of the network in the present situation is good and the hydraulic model showed that the water age in the network is more than 3 days, nonetheless the residual chlorine level is within the acceptable standards of the country.

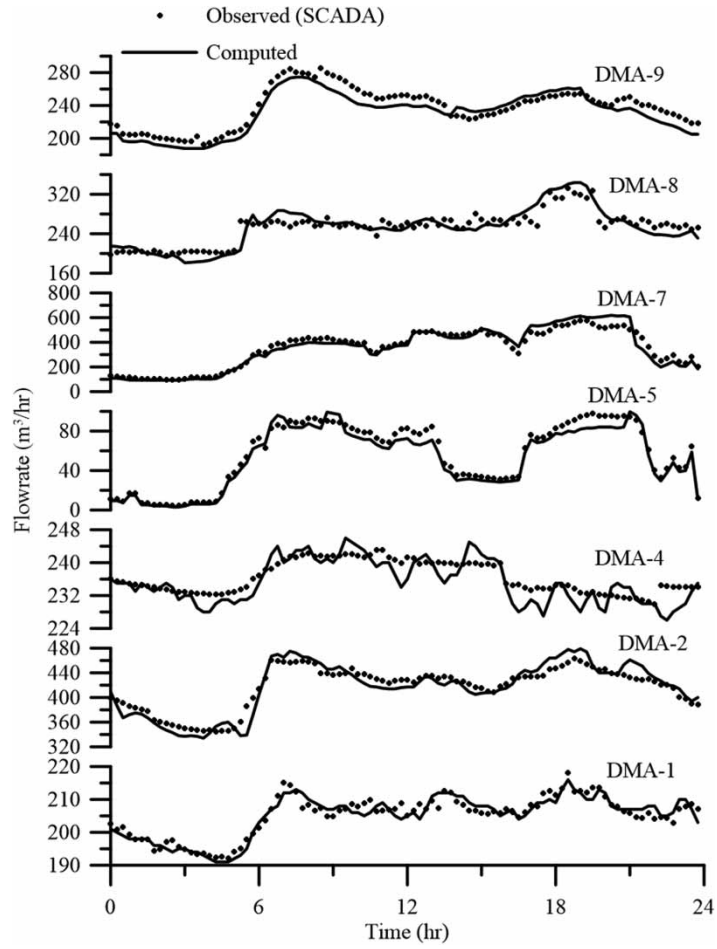


Figure 6 | Flowrate at selected DMAs after calibration of the hydraulic model.

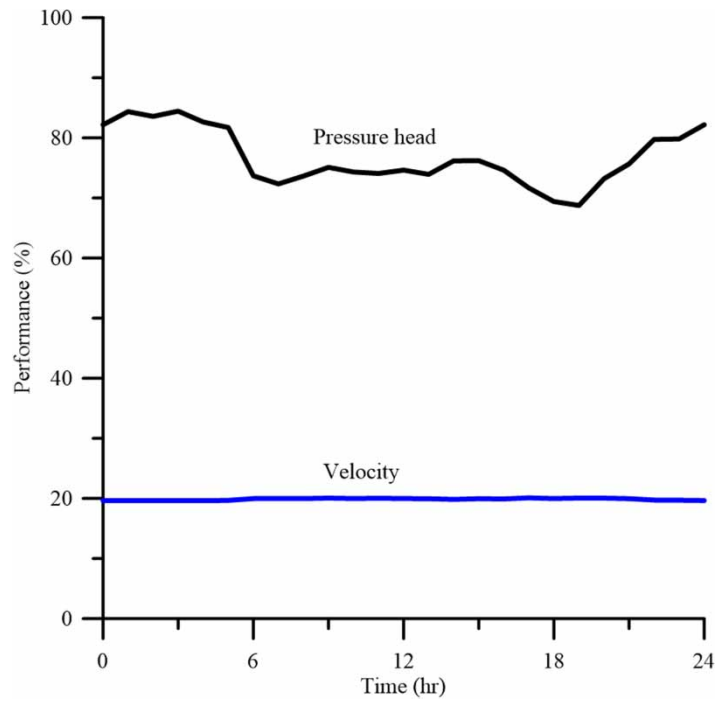
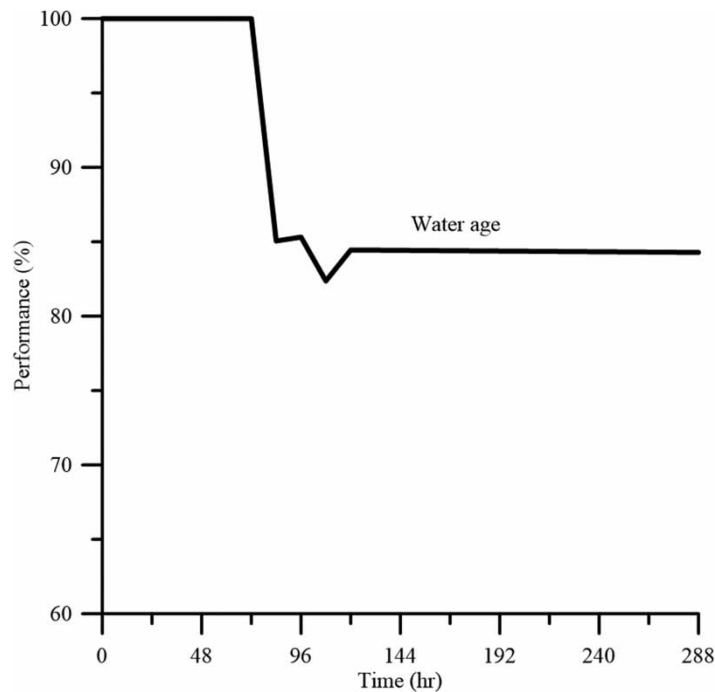


Figure 7 | Pressure head and velocity performance for the network.

Table 4 | Residual chlorine measurements in the network at various DMAs

DMA	1	2	3	4	5	7	8
Residual chlorine(mg/L)	0.52	0.22	0.35	0.37	0.45	0.40	0.30

**Figure 8** | Water age performance for the network.

This study highlighted some important features of the water distribution network in an arid country, making it useful for the decision makers to plan actions for improvements in operational practices.

ACKNOWLEDGEMENT

The permission by PAW, Oman to utilize the license of WaterGEMs for this study is acknowledged.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- Alegre, H. & Coelho, S. T. 1995 Hydraulic performance and rehabilitation strategies. In: *Improving Efficiency and Reliability in Water Distribution Systems* (Cabrera, E. & Vela, A. F., eds.). Kluwer Academic Press, London, UK.
- Alegre, H. & Coelho, S. T. 2012 Infrastructure asset management of urban water systems. In: *Water Supply System Analysis – Selected Topics* (Ostfeld, A., ed.). ISBN 978-953-51-0889-4. Available from: <http://www.intechopen.com/books/water-supply-system-analysis-selected-topics/> (accessed 8 November 2020).
- Alegre, H., Hirner, W., Baptista, J. M. & Parena, R. 2000 *Performance Indicators for Water Supply Services*. Manual of Best Practice Series. IWA Publishing, London, UK.

- Alegre, H., Baptista, J. M., Cabrera, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W. & Parena, R. 2006 *Performance Indicators for Water Supply Services*. – Second Edition, Manual of Best Practice. IWA Publishing, London, UK. ISBN 1843390515.
- Alegre, H., Hirner, W., Baptista, J. M. & Parena, R. 2015 *Highlights of the IWA System of Performance Indicators for Water Supply Services*. ResearchGate, Lisbon, Portugal.
- Cardoso, M. A., Coelho, S. T., Matos, R. & Alegre, H. 2004 *Performance assessment of water supply and wastewater systems*. *Urban Water Journal* **1** (1), 55–67.
- Coelho, T. S. 1997 *Performance in Water Distribution: A Systems Approach*. Wiley, New Jersey, NY.
- Gargano, R. & Pianese, D. 2000 *Reliability as tool for hydraulic network planning*. *Journal of Hydraulic Engineering* **126** (5), 354–364.
- Jacob, A. 2006 *Assessment of Water Loss in Water Distribution Systems: the Study Case of ZMC 320 EPAL*. Master Thesis in Hydraulic and Water Resources, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal.
- Jalal, M. M. 2008 *Performance Measurement of Water Distribution Systems (WDS), A Critical and Constructive Appraisal of the State-of-the-Art*. Master of Applied Science Thesis, University of Toronto, Toronto, Canada.
- Kanakoudis, V., Taitsifki, S., Samaras, P., Zouboullis, A. & Demetriou, G. 2011 Developing appropriate performance indicators for distribution systems evaluation at Mediterranean countries. *Water Utility Journal* **1**, 31–40.
- Karakouzian, M., Karami, M., Nazari-Sharabian, M. & Ahmad, S. 2019 *Flow-induced stresses and displacements in jointed concrete pipes installed by pipe jacking method*. *Fluids* **4** (34), 4010034. <https://doi.org/10.3390/fluids4010034>.
- Karami, M., Kabiri-Samani, A., Sharabian, M. N. & Karakouzian, M. 2019 *Investigating the effects of transient flow in concrete-lined pressure tunnels, and developing a new analytical formula for pressure wave velocity*. *Tunnelling and Underground Space Technology* **91**, 102992. ISSN 0886-7798, <https://doi.org/10.1016/j.tust.2019.102992>.
- Lambert, A. O., Brown, T. G., Takizawa, M. & Weimer, D. 1999 *A review of performance indicators for real losses from water supply systems*. *Journal of Water Supply: Research and Technology-Aqua* **48** (6), 227–237. doi: <https://doi.org/10.2166/aqua.1999.0025>.
- Liemberger, R. & McKenzie, R. 2005 Accuracy limitations of the ILI: is it an appropriate indicator for developing countries? In: *Conference Proceedings, IWA Leakage 2005 Conference in Halifax*, Nova Scotia, Canada. Available from: https://www.miya-water.com/fotos/artigos/02_accuracy_limitations_of_the_ili_is_it_an_appropriate_indicator_for_developing_countries_7298335635a32647d41708.pdf
- Muranho, J., Ferreira, A., Sousa, J., Gomes, A. & Sá Marques, A. 2014 Technical performance evaluation of water distribution networks based on EPANET. In: *12th International Conference on Computing and Control for the Water Industry, CCWI2013*. *Procedia Engineering*, **70**, 1201–1210.
- Nazari-Sharabian, M., Taheriyoun, M., Ahmad, S., Karakouzian, M. & Ahmadi, A. 2019a *Water quality modeling of Mahabad dam watershed-reservoir system under climate change conditions, using SWAT and system dynamics*. *Water* **11** (2), 394. <https://doi.org/10.3390/w11020394>.
- Nazari-Sharabian, M., Taheriyoun, M. & Karakouzian, M. 2019b *Surface runoff and pollutant load response to urbanization, climate variability, and low impact developments – a case study*. *Water Supply* **19** (8), 2410–2421. <https://doi.org/10.2166/ws.2019.123>.
- Newbold, J. R. 2009 *Comparison and Simulation of A Water Distribution Network in EPANET and A New Generic Graph Trace Analysis Based Model*. MSc Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.
- Public Authority for Water (PAW) 2015 *Design Guidelines: Basic Design Criteria. Draft Report*. Muscat, Oman.
- Sousa, C. 2007 *Multi Objective Optimization of Water Supply Systems Operation Using Genetic Algorithms*. Master of Science Thesis in Hydraulics and Water Resources, Instituto Superior Técnico, Technical University of Lisbon, Lisbon, Portugal.
- Tabesh, M. & Dolatkhahi, A. 2006 *Effects of pressure dependent analysis on quality performance assessment of water distribution networks*. *Iranian Journal of Science and Technology Transactions of Civil Engineering* **30** (1), 119–128. doi:10.22099/ijstc.2006.768.
- WAREG. 2017 *An Analysis of Water Efficiency KPIs in WAREG Member Countries*, European Water Regulators. Available from: <https://www.wareg.org/documents/an-analysis-of-water-efficiency-kpis-in-wareg-member-countries/>.
- Zyoud, S. 2003 *Hydraulic Performance of Palestinian Water Distribution Systems: Jenin Water Supply Network as A Case Study*. M.Sc Thesis, Faculty of Graduate Studies, An-Najah National University, Nablus, Palestine.

First received 23 November 2020; accepted in revised form 17 June 2021. Available online 29 June 2021