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Minimum night flow (MNF) and corrosion control in compliance with internet of things (IoT) for water systems

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ABSTRACT

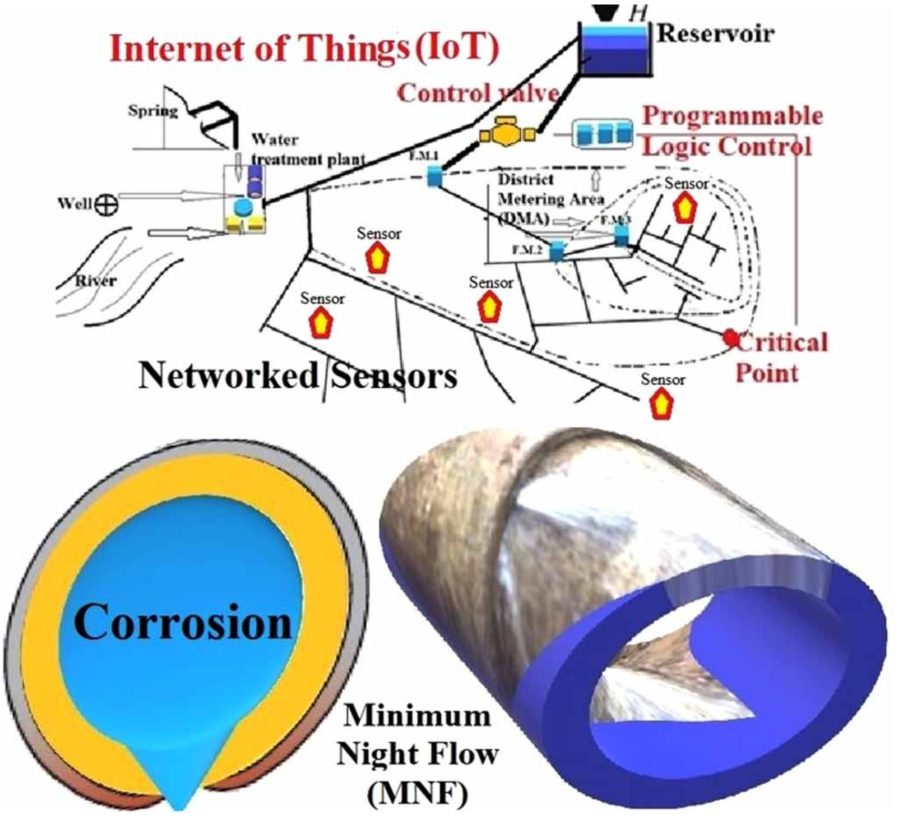
In the new world view, water is considered an economic-social commodity and a basic human need. This work aims to investigate the relationship between corrosion and changes in the minimum night flow (MNF) rate in water systems. Changes in MNF as a dependent variable are affected by changes in independent variables such as total unreported water loss, allowed night consumption, and network field leakage. First of all, the share of water loss due to network corrosion in total unreported water loss was investigated through a mathematical model and regression analysis according to Geography Information System (GIS). As a result, the *p*-value for pressure was .564. The Power function had a suitable correlation on the scatter diagram and best-fit curve which was used for Inflow to the water distribution network based on the regression model. The error of the consumers' meter and the correction of these errors were discussed in the apparent water loss section. The apparent water loss value was equal to 1.12% of produced water. This amount of apparent water loss showed the share of the actual water loss due to network corrosion from the total unreported water loss in the facilities.

Key words: corrosion, Geography Information System, internet of things, minimum night flow, networked sensors, non-revenue water

HIGHLIGHTS

- Improvement of networked sensors.
- Connection between GIS, RS, and IoT.
- Relationship class definition for the water system.
- Access to leakage locations by GIS, RS, and IoT.
- Conceptual model for MNF and corrosion control.

GRAPHICAL ABSTRACT



INTRODUCTION

In the present century due to population growth, expansion of industry, and rising levels of public health and well-being, per capita renewable resources are decreasing. One of the most important renewable resources is water. Hence, the saving of drinking water all over the world assumes a strategic action plan. This action plan certainly will lead to reducing the non-revenue water (NRW) and saving drinking water (Hariri Asli & Hozori 2021; Hariri Asli & Nazari 2021; Hariri Asli 2022). Refer to the presented background, the aims of this work included investigating the relationship between corrosion and changes in the minimum night flow (MNF) rate in compliance with the internet of things (IoT) (https://fa.wikipedia.org/wiki/IoT) for water facilities with the following goals (https://en.wikipedia.org/wiki/Artificial_intelligence):

- Management of consumption in the water supply facilities.
- Increasing the useful life of water distribution facilities by reduction of water loss.

What is the corrosion?

The corrosion phenomenon of water facilities in water transmission lines, water distribution networks and water supply is affected by the following factors (Vardy *et al.* 2015; Lema *et al.* 2016):

- Contact with the soil in terms of chemistry, physics and biology.
- Chemical properties of the water inside the pipe.
- Water instabilities such as water hammer (Figure 1), pulsation, and cavitation.
- Composition of various types of pipes.

In nature, there is a large amount of dissolved oxygen gas in water. It is known as the main constituent element of water. Due to the reactivity of oxygen with metals, there is the ability to cause corrosion. Dissolved oxygen in the water inside the pipes is one of the important factors in corrosion.

Figure 1 | Corrosion phenomenon (rupture) and water loss in the facilities.

Corrosion is considered as the biggest problem for water facilities, especially at mid night (from 2 to 4 o' clock in the morning). This problem is named the MNF (Duan *et al.* 2020).

The corrosion and the changes in the MNF are important in desalination and brine treatment applications. Apart from being a source of freshwater, brine can also be a source of salts, minerals, metals, chemicals, bioactive compounds, and even energy (Panagopoulos 2022). Brine treatment and valorization is considered a promising strategy to eliminate brine discharge and recover valuable resources such as water, minerals, salts, metals, and energy (Panagopoulos & Giannika 2022). As a result, desalination is an important choice to solve the global problem of water scarcity (Panagopoulos 2021).

What is the MNF?

The low working pressure of water during peak consumption at the water system indicates the low efficiency of the distribution system. The capacity of distribution network pumps should be such that during peak consumption, the pressures remain at the standard level (Ferras *et al.* 2018). This problem increases the pressure in the distribution network when there is no consumption (at 2–4 o'clock in the morning), which is approximately unavoidable. The inflow to the water distribution network at 2–4 o'clock in the morning indicates the MNF (Lambert 2012).

This problem can be seen in the results of pressure measurement, and the use of the usual methods of pressure control during low consumption times (by using pressure relief valves, pressure reducing valves, pumps with lower power during these hours or inverter installation for pump stations) (Zecchin *et al.* 2005; Zhao *et al.* 2020). On the other hand, due to a large number of wells and other water resources, will not be cost-effective to concentrate them in one place. Therefore, it should control the pressure in the wells and other water resources during low consumption hours in order to reduce the water leakage. The experience and history of implementation of consumption management based on the intelligent pressure management projects have been carried out at the world level includes industrially developed and developing countries (Sarkardeh *et al.* 2014). The main points of consumption management based on intelligent pressure management include the following:

- Active leakage management.
- Pressure management.
- Increasing the repair speed of reported leaks.
- Optimization of flow measurement systems.

Water is one of the renewable resources, but its quantity is limited. Therefore, it is necessary for water facilities to exploit the relationship between corrosion and changes in the MNF rate based on a new method, so that water facilities can have a proper function, useful production, and minimum cost in a suitable period of time (Andrade & de Freitas Rachid 2022). The first step in the scientific exploitation of the facilities is to update the map information of the facilities in the form of GIS (Asli *et al.* 2012).

GIS is a system consisting of data, hardware, software, methods and algorithms, human power and a network, which has the ability to enter, manage, analyse, and display 'spatial information'. The components of the GIS are:

- Spatial feature is a spatial phenomenon.
- Information/display of processed data.
- Personnel/dynamic thinking is the main key to GIS power.
- System establishes the connection between software, hardware, and data.

In the international arena and in the 21st century, the attitude based on saving water and energy emphasizes the necessity of using the GIS in the management of various industries, including the water and sewage industry, based on the intelligent exploitation method. The GIS is not just a software, but a science that categorizes and places geographic information and urban planning by different software. This science has recently found its place in urban science and is used by urban science specialists and city planners in civil engineering (Möller *et al.* 2015; Asli *et al.* 2020; Asli & Arabani 2022).

The purpose of this work also was to provide a suitable condition for working the water distribution network. In order to make it possible for the network to work within the range of its useful life, it was considered to investigate the relationship between corrosion and changes in the MNF rate in water distribution facilities.

The differences between their work and previous articles are to special attention to the use of modern techniques such as networked sensors, IoT, GIS, and remote reading of data distinguishes this work against similar cases.

The differences between the present work and the previous works are as the following:

- Investigation of the corrosion and changes in the MNF rate in water distribution facilities.
- Improve the advanced techniques including networked sensors, remote sensing (RS), GIS, and the IoT to control the water loss due to corrosion.

METHODS

The aim of the current work was at the scientific exploitation of facilities through the reduction of NRW in June 2017. By examining the relationship between corrosion and changes in the MNF rate in facilities, it must be possible to reduce NRW. The statistics of allowed night users and network field leakage were available. The value of each of them could be calculated. In order to check the amount of leakage caused by corrosion, it was necessary that the present work should focus on the investigation of unreported leakage of water distribution network, water transmission line, water consumers (branches). It should be noted that total unreported water loss (UWL) includes the water flow of unauthorized withdrawal from the network and the water loss due to corrosion and permanent breaks in the network. Therefore, the foundation of this research was based on two main axes. In the first step, the amount of total UWL was checked. In order to determine the share of water loss due to corrosion of the network, a mathematical model based on regression analysis according to the GIS was considered while examining the relationship between corrosion and changes in the MNF. The water loss due to corrosion was assumed as a part of the amount of total UWL. Another part of total UWL is related to apparent water loss. The sum of these two parameters, along with the unauthorized withdrawal from the network, constitutes the value of the total UWL. In the second step, due to the importance of investigating the leak age caused by corrosion, the necessity of clarifying the error of the consumers' meters and correcting these errors in the apparent water loss section was included in this work. Therefore, the meters were tested during the pilot operation.

GIS, RS, and IoT data intercommunication process

This work led to data intercommunication process to improve modelling for the water system's MNF control based on the following items:

- Make the connection between GIS, RS, and IoT for rapid data intercommunication to record MNF.
- Conceptual modelling definition for prediction of the MNF variation.
- Improvement of RS facilities installation equipped with data loggers, IoT, and GEO-database intercommunication process.
- Relationship class definition for MNF monitoring system elements.

Research model

The hydraulic model of the present work was defined by WATERGEMS software in accordance with the ArcGIS – ArcMap software. This hydraulic model was designed to achieve the following goals:

- Determining the rate and locations of the leakage.
- Estimation and evaluation of the water distribution system.
- Flow and pressure variation investigation of the water distribution system.

Research formulation

The first step

Determining the share of water loss due to network corrosion and MNF. Corrosion in facilities leads to water loss and financial resources (1)–(4). Corrosion is a chemical reaction between the components of the facility equipment and its surrounding environment. It also affects the MNF.

$$\text{Total UWL} = \text{Allowable unavoidable water loss without income} + \text{Actual unavoidable water loss} + \text{Apparent unavoidable water loss}$$

$$\text{Total UWL} = ((\text{CD}/1000)25 + \text{C}(0.8) + 18(\text{A} + \text{B}))4\text{E} \tag{1}$$

where A is the length of the transmission line (km); B is the length of the distribution network (km); C is the number of subscribers (no. of branches); D is the average branching length (m); E is the average pressure (kPa).

$$Q_L = Q_{MNF} - (Q_{NC} + Q_{BL}) \tag{2}$$

$$Q_B L = (0.25)(Q_{MAX}) \tag{3}$$

$$Q_{NC} = (0.6)N_P \tag{4}$$

Here, Q_{MNF} is the MNF of the water distribution network; Q_{NC} is the night allowable consumption; Q_{BL} is the night field leakage or unavoidable real water loss; Q_L is the total UWL or unreported leakage of the water distribution network, water transmission line, and branches (consumer's meters); Q_{MAX} is the number of population in the pilot; N_P is the maximum consumption in the pilot.

MNF and district metering area. Changes in MNF as a dependent variable are affected by changes in independent variables. The independent variables include the total UWL and total unavoidable water loss.

This means allowed unavoidable water loss without income plus real unavoidable water loss plus apparent unavoidable water loss and allowed network background leakage. The network background leakage measuring needs to regression analysis for district metering of the water inflow to the district area in compliance with IoT. The measuring of total UWL and total unavoidable water loss also needs to district metering of water inflow to district metering area (DMA) (Figure 2).

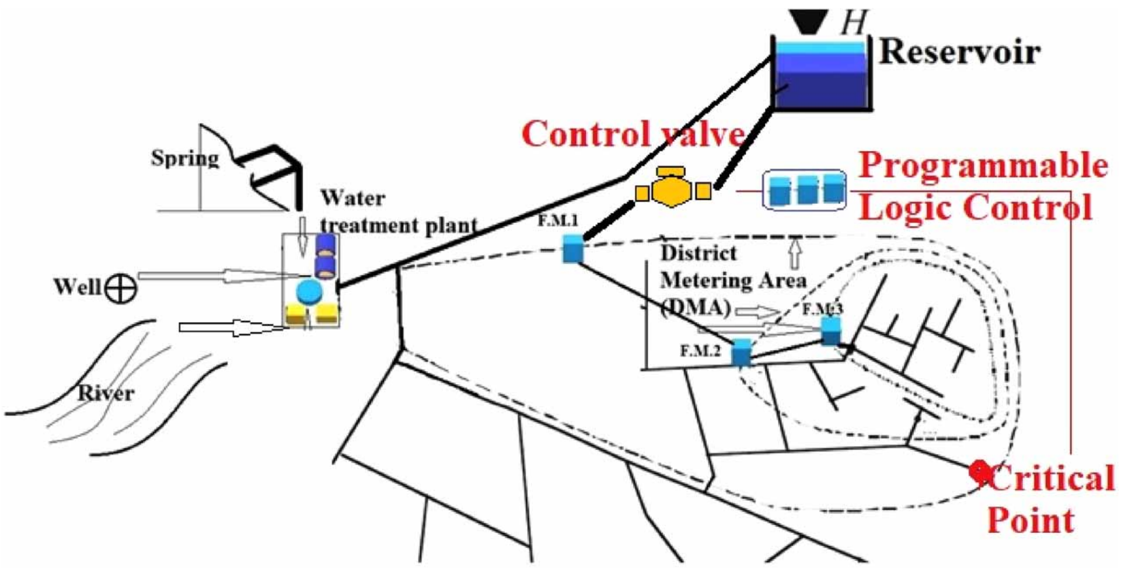


Figure 2 | DMA for MNF and corrosion control in compliance with IoT for the water system.

Research hypotheses of regression analysis for MNF. The research hypotheses research hypotheses of regression analysis for MNF in this work were:

Hypothesis One:

There are significant relationships between Input (independent variable) and Outputs (dependent variable) (5):

$$Output = f(Input) \quad (5)$$

Dependent variable: Outputs/Inflow to the water distribution network (l/s); Outputs/Pressure (kPa). *Independent variable*: Input/Time (h).

Hypothesis Two:

There is a significant relationship between dependent and independent variables (6):

$$Outputs = f(\text{Pressure, Time}) \quad (6)$$

Dependent variable: Outputs/Inflow to the water distribution network (l/s). *Independent Variables*: Input/Pressure (kPa); Time (h).

The second step

Clarifying the error of consumers' meters. The calculation of error percentage and correction factor (CF) were as the following formulation (7)–(10):

$$100 \times \left[\frac{\text{reference meter function}}{(\text{reference meter function} - \text{consumer's meter function})}\right] = \text{error percentage} \quad (7)$$

Usually, meters were tested according to the request of the consumers. The error percentage of the majority of them was positive (the consumer's meter shows more than the real value). In the cases that were reported in this work by the meter's reader, the meters have stopped. In general, after testing the meters, the following three situations are possible:

- The error percentage of the consumer's meter should be less than 5%.
- The error percentage of the meter should be more than 5%.
- The meter must have stopped.

In two cases (b) and (c), that is, when the percentage of error was more than 5% or the meter was stopped, the consumer's meter was sent to the workshop. In order to calculate the water price of consumer's consumption, the global consumption was taken into account as follows (8)–(9):

$$\text{Consumer's meter function/reference meter function} = \text{correction factor} \quad (8)$$

$$\text{Correction factor} \times \text{consumer's meter function} = \text{actual consumption in considered period} \quad (9)$$

Q_{ma} is the consumer's consumption based on the average CF (liters per day). Q_m is the average consumer's consumption, during the reading period of 60 days (liters per day). 15CF is the CF in discharge of 15 l/h. 30CF is the CF in discharge of 30 l/h. 60CF is the correction coefficient in discharge of 60 l/h. 120CF is the correction coefficient in discharge 120 l/h. 300 CF is the correction coefficient in discharge 300 l/h.

In the case that the CF became infinite, in order to determine the average CFM consumption coefficient, the relationship was corrected in such a way that the density of consumption coefficients related to the infinite discharges obtained with the density of consumption coefficient of the adjacent discharge was added in the relevant table and in the overall relationship interference was given. Therefore, for this situation, a compensatory consumption Q_{ad} was considered for the infinite CF according to Equation (10).

$$Q_m * Q_{ad} = W_{\inf} \quad (10)$$

In this relation, $W_{\inf}$ is the set of the density of consumption coefficients related to the ranges with infinite discharge, that was, the range that did not show the consumer's meter, consumption.

The second step

Unauthorized consumption. In general, the term 'unauthorized consumers' refers to consumers who have legal branching and sharing, but because of interfering with the state of the meter or branching with the aim of abusing the network facilities, not complying with the rules and regulations, and not fulfilling their obligations in one of the following ways:

- Branches with pumps for suctioning the network.
- Consumers who have made their taps invisible.
- Unauthorized branching before the contour.
- Unauthorized branching after the meter to another property.
- Reverse contour.
- Open seal contour.
- Broken meters.

After processing the information related to the control of all the non-standard branches and consumers' violations, a list is prepared.

Research tools

The research tools for the first step (determining the share of water loss due to network corrosion and MNF were included: meters for water production; global positioning system (GPS) for production of geospatial data; WATERGEMS software; ArcGIS-ArcMap software; meters' tester; RS facilities; advanced modems; data loggers; networked sensors.

Research tools for the second step (clarifying the error of consumers' meters) were included the hydraulic model, the map of the meters' cluster test, the map of the DMA and meters for water consumption. For two percent of consumers cluster, test of consumption classes was done. In order to reduce the error of the measuring equipment and correct these errors in the apparent water loss section, the objectives of the DMA operation of the cluster test of the meters were as follows:

- Checking the correct operation of the meter at the installation site.
- Periodic testing of meters (DMA for cluster testing of meters).
- Registration and storage of information (volume and flow rate) in a specific period.

The technical specifications of the meter cluster testing equipment are as follows:

- Flow range: 8–1,200 (l/h).
- Rechargeable battery for 8 h of continuous work.
- Testable meters from 15 DN to 20 DN.
- Measurement accuracy: 1% of the read volume with CC10 resolution.
- LCD display: eight lines with volume and flow direction.

The results of the accuracy test for the meters were recorded in the query of GIS. The forms of the tested meters were determined for the pilot ranges and test equipment (Table 1).

Table 1 | Equipments of meter testing operation

No.	Equipment	Description of operation
1	Portable flowmeter	Portable reading of inlet flow to the pilot
2	Remote reading pressure gauge	Remote reading of pilot working pressure
3	Geophone device (leak detector)	Leakage monitoring of the pilot facility
4	Cap detector	For visibility and maintenance
		On network valves
5	Branch test device	To ensure that there is no leakage
		Leakage detection after the meter
6	GPS	Registration of the geographic location of tolls
7	Flow meter with remote reading	Readout from remote input to pilot

Hydraulic model and GIS

In this work, the modelling of the network was defined based on the GIS in the following ways:

- Completed the descriptive and spatial information layers and fixing the errors.
- Separated parts were snapped together with proper tolerance.
- Removed toll errors that were in the wrong place.
- Established tolerance and exchanged complications from spaghetti space to topology space.
- Prepared the conceptual model for network modelling in GIS space.
- Created a proper geo-database.
- Created tracking capability and performed network analysis.
- Determined the extent of corrosion for the water distribution network in compliance with GIS.

Water loss effects were implemented on the GIS map. The hydraulic model was calibrated by the spatial data infrastructure (SDI). In this model, spatial data related to the network and hydraulic data were also analysed. The hydraulic model was also abled to record the coordination of facilities location at any moment of the day and night for the network. These data were related to the location of pressure zones, pressure relief valves, shut-off valves, air valves, butterfly valves, pressure reducing valves, fire hydrant valves, pumps, reservoirs, surge tanks, and one-way valves. The hydraulic analysis of network parameters such as pressure and flow velocity was also recorded. In addition, the flow and pressure variations in the pipes, the discharge pressure of the pumps, the working pressure of the water distribution network and the water level in the reservoirs were obtained ON-LINE. In this work, maps were prepared by CAD and SCAN files for several DMAs. Then, separately, the range of selected DMA implementation was determined. For the maps of the selected DMA, the GPS coordinates of two points were provided. The Shape-file prepared for all geo-referenced maps. The spatial and descriptive information fields were created in GIS. The network model was calibrated by using the hydraulic analysis results. The calibration was done in the WATERGEMS software and ArcGIS-ArcMap software. All data were detected by remote reading flowmeters and pressure gauges. The actual model of water distribution networks was analysed by the curve estimation method during the regression test. The actual model was checked by using these geo-referenced data. The model was calibrated by using a set of data without changing the parameter values.

RESULTS AND DISCUSSION

The first-step results

An efficient database of facilities and consumers as the main server can solve many problems. In addition, it is necessary to reflect the subsequent changes in the network and places on these maps so that they do not lose their effectiveness over time. If the information about the facilities be in the memory of experts and experienced workers, it will be out of reach of the system with the passage of time. By updating the map information of facilities in GIS format, different data can be extracted from it in a short time. Therefore, in the present work, at first, the maps of facilities and the maps of consumers were scanned, edited, and layered in GIS format.

In the NRW reduction plan, network analysis calculations were done to achieve the following goals:

- Investigation of incoming and outgoing flows from each DMA.
- Evaluation of the system simultaneously with the operation.
- Economic evaluations of the distribution system.
- Determining the size, type and location of faucets, regional meters, and pressure booster pumps.
- Examining different network isolation options and choosing the best option.
- Determining the value of inflow to the network and the capacity of the network.
- Adjust pressure and flow in order to reduce physical and non-physical leaks.
- Determining the amount of flow passing through different DMAs and the maximum pressure in the pipe, speed, and flow direction.
- Providing information to estimate water loss caused by pipe breaks and other incidents.
- Comparison of the field measurements of water flow and pressure in different locations of the network (by computer model and determining the zones with the most leakage).

In the present work, the main purpose of the network analysis was the water loss reduction plan. This procedure led to evaluating the theoretical parameters with real conditions of the distribution system.

Hydraulic model

In this work, the choice of model and the modelling of the distribution network were considered in the water loss reduction plan by IoT. There are many issues in choosing a model and the ability of models to meet these needs will depend on them. In choosing a model, there are various questions that can be answered easily by reviewing the capabilities of the available software, and the desired software can be selected and used. In the present work, the hydraulic model of the distribution system has been prepared by WATERGEMS software.

Hydraulic model calibration

During the field operation, DMAs were selected for cluster test of the consumers' meters due to apparent water loss and statistical population. The hydraulic model calibration process was defined in compliance with GIS and IoT. The calibrated model revealed the range of the leakage positions. This procedure showed the error of the measuring equipment and the correction of these errors. It provided the intelligent pressure management and water loss control for the distribution network (Figures 3 and 4).

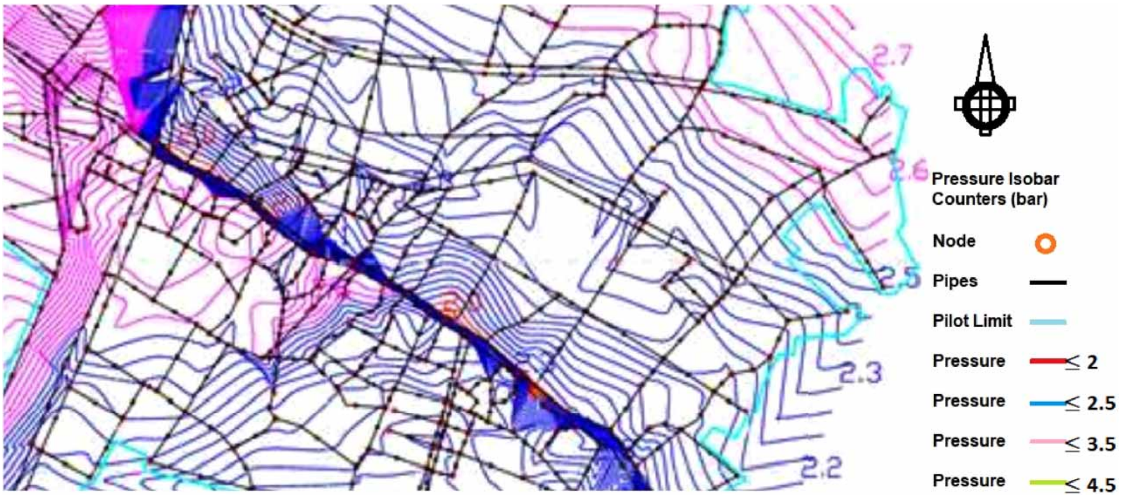


Figure 3 | Pressure curves for intelligent pressure management of the water distribution network (WATERGEMS and ArcGIS-ArcMap) software, at 2–4 O'clock in the morning.

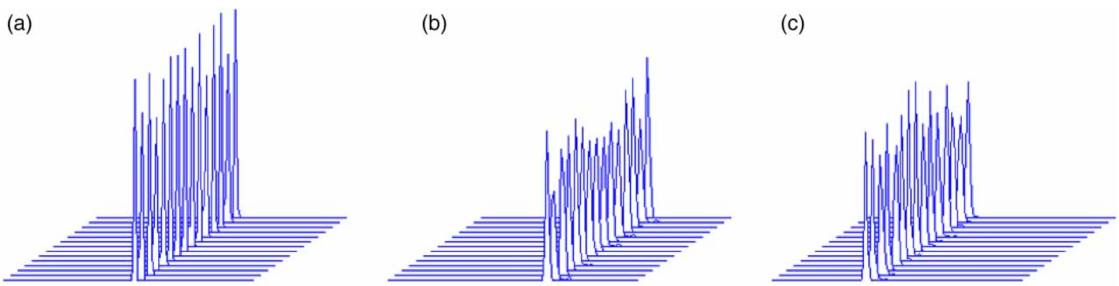


Figure 4 | Leakage locations at water distribution network for leakage detection range: 0–100 dB; (a) at 2–4 O'clock in the morning, (b) before 2–4 O'clock in the morning, and (c) after 2–4 O'clock in the morning.

Hydraulic model and regression analysis

The inflow to the independent DMA compared with the consumers' consumption. This procedure led to the clarification and correction of the amount of NRW and its components. Regression analysis showed the inflow to the independent DMA effects on MNF. The Regression parameters included pressure (kPa) and inflow to the water distribution network (l/s) as the independent variables (Figures 5–10) (Tables 2–6). Analysis of consumption curve and MNF beside the pressure isobar counter done along with hydraulic modelling. The intelligent pressure management in GIS platform used regression and a hydraulic model for the distribution network. According to

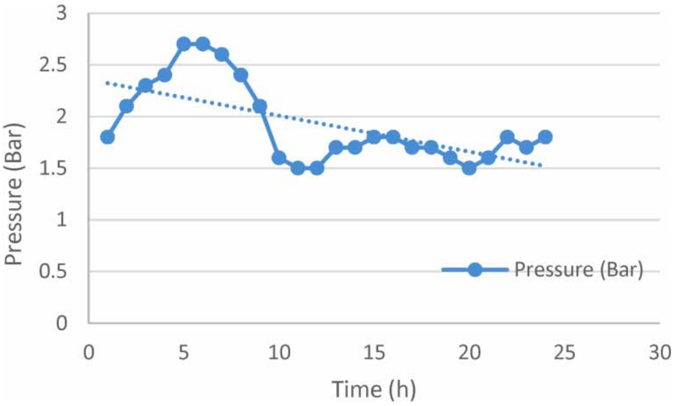


Figure 5 | Analysis of the pressure curve and the MNF.

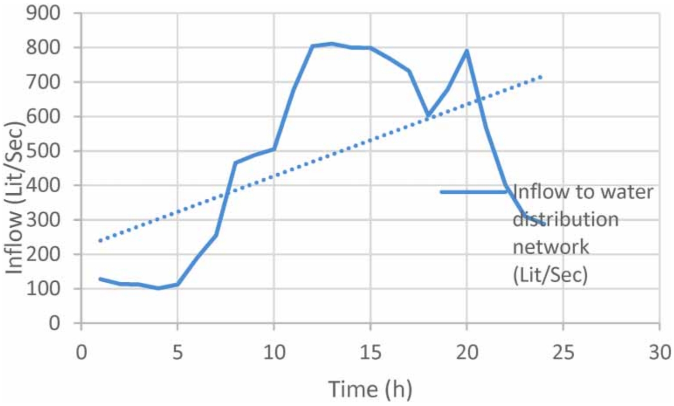


Figure 6 | Analysis of the consumption curve and the MNF.

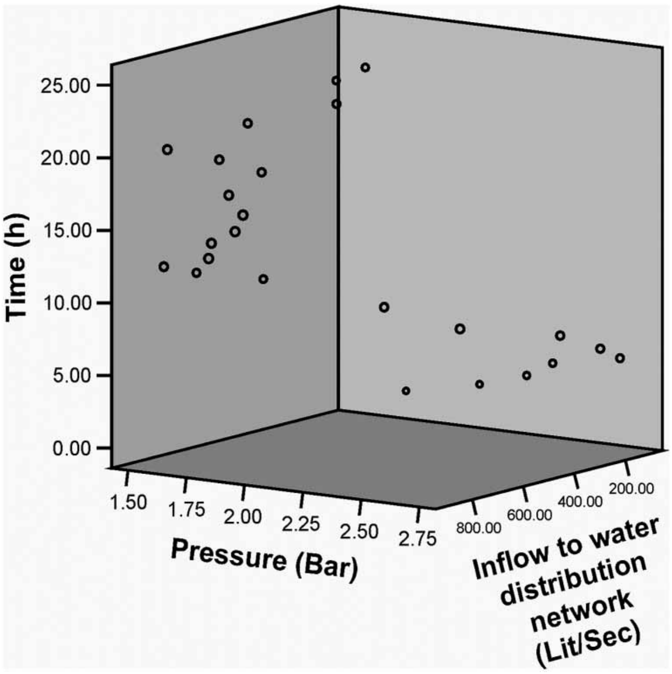


Figure 7 | 3D scatter diagram of time, pressure, and inflow to the water network.

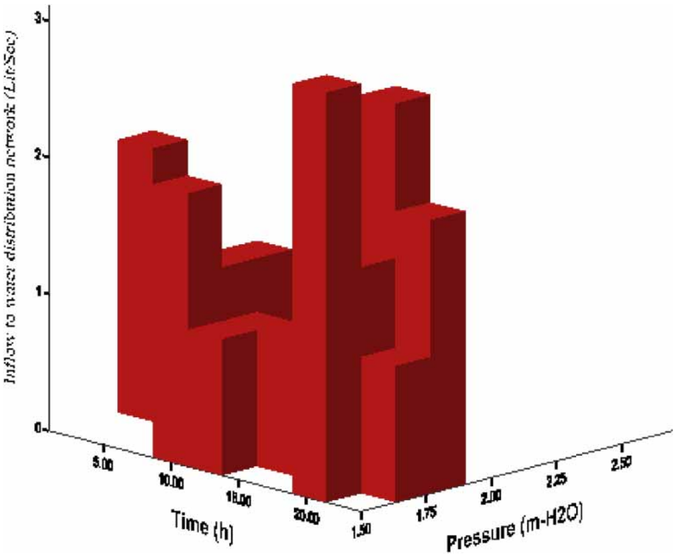


Figure 8 | 3D interactive graph of time, pressure, and inflow to the water distribution network.

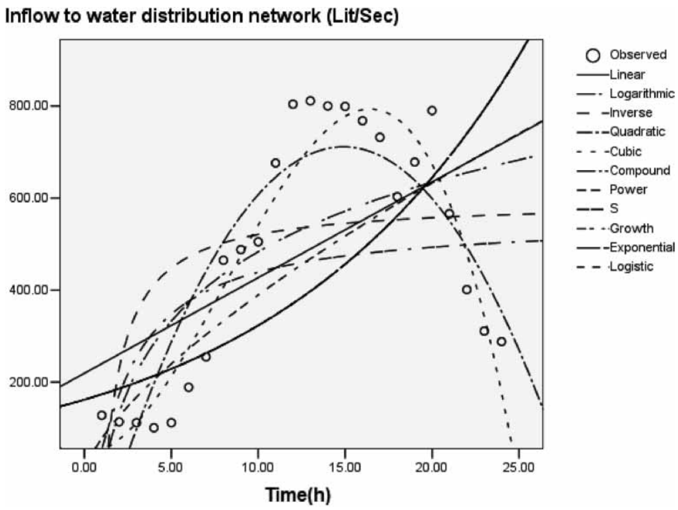


Figure 9 | Curve fit for the inflow of the water distribution network and time.

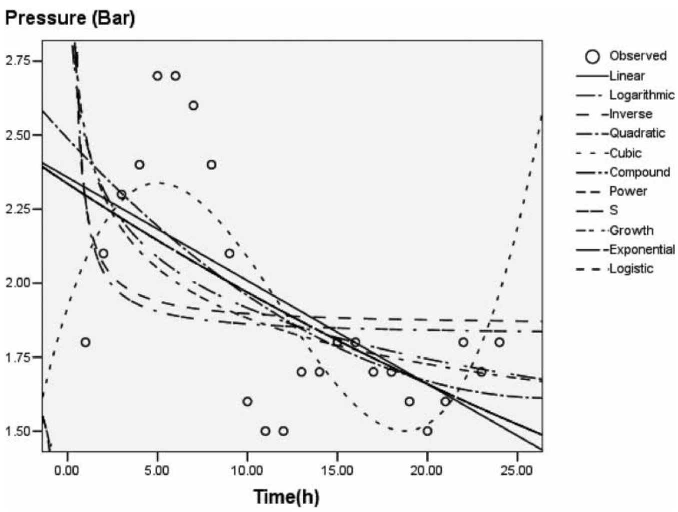


Figure 10 | Curve fit for the pressure of the water distribution network and time.

Table 2 | Working pressure of the water distribution network (l/s)

Time (h)	Pressure (kPa)	Inflow to the water distribution network (l/s)
1	1.8	128
2	2.1	114
3	2.3	112
4	2.4	101
5	2.7	112
6	2.7	189
7	2.6	255
8	2.4	465
9	2.1	488
10	1.6	505
11	1.5	676
12	1.5	804
13	1.7	811
14	1.7	800
15	1.8	799
16	1.8	768
17	1.7	732
18	1.7	603
19	1.6	678
20	1.5	790
21	1.6	566
22	1.8	401
23	1.7	311
24	1.8	288

Table 3 | Descriptive statistics of the water distribution network

Variables	*N*	Minimum	Maximum	Mean	Std. deviation
Time (h)	25	1.00	24.00	12.0400	7.29429
Pressure (m-H2O)	25	1.50	2.70	1.9160	.38262
Inflow to the water distribution network (l/s)	25	101.00	811.00	464.9600	270.79166
Valid N (listwise)	25				

the results of the work, in the first stage, the replacement of contours with a negative error was given the first priority.

The results of the hypothesis one (Equation 11) due to regression analysis were as the following (Figures 5 and 6):

$$Output = f(Input), \tag{11}$$

Dependent variable: Inflow to the water distribution network (l/s); Pressure (kPa); *Independent variable*: Time (h).

The results of the hypothesis two (Equation 12) due to regression analysis and descriptive statistics and standard deviation were as the following (Figures 7 and 8) (Table 3):

$$Outputs = f(\text{Pressure, Time}), \tag{12}$$

Dependent variable: Inflow to the water distribution network (l/s); *Independent variables*: Pressure (kPa); Time (h).

Table 4 | Equations using the obtained regression models for the present work (Equations (13)–(23))

Equation	Model summary					Parameter estimates			
	R^2	F	df1	df2	Sig.	a_0	a_1	a_2	a_3
Linear (13) $\mathbf{y} = \mathbf{a}_0 + \mathbf{a}_1 x$	.302	9.533	1	22	.005	219.326	20.774		
Logarithmic (14) $\log y = \log(a) - (b)\log x$	.458	18.591	1	22	.000	−17.970	217.712		
Inverse (15) $\mathbf{y} = f^{-1}(\mathbf{y})$	.327	10.685	1	22	.004	593.680	−728.909		
Quadratic (16) $\mathbf{y} = \mathbf{a}_0 + \mathbf{a}_1\mathbf{x} + \mathbf{a}_2\mathbf{x}^2$	.802	42.535	2	21	.000	−249.216	128.899	−4.325	
Cubic (17) $\mathbf{y} = \mathbf{a}_0 + \mathbf{a}_1\mathbf{x} + \mathbf{a}_2\mathbf{x}^2 + \mathbf{a}_3\mathbf{x}^3$	.910	67.115	3	20	.000	42.518	1.666	8.142	−.332
Compound (18) $\mathbf{A} = \mathbf{C}\mathbf{e}^{\mathbf{kt}}$	.419	15.871	1	22	.001	162.119	1.071		
Power (19) $\mathbf{y} = c\mathbf{x}^{\mathbf{p}}$	.595	32.361	1	22	.000	77.670	.700		
S (20) $\mathbf{y} = f_0(\mathbf{T}, \mathbf{X}, \mathbf{U})$	.420	15.900	1	22	.001	6.317	−2.330		
Growth (21) $(\mathbf{dA}/\mathbf{dT}) = \mathbf{KA}$	.419	15.871	1	22	.001	5.088	.069		
Exponential (22) $\mathbf{e}^x = \lim_{n\to\infty}\left(1+\frac{1}{n}\right)^n$	.419	15.871	1	22	.001	162.119	.069		
Logistic (23) $\mathbf{f}(x) = \frac{L}{1+e^{-k(x-x_0)}}$	.419	15.871	1	22	.001	.006	.933		

Table 5 | Model summary and parameter estimates

Equation	Model summary					Parameter estimates			
	R^2	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.302	9.533	1	22	.005	219.326	20.774		
Logarithmic	.458	18.591	1	22	.000	−17.970	217.712		
Inverse	.327	10.685	1	22	.004	593.680	−728.909		
Quadratic	.802	42.535	2	21	.000	−249.216	128.899	−4.325	
Cubic	.910	67.115	3	20	.000	42.518	1.666	8.142	−.332
Compound	.419	15.871	1	22	.001	162.119	1.071		
Power	.595	32.361	1	22	.000	77.670	.700		
S	.420	15.900	1	22	.001	6.317	−2.330		
Growth	.419	15.871	1	22	.001	5.088	.069		
Exponential	.419	15.871	1	22	.001	162.119	.069		
Logistic	.419	15.871	1	22	.001	.006	.933		

Table 6 | Test statistic and *p*-value calculation

Parameters	Inflow to the water distribution network (l/s)	Pressure (kpa)	Time (h)
χ^2	.917	6.750	.000
df	22	8	23
Asymp. Sig.	.988	.564	.961

Pressure control and network behaviour

This work made the connection between GIS, RS, and IoT for rapid data intercommunication. In such a way, it became to record the pressure and flow variation of the water distribution network. The conceptual model was defined for the prediction of the relationship between corrosion and changes in the MNF rate in water distribution facilities. By Improvement of RS facilities installation equipped with data loggers, IoT and geo-database intercommunication process, the present work investigated the use of modern techniques such as networked sensors, IoT, GIS and RS. Results of work accessed the leakage points in the calibration process of the water distribution network. The following common forms were assumed for control of the working pressure of water distribution network.

Fixed outlet

- Delivers constant outlet pressure.
- Designed to give target pressure at CP at peak flow.

Time-switched control

- Stepped variation in the pressure regulating valve (PRV) outlet pressure at specific times.
- Removes excess pressure at a specific time.
- Simple and low cost.
- Can cause pressure surges when reopening.

Flow modulation

- PRV outlet pressure varied according to through flow.
- The aim is to achieve flat pressure at CP.
- More complex, higher cost of construction.
- If PRV is sized correctly, it will deal with fire demands and create a clam network.

Regression analysis and curve fit

Curve fit for the inflow to the water distribution network against time and pressure of the water distribution network against time was provided by regression analysis (13)–(23) (Figures 9 and 10) (Tables 4–6).

The independent variable is time (h) and dependent variable is the inflow to the water distribution network (l/s).

$\mathbf{A} = 219.326 - 20.774x$	Linear function (13)
$\log y = \log(-17.970) + (217.712)\log x$	Logarithmic function (14)
$\mathbf{y} = 593.680 - 728.909f^{-1}(\mathbf{y})$	Inverse function (15)
$\mathbf{y} = -249.216 - 128.899\mathbf{x} - 4.325$	Quadratic function (16)
$\mathbf{y} = 42.518 + 1.666\mathbf{x} - 8.142\mathbf{x}^2 - .332x^3$	Cubic function (17)
$\mathbf{A} = 162.119\mathbf{e}^{\mathbf{t}} + 1.071$	Compound function (18)
$\mathbf{y} = 77.670\mathbf{x}^{.700}$	Power function (19)
$\mathbf{y} = f_0(6.317\mathbf{X}, -2.330)$	S function (20)
$(\mathbf{dA}/\mathbf{dT}) = 5.088\mathbf{A} + .069$	Growth function (21)
$\mathbf{y} = (162.119 - .069)^{\mathbf{x}} + \mathbf{g}$	Exponential function (22)
$\mathbf{y} = .006\mathbf{x} + .933$	Logistic function (23)

Due to the parameter limitations, the power function had a suitable correlation on the scatter diagram and best-fit curve which was used for the inflow to the water distribution network (l/s) based on the regression model shown in (Tables 4–6). The inflow to the water distribution network (l/s) varied with the time (h), as shown in (24)–(25):

$$\mathbf{y} = c\mathbf{x}^{\mathbf{p}} \tag{24}$$

$$\mathbf{y} = 77.670\mathbf{x}^{.700} \tag{25}$$

where **y** is the inflow to the water distribution network (l/s), **x** is the time (h), *c* and *p* are parameters determined by the linear least-squares method using data from the ten parameters tested.

The *p*-value is the level of marginal significance within a statistical hypothesis test representing the probability of the occurrence of a given event. The *p*-value is used as an alternative to rejection points to provide the smallest level of significance at which the null hypothesis would be rejected. In this work, the following procedure was done for the *p*-value evaluation:

- Determine the experiment's expected results.
- Determine the experiment's observed results.
- Determine the experiment's degrees of freedom.
- Compare expected results to observed results with χ^2.
- Choose a significance level.
- Use a χ^2distribution table to approximate the *p*-value.
- Approximate *p*-value for the experiment, it can be decided whether or not to reject the null hypothesis of the experiment.

Generally, based on the hypothesis and the experimental results, If the *p*-value is lower than the significance value, it can be shown that the experimental results would be highly unlikely to occur if there was no acceptable relation between the variables which be manipulated.

In this work, the *p*-values for three variables included the Inflow to the water distribution network (l/s); Time (h) and Pressure (kpa) were as the flowing (Table 6):

- *p*-value for Inflow to the water distribution network (l/s):

  $\chi^2 = .917$, $DF = 22$
  The *p*-value equals .988.

By conventional criteria, this difference was considered to be not statistically significant.

- *p*-value for pressure (kpa):

  $\chi^2 = 6.750$, $DF = 8$
  The *p*-value equals .564.

By conventional criteria, this difference was considered to be not statistically significant.

- *p*-value for time (h):

  $\chi^2 = .000$, $DF = 23$

  The two-tailed *p*-value equals .961.

The second-step results

In this work, a cluster test of consumers' meters was performed for the statistical population in the separate range of DMA measurement. Due to the heterogeneous situation of fluid working pressure distribution in the distribution network, high correction coefficients could be expected. According to the results of the current work and the statistical testing of the meters of the consumers in the sales and income department, it was suggested that the meters with negative errors should be identified and replaced as a priority in the first stage (Figure 11).

Finally, in order to accurately calculate the average correction coefficient of consumers' meters, unrealistic correction coefficients (greater than 2) were removed. These meters were assumed that stopped in discharge. The number of meters with a negative error, with a positive error, and the number of stopped meters are shown in Figure 11. As part of the implementation of intelligent pressure management in the cluster test pilot, the frequency of consumption classes was determined for all pilot subscribers. This meter stopped the necessary efficiency due to the corrosion of the meter housing and the wear of the internal parts. These meters are not able to measure the flow in high flows and are effective in water losses. In general, the results of the work, and the analysis of water loss caused by broken meters are as follows. The correction coefficient of the joint meters is very large, which indicates the low accuracy of the joint meters. Usually, in this flow, the internal leakage of the water network of the consumers and very low flows occur and almost all the meters of the consumers lack accuracy in measuring this amount of flow. This can eliminate the necessary incentives for the repair of small

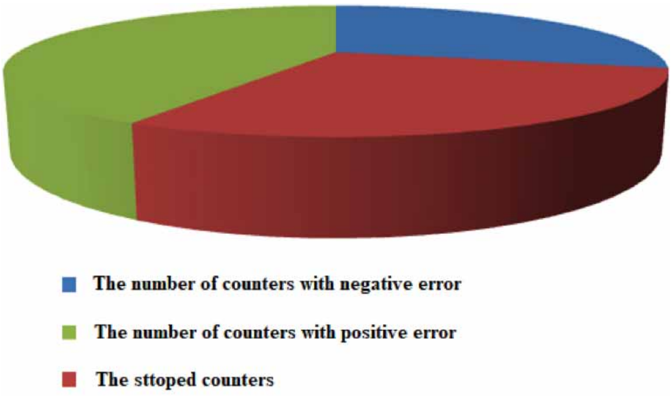


Figure 11 | The results of the pilot operation of the cluster test of the consumers' meters.

and internal network leaks for consumers. In this regard, based on the results of the research, in order to reduce the leakage in the internal network of the consumers, it is necessary to conduct a periodic test of the consumers' meters based on the guidelines of the internal requirements of the consumers. Taking into account the allowed expenses without income, the amount of actual water loss was equivalent to 1.12% of the volume of produced water. Therefore, the results of the work put the economic justification of replacing the meters with negative error as the first priority.

The third-step results

The solution presented in this work emphasized on all places and neighbourhoods should be monitored, controlled, audited, and surveyed. Then, the condition of the water branches should be determined. At the same time, a correct coding system should be applied and all defective contours as well as non-technical and unprincipled branches should be corrected. Pressure should be measured in the main pipe and in the branches of the water pipes in the alleys and streets after the local visit and timely maps. By transferring the results of the pressure measurement on the coded map of the network, draw a pressure curves map. In the end, with the identification of different pressure ranges, in relation to the hydraulic analysis and pressure adjustment of the water distribution network, corrections related to unauthorized branches in the water distribution network should be made.

CONCLUSIONS

In this work, the mathematical and hydraulic models were defined for the MNF and pressure variation investigation in the water distribution network due to corrosion. The hydraulic model was calibrated during the share investigation process of water loss related to the total UWL. The other effective factor for hydraulic model calibration was the querying of corrosion regions based on the GIS. The total UWL also was investigated through a mathematical model based on the regression analysis. In this regard, changes in the MNF were considered. The error of the consumers' meters and the correction of these errors were calculated in the apparent water loss section. The main results of this work, and suggestion for future research were as the following:

- The replacement of contours with a negative error was given the first priority.
- The error percentage of the majority of meters was positive.
- The Power function had a suitable correlation on the scatter diagram.
- The value of apparent water loss was equal to 1.12% of produced water.

Therefore, by using the results of model calibration and checking the incident density of the network, the range of the leakage positions (the real water loss section), the error of the measuring equipment and the correction of these errors (the apparent water loss section) were determined. In the present work, the field operation of cluster test for the consumers' meters was informed in the selected DMA. The statistical population in the measurement area was compared with the consumption of the consumers. Finally, these procedures led to the clarification and correction of the amount of NRW and its components. The results also showed that the measurement error of the meters in sensing the flow rate (below the start flow of counters) is one of the obvious cases in the apparent water loss section. The result of this work reduced the NRW and led to saving drinking water.

Applicability of findings and suggestion for future research

This work helps to water-saving modelling for the MNF and pressure variation in the water distribution network due to corrosion and led to raising the following suggestions for future research:

- Make the connection between GIS, networked sensors, RS, and IoT for rapid data intercommunication to record the water pressure and MNF rate detection in a little time of up to 1 s.
- Conceptual modelling definition for prediction of the water pressure and MNF variation due to corrosion.
- Improvement of RS facilities installation equipped with data loggers, IoT and GEO-database intercommunication process.
- Relationship class definition for water system elements according to the type of connections (simple or complex) to apply the advanced method for accessing the leakage points in the calibration process of the water distribution networks.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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