

# A MODEL - BASED APPROACH FOR LEAK DETECTION IN WATER DISTRIBUTION NETWORKS BASED ON OPTIMISATION AND GIS APPLICATIONS

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## Abstract

This paper describes the development of an integrated approach for water pipe network calibration and quantifying leaks. The approach merges both field measurements and linear programming to pinpoint pipe leaks (physical losses); then applies Genetic Algorithms (GA) to identify faulty meters and meter thefts (apparent losses). Besides; throughout the process, GIS is used for input data integration and output representation. The developed model is based on GA but is different in its representation, introducing a new adaptive constraint handling function and a new mutation function. Also, the use of floating-point representation enables the calibration of a large number of unknown parameters without compromising the accuracy and precision of the solutions. While the newly introduced constraint handling function robust the solution towards a near level of agreement between real and calculated values. A pilot site is used to test the model and approach, comparing before and after field results to ensure accuracy. The model integrates EPAnet for the required hydraulic modeling during the simulation. The results prove the approach's accuracy and efficiency.

## Keywords:

Leak detection;  
Network calibration,  
Optimization;  
Water losses;  
GIS.

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## 1 Introduction

The national volume of (NRW) or water losses is staggering. Based on The National Water Resources plan of Egypt 2037 and the ministry of water resources and irrigation; both estimate the annual drinking water consumption by around 10 billion m<sup>3</sup> per year. Each year around 3.5 billion m<sup>3</sup> of treated water are lost through leakage from distribution networks; theft, inefficient metering. As a prediction of 35 % of water losses exist in the system. A conservative estimate of the total annual loss to water utilities in Egypt is 4.5 billion Egyptian Pounds (equivalent to 250 Million EUR) based on Holding Company for Water and Waste Water (HCWW). Saving just half of this amount would supply water to an additional 11 million people without further investment. Given the above; the need to reduce both physical and apparent water losses in drinking water distribution systems is an absolute necessity matter at the national level given water scarcity, as well as, for researchers and industrialists [1, 2].

There are additional benefits such as; Water utilities gain access to a further 2.1 billion m<sup>3</sup> per year. Eventually, through applying active leak management new business opportunities will be created; thus benefiting the overall economy. Therefore, the development of technologies and strategies for detecting, providing, advancing warning, and controlling water pipeline leakage is crucial for both the water supply companies and the public [3].

## 2 Water loss terms and concepts

### 2.1 General concepts

There is no current broad national regulatory policy that limits the amount of water loss from a public water supply's distribution system.

Non-revenue water (NRW) equal to the gross amount of water flowing into the water supply Network from a water treatment plant (the 'system input volume') minus the total amount of water that is authorized to use (the 'Authorized Consumption').

$$\text{NRW} = \text{System Input Volume} - \text{Billed Authorised Consumption.} \quad (1)$$

Equation (1) assumes that the billed metered consumption period for customer billing records is consistent with the system input volume period.

## 2.2 Active field leak detections techniques

Perhaps the most common form of water loss leak detection is from proactively searching for leaks in the field. The three main technologies as stated below [4]:

- Noise loggers: Noise loggers limit the search area of the network that contains suspected bursts or number of leaks. A cluster of loggers, usually 15, 20 should be installed surrounding the network inlets and outlets in the survey area. Each logger should be placed on a fixed point (such as check valve, hydrant, master meter, bulk meter ...etc.). The logger signals an indicator of whether a suspected noise being caused by leaks is detected or not.

- Leak noise correlators: This instrument pinpoints the leak(s) position along a specific pipeline through the use of the velocity of sounds made by the leak as it travels along the pipe toward each of two correlators placed on either side of the suspected leak. The device calculating the distance of leak is based on the Cross-correlation technique, in which a signal is processing techniques established in engineering applications [5].

- Ground microphones: The ground microphone electronically amplifies the sound of a leak. It could be used as a manual check device, or as a blanket survey instrument for searching for leaks on lengths of a pipeline between fittings. Usually, they are used to identify leaks in house connections.

## 3 Case study

Faisal City area consists of 86 buildings, each one contains 13 floors, a Mosque and two schools and several commercial stores and also governmental offices, 9 gardens, 5 hydrants, and 159 master meters installed in the block. The total pipe length of the water distribution network is 6.7 km and, the block area is 0.252 km<sup>2</sup>. The average pressure is between 1.6-1.8 bars, and the population count is 15000 per capita. The area is feed from three sources, two of them were closed and an ultrasonic flow meter was installed on the main entrance (8" inch pipe), and 10 pressure recorders were distributed around. Fig. 1 shows the layout of the pilot area indicating the locations of both pressure recorders and leak noise loggers using ArcGIS.

The operational steps for minimizing NRW in Faisal started by creating raster GIS maps using Google Earth™ Second, conducting a site field survey.

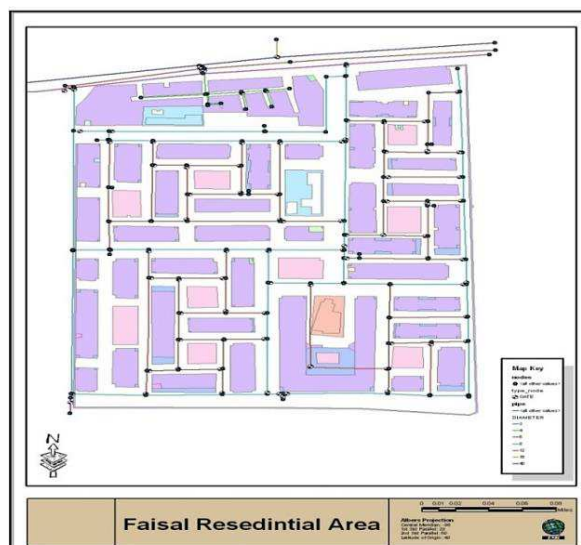


Fig.1: Faisal city block layout

To check valves; exposing, repairing, and replacing of Faulty valves, and locating main distribution pipelines, distribution pipelines, and house connections. Afterward, a GIS map is created containing all relevant data (network – valves – meters). The procedure continues with implementing zero pressure tests to identify zone inlet. Followed by, closing all inlets except one, to ensure control of water entering the zone. Then, installing ultrasonic flow meters at the inlet point to record flow for 48 h period, along with installing pressure data recorders meters at the inlet point and various pipes throughout the network to record flow for the same period. At the same time, a field survey is conducted to read the master meters readings. Fig. 2 summarizes the procedure.

These data are analyzed to calculate the NRW (NRW= system input – master meters readings), and analyzing the inlet flow meter data to estimate the amount of real (physical) losses on a minimum night flow basis. The possible apparent (commercial) losses are considered the difference between total NRW and physical losses.

Noise loggers are installed throughout the system to detect possible leaking pipes. Afterward, noise correlators are used to identify and pinpoint leak positions for the distribution network and using an acoustic ground microphone to pinpoint leaks in house connections.

Once finalized, a twofold approach is implemented:

1) Field measurements used to identify pipe leakages and then use an empirical orifice-based equation to estimate the amount of water lost (physical losses), and add it as junction points in GIS and EPAnet.

2) Running the custom made an application for apparent losses detection through network calibration (EAcalib) to calibrate the network junction (meters) demand and identify high demand variation junctions (meters) as faulty meters (source of Real Losses) to be replaced Along with calculating near actual pipe roughness coefficient CHW, and quantifying leak quantities at found leak points. A comparison is made to check the percentage of apparent losses and physical losses deduced from the optimization model, empirical equation, and field measurement is made for calibration purposes.

Once replacing the suspicious Master meters, the network is repaired after pinpoints leaks, flow meters and, pressure recorders are installed to calculate the % of NRW after repairing leaks. Finally, running flow and pressure test again to check the amount of water saved. Fig. 2 summarizes the workflow for the Faisal city block minimizing NRW methodology.

**4 Results analysis**

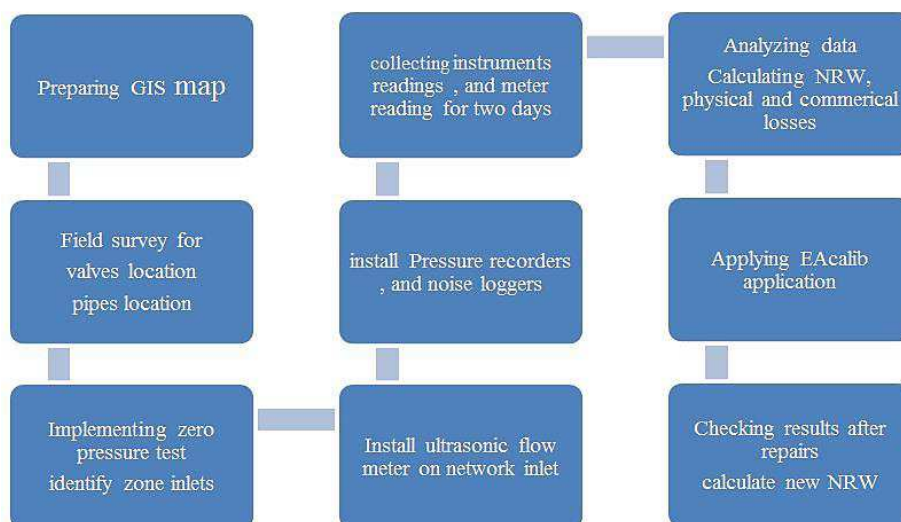


Fig. 2: Leak detection methodology workflow.

First, flow and pressure curves are being analyzed for a single-day run. The data gathered by an ultrasonic flow meter, pressure recorder, and meter reading at the "Faisal City Block" inlet to identify the estimated amount of leak.

Fig. 3 explains the flow and pressure curve obtained and the calculated NRW, predicted physical losses, and commercial losses percentages.

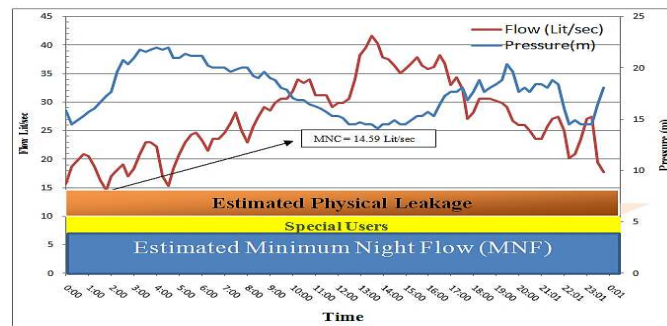


Fig. 3: Faisal city block flow and pressure profile.

$$NRW = \text{Total System Input} - \sum \text{Meter Reading}, \tag{2}$$

where Total System Input = Total volume of water entering the area,  $\sum \text{Meter Reading}$  = summation of meter reading in all areas for the same duration.  $NRW = 2380.313 - 1023.54 = 1356.773 \text{ m}^3/\text{day}$ ;  $NRW \% = 57 \%$

The Minimum Night Flow (MNF) normally occurs during 02:00 and 04:00 hours. Yet, the exact timing might differ from one area to another. Therefore, it is recommended to identify the minimum period from the flow calculations, Fig 3. In the case of Faisal, the minimum Night flow occurred between 4-6 am. The MNF is the most meaningful piece of data as far as physical loss levels are concerned. During this period, consumption is at a minimum and therefore physical losses are at the maximum percentage of the total flow. According to the Egyptian code of Practice (ECP) for designing pipelines of drinking water and sanitation, the dry weather flow discharge  $Q_{D,W,F}$  is the minimum flow occurring at night or winter. Thus, in the present paper, it is suggested to use it as MNF [17].

$$MNF = (0.2 \times \text{Pop}^{1/6}) \times Q_{avg}, \tag{3}$$

where Pop = Population in thousands,  $Q_{avg}$  = average flow in l/sec, Average Daily Flow  $Q_{avg}$  = total volume of water entering the network for 24 hours/24 which equals  $99 \text{ m}^3/\text{h}$  or  $27.55 \text{ l/sec}$ .  $MNF = (0.2 \times \text{Pop}^{1/6}) \times Q_{avg} = 8.66 \text{ l/sec}$ .

Assuming additional 10 % for special users total MNF = 9.52 l/sec.

Minimum night consumption (MNC) is the least flow rate occurring at the network; usually, it occurs between 1:00 am and 4:00 am. As shown in Fig. 3 MNC occurs at 1:45 am with a flow of 14.76 l/sec.

Net Night Flow (NNF) is the difference between Minimum Night Flow and Minimum Night Consumption and could be considered as an equivalent to physical leakage.

$$NNF = \text{Minimum Night Flow} - \text{Minimum Night Consumption}. \tag{4}$$

$NNF = 14.59 - 9.52 = 5.07 \text{ l/sec}$ . Therefore, estimated % of physical Leak = 34.75 % (=  $NNF/MNF$ ), [6].

#### 4.1 Calculating NRW for faisal block area

The Calculated percentage of losses in equation (4) is the percentage of physical losses (leaks) in the water distribution network.

For calculating the total amount of NRW (both physical and commercial losses), another survey was made. At the same duration, all master meters (Building consumer meters) in the area were being read.

From equation (3) and equation (4) we get;

Estimated physical losses % = 34.75 %, and estimated commercial losses = 22.25 %

#### 4.2 Pinpointing leaks

Noise loggers are used to identifying suspicious segments on the network. Noise Loggers have two options either (Leak) or (No leak), and from such indicators, schematic maps are created connecting the (Leak signaled Loggers) pipes; highlighting them as (suspicious for Leak), [7]. Fig. 4 explains the results obtained from noise loggers.

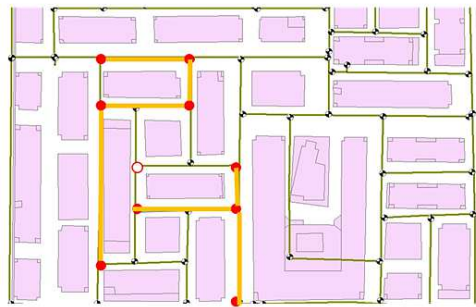


Fig.4: Noise loggers output.

In Fig. 4 the presence of two types of colorful dots is noticed; the hollow dots represent (no leak) result noise loggers, while filled dots represent (leak) resulted from noise loggers. Fig. 5 explains leak noise correlators device interface

The following step is pinpointing leaks using leak noise correlators. Leak noise correlators are placed on each side of the suspected leak pipe and transmit (or connect by hard-wiring) to a computer that filters and calculates a leak's location relative to the sensor array.

Once Physical leakage points are identified they are introduced to the GIS system as junctions with unknown outflow. Then using the model, having specific actual pressure measurements as reference points, an optimization model is applied to quantify leakage quantities per located physical losses, as well as, identifying faulty meters (apparent losses).

### 5 Leak detection and calibration using evolutionary algorithms

Leak detection and calibration of pipe CHW in water distribution networks are important subjects for all water utilities. An innovative approach for leak detection and calibration is being developed. This section discusses the usage of EAs in conjunction with a field survey to detect water losses and friction factors in WDN.

#### 5.1 GA for continuous parameter optimization

The model created under the name “EAcilib” combines either GA model with EPANet as hydraulic analysis models to determine leak quantities from pipelines and identify faulty meters. The presented model uses an interface between the GA-created code and the EPANET software. A MATLAB–EPANET interface was created [8]. The interface facilitates the data exchange between EPANET and GA models within MATLAB with minimal interference. This toolkit was used to integrate the overall optimization–simulation methodology.

#### 5.2 Model solution methodology

The optimization process adopted and carried out by the current paper comprised of the following tasks:

- 1) to calculate the CHW of the pipes;
- 2) by network calibration, identified through the use of GA the suspicious faulty meters (Apparent Losses), as well as, the identified leakages (Physical losses) outflow.

A new constraint handling function is suggested for usage as mentioned in equation (5)

$$f(x) = p_1 \sum_{i=1}^j \left( (H_i^p - |H_i^o|) \right)^2 + p_2 \sum_{i=1}^j \left( (Q_i^p - |Q_i^o|) \right)^2, \tag{5}$$

where  $H_i^p$  and  $H_i^o$  Are the predicted and observed heads at node  $i$ , respectively,  $Q_i^p$  and  $Q_i^o$  are the predicted and observed flows at pipe  $i$ , and  $p_{1,2}$  Are normalizing coefficients and suggested in this study to be

$$p_1 = \max \left( \text{abs} \left( (Q_i^p - |Q_i^o|) \right)^2 \right), \tag{6}$$

$$p_2 = \max \left( \text{abs} \left( (H_i^p - |H_i^o|) \right)^2 \right). \tag{7}$$

## 5.2 Materials

The network consists of 214 Pipes and 180 Junctions and a single source point. The Pressure readings were recorded at 10 different junction points. The hydraulic analysis was conducted using EPANet and results were transmitted through an external GIS link in spreadsheets form. The loading condition was considered at Average Demand, Fig. 1 – at 21:45 h. Table 1 shows the pressure reading at the pressure loggers' location at analysis time.

Table 1: Faisal city block observed pressure.

Junction ID	Pressure at 21:45 [m]
R-1 (inlet)	18.4
177	17.132
167	17.448
161	16.53
145	17.556
126	16.339
120	18.648
92	16.925
66	17.134
31	16.255
18	17.041

## 6 Results and discussion

The results Faisal city block network are presented here. For Faisal City Block, there were 3 physical leaking positions (considered as junction points with unknown demand), and additional 10 suspicious faulty master meters, along with an unknown CHW coefficient for the PVC pipes in the network.

For CHW of the network pipes, as the network was installed at the same time; the CHW coefficient will be assumed to be one in all pipes. CHW for PVC pipes according to international standards ranges from 150 to 100. Table 3 illustrates the observed pressure reading from the 10 different pressure loggers, and the results obtained from EAnet runs. Also, average values from different 4 runs are calculated to be compared by the actual readings.

Table 2 shows the observed and calculated nodal heads at pressure recorders locations. It is clearly shown that close results are obtained. While, Table 4 shows the summary for the calculated outflows from each junction and the type of water loss it represents; either physical (pipe leak), or commercial (faulty meter). The total physical and commercial loss percentage was calculated to be checked later with assumed results.

Table 2: Observed and calculated network data for the Hanoi network.

Junction ID	Observed pressure	GA 1	GA2	GA3	SCE UA	Avg
177	17.132	17.140	17.142	17.141	17.14	17.14
167	17.448	17.454	17.457	17.456	17.454	17.456
161	16.53	16.537	16.540	16.539	16.537	16.539
145	17.556	17.562	17.564	17.563	17.562	17.563
126	16.339	16.346	16.348	16.348	16.346	16.347
120	18.648	18.648	18.648	18.648	18.648	18.648
92	16.925	16.933	16.935	16.936	16.933	16.935
66	17.134	17.141	17.142	17.143	17.14	17.142
31	16.255	16.265	16.265	16.265	16.263	16.265
18	17.041	17.047	17.048	17.049	17.046	17.048
CHW	-----	128.92	127.91	129.89	129.1	128.96
Difference [%]	-----	0.04	0.05	0.049	0.0356	17.14
Eval	-----	5200	3100	4000	4912	-----

From Table 2 it was found that the result varies, because the observed points are relatively few for the number of unknown parameters and the flows are relatively low, yet the average results show that there is a similarity between obtained results and field results. Thus it is recommended in similar cases to run the model more than once with different seed numbers to obtain good average results. Table 3 explains the total NRW percentage per week, and the number of faulty meters replaced.

Table 3: Observed and calculated pressure head for Faisal city block network.

Junction ID	Type of losses	GA 1	GA2	GA3	SCEUA	Avg
99	Physical	3.533	3.966	3.744	3.915	3.792
77	Physical	2.738	3.012	3.721	3.73	3.288
60	Physical	2.455	2.916	2.945	2.432	2.689
15	Commercial	0.693	0.801	1.002	0.751	0.811
159	Commercial	0.671	0.684	0.607	0.794	0.688
86	Commercial	0.98	0.617	0.636	0.62	0.713
128	Commercial	1.078	0.548	0.508	0.616	0.696
6	Commercial	0.213	0.748	0.696	0.544	0.553
23	Commercial	0.866	0.778	0.652	0.652	0.736
100	Commercial	0.527	0.44	0.516	0.5	0.495
120	Commercial	0.753	0.444	0.121	0.398	0.428
140	Commercial	0.518	0.429	0.326	0.289	0.391
160	Commercial	0.649	0.291	0.201	0.434	0.394
Total (L/s)	Commercial	6.948	5.780	5.265	5.598	5.905
Total (L/s)	Physical	8.726	9.894	10.410	10.077	9.769
Total %	Commercial	25.27	21.02	19.15	20.36	21.48
Total %	Physical	31.73	35.98	37.85	36.64	35.52

Table 4 shows that with replacing 9 out of 10 faulty meters the total NRW decreased from 57 % to 38 %, meaning that the estimated commercial losses are around 19 %; which indicates a similar result for commercial losses percentage obtained by EAcilib application, 10 faulty meters, and 21.5 %.

Table 4: The actual NRW after preparing the highest 9 faulty meters.

Week	NRW [%]	Sum of master meter [m <sup>3</sup> ]	Inlet flow meter [m <sup>3</sup> ]	Number of faulty meter replaced
1	57%	9512	21818	0
2	45%	9287	16822	6
3	41%	7997	13477	8
4	38%	5590	9031	9

Table 5 shows a comparison between field survey results, EAcilib application, and Egyptian code of practice in estimating NRW %.

Table 5: Comparison between obtained percentages of losses for different approaches.

	NRW [%]	Physical losses [%]	Commercial losses [%]
Field	57	38	19
Empirical model	57	34.75	22.25
EAcilib	57	35.52	21.48

It worth mentioning that in actual fieldwork; only 9 meters were replaced out of 10 faulty meters. Thus, the actual percentage of commercial losses should be slightly greater than calculated and closer to one calculated by EAcilib application.

7 GIS integration

GIS was used to manage data obtained from different sources, link data from both field and office. In this study, ArcGIS10.2 has been chosen to help to analyze the water losses in the network. The main four feature classes used are [9]:

- a) Pipeline layer: a line shapefile of the water network;
- b) Meter layer: a point feature class of house meters to calculate nodal demand.
- c) Elevation map: a DEM (digital elevation model) to assign elevation of each node of the network was obtained through the use of a special link between Google earth™ and ArcGIS [20].
- d) Field operations layer; a point feature class to store field located leaks and suspected faulty meters. Along with a special tool to link the results obtained from the later mentioned model to be visualized through GIS.

ArcGIS is used to visualize results obtained from both field and ECalib. Fig. 5 shows a custom valve isolation application used to identify valves that need to be closed to replace leaking pipes. Also, Fig. 6 shows the contour map obtained by using Google Earth and ArcGIS link used to automatically identify nodal elevation. Fig. 7 shows pressure and velocity contour map applied using both EPAnet as hydraulic analysis model, ECalib to calibrate network, and finally ArcGIS to visualize results. Finally, Fig. 8 shows Pipe leaks and faulty meters locations over Google Maps.

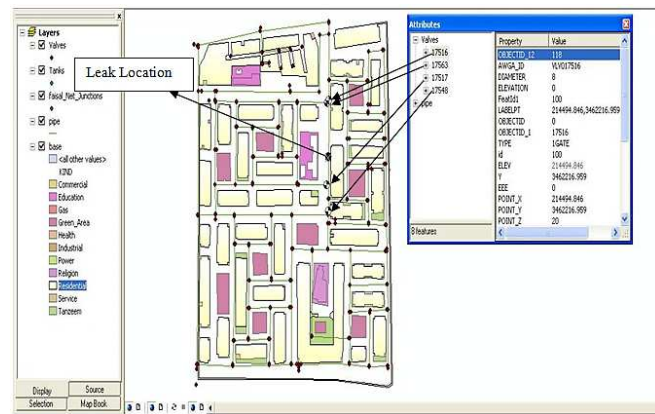


Fig. 5: Custom valve isolation application output for Faisal pipe leaks.



Fig. 6: Faisal city contour map using Google Earth and ArcGIS.

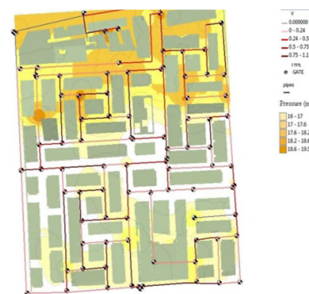


Fig. 7: Faisal city pressure head contour map.



Fig. 8: Pipe leaks and faulty meters locations over Google Maps using ArcGIS.

## 8 Conclusions

This paper describes the development of an integrated approach for pipe network calibration and quantifying leaks. The model developed departs from classical GAs in its representation, introducing a new constraint handling function and a new mutation function. The capabilities of the developed model are determined using data of an actual water distribution network. The efficiency of the procedure is tested by running the model several times with different seed values for the random number generator. Run of the EA-CALIB model produces a solution (with respect to relative error) that is better than previous objective functions. The high level of agreement between the results also demonstrates the robustness of the procedure elements. With respect to other optimization or analytical models, presented tools easier to use because it does not need complex mathematical apparatus to evaluate partial derivatives or to invert matrices.

Also, the proposed constraint handling function is easy to implement, requires no parameter tuning, furthermore, the external link between the model and GIS reduces the time needed to collect and store data in the distribution networks. Transferring data between the GIS system and the EA model helped optimize the engineering analyses. Finally, Results of the model can be displayed in the GIS, and in combination with other layers such as the topographic layer of the city, DMA zones, and WTP service areas, greatly assist in the understanding of the critical zones of the water distribution network for optimal operation and management of the network. The model integrates EPANet for the required hydraulic modeling during the simulation. The results prove the approach's accuracy and efficiency.

## Nomenclature

DEM - Digital Elevation Model, DMA - District Metered Area, EAcalib - Evolutionary Algorithms for calibration program, GA - Genetic Algorithms, GIS - Geographic Information Systems, MNF - Minimum Night Flow, NNF - Net Night Flow, NRW - None Revenue Water, SCE-UA - Shuffled Complex Evolution University of Arizona, WDN - Water Distribution Networks.

## References

- [1] KLEINER, Y. - RAJANI, B.: Comprehensive review of structural deterioration of water mains: Statistical models. *Urban Water*. Vol. 3, 2001, pp. 131-150, 10.1016/S1462-0758(01)00033-4.
- [2] POULAKIS, Z. - VALOUGEORGIS, D. - PAPANIMITRIOU, C.: Leakage detection in water pipe networks using a Bayesian probabilistic framework. *Probabilistic Eng. Mech.*, Vol.18, 2003, pp. 315–327.
- [3] KISHAWY, H. A. - GABBAR, A. H.: Review of pipeline integrity management practices. *International Journal of Pressure Vessels and Piping*, Vol. 87, 2010, pp. 373-380, 10.1016/j.ijpvp.2010.04.003.
- [4] FARLEY, M.: Leakage management and control. A best practice training manual, World Health Organization, Geneva, 2001.
- [5] NOPENS, INGMAR, VILLEZ, K.: Monitoring the Water Cycle - State of the Art and Future Needs. *IWA Yearbook 2007*. IWA Publishing, 2007, pp. 33–37.
- [6] Egyptian Code of Practice for designing and installation of pipelines of drinking water and sanitation. 10th Edition, 2007.
- [7] MUTIKANGA, H. E. - VAIRAVAMOORTHY, K.: Methods and Tools for Managing Losses in Water Distribution Systems. *J. Water Resources Planning Management*, Vol. 139, 2013, pp. 166-174.
- [8] ELIADES, D.: EPANET-MATLAB-Toolkit. Republic of Cyprus: KIOS-Research Center, University of Cyprus, 2016. <https://www.mathworks.com/MATLABcentral/fileexchange/25100-kios-research-epanet-MATLAB-toolkit/>
- [9] KHADRI, S. - PANDE, C.: Water Supply Systems-A Case Study On Water Network Distribution in Chalisingaon City in Dhule District Maharashtra Using Remote Sensing & GIS Techniques. *Iosrjournals.Org*, 2014, pp. 1–12. Retrieved from <http://iosrjournals.org/iosr-jmce/papers/ICAET-2014/ce/volume-4/1.pdf>.