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A new approach to model development of water distribution networks with high leakage and burst rates

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Abstract

Modelling real distribution networks can be particularly difficult if they are so leaky that the types of leak and their nature can hardly be determined from scarce field measurements. In this context, a new approach to model development of such WDNs is proposed. The method is based on leakage estimation from MNF and the burst frequency of AZPs. After applying it to a real DMA in Mauritius, the resulting calibrated model from EPANET is found to approach the actual status of the network very closely in terms of overall real losses, coefficients of discharge, nodal flow and pressure.

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Keywords: *District metered area (DMA), Water distribution network (WDN), Minimum Night Flow (MNF), Average Zone Point (AZP)*

1. Introduction

In many African and sub-Sahara African countries, the state of the water distribution network (WDN) is such that corrective maintenance is carried out only when there are pipe bursts and heavy leaks. Monitoring water losses through flowmeters and pressure sensors is quite costly within an old infrastructure which just needs replacement. However, replacement is a long term process which requires a lot of investment. The only of way of alleviating the problem in the short term, is to adopt a proper pressure control strategy in order not to further damage the old existing pipes and avoid excessive water losses since it is now well established that the rate of leakage depends on pressure. System analysis techniques (modelling, simulation and optimisation) are now widely accepted within the water utility industry as a mechanism for reducing the spatial and temporal complexities of water distributions. The

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present work focusses on model development of heavy leaking WDN using Rossman's [6] Epanet software. The idea is to develop a model which can be used for pressure management rather than to locate exactly the leaks in the networks. The method developed here is a sustainable one which is valid even when the old infrastructure is replaced since leakage is inherent in any WDN. The research has been carried out taking into account the relevant burst frequency of pipes of the average zone points in the DMA as well as the minimum night flow in order to quantify the leakage rate at specific locations.

1.1 Background leakage

According to Torricelli's theorem, the rate of leakage Q_l is proportional to the square root of the pressure head H in a pipe.

$$Q_l = C_l A_l \sqrt{2gH} \tag{1}$$

where
C_l= the discharge coefficient
A_l= leak area
g=acceleration due to gravity
H= total head at the point of leak

Several researchers have conducted tests on orifice in pipes and the hydraulics is now very well understood. The rate of leakage is in fact proportional to the square root of the head at that particular leak point according to Hikki [7], Greveinstein and Van Zyl [2] irrespective of the pipe material and size of hole, thereby confirming the relationship:

$$Q_l \,\alpha\, H^{0.5} \tag{2}$$

However, leaks are not always of orifice type and therefore other shapes like circumferential and longitudinal cracks were investigated. A more general form of the leak equation which is proposed by Lambert [7] is:

$$Q_l = C\, H^N \tag{3}$$

where
C is the leakage coefficient
N is the leakage exponent

Rewriting the leak flow equation 1 according to FAVAD:

$$Q_l = C_d \sqrt{2g}\,(A_0 H^{0.5} + m\, H^{1.5}) \tag{4}$$

where
A_0 is the initial leak area
m is the slope of the head-area curve

This relationship, however as it is, can only be applied if we know the leak characteristics (A_0 and *m*) of the network beforehand and one leak is unlikely to be similar to another. Therefore, the use of this equation is limited and cannot be readily applied to a distribution network. Furthermore, the equation above predicts a maximum value of *N* of 1.5 and therefore does not explain the higher values of 2.79 for example found in field tests.

1.2 Real loss estimation using minimum night flow

P.Cheung et al. [1] used the Minimum Night Flow measurements in order to calculate the real losses of a DMA. They showed that the MNF method and the calibration process yield similar results in terms of leakage estimation.

The Daily Real loss Volume DRLV is given by

$$DRLV = F_{nd} \times Q_{mn} \tag{5}$$

where
Q_{mn} is the average minimum nightly leak flow rate (m^3/h)
F_{nd} is the night day factor

Since the leak volume varies with demand pattern, the minimum night flow is multiplied by F_{nd} where

$$F_{nd} = \sum_{i=0}^{24} \left(\frac{P_i}{P_{3-4}}\right)^{N1} \tag{6}$$

P = the average pressure at the point of observation in the DMA for every hour *i*
$P_{3\text{-}4}$ is the average pressure during minimum night consumption between 3 to 4 am
N_1 being the leak exponent obtained from the MNF

The development of the present modelling algorithm is based on the history of repairs and the burst frequency of pipes, an estimation of real losses, the Minimum Night Flow and field data for calibration. It is outlined in the next section and applied to a real DMA in Mauritius for case study.

1.3 Relation between pipe burst frequency and pressure

The history of BF can help to locate approximately the leaking nodes in such a DMA. Often it has been found that replacing or repairing an old pipe which has burst, gives rise to another burst somewhere downstream the network because the AZNP is predominantly responsible for background leakage.

$$BF = BF_{npd} + A.\,P_{max}^{N_2} \tag{7}$$

where
BF_{npd}= the burst frequency for non-pressure dependent
A= constant
P_{max}= Average Zone Point maximum pressure
N_2= burst exponent (typically equal to 3)

From equation 7,

$$BF - BF_{npd} = A.\,P_{max}^{N_2}$$

If the AZP maximum pressure corresponds to the Minimum Night Flow pressure then from equation 3, leakage at the AZP:

$$Q_l \ \alpha \ {P_{max}}^{N_1} \tag{8}$$

$$Q_l \ \alpha \ (BF - BF_{npd})^{\frac{N1}{N2}} \tag{9}$$

Now for an old leaky network, it may reasonably be assumed that after some time, $BF \gg BF_{npd}$ since BF_{npd} is determined for the first time when the piping is new. Therefore the rate of leakage,

$$Q_l \ \alpha \ BF^{\frac{N1}{N2}} \tag{10}$$

According to Fantozzi and Lambert [9], the value of N_2 is typically equal to 3 and hence

$$Q_l \ \alpha \ BF^{\frac{N1}{3}} \tag{11}$$

Equation 11 shows that there is a clear relationship between the rate of leakage and the burst frequency. Knowledge of this equation is exploited in the methodology section 2.4 below.

2. Methodology

The steps are outlined in the flowchart of figure 2 on following page and detailed in the following section taking DMA 32810 in Mauritius as case study. This DMA comprises 229 nodes and the source of water comes a borehole. The total number of subscribers is 2174 with the length of mains is 15 km and the network piping is made of HDPE, Asbestos Cement, Cast Iron and Galvanised Iron. The average system's input is around 2174 m^3/day and an average efficiency of about 60%.

2.1 Choosing the Average Zone Point

The AZP is defined as the point where the pressure variations supposed to be representative of the zone average pressure. The method developed by WSAA (Water Services Association of Australia) for determining the AZP is outlined below:

1. Calculate the weighted average elevation of each zone.
2. Identify a hydrant AZP representative of the each zone.
3. Evaluate the pressure near the AZP of each node
4. Calculate the average pressure in the network from these zones.

In order to get a more reliable AZP, the DMA under consideration is sectorised in 5 different groups as shown in figure 1(b) below according to the type of pipes used. The AZP obtained is then taken as the point of monitor (figure 1(a)) for the group.

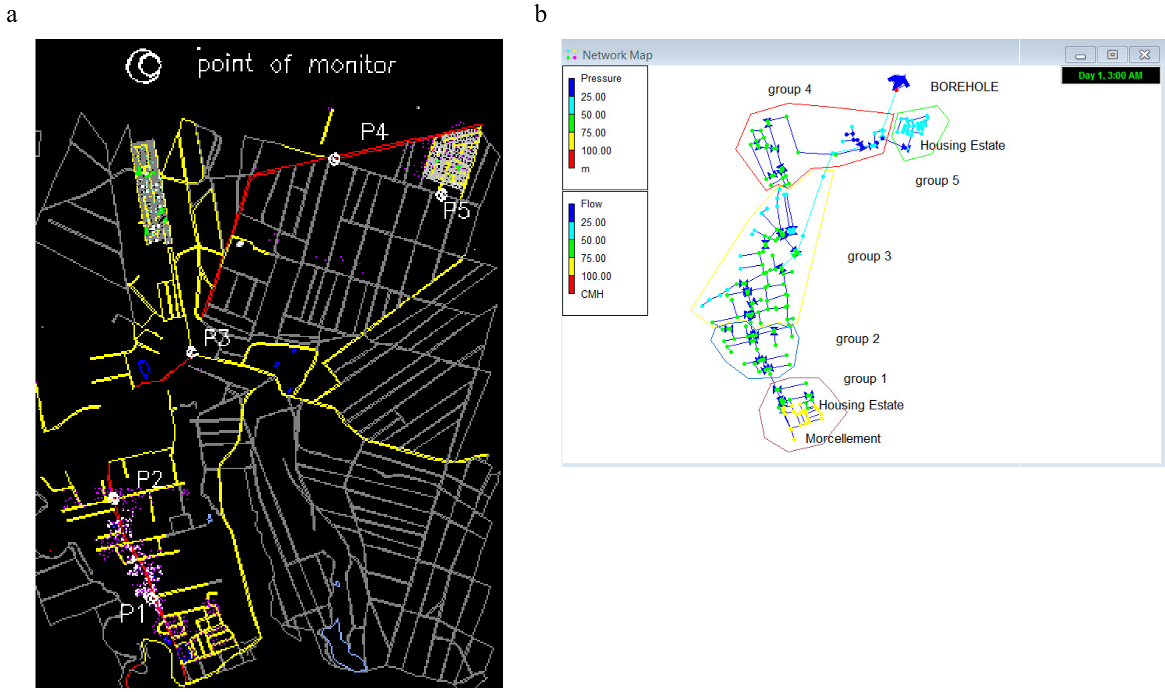


Figure 1 :(a) Strategic choice of the AZP; (b) Sectorised DMA on Epanet

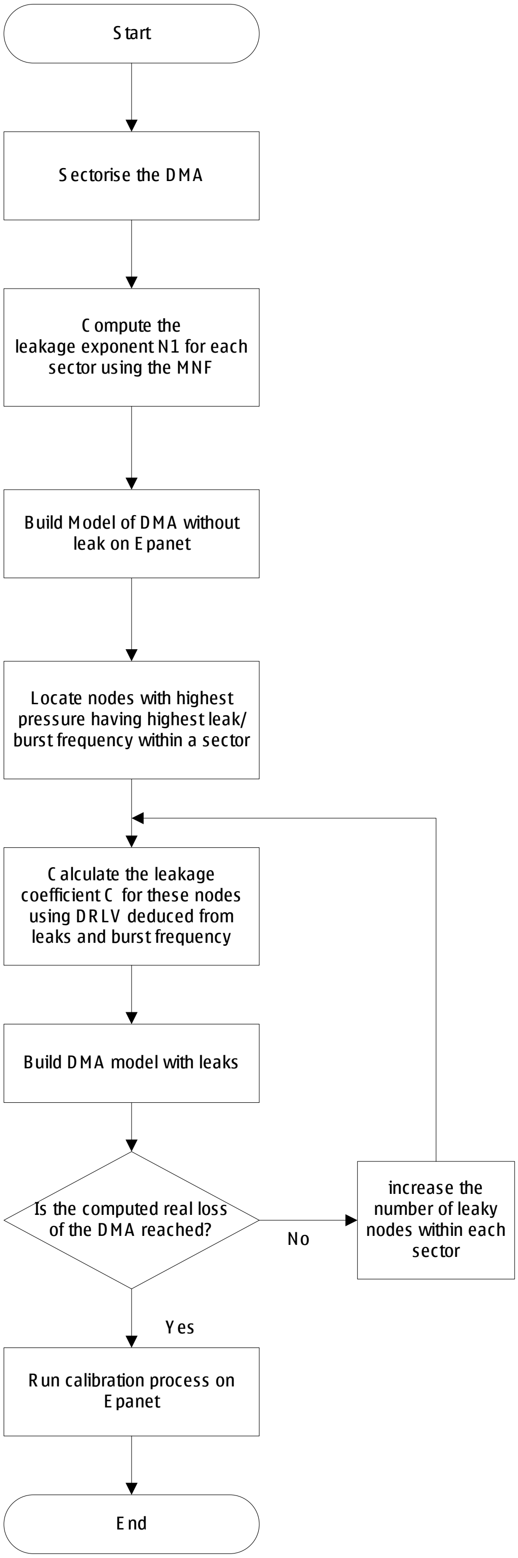


Figure 2: Flowchart of proposed scheme

2.2 Computing the leakage exponent and the DRLV from MNF

Using the Minimum Night Flow measurements between 0200 and 0400 at the monitored point of figure 2 (b) in each group, the corresponding average leakage exponent N_1 is calculated from equation 10 below using relative values of flow and pressure so as to eliminate the leakage coefficient C of equation 3. In order to obtain variations in flow and pressure, the PRV1 setting at the start of the distribution channel is varied every 30 minutes between 0200 and 0400. Computation of leakage exponents *N1* in each group is summarised in table 1.0. The overall leakage exponent of the DMA is obtained as 1.645.

$$\frac{Q_1}{Q_0} = \left(\frac{P_1}{P_0}\right)^{N_1} \tag{12}$$

where Q_1= final pressure, Q_0= initial flow, P_1= final pressure head and P_0= initial pressure head.

Table I: using MNF to compute the leakage exponent

Point	Time	Flow	Pressure	N1
P1	02:00	0.267	6.57	average N1= 1.654
	02:30	0.236	5.78	
	03:00	0.192	5.01	
	03:30	0.152	4.82	
	04:00	0.123	4.38	
P2	02:00	0.442	5.34	average N1=1.804
	02:30	0.337	4.59	
	03:00	0.257	3.95	
	03:30	0.229	3.71	
	04:00	0.191	3.35	

The computed average night day factor F_{nd} for the 5 groups using equation 6 is 20.01 h/day and the observed average MNF at the DMA entrance from data logger is 2.9 L/s or 10.44 m^3/h. Therefore the DRLV according to equation 5 must be 8.708 m^3/h.

2.3 Building model without leak on Epanet

From collected flow meter data, node elevation, pipe lengths and other characteristics, an ideal Epanet model of the DMA is constructed. The pressure distribution throughout the DMA is shown by the contour diagram of figure 3

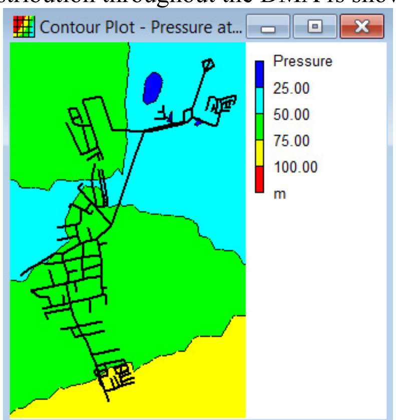


Figure 3: Pressure distribution of DMA

at 2.00 am. It can be observed that pressure builds up as expected near the DMA closure and this accounts for the highest burst frequency.

2.4 Determining real loss volume on the basis of reported leakage and burst frequency

Within each group, the nodes having highest registered leaks and/or burst frequency and pressure higher that the AZP are located. It is well established that pipe bursts are occasioned by abnormally high pressures and are usually the result of a persistent leakage. According to Lambert [9], the annual real loss must be computed based on the background leakage, unreported leakage and reported leaks and bursts. Therefore the DRLV calculated in section 2.2 is underestimated. Background leakage and unreported leakage are accounted for in the MNF. In order to take care of the third parameter, the groups are allocated a proportional value of the DRLV based on the number of leaks and bursts reported. First, assume that the total number of 190 leaks and bursts correspond to the MNF of 10.44 m^3/h. Subsequently, the group DRLV is obtained by using equation 11 from section 1.3 in the form shown below:

$$\frac{Q_1}{Q_2} = \left(\frac{BF_1}{BF_2}\right)^{\frac{N1}{N2}} \tag{12}$$

Table II: Allocation of DRLV per group

Group	No. of bursts and leaks/year	Real loss volume (m3/h)
1	57	4.174
2	43	3.576
3	39	3.390
4	30	2.936
5	21	2.414
	190	**16.49**

In table 2, the recorded no. of leaks and pipe bursts for the year amounts to 190 comprising of both service and main trunks. It can be observed that the total DRLV here is approximately twice that obtained in section 2.2. This overestimated value is probably occasioned by the reported high burst frequencies within the different zones. The option of using the leaks and burst frequency as well as the maximum pressure in each group is a more realistic way of approaching the true value of real loss in each zone.

2.5 Setting leaks in the ideal model

EPANET uses emitters (sprinkler heads) to simulate leakage at a node according to the equation:

$$\mathbf{Q_l = C\, p^{\gamma}} \tag{13}$$

where q = flow rate, p = pressure, C = discharge coefficient and γ= leakage exponent.

The sensitivity of leakage rate Q_l to the coefficient C has been investigated by many researchers [8]. It has been found that C depends very much on the nature and type of the leaking point. This is very difficult to estimate in a large network. Therefore an approximate value is determined from the Daily Real Loss Volume of table 2. However, in Epanet, the leakage exponent is fixed for the whole network. Therefore the calculated average value of γ is taken as 1.645 (N_1) from section 2.2 and will be used throughout the simulation.

The aim of the model here is not to locate exactly the leaks but rather to quantify it within a particular group such that the minimum pressure and demand are satisfied in the DMA. To deal with the problem of leakage coefficient C, equation 13 is solicited within each group whereby:

$$C = \frac{Q_l}{P_{azp}^{\gamma}} \quad (14)$$

P being the average zone point pressure obtained from model
Q_l is the DRLV obtained from table 2.

The algorithm for embedding leakage within the network has been developed with Epanet's Toolkit and is outlined in the pseudo code below:

- Within each group, determine the number of nodes and their ID having a high burst frequency as well as a P_{max} above the AZP.
- Starting with the monitoring node point, calculate the leakage coefficient C at the average zone pressure for the corresponding group DRLV from table 2.
- Insert the coefficient C and the exponent ɤ in Epanet and run the Hydraulic Simulator.
- If the network's DRLV is not reached, the number of leak nodes is incremented and procedures repeated until a convergence is attained.

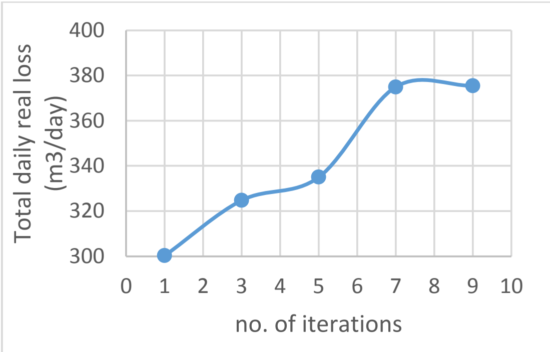
```
Node=1;                                   // start with the first AZP
Engetnodeindex();                         // get nodes whose Pressure > AZP and having high BF
while (NetLeakage < DRLV)
{
      for (group=1;group<=5;group++)
      {
            Compute_C(nodeindex[N])         // discharge coefficient C for nodes
            ENsetnodevalue(nodeindex[N]);   //set the coefficient of leakage for nodes
      }
      ENsolveH();                           //run the hydraulic simulation
      Node++;                               //increase no. of leakage nodes
      If (NetLeakage i+1 – NetLeakage i <=0.1)   //set a boundary value to exit loop when convergence is reached
      Exit;
}
```

Owing to changing demands and pressure heads at the leaking nodes, the overall network leakage will always be less than the total computed DRLV obtained in table 2. The final step is to calibrate the model using flowmeter and pressure sensor readings over an extended period of time.

3. Simulation Results

Based on the redistribution of the leakage coefficient C among leaking nodes at AZP pressure under the algorithm of section 2.5, the average daily real loss volume converges to 375.45 m^3 i.e. 15.64 m^3/h which is very close to 16.49 m^3/h obtained in table 2 after 9 iterations as depicted in figure 4(a) below. Further extension to the number of leaking nodes does not contribute significantly to this DRLV because of a lower pressure head and leakage coefficient C. After calibrating the model with flow and pressure measurements from data loggers at the five monitoring points on a 24-h basis, a simulated system input flow of 2058 m^3/day is obtained compared to the average observed value of 2174 m^3/day i.e. with a discrepancy of only about 5%. The profile of the model matches that of the observed input very closely as depicted in figure 4(b). Table III shows that there is a good correlation (0.990) between the observed and computed means of flow. The divergent values for links 147 and 66 can be explained by the fact that the associated AZP might have been wrongly chosen. Otherwise the profile of the flow at other links such as 174, depicted in figure 5, follows the observed pattern quite closely.

a



b

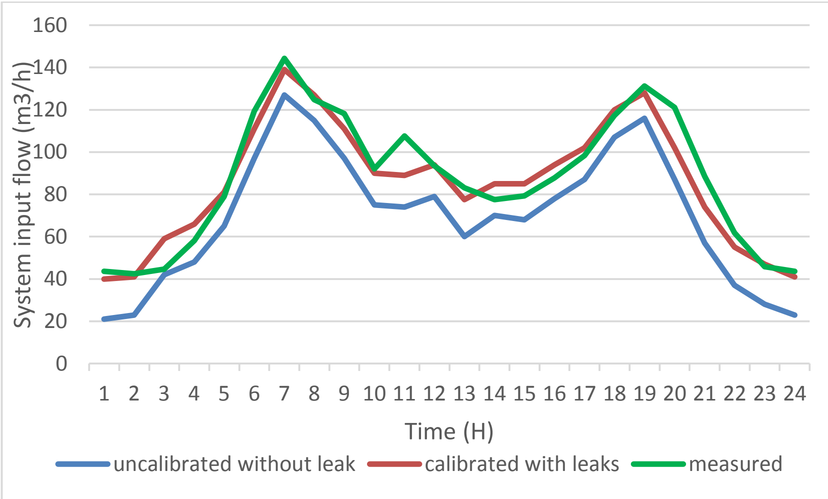


Figure 4: (a) Simulation of uncalibrated total daily real loss volume; (b) Comparison of observed and simulated system inputs

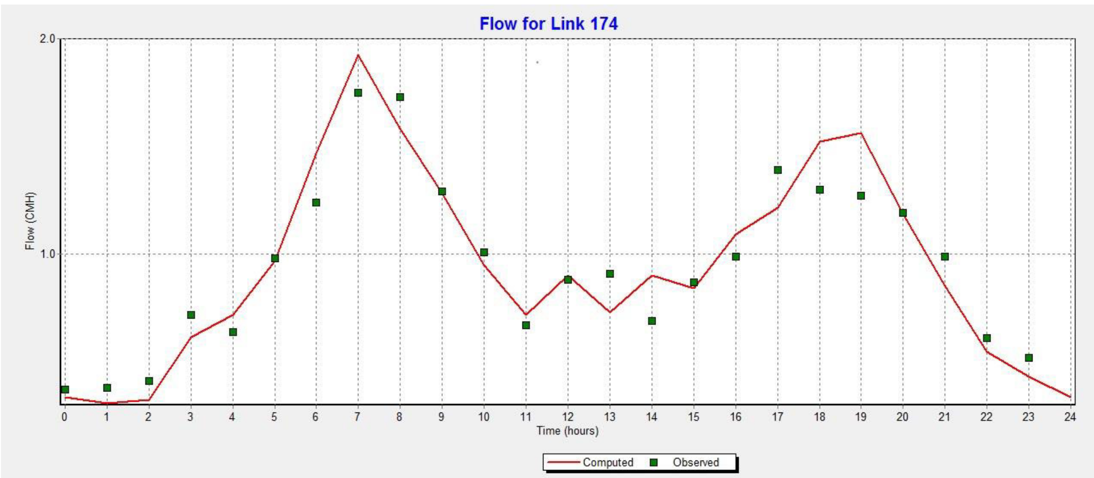


Figure 5: Profile of computed vs observed flow for pipe 174

Table III: Summary of calibrated flow statistics

Scenario: Base
Calibration Statistics for Flow

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
174	24	0.95	0.96	0.107	0.133
147	24	43.01	28.20	14.816	17.905
66	24	81.08	71.97	11.095	13.079
45	24	5.74	3.64	2.115	2.716
195	24	6.69	4.24	2.469	3.142
Network	120	27.49	21.80	6.121	10.089

Correlation Between Means: 0.990

4. Discussion

A new approach for modelling leakage in old water distribution networks has been proposed in this research work. Within a perspective of pressure management, it is more useful to quantify the real losses rather than to know their exact location. Calculating the DRLV from the MNF might not give a realistic value if night consumption is not known exactly. In order to compensate this discrepancy, a new relationship developed between the rate of loss and the leaks and burst frequency at AZP has been used. It allocates the leaks across nodes that have the highest pressure and usually the largest number of pipe bursts. The resulting model exhibits quite similar characteristics of flow and pressure which are actually observed on fields. Furthermore, the computed system's input agrees with the observed value within a margin of 95%. However, the method needs to be tested and validated on other DMAs. An optimal model can be developed if more field data is available for calibration which is not always possible on old networks. For more accuracy, the number of nodes within a group can be decreased thereby increasing the number of monitoring points. Finally, the resulting model is a more realistic one whereby the leakage coefficient and the pipe roughness remain within reasonable margins.

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