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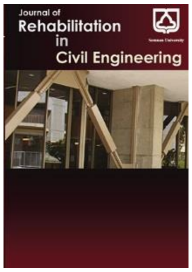

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Leak Detection in Water Collection and Transmission Networks Using the Minimum Nodal Pressure Measurement

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ABSTRACT

Leak has always been one of the problems in water distribution networks, whose preventing not only results in the saving of water sources but also has profound effects on the maintenance cost of networks. In the present paper, a new method is applied for leak detection in water collection and transmission network. In this method, detection of leak location is performed by pressure difference analysis at junctions and by the help of the relative index of the leak. The pressure measurements should be performed at least at two nodes for two cases of with and without the presence of leak. The minimum number of pressure measurements to form a relative leak index is two. However, in this case, two nodal pressure measurements are too few, and the number of pressure measurement should be increased. Therefore the next option for the number of measurements is three. The investigated network in this research includes 7 wells with an approximate length of 7800 m located in the northwestern city of Mashhad. A real leak with a rate of 7.57 l/s is created at one of the network nodes whose amount is measurable by a volume counter. The real leak is a hypothetical leak which is known in advance, and its magnitude is not necessarily a round number in term of a liter per second. Finally, this leak is identified by the proposed method via 3 nodal pressure measurements.

1. Introduction

One of the main issues in water distribution systems is the hidden break of the pipes occurring far from authorities' eyes and its consequent leak and disturbance in servicing. Even a small leak could result in huge environmental loss and put people at

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risk. There are different solutions for leak detection in a water transmission system. Leak detection in networks with different existing methods have always been with some problems; on the other hand, each of these methods has its own limitations, which leads to lack of all-purpose efficiency in different conditions. Most of these techniques can only identify the leakage in limited sections of the system depending on the network parameters used for initial estimation and work based on the difference in computational and measured pressure in a leaked flow; therefore it may need to separate a part of the water distribution system or even its outage.

Different models have been developed for analysis based on pressure parameter along with the evaluation of network reliability. [1,2] described a simulation based on the pressure of the network according to energy and mass conservation. Also, [3] presented a method for identification of leak location in-network by application of pressure observation collected through a transient flow phenomenon concentrated on minimization of the difference between the observational and computed parameters. Some of the researchers have focused on the development of methods in which by application of network survey and recording some data of the network, more accurate identification of leak will be possible. These methods mainly seek for leak throughout the network via modeling and network calibration [4]. Wu and Sage [5] have developed the proposed method of Sage via simultaneous adjustment of methods for determination of the closed valves and investigated this method on two networks including a hypothetical network and a section of a real network. In the hypothetical network, among 18 nodes whose consumption are adjusted, the pressure in 6 nodes and the input flow to the network are measured, then different states of leakage including uniform leak at all the nodes, and presence of a huge leak at different points are studied. The results have shown that the applied method in the hypothetical network has led to proper results in leak identification and can be a good guide in the identification of large leaks.

Most of the studies conducted in this field have attempted to improve the accuracy of the existing/current methods by increasing the number of observations by collecting the data in a system during a time period. Also, for avoiding the increase of unknowns of nodes' consumption, pressure-dependent leak detection are used for the analysis of these data [6,7]. In the current paper, leak detection will be evaluated based on modeling a collection and transmission network by application of pressure and discharge measurements. The proposed method is applied via modeling a real transmission line according to the existing maps and virtual pressure data. One of the limitations of the mentioned method is the necessity of having an isolated transmission line. If the structural data of the network, such as material, diameter, connections and accessories, depth of project line, flow discharge and node pressure (at some nodes) are determined, then any changes in hydraulic loading of network implying the changes in flow discharge due to the leak, will be detected by this method.

2. Case study

The proposed method in the current paper can be applied to water distribution systems. In other words, any form of arrangement in pipes, in term of the numbers, forms, and sizes can be analyzed to determine the leak location. A real case of Water Conveyance System (WCS) is used in this study (Figure 1). The case study is located approximately 35 km from the city of Mashhad towards the northwest along the road of Mashhad-Ghuchan. The harvested water from seven wells is collected and then transmitted through a 7.8 km pipeline to a water reservoir (Kavardeh reservoir). The reservoir has a storage volume of 5000 m3. All existing wells and their facilities, including pumps, pressure gauges, and flow meter are installed in chambers.

3. Calibration

Discharge of the pipelines and pressure at nodes are among the important parameters in distribution network analysis. For measuring the discharge in all the wells, electromagnetic current meters (Dafuss Magflow) with an accuracy of ± 0.01 l/s were used. To guarantee the accuracy and reliability of flow meters, they were recalibrated. In this regard, a portable ultrasonic counter (General Electric PT 875 Panametrics), was used to measure the discharge of each well, and the results were compared with the results obtained from magnetic flow meters. In this content, some collections were also made by magnetic flow meters. Moreover, the pressure of wells and other proposed locations were collected by the installation of portable pressure probes remotely.

4. Data collection

The pressure is one of the determinative hydraulic parameters in performance and service presentation of water distribution networks. It can be said that among all the effective factors, the pressure is the most important parameter in new methods of leak detection. The exact as-built map of the transmission pipeline was used for exploring the possible locations for installation of pressure measurement devices. It is shown that pressure measurement devices can be installed only in place of valve chambers (7 nodes). Among these nodes, regarding the location of valves and connection within the chambers and also the dimension of chambers, 3 nodes (1, 3, and 5) are selected (Figure 2). As the creation of an artificial leak was not possible in the path of distribution line, therefore well W12 is removed from the circuit, and its pipeline is used for simulation of the leak. The input data to the model are wells' and pipes' specifications and nodes coordinates (Table 1). The abbreviations of AC and CI are Asbestos Cement and Cast Iron, respectively.

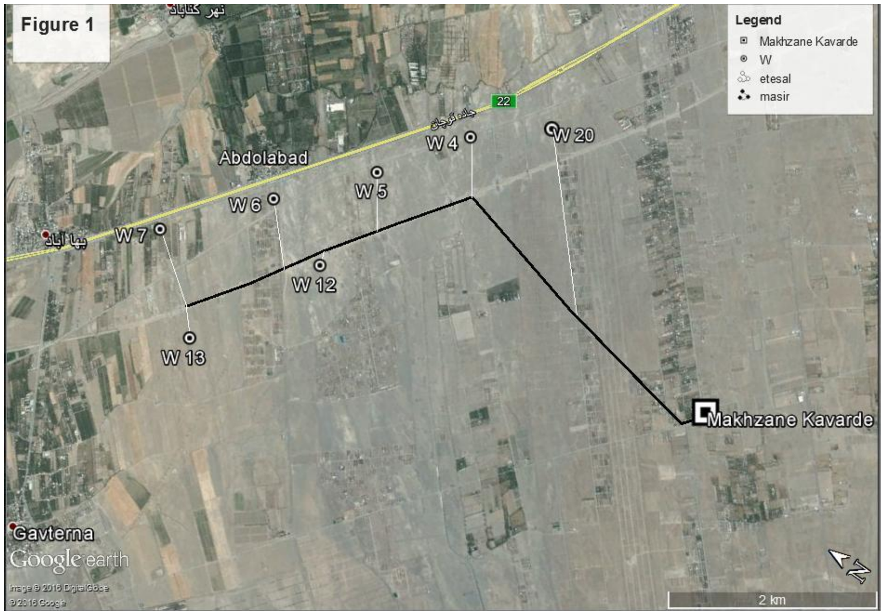

Fig. 1. Wells locations and Kavardeh collection reservoir.

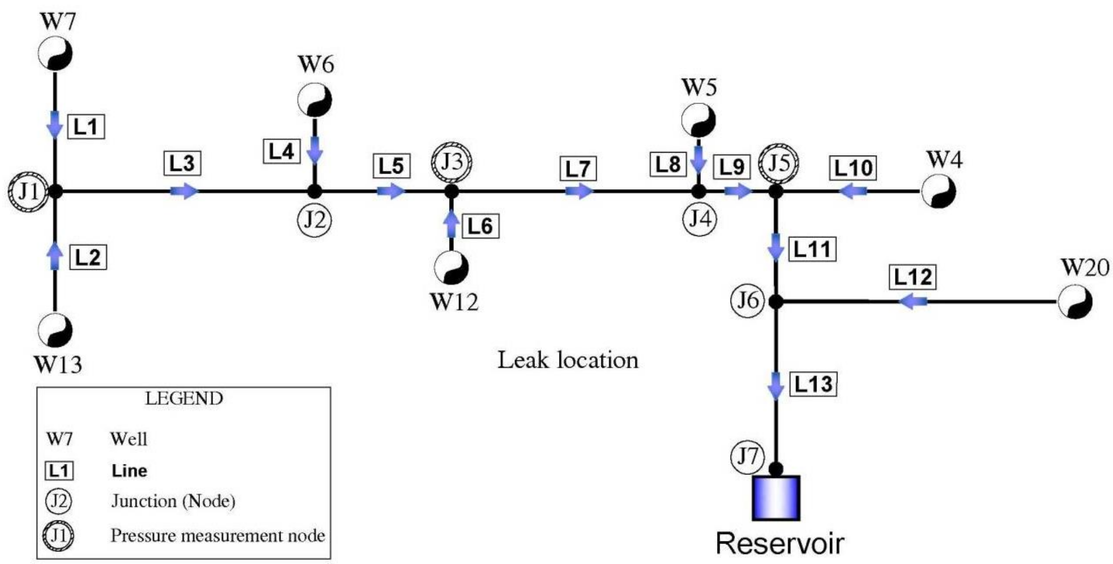

Fig. 2. Schematic location of the wells and pressure measurement of the nodes.

Table 1. Specifications of pipes in the network.

Link / Specifications	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
Material	AC	AC	AC	AC	AC	AC	CI	CI	AC	CI	AC	AC	CI
D (mm)	200	200	200	150	300	200	400	150	500	200	500	200	500
L (m)	633.5	519.0	852.0	526.0	361.0	211.0	679.0	374.0	620.0	457.9	2316.0	2280.3	1079.7

Collection of the required data, including discharge and pressure at nodes, are performed in two steps. At first step and in leak-free condition, the amount of discharge and pressure of the active wells such as W4, W5, W6, W7, W13, and W20 are measured as listed in Table 2. These data are collected by current electromagnetic meters and digital pressure meters installed in the chamber of each well. Also, at this stage, the pressure of the pressure meters installed at nodes 1, 3, and 5, are read by data logger with an accuracy of ± 0.01 atmospheric pressure. In the second stage, an artificial leak is created by the outlet valve installed on W12 (Figure 2), which can be identified at node 3. The collected data, such as discharge and pressure of each well, is actually associated with the leaky condition. At this stage, similar to leak-free conditions, the pressure measurements are carried out. The amount of leak is measured by the volumetric flow meters installed at the leaky node (Figure 3). In Table 3, the values of pressure of the nodes before application of leak and after that are shown for leak discharge of 7.57 l/s.

Table 2. Discharge and pressure of the wells in leak-free case.

Well Number / Parameter	W4	W5	W6	W7	W13	W20
Q (l/s)	15.17	24.70	28.30	12.66	18.70	24.36
p/γ (m)	54.00	54.44	55.92	50.52	42.18	58.86

Table 3. Pressure at nodes in the leaky and leak-free condition.

Node number	J1		J3		J5	
p/γ (m)	Leak-free	leaky	Leak-free	leaky	Leak-free	Leaky
	41.6	40.89	40.32	39.61	47.18	46.71

Fig. 3. Created leak in well number W12.

5. Hydraulic modeling

For modeling the network, EPANET 2.0 is used. This software is a computer program which is a product of the United States Environmental Protection Agency (EPA). Hydraulic analysis, qualitative modeling of water distribution systems, hydraulic calibration, and graphical capabilities are among the abilities of this software. The Hazen-Williams formula is selected in the model for hydraulic analysis for its simplicity. The Hazen-Williams roughness coefficient for hydraulic modeling is chosen 140.

6. Leak index

In the monitoring of a water collection and transmission network, two conventional quantities are frequently measured. They are namely nodal pressure heads and pipe flow rates. In the developed methodology, only pressure measurements are required to detect and locate leaks in a water collection and transmission network. On the contrary to other methods, this method, which does not require flow measurements, is based on the parameter of the "leak index," which will be introduced afterward.

In order to understand the leak effect on the pressure variations of a water collection and transmission network, two kinds of analysis with and without the presence of a leak should be performed. Although leak may occur either in a pipeline or at a node, in the current paper, it is assumed that the leak takes place at a node.

Due to leak out of each node, there will be a pressure decrease at other nodes, including the leaky node. For example, the pressure difference between the two cases of no leak and leaky conditions can be calculated as the followings:

$$\Delta H_i^k = H_i - H_i^k \tag{1}$$

where ΔH_i^k is the head difference of node i due to leak at the node k. Then the leak index LI_i^k is defined in a non-dimensionalized form by the following equation:

$$LI_i^k = \frac{\Delta H_i^k}{\Delta H_{\max}^k} \tag{2}$$

in which $\Delta H_{\max}^k$ is the maximum head difference among the whole nodes of the network which most likely occurs at the leaky node. This index shows an important characteristic of a water collection and transmission network. The leak index has its maximum value at the leaky node in most of the cases. When nodal pressure measurement is carried out at a certain node, the numerator of Eq. 2 can be calculated. To normalize the variation of pressure changes in two cases of no leak and leaky conditions, it is required to know the exact location of the leak as it appears in the denominator of Eq. 2. As a matter of fact, it is impossible to measure this value, because the location of the leak is unknown, and the pressure reading at other nodes of the network will lead to no useful information. However, to get rid of the denominator, a relative leak index $LI_{i/j}^k$ is introduced, which is actually equal to the ratio of leak index at i to j when the leak occurs at the node k. It has the following formulation:

$$LI_{i/j}^{k}=\frac{\Delta H_{i}^{k}/\Delta H_{\max}^{k}}{\Delta H_{j}^{k}/\Delta H_{\max}^{k}} \qquad (3)$$

Or it can be expressed in terms of leak indexes of nodes i and j as:

$$LI_{i/j}^{k}=\frac{LI_{i}^{k}}{LI_{j}^{k}} \qquad (4)$$

The advantage of this equation is that the numerator and denominator represent pressure drop at nodes i and j, respectively, due to a common leak at an unknown node k where we are actually looking for. It should be noted that the relative leak indexes are defined for two cases of observed and calculated leak discharges. For the case of observed leak discharge which is assumed to occur at the unknown node, the relative observed leak index for any two nodal pressure measurements could be obtained which is shown by $(LI_{i/j}^{k})_r$ where k is the leaky node. On the other hand, the calculated leak based on a number of discharge for each node in the network should be analyzed. The relative calculated leak index for the same nodal pressure measurements can be obtained for each node, which is shown by $(LI_{i/j}^{k'})_s$ where k' is the calculated leaky node which is assigned to any node number of the network. Hereafter for the sake of simplicity, the above-mentioned relative observed and calculated leak indexes are replaced by $LI_{i/j}^{k}$ and $LI_{i/j}^{k'}$, respectively. The observed leaky node will be definitely among the calculated leaky nodes [8].

7. Methodology

To examine the capability of the proposed methodology, a hypothetical leak is considered at a node. Then a number of nodes should be considered for the pressure measurements. Comparison of $LI_{i/j}^{k}$ and $LI_{i/j}^{k'}$ can be used to identify the leaky node. In an ideal situation $LI_{i/j}^{k}$ and $LI_{i/j}^{k'}$ for the leaky node are identical. The following reasons are given to reveal the source of fluctuations:

I. The pressure measurements are essentially accompanied by some errors which affect the real leak index.

II. In system calibration, the measurements should be performed at the greatest possible extent; however, due to some practical limitations, calibration will be performed for a few certain data taken from field measurements. Therefore the model will not exactly match the field results. This can be considered as another source of mismatch in observed and calculated leak indexes.

III. Actually, the magnitude of a real leak discharge in an observed water collection and transmission network is most likely different from the calculated one. Thus the observed and calculated leak indexes will be different from each other. However, fortunately, even for a big difference between the magnitudes of observed and calculated leak discharges, the differences between the observed and calculated leak indexes will be trivial. In another word, the sensitivity of the leak index to the magnitude of the leak is low.

To investigate the sensitivity of the leak index to the magnitude of leak discharge, ΔLI the following definition is introduced:

$$\Delta LI = (LI_{i/j}^{k} - LI_{i/j}^{k'}) \times 100 \quad (5)$$

It is predictable that if the calculated leak discharge is lower than the observed one, ΔLI takes negative values and vice versa. A swing interval of ±5% for the variation of leak index is recognized as a suitable range. The hypothetical observed magnitude of the leak is unlikely to equal to the calculated one. The observed leak occurs at node 3, which is used to determine the relative observed leak index ($LI_{i/j}^{k}$). However, to determine the relative calculated leak index ($LI_{i/j}^{k'}$) leak with a size of 5 l/s at each node of the network is considered.

How can the number of nodal pressure measurements be determined? The minimum number of pressure measurements to form a relative leak index is two. However, in this case, two nodal pressure measurements are too few, and the number of pressure measurement should be increased. Therefore the next option for the number of measurements is three. Here the arbitrary nodes 1, 3, and 5 are chosen.

Three types of relative leak indexes, namely $LI_{1/3}^{3}$, $LI_{1/5}^{3}$ and $LI_{3/5}^{3}$ should be calculated for observed leak discharges. On the other hand, the associated calculated relative leak indexes $LI_{1/3}^{k'}$, $LI_{1/5}^{k'}$ and $LI_{3/5}^{k'}$, as office work, for all of the network nodes should be obtained. The bands located between the two horizontal dashed lines are related to $\left(1 \pm 0.05\right) LI_{i/j}^{k}$. The intersection of the list of nodes suspicious to leak from all of the pairs of pressure measurements are the leaky nodes.

8. Leak matrix

In order to determine the pressure difference in the pipes of the conveyance system in leaky and leak-free conditions, it is needed to determine the leak matrix. As a part of software computations, a leak with a definite discharge will be applied to all the nodes, and the amount of pressure difference in these nodes will be obtained. The choice of leak discharge is arbitrary, and in this section is considered as 5 l/s, and the results are shown in Table 4.

Table 4. Pressure difference (m) at nodes, by application of model, to the leaky and leak-free condition of the conveyance system

Number of nodes \ leaky node	1	2	3	4	5	6	7
1	1.45	0.54	0.45	0.34	0.29	0.11	0.02
2	0.54	0.54	0.45	0.34	0.29	0.1	0.02
3	0.45	0.45	0.45	0.34	0.29	0.11	0.02
4	0.34	0.34	0.34	0.34	0.3	0.11	0.03
5	0.3	0.3	0.3	0.3	0.3	0.11	0.02
6	0.11	0.11	0.11	0.11	0.11	0.11	0.03
7	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Finally, the leak matrix will be determined by Eq. 1. The results are presented in Table 5.

Table 5. Leak matrix (-) with a leak discharge of 5 l/s

leaky node / Number of nodes	1	2	3	4	5	6	7
1	66.67	100.00	83.33	5.19	100.00	96.67	100.00
2	66.67	66.67	83.33	5.19	90.91	96.67	37.24
3	66.67	100.00	83.33	5.19	100.00	96.67	31.03
4	100.00	100.00	100.00	5.19	100.00	100.00	23.45
5	66.67	100.00	100.00	5.19	100.00	100.00	20.69
6	100.00	100.00	100.00	5.19	100.00	36.67	7.59
7	66.67	66.67	33.33	49.63	18.18	6.67	1.38

8.1. Determination of leak index

Computed relative leak index could be determined for each pair of pressure measurement nodes, (1, 3), (1, 5) and (3, 5), for an arbitrary leak amount at node 3. For instance, the leakage value of 5 l/s is considered in this case. On the other hand, by reading from the installed pressure meters at nodes 1, 3 and 5, and recording the pressure in leaky and leak-free conditions in the case of 7.57 l/s leakage, calculation of the observed relative leak index is possible. In Figures 4, 5, and 6, the solid circles indicate the calculated relative leak indices and the hollow circles show the observational relative leak indices. The variational range of the observed relation leak indexes is also shown. It should be mentioned that for three nodal pressure measurements (nodes 1, 3 and 5), the number of ways of choosing 2 nodal pressure to compute the relative leak index of 3 measured nodes without regard to order is the binomial coefficient which can be written as .

As it can be seen, at node 3, the amount of observed leak index, according to the applied artificial leak, is equal to 7.57 l/s, in accordance with the computed leak index based on the considered discharge of 5 l/s. This is due to the proximity of these two values of leakage. Also, the constant amount of computed leak index at different nodes is due to equality in pressure difference for leaky and leak-free conditions at three nodes.

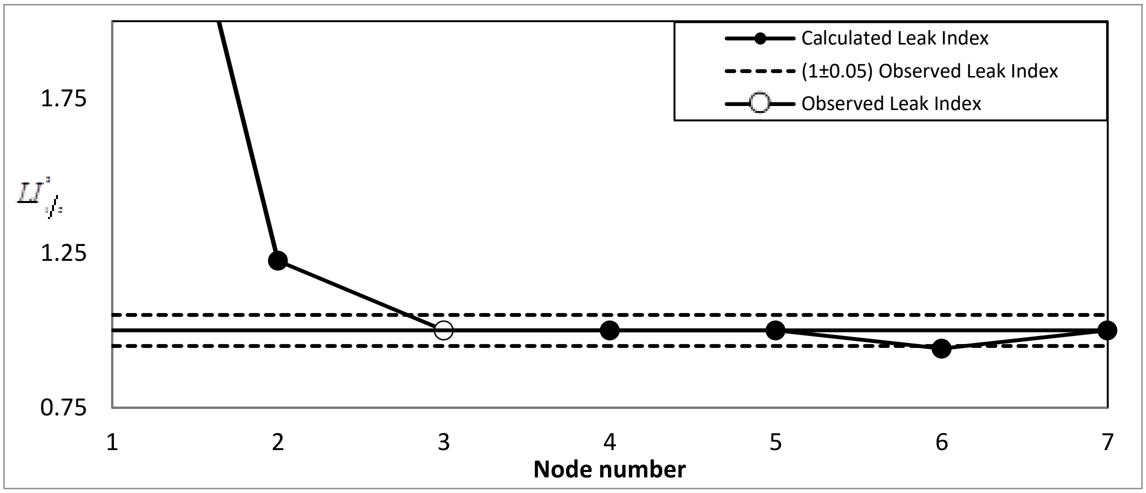

Fig. 4. Leak index for leak value of 7.57 l/s and pressure measurement at nodes 1 and 3.

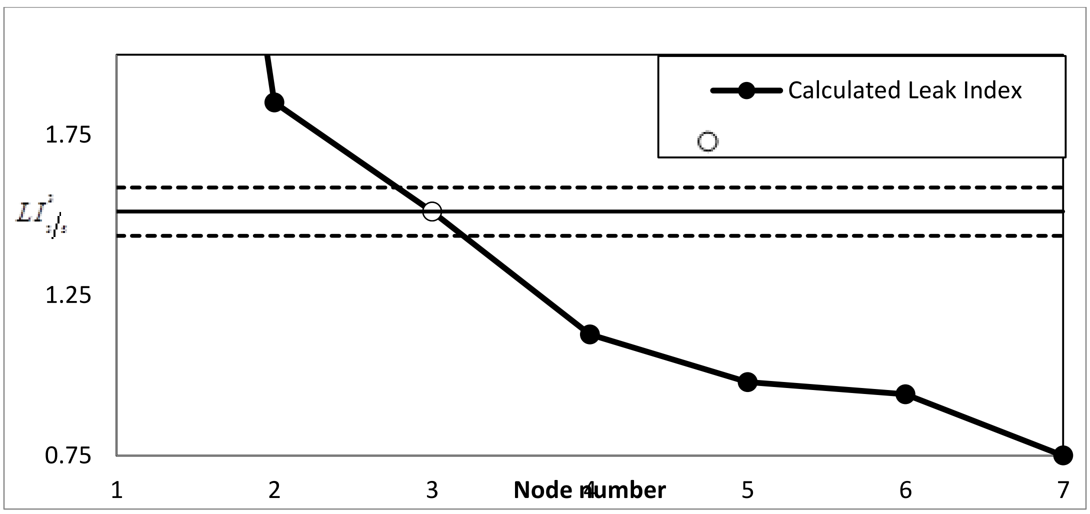

Fig. 5. Leak index for leak value of 7.57 l/s and pressure measurement at nodes 1 and 5.

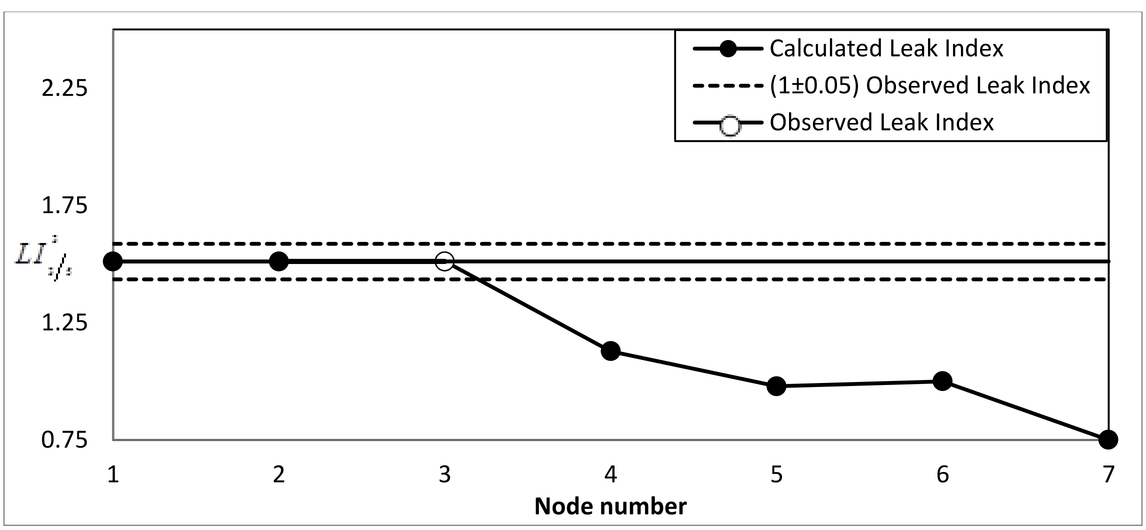

Fig. 6. Leak index for leak value of 7.57 l/s and pressure measurement at nodes 3 and 5.

8.2. Determination of suspected leaky nodes

By application of the presented results in Figures 4 to 6, the suspected leaky nodes in different conditions are determined. Finally, in each condition, the common node repeated in all three pairs of pressure measurements is determined. The results are shown in Table 6. As it can be observed, a hypothetical leak was considered at node 3; this means that the mentioned node is considered as the leaky one. The common node(s) located in the range of $\pm 5\%$ of the real leak index, are determined. At this stage, the common node is node 3, which shows the workability of the applied method in determining the leaky node in the collection and transmission network.

Table 6. The suspected leaky nodes by application of the leak indices obtained from field data

Pairs of nodal pressure measurement	Suspected leaky nodes
(1,3)	3,4,5,7,8,9,10
(1,5)	3
(3,5)	1,2,3
Common node	3

9. Conclusion

A wide range of leak discharges was applied to Kavardeh water collection system as a part of field measurements. It was observed that the choice of node 3 as a leaky node was also reconfirmed by the present technique. This shows the accuracy of the calculations and the fact that by application of 3 nodal pressure measurements, i.e. nodes 1, 3, and 5, the desired results are obtainable. According to the performed analysis in the current network, it can be definitely declared that changing the location of the simulated leak has no effect on the success of the presented leak detection method. Selection of J3 as the real leaky node was only due to some limitation of the simulated leaks at the rest of the nodes in the network.

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