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# Sensor Location for Hydraulic Transient Monitoring and Leakage Location †

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**Abstract:** Distribution Networks operate dynamically due to variable water consumption, but optimal operation is hindered by leakages, which increase treatment costs, energy consumption, and water shortage risks. Detecting and locating leaks, especially slow or low-flow ones, is challenging with steady-state data. However, during transient events, pressure oscillations are influenced by leaks, providing valuable signal attenuation for leak location. This study evaluates the pressure signal during valve closures to identify optimal monitoring points and valve operation rules, aiming to maximize information collection during transients. The findings aim to enhance leak detection strategies and improve network efficiency.

**Keywords:** leakage; hydraulic transient; sensor location



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## 1. Introduction

Water Distribution Networks (WDNs) will always be subject to the presence of leakages, as the extension of the network, complexity of the operation, and costs of maintenance create an unfeasible scenario for the leakage location and repair [1]. However, the leakage rate varies significantly among different WDNs, reaching values as low as 3% and higher than 50% [2]. As expected, leakage causes a direct economic loss due to the treatment and distribution costs. In addition, it can also reduce the water quality by introducing particles during low-pressure periods and reduce water availability for other users of the water source [3].

An effective approach to reduce water losses through leakages is to manage the operating pressure of the WDN. Creating District Measurement Areas (DMAs) is the first step for pressure management, as it allows to adjust the operation of each DMA according to its consumption and especially topographic conditions [4]. Pressure Reduction Valves (PRVs) and pumps with Variable Speed Drives (VSD) are commonly used in this case, showing good results for leakage reduction [5]. Even with good results, these approaches do not effectively fix the problem; i.e., the cracks that allow the water to escape remain in the WDN, only the flow through them is reduced.

To make a repair, first, the leakage must be detected, and then it has to be located. The detection stage can be as simple as the consumers noticing water flowing in streets and sidewalks (visible), or more complex, based on data analysis to identify anomalies (non-visible). For the non-visible leakages, the exact location is still unknown. A field team can be assembled to try and locate the leakage using mainly acoustic equipment that can identify the leakage noise. However, this is a trial and error procedure, as the team has to travel to the WDN to identify the leakage noise. Thus, mathematical methods, based on hydraulic modeling and machine learning, are being developed to assist in leakage location [6]. Most of the models and data acquired are in steady-state conditions. When the leakage flow is low or when it slowly increases over time, the changes in the hydraulic parameters of the WDN are negligible, and can be interpreted as the sensor's noise or as a slight increase in water demand over time. Thus, transient data collected during a valve or pump operation could provide more useful information. The research shows promising results in this case. However, this approach requires a safety procedure to avoid problems with water hammer.

Therefore, in this paper, the operation rule of valves is evaluated to maximize the information collected during a transient event, maintaining safety conditions, both for the infrastructure and for consumers. In addition, the positions of the operating valve and pressure sensors are also analyzed. Considering the safety aspect, only slow maneuvers are considered. Thus, the rigid model proposed by [7] is used for the hydraulic simulation of different scenarios. The quality of the information generated by the valve closure is evaluated through a sensitivity index, defined as the sum of the differences between the signals in the non-leak scenario with different leakage conditions. The results showed that operating valves in pipes with higher velocities have higher sensitivity in the pressure signal.

## 2. Methodology

The methodology comprises three stages: (i) hydraulic modeling; (ii) maneuver allocation; and (iii) sensor allocation.

In the first stage, a hydraulic simulator was developed for the transient regime. The rigid model was chosen to simplify computational complexity and avoid, for instance, the spatial discretization required in the elastic model. Slow and controlled maneuvers were conducted to validate the conditions of the rigid model (non-deformable pipes and incompressible fluid) and to ensure network safety in the presence of pressure surges. The model for the steady-state regime was adopted and adapted for the transient regime, as described by [7] in the Equation (1).

$$\begin{bmatrix} B & \vdots & A_{12} \\ \cdots & \cdots & \cdots \\ A_{21} & \vdots & 0 \end{bmatrix} \cdot \begin{bmatrix} Q \\ \cdots \\ H \end{bmatrix} = \begin{bmatrix} -G \cdot Q_0 - A_{10} \cdot H_0 \\ \cdots \\ -q \end{bmatrix} \tag{1}$$

where $B$ is division of pipe inertia ($I$) by time discretization ($\Delta t$); $A_{12} = {A_{21}}^T$ is the matrix of nodal head unknowns incidence; $A_{10}$ is the matrix of nodes with fixed head incidence; $Q$ is the unknown flow in each pipe at time $t + \Delta t$; $H$ is the unknown head in each node; $Q_0$ is the known flow in each pipe at time $t$; $H_0$ is the head of nodes with known or fixed heads; $G$ represents a diagonal matrix of the difference between flow resistance and pipe inertia.

In the second stage, the results of the transient regime simulation, caused by the maneuver, are analyzed in the identified critical sections with and without leaks. Leaks were simulated at each node, and the maneuver that produced the greatest difference between the data (head and flow signals) in the conditions with and without leaks is sought, i.e., the most sensitivity, as described in Equations (2) and (3).

$$S_{M_k} = \sum_{j=1}^{NN} \sum_{n=1}^{NN} \sum_{t=0}^{T} \left( H_{S\,n,t} - H_{V\,j,\,n,t} \right) \tag{2}$$

$$S_{M_k} = \sum_{i=0}^{NN} \sum_{n=1}^{NN} \left[ \max\left( H_{S\,n} - H_{V\,j,n} \right) \right] \tag{3}$$

where $S_{M_k}$ is the sensitivity of the maneuver at position $k$; $H_{S\,n}$ is the head in the condition without leakage for node $n$ at time $t$; $H_{V\,j,n}$ is the head in the condition with leakage for node $n$ at time $t$ and leakage at position $j$; $NN$ is the number of nodes; $T$ is the total simulation time.

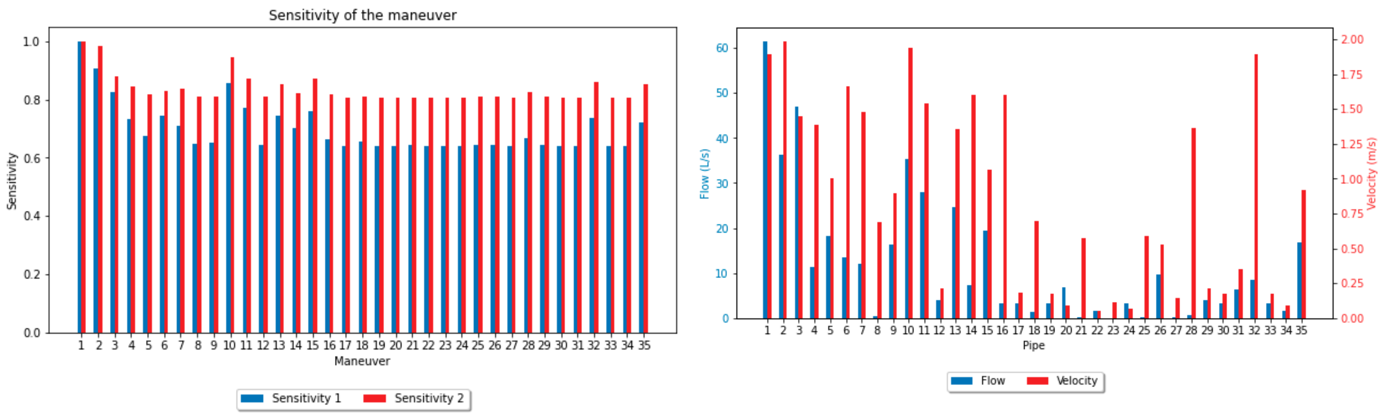
In the third stage, after determining the optimal maneuver position, the sensitivity of each node with the fixed maneuver position (the best maneuver) is evaluated. The overall sensitivity of a given node is determined by accumulating the sensitivity of all nodes for each leak position, as described in Equations (2) and (3), previously, but now specifically for the best position of maneuver $k$.

## 3. Results and Discussion

In order to validate the methodology, addressing the functioning of the algorithm with the rigid model, as well as the determination of maneuver locations and sensor positions, a case study is presented using the BLA network. This model is a part of the city of Blacksburg in the state of Virginia, United States. This infrastructure consists of 30 pipes and 35 junctions, with a total demand of approximately 98 L/s, gravity-fed from a fixed-level reservoir.

The leak was adjusted to approximately 1.0 L/s at the location with the lowest pressure. To generate a disturbance in the WDN, the following procedure was adopted: after 1 s of simulation in steady-state, a valve was gradually closed over 15 s, followed by 1 s with a constant singular headloss coefficient of maximum value (200).

Analyzing Figure 1a, it can be observed that the behavior of the two sensitivities is similar, classifying pipes 1, 2, and 10 as the most sensitive. Figure 1b shows that pipes with higher velocities also exhibit higher sensitivities. The result may suggest that pipes with lower flow rates and velocities have less impact when maneuvered in the network. Since every pipe is a potential candidate for maneuvering, excluding the less relevant pipes when conducting the search for the best maneuvers can reduce the need for hydraulic simulations, leading to greater computational efficiency.

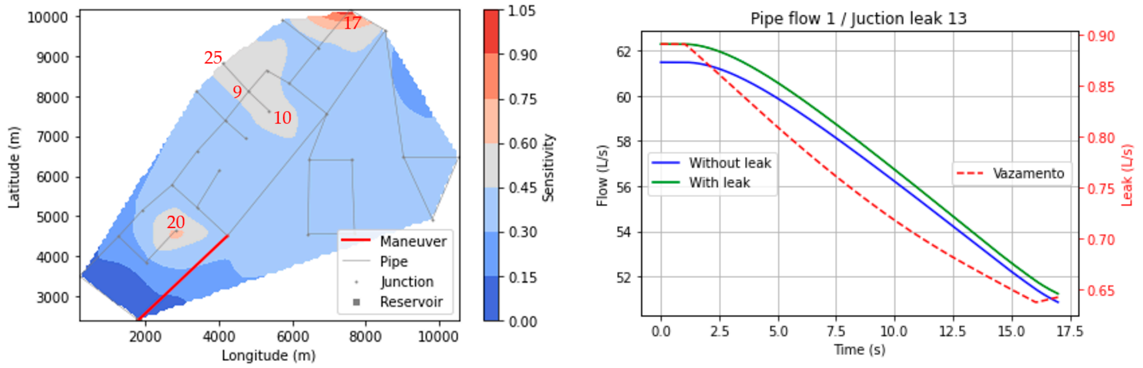



(**a**) (**b**)

**Figure 1.** Results of the maneuver in the BLA network: (**a**) maneuver law; (**b**) sensitivity.

Considering the maneuver in pipe 1, identified as the most sensitive position as shown in Figure 1a, Figure 2a displays the maximum sensitivity, which is the greatest difference between the signal in the condition with and without leakage. Figure 2b presents the variation in head and leakage in the condition with and without leakage.

To identify the most sensitive nodes, it was necessary to assign leakage to all other nodes and accumulate the sensitivity for each node. As shown in Figure 2a, node 17 exhibited the highest sensitivity, followed by a nearby region (nodes 9, 10, and 25) and node 20, which is further spatially from node 17. For sensor allocation, as there was a good spatial distribution between nodes 17 and 20, they were selected. However, for allocating more sensors, a clustering algorithm may be necessary to ensure sensor spatiality and acquire data that better represent the existing infrastructure.




(**a**) (**b**)

**Figure 2.** Results of the maneuver in the BLA network: (**a**) maneuver law; (**b**) sensitivity.

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