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Pressure Sensors Deployment for Water Distribution Network Using Flow-Tracking Analysis

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Abstract. *This paper presents a novel approach for efficient placement of top pressure sensors in water distribution network. Flow-Tracking analysis using head loss coverage ratio explores a least number of top sensors in network topologies. The following sequence of top sensor plans can be effortlessly determined by simple greedy algorithm. A regular hydraulic model with 33 sensor nodes is to validate the fast and effective feature of flow-tracking analysis. A top set of 5 sensor nodes selected by head loss coverage ratio H_{cr} in flow-tracking analysis agree exactly with top set of 5 sensitive nodes selected by objective function $f(X_k)$ by means of Sensitivity Analysis. A linear relationship between objective function $f(X_k)$ and heads loss coverage ratio H_{cr} of top sensor nodes reveals high accuracy mapping from flow-tracking analysis to Sensitivity Analysis. Time complexity of searching top sensors node set by flow-tracking analysis is $O(m \times n)$. Average pressure error can be expected as low as 0.08 m with top-two sensors in sensors layout. As top sensors in placement plan are all used, minimum error of 0.04 m is achieved. Flow-Tracking analysis has the advantages of little time complexity and accurate top sensors strategy as a new efficient solution for pressure sensors placement in associated flow network.*
Keywords: Water distribution network, Pressure sensors, Flow-Tracking analysis, Greedy algorithm

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1. **Introduction.** Pressure monitoring plays a crucial role in resources management of urban water distribution network (WDN) [1, 2, 3]. Pressure sensors should be located in least places where they can offer most valuable monitored data in WDN. It is unfeasible to install pressure sensors all around the network, but efficient placement of pressure sensors using hydraulic model may assist performance insufficiency of network operation and become a viable alternative [4, 5]. As a project buried underground, WDN is complicated because it is composed of hundreds of thousands of pipes, junctions, pumps, valves, and storage tanks [6]. Thus, a hydraulic modeling (e.g. EPANET [7, 8]) is required as a simulation to have a comprehensive grasp on flow patterns and pressure variations of distributed network [9]. WDN [10, 11, 12, 13] modeling requires parameters such as water consumption, valve open/close status, and pipe roughness, etc. Water consumption [14, 15] and valve open/close vary with daily life and water supply operating condition. Such variables are only be monitored by instruments or mathematical predictions. But the roughness of pipes, which represent the flow resistance of pipes and fittings in the network, are parameters that will not change for a long time [16, 17]. Moreover, pipe roughness is an important parameter for simulating the pressure distribution of the network. Therefore, the calibration of pipe roughness coefficient is important for the application of the hydraulic model [18]. For the calibration of the pipe roughness coefficient, the first step is to estimate the initial value of every pipe. Then compare the simulated pressure values from hydraulic model with the values from measurement [19, 20, 21].

How to select the pressure sensor nodes in a water distribution network is critical to the pipe roughness calibration. Schaetzen et al. [22] presented three methods to select pressure sensor nodes to calibrate pipe roughness coefficients, one of which rank the sampling locations based on shortest path algorithms. Klapcsik et al. [23] discussed two approaches to tackle the problem of locating the top pressure sensor nodes in a hydraulic system. One of them applies the concept borrowed from graph theory to optimize the pressure measuring locations, and the other applies the sensitivity analysis of the pipe roughness affecting the node pressure. However, the above methods lack the physical bases for the fluid dynamics of water supply. Yoo et al. [24] developed a method considering the pipe connectivity of water distributed network and the impact among nodes by pressure driven analysis and entropy method. Lee et al. [25] defined a concept of coverage, and proposed methods on how to locate monitoring sites by an analysis of the pathways of water flows in a designated water network. Even though Yoo and Lee's works are connected to the physical properties of the pipe network, both of them do not grasp the pressure change of entire loop from the water source to the pressure sensor node.

This paper proposes a new approach, relying on coverage concept of head loss in flow tree diagram, to select the top location set for pressure sensors placement efficiently. According to the energy conservation law of fluid dynamics, their relationships are developed by means of the flow tracking analysis from water source to pressure sensor node. Sequence configuration for these selected top sensor nodes group is easily constructed by greedy algorithm [26, 27], and hence improving the computational efficiency significantly.

2. **Flow-Tracking Analysis.** Water head refers to the pressure of a pipe water at the node (expressed in meters of water), plus the elevation of the node (expressed in meters) [28, 29]. Therefore, unit for pressure and water head used in this paper is meter. For convenience, the term pressure can replace water head if the elevation of the node is zero. The head loss of pipe is the pressure drop caused by the surface friction inside the pipe. Head loss in the pipe can be calculated with the Hazen-Williams formula [30, 31], which is known as empirical equation frequently for evaluation of pressure drop in water distribution networks [9]. Head loss h_L is determined by flow rate q, pipe roughness

coefficient C, pipe diameter d, and pipe length L as expressed in following Hazen-Williams equation,

$$h_L = A \cdot q^{1.852} \tag{1}$$

where

$$A = 4.727 \cdot C^{-1.852} \cdot d^{-4.871} \cdot L \tag{2}$$

A network $W(R,\ V,\ A)$ as shown in Figure 1, where R is the set of water sources, V is the set of nodes and A is the set of edges (or pipes) in the network. The water head (or pressure) at node $i \in V$, can be calculated by the following hydraulic model formula.

$$P_i = f\,(HR_j, HL_k) \tag{3}$$

where P_i is the simulated pressure at ith node, $1 \leq i \leq |V|$. $|V|$ is the number of nodes. HR_j is the set of all water heads (or pressures) of water sources, $1 \leq j \leq |R|$, and HL_k is the set of all head losses of the pipes, $1 \leq k \leq |A|$. $|R|$ and $|A|$ are the number of water sources and the number of pipes, respectively. If HR_j is known and C_k represents the roughness coefficient of kth pipe in Equation (3), we can compute the head loss h_L for all the pipes. As a result, the pressure at each node P_i is then obtained by Equation (3), $1 \leq i \leq |V|$. In the practical network operations, it is often assumed that the values of q, d, and L in Equation (1) are given. Hence, the problem of given HL_k set is corresponding to the problem of getting appropriate C_k. Where C_k is the set of all pipe roughness coefficients, $1 \leq k \leq |A|$. To avoid random speculation of HL_k, a node subset $U(U \subseteq V, |U| = m)$, installed with pressure sensors is necessary. An typical hydraulic model with two water sources, 33 nodes, and 50 pipes was adopted as shown in Figure 1. All node elevations are set to be zero for simplicity. The thick black lines denote the main pipes whose diameters are 200 mm, the diameters of the other pipes are 100 mm, and the length of each pipe is 1000 m. All nodal demands are set to be 4.0 m^3/h and the supply pressure head of both water sources are 35 m. Several methods for optimal

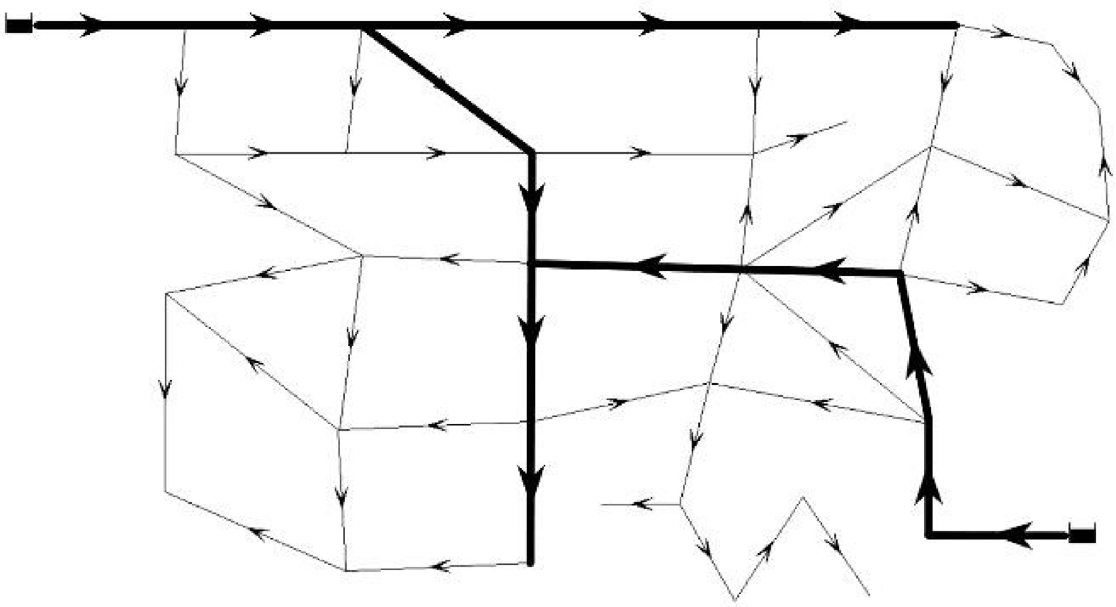

Figure 1. A typical hydraulic model with flow direction.

location of pressure sensors in earlier works were introduced. The following will describe in detail how to use flow-tacking analysis to find optimal sensor nodes. According to fluid dynamics, head-loss coverage ratio H_{cr} is defined as

$$H_{cr} = \frac{\sum_{j=1}^{M} h_j^*}{\sum_{i=1}^{N} h_i} \tag{4}$$

where N and M are total number of pipes in the network and on the flow-tracks with measuring nodes, respectively. h_j^* represents the head loss of the jth pipe in those flow-tracks. H_{cr} is a fraction of coverage desired to be unity, as indicating the preferred sensor nodes can cover total pipes loss in network entirely. Figure 2 shows a typical two

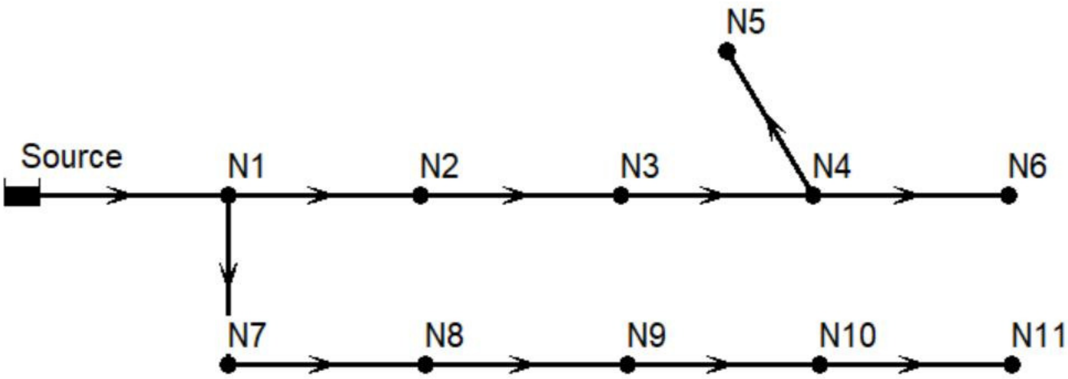

FIGURE 2. Flow-Tracking of end nodes in two branches in water distribution system.

branches on the water distribution system with three end nodes of $N5$, $N6$, and $N11$. All the pipes in Figure 2 have same roughness coefficient, diameter, and length. However, if two pressure sensors can only be installed, two options $N11$-$N5$ and $N11$-$N6$ are better than $N5$-$N6$. Since more pipes are covered by first two options than by the third option. The H_{cr} of $N6$-$N11$ is 0.994 higher than 0.739 of $N5$-$N6$. It means that $N6$-$N11$ is a better choice than $N5$-$N6$ mostly because $N11$ is a major end node as mentioned above. Therefore, this study will begin a procedure by evaluating H_{cr} as the index of priority rank in the greedy algorithm as follows. Steps (1)-(7) are flow-tracking analysis and greedy algorithm proceeds as described:

(1) Calculate flow directions of all pipes with EPANET. The pipe connects two nodes, and water flows from the upstream node to the downstream node.

(2) Search for nodes where water flow can only enter and no out. These sensor nodes are candidates for installing pressure sensors.

(3) Calculate H_{cr} for each sensor node.

(4) Sort all the H_{cr} values in descending order.

(5) The node with the largest H_{cr} is the first priority sensor node.

(6) In addition to the maximum H_{cr}, select another sensor node among the other sensor nodes, so that the combination H_{cr} of the two nodes is maximized. This is the second priority sensor node.

(7) With the same routine as step (6), the third, fourth, and until the last priority sensors all get into positons.

3. **Results and Discussion.** Five top sensor nodes in Figure 3 are determined according to step (2). The flow-tracking of node 21 is shown in Figure 4. The H_{cr} of node 21 is

calculated from pipes with red color. The H_{cr} of five sensor nodes is shown in Table 1. Column I in Table 1 is the sensor nodes sorted by H_{cr} in descending order. Table 1 is the result of flow-tracking analysis. The next stage is continued by greedy algorithm. Since node 28 is the first priority, all combinations of the other nodes with node 28 are shown in column III in Table 2. Since H_{cr} of node 28 and 30 is the highest in column IV, node 30 is the second priority of the list. It can be seen from Table 1 that H_{cr} of node 16 is ranked second, but its jointed result with node 28 is far inferior to the jointed result of node 30 and node 28. After greedy algorithm, node 16's final selection ranking fell to fifth. The reason is obvious from Figure 3 that nodes 16 and 28 are only one pipe (pipe 48) in difference.

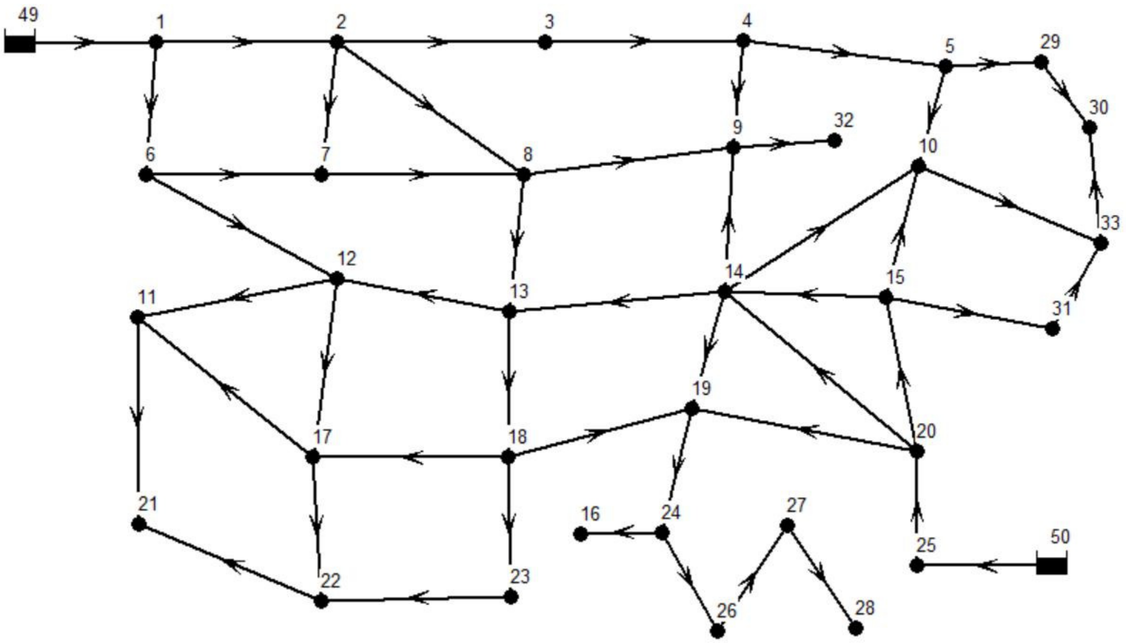

Figure 3. Five optimal sensor nodes marked with dotted circle.

Table 1. H_{cr} and FTA rank of optimal sensor nodes by flow-tracking analysis.

Node	H_{cr}	FTA rank
28	0.758	1
16	0.632	5
21	0.373	3
32	0.297	4
30	0.271	2

4. **High Compatibility with Sensitivity Analysis.** Just like flow-tracking analysis trying to find the pressure sensors placement by fluid dynamics, Sensitivity analysis (SA) [3, 32, 33, 34] uses an intuitive method to search the most sensitive pressure sensor point [22, 23]. To find the best combination of k sensor nodes, Equation (5) is proposed by Klapcsik et al. [23].

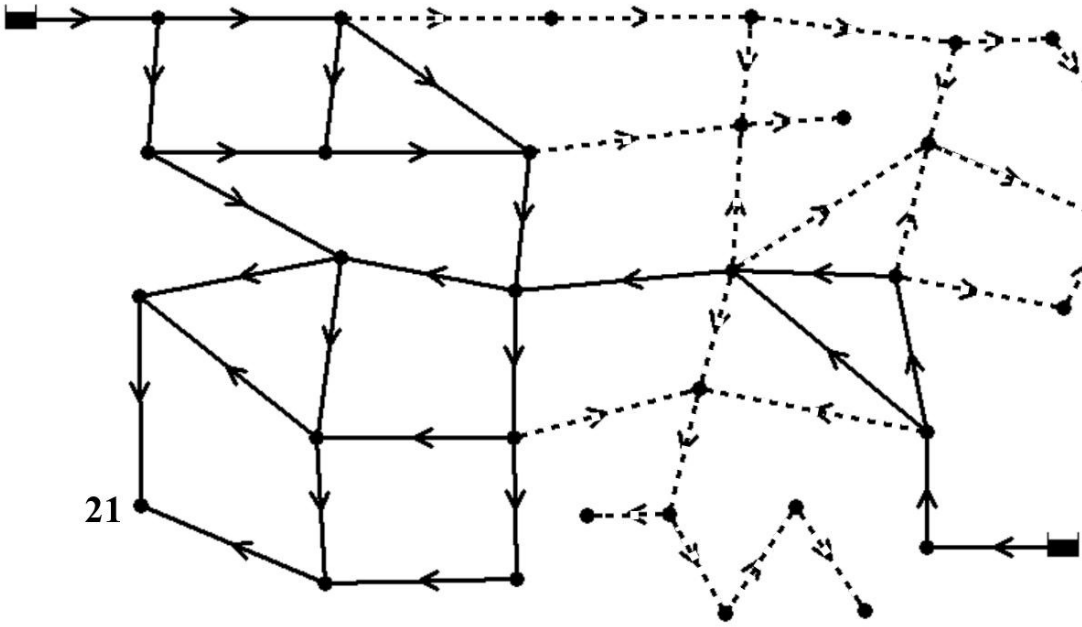

Figure 4. Flow-Tracking tree diagram (solid line) of node 21.

Table 2. Rank of grouped sensor nodes by Greedy algorithm.

1^{st} node	H_{cr}	1^{st}-2^{nd} nodes	H_{cr}	1^{st}-2^{nd}-3^{rd} nodes	H_{cr}	1^{st}-2^{nd}-3^{rd}-4^{th} nodes	H_{cr}	1^{st}-2^{nd}-3^{rd}-4^{th}-5^{th} nodes	H_{cr}
28	0.758	28-30	0.863	28-30-21	0.962	28-30-21-32	0.989	28-30-21-32-16	1.000
16	0.632	28-21	0.857	28-30-32	0.890	28-30-21-16	0.973	–	–
21	0.373	28-32	0.800	28-30-16	0.874	–	–	–	–
32	0.297	28-16	0.769	–	–	–	–	–	–
30	0.271	–	–	–	–	–	–	–	–

$$f\left(X_k\right) = \sqrt{\sum_{i=1}^{2}\left[\frac{F_i\left(X_k\right) - F_{i,\max}}{F_{i,\min} - F_{i,\max}}\right]^2 w_i} \tag{5}$$

where w_i is the weight of $F_1(X_k)$ and $F_2(X_k)$, $F_{2,max} = \ln\ (N)$ and N is the total number of pipes. The objective is to define the sampling set that has the minimum values of Equation (1). Obviously, the flow-tracking analysis (FTA) and sensitivity analysis (SA) use different index, H_{cr} and $f(X_k)$ as the parameters for selecting the sensor nodes. However, no matter which possible order among the optimal set would be, optimal set of sensor nodes by both FTA and SA are exactly the same (Table 3). In order to verify this unique relationship, $f(X_k)$ in Table 3 shows an excellent matching in each possible combination. FTA demonstrates a great agreement and perfect link directly to Sensitivity analysis.

Head loss has exponential power sensitivity to roughness coefficient as in Equation (5). In other words, head loss H_{cr} and sensitivity $f(X_k)$ reach one goal. $f(X_k)$ is a search strategy function in SA and H_{cr} is the flow-tracking principle behind search strategy of SA. Figure 5 reveals a linear correlation between $f(X_k)$ and H_{cr} in optimal combination of top sensors. The correlation coefficient r closes to -1 indicating that a perfect linear relationship is found.

TABLE 3. Comparison of $f(X_k)$ in Sensitivity analysis, H_{cr} in flow-tracking analysis, and P_{err} (in meter) of optimal set.

Node	$f(X_k)$	H_{cr}	P_{err}
28	0.378	0.758	0.196
28,30	0.324	0.863	0.078
28,30,21	0.285	0.962	0.065
28,30,21,32	0.267	0.989	0.058
28,30,21,32,16	0.255	1.000	0.041

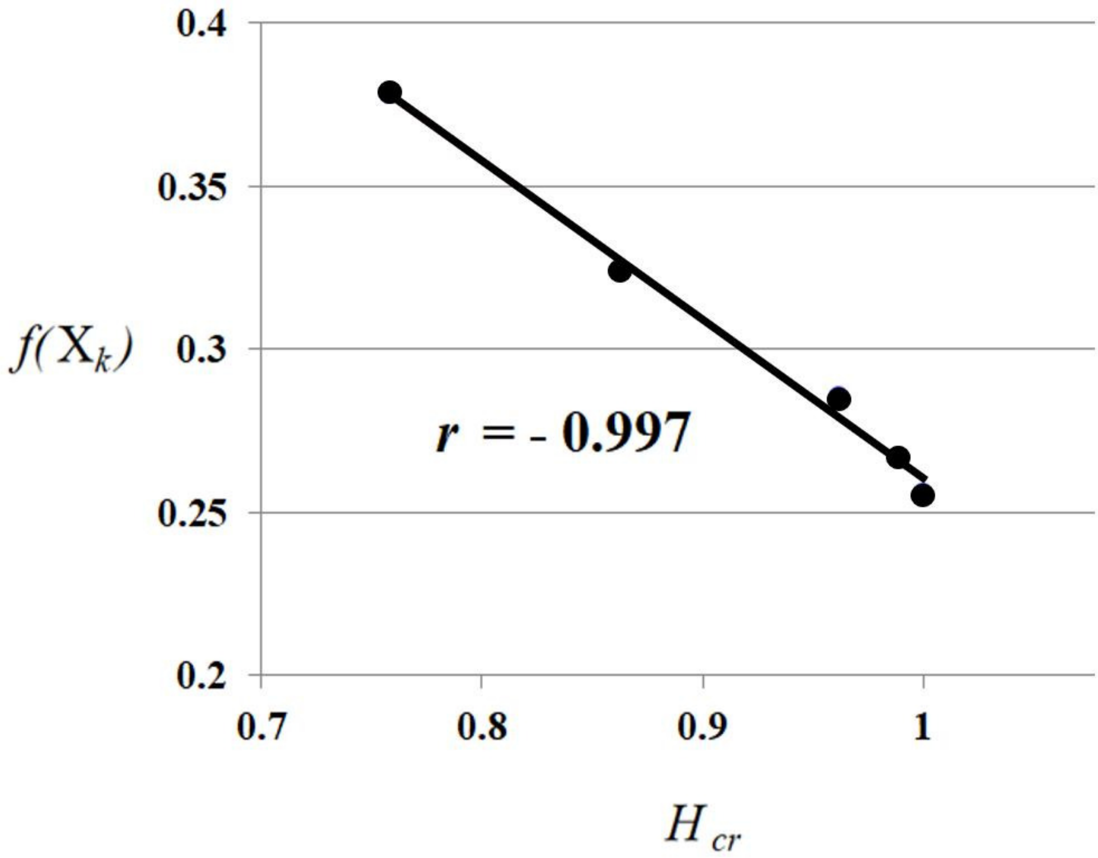

FIGURE 5. A perfect linear correlation between $f(\mathrm{X}_k)$ and H_{cr} in best combination of optimal sensors.

The difference in solving pressure sensor placement problems from theory or phenomenon is their efficiency. Equation (6) is the time complexity of SA. Therefor the time complexity of SA is the number of combinations of m sensor nodes selected from n network nodes.

$$T_{SA}(n,m) = O\left(C_n^m\right) = n!/(m! * (n-m)!) \tag{6}$$

Time complexity regarding algorithm is generally expressed in terms of big O notation, which describes operation time run an algorithm taken for performance evaluation. Equation (7) is the time complexity $T(n)$ of the FTA.

$$T_{FTA}(n+p,m) = O(m \times (n+p)) \tag{7}$$

where n is the number of all nodes, m is the number of sensors and p is the number of all pipes. Because SA lacks the fluid dynamics guidance for selecting sensor nodes, it can only choose randomly and compare the value of Equation (5).

The ratio of time complexity in choosing optimal 5 sensor nodes out of 33 nodes and 50 pipes by Equation (7) of FTA to Equation (6) of SA is

$$\text{TFTA}(33+50,5) = 5 \times (33+50) = 415 \quad to \quad \text{TSA}(33,5) = C_{33}^{5} = 237336 \tag{8}$$

The average pressure simulation error P_{err} will improve the reliability.

$$P_{\text{err}} = \frac{\sum_{j=1}^{T_n} E_{dj}}{T_n} \tag{9}$$

Where E_{dj} is pressure error of the jth test and T_n is the total test number set to 100 in this paper. The P_{err} of top rank combination in optimal set is shown in Table 3. P_{err} less than 0.1 m can satisfy the error requirement of the hydraulic model calibration. In this case, FTA needs only two sensor nodes 28 and 30 for the model verification.

In the future, moreover, FTA can make the work of pressure sensor placement in massive water distribution network much easier by partitioning WDN into several smaller sub-networks. Then pressure sensor placement in sub-networks can be resolved one by one with FTA algorithm. Optima sensors node set in each sub-network can be integrated, and successive execution using FTA becomes faster and simpler. The resulting placement process for P in enormous complicated WDN by means of FTA saves more time and work. Consequently, FTA highlighting fast and little time complexity is especially valuable to offer optimal top sensors set of the placement layout efficiently and cost-effectively.

5. **Conclusions.** In the future, moreover, FTA can make the work of pressure sensor placement in massive water distribution network much easier by partitioning WDN into several smaller sub-networks. Then pressure sensor placement in sub-networks can be resolved one by one with FTA algorithm. Optima sensors node set in each sub-network can be integrated, and successive execution using FTA becomes faster and simpler. The resulting placement process for P in enormous complicated WDN by means of FTA saves more time and work. Consequently, FTA highlighting fast and little time complexity is especially valuable to offer optimal top sensors set of the placement layout efficiently and cost-effectively.

In this paper, a new approach for placing top pressure sensors in water distribution networks is proposed. The minimum number of sensors can be found in the pipe network topology by performing a flow analysis of the head loss coverage. Currently, a simple greedy algorithm determines the sequence of top pressure sensor plans, which limits the performance of the algorithm. In the future, more advanced heuristic algorithms [35, 36, 37, 38, 39, 40] can be considered. In addition, we can research smart water distribution networks by combining the Internet of Things [41, 42, 43, 44, 45].

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