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Subsystem-Based Pressure Dependent Demand Analysis in Water Distribution Systems Using Effective Supply

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Abstract

In this study, Subsystem-Based Pressure Dependent Demand (SPDD) analysis is implemented using the concept of effective supply to eliminate the uncertainties caused by the Head-Outflow Relationship (HOR) in Pressure Dependant Demand (PDD) analysis. This study optimizes the nodal water demands to satisfy the nodal pressure requirement under the abnormal condition defined as the part of the water distribution systems that is closed due to maintenance, rehabilitation, or accidents. The total water supply is optimized and defined as the effective supply, which is the maximum water supply while maintaining the nodal pressure requirements (25 psi) to guarantee the customer's convenience. A meta-heuristic algorithm, the Harmony Search (HS) algorithm, is applied to optimize the system. To decrease the effect of the HOR uncertainties, an optimization method is proposed in this study using the EPANET model that is widely used for the hydraulic simulation. To evaluate the applicability of the suggested model, Supply Index (SI), Pressure Index (PI), Effective Supply Index (ESI), and Subsystem Importance Index (SII) are also defined and calculated from a real-sized network. This paper firstly tried to perform pressure dependent demand analysis for subsystem without the HOR equation that has been an important issue in water distribution system analysis. The developing method could be a good alternative for the design and maintenance of water distribution systems.

Keywords: *water distribution systems, effective supply, subsystem, pressure dependent demand analysis, harmony search*

1. Introduction

As water distribution pipes become deteriorated in many urban areas, sections of the network have to be closed by isolation values for maintenance or rehabilitation. The sets of pipes isolated by these values are defined as segments (Walski, 1993). In addition to the segment, an additional region could be isolated when the only pipe supplying water from the source to the region is disconnected. This additional region is defined as the Unintended Isolation (UI) by Jun (2005).

If a segment is closed for maintenance or rehabilitation, the hydraulic condition in the network such as the amount of discharge flowing in the pipes might be changed, so that the nodal pressure might be insufficient to supply the water demands of the users, which is defined as the abnormal condition. On the other hand, the normal condition means that all pipes are opened and the users are supplied with enough water. This normal condition has been analyzed using Demand-Driven Analysis (DDA), which assumes that all of the nodal water demands are supplied even though the nodal pressure is less than the capable pressure to supply that amount. A negative pressure sometimes appears in the DDA. The most popular hydraulic simulation model using DDA is EPANET 2.0. The DDA provides reasonable results if the system is under the normal condition and has enough conveyance capacity, that is, the nodal pressures of the entire network over the simulation time is greater than the minimum pressure requirement defined for the user's convenience.

However, if the nodal pressure is less than the minimum requirement, the hydraulic simulation model is not able to provide an appropriate solution. In the real network, if the nodal pressure is less than the minimum pressure requirement, the water demand could not be supplied because the amount of supplied water totally depends on the nodal pressure. This is defined as the pressure-deficient condition.

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Over the last two decades, different methods have been proposed and applied for water distribution system analysis under the pressure-deficient conditions. Gupta and Bhave (1996) compared the various head and discharge formulations that have been developed by different researchers (Bhave; 1981, Carey and Hendrickson; 1984, Wagner *et al.*; 1988, Fujiwara and De Silva; 1990, Chandapillai; 1991; Park and Liebman; 1993; Tanyimboh and Tabesh; 1997, Mays; 2003). The pressure-deficient conditions have to be analyzed using the relationship between the nodal head and discharge. Salgado-Castro (1988) considered a linear relationship between the ratio of nodal demand change and the nodal pressure change that is not really the case in the real network. Ackley *et al*. (2001) and Udo and Ozawa (2001) also proposed the head-discharge loss function to simulate the pressure-deficient conditions. Rossman (2000) used an emitter to calculate the pressure-dependent discharge in EPANET software. However, none of the methods could be a genetic solution for practical applications or could consider the transition between the pressure-deficient and pressure-sufficient conditions. Therefore, Ang and Jowitt (2006), Wu *et al*. (2006) and Todini (2006) proposed a modeling approach to solve pressure-deficient conditions using a global-gradient algorithm (Todini and Pilati, 1988). The extended global-gradient algorithm has been applied in three example networks and a generic relationship between pressure head and nodal demand is proposed in Wu *et al*. (2009). However, the global-gradient algorithm required a long computation time and rebuilding the solution matrix was computationally intensive due to topology variations (Wu, 2007). To avoid these difficulties, Baek *et al*. (2010) used a stochastic search technique, the Harmony Search (HS) algorithm, to calculate the hydraulic condition of the applied network. However, not only were the computational difficulties caused by the stochastic search technique a problem, but also the global optimum was not provided or guaranteed.

In this study, Subsystem-based Pressure Dependent Demand (SPDD) analysis is implemented using the concept of effective supply with the conventional DDA to eliminate the difficulties caused by the relationship between nodal head and discharge in Pressure Dependant Demand (PDD). The effective supply is defined as the maximum supply under the abnormal condition while maintaining the minimum pressure requirement. The entire area, including the segment and the UI closed together, is defined as the subsystem. The system is optimized to find the effective supply amount (i.e., the optimized water supply amount) using a meta-heuristic HS algorithm. As a result, the Subsystem Importance (SII) and Effective Supply (ESI) Indices are proposed to evaluate the effects of the abnormality on the systems and com- pare the results from the proposed method with those of the traditional pressure-dependent demand analysis using the iterative method.

2. PDD Analysis

2.1 Traditional PDD Analysis

The popular simulation tool for PDD analysis is WaterGEMS (Bentley Systems, 2006), which includes typical Head-Outflow Relationship (HOR; nodal head and discharge relationship) curves such as an exponential function [Eq. (1)] and piece-wise linear function. Different HOR curves can be selected in each node.

$$\frac{q_i^c}{q_i^r} = \begin{cases} 0 & H_i^c \le 0 \\ \left(\frac{H_i^c}{H_i^r}\right)^{\alpha} & 0 < H_i^c < H_i^t \\ \left(\frac{H_i^t}{H_i^r}\right)^{\alpha} & H_i^t \le H_i^c \end{cases} \tag{1}$$

Where, H_i^c: Calculated pressure at node i

H_i^r: Reference pressure that is deemed to supply full required (reference) demand

H_i^t: Pressure threshold above which the demand is independent on nodal pressure

q_i^r: Reference demand at node i

q_i^c: Calculated supply at node i

α: Exponent of the pressure and discharge relationship

The reference pressure (H_i^r) is defined as the minimum pressure considered necessary to supply the users' need. If the nodal pressure (H_i^c) is greater than the threshold pressure (H_i^t), the water supply (q_i^c) does not depend on the nodal pressure and is constant irrespective of the nodal pressure as the ratio between the threshold pressure and reference pressure with the exponent of α. The threshold pressure depends on the physical capacity of the pipes.

To apply the HOR curves, enormous data on the observed pressure and demand data are needed. Due to the data deficiency, the HOR curves are frequently assumed in practice, which leads to uncertain results on the hydraulic simulation.

2.2 Uncertainty with HOR

A hypothetical water distribution system proposed by Ozger (2003) consisting of 13 nodes, 21 pipes, and 2 water sources (Fig. 1) is analyzed using traditional PDD analysis with different HOR curves when a pipe P3 (the circled pipe in Fig. 1) is closed. Five HOR curves - four exponential [Eq. (1)] and one piece-wise linear functions - are applied in the network. Tables 1 list the parameters used in the five HOR curves. The same HOR curve is applied at all nodes of the network.

Table 1. Parameters of the Four Exponential and One Piecewise Linear Functions as the HOR Curves

HOR Index	α	$H_i^r = H_i^t$	HOR Index	Percent of Reference Pressure (%)	Percent of Reference Demand (%)	$H_i^r = H_i^t$
1	0.2			0	0	
				10	30	
2	0.5	15m	5	30	70	15m
3	0.8			50	90	
4	2			100	100	

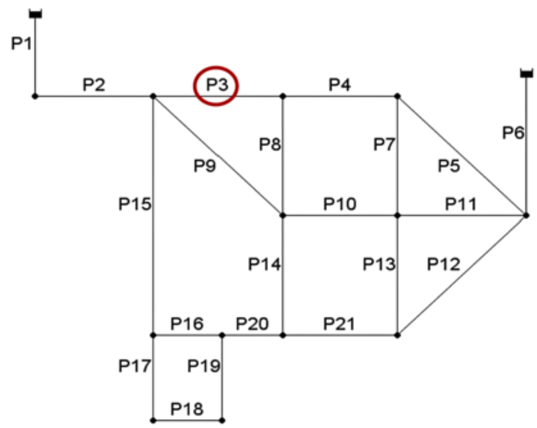

Fig. 1. Hypothetical Water Distribution Network with a Closed Pipe P3 (The circled one) (Ozger, 2003)

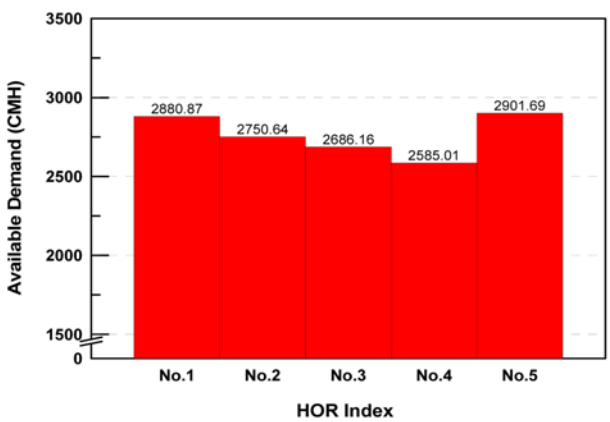

Fig. 2. The Total Water Supply Depending on HOR Curve

Figure 2 shows the total water supply depending on the HOR curves. The range of supplied water shows from 2,901.69 m^3/hr as maximum flow to 2,585.01 m^3/hr as minimum flow, giving a large difference of about 317 m^3/hr, leading to severe uncertainty in the hydraulic simulation.

2.3 New PDD Analysis

In this study, the nodal water demand is optimized to satisfy the minimum pressure requirement over the entire network. The optimized water supply calculated by the proposed method might be smaller than the supplied water calculated by the conventional PDD analysis because all of the nodal pressures are greater than the requirement. To increase the nodal pressure, the water demands have to be decreased. In the PDD analysis, the water supply is calculated based on the nodal pressure using the HOR curve; thus, the nodal pressures can be lower than the pressure requirement.

2.3.1 Effective Supply

The effective supply is defined as the maximum water supply under the abnormal condition. As mentioned earlier, if the effective supply is smaller than the nodal demand due to the low nodal pressure so that the users experience difficulty in using the water, it is defined as the abnormal condition of the system. To analyze the abnormal condition more accurately, the HOR has to be considered. However, the HOR curve might introduce additional uncertainty into the system due to the difficulty in estimating the relationship and the spatially and temporally variation. Therefore, in this study, instead of using the HOR curve, the PDD analysis is implemented by decreasing the water supply to the optimal water supply to satisfy the nodal pressure requirement. This method allows the hydraulic simulation to be implemented using EPANET. Since the system is assumed to be operating under the normal condition after decreasing the nodal water demand, EPANET could give accurate simulation results.

2.3.2 Objective Function

The proposed model is used to maximize the sum of the nodal water demands when the nodal pressure is greater than the minimum pressure requirement.

$$\max\ Q_k^{es} = \Sigma_{i=1}^{n} q_i^{abs} \quad (2)$$

s.t.

$$H_i^c \ge H_i^{min}, \qquad i = 1, 2, 3, ..., n \quad (3)$$

Where, H_i^c: calculated nodal pressure at node i

H_i^{min}: minimum pressure requirement

n: number of nodes

Q_k^{es}: Total Effective Supply when Subsystem k Isolated

q_i^{abs}: nodal available water supply at a node i under abnormal condition

The minimum pressure requirement (H_i^{min}) is assumed based on the nodal status.

- If the nodal pressure under the normal condition is less than H_i^{min}, the normal pressure under the normal condition is assumed as H_i^{min}.
- If the nodal water demand is satisfied and the nodal pressure is greater than the minimum pressure requirement, even when a subsystem is isolated, the original water demand is set as the optimized water demand.

2.3.3 Optimization using Harmony Search

The Revised HS (Baek, 2002) linked to EPANET using Visual Basic 6.0 is applied for effective optimization of the supply.

The procedure of the proposed method (Fig. 3) is described as follows:

1. The nodal water demand is randomly generated to construct the Harmony Memory (HM).
2. The nodal pressure using the generated water demand is calculated by EPANET.
3. If the calculated nodal pressures are greater than the minimum pressure requirement, select the corresponding water demands, otherwise discard the generated water demands from the HM.
4. Apply the HM Considering Rate (HMCR) and the Pitch Adjusting Rate (PAR) and go to step. Find the HM with the maximum nodal water demand until the termination criterion is met.

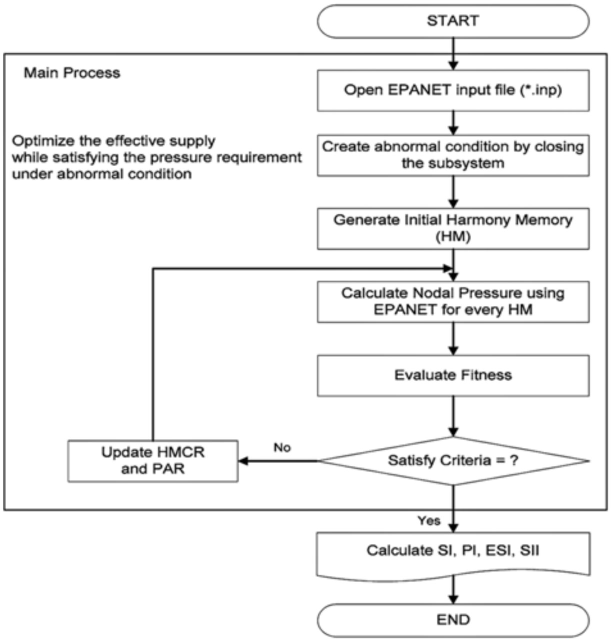

Fig. 3 Flowchart of the Proposed Optimization Model

Where, HM: The size of the harmony memory
HMCR: The rate of choosing a value from the harmony memory
PAR: The rate of choosing a neighboring value

2.4 Subsystem-based PDD Analysis

In a real network, it is impossible to install control valves into all pipes due to economic reason. Therefore, if a valve is closed, multiple pipes are closed together. This part of the network is defined as a segment by Walski (1993). Fig. 4 shows an example of a segment. If pipe P4 or P5 are broken, three values located in N1, N3, and N4 have to be closed. By doing so, P4, P5, and N3 are isolated together and defined as the segment. Isolation of the segment causes UI (Jun, 2005), which is defined as the area where the water is not supplied because the only pipe (P6) from the water source is closed. The subsystem is defined as the entire area including the segment and the resulting UI.

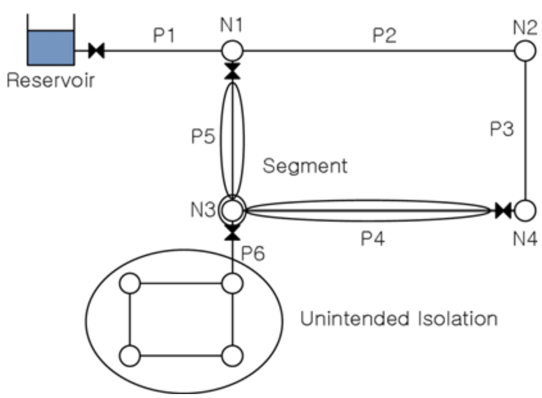

Fig. 4. Segment and Unintended Isolation (Walski, 1993; Jun, 2005)

3. Evaluation Index

3.1 ESI

3.1.1 Pressure Index (PI)

The Pressure Index (PI) is introduced to evaluate the effect of the abnormality of the system on the nodal pressure. The abnormality is caused mainly by the isolation of a subsystem. The PI is calculated using Eq. (4) with a range of 0 to 1. The PI is only calculated when the nodal pressure is lower than the minimum pressure requirement.

$$PI = 1 - \frac{\Delta P}{H_i^{min}} \tag{4}$$

Where, ΔP is the pressure difference at a node between the normal and abnormal conditions and is calculated using Eq. (5).

$$\Delta P = \begin{cases} |H_i^{min} - H_i^{ab}|, & \text{if } H_i^n \geq H_i^{min} \text{ and } q_i^{abs} < q_i^d \\ 0, & \text{if } H_i^n \geq H_i^{min} \text{ and } q_i^{abs} \geq q_i^d \\ |H_i^{min} - H_i^n|, & \text{if } H_i^n < H_i^{min} \end{cases} \tag{5}$$

Where H_i^{min} is the minimum pressure requirement at a node, H_i^{ab} is the calculated nodal pressure under the abnormal condition, H_i^n is the calculated nodal pressure under the normal condition, q_i^{abs} is the calculated nodal water supply under the abnormal condi- tion, and q_i^d is the nodal demand.

If the pressure difference between the normal and abnormal conditions is zero, i.e., a zero pressure drop under the abnormal condition, the PI becomes 1. The PI is decreased with increasing pressure drop. Finally, if the pressure difference is the same as the minimum pressure requirement, the PI is zero.

3.1.2 Supply Index (SI)

The Supply Index (SI), with a range of 0 to 1, is introduced to evaluate the difference of nodal water supply under the normal and abnormal conditions and is calculated using Eq. (6).

$$SI = \frac{q_i^{abs}}{q_i^d} \tag{6}$$

Where, q_i^{abs}: Nodal available water supply at a node i under abnormal condition
q_i^d: Nodal water demand at node i under normal condition

If the water supply under the abnormal condition is the same as the water demand, the SI is 1.

3.1.3 Effective Supply Index (ESI)

The ESI is a standardized index that uses the PI and SI to evaluate the hydraulic effects of the abnormality such as the subsystem isolation on the entire water distribution network. This result can be useful for the network maintenance or rehabilitation.

The Euclidean Distance Method proposed by Baek (2007) is used to calculate the ESI using PI and SI [Eq. (7)]. As shown in

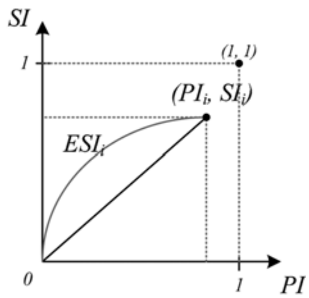

Fig. 5 Relationship among PI, SI, and ESI

Fig. 4, the maximum ESI is $\sqrt{2}$ since the maximum values of PI and SI are 1.

$$ESI = \sqrt{PI^2 + SI^2} \tag{7}$$

3.2 SII

The ESI value of a subsystem is influenced by the isolation condition of the subsystem. If the subsystem has a low ESI, that is, the isolation has a strong influence on the entire network, the isolation might cause severe damage to the network or inconvenience to the users. The section of the system with such strong effects has to be adequately maintained. To evaluate the severity of the effect, the SII is introduced [Eq. (8)] with a range of 0 to 1. A large SII value indicates that the water supply and pressure of an entire water distribution system are decreased severely by the isolation of the corresponding subsystem including the segment and the UI.

$$SII_k = \frac{Q^n - Q_k^{es}}{Q^n} \tag{8}$$

Where, SII_k: SII of Subsystem k
Q^n: Total water Demand under normal condition
Q_k^{es}: Total Effective Supply when Subsystem k Isolated

4. Application

The second example network is the Cherry Hill/Brushy Plains network, which is a portion of the South Central Connecticut Regional Water Authority's service area. This network, shown in Fig. 6, is a branched-type network consisting of 88 nodes, 104 pipes, 94 valves (Jun, 2005), 1 reservoir, and 1 tank, with pipe diameters of 6, 8, and 12 inches.

The network comprises 80 segments, each of which contains 1~3 pipes. The maximum number of pipes in S(20) segment is 7. However, since the network is a branched type, UIs are included in the subsystem. With 30 nodes and 40 pipes, the largest UI has a potentially huge hydraulic effect on the water distribution systems.

Under the normal condition, the minimum and maximum nodal pressures are 26 psi and 110 psi, respectively. The minimum pressure requirement is set as 25 psi. The SII is calculated when a subsystem is isolated as shown in Fig. 7. When calculating the SII, the valve operation is assumed to proceed without any error.

As most of the SIIs are less than 0.2, the effect on the water distribution systems was insignificant. However, the SIIs of the largest seven subsystems are much greater than the others and over than 0.1. If these seven subsystems are closed simultane-

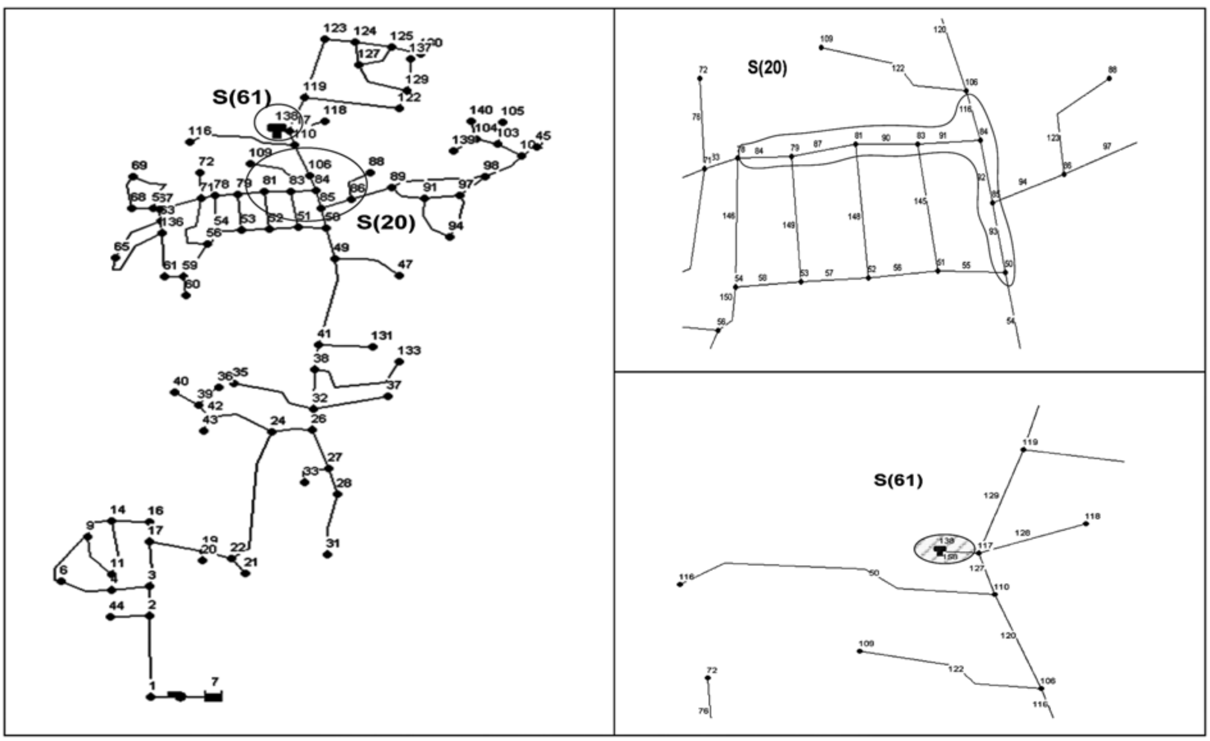

Fig. 6. Cherry Hill Network, S(61), and S(20)

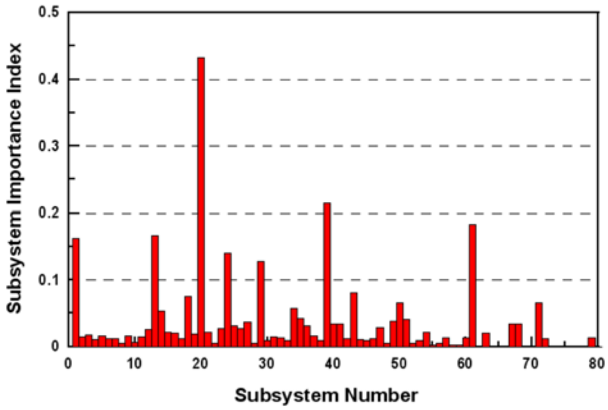

Fig. 7. Subsystem Importance Index (SII) of Cherry Hill Network

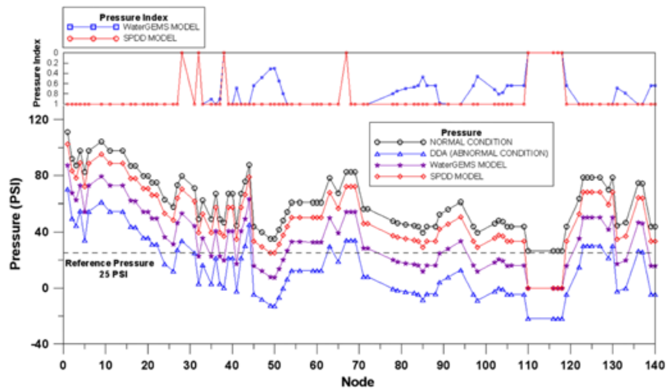

Fig. 9. Nodal Pressure and Pressure Index (PI) when Subsystem (S61) is Isolated

ously, the total water supply is decreased by 10%. Subsystem 20 (S20), comprised of 6 nodes and 7 pipes is the largest SII (Fig. 6). S20 has a UI consisting of 32 nodes and 41 pipes because it is located in the middle of the system. If S20 is closed, the downstream segment of the subsystem is also isolated. In a real network, the UI can be removed by installing bypass pipes or additional valves. The third largest effect is caused by S61 (Fig. 6), which is located at the upstream of the network directly connected to the tank. Therefore, if subsystem S61 is closed, the tank is also disconnected and the network is only supplied from the reservoir located at the downstream end of the network, leading to severe head loss. Therefore, the nodal pressure of the nodes located at the upstream end of the network is severely reduced and PDD analysis might provide more useful results.

The ESI is estimated when S61 is isolated. S61 has high SII and composed of one major tank and one pipe, so that effect of tank failure could be measured and compared conventional PDD model with proposed model. The results from the proposed method (SPDD) and the conventional PDD analysis (WaterGEMS, HOR 1 in Table 1) are compared in Figs. 8~10. The normal condition means that no subsystems are closed and the nodal pressures are higher than minimum requirement, which is assumed to be 25 psi (H_i^r, H_i^t). In the SPDD model, S61 is assumed to be closed and the optimal water supply is determined under the constraint of the pressure requirement. As shown in Fig. 8, the total water supply calculated under the normal condition is the largest and the SPDD model provides the smallest water supply. Therefore, the SI of the SPDD model is smaller than that of the WaterGEMS model. However, in Fig. 9, the nodal pressure from the SPDD model is higher than the minimum requirement (25 psi), which is the pressure calculated from the WaterGEMS and DDA models when S61 is closed. The nodal pressure from the WaterGEMS and DDA models is sometimes less than the minimum requirement, which prevents any guarantee that the calculated water supply is really delivered. However, the SPDD model maintains the nodal pressure higher than the minimum requirement while sacrificing the water supply to guarantee the usability.

As an overall evaluation index, the ESI from SPDD model is higher than that from the WateGEMS model (Fig. 10). This suggests that the overall evaluation of the network performance is better to guarantee the customer's convenience in the SPDD model than in the WaterGEMS model. However, this result can not imply SPDD model is more realistic and better than WasteGEMS model. The suggested model and indices can be useful tool and indicators for quantitative estimation of water supply usability under the abnormal condition. The SPDD model could be a good alternative for the design and maintenance of water distribution systems.

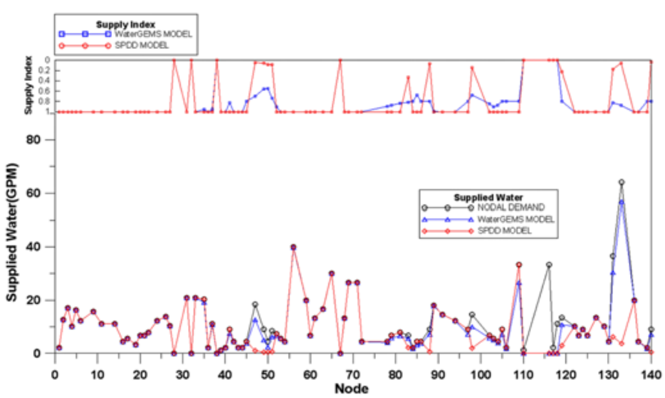

Fig. 8. Total Water Supply and Supply Index (SI) when the Subsystem (S61) is Isolated

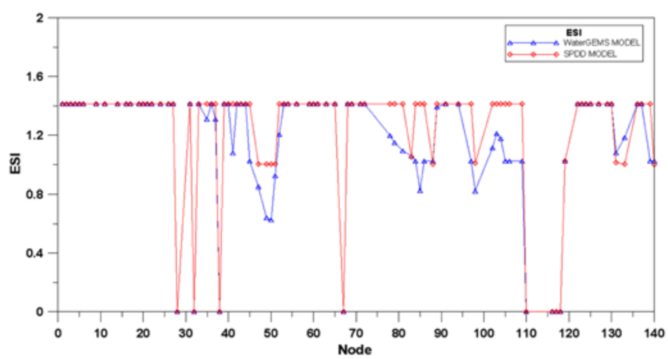

Fig. 10. Effective Supply Index (ESI) when Subsystem (S61) is Isolated

5. Conclusions

This paper firstly tried to perform pressure dependent demand analysis for subsystem without the HOR equation that has been an important issue in water distribution system analysis. This study optimizes the nodal water supply to satisfy the nodal pressure requirement under the abnormal condition, which arises when part of the water distribution system is closed for maintenance or rehabilitation, or as a result of an accident. The maximum water supply while maintaining the nodal pressure requirements (25 psi) is defined as the effective supply to guarantee the customer's convenience. HS is applied to find the optimal solution. The common application for the abnormal condition is PDD analysis using an HOR curve. However, the HOR curve suffers inherent uncertainty due to the requirement for an enormous amount of observed data to develop the relationship. The effective supply is optimized when subsystem 61, which has the third largest effect on the network, is closed to overcome the difficulties and uncertainties of the PDD model caused by the HOR curves. To evaluate the effect of the subsystem isolation, the SII is suggested. As the water supply and nodal pressure reductions are increased under the abnormal condition, the SII increases as well. To evaluate the usability of the suggested model, three indices are suggested: SI, PI and ESI. In the results, the suggested model supplies less water to the users, but the nodal pressure remains higher than the minimum requirement over the entire network in order to guarantee the customer's convenience. Since the nodal pressure of the WaterGEMS model is sometimes lower than the minimum pressure requirement, the water supply calculated from the applied HOR curve is not guaranteed to be delivered in the real network. Despite the sacrifice of the water supply, the overall performance, as evaluated by the ESI of the SPDD model, is better than that of the WaterGEMS model. This result can not imply SPDD model is more realistic and better than WasteGEMS model. However, the suggested model could be considered a viable alternative to estimate the real water supply under the abnormal condition without any difficulty caused by the uncertainty of the HOR curve. The suggested model and indices can be useful tool and indicators for quantitative estimation of water supply usability under the abnormal condition. The SPDD model could be a good alternative for the design and maintenance of water distribution systems.

However, additional applications to various networks are necessary to verify applicability in real network. Furthermore, subsystem-based multiple failures have to be considered to reflect the state of reality.

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