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Pressure dependent analysis for managing contaminant propagation in water supply systems

M. Zafari[1*], M. Tabesh[2] and S. Nazif [1]
[1] *School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran*
[2] *Center of Excellence for Engineering and Management of Civil Infrastructures, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran*
[*] *e-mail: mohsen.zafari@ut.ac.ir*

Abstract: Since water distribution Network is consisted of different components which are easy to access, they can be contaminated accidentally or deliberately. Therefore, consequence management and withdrawal of contaminant from water distribution network could be a key factor in minimizing the disastrous effects of contaminant propagation on the public health. A number of actions such as contaminant isolation throughout closing valves and opening the hydrants in order to flush out the polluted water were suggested by previous studies to manage the contamination. These response actions lead the network to the critical state which in some nodes, pressure is lower than standard measure. In this situation head driven analysis of water distribution network would be necessary. In this study combination of hydraulic simulation based on head driven analysis method and particle swarm optimization is used for minimizing negative effects of contaminated water to public health as an emergency response after contaminant entrance detection. In addition, the results of consequence management are compared when another kind of hydraulic simulation – demand driven simulation method – is used. The proposed model is applied on network number 3 of EPANET to demonstrate the model applicability in water distribution system and its effectiveness in dealing with contaminant intrusion into the water distribution network.

Key words: Water Distribution Networks, Pressure Driven Analysis, Particle Swarm Optimization, Contaminant Intrusion, Contaminant Propagation

1. INTRODUCTION

Over recent years, there has been much debate about the issue of water safety and what is the best solution to ensure the quality of water. Water distribution networks (WDN) are considered as vulnerable systems to accidental or terrorist attacks because of their dimension and availability of number of nodes. Contaminant intrusion into WDN may lead to many diseases or even human death. Since these systems have significant roles in each society as an infrastructure, suggesting solutions in order to minimize the potential threats is indispensable. Consequence management after detection of contamination is one of the required and major stages to manage the contaminant propagation (U.S. EPA, 2003). Up to now, a few studies have been focused on this stage (Shafeei and Berglund, 2014). Opening hydrants to flush out the contaminated water and valve closure are main solutions that have been recommended by most of them. Although these strategies may reduce the negative effect on public health, considering the proper hydraulic analysis seems to be crucial. On other words, one of the prominent features of consequence management strategy is hydraulic analysis that can influence the reliability of final answer. But majority of previous research focused on optimization modelling and objectives function. Several objective functions have been proposed and effectiveness of them have been indicated. A few numbers of researchers, however, have examined the influence of hydraulic analysis on consequence management.

The aim of this paper is developing a practical method for consequence management in WDNs after recognizing contaminant intrusion. Hydraulic simulation based on HDA is linked with appropriate optimization model to find the optimal hydrants and valves. This could be beneficial for managers of WDN to remove the contaminated water under pressure deficit condition in the shortest time. In developed model minimizing the total number of contaminated nodes and minimizing the total number of response actions are considered as objective functions. The DDA based model that was proposed before is used to evaluate the approach and examine the effect of hydraulic simulation on optimal answer.

2. PROBLEM STATEMENT AND SOLUTION APPROACH

Three different classes have been introduced to classify the response actions: 1) assessment actions which monitor situation of WDN, 2) corrective actions which systematically alter WDN operation to alleviate negative impacts, 3) protective actions which should be performed by the public to deteriorate exposure (Rasekh and Brumbelow 2011). This research concentrates on corrective actions and how selection of these actions subjects to hydraulic simulation approach.

Since applying DDA method in valve closure or flushing approaches would result in undesirable solutions for emergency response strategy that some nodes have an inadequate or negative nodal pressure, some DDA based studies have considered a minimal pressure (P^{min}) which answers with nodal pressure less than P^{min} are omitted (Alfonso et al., 2010). However, even consideration of P^{min} does not guaranty optimal solution attainment, because calculated pressure values by DDA approach are lower than HDA (Shirzad et al., 2013). In fact, search space inevitably has been restricted to response actions that do not cause excessively low pressure in the WDN by using DDA method.

To date, limited research has focused on significance of hydraulic simulation approach to selection of emergency response strategy. To address the issue this study develops a HDA based model to find the optimal valves and hydrants to eliminate the contamination from WDN. A previous DDA based study is chosen and the proposed HDA based model is tested on the similar WDN. Identical objective functions and contamination scenario are assumed to compare the results of using two different approaches. Also, the impact of applied hydraulic simulation on ultimate corrective actions is demonstrated.

3. MODEL DEVELOPMENT

Contamination scenario and the hydraulic simulation and optimization approaches are integrated to propose the model that select the proper valves and hydrants to eradicate the contamination from WDN.

Contamination intrusion scenario should be clarified as the input required information for optimization of consequence management operations. This scenario is defined by a set of factors including contaminant mass, location(s) of contaminant intrusion, exact time and day of year which contamination event is triggered, type of the pollutant and the duration of intrusion (Rasekh and Brumbelow, 2013). Since in most of the real occurrences of contamination in WDN the emergency response strategy is identified after verification of contaminant intrusion, local quality test execution and source identification, some initial data needed for contamination scenario are predetermined. Therefore, several researches determine a set of response actions based on source characteristics (Afshar and Najafi, 2014). The proper operational response can be also determined only based on sensors' information (Shafiee and Burglund, 2014) or critical situation (Rasekh and Brumbelow, 2013). Contamination scenario can be determined based on source characteristics (Afshar and Najafi, 2014). The proper operational response can be also determined only based on sensors' information (Shafiee and Burglund, 2014) or critical situation (Rasekh and Brumbelow, 2013). The scenario which is proposed here is identical to the contamination scenario of Afshar and Najafi (2013).

To implement HDA based hydraulic simulation, replacement of head-discharge relationship with fixed nodal outflow in continuity equation is required. The suggested equation by Wagner et al.

(1988) seems to be more realistic (Shirzad et al., 2013). Wagner et al. (1988) equation based on pressure is as follow:

$$\begin{cases} Q_j^{avl} = Q_j^{req} & ; if \quad P_j \geq P_j^{des} \\ Q_j^{avl} = Q_j^{req} (\dfrac{P_j - P_j^{min}}{P_j^{des} - P_j^{min}})^{1/n_j} & ; if \quad P_j^{min} < P_j < P_j^{des} \\ Q_j^{avl} = 0 & ; if \quad P_j \leq P_j^{min} \end{cases} \tag{1}$$

whereas P_j^{min} and P_j^{des} are minimum required and desired pressure in node *j* respectively, P_j is calculated pressure value at node *j*, Q_j^{avl} is available outflow at node *j*, Q_j^{req} is required outflow at node *j* and n_j is a constant depending on the system situation which varies between 1.5 and 2 (Shirzad et al., 2013). The idea of the applied method is taken from Pathirana (2010) which the minimum required pressure (P^{min}) is presumed zero and the emitter coefficient (*K*) is defined as illustrated in Equation (2) to replace nodal demand with emitter:

$$\begin{cases} k = Q_j^{req} \times (\dfrac{1}{p_j})^{1/n_j} & ; if \quad P_j \geq P_j^{des} \\ k = Q_j^{req} \times (\dfrac{1}{P_j^{des}})^{1/n_j} & ; if \quad P_j^{min} < P_j < P_j^{des} \\ k = 0 & ; if \quad P_j \leq P_j^{min} \end{cases} \tag{2}$$

Identical formulations with Najafi and Afshar (2013) are used to quantify these objectives as follows:

$$F_1 = \sum_{i=1}^{n} \sum_{t=t_s}^{t_{end}} N(i,t) \text{ , } N(i,t) = 1 \ if \ \ C_{i,t} > C_p \text{ , } N(i,t) = 0 \ \ otherwise \tag{3}$$

whereas F_1 is the total number of contaminated junctions in all time steps of simulation, *i* is the consumer node index, *n* is the total number of consumer nodes, t_s and t_{end} are the beginning and ending time of simulation, $C_{i,t}$ is the contaminant concentration in node *i* at time *t*, C_p is the allowed contaminant threshold based on local standards which is equal to 0.01 mg/lit based on Najafi and Afshar (2013) and $N(i,t)$ is a binary variable that is equal to one when the concentration of contaminant is more than allowed threshold in node *i* at time *t* and otherwise it is equal to zero.

$$F_2 = \sum_{k=1}^{VA} VA_k + \sum_{j=1}^{HY} HY_j \tag{4}$$

whereas F_2 is the total number of field operations (i.e. valves closure and opening the hydrants), *k* is the valve index, *j* is the hydrant index, *VA* is the total number of valves in WDN, *HY* is the total number of hydrants in WDN, VA_k is a binary variable that is equal to one when the status of valve *k* is changed (the initial status of all valves are open) and HY_j is a binary variable that is equal to one when the status of hydrant j is changed (the initial status of all hydrants are close).

Several methods have been proposed to solve multi-objective problems based on PSO (Hu and

Yen, 2015). The approach that presented by Coello et al. (2004) have been demonstrated as a useful and strong tool for solving multi-objective problems. This method is based on using an external repository which keeps a historical record of the non-dominated solutions (i.e. particles). The main parts of external repository are: 1-the archive controller that determines whether a certain particle should be added to the repository or not and 2-the grid that produces well-distributed Pareto fronts. Each particle regarding to its *pbest*, is compared with non-dominated particles which exist in repository in each iteration, then archive members are updated. Finally the members remain in external repository represent the Pareto fronts.

4. RESULTS AND DISCUSSION

EPANET example 3 network (Rossman, 2000) is utilized to evaluate and demonstrate capability of developed model proposed in this study. This network comprises two constant head sources, a lake and a river, three elevated storage tanks, two pumping stations, 117 pipes, 59 consumer nodes and 35 internal nodes (Figure 2). It is assumed that 20 hydrants and 31 valves are available in this WDN, so the total number of decision variables are equal to 51. The situation of decision variables (i.e. valves or hydrants) are coded as binary numbers (0, 1). The valves and hydrants situation in the onset of the procedure are assumed open and closed, respectively. Code 0 represents the steady state of the primary situation of valves or hydrants whereas code 1 represents the alternation in primary state. The outflow of hydrant is presumed constant and equal to 3.473 lit/s (55 gal/min). In EPANET a hydraulic and constituent time step of 15 min was used for a 24-hour simulation period. All of these assumptions are based on Najafi and Afshar (2013).

Contaminant with C_p = 0.01 mg/l is injected with a mass rate of 0.006 kg/s at 9:00 am for a duration of 7 hours. Location of injection is illustrated in Figure 2. Operational responses are performed after finishing the response delay (4 hours) at 1:00 pm and remain unchanged by the end of the contamination withdrawal from the WDN. Response delay is the elapsed time after the contaminant entrance in the WDN until finishing the field operations (valve closure and hydrant opening).

The number of contaminated nodes in which the contaminant concentration were above the acceptable threshold, are determined at each time step (every 15 minutes) after starting the simulation. Total number of contaminated nodes is considered at each simulation by summation of their number in different time steps (F_1). Also, total number of execution of field operations is calculated by using Eq. (6). The Pareto-optimal solution that has been obtained by using DDA based approach (Najafi and Afshar, 2013) is illustrated in Figure 1.

The total number of contaminated nodes are decreased to 464 by performing 14 field operations, while it is equal to 1545 when no response action is employed. Therefore, it seems that execution of field operations reduced the total number of contaminated nodes by near 70%. Regarding the answers, only by closing one valve (Valve 177) substantial reduction in number of field operations is occurred.

Although some answers that is shown in Figure 1 are highly effective in decline the negative impact of contamination, they can lead to escalate the nodal pressure in some junctions. Therefore, these solutions may be impractical due to strong possibility of burst pipes in WDN. Take for example, closing the valves 111 and 173 decrease the total number of contaminated nodes by near 60%, but this answer causes considerable increase in pressure of a tremendous number of nodes that is represented in Figure 2. As shown in this figure, by closing the valves 111 and 173 the upper reaches of these valves experience the pressure above 60 meter (85.7 psi). Accordingly, if the prominence of hydraulic of WDN is ignored and only the quality of water and withdrawal of contamination are considered, some impractical solutions may be proposed that can contribute to wasting time and money. It seems that considering the maximum threshold of pressure which is ignored in most of the previous researches is necessary. This threshold will be considered in the developed HDA based model to make the final solutions more effective.

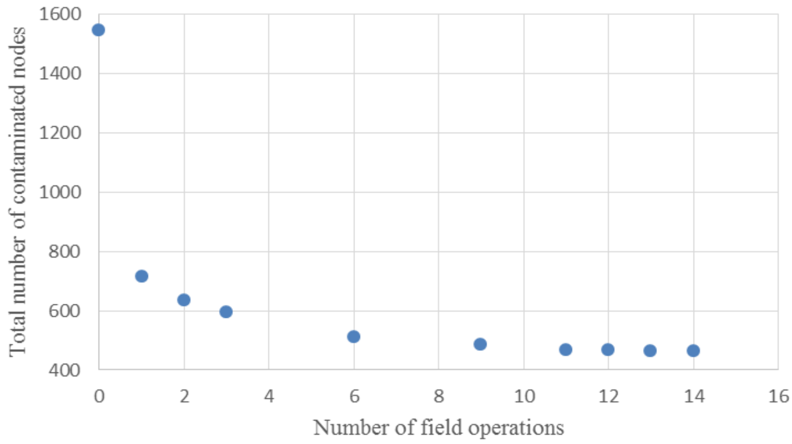

Figure 1. Pareto-optimal solution of the multi-objective optimization by using DDA-based approach (Najafi and Afshar, 2013)

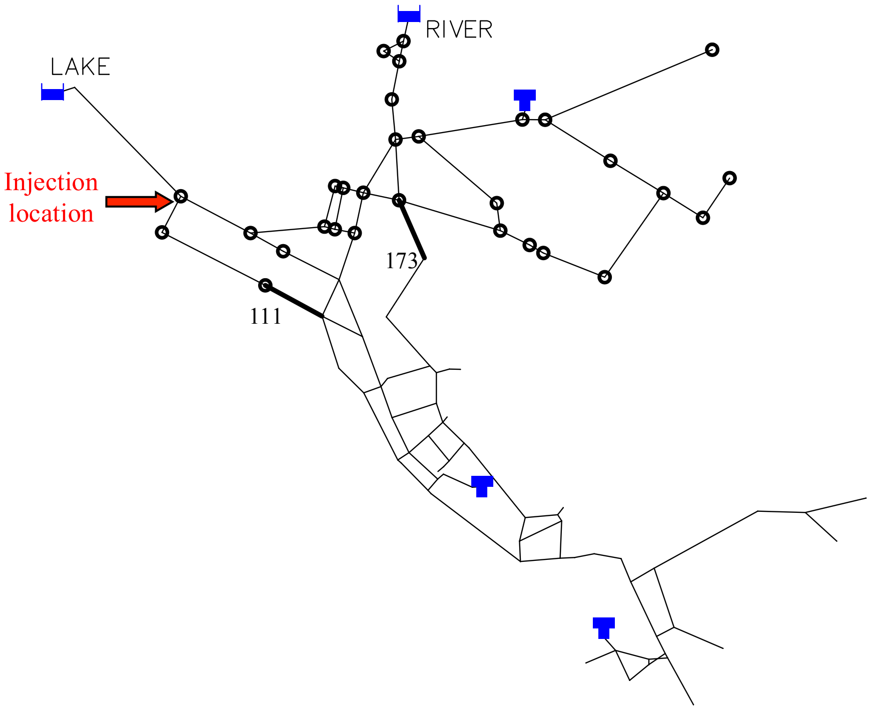

Figure 2. Schematic of EPANET's example 3-The nodes with pressure above 60 m by closing the valves 111 and 173

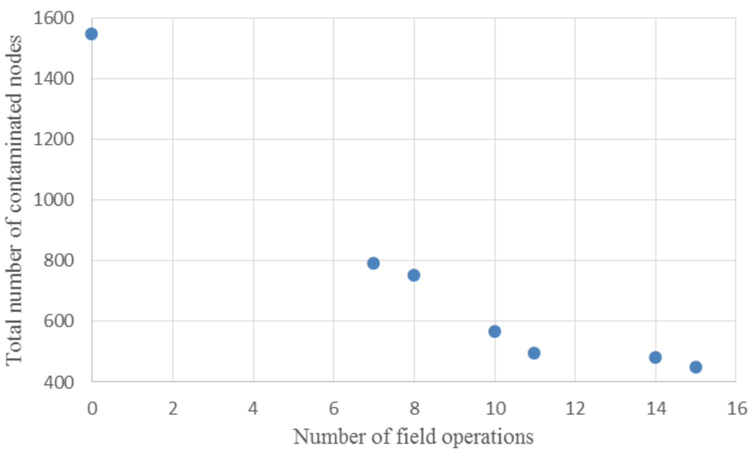

Figure 3. Pareto-optimal solution of the multi-objective optimization by using proposed HDA based approach

The pareto-optimal solution that is acquired by using proposed HDA based approach is shown in Figure 3. The positive constant parameters of PSO (i.e. c_1 and c_2) and the inertia weight were assumed 2 and 1 respectively similar to the main version of PSO (Eberhart and Kennedy, 1995). Also, the number of particles were set equal to 100.

Regarding this figure, it is clear that some over-optimistic and impractical solutions that lead to substantial reduction by only a few field operations are omitted. The total number of contaminated nodes are declined to 448 by performing 15 field operations, while it is equal to 1545 when no response action is employed. It is noteworthy that if the DDA based model is used, this solution will be omitted due to emerging negative pressure in seven nodes of WDN. On other words, the search space is restricted by using DDA based approach, so it is probable that some optimal solutions are not considered. Comparing the answers with answers of Najafi and Afshar (2013), it is obvious that there is a difference between the chosen valves and hydrants. This difference is mainly because of using HDA approach with considering maximum pressure threshold. In fact, some unpractical solutions were omitted due to using maximum pressure threshold, and search space was extended by using HDA based model instead of DDA based approach.

4. SUMMARY AND CONCLUSIONS

Most of the consequence management researches have used the similar response actions such as valves closure for isolating the contaminant and flushing out the polluted water by hydrants opening. However, a few previous studies have considered the significance of their hydraulic simulation approach that may have a major impact on final optimal solutions. This study introduced and tested an effective HDA based approach to find the optimal valves and hydrants and demonstrated the necessity of using HDA method in finding appropriate emergency response actions after intrusion of contamination in WDNs. To substantiate the claim that using DDA method does not guaranty optimal solution achievement the results of developed model was compared with DDA based method. Two important findings that can be reported as a result of this comparison:

1. Corrective actions such as valves closure or opening hydrants may contribute to pressure deficit condition in some junctions of WDN. In this occasion using DDA based model might omit some optimal solutions. Therefore, utilizing DDA based model to find the corrective actions may lead to spending more time compared to using HDA based method. It is noteworthy that minimizing the duration of eliminating contaminant from WDN is absolutely crucial due to importance of public health.
2. Not paying attention to hydraulic of WDN in addition to water quality may cause wasting a great amount of time and money. Take for example, if pressure maximum threshold is not considered, some non-practical response actions might be attained that lead to bursting a number of pipes of WDN.

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