Drink. Water Eng. Sci. Discuss., 5, 351–373, 2012
www.drink-water-eng-sci-discuss.net/5/351/2012/
doi:10.5194/dwesd-5-351-2012

Open Access
Drinking Water
Engineering and Science
Discussions

Reliability of water distribution networks due to pumps failure: comparison of VSP and SSP application

N. Mehzad[1], M. Tabesh[2], S. [illegible][3], and B. Ataee Kia[3]

[1]School of Civil Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran
[2]Centre of Excellence for Engineering and Management of Infrastructures, School of Civil Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran
[3]School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran

Received: 31 May 2012 – Accepted: [illegible] 2012 – Published: 9 July 2012

Correspondence to: N. Mehzad (nazlimehzad@ut.ac.ir)

Published by Copernicus Publications on behalf of the Delft University of Technology.

Abstract

Reliability is an important indicator to ensure the operation of Water Distribution Networks (WDNs). To optimize the operation of WDN, it is necessary to incorporate the reliability of active components (such as pumps and tanks) besides the reliability of pipes. In this research, a concept is suggested to calculate the reliability of WDNs' pumping stations. A computer code is provided in Visual Basic and is linked to EPANET2.0. To evaluate the proposed methodology a real WDN near the city of Tehran is considered. According to the obtained results, it is concluded that by increasing the demand of the WDN during a day, the reliability of pumps decrease. Therefore, it seems that decision-making is necessary if high demand hours are considered, in order to increase the reliability of the system. On the other hand, it is observed in this research that using variable speed pumps not only reduces the energy cost of the network, but also the reliability of the pumping stations with variable speed pumps is higher than single speed pumps. Therefore, using VSP is highly recommended in WDNs.

1 Introduction

Reliability of WDNs is an extremely important indicator for estimating the level of WDNs' service sustainability. For managers of WDNs, providing customers with desirable head and discharge at a particular moment is a primary goal. ~~In other words, a decision-maker must be exactly aware that to what extent they are close to critical situation which can jeopardize WDN's services.~~ Accordingly, overcoming the critical situations as well as meeting the required head and discharge is a major concern in decision-making.

Water pumping stations are the cornerstone of water distribution networks not only because they are essential for providing efficient and sufficient pressure and discharge of water, but also development of pumping stations in a water distribution network, their operation, and maintenance are costly. Therefore, a careful analysis of pumping

DWESD
5, 351–373, 2012
Reliability of water distribution networks
N. Mehzad et al.

stations should be conducted, and the number of installed pumps in pumping stations should be calculated by an accurate cost analysis. In many pumping stations, several pumps are used to increase the reliability, efficiency and flexibility of WDNs.

In the past conducted studies, optimization of water distribution networks is based on using single speed pumps. Multi-pattern of electricity tariff is employed to optimize the energy costs in such studies (Broad et al., 2010). Therefore, the energy consumed, remains constant with single speed pumps and therefore, they cannot generate tangible solutions in saving energy consumption. However, on th… nd, variable speed pumps are studied in order to make the system's pressur… conformity with the efficiency curve (Wood and Reddy, 1994). The ~~deference~~ between single speed pumps and variable speed pumps is in the speed control system which is used to change the speed of the pumps' electromotor by means of changing the frequency of electricity input (Samoty, 1989). Variable speed pumps are perfectly beneficial as they can reduce the ener… ption, especially in water … demand. Hashemi et al. (2011) investigated … works by means of ~~varied~~ speed pumps. T… minimize the energy consumption in pumpi… in reducing the energy costs of the Vardavar's water distribution network (located in the west part of Tehran) ~~up to 5.43 percent by using the variable speed pumps which were replaced the single speed pumps.~~

(C25) difference

variable

(C26) .The study reveals that using VSP instead of SSP was effective in reducing the energy costs of Vardavard's WDN up to 5.43 percent.

According to Tabesh (1998), a water system is re… enough water for consumers with an adequate pre… WDNs is a major concern among professionals and s… definitions of reliability, there is no single accepted … of water distribution networks (Gupta and Bhave, 1994). ~~Reliability analysis of water distribution networks is too complicated. This complexity is due to dependency of many different parameters.~~ Gupta and Bhave (1994) found some major parameters that play important role as follow: quality and quantity of water available at source, failure rates of supply pumps, power outages, roughness characteristics, pipe breaks and valve

(C27) Because many different parameters are highly correlated in WDNs, reliability analysis of WDNs is very complicated.

DWESD
5, 351–373, 2012

failures, variation in daily, monthly and seasonal demands, as well as demand growth over the years.

Reliability of a system is the extent to which a system thus determined by the reliability of its elements and by elements. In consideration of the reliability of an element, bility of failure is an essential issue. When a system or par more desired functions, it is known as failure. The state different ways. Such a way that leads to failure is known a to Misirdali (2003), hydraulic and mechanical failure mode distribution networks. Failure in pipelines, valves, pumps, and etc. are the sources of mechanical failure of WDNs. ~~On the other hand, the inability of the system in providing the demanded water discharge with a well-defined range of pressure is encountered as hydraulic failure of water distribution networks which either the mechanical failures or increase in water demand can be the causes of this type of failures (Tabesh, 1998).~~

(C28) On the other hand, inability of a system in providing the demanded water discharge with acceptable defined pressure is a hydraulic failure. The mechanical failures or increase in water demand are the source of this type of WDN's failure (Tabesh, 1998).

Reliability of the system in terms of the mechanical failure has been studied by many individuals, namely, Mays and Cullinane (1986), Wagner et al. (1988b), Su et al. (1987), and others. On the other hand, Bao and Mays (1990) and ~~Tanyiemboh~~ et al. (2001) only considered the hydraulic reliability of the system. The reliability analysis is more accurate when both mechanical and hydraulic failures are considered. ~~Goupta~~ and Bhave (1994) considered both hydraulic and mechanical reliability of the water distribution networks. Zhao et al. (2010) considered hydraulic failures and quality of water in reliability analysis of water distribution networks. Yildiz (2002) made use of simulation method in order to analyze the mechanical reliability of WDNs.

(C48),(C29) Tanyimboh

(C48), (C30) Gupta

Cullinane et al. (1992) offered different indicators for reliability of WDN's pipes which are linked to different components such as pumps, tanks and valves via different equations. They assessed the mechanical reliability of these pipes which are connected to pumps, tanks and valves, as a function of the design discharge of pump, the capacity of tank and the diameter of a related pipe respectively. Accordingly, information about the failure of each component must be available for a particular time period.

Duan and Mays (1990) presented the reliability analysis of pumping station in water supply systems. They considered both mechanical and hydraulic failures and used bi-variate analysis and conditional probability approaches to model the ava

(C31) In this research, reliability of pumping stations in WDNs is calculated through linking the optimization model in Visual Basic by simulation in EPANET2.0. In the simulation, the failure scenarios of pumps in pumping stations are considered.

of pumping station as a continuous-time markov process.

Due to the fact that pumping stations are economically important in WD and proper definition of pumping s an appropriate cessary in order to costs and improve the performance of a network through ~~a good~~ asset tions) management. The reliability of the water distribution networks in terms of pipeline failures was conducted in previous researches. ~~In this research, reliability of pumping stations in water distribution networks is studied by linking the optimization model in Visual Basic and simulation in EPANET2.0. In the simulation, the failure scenarios of pumps in pumping stations are conducted.~~ In addition, the reli (C32) of pumping stations in the city of Vardavard with two different types of single speed pumps (SSP) and variable speed pumps (VSP) is studied ~~in this research~~.

2 Methodology

(C11) In the EPANET2.0 model which uses Demand-Driven Simulation Method (DDSM), the network satisfies the nodal demands but it is possible that the head goes below the allowable head and sometimes the negative pressures are also possible.

In this study, the p rovide enough water to consumpti able software, such as EPANET2.0 is developed based on hydraulic analysis which satis (C8) Nodal pressure demand. Although the demand may be satisfied in nodes, the minimum pressure in those nodes may be not fulfilled. ~~In this research three different~~ ~~fuzzy~~ relationships are introduced to be applied in reliability analysis and their advantages are investigated. The first ~~fuzzy~~ equation proposed for the reliability of pumping stations with several nodes is as follows. (C8)

$$\mathrm{Coef}_{(i,t,sc)} = \begin{cases} 0 & \text{if} \quad \mathrm{HAV}_{(i,t,sc)} < \mathrm{HMIN}_{(i,t,sc)} \\ \dfrac{\mathrm{HAV}_{(i,t,sc)}}{\mathrm{HDES}_{(i,t,sc)}} & \text{if} \quad \mathrm{HMIN}_{(i,t,sc)} \le \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HDES}_{(i,t,sc)} \\ 1 & \text{if} \quad \mathrm{HAV}_{(i,t,sc)} > \mathrm{HDES}_{(i,t,sc)} \end{cases} \tag{1}$$

where $\mathrm{HAV}_{(i,t,sc)}$ = the available pressure in node *i* at time *t* and in the *sc*-th scenario, $\mathrm{HDES}_{(i,t,sc)}$ = minimum desired pressure in node *i* at time *t* and in the *sc*-th scenario, and $\mathrm{HMIN}_{(i,t,sc)}$ = minimum absolute standard pressure in node *i* at time *t* and in the *sc*-th scenario' all in meter unit. Maximum allowable pressure is not considered in this equation. For a node with higher pressure than the maximum allowable pressure, the coefficient is assumed equal to one.

The second ~~fuzzy~~ relation is as below:

$$\mathrm{Coef}_{(i,t,sc)} = \begin{cases} 0 & ,\text{if } \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HMIN}_{(i,t,sc)} \\ \dfrac{\mathrm{HAV}_{(i,t,sc)} - \mathrm{HMIN}_{(i,t,sc)}}{\mathrm{HDES}_{(i,t,sc)} - \mathrm{HMIN}_{(i,t,sc)}} & ,\text{if } \mathrm{HMIN}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HDES}_{(i,t,sc)} \\ \dfrac{\mathrm{HAV}_{(i,t,sc)} - \mathrm{HMAX}_{(i,t,sc)}}{\mathrm{HDES}_{(i,t,sc)} - \mathrm{HMAX}_{(i,t,sc)}} & ,\text{if } \mathrm{HDES}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HMAX}_{(i,t,sc)} \\ 0 & ,\text{if } \mathrm{HAV}_{(i,t,sc)} > \mathrm{HMAX}_{(i,t,sc)} \end{cases} \quad (2)$$

where $\mathrm{HMAX}_{(i,t,sc)}$ = maximum allowable pressure (in m) in node *i* at time *t* and in the *sc*-th scenario. This ~~fuzzy~~ coefficient (Eq. 2) is shown in Fig. 1.

The third ~~fuzzy~~ equation ~~that is considered in this study~~ is Eq. (3) which is proposed by Tabesh and Zia (2003). $H1_{(i,t,sc)}$, $H2_{(i,t,sc)}$ and $H3_{(i,t,sc)}$ are shown in Fig. 2.

$$\mathrm{Coef}_{(i,t,sc)} = \begin{cases} 0 & ,\text{if } \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HMIN}_{(i,t,sc)} \\ \dfrac{0.25(\mathrm{HAV}_{(i,t,sc)} - \mathrm{HMIN}_{(i,t,sc)})}{(\mathrm{H1}_{(i,t,sc)} - \mathrm{HMIN}_{(i,t,sc)})} & ,\text{if } \mathrm{HMIN}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{H1}_{(i,t,sc)} \\ \dfrac{0.25(\mathrm{HAV}_{(i,t,sc)} + \mathrm{H2}_{(i,t,sc)} - 2\mathrm{H1}_{(i,t,sc)})}{(\mathrm{H2}_{(i,t,sc)} - \mathrm{H1}_{(i,t,sc)})} & ,\text{if } \mathrm{H1}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{H2}_{(i,t,sc)} \\ \dfrac{0.25(\mathrm{HAV}_{(i,t,sc)} + 2\mathrm{H3}_{(i,t,sc)} - 3\mathrm{H2}_{(i,t,sc)})}{(\mathrm{H3}_{(i,t,sc)} - \mathrm{H2}_{(i,t,sc)})} & ,\text{if } \mathrm{H2}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{H3}_{(i,t,sc)} \\ \dfrac{0.25(\mathrm{HAV}_{(i,t,sc)} + 3\mathrm{HDES}_{(i,t,sc)} - 4\mathrm{H3}_{(i,t,sc)})}{(\mathrm{HDES}_{(i,t,sc)} - \mathrm{H3}_{(i,t,sc)})} & ,\text{if } \mathrm{H3}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HDES}_{(i,t,sc)} \\ \dfrac{0.5(2\mathrm{HMAX}_{(i,t,sc)} - \mathrm{HDES}_{(i,t,sc)} - \mathrm{HAV}_{(i,t,sc)})}{(\mathrm{HMAX}_{(i,t,sc)} - \mathrm{HDES}_{(i,t,sc)})} & ,\text{if } \mathrm{HDES}_{(i,t,sc)} < \mathrm{HAV}_{(i,t,sc)} \le \mathrm{HMAX}_{(i,t,sc)} \\ 0.25 & ,\text{if } \mathrm{HAV}_{(i,t,sc)} > \mathrm{HMAX}_{(i,t,sc)} \end{cases} \quad (3)$$

C12

(C8)

(C8) Nodal pressure

(C8)

(C9) The maximum allowable nodal pressure is not considered in this equation. Therefore, it does not reflect the real behavior of WDNs and it is stated here as a comparison with other following equations.

(C9) This equation to some extent corrects the first equation and it can model the nodal pressures more accurately.

(C9) According to Tabesh and Zia, this equation better reflects the real behavior of a WDN in terms of nodal pressure calculation. Therefore, this equation plays a major role in this research and the first two equations are used as a means to compare.

(C13) H1, H2 and H3 are some sample values which are introduced to describe a better behavior in the first part of this curve.

(C8)

Aforementioned fuzzy Eqs. (1), (2), (3) are used to form the Eq. (4) as a reliability of pumping station in this research.

$$\mathrm{RE}_{p,t,sc} = \frac{\sum_{i=1}^{N} \mathrm{Coef}_{(i,t,sc)} \times \mathrm{DEM}_{(i,t,sc)}}{\sum_{i=1}^{N} \mathrm{DEM}_{(i,t,sc)}} \tag{4}$$

where N = the number of demand nodes, $\mathrm{DEM}_{(i,t,sc)}$ = the required discharge ($\mathrm{m}^3\,\mathrm{s}^{-1}$) in node i at time t and in the sc-th scenario, and $\mathrm{RE}_{p,t,sc}$ is reliability of pumping station at time t and in the sc-th scenario. In this equation, $\mathrm{DEM}_{(i,t,sc)}$ is used as a weighting factor in order to increase the accuracy of the reliability calculation.

If the pumping station consists of several pumps with different failure scenarios, it is much easier for decision-makers to calculate the reliability of pumping station at the specific time through weighted average equation. In this respect, if the probability of occurrence of the failure scenario of sc is r_{sc}, the reliability calculation is as follow:

(C33)

(C51) NSc

$$\mathrm{RE}_{p,t} = \frac{\sum_{sc=1}^{NP} \mathrm{RE}_{p,t,sc} \times r_{sc}}{\sum_{sc=1}^{NP} r_{sc}} \tag{5}$$

(C51) scenarios

where NP = the number of pumps in the pumping station, and $\mathrm{RE}_{p,t}$ = the reliability of pumping station at time t for the total probable failure scenarios. Moreover, in this equation r_{sc} should be calculated through failure analysis of pumps.

(C51) NSc

3 Case study

To assess the proposed method for evaluating reliability of pumping stations in mechanical failure condition, the real water distribution network of Vardavard city (West of

DWESD

5, 351–373, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

(C17). The low zone of this network,

Tehran) is considered. This network, that does not have any tanks or reservoirs, consists of 113 pipes, 1 pumping station with 4 pumps that works in parallel and 78 nodes. It should be mentioned that, these pumps have the same characteristics. The downer zone of this WDN is shown in Fig. 3.

(C34) low

If the pumps of pumping stations are operated with their full capacity, it is possible that the nodal demands will be satisfied with the pressure above the minimum allowable value. It is possible that sometimes the demand is reduced and therefore the pressure goes above its allowable range and causes more leakages and thus the reliability of pumping stations decreases. Moreover, pumping with the maximum capacity causes high [...] nd also the consumption [...] Therefore, an accurate pumping scheduling is crucial for the WDNs.

(C19) For this network, the pumping scheduling after developing the pumping station with VSP is presented in Table 1

For this network, the various demand levels after developing the pumping scheduling with VSP are presented in Table 1. In this study, single speed pumps are evaluated, as well. Thus VSPs are replaced by SSPs. Therefore, pumps' status is changed from off to on and vice versa. Table 1 denotes the pumping station scheduling which is obtained from optimization modeling with its linkage to EPANET2.0, for two types of pumps (VSP, SSP). It is important to note that in this table, 0 and 1 represent the fact that the pump is off or on, respectively. Moreover, for the variable speed pumps the numbers below 1 means that this pump operates, however, its speed is lower than the normal speed.

It can be seen in Fig. 4 that if all the four pumps work in the station, the demand multiplier fulfills till 2.4 and the demand will be completely satisfied even in the peak time which is at 13:00. If one of the pumps fails and the other ones work, the demand multiplier fulfills till 1.9. Likewise, f[...]d one working pump(s) in the network, the demand m[...] fulfills till 1.4 and 0.7, respectively. It is clear that if all the four pumps work, the d[...] will be completely satisfied.

(C52) 1.3

(C11)

In the EPANET2.0 model which uses Demand-Driven Simulation Method (DDSM), the network satisfy the nodal demands but it is possible that the head goes below the allowable head and sometimes the negative pressures are also possible. In the

DWESD

5, 351–373, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Vardavand's network, there is no tank and all the demands will be satisfied by the pumps operation. Therefore, the nodal pressu ... station.

[(C35) If mechanical failure occurs in the system and the pumps in pumping stations are failed accordingly, spare pumps are working and satisfy the nodal demand. However, the nodal pressures lower than the minimum allowable pressure in WDN may occur more probably.]

In WDNs, the pumping stations work autom ... pumping scheduling three pumps are require ... efficiency of the pumping station will be mai ... gins its operation automatically. For this case, the pumping station works automatically, as well.

~~If the network is faced the mechanical failure and the pumps in pumping station are failed respectively, spare pumps will satisfy the nodal demand but the probability of reduction the nodal pressure less than the minimum allowable pressure in WDN will be increased.~~ Table 2 presents the pumping station reliability for two types of pump (VSP, SSP) by using Eqs. (1), (2) and (3) through four scenarios. The required, maximum allowable and minimum absolute pressure values in each node are assumed as 30 m, 50 m and 0 m, respectively. Using Eqs. (1) to (5), the weighted average is calculated by assuming the fact that each scenario may occur. For this pumping station r_1 to r_4 (failure probability of 1, 2, 3 and 4 pumps) are considered as ~~85 %~~ [10%], ~~10 %~~ [1%], ~~4 %~~ [0.1%] and ~~1 %~~ [0.01%], respectively. HDES in various times [(C54)] during a day could be different especially in the low-demand hours. ~~In Table 2, the calculated negative reliabilities were replaced by 0.~~ In this table, 3, 2, 1 and 0 pump(s) on, means that 1, 2, 3 and 4 pumps are failed, respectively. Figure 5 shows the reliability of pumping station in each scenario, by using a weighted average in each equation. According to the optimization model of the network, the costs of the electricity consumption [per day] are ~~694.78 \$ kw^{-1}~~ [(C55) 871,684 (Rials) (1USD=20,000 Rials)] and ~~597.75 \$ kw^{-1}~~ [(C55) 654,767 (Rials)] for the network which consists of pumping station with single speed and variable speed pumps, respectively. Therefore, reducing energy costs through variable speed pumps are recommended over single speed pumps.

In Fig. 6, ~~the~~ comparison of two types of pumping stations (VSP, SSP) for the four scenarios are illustrated by means of employing three different ~~fuzzy~~ [(C8)] equations. As it was expected, in the peak hours of a day in which higher numbers of pumps are failed, (C8) (C8)

the reliability will be decreased in different scenarios with each fuzzy equation. In Table 2 which is resulted from the fuzzy Eq. (1), the average reliability of pumping station with single speed pumps and variable speed pumps are 0.856 and 0.764 in a day, respectively. Comparison the results are n Fig. 5 reveals that, by using reliability o when ping station with single speed pumps is more than the va pumps. On the contrary, using Eqs. (2) and (3) is vice versa. In Eq. (1), of pumping station is calculated regardless of the maximum allowable no Therefore, the major coefficient is spotted for these nodes. In order to a pressure in nodes (surplus pressure occurs when the required nodal pre than available water pressure in nodes), the variable speed pumps are u surplus pressure in nodes will be decreased. Howe es of le speed pum while they m value ill the nodal demands, it is possible that the nodal press the maximum allowable as thes (C8) Nodal pressure y have status On and plus pressure causes more leakage and water consumption in WDNs. Equations (2) and (3) allocate lesser fuzzy coefficient to the nodes with surplus pressure than the Eq. (1). Thus, by using the Eq. (2) and (3) and also considering variable speed pumps, the energy cost of the network is decreased and the reliability of pumping station is increased simultaneously (Fig. 5). The Eqs. (2) and (3) are similar to the real conditions which are happened in the network. Therefore, it can be concluded that by using the defined concept of the reliability of pumping station in line with the energy costs of a system, the necessity of using variable speed pump is justifiable.

(C21) In order to discuss these results in detail, this part is changed to:
Therefore, by considering the maximum allowable nodal pressure, in Eqs. (2) and (3), surplus pressure in the network decreases in the low consumption hours which leads to a more reliable network. It is important to note that surplus pressure causes leakage and damages to the network. Eq. (1), for higher nodal pressure, higher reliability coefficient is allotted. For single speed pumps (SSP) which produce higher pressure in the network, higher reliability coefficient is allotted. In Eqs. (2) and (3), smaller reliability coefficient is allotted to the SSP because they produce surplus pressures.

4 Conclusions

(C36) In this research, reliability calculation of pumping stations in a water distribution network is analyzed.

In this study the reliability of pumping stations in WDNs was conducted. Same some scenarios of pump failure are considered as a mechanical failure of water distribution network. The proposed method was implemented in the water distribution network of V rd city in Iran. The pumping station in this network was analyzed two times using three fuzzy equations for both SSP and VSP. Based on the result of this case study, it can

(C8)

be concluded that with increase of demand in the peak demand time of a day, the capacity of the network in providing enough water with determined pressure, decreases ... Moreover, increase in ... the amount of water ... WDNs. This research ... speed pumps is less ... ation which does not ... reliability equations ... e reliability of WDNs' pumping stations wit... gle speed pumps.

> (C37)According to the obtained results of this research, it can be concluded that if demand increases during the peak demand time of a day, the capacity of the network in providing the required water with specific pressure decreases, especially while the system experiences the mechanical failures. Moreover, if the number of mechanically failed pumps in pumping stations of a WDN increases, the amount of supplied water by pumps decreases. Therefore, it leads to a less reliable water distribution network.

> (C22) It is important to mention that the conclusions are drawn exactly based on the chosen equation for calculating the reliability of water distribution network. According to this fact,

> (C3) According to Figure 3, especially in low consumption hours of a day in which high surplus pressure is generated in the network, reliability of WDNs' pumping stations with VSPs is much higher than pumping stations with SSPs. Therefore, Eqs. (1) and (2) do not reflect the real conditions of the network accurately for reliability calculations. Using VSP plays significant role in increasing the reliability of the system. This is analyzed for this case and the results are well-proved. However, for other networks which have different SSP pumps and their system is well-designed based on the requirements of those networks, the aforementioned conclusion may be less tangible

In the case of failur... ork with higher velocity r... the network performance ... sed with an adequate plar... city higher than normal va... its life cycle. On the othe... Ns is quite effective when a failure occurs (mechanical or hydraulic modes). Extra or spare pump increases the reliability of pumping stations in water distribution networks. In addition, using water supply tanks in the water distribution network definitely increase the reliability of the system tanks by using water stored in the tanks when facing crisis and to some extent compensating lack of pressure by providing enough head.

> (machanical or hydraulic)

> (C38)

When considering the reliability of pumping station in a real WDN, it is necessary to study and collect data about the possibility of pump failure. Moreover, it is appropriate to generate equations to calculate the mechanical reliability of pumping station.

Acknowledgements. The authors would like to acknowledge the financial support of university of Tehran for this research under grant number 8102050/1/02.

References

Bao, Y. X. and Mays, L. W.: Model for water distribution system reliability, J. Hydraul. Eng.-ASCE, 116, 1119–1137, 1990.
Broad, D. R., Maier, H. R., and Dandy, G. C.: Optimal operation of complex water distribution systems using metamodels, J. Water Res. Pl.-ASCE, 136, 433–443, 2010.
Cullinane, M. J., Lansey, K. E., and Mays, L. W.: Optimization-availability-based design of water distribution networks, J. Hydraul. Eng.-ASCE, 118, 420–441, 1992.
Duan, N. and Mays, L. W.: Reliability analysis pumping systems, J. Hydraul. Eng.-ASCE, 116, 230–248, 1990.
Gupta, R. and Bhave, P. R.: Reliability analysis of water distribution systems, J. Environ. Eng.-ASCE, 120, 447–460, 1994.
Hashemi, S. S., Tabesh, M., and Ataee Kia, B.: Ant-colony optimization of energy cost in water distribution systems using variable speed pumps, in: Proceedings of 4th ASCE-EWRI International Perspective on Water Resources and The Environment, 4–6 January, National University of Singapore, Singapore, 2011.
Mays, L. W. and Cullinane, M. J.: A review and evaluation of reliability concepts for design of water distribution systems, US Engineer Waterways Experiment Station, Vicksburg, Miss, 1986.
Misirdali, M.: A methodology for calculating hydraulic system reliability of water distribution networks, M. Sc. thesis, METU, Dept. of Civ. Eng., Turkey, 2003.
Samoty, M.: Adjustable-speed-drive application, J. EPRI, 14, 34–36, 1989.
Su, Y., Mays, L., Duan, N., and Lansey, K.: Reliability-based optimization model for water distribution systems, J. Hydraul. Eng.-ASCE, 113, 1539–1556, 1987.
Tabesh, M.: Implications of the pressure dependency of outflows on data management, mathematical modeling and reliability assessment of water distribution systems, Ph.D. thesis, University of Liverpool, UK, 1998.
Tabesh, M. and Zia, A.: Dynamic management of water distribution networks based on hydraulic performance analysis of the System, J. Water Sci. Technol.: Water Supply, 3, 95–102, 2003.
Tanyimboh, T. T., Tabesh, M., and Burrows, R.: Appraisal of source head methods for calculating reliability of water distribution networks, J. Water Res. Pl.-ASCE, 127, 206–213, 2001.
Wagner, J., Shamir, U., and Marks, D.: Water distribution system reliability: simulation methods, J. Water Res. Pl.-ASCE, 114, 276–294, 1988.

DWESD
5, 351–373, 2012

Wood, D. J. and Reddy, L. S.: Using variable speed pumps to reduce leakage and improve performance, in: Proceedings of Short Courses on Improving Efficiency and Reliability in Water Distribution Systems, edited by: Cabrera, E. and Vela, A. F., Valencia, Spain, 1, 145–169, 1994.

Yildiz, E.: Reliability of water distribution systems, M. Sc. thesis, METU, Dept. of Civ. Eng., Turkey, 2002.

Zhao, Y., Luo, B., Zhuang, B., and Zhao, X.: Hydraulic and water quality reliability analysis of water distribution system, 2th Conference on Environmental Science and Information Application Technology, IEEE, 1, 580–583, 2010.

DWESD

5, 351–373, 2012

Table 1. Pumping schedules for the two types of pumping station (VSP, SSP) in one day.

Hour	(1) Pumping Status (VSP) Hashemi et al.				(2) Pumping Status (SSP)			
	Pump1	Pump2	Pump3	Pump4	Pump1	Pump2	Pump3	Pump4
1–5	0.96	0	0	0	1	0	0	0
6–8	1	0.88	0	0	1	1	0	0
9	1	0.89	0	0	1	1	0	0
10	1	0.91	0	0	1	1	0	0
11	1	1	0.9	0	1	1	1	0
12	1	1	0.91	0	1	1	1	0
13	1	1	1	0.95	1	1	1	1
14–15	1	1	1	0.93	1	1	1	1
16	1	1	0.91	0	1	1	1	0
17	1	1	0.9	0	1	1	1	0
18	1	0.91	0	0	1	1	0	0
19	1	0.9	0	0	1	1	0	0
20	1	0.89	0	0	1	1	0	0
21–23	1	0.88	0	0	1	1	0	0
24–25	0.96	0	0	0	1	0	0	0

DWESD
5, 351–373, 2012

Table 2. Reliability of pumping station in four different scenarios and weighted average of four scenarios for the two different types of pumps (VSP, SSP).

			Reliability (VSP)					Reliability (SSP)				
	Demand factor	Hour \ Number of pumps with status 1	3	2	1	0	Weighted average	3	2	1	0	Weighted average
Using equation 1	0.7	1	0.728	0.728	0.728	0	~~0.721~~	0.841	0.841	0.841	0	~~0.832~~
	0.68	2	0.728	0.728	0.728	0	~~0.721~~	0.841	0.841	0.841	0	~~0.832~~
	0.66	3	0.77	0.77	0.77	0	~~0.762~~	0.878	0.878	0.878	0	~~0.869~~
	0.67	4	0.807	0.807	0.807	0	~~0.799~~	0.911	0.911	0.911	0	~~0.902~~
	0.69	5	0.789	0.789	0.789	0	~~0.781~~	0.895	0.895	0.895	0	~~0.886~~
	0.71	6	0.892	0.892	0.86	0	~~0.882~~	1	1	0.86	0	~~0.984~~
	0.75	7	0.891	0.891	0.821	0	~~0.879~~	1	1	0.821	0	~~0.983~~
	0.84	8	0.888	0.888	0.729	0	~~0.873~~	1	1	0.729	0	~~0.979~~
	0.96	9	0.9	0.9	0.446	0	~~0.872~~	1	1	0.446	0	~~0.968~~
	1.2	10	0.919	0.919	0	0	~~0.873~~	1	1	0	0	~~0.95~~
	1.5	11	0.948	0.948	0	0	~~0.9~~	1	0.948	0	0	~~0.945~~
	1.69	12	0.875	0.664	0	0	~~0.81~~	0.995	0.664	0	0	~~0.912~~
	2.24	13	0.93	0.345	0	0	~~0.825~~	0.93	0.345	0	0	~~0.825~~
	2.1	14	0.572	0	0	0	~~0.486~~	0.572	0	0	0	~~0.486~~
	2	15	0.694	0	0	0	~~0.59~~	0.694	0	0	0	~~0.59~~
	1.7	16	0.679	0	0	0	~~0.577~~	0.767	0	0	0	~~0.652~~
	1.44	17	0.815	0.324	0	0	~~0.725~~	0.925	0.325	0	0	~~0.819~~
	1.2	18	0.602	0.602	0	0	~~0.572~~	0.739	0.739	0	0	~~0.702~~
	1.08	19	0.811	0.811	0	0	~~0.771~~	0.948	0.948	0	0	~~0.9~~
	0.96	20	0.854	0.854	0	0	~~0.812~~	1	1	0	0	~~0.95~~
	0.84	21	0.868	0.868	0	0	~~0.825~~	1	1	0	0	~~0.95~~
	0.8	22	0.882	0.882	0.446	0	~~0.856~~	1	1	0.446	0	~~0.968~~
	0.75	23	0.885	0.885	0.586	0	~~0.864~~	1	1	0.586	0	~~0.973~~
	0.7	24	0.604	0.604	0.604	0	~~0.598~~	0.729	0.729	0.729	0	~~0.722~~
	0.7	25	0.728	0.728	0.728	0	~~0.721~~	0.841	0.841	0.841	0	~~0.832~~
							Ave. = ~~0.764~~					Ave. = ~~0.856~~

DWESD
5, 351–373, 2012

Table 2. Continued.

Using equation 2	0.7	1	0.547	0.547	0.546	0	~~0.541~~	0.410	0.410	0.410	0	~~0.406~~
	0.68	2	0.547	0.546	0.546	0	~~0.541~~	0.410	0.410	0.410	0	~~0.406~~
	0.66	3	0.495	0.495	0.495	0	~~0.490~~	0.354	0.354	0.354	0	~~0.350~~
	0.67	4	0.447	0.447	0.447	0	~~0.443~~	0.297	0.297	0.297	0	~~0.294~~
	0.69	5	0.469	0.469	0.469	0	~~0.464~~	0.324	0.324	0.324	0	~~0.321~~
	0.71	6	0.330	0.330	0.385	0	~~0.328~~	0.075	0.075	0.385	0	~~0.086~~
	0.75	7	0.331	0.331	0.432	0	~~0.332~~	0.077	0.076	0.432	0	~~0.09~~
	0.84	8	0.335	0.335	0.545	0	~~0.340~~	0.080	0.080	0.545	0	~~0.098~~
	0.96	9	0.314	0.314	0.667	0	~~0.325~~	0.090	0.090	0.667	0	~~0.112~~
	1.2	10	0.280	0.280	0.028	0	~~0.267~~	0.110	0.110	0.028	0	~~0.105~~
	1.5	11	0.233	0.233	0	0	~~0.222~~	0.104	0.233	0	0	~~0.111~~
	1.69	12	0.343	0.640	0	0	~~0.355~~	0.161	0.640	0	0	~~0.200~~
	2.24	13	0.250	0.580	0	0	~~0.270~~	0.250	0.578	0	0	~~0.27~~
	2.1	14	0.741	0	0	0	~~0.630~~	0.741	0	0	0	~~0.63~~
	2	15	0.608	0	0	0	~~0.517~~	0.608	0	0	0	~~0.517~~
	1.7	16	0.628	0	0	0	~~0.533~~	0.499	0	0	0	~~0.424~~
	1.44	17	0.430	0.548	0	0	~~0.421~~	0.255	0.548	0	0	~~0.272~~
	1.2	18	0.703	0.703	0	0	~~0.668~~	0.537	0.537	0	0	~~0.510~~
	1.08	19	0.438	0.438	0	0	~~0.416~~	0.233	0.233	0	0	~~0.222~~
	0.96	20	0.387	0.387	0	0	~~0.367~~	0.147	0.147	0	0	~~0.139~~
	0.84	21	0.366	0.366	0.028	0	~~0.349~~	0.110	0.110	0.028	0	~~0.105~~
	0.8	22	0.345	0.345	0.667	0	~~0.354~~	0.090	0.090	0.667	0	~~0.112~~
	0.75	23	0.340	0.340	0.687	0	~~0.350~~	0.085	0.085	0.687	0	~~0.108~~
	0.7	24	0.682	0.682	0.682	0	~~0.675~~	0.545	0.545	0.545	0	~~0.540~~
	0.7	25	0.546	0.546	0.546	0	~~0.541~~	0.410	0.410	0.410	0	~~0.405~~
							Ave. = ~~0.430~~					Ave. = ~~0.273~~

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

DWESD

5, 351–373, 2012

Reliability of water distribution networks

N. Mehzad et al.

Table 2. Continued.

Using equation 3	0.7	1	0.757	0.757	0.757	0	~~0.749~~	0.629	0.629	0.629	0	~~0.623~~
	0.68	2	0.757	0.757	0.757	0	~~0.749~~	0.629	0.629	0.629	0	~~0.623~~
	0.66	3	0.720	0.720	0.720	0	~~0.713~~	0.598	0.598	0.598	0	~~0.592~~
	0.67	4	0.670	0.670	0.670	0	~~0.663~~	0.560	0.560	0.560	0	~~0.555~~
	0.69	5	0.707	0.707	0.707	0	~~0.700~~	0.583	0.583	0.583	0	~~0.578~~
	0.71	6	0.586	0.586	0	0	~~0.581~~	0.352	0.352	0.616	0	~~0.359~~
	0.75	7	0.587	0.587	0.653	0	~~0.584~~	0.353	0.353	0.653	0	~~0.362~~
	0.84	8	0.589	0.589	0.756	0	~~0.589~~	0.355	0.355	0.756	0	~~0.367~~
	0.96	9	0.577	0.577	0.816	0	~~0.581~~	0.360	0.360	0.816	0	~~0.374~~
	1.2	10	0.549	0.549	0.072	0	~~0.525~~	0.374	0.374	0.072	0	~~0.358~~
	1.5	11	0.511	0.511	0	0	~~0.486~~	0.369	0.511	0	0	~~0.365~~
	1.69	12	0.593	0.820	0	0	~~0.586~~	0.456	0.820	0	0	~~0.470~~
	2.24	13	0.520	0.745	0	0	~~0.517~~	0.520	0.745	0	0	~~0.517~~
	2.1	14	0.870	0	0	0	~~0.740~~	0.870	0	0	0	~~0.740~~
	2	15	0.804	0	0	0	~~0.683~~	0.804	0	0	0	~~0.683~~
	1.7	16	0.814	0	0	0	~~0.692~~	0.724	0	0	0	~~0.615~~
	1.44	17	0.684	0.720	0	0	~~0.654~~	0.523	0.720	0	0	~~0.517~~
	1.2	18	0.851	0.851	0	0	~~0.809~~	0.747	0.747	0	0	~~0.710~~
	1.08	19	0.676	0.676	0	0	~~0.642~~	0.511	0.511	0	0	~~0.486~~
	0.96	20	0.617	0.617	0	0	~~0.587~~	0.449	0.449	0	0	~~0.426~~
	0.84	21	0.605	0.605	0.072	0	~~0.578~~	0.374	0.374	0.072	0	~~0.358~~
	0.8	22	0.593	0.593	0.816	0	~~0.596~~	0.360	0.360	0.816	0	~~0.374~~
	0.75	23	0.591	0.591	0.843	0	~~0.595~~	0.357	0.357	0.843	0	~~0.373~~
	0.7	24	0.841	0.841	0.841	0	~~0.832~~	0.756	0.756	0.756	0	~~0.749~~
	0.7	25	0.757	0.757	0.757	0	~~0.749~~	0.629	0.629	0.629	0	~~0.623~~
							Ave.=~~0.647~~					Ave.=0.~~512~~

DWESD
5, 351–373, 2012

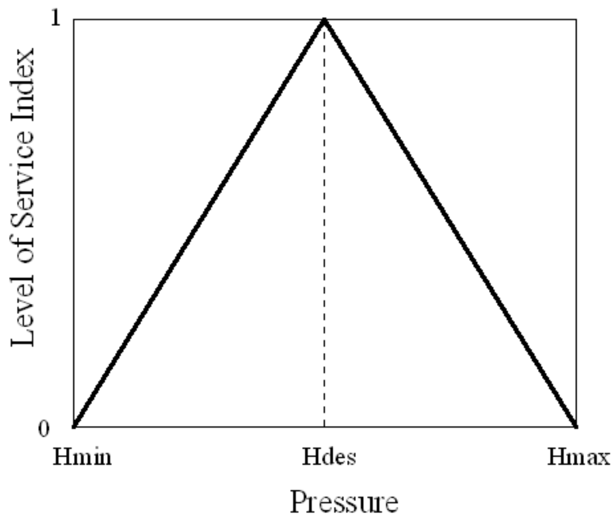

Fig. 1. Degree of membership of the ~~fuzzy~~ function in Eq. (2).

(C8) nodal pressure

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

DWESD
5, 351–373, 2012

Reliability of water distribution networks

N. Mehzad et al.

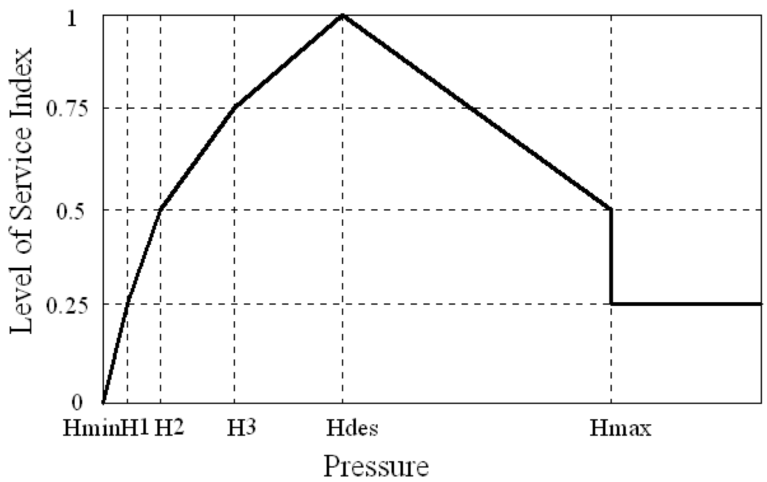

Fig. 2. Degree of membership of the ~~fuzzy~~ function in Eq. (3).

(C8) nodal pressure

DWESD
5, 351–373, 2012

Reliability of water distribution networks

N. Mehzad et al.

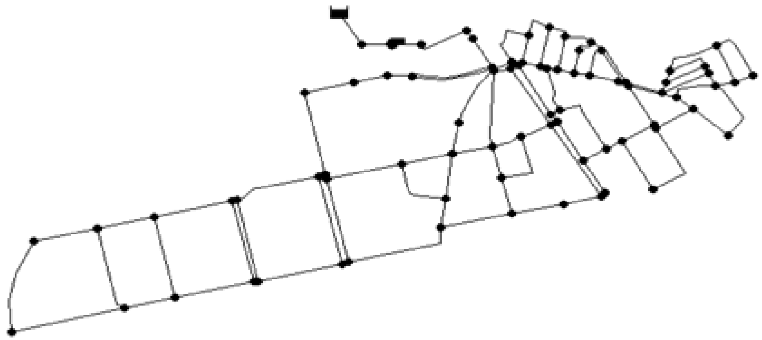

Fig. 3. The ~~downer~~ zone of the Vardavard water distribution network (Hashemi et al., 2011).

(C34) low

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

DWESD

5, 351–373, 2012

Reliability of water distribution networks

N. Mehzad et al.

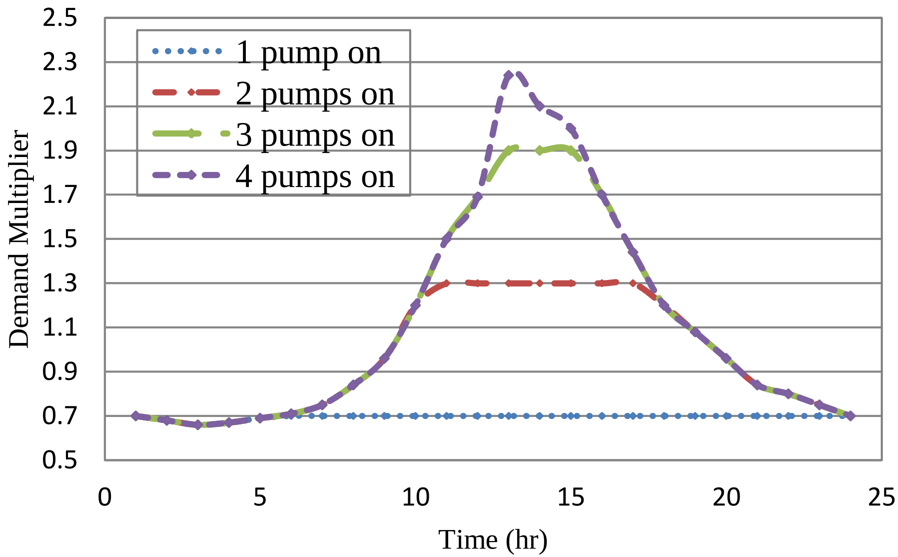

Fig. 4. Deviation in the level of satisfying the network's demands.

DWESD
5, 351–373, 2012

figures in this page should be replaced by the figures in a seperate file

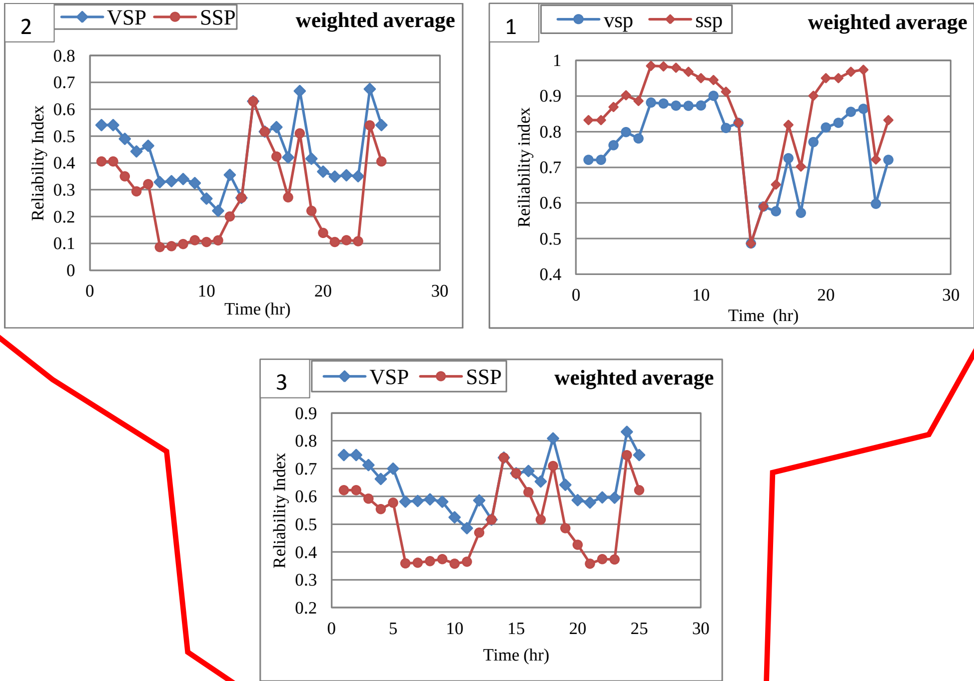

Fig. 5. The comparison of reliability of two type of pumps (VSP, SSP), with weighted average of four scenarios using three ~~fuzzy~~ equations.

(C8) nodal pressure

DWESD

5, 351–373, 2012

Reliability of water distribution networks

N. Mehzad et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

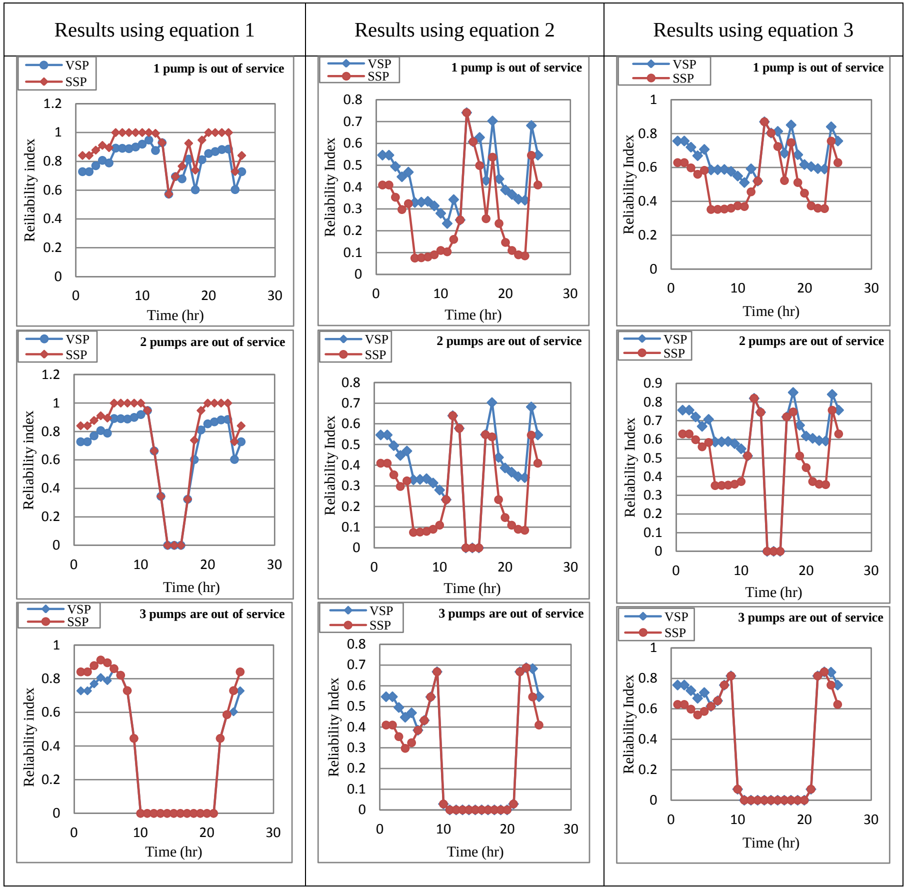

Fig. 6. Evaluation of reliability of two different pumps (VSP, SSP) using three ~~fuzzy~~ equations.

(C8) nodal pressure

DWESD

5, 351–373, 2012

Reliability of water distribution networks

N. Mehzad et al.