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

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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

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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 the other hand, variable speed pumps are studied in order to make the system's pressure conformity with the efficiency curve (Wood and Reddy, 1994). The difference 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 energy consumption, especially in water distribution systems with high variation in demand. Hashemi et al. (2011) investigated works by means of varied speed pumps. Their research was successful in minimizing the energy consumption in pumping stations. Their research was successful 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.

According to Tabesh (1998), a water system is reliable when it is able to provide enough water for consumers with an adequate pressure. Although the reliability of WDNs is a major concern among professionals and so far they have developed several definitions of reliability, there is no single accepted universally definition for reliability 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

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difference

(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.

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Duan and Mays (1990) presented the reliability analysis of pumping station in water supply systems. They considered both mechanical and hydraulic failures and used bivariate analysis and conditional probability approaches to model the availability of pumping station as a continuous-time markov process.

Due to the fact that pumping stations are economically important in WDNs and proper definition of pumping station reliability is necessary in order to reduce costs and improve the performance of a network through a good asset 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 considered. In addition, the reliability 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.

(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.

(C32)

2 Methodology

In this study, the program is developed based on hydraulic analysis which satisfies the 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.

(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.

(C8) Nodal pressure

(C8)

$$\text{Coef}_{(i,t,sc)} = \begin{cases} 0 & \text{if } HAV_{(i,t,sc)} < HMIN_{(i,t,sc)} \\ \frac{HAV_{(i,t,sc)}}{HDES_{(i,t,sc)}} & \text{if } HMIN_{(i,t,sc)} \leq HAV_{(i,t,sc)} \leq HDES_{(i,t,sc)} \\ 1 & \text{if } HAV_{(i,t,sc)} > HDES_{(i,t,sc)} \end{cases} \quad (1)$$

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where $HAV_{(i,t,sc)}$ = the available pressure in node i at time t and in the sc -th scenario, $HDES_{(i,t,sc)}$ = minimum desired pressure in node i at time t and in the sc -th scenario, and $HMIN_{(i,t,sc)}$ = 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:

$$Coef_{(i,t,sc)} = \begin{cases} 0 & , \text{ if } HAV_{(i,t,sc)} \leq HMIN_{(i,t,sc)} \\ \frac{HAV_{(i,t,sc)} - HMIN_{(i,t,sc)}}{HDES_{(i,t,sc)} - HMIN_{(i,t,sc)}} & , \text{ if } HMIN_{(i,t,sc)} < HAV_{(i,t,sc)} \leq HDES_{(i,t,sc)} \\ \frac{HAV_{(i,t,sc)} - HMAX_{(i,t,sc)}}{HDES_{(i,t,sc)} - HMAX_{(i,t,sc)}} & , \text{ if } HDES_{(i,t,sc)} < HAV_{(i,t,sc)} \leq HMAX_{(i,t,sc)} \\ 0 & , \text{ if } HAV_{(i,t,sc)} > HMAX_{(i,t,sc)} \end{cases} \quad (2)$$

where $HMAX_{(i,t,sc)} = \max_{(i,t,sc)} \text{Nodal pressure}$ (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 (2009). $H1_{(i,t,sc)}$, $H2_{(i,t,sc)}$ and $H3_{(i,t,sc)}$ are shown in Fig. 2.

$$Coef_{(i,t,sc)} = \begin{cases} 0 & , \text{ if } HAV_{(i,t,sc)} \leq HMIN_{(i,t,sc)} \\ \frac{0.25(HAV_{(i,t,sc)} - HMIN_{(i,t,sc)})}{(H1_{(i,t,sc)} - HMIN_{(i,t,sc)})} & , \text{ if } HMIN_{(i,t,sc)} < HAV_{(i,t,sc)} \leq H1_{(i,t,sc)} \\ \frac{0.25(HAV_{(i,t,sc)} + H2_{(i,t,sc)} - 2H1_{(i,t,sc)})}{(H2_{(i,t,sc)} - H1_{(i,t,sc)})} & , \text{ if } H1_{(i,t,sc)} < HAV_{(i,t,sc)} \leq H2_{(i,t,sc)} \\ \frac{0.25(HAV_{(i,t,sc)} + 2H3_{(i,t,sc)} - 3H2_{(i,t,sc)})}{(H3_{(i,t,sc)} - H2_{(i,t,sc)})} & , \text{ if } H2_{(i,t,sc)} < HAV_{(i,t,sc)} \leq H3_{(i,t,sc)} \\ \frac{0.25(HAV_{(i,t,sc)} + 3HDES_{(i,t,sc)} - 4H3_{(i,t,sc)})}{(HDES_{(i,t,sc)} - H3_{(i,t,sc)})} & , \text{ if } H3_{(i,t,sc)} < HAV_{(i,t,sc)} \leq HDES_{(i,t,sc)} \\ \frac{0.5(2HMAX_{(i,t,sc)} - HDES_{(i,t,sc)} - HAV_{(i,t,sc)})}{(HMAX_{(i,t,sc)} - HDES_{(i,t,sc)})} & , \text{ if } HDES_{(i,t,sc)} < HAV_{(i,t,sc)} \leq HMAX_{(i,t,sc)} \\ 0.25 & , \text{ if } HAV_{(i,t,sc)} > HMAX_{(i,t,sc)} \end{cases} \quad (3)$$

(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.



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

$$RE_{p,t,sc} = \frac{\sum_{i=1}^N \text{Coef}_{(i,t,sc)} \times DEM_{(i,t,sc)}}{\sum_{i=1}^N DEM_{(i,t,sc)}} \quad (4)$$

where N = the number of demand nodes, $DEM_{(i,t,sc)}$ = the required discharge ($m^3 s^{-1}$) in node i at time t and in the sc -th scenario, and $RE_{p,t,sc}$ is reliability of pumping station at time t and in the sc -th scenario. In this equation, $DEM_{(i,t,sc)}$ 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 calculation. In this respect, if the probability of occurrence of the failure scenario of sc is r_{sc} , the reliability calculation is as follow:

$$RE_{p,t} = \frac{\sum_{sc=1}^{NP} RE_{p,t,sc} \times r_{sc}}{\sum_{sc=1}^{NP} r_{sc}} \quad (5)$$

where NP = the number of pumps in the pumping station, and $RE_{p,t}$ = 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.

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

(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.

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(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

(C19) For this network, the pumping scheduling after developing the pump

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, if (C52) 1.3 and one working pump(s) in the network, the demand multiplier (C11) fulfills till 1.4 and 0.7, respectively. It is clear that if all the four pumps work, the demand will be completely satisfied.

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



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 of the results shown in Fig. 5 reveals that, by using reliability of pumping station with single speed pumps is more than the variable speed pumps. On the contrary, using Eqs. (2) and (3) is vice versa. In Eq. (1), the reliability of pumping station is calculated regardless of the maximum allowable nodal pressure. Therefore, the major coefficient is spotted for these nodes. In order to avoid surplus pressure in nodes (surplus pressure occurs when the required nodal pressure is more than available water pressure in nodes), the variable speed pumps are used. Surplus pressure in nodes will be decreased. However, if single speed pumps are used while they may fulfill the nodal demands, it is possible that the nodal pressure will be the maximum allowable as these nodes have status On and Off. Surplus 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.

4 Conclusions

~~In this study the reliability of pumping stations in WDNs was conducted.~~ Same 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 Vardavard 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

(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.

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

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(C8) Nodal pressure

be concluded that with increase of demand in the peak demand time of a day, the ca-
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(C37) According to the obtained results of this research, it can be concluded t

(C22) It is important to mention that the conclusi

10 pumping stati
 speed pumps.
 In the case
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 15 with an adequ
 higher than no
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(C3) According to Figure 3, especially in low consumption hours of a day in which h

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 VNs

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
 20 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.

(C38)

25 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.

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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

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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).

Demand factor	Hour	Number of pumps with status 1	Reliability (VSP)				Weighted average	Reliability (SSP)				Weighted average
			3	2	1	0		3	2	1	0	
			0.7	1	0.728	0.728		0.728	0	0.721	0.841	
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	

Using equation 1

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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

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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

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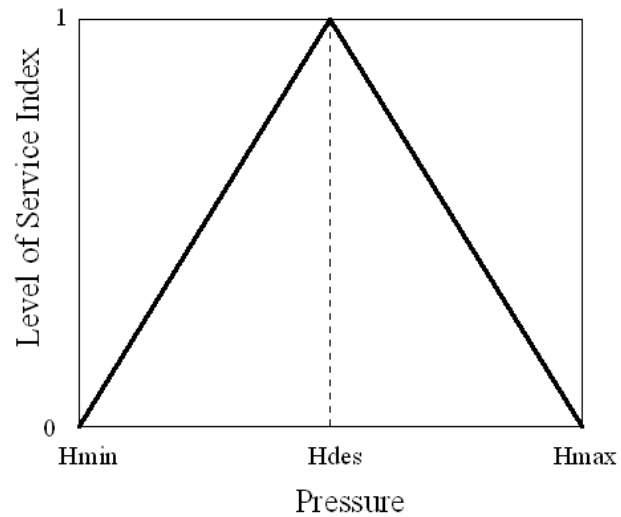


Fig. 1. Degree of membership of the fuzzy function in Eq. (2).

↑ fuzzy
(C8) nodal pressure

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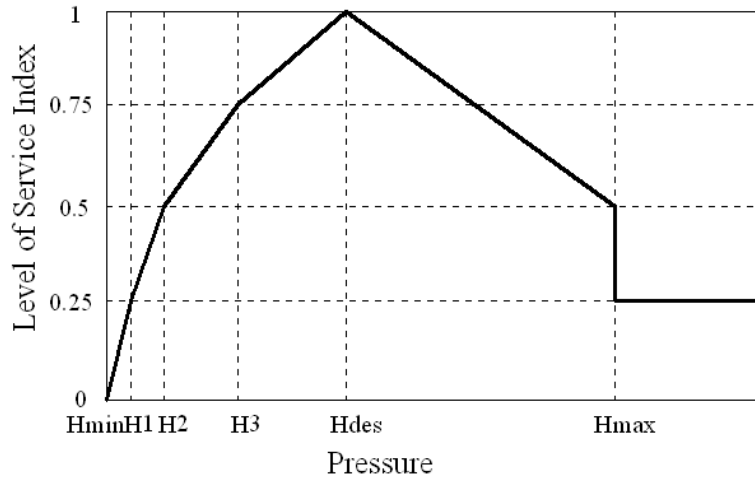


Fig. 2. Degree of membership of the fuzzy function in Eq. (3).

(C8) nodal pressure

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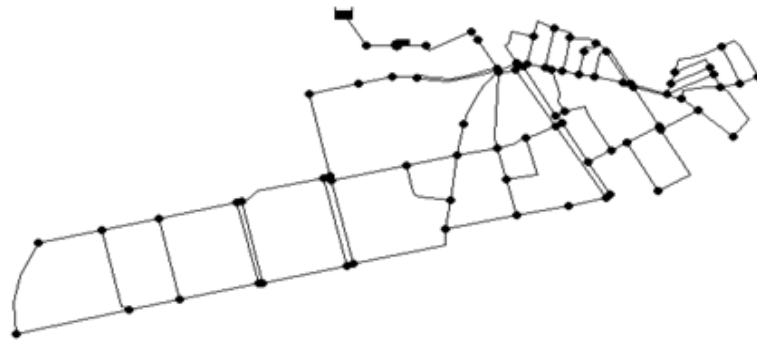


Fig. 3. The ~~downer~~ zone of the Vardavard water distribution network (Hashemi et al., 2011).

(C34) low

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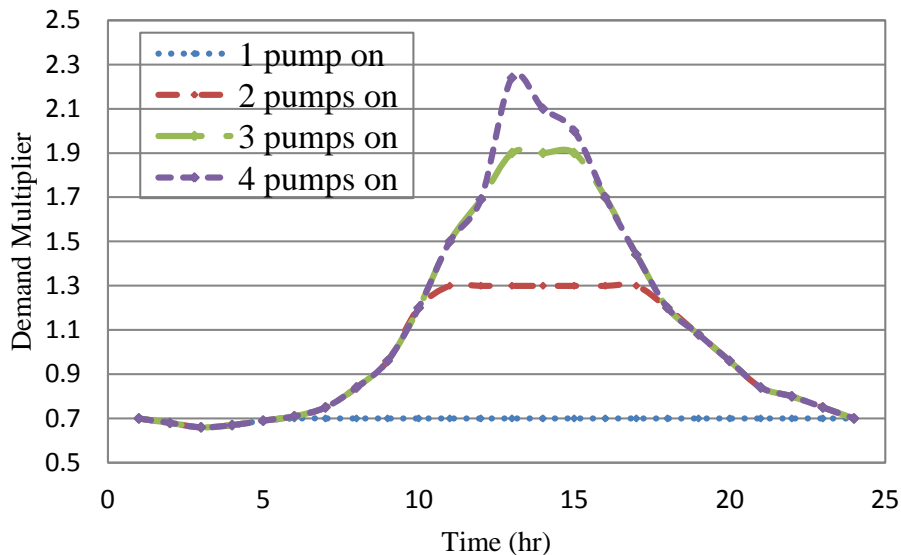


Fig. 4. Deviation in the level of satisfying the network’s demands.

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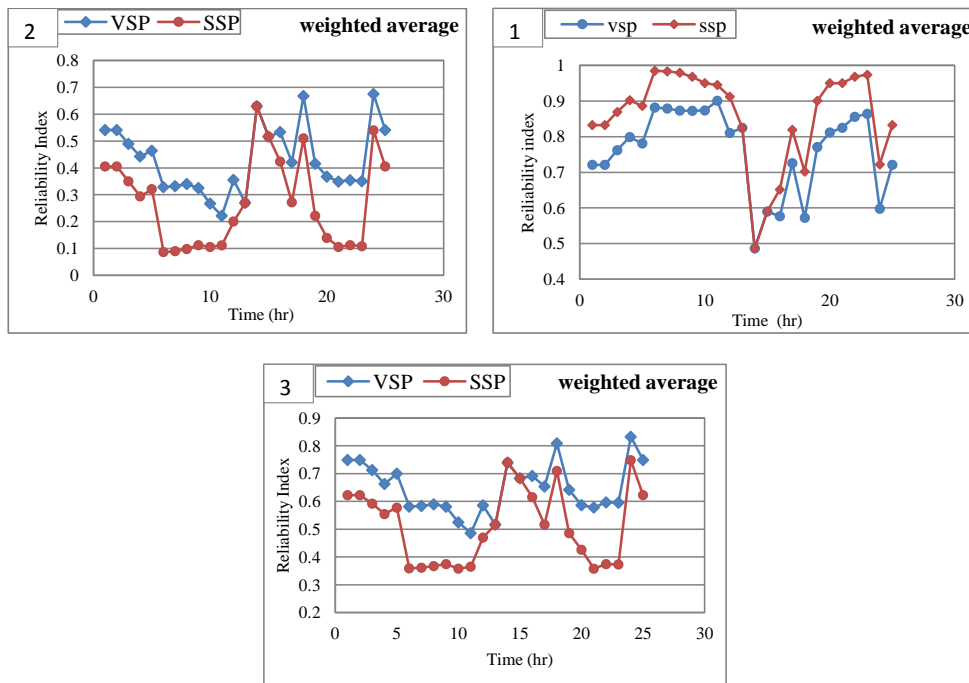


Fig. 5. The comparison of reliability of two type of pumps (VSP, SSP), with weighted average of four scenarios using three fuzzy equations.

→ (C8) nodal pressure

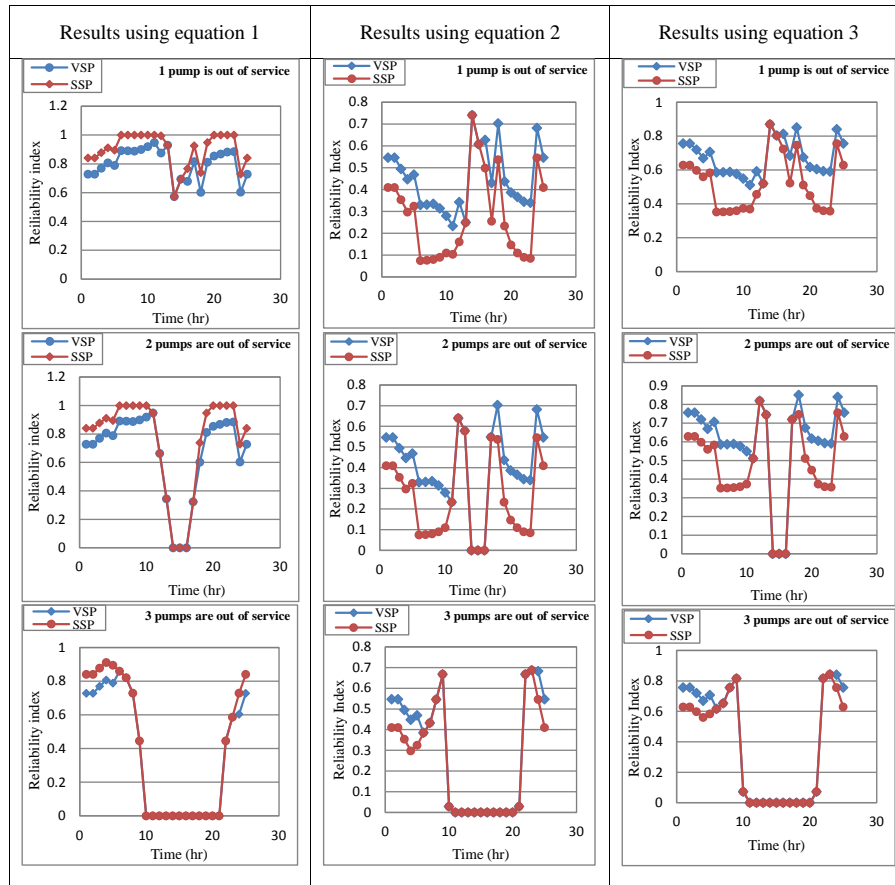


Fig. 6. Evaluation of reliability of two different pumps (VSP, SSP) using three fuzzy equations.

↑ (C8) nodal pressure

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