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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 curve in 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 energy consumption, especially in water distribution systems with high variation in demand. Hashemi et al. (2011) investigated the optimization of water distribution networks by means of varied speed pumps. The major objective of this research was to minimize 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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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 meets its requirements. It is thus determined by the reliability of its elements and by the relations between those elements. In consideration of the reliability of an element, determination of the probability of failure is an essential issue. When a system or part of it no longer fulfills one or more desired functions, it is known as failure. The state of failure can be reached via different ways. Such a way that leads to failure is known as a failure mode. According to Misirdali (2003), hydraulic and mechanical failure modes are distinguished for water 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).

Reliability of system in terms of the mechanical failure has been studied by many individuals, namely, Mays and Cullinane (1986), Wagner et al. (1988b), Sue 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. Gupta 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.

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.

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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 available capacity of pumping station as a continuous-time markov process.

Due to the fact that pumping stations are economically important in WDNs, a realistic and proper definition of pumping station reliability is necessary in order to decrease the costs and improve the performance of a network through a good asset (pumping stations) 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 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.

## 2 Methodology

In this study, the pumping station reliability is the ability of pumps to provide enough water to consumption nodes with allowable pressure. Most of the available software, such as EPANET2.0 is developed based on hydraulic analysis which satisfies the total 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.

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

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:

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

where  $HMAX_{(i,t,sc)}$  = 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.

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

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 equation. 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

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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.

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 higher pump erosion which increases the costs of replacement and also the consumption of electricity. This situation is not desirable for the network. Therefore, an accurate pumping scheduling is crucial for the WDNs.

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, for two and one working pump(s) in the network, the demand multiplier 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

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Vardavand's network, there is no tank and all the demands will be satisfied by the pumps operation. Therefore, the nodal pressures are highly dependent on the pumping station.

In WDNs, the pumping stations work automatically. For example, suppose that in the pumping scheduling three pumps are required to be on, and one of them is failed. The efficiency of the pumping station will be maintained, if only another reserve pump begins 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%, 4% and 1%, respectively. HDES in various times 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 are  $694.78 \$ kw^{-1}$  and  $597.75 \$ kw^{-1}$  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 equations. As it was expected, in the peak hours of a day in which higher numbers of pumps are failed,

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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 Eq. (1), the 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 less than available water pressure in nodes), the variable speed pumps are used. So, the 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 exceeds the maximum allowable as these pumps could only have status On and Off. This 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

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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 specially while the system experiences the mechanical failures. Moreover, increase in number of pumps in which mechanical failure occurs, decreases the amount of water supplied via pumps and as a result, decreases the reliability of WDNs. This research reveals that the reliability of WDNs' pumping stations with variable speed pumps is less than the reliability with single speed pumps, when using an equation which does not consider maximum allowable nodal pressure. However, by using reliability equations which consider the real condition of the network more precisely, the reliability of WDNs' pumping stations with variable speed pumps is higher than the reliability with single speed pumps.

In the case of failure in any pump in the pumping stations, if other pumps can work with higher velocity rate to compensate lack of pressure in the demand nodes, the network performance can be improved and the reliability of the network is increased with an adequate planning for pumping stations. It is important to note that the velocity higher than normal value causes erosion of pumps sooner than the expected time in its life cycle. On the other hand, providing extra pumps in the pumping stations of WDNs 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.

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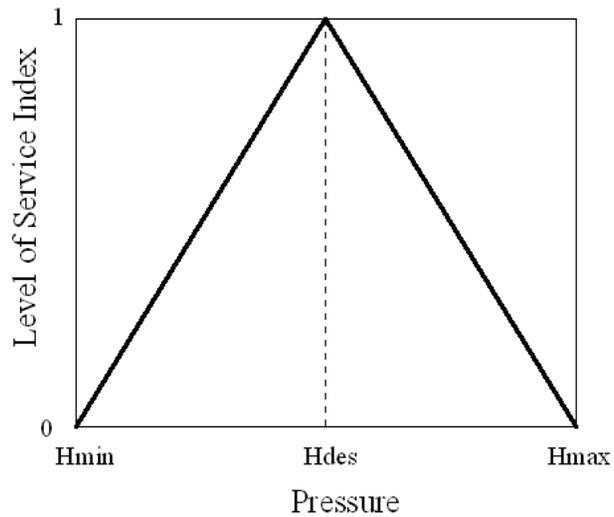


Fig. 1. Degree of membership of the fuzzy function in Eq. (2).

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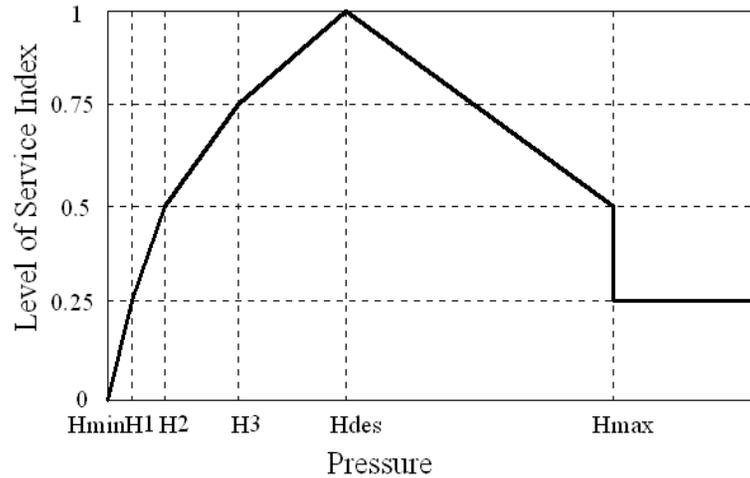
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**Fig. 2.** Degree of membership of the fuzzy function in Eq. (3).

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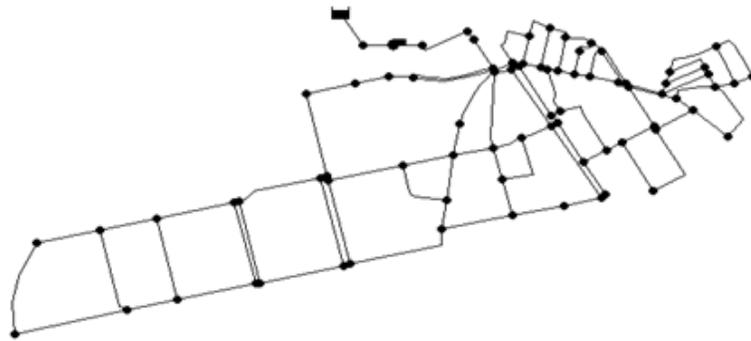
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**Fig. 3.** The downer zone of the Vardavard water distribution network (Hashemi et al., 2011).

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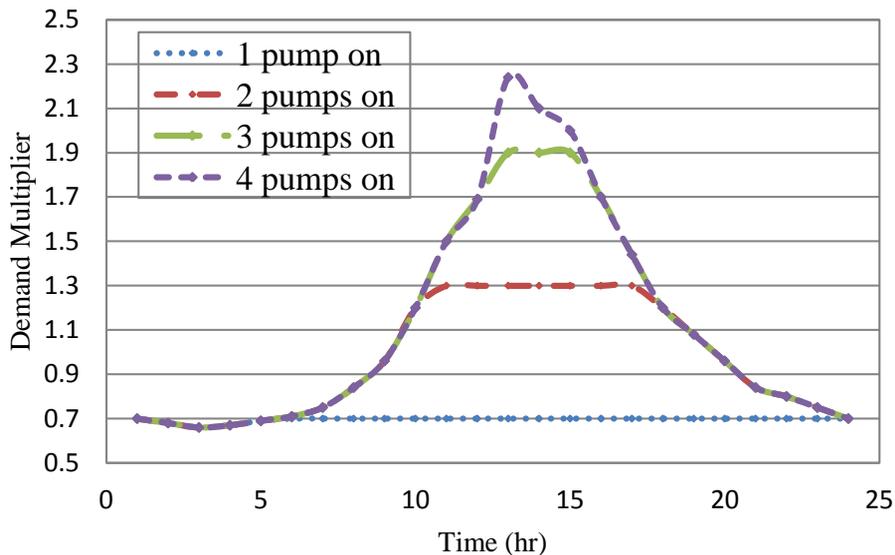


Fig. 4. Deviation in the level of satisfying the network’s demands.

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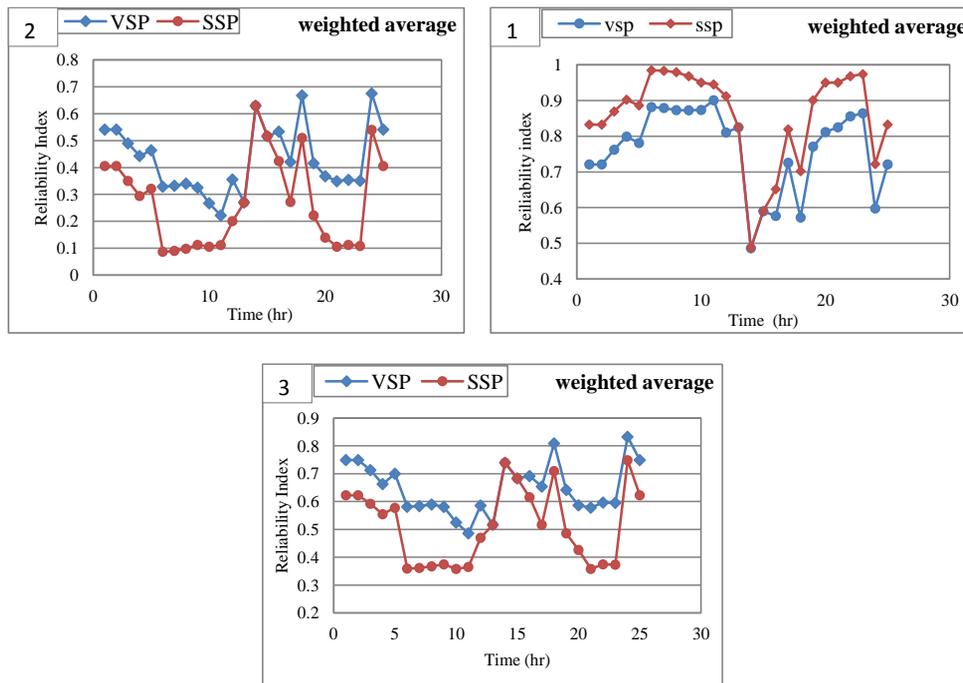
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**Fig. 5.** The comparison of reliability of two type of pumps (VSP, SSP), with weighted average of four scenarios using three fuzzy equations.

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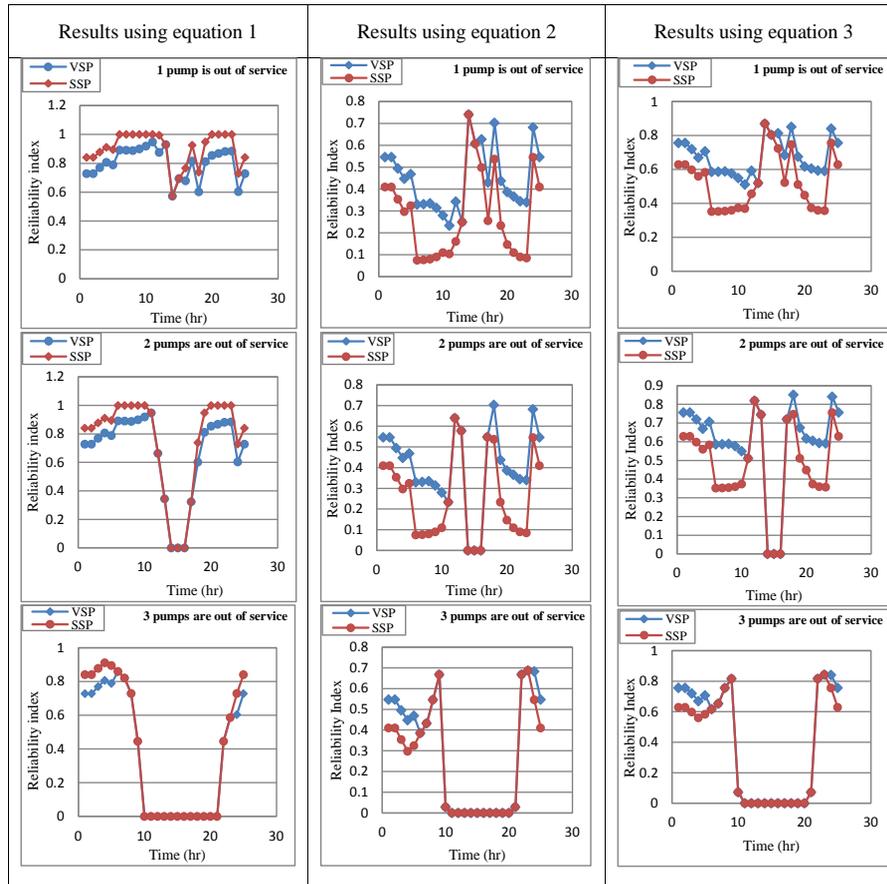
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**Fig. 6.** Evaluation of reliability of two different pumps (VSP, SSP) using three fuzzy equations.

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