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A pressure dependent analysis-based index to assess reliability of water distribution networks

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Abstract—**Reliability of Water Distribution Networks (WDNs) is one of the most important issues in planning and management of these networks. In the previous studies various indices have been proposed to evaluate the reliability of WDNs. These indices which have some advantages and disadvantages can also be an indicator for efficiency of WDNs. Since the Pressure Dependent Analysis (PDA) of WDNs has more accurate results than the Demand Dependent Analysis (DDA), then in this study a new index is proposed for reliability assessment of WDNs based on PDA. According to this index, the nodal pressures and the nodal available demands are the most factors influencing the reliability of WDNs. A sample network is also used to compare the new proposed index and the available indices and their efficiencies in assessing the reliability of WDNs.**

Keywords—**Water distribution network, Reliability, Pressure dependent analysis**

I. Introduction

Knowledge about actual water distribution network (WDN) performance during different operation situations is a significant tool to control and manage the existing WDNs or design new WDNs. This concept has been known as reliability. Reliability is the ability of WDN to supply the required demand under sufficient pressure during normal and abnormal operation conditions [1]. Many reliability indices and models have been proposed up to now. For example Su et al. (1987) proposed a model for reliability assessment named the minimum cut set model [2]. They introduced a mechanical reliability criterion based on the direct simulation of WDS's operation by means of mathematical modelling. Bao and Mays (1990) considered failures resulting from hydraulic causes, such as high values of water demand and simulated system behavior by using Monte Carlo method and a hydraulic model [3]. Cullinane et al. (1992) [4] and Gupta and Bhave (1994) [5] combined hydraulic and mechanical availability into a single assessment of reliability. Other researchers (such as Tanyimboh, 1993 [6]; Todini, 2000 [7]; Jayaram, 2006 [8]; Ghajarnia et al., 2009 [9]) have also studied in this regard and have proposed indices for evaluating the reliability of WDN.

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Since the Pressure Dependent Analysis (PDA) of WDNs has more accurate results than the Demand Dependent Analysis (DDA), then in this paper an index is introduced based on PDA for determining WDN reliability to ensure a suitable design of these networks and also to establish the rehabilitation schedules for existing WDNs. According to the proposed reliability index the nodal pressures and nodal available discharges are the most factors influencing the reliability of WDNs. A sample network is used to compare the new proposed index and some of the available indices and their efficiencies in assessing the reliability of WDNs.

II. Material and Methods

In this paper some of the available reliability indices (Table 1) are evaluated using a sample WDN (Fig. 1). Then based on the weakness and strength points of the studied indices and implementing PDA, a new reliability index is presented. The general characteristics of the sample WDN are shown in Table 2. The pressure-discharge relation used in the PDA is as below [10]:

$$Q_j^{avl} = \begin{cases} 0 & if \quad P_j \le 0 \\ 0.176(Q_j^{req} \times P_j^{0.51}) & if \quad 0 < P_j \le 30\,m \\ Q_j^{req}(0.5 + 0.0882 P_j^{0.51}) & if \quad 30 < P_j \le 100\,m \\ 1.424\, Q_j^{req} & if \quad P_j > 100\,m \end{cases} \quad (1)$$

in which Q_j^{avl}: is the available discharge at node *j*, Q_j^{req}: is the required discharge at node *j*, and P_j: is the pressure at node *j*.

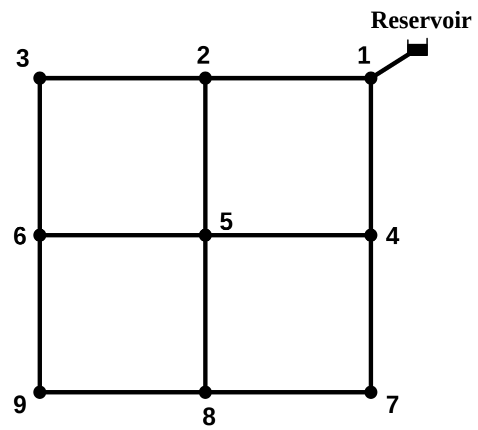

Figure 1. The sample network [11]

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TABLE 1. THE EVALUATED RELIABILITY INDICES

Index	Researcher	Formula
Nodal reliability index	Tanyimboh (1993) [6]	$R_j = P(0) \sum_{M=0}^{NP} r_j(M) \prod_{l=1}^{M} \frac{UA_l}{A_l} = P(0) r_j(0) + \sum_{l=1}^{NP} P(l) r_j(l) + \sum_{l=1, m \neq l}^{NP} P(l,m) r_j(l,m) + ...$ $r_j(M) = \frac{Q_j^{avl}(M)}{Q_j^{req}} \quad , M = 1,..., NP \; ; \nabla j$ $P(0) = \prod_{l=1}^{NP} A_l \quad , \quad P(M) = P(0) \prod_{l=1}^{M} \frac{UA_l}{A_l} \quad , \quad UA_l = 1 - A_l$
Resilience index	Todini (2000) [7]	$I_r = \frac{\sum_{j=1}^{NN} q_j^{req}(h_j - h_j^{des})}{[\sum_{r=1}^{NR} q_r h_r + \sum_{pu=1}^{NPU} \frac{P_{pu}}{\gamma} - \sum_{j=1}^{NN} q_j^{req} h_j^{des}]}$
Modified resilience index	Jayaram (2006) [8]	$MI_r = \frac{\sum_{j=1}^{NN} q_j^{req}(h_j - h_j^{des})}{\sum_{j=1}^{NN} q_j^{req} h_j^{des}} * 100\,\%$
Fuzzy reliability index	Ghajarniaet al. (2009) [9]	$FRI_j = MemF_j \times C_j^1 \times C_j^2$ $MemF_j = \begin{cases} 0 & if \quad H_j \leq H_j^{des} \\ \frac{2}{H_j^{max} - H_j^{des}}(H_j - H_j^{des}) & if \quad H_j^{des} < H_j \leq \frac{H_j^{des} + H_j^{max}}{2} \\ \frac{2}{H_j^{des} - H_j^{max}}(H_j - H_j^{max}) & if \quad \frac{H_j^{des} + H_j^{max}}{2} < H_j \leq H_j^{max} \\ 0 & if \quad H_j > H_j^{max} \end{cases}$ $C_j^1 = 1 - \frac{q_j^{req}}{\sum_{j=1}^{NJ} q_j^{req}} \quad , \quad C_j^2 = \frac{\sum_{i=1}^{NP_j} D_{ij}}{NP_j \times D_{Max_j}}$

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TABLE 2. INFORMATION OF PIPES AND NODES IN THE SAMPLE NETWORK

Pipes information				Nodes information			
Pipe	Diameter (mm)	C_{HW} (-)	Length (m)	Node	$H_j^{\min}$ (m)	H_j^{req} (m)	Q_j^{req} (m^3/s)
1-2 , 1-4	250	130	1000	1 (reservoir)	-	100	0.2081
2-3 , 4-7	175	130	1000	2 , 4	0	30	- 0.0208
2-5 , 4-5	145	130	1000	3 ,7	0	30	-0.0208
3-6 , 7-8	115	130	1000	5	0	30	-0.0208
5-6 , 5-8	100	130	1000	6 , 8	0	30	-0.0208
6-9 , 8-9	100	130	1000	9	0	30	-0.0625

III. Results and Conclusions

The new reliability index which is called as total nodal reliability, is written as (2).

$$TRe_{Node} = \frac{\sum_{j=1}^{NJ} (Re_{Node\,j} \times Q_j^{req})}{\sum_{j=1}^{NJ} Q_j^{req}} \quad (2)$$

in which TRe_{Node}: is the total nodal reliability, Q_j^{req} : is the required discharge at node *j*, NJ : is the total number of network nodes, and Re_{Node_j} : is the reliability of node *j* and is calculated from (3).

$$Re_{Node\,j} = \begin{cases} 0 & if \quad P_j \le 5 \\ \left(\dfrac{P_j - 5}{30}\right)^{0.51} & if \quad 5 < P_j \le 35 \\ 1 - \dfrac{P_j - 35}{30} & if \quad 35 < P_j \le 50 \\ 0.25 & if \quad P_j > 50 \end{cases} \quad (3)$$

where P_j : is the pressure at node *j*. Diagram of nodal reliability based on (3) is shown on Fig. 2.

The reliabilities of the sample WDN for different head values of the reservoir based on the various reliability indices are proposed in Table 3. As it can be seen in this table, according to the index proposed by Tanyimboh (1993) [6], increase in reservoir head and then increase in nodal pressures up to and higher than the maximum allowable amount, will lead to increase in the reliability of WDN. While for pressures higher than the maximum allowable amount, pipe burst rate and leakage volume increase and then the reliability will be decreased. In fact in the index proposed by Tanyimboh (1993) [6], irregular increase of pressure has not been taken into consideration. The indices proposed by Todini (2000) [7] and Jayaram (2006) [8] sometimes have negative values. These indices also increase by increasing the nodal pressures to values higher than the maximum allowable amount which is an evidence for their weakness. Between the examined reliability indices, the index proposed by Ghajarnia et al. (2009) [9] is the only reliability index in which the increase of pressure to values higher than the maximum allowable amount has been taken into consideration as a decreasing factor of WDN reliability. This index is preferred among the other indices from this point of view.

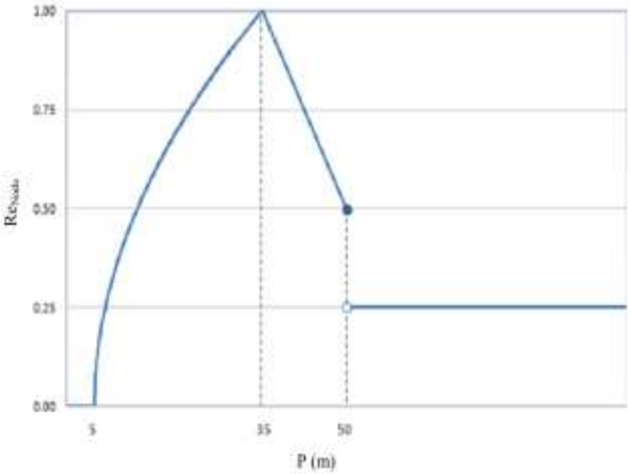

Figure 2. Diagram of nodal reliability variation

TABLE 3. THE RELIABILITY OF THE SAMPLE WDN FOR DIFFERENT HEAD VALUES OF THE RESERVOIR

Case No.	Reservoir head	Tanyimboh (1993)	Todini (2000)	Jayaram (2006)	Ghajarnia et al. (2009)	The new index
1	30	0.5646	1.3787	-0.5999	0.0587	0.4132
2	70	0.8281	-0.0131	-0.0122	2.2014	0.4108
3	100	0.9580	0.2111	0.4633	0.2065	0.3121
4	150	1.1008	0.2961	1.3344	0.6888	0.2704
5	200	1.1682	0.3394	2.3056	0.0507	0.3224

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Since the proposed reliability index is a normalized index and has values between zero and 1, then the size of WDN has not any impact on the value of this index and comparison of various WDNs using this index will be possible. But abnormal indices such as one proposed by Ghajarnia et al. (2009) [9] cannot be used for comparison of various WDNs with different sizes. Because according to an abnormal index, the reliability of WDNs increases by increasing their size and then the comparison results will be ambiguous.

IV. Conclusions

Since the PDA has more realistic results in comparison to DDA and on the other hand the presented reliability index is based on PDA, then this index is a more appropriate one for evaluating the reliability of WDNs. Another advantage of the presented reliability index is that, it is a normalized index and has values between zero and 1.

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