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Multi-aspect performance analysis of water distribution systems under pipe failure

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Abstract

Performance analysis of a water distribution system (WDS) under pipe failure can be studied from different aspects. Performance analysis techniques are mostly restricted to the single performance index of supply ratio. This research applied novel technique of octant analysis to study the performance of a WDS in three aspects of adequacy, equity and efficiency of water delivery simultaneously. Results reveal that evaluating the performance of a WDS in just one aspect cannot guaranty the perfect overall performance of the WDS in future from all aspects. This study recommends octant/quadrant analysis as a more comprehensive tool for multi-aspect performance analysis of WDSs.

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Keywords: Water distribution system; multi-aspect performance analysis; Octant/quadrant analysis; pipe failure.

1. Introduction

An urban water sector is identified and prioritized by the authority of Homeland Security as one of the sixteen critical infrastructure sectors which should promise high level of reliability. It is typically comprised of infrastructures for the collection, treatment, transmission, storage, and distribution of water. Among the aforementioned infrastructures, water distribution system (WDS) of an urban water supply sector is highly vulnerable with the least amount of protection [1]. An urban WDS is a complex system with vast variety of mechanical, hydraulic and electromechanical interconnected components. This study was chiefly focused on the most vulnerable part of an urban water sector and investigated WDS performance under pipe failure. Pipe failure in a WDS may happen at different states of one failure at a time, two simultaneous failures at a time and three

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simultaneous failures at a time known as first, second and third states pipe failures and so on [2, 3]. On the one hand, different states of pipe failure could have different effects on the performance of a WDS, and on the other hand a specific state of pipe failure in a WDS could have several impacts simultaneously on the performance of the system in different aspects (e.g. quantity and/or quality of delivered water, water leakage). However, current reliability analysis techniques in the literature are not able to demonstrate this fact. Researchers generally apply a specific performance index and evaluate the performance of a WDS in just one specific aspect or two aspects separately (i.e., providing the consumers with adequate amount of water or water with acceptable quality) [4]. Techniques which evaluate the performance of a WDS in two aspects separately are not able to demonstrate the interaction that may exist between these two aspects. This research applied novel technique of octant analysis to study the performance response of a WDS in three aspects/dimensions simultaneously at a specific state of failure. This novel technique can significantly help researchers to have a clearer picture about the reliability and also vulnerability of a WDS in three aspects under a specific state of failure.

2. Methodology

This research applied the novel technique of octant analysis to study the response of a WDS to first state pipe failures in three aspects simultaneously. Octant base response analysis enable researchers to evaluate the performance of a WDS in any three quantifiable aspects simultaneously under a particular state of failure.

Octant analysis is an extended version of quadrant analysis. Quadrant analysis has been applied widely in many disciplines (e.g. turbulent flow analysis, marketing research and sport performance analysis). In turbulent flow analysis, initially Grass [5] and Willmarth and Lu [6] applied quadrant analysis to classify the coherent near the bed turbulent flow structures known as bursting events in two dimensions. However, Gheisi et al. [7] and Keshavarzi and Gheisi [8, 9] extended the technique of quadrant analysis to octant analysis for three-dimensional analysis of near bed turbulent bursting events. In marketing research, initially Martilla and James [10] applied quadrant analysis based on the concept of importance-performance analysis (IPA) to measure and manage the customer satisfaction.

This study applied the technique of octant analysis based on the concepts of water adequacy, equity and efficiency (due to water leakage). Three-dimensional study was conducted for first state of pipe failure. Each dimension represents the performance of a WDS or the response of WDS to pipe failure in one aspect (e.g. water adequacy, equity and losses). Accordingly, three different performance indices were defined and also applied to measure the adequacy, equity and efficiency of water delivery to consumers.

Adequacy of Water Delivery

Water utility index defined as the ratio of supplied water to demand is the most commonly practiced performance index in the concept of simulation-based WDS reliability analysis. The index reflects the level of agreement between supply and demand [11, 12, 13, 14, 15]. This study employed the index of supply ratio to check the adequacy of water delivery to consumers as [13, 14, 15]:

$$PI_j^{ad} = \frac{Q_j^{su}}{Q_j^{re}} \tag{1}$$

$$PI_{sys}^{ad} = \frac{\sum_{j=1}^{n_n} Q_j^{su}}{\sum_{j=1}^{n_n} Q_j^{re}} \tag{2}$$

Where PI^{ad} is the performance index for the adequacy of water delivery; n_n is the number of nodes in WDS; Q^{su} is the supplied water (L/s); and Q^{re} is the demanded water (L/s). The subscripts “j” and “sys” refer to node number and system, respectively.

Equity of Water Delivery

Although the adequacy of delivered water to consumers is crucial, but an important question still remains unanswered. The question is whether the available water at demand nodes is distributed in a fair manner. Index of supply ratio reveals how much water is available at demand nodes, but it does not give any information about how fairly the available water is distributed. Equity index can address this question by revealing how uniformly and equally the water shortage is shared among different users in pressure deficient condition.

Performance index of equity has been widely employed in field of irrigation water management [16, 17] and less frequently in WDS analysis [18, 19]. Knowing the supply ratio for each demand node, the equity index can be obtained easily. Initially, the average of nodal supply ratios in a WDS should be computed then the deviation of each nodal ratio from the average can be obtained easily. Average of deviations over the average of supply ratios represents the amount of variations in the WDS. Accordingly, the uniformity or equity index is one minus the variations [19]:

$$PI_{sys}^{eq} = 1 - \left[\frac{\sum_{j=1}^{n_n} \left| PI_j^{ad} - \frac{1}{n_n} \sum_{j=1}^{n_n} PI_j^{ad} \right|}{\sum_{j=1}^{n_n} PI_j^{ad}} \right] \quad (3)$$

where PI^{eq} is equity index and the subscript “*sys*” refers to system. Gottipati and Nanduri [19] indicated that location of the supply tank and the WDS layout has significant impact on the equity results. Gottipati and Nanduri [19] discussed many factors that may improve PI^{eq}. Increasing water level in supply tanks to some levels, decreasing water demand at nodes very close or far away from the tanks, increasing the diameter and addition or elimination of some key linking pipes in a WDS can significantly improve the equity of water delivery.

Efficiency of Water Delivery

Another important parameter in performance analysis of a WDS is the water leakage due to system deterioration. As WDS age, the loss of water due to leakage increases and becomes more controversial issue. Nowadays, a large proportion of supplied water in WDS is wasted daily due to leakage and is gradually reaching alarming level [20]. The inevitable phenomenon of water leakage in an aged WDS wastes a huge portion of supplied water every day and also has significant effect on the operation of the system, which cannot be ignored [21]. Twort and Hoather [22] reported 5 to 55% of total supply as the global average of water losses from different parts of a WDS depending on the available residual pressure inside the system.

In this study to consider water losses due to leakage in WDS response analysis the performance index of efficiency was proposed and implemented. The loss of water due to leakage depends on many factors including (but not limited to) available pressure in WDS, shape and hydraulics of the leak opening, material properties of pipes, hydraulic characteristics of the surrounding soil and also the pressure-dependent water discharge at demand nodes [20].

Knowing the pressure head in pipes, a number of relationships have been proposed in literature to estimate the leakage losses [21, 23, 23, 25, 26, 27, 28, 29, 30]. The technique proposed by Germanopoulos [21] is commonly employed in the literature [31, 32, 33, 34] due to its simplicity. The technique assumes leakage to be uniformly distributed along the pipe. Similar to literature, this research applied this technique due to its simplicity. Accordingly, the water leakage in a pipe is [21]:

$$Q_n^{leak} = C \cdot L_n \cdot (P_n^{ave})^{1.18} \quad (4)$$

where Q_{leak} is the discharge (L/s) due to leakage from a pipe, L is the pipe's length (m), P^{ave} is the average residual pressure in the pipe, and the subscript n is the pipe number. Note that Pave can be estimated by pressure averaging at the beginning and ending nodes of each linking pipe. The coefficient C is a constant related to characteristics of the WDS including the material, age, and number of leakage points per unit length of pipes, which can be estimated easily using the model calibration [35]. According to the range of global water leakage this study set C as 0.0001, which gives efficiency of 0.7 when all pipes are in operation. The WDS performance index of efficiency (PI^{ef}) due to leakage is [36]:

$$PI_{sys}^{ef} = \frac{\sum_{j=1}^{n_n} Q_j^{su}}{\sum_{j=1}^{n_n} Q_j^{su} + \sum_{n=1}^{N} Q_n^{leak}} \quad (5)$$

where N is total number of pipes and the subscript "*sys*" refers to system.

Octant Analysis

In three dimensional/aspect analysis, the x-, y- and z-axes of the Cartesian system divide the space into eight cube zones known as octant I, II, III, IV, V, VI, VII and VIII. Each octant is restricted by three half-axes, which reflect the performance of the WDS in three aspects simultaneously (e.g. water adequacy, equity and efficiency). The point where all the x-, y- and z-axes meet represents the mean performance of the WDS in all three aspects (mean condition). Thus, x_0 = mean (PI_x), y_0 = mean (PI_y), and z_0 = mean (PI_z). Fig.1 demonstrates the eight-octant zones of the three-dimensional/aspect performance analysis. In octant analysis the response of a WDS to different state of pipe failure is defined as follows:

- Octant Zone 1: Performance of the WDS in x, y and z directions (PI_x, PI_y, PI_z) remain higher than the mean condition (mean (PI_x), mean (PI_y), mean (PI_z)).
- Octant Zone 2: Performance of the WDS in x direction (PI_x) is less than the mean condition (mean (PI_x)), but in y and z directions the performance is still higher than the mean condition (mean (PI_y), mean (PI_z)).
- Octant Zone 3: Performance of the WDS in x and y directions (PI_x, PI_y) become less than the mean condition (mean (PI_x), mean (PI_y)), but in z direction the performance is still higher than the mean condition (mean (PI_z)).
- Octant Zone 4: Performance of the WDS in x and z directions (PI_x, PIz) is still higher than the mean condition (mean (PI_x), mean (PI_z)), but in y direction the performance goes to less than the mean condition (mean (PI_y)).
- Octant Zone 5: Performance of the WDS in x and y directions (PI_x, PI_y) is still higher than the mean condition (mean (PI_x), mean (PI_y)), but in z direction the performance goes to the less than the mean condition (mean (PI_z)).
- Octant Zone 6: Performance of the WDS in x and z directions (PI_x, PI_z) goes to the less than the mean condition (mean (PI_x), mean (PI_z)), but in y direction the performance is still higher than the mean condition (mean (PI_y)).
- Octant Zone 7: Performance of the WDS in all x, y and z directions (PI_x, PI_y, PI_z) goes to less than the mean condition (mean (PI_x), mean (PI_y), mean (PI_z)).
- Octant Zone 8: Performance of the WDS in x direction (PI_x) is still higher than the mean condition (mean (PI_x)), but in y and z directions the performance goes to less than the mean condition (mean (PI_y), mean (PI_z)).

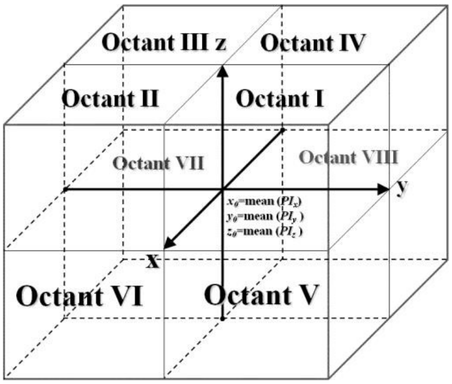


Fig. 1. Eight octant zones of the three dimensional/aspect performance analysis.

3. **Test Case**

Following the literature [37, 38, 39, 3] this research tested the hypothetical WDS in Fig. 2 with a set of 22 different layouts (alternatives) of in Fig. 3. Elevation of all the demand nodes is 0 m. The pipes are 1 km long with a Hazen-Williams coefficient of 130. Table 1 shows the diameter of the pipes for each layout. The pressure head at source node 1 is 100 m. Minimum required residual head at each node is 30 m. Failure of a pipe may cause a sudden pressure drop in the WDS. The original version of EPANET2 [40] is unable to study with the pressure deficient condition when the residual pressure head at nodes is not enough to fully satisfy the demands. Therefore, this study applied the modified version of EPANET2 known as EPANET-Emitter [41] to perform the hydraulic simulations in pressure-deficient conditions.

Table 1. Diameter of pipes for the case study (data derived from Tanymboh and Templeman [37]).

	Diameter for the pipes connecting the following nodes (mm)																
Design #	**1-2**	**1-4**	**2-3**	**2-5**	**4-5**	**4-7**	**3-6**	**5-6**	**5-8**	**7-8**	**7-10**	**6-9**	**8-9**	**8-11**	**10-11**	**9-12**	**11-12**
1	348	310	266	226		289	238		189	186	185	213		202	143	105	177
2	284	368	268		225	286	240		188	184	184	215		200	143	105	176
3	328	335	275	169	174	272	248		189	174	259	225			229	143	151
4	326	336	265	185	186	270	237		221	161	177	212		213	130	100	180
5	298	360	223	191	190	298	184		229	166	219	139	227		191	182	100
6	310	354	206	227	226	265	160	209	209	157	172	231		200	123	139	157
7	294	365	194	214	212	291	141	181	206	154	216	190	194		188	185	100
8	302	361	192	228	226	275	138	175	239	179	169	182	178	184	119	162	135
9	325	337	227	231	232	234	190		293		185	149	194	178	139	149	147
10	353	307	225	273		286	187	181	178	182	184	227		190	142	135	159
11	315	345	231	210	210	265	195		260		226	156	211		198	175	109
12	350	309	275	214		289	249		165	200	257	226			227	145	147
13	307	355	221	208	206	282	182		255	188	172	137	204	189	124	150	147
14	318	346	197	246	247	233	146	182	270		184	197	160	170	139	162	133
15	345	319	205	276		299	159	153	207	210	177	179	178	177	133	158	137
16	231	404	210		275	295	162	152	206	206	176	181	176	175	133	158	137
17	361	314	266	245	251	162	238		315	276	276	214			248	113	180
18	405	236	267	308		208	240		283	238	269	217			241	124	170
19	251	390	232		302	244	193	182	223		199	233		163	163	146	148
20	375	274	227	302		249	189	183	223		204	230		162	166	145	149
21	323	336	227	227		318	190	190		226	195	235		164	159	148	147
22	250	390	231		225	315	192	189		224	194	236		163	159	148	147

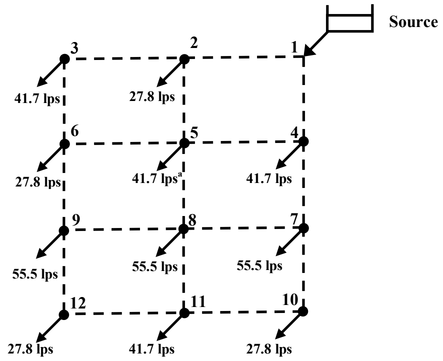


Fig. 2. A schematic view of the hypothetical WDS [37].

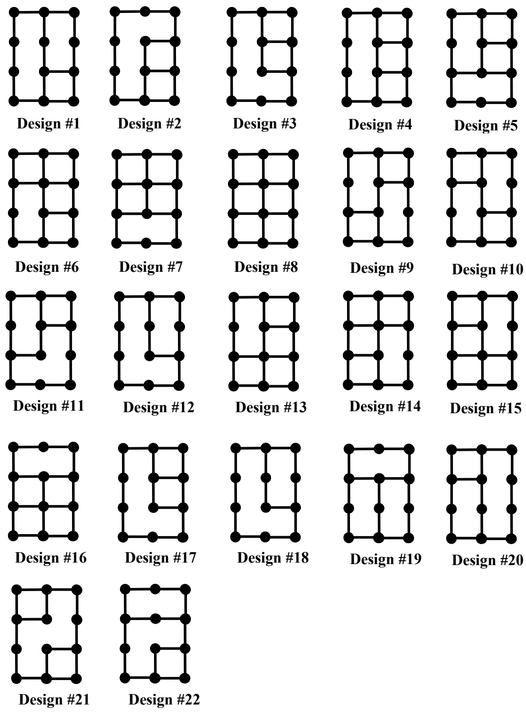


Fig. 3. Designs #1 to #22 for the hypothetical WDS [37].

4. Results and Discussion

Using equations 2, 3 and 5 the response of 22 different WDS layouts to one pipe failure at a time was studied in three aspects of adequacy, equity and efficiency. Mean of the performance responses and the performance deviations from the mean in three dimensions/aspects were evaluated using the octant analysis. Contribution probability of pipe failures events to each octant zone in every three dimensions/aspects was computed and the results are shown in Tables 2 along with the mean performance responses in Table 3. Mean of performance responses for the set of 22 layouts revealed that Layout 8 had the best water adequacy and equity responses to pipe failures, while Layout 18 showed the worst adequacy response. Layouts 14 and 6 also showed high water adequacy and equity responses. However it is interesting to see that the layouts with the highest adequacy and equity in water delivery had the lowest efficiency due to the water leakage losses.

Figs. 4a and b demonstrate the mean responses of the layouts in term of water adequacy against water equity and efficiency and Fig. 4c shows the equity in water delivery to consumers versus efficiency of the WDS Layouts. Fig. 4a shows a strong positive correlation between adequacy and equity in water delivery. This indicates that the layouts which can provide more water for consumers during pipe failures were also able to distribute the water among users in a more fairly manner. However, in Figs. 4b and 4c an evident negative correlation can be observed between efficiency of the layouts and water adequacy and equity performance indices. Distribution systems with high ability to deliver water to consumers in a fair manner (high adequacy and equity) during pipe failures suffer from low efficiency and higher amount of leakage losses. Hence, engineers/designers should be careful about this fact and evaluating the performance of a WDS in just one aspect/dimension cannot guaranty an ideal performance of the system in future for all aspects. This highlights the necessity for multi-aspect performance analysis of WDSs, which unfortunately has been highly neglected in the literature.

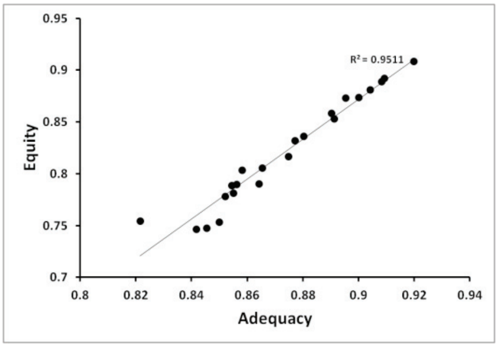
Results of octant performance analysis of layouts in table 2 reveal that when a pipe fails the water consumers of Layouts 20 and 21 have more chance of receiving more water in a fairly manner comparing to the mean condition. However, consumers of Layouts 17 and 12 have more chance of receiving less water in a fairly manner comparing to the mean condition during the pipe failures.

Table 2 – Contribution probability of pipe failures events to each octant zone in adequacy, equity and efficiency aspects.

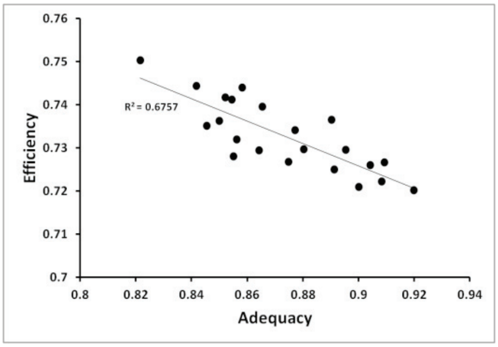
Design #	Octant I (%)	Octant II (%)	Octant III (%)	Octant IV (%)	Octant V (%)	Octant VI (%)	Octant VII (%)	Octant VIII (%)
1	21.42857143	0	21.42857143	0	42.85714286	0	14.28571	0
2	28.57142857	0	21.42857143	0	35.71428571	0	14.28571	0
3	21.42857143	0	21.42857143	0	35.71428571	0	21.42857	0
4	20	0	20	0	46.66666667	0	13.33333	0
5	13.33333333	0	20	0	46.66666667	0	13.33333	6.666666667
6	18.75	0	18.75	0	50	0	6.25	6.25
7	18.75	0	12.5	0	50	0	12.5	6.25
8	11.76470588	0	17.64705882	0	52.94117647	0	5.882353	11.76470588
9	13.33333333	0	13.33333333	0	53.33333333	0	20	0
10	6.666666667	0	26.66666667	0	60	0	0	6.666666667
11	14.28571429	0	21.42857143	0	42.85714286	0	21.42857	0
12	15.38461538	0	23.07692308	0	38.46153846	0	23.07692	0
13	12.5	0	18.75	0	56.25	0	12.5	0
14	18.75	0	12.5	0	50	0	12.5	6.25
15	6.25	0	25	0	68.75	0	0	0
16	18.75	0	25	0	56.25	0	0	0
17	21.42857143	7.142857143	7.142857143	0	21.42857143	0	28.57143	14.28571429
18	15.38461538	7.692307692	15.38461538	0	38.46153846	0	15.38462	7.692307692
19	7.142857143	0	21.42857143	0	57.14285714	0	7.142857	7.142857143
20	42.85714286	0	21.42857143	0	28.57142857	0	7.142857	0
21	35.71428571	0	7.142857143	0	42.85714286	0	14.28571	0
22	28.57142857	0	14.28571429	0	50	0	7.142857	0

Table 3 – Mean performance responses of WDS designs to one pipe failure at a time in adequacy, equity and efficiency aspects.

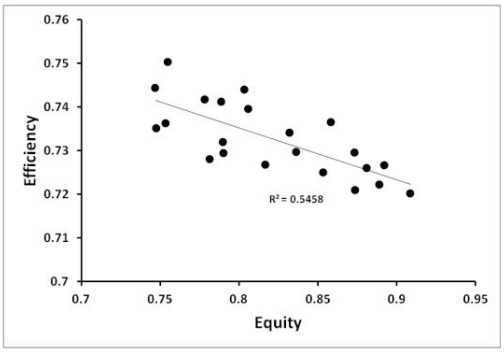
Design #	Adequacy	Equity	Efficiency
1	0.852140447	0.778211	0.741759184
2	0.84534951	0.747625	0.735134462
3	0.864290535	0.790276	0.729492548
4	0.874848144	0.816593	0.726721933
5	0.880260967	0.836345	0.72967621
6	0.908287402	0.888991	0.722261967
7	0.900091395	0.873842	0.72097653
8	0.91985046	0.908758	0.72019539
9	0.890201725	0.858518	0.736587352
10	0.877147357	0.832181	0.734157147
11	0.865421822	0.805922	0.739572268
12	0.841676906	0.746862	0.74443312
13	0.90416198	0.880974	0.72600184
14	0.909187289	0.892372	0.726594418
15	0.895260124	0.873407	0.729595702
16	0.891248594	0.853349	0.725018249
17	0.856116021	0.789888	0.731921869
18	0.821547114	0.754779	0.750393683
19	0.858243612	0.803378	0.744002108
20	0.855000803	0.781416	0.728077968
21	0.849950185	0.753673	0.736310472
22	0.854488189	0.788924	0.741209405



a)



b)



c)

Fig. 4. Mean responses of the WDS designs in term of (a) water adequacy against water equity; (b) water adequacy against efficiency; (c) equity in water delivery against efficiency.

5. Conclusions

Single-aspect WDS performance response analysis based on the performance index of supply ratio is the most commonly applied technique in simulation-based WDS reliability analysis. However, a failure in a WDS can affect the performance of a WDS in various aspects simultaneously (not necessarily just in the quantitative aspect of adequacy).

To address this problem, this study developed the novel technique of multi-aspect WDS performance analysis. This novel technique enables researchers to evaluate the performance of a WDS in any three quantifiable aspects simultaneously under a particular state of failure. Octant analysis was applied to study the response of a WDS to pipe failures in three dimensions/aspects of adequacy, equity and efficiency of water delivery simultaneously. Contribution probability of pipe failure events to each octant zone in three dimensions/aspects revealed which WDS layouts have more/less chance of receiving less/more water in a fairly manner with more/less efficiency relative to the mean condition. A strong positive correlation was observed between adequacy and equity in water delivery. However, layouts with the highest adequacy and equity in water delivery showed the lowest efficiency due to high amount of water leakage losses. Therefore, evaluating the performance of a WDS in just one aspect/dimension cannot guaranty the perfect overall performance of the WDS in future from all aspects.

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