Reliability Indicators for Water Distribution System Design: A Comparison

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Abstract

When designing a water distribution system (WDS) it is imperative that the reliability of the network is taken into consideration. It is possible to directly evaluate the reliability of a WDS, although the calculation processes involved are computationally intensive and thus undesirable for some state-of-the-art, iterative design approaches (such as optimisation). Consequently, interest has recently grown in the use of reliability indicators, which are simpler and faster to evaluate than direct reliability methods.

In this study, two existing reliability indicators, the Todini resilience index and entropy for WDS, are examined by analysing their relationships with different sub-categories of reliability, namely the mechanical (network tolerance to pipe failure) and hydraulic reliability (network tolerance to demand change). The analysis is performed by generating comparable solutions through optimisation of cost against the chosen indicators using the well known Anytown WDS benchmark as a case study.

It is found that WDS solutions with high entropy have increased mechanical reliability, yet are expensive and have poor hydraulic operation and water quality. In contrast, high resilience index networks are relatively cheaper and present reasonable hydraulic operational performance, yet have limited improvement in mechanical reliability. Both indicators appear to be correlated to hydraulic reliability but each has its own associated disadvantages. When optimised together, a trade-off between the two indicators is identified, inferring that significantly increasing both simultaneously is not possible, and thus a new indicator is recommended in order to account for both the mechanical and hydraulic reliability whilst ensuring reasonable standards of hydraulic operation.

CE Database subject headings: Water Distribution Systems, Reliability, Rehabilitation, Optimization, Pumps, Water Tanks, Water Quality

Introduction

Water distribution systems (WDS) are designed to provide consumers with a minimum acceptable level of supply (in terms of pressure, availability and water quality) at all times under a range of operating conditions. The degree to which the system is able to achieve this, under both normal and abnormal conditions, is termed its *reliability*. An indication of system reliability can in principle be calculated though the simulation of multiple system states under an array of different network conditions and configurations (Maier et al. 2001). However, this is likely to be computationally intensive and infeasible if optimal system solutions are being sought. To overcome this limitation, various indicators have been developed that aim to represent reliability yet do not have the computational requirements associated with the direct analysis techniques (Baños et al. 2011). Ostfeld (2004) and Lansey (2006) reviewed a number of definitions for reliability, spanning from simple topology or connectivity to more complex definitions accounting for the hydraulic operation of a network and concluded that each indicator has its strengths and weaknesses, but will typically only capture (to some extent) the particular feature of reliability for which it was designed.

Reliability is typically sub-divided into two aspects. Mechanical reliability reflects the degree to which the system can continue to provide adequate levels of service under unplanned events such as component failure (e.g. pipe bursts, pump malfunction). Hydraulic reliability reflects how well the system can cope with changes over time such as deterioration of components or demand variations. Wagner et al. (1988) argued that both mechanical and hydraulic reliability are important factors to consider during WDS design and both should be accounted for explicitly.

Previous studies (Farmani et al. 2005; di Nardo et al. 2010; Raad et al. 2010) have examined the extent to which key indicators (singly or in combination) are able to quantify both forms of reliability (mechanical and hydraulic) within simple water distribution networks. This paper presents a comprehensive, comparative analysis of popular reliability indicators based on a more complex network containing pumps and tanks. The aim is to establish which indicator, or combination of indicators, is able to accurately represent both the mechanical and hydraulic reliability of a WDS, or whether a more comprehensive indicator is required.

Reliability Indicators

As mentioned a range of reliability indicators have been developed of various degrees of sophistication. In general, these all give some indication of the ability of a WDS to cope with changing conditions and are straightforward to calculate so are useful for optimisation studies that compare the performance of one instance of a network design with another. None are particularly significant as standalone values. This section presents the definition of the key indicators and their derivatives, together with advantages and disadvantages where known.

Resilience Index

Todini's resilience index is a popular surrogate measure within the WDS research field (Todini 2000; Prasad and Park 2004; Farmani et al. 2005; Saldarriaga and Serna 2007; Reca 2008), which considers surplus hydraulic power as a proportion of available hydraulic power. The resilience index, I_r, is measured in the continuous range [0…1] (for feasible solutions of $h_{a,i} \geq h_{r,i}$) and is formulated as (Todini 2000):

$$I_r = \frac{\sum_{i \notin IN}^{nn} q_i \left(h_{a,i} - h_{r,i}\right)}{\left(\sum_{i \in IN}^{nn} Q_i H_i + \sum_{j=1}^{np} \frac{P_j}{\gamma}\right) - \left(\sum_{i \notin IN}^{nn} q_i h_{r,i}\right)} \quad (1)$$

nn	*Number of supply and demand nodes*
np	*Number of pumps*
IN	*Set of supply nodes (reservoir/emptying tanks)*
$h_{a,i}$	*Available head at supply node i (kPa)*
$h_{r,i}$	*Required head at supply node i (kPa)*
q_i	*Demand at node i* (m^3/s)
Q_i	*Supply at input node i* (m^3/s)
H_i	*Head from input node i (kPa)*
P_j	*Power from pump j (kW)*
γ	*Specific weight of water* (N/m^3)

The resilience index has been shown to be correlated to hydraulic and to some extent mechanical reliability (Farmani et al. 2005), yet the function has also been shown to exhibit some weaknesses. Several adaptations of the resilience index have been developed in order to account for (a) the degree of uniformity of pipe diameters entering nodes, i.e. the *network resilience* (Prasad and Park 2004), and (b) to combat inconsistencies with the indicator when considering multiple sources, i.e. the *modified resilience index* (Jayaram and Srinivasan 2008). Baños et al. (2011) compared the three indexes in a two objective (cost vs. reliability indicator) study and revealed that there was some correlation between each resilience indicator and hydraulic reliability but that the two newer indicators did not particularly improve on the original. Indeed, with no overall 'best' indicator, it was suggested that all of these resilience indicators are incapable of fully considering the connectivity of a network and thus are unable to identify the most critical areas in systems requiring reinforcement.

Entropy

The entropy reliability indicator was first developed by Awumah et al. (1990) and later used by Tanyimboh & Templeman (1993). It assesses the 'disorder' of flow around a network by taking into account the proportions of flow entering individual nodes, thus providing a surrogate measure of network connectivity (number of possible flow paths). Maximising entropy has been shown to increase a network's mechanical reliability (Awumah et al. 1990). The maximum achievable entropy value has no standard range, and is dependent upon the number of nodes within a network and the number of pipes attached to these. Tanyimboh and Templeman's (1993) formulation of entropy (S) is given in equation 2:

$$S = -\sum_{i \in IN}^{nn} \left(\frac{Q_i}{T}\right) \ln\left(\frac{Q_i}{T}\right) - \frac{1}{T} \sum_{i \notin IN}^{nn} T_i \left[\left(\frac{q_i}{T_i}\right) \ln\left(\frac{q_i}{T_i}\right) + \sum_{j \in N_i} \left(\frac{q_{ij}}{T_i}\right) \ln\left(\frac{q_{ij}}{T_i}\right) \right] \quad (2)$$

T *Total network inflow from reservoir/tanks* (m^3/s)
T_i *Total flow reaching node i* (m^3/s)
N_i *Set of direct upstream nodes j connected to node i*
q_{ij} *Flow rate in pipe ij* (m^3/s)

Setiadi et al. (2005) performed a comparative study between entropy and mechanical reliability (operation of the network after pipe failure) concluding that the two have a strong correlation despite having different methods of calculation. Further developments in entropy have been made through examining its application to more advanced networks (e.g. multiple sources with demands split between them (Yassin-Kassab et al. 1999)).

Minimum Surplus Head

In a WDS, Minimum surplus head, I_s, is defined as the lowest nodal pressure difference between the minimum required and observed pressure, formulated as:

$$I_s = \min\left(h_{a,i} - h_{r,i}\right); \qquad i = 1, \dots nn \quad (3)$$

Farmani et al. (2005) found that increasing the minimum surplus head in addition to the resilience index can improve the connectivity and thus mechanical reliability. It is not known if this same conclusion is valid with respect to the entropy indicator.

Performance

Two recent studies have shed some light on the performance of the resilience index and entropy. Di Nardo et al. (2010) concluded that the two measures provided different information about network hydraulic behaviour. The resilience index was shown to be strongly correlated with system pressure under failure conditions while entropy was revealed to have no significant correlations with any hydraulic performance measure. Their study also highlighted that entropy values were sensitive to minor changes in the structural layout of the simple network test.

Raad et al. (2010) examined the relationship between resilience index, network resilience, entropy, and a combination of resilience index and entropy with hydraulic and mechanical reliability. Their research concluded that although the resilience index correlated more significantly with both forms of reliability than the other indicators, it was less effective in ensuring the good connectivity needed in effective WDS design (Walski 2001). It was concluded that a combination of resilience index and entropy gave the best alternative to the resilience index alone.

Method

Multi-objective design optimisation will be used to generate a wide range of comparable WDS solutions (i.e. with similar costs but varying reliability indicator values) based on a basic case study. WDS solutions associated with different indicator values will be compared through analysis of cost-indicator trade-offs and network components identified that contribute most to increasing the magnitude of the indicators. Relationships between the optimisation objectives will be explored to understand whether and how they are correlated. Finally, the performance of the various indicators will be evaluated in terms of their effectiveness in promoting high mechanical and hydraulic reliability of the WDS solutions.

The indicator combinations will be used for multi-objective optimisation to generate a selection of cost-benefit trade-off solutions:

A) Cost (C_{TOTAL}) vs. Resilience Index (I_r)
B) Cost vs. Entropy (S)

C) Cost vs. Resilience Index vs. Minimum Surplus Head (I_s)
D) Cost vs. Entropy vs. Minimum Surplus Head
E) Cost vs. Resilience Index vs. Entropy

Optimisation analysis for cases A-E will be performed using a WDS hydraulic simulation of the Anytown network (see below) in EPANET2 (Rossman 2000) coupled with the NSGAII genetic algorithm (Deb et al. 2000).

Case Study: Anytown

The widely used benchmark network Anytown is a reasonably complex WDS with requirement for both pumping and storage tanks and is thus well suited to this comparative study (Walski et al. 1987). The underperforming Anytown network requires rehabilitation and expansion in order to meet new nodal demands while satisfying all constraints presented in Table 1. The network re-design requires the selection of existing pipes for cleaning or duplication, along with sizing and siting of new tanks and identification of an appropriate pump schedule for normal-day operation. In this study, this gives an opportunity not merely to design to the minimum level of network operation (lowest cost feasible network) but to allow for additional operational benefit (through optimisation of the surrogate reliability measures against cost) in order to make the WDS more reliable under uncertain conditions (the extent of which is to be determined through in this study). This will allow generation of solutions with differing values of the surrogate reliability measures that can be used for comparison. The Anytown WDS layout is shown in Fig. 1. The network is divided into two costing-zones; the city (bold lines) and suburban (thin lines), where rehabilitative actions taken inside the city-zone are more costly to instigate. The total cost (C_{TOTAL}) for implementing the selected rehabilitation procedures for a given solution are calculated as the sum of pipe costs (C_{PIPE}), new tank costs (C_{TANK}) and the net present value of pump operational costs over a period of 20 years (C_{PUMP}). Where:

$$C_{PIPE} = \sum_{i=1}^{nl} L_m c_p(D_m, Z_m, A_m) \tag{4}$$

$$C_{TANK} = \sum_{n=1}^{nt} c_t(V_t) \tag{5}$$

$$C_{PUMP} = \left(\frac{1-a}{1-a^n}\right) c_e \sum_{i=1}^{np} E_P \tag{6}$$

Where $a = \frac{1}{1+r}$

$$C_{TOTAL} = C_{PIPE} + C_{TANK} + C_{PUMP} \quad (7)$$

nl	*Number of pipes*
L_m	*Length of pipe m (m)*
c_p	*Unit length cost of pipe to perform action ($/m)*
D_m	*Diameter of pipe m (m)*
Z_m	*Pipe zone of pipe m (city or suburbs)*
A_m	*Action for pipe m (clean, duplicate or new)*
V_t	*Total volume of tank t* (m^3)
c_t	*Cost of tank t as a function of volume (see CWS for calculation)*
c_e	*Unit energy cost ($/kWh)*
E_p	*Total energy used by pump p over 24h (kWh)*
n	*Investment period (yrs)*
r	*Rate of return (r=12%)*

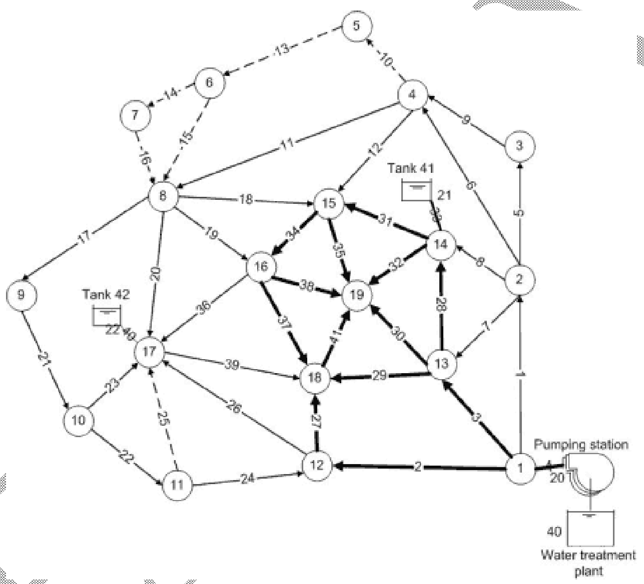


Fig. 1. Anytown Benchmark Network (Farmani et al. 2005)

The location-dependant unit-length costs for cleaning, duplicating and adding new pipes (8 discrete pipe diameters), $c_p(D,Z,A)$, new tank installation costs, $c_t(V)$, and unit energy costs for pumping, c_e, along with further definition of the benchmark, are available from CWS (2004). A set of constraints used within the study (defining a feasible solution) are presented in Table 1, including ensuring existing tanks are used to their full daily operational capacity in addition to satisfying minimum individual nodal pressures for the five operational scenarios (by by changing nodal demand to simulate peak flow and fire-flow conditions). The variables used for optimisation, associated with the selection of new and duplicate pipes, cleaned pipes, tank properties and pump scheduling, are given in Table 2.

Table 1. Design Constraints

Description	Violation Condition
24h normal-day operation	Any node < 276kPa
Instantaneous peak demand (1.8 times average demand)	Any node < 276kPa
0.158m^3/s (2500gpm) fire flow in node 19, DM of 1.3 at all other nodes	Any node < 138kPa
0.095m^3/s (1500gpm) fire flow in nodes 5,6 & 7, DM of 1.3 at all other nodes	Any node < 138kPa
0.063m^3/s (1000gpm) fire flow in nodes 11 & 17, DM of 1.3 at all other nodes	Any node < 138kPa
Existing tanks use their full operational volume	< 100%
Tank start level same as tank end level over 24h	> 0m

Table 2. Design Variables

Description	Range	Number of variables
Tank maximum level relative to attached node	61.0-76.2m	2
Tank simulation start level	0-100%	4
Size of emergency storage (height below minimum operating tank level)	0-7.6m	2
Diameter for new cylindrical tanks	1.5-30.5m	2
Level difference for normal day operation tank storage	0-15.2m	2
Locations of new tanks	0-32	2
Do nothing, clean an existing pipe or duplicate it	0-15	35
Assign discrete diameter to new pipe	0-15	8
Pump schedule for each time period of a 24h simulation	0-4	8

Results

General Performance

In order to understand which network components may influence or be influenced by the reliability indicators, results from cases A-E were used to identify correlations (through regression analysis) between the reliability indicators and the following:

- Total network costs and cost breakdown (pipes, tanks and operation)
- Minimum surplus head
- Alternative indicator comparison (Resilience Index vs. Entropy)

Network Costs

Examination of the two-objective (total rehabilitation cost (Eq.7) vs. indicator) trade off curves produced for cases A and B showed that the maximum resilience index for the Anytown benchmark can be achieved at much lower total cost (C_{TOTAL}) than that of the maximum entropy. Cost was examined in more detail by breaking it down into components

(Eq. 4-6). The analysis showed that overall costs (C_{TOTAL}) for both sets of reliability indicators were strongly correlated (R^2=0.998 in both cases) to network pipe cost (C_{PIPE}). However, for case A, an initial improvement of the resilience index appeared to be achievable by altering pump scheduling and tank properties whilst maintaining consistent piping expenditure (Fig. 2a). In contrast, case B (entropy) was mostly dependant on pipe costs, which followed a linear path. For operational pumping cost (C_{PUMP}), a moderate negative correlation (R^2=0.51) was noted against overall cost in case B suggesting that higher cost entropy solutions have reduced operational cost. On inspection of Fig. 2b, the pumping operational cost data for solutions was divided into several "clusters," for which the optimised tank locations were deemed as a possible cause (each cluster could be attributed to separate new tank locations).

The overall cost of resilience index solutions (C_{TOTAL}) presented limited correlation (R^2=0.171) with respect to tank cost (C_{TANK}) (Fig. 2c). This is most likely because tank cost is directly related to volume rather than height, operation or location, which necessitate additional pumping capacity and thus are instead most likely reflected in operational cost (C_{PUMP}). In contrast, the entropy index presented a reasonable correlation against tank cost (R^2=0.7), although arguably this could be attributed to the weighting influence of the previously identified location-dependant clusters.

Minimum Surplus Head

The influence of minimum surplus head was also investigated. The results from case A (Fig. 3a) show a positive correlation between the resilience index and minimum surplus head (R^2=0.94). However, case C (Fig. 3a) shows that the level of minimum surplus head can be further increased for most resilience index values if considered together. For entropy, a weak negative correlation (R^2=0.39) was noted against minimum surplus head (Fig. 3b). In a similar manner to the resilience index, there is potential to increase the minimum surplus head for different entropy values if optimised together (Case D). This suggests for both cases that the inclusion of minimum surplus head as a third objective should allow identification of more valuable network solutions at equivalent cost. This conclusion, at least for the case of resilience index, is supported by Farmani et al. (2005).

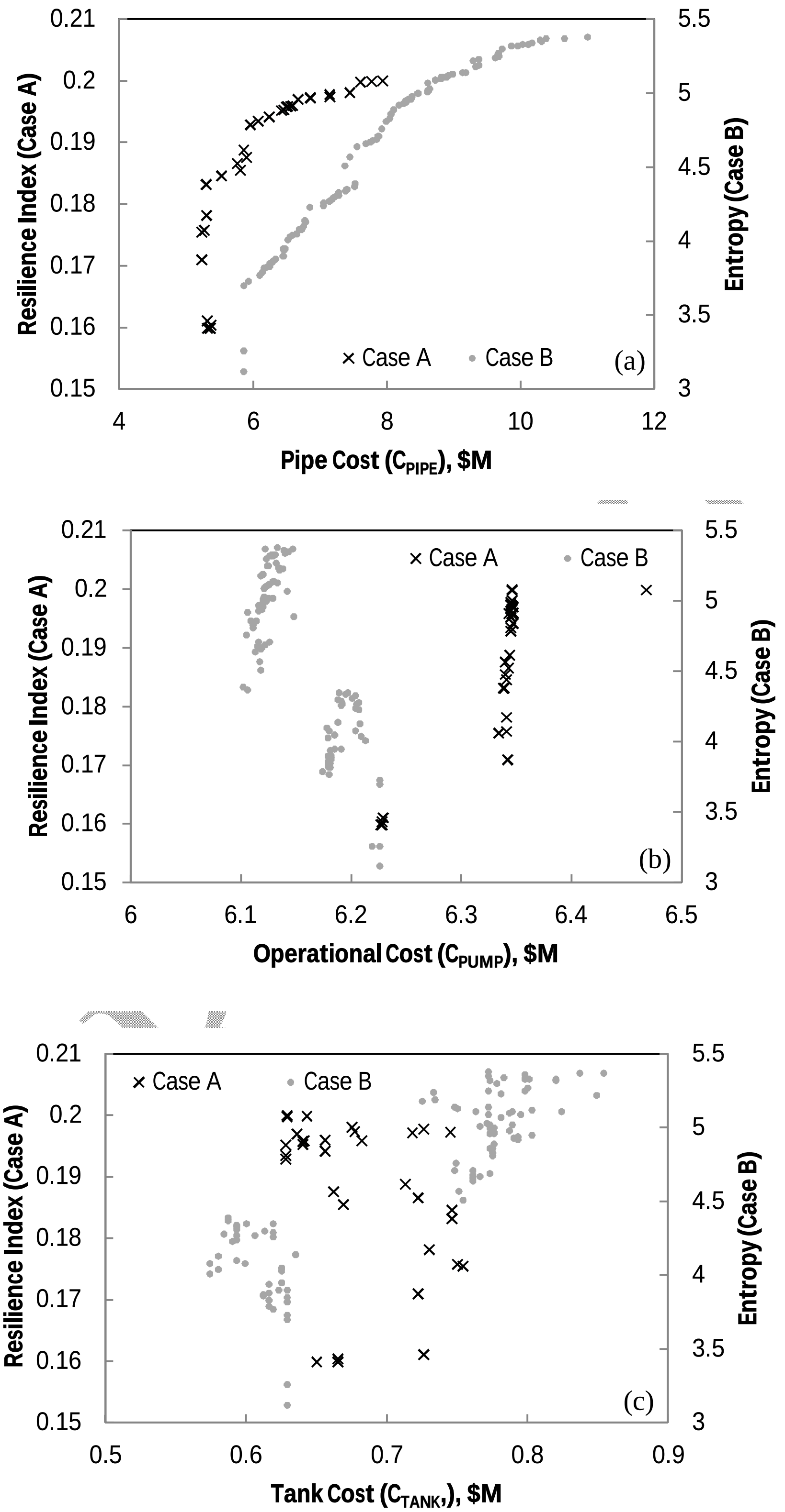
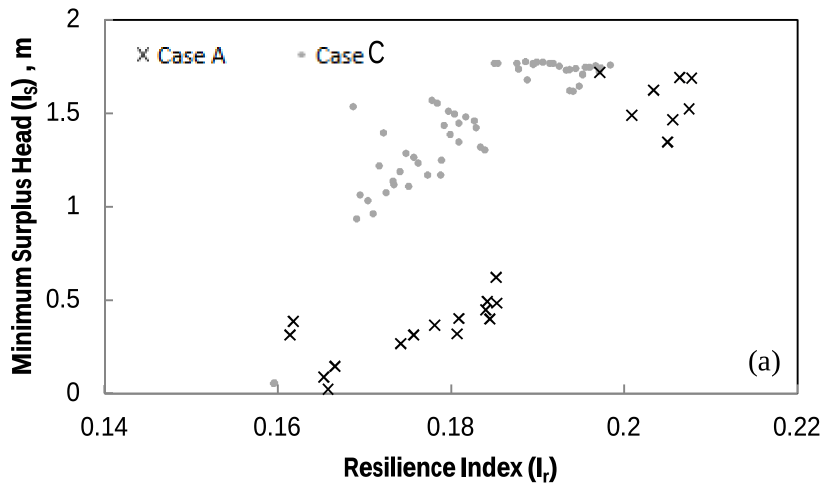


Fig. 2. Cost breakdown for solutions; Cases A & B (a) Total pipe costs (for new, clean and duplicated pipes) (b) Pumping energy costs (NPV over 20 years) (c) New tank installation costs



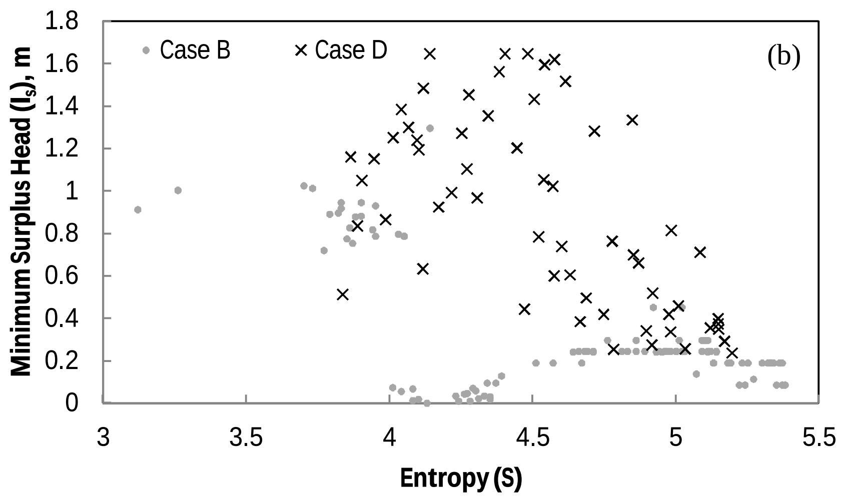


Fig. 3. Cost vs. Minimum Surplus Head Relationship (A-D) (a) Minimum surplus head for resilience index solutions (b) Minimum surplus head for entropy solutions

Alternative Indicator Comparison: Resilience Index vs. Entropy

In a similar manner to the minimum surplus head test, the relationship between the resilience index and entropy of optimised solutions was also investigated. Fig. 4 indicates no correlation for case A (R^2=0.067) and a weak positive correlation (R2=0.356) for case B; yet data for case B was clustered (clusters again related to separate tank locations). This implies that optimising for either indicator individually will not necessarily achieve a high value of the other indicator and simultaneous consideration (as in case E) may be necessary to improve both.

Examination of the trade off between entropy and resilience index for the Anytown network provides a clearer picture as to the interactions between the two indicators. Case E (where both resilience index and entropy are optimised) in Fig. 4 clearly shows a maximum resilience index after a certain level of entropy (S=3.74) is achieved. This suggests that there is a considerable trade off between the two if higher entropy is desired. A similar shape can also be noted in Fig. 3b (case D) for entropy and minimum surplus head.

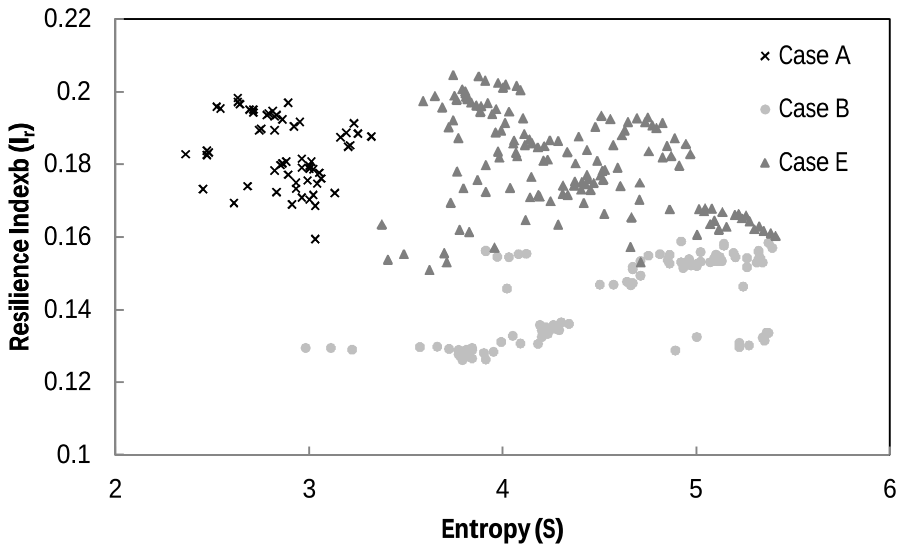


Fig. 4. Entropy vs. Resilience Index Relationship Analysis (cases A, B & E)

Network Layout and Operation

This section focuses on identifying the extent to which the indicators improve the hydraulic operation and reliability of the WDSs. This exercise is clearly important as the identified trade-off between the resilience index and entropy means that it is unlikely that both can be maximised simultaneously and therefore the reliability benefits from each will most likely require trade-off.

Selected optimised solutions for cases A-E were considered for network level analysis to identify which reliability indicator combinations were correlated to more desirable network layout and operational features in terms of new pipe distribution (related to connectivity) and hydraulic operation (in terms of pump scheduling and tank operation). Individual solutions were selected systematically from the case A-E pareto-sets with the intention of providing a range of indicator levels, while maintaining a similar cost for comparison between cases (Table 3). This table provides a breakdown of information for each of the solutions considered in this section.

On examination of the network layouts, it was noted that networks with mid-value resilience indices (in cases A and C) appear to have duplicated pipes resembling a branched network (Fig. 5a). This most likely ensures additional flow reaches each node with minimum expenditure. In contrast the high resilience index solutions appear to exhibit additional looped zones reinforcing supply to nodes furthest from the source (Fig. 5a).

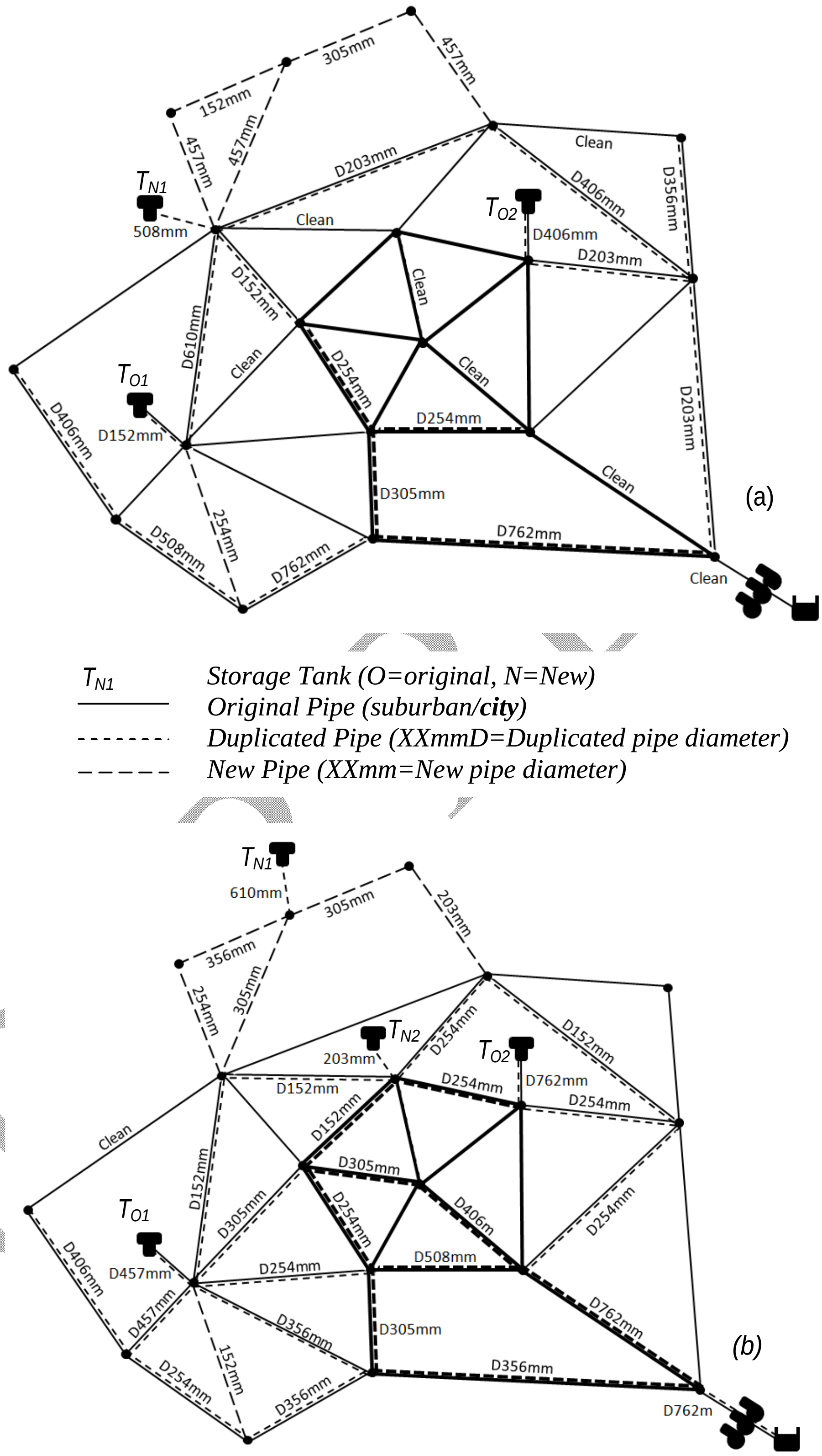


Fig. 5. Network example layouts for selected solutions (Both approx C_{TOTAL}= \$14.5M) (a) Resilience index solution (C3), (b) Entropy solution (D2).

Examining the networks for cases B and D it is evident that increasing entropy solutions exhibit an even distribution of duplicated pipes and thus a consistently increasing overall system capacity (relative to solution cost) (Fig. 5b). This seems to have a generally negative effect on the maximum water age for the networks (probably due to decreasing network velocity and an increased number of available paths to each node), which is further magnified with an increased minimum surplus head (case D).

The locations of new tanks are fairly consistent among the mid to high resilience index-based solutions, both in case A, and even more so in case C. In contrast, new tank locations in entropy solutions are more variable. Furthermore, the entropy indicator is not formulated to directly consider tank operation, and indeed this has been apparent through notably poor tank sizing in entropy solutions; in many cases increasing average storage time. Consequently, it is plausible that the new tanks within (optimised) high entropy networks also add to the problem of water aging (Table 3).

Examining system operation, it was noted that higher resilience index solutions generally have higher new tank elevations (Fig. 6a) than the majority of those within high entropy solutions (Fig. 6b). High entropy network tanks are also empty for extended periods of time which could be problematic for both water aging and uncertain changes in demand as there is consequently limited additional volume available.

Table 3. Cases A-E: Parameters for selected solutions (Objective in **gray**)

				Max Age	Solution cost breakdown ($M)			
Case ID	I_s(m)	I_r	S	(hours)	Pipes	Tanks	Operation	Total
A1	1.13	**0.18**	2.9	39.1	4.81	0.6	6.00	**11.15**
A2	1.26	**0.19**	2.91	41.8	6.11	0.59	6.05	**12.75**
A3	1.37	**0.21**	2.91	42.7	7.62	0.59	6.27	**14.47**
B1	1.01	0.13	**3.26**	39	5.86	0.63	6.23	**12.71**
B2	0.95	0.13	**3.83**	39	6.22	0.62	6.18	**13.01**
B3	0.25	0.15	**4.66**	49	7.68	0.76	6.12	**14.56**
B4	0.19	0.15	**5.30**	48	9.72	0.78	6.12	**16.62**
C1	**1.06**	**0.17**	2.61	40	4.74	0.68	6.18	**11.62**
C2	**1.46**	**0.18**	2.47	37	5.96	0.69	6.17	**12.82**
C3	**1.75**	**0.20**	2.52	44	7.69	0.68	6.16	**14.52**
D1	**1.16**	0.14	**3.86**	51	6.36	0.66	6.14	**13.14**
D2	**1.36**	0.15	**4.34**	66	7.72	0.74	6.20	**14.67**
D3	**1.02**	0.16	**4.57**	53	8.53	0.71	6.11	**15.36**
D4	**0.71**	0.16	**5.08**	84	13.0	0.77	6.25	**20.06**
E1	1.11	**0.17**	**3.79**	42	6.81	0.63	6.13	**13.57**
E2	1.04	**0.16**	**9.96**	47	7.96	0.59	6.34	**14.88**
E3	0.58	**0.18**	**4.53**	42	8.69	0.98	6.21	**15.88**
E4	0.66	**0.17**	**5.01**	61	11.5	0.98	6.04	**19.01**

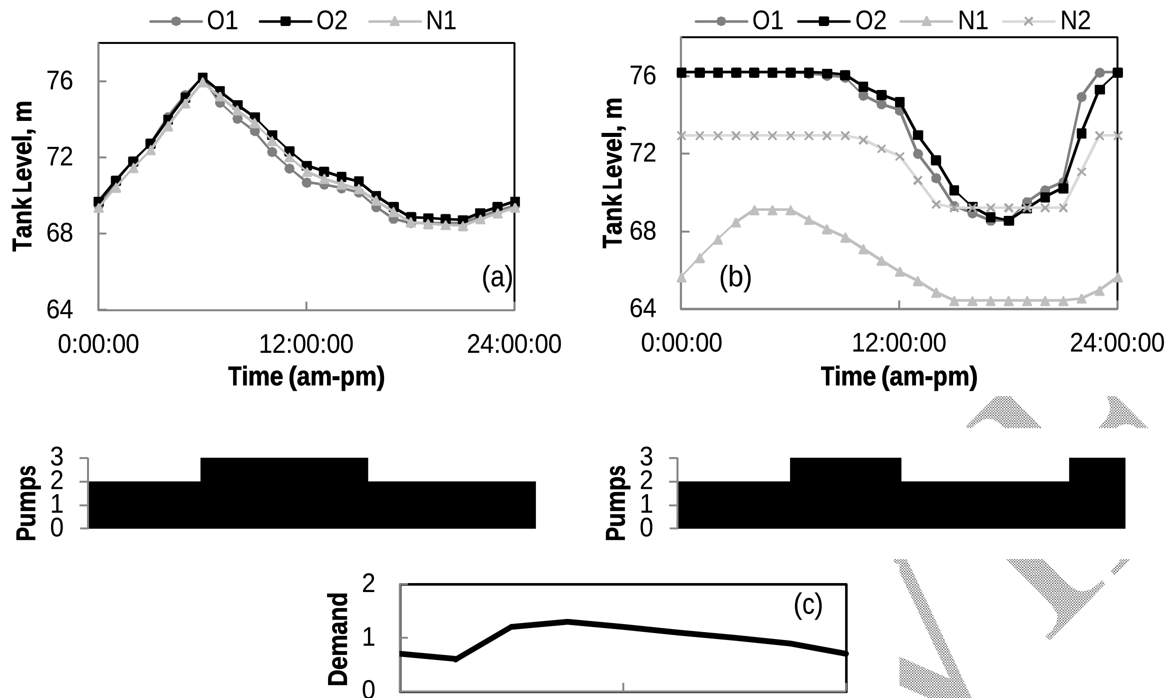


Fig. 6. Tank Levels & Pump Scheduling for Solutions (a) C3 and (b) D2 (with (c) the average 24h demand profile). Refer to Fig. 5 for tank labelling

Mechanical Reliability

The correlation between the reliability indicators and mechanical reliability was next considered. A similar approach to that developed by Farmani et al. (2005) was used to examine the effects of individual pipe failure against the available level of supply. Pipes were closed individually and the fixed network was hydraulically simulated for a 24h average-day operational demand profile (see Fig. 6c). The first hourly time period at which hydraulic failure (pressure deficiency) occurred was noted and the next pipe in the series assessed. If the failure time was in excess of 24h, the pipe was ignored within the simulation, as major pipe failures are expected to be repaired within a day. Table 4 shows the results from the mechanical reliability assessment (cumulative pipes that cause failure over 24hrs) for the selected solutions investigated in section 4.2.

Examination of the results in Table 4 indicates that the resilience index in case A solutions showed limited correlation to total pipes causing pressure failure over 24h. In contrast, case B solutions demonstrated a gradual improvement with increasing entropy. This could be explained by the notion that resilience index (case A) considers the average performance of the network and localised issues (at individual nodes/zones) may not be captured. For increasing entropy, an improvement is unsurprising, as the indicator promotes extra capacity within networks.

A notable improvement in correlation between the indicators and pipes that caused failure over 24h was observed through failure testing of the selected networks both for case C and D. Of these, a considerable improvement was noted in case D, which at the maximum level of entropy resulted in no failures over the 24 hour testing period for any single pipe out of action. Although for this case, the cost of designing to the maximum level of entropy (which exhibited the best mechanical reliability) was almost double that of the minimum cost feasible network solution.

Case E demonstrated a reasonable compromise for the two sets of indicators, with mechanical reliability not necessarily as high as observed in case D, but an improvement on high resilience index only networks. Although the utilisation of a combination of indicators (as in case E) was also deemed a reasonable compromise by Raad et al. (2010), the results for this section indicated some differences to this previous work, as it was identified that the resilience index exhibited improved mechanical reliability as compared with entropy. This suggests that either the consideration of minimum surplus head or additional WDS components (as in this study) may alter the correlation with mechanical reliability for both surrogate reliability measures.

Table 4. Cases A-E: Results for mechanical reliability assessment: cumulative pipes that cause pressure failure

	Failure Test Results (hours to failure)									
Case ID	15	16	17	18	19	20	21	22	23	24
A1	4	6	6	6	6	6	6	6	6	6
A2	5	6	6	6	6	6	6	6	6	6
A3	3	6	6	6	6	6	6	6	6	6
B1	3	4	5	5	5	5	5	5	5	5
B2	3	4	4	4	4	4	4	4	4	4
B3	2	2	2	3	3	3	3	3	3	3
B4	0	0	0	1	1	1	1	1	1	1
C1	3	3	3	4	4	4	4	4	4	4
C2	3	4	4	4	4	4	4	4	4	4
C3	2	3	3	3	3	3	3	3	3	3
D1	2	2	2	2	2	2	2	2	2	2
D2	1	1	1	1	1	1	1	1	1	1
D3	1	1	1	1	1	1	1	1	1	1
D4	0	0	0	0	0	0	0	0	0	0
E1	1	1	1	1	2	2	2	2	2	2
E2	0	0	1	1	1	1	1	1	1	1
E3	0	1	1	1	1	1	1	1	1	1
E4	0	1	1	1	1	1	1	1	1	1

Hydraulic Reliability

Hydraulic reliability was evaluated by calculating the maximum average daily demand that a given WDS solution is able to tolerate whilst maintaining feasible operation. This method is used to represent a network in the future, when pump scheduling is a low cost option to alter the hydraulic operation without costly or invasive rehabilitation procedures. For this assessment, the pumping is optimised for each systematic change in demand to find if the network is able to operate feasibly (with respect to minimum pressure and tank operation) under these new demand conditions (further detail of this procedure is presented in Atkinson et al.(2011).

Results from the analysis showed that both the resilience index and entropy alone (cases A and B) presented limited correlation with hydraulic reliability. This could be attributed to limited surplus head at underperforming nodes (which are not directly considered within either indicator). With the additional improvement of minimum surplus head (in cases C and D) a major improvement in correlation with the hydraulic reliability was noted. Case C solutions revealed a positive relationship against hydraulic reliability; with the improvement most likely due to the combination of new tank elevations (higher than entropy solutions) and additional minimum surplus head. In contrast, the high tank elevations previously attributed to more expensive case C solutions also appeared constraining for higher future demands (the networks were unable to provide enough head to fill new tanks due to increased head-loss when attempting to meet higher demands). This resulted in a capping effect in high resilience index networks, where the maximum achievable demand is restricted (in the case of Anytown it was found to be capped at around a 20% demand increase), and thus additional capital expenditure was required in order to facilitate further demand increase. Case D solutions revealed a positive correlation between network cost and hydraulic reliability although it was more expensive to achieve similar hydraulic reliability levels in comparison to that observed with case C. Nevertheless, a proportion of higher costing case D solutions outperformed any other case solutions investigated under this category with a tolerance of up to a 25% increase in demand, most likely due to the reduced system head-loss, and therefore more effective pump operation (Atkinson et al. 2011). It is therefore difficult to distinguish whether case C or D could be deemed more beneficial for improving hydraulic reliability, with the resilience index showing a sharp but capped improvement in hydraulic reliability (against cost) compared to a steady but less constrained improvement as observed within entropy solutions.

Conclusion

A comparison was conducted between two popular WDS reliability indicators. Comparable WDS solutions, with respect to cost, were generated through optimisation of the Anytown case study for each indicator (both individually and combined). The resultant solutions were compared with respect to their ability to tolerate pipe failure (mechanical reliability) and change in demand (hydraulic reliability), along with examination of the technical quality of hydraulic operation.

It was found that networks with increased minimum surplus head alongside the reliability indicators had generally improved all round performance in all tests performed. Solutions with high entropy had notably improved mechanical reliability, while the resilience index solutions were influenced to a lesser extent. Both indicators showed an improvement in hydraulic reliability for higher magnitude solutions, although there was identification of a trade-off between the relatively cheaper resilience index networks (limited to a maximum redundant capacity) and the more expensive (but less limited capacity) high entropy networks. In terms of hydraulic operation, the majority of the resilience index solutions showed more desirable performance in terms of storage tank operation and the average system water age (which was in many cases unacceptable in high entropy solutions).

For the case that the resilience index and entropy were optimised together, the performance of resultant WDS networks over all testing categories was reasonable but could not easily be accounted to either indicator individually. For this reason, and the significant observation that there was considerable trade-off between the resilience index and entropy for higher cost solutions, it is suggested that a new indicator is required that is able to measure/influence both the connectivity and demand capacity of a WDS whilst also accounting for the quality of hydraulic operation and water ageing.

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References

Atkinson, S., Farmani, R., Memon, F. A., and Butler, D. (2011). "Comparing reliability indicators for water distribution networks with a future perspective." Computing and Control for the Water Industry 2011, Exeter, UK.

Awumah, K., Goulter, I., and Bhatt, S. (1990). "Assessment of reliability in water distribution networks using entropy based measures." Stochastic Hydrology and Hydraulics, 4(4), 309-320.

Baños, R., Reca, J., Martínez, J., Gil, C., and Márquez, A. (2011). "Resilience Indexes for Water Distribution Network Design: A Performance Analysis Under Demand Uncertainty." Water Resources Management, 25(10), 2351-2366.

Centre for Water Systems (2004). Benchmark networks for design and optimisation of water distribution networks, <http://www.exeter.ac.uk/cws/benchmarks>. (Mar. 01, 2011).

Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. (2000). "A fast and elitist multiobjective genetic algorithm: NSGA-II." Technical Report 200001, Indian Institute of Technology, Kanpur: Kanpur Genetic Algorithms Laboratory (KanGAL).

di Nardo, A., Greco, R., Santonastaso, G. F., and di Natale, M. (2010). "Resilience and entropy indices for water supply network sectorization in district meter areas." 9th International Conference on Hydroinformatics. HIC 2010, Tianjin, China.

Farmani, R., Walters, G. A., and Savic, D. A. (2005). "Trade-off between Total Cost and Reliability for Anytown Water Distribution Network." Journal of Water Resources Planning and Management, 131(3), 161-171.

Jayaram, N., and Srinivasan, K. (2008). "Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing." Water Resour. Res., 44(1), W01417.

Lansey, K. E. (2006). "The evolution of optimizing water distribution system applications." 8th Annual Water Distribution Systems Analysis Symposium, Cincinnati, Ohio, USA.

Maier, H. R., Lence, B. J., Tolson, B. A., and Foschi, R. O. (2001). "First-order reliability method for estimating reliability, vulnerability, and resilience." Water Resour. Res., 37(3), 779-790.

Ostfeld, A. (2004). "Reliability analysis of water distribution systems." Journal of Hydroinformatics, 6(4), 281-294.

Prasad, T. D., and Park, N.-S. (2004). "Multiobjective Genetic Algorithms for Design of Water Distribution Networks." Journal of Water Resources Planning and Management, 130(1), 73-82.

Raad, D. N., Sinske, A. N., and van Vuuren, J. H. (2010). "Comparison of four reliability surrogate measures for water distribution systems design." Water Resour. Res., 46(5), W05524.

Reca, J. (2008). "Optimal Design of Gravity-Fed Looped Water Distribution Networks Considering the Resilience Index." Journal of Water Resources Planning and Management, 134(3), 234.

Rossman, L. A. (2000). "EPANET Users Manual." U. S. E. P. Agency, ed., Cincinnati, Ohio.

Saldarriaga, J. G., and Serna, M. A. "Resilience Analysis as Part of Optimal Cost Design of Water Distribution Networks." ASCE, 496-496.

Setiadi, Y., Tanyimboh, T. T., and Templeman, A. B. (2005). "Modelling errors, entropy and the hydraulic reliability of water distribution systems." Advances in Engineering Software, 36(11-12), 780-788.

Tanyimboh, T. T., and Templeman, A. B. (1993). "Calculating Maximum Entropy Flows in Networks." The Journal of the Operational Research Society, 44(4), 383-396.

Todini, E. (2000). "Looped water distribution networks design using a resilience index based heuristic approach." Urban Water, 2(2), 115-122.

Wagner, J. M., Shamir, U., and Marks, D. H. (1988). "Water distribution reliability: simulation methods." Journal of Water Resources Planning and Management, 114(3), 276-294.

Walski, T. M. (2001). "The wrong paradigm - why water distribution optimization doesn't work." Journal of Water Resources Planning and Management, 127(4), 203-205.

Walski, T. M., Brill, J. E. D., Gessler, J., Goulter, I. C., Jeppson, R. M., Lansey, K., Lee, H.-L., Liebman, J. C., Mays, L., Morgan, D. R., and Ormsbee, L. (1987). "Battle of the Network Models: Epilogue." Journal of Water Resources Planning and Management, 113(2), 191-203.

Yassin-Kassab, A., Templeman, A. B., and Tanyimboh, T. T. (1999). "Calculating Maximum Entropy Flows in Multi-Source, Multi-Demand Networks." Engineering Optimization, 31(6), 695 - 729.