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Water distribution network reliability: are surrogate measures reliable?

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Abstract. Water distribution networks are known to be costly infrastructures. A few decades ago the research efforts concerning water distribution network design were focused on economic aspects and the goal was to obtain least cost solutions. Beyond economic, these infrastructures must be reliable since they provide an essential service to society. Reliability assessment is a complex task and involves various aspects: mechanical, hydraulic, water quality, water safety, among others. This paper focus is on the hydraulic reliability.

As hydraulic reliability is computationally hard to measure directly, researchers came up with surrogate measures, like the resilience index or the flow entropy. But these surrogate measures had some flaws and researchers quickly started suggesting new ones trying to avoid those known flaws, like the modified resilience index or the diameter-sensitive flow entropy. But are these surrogate measures reliable to be used in the design of water distribution networks?

This paper presents a thorough analysis of these reliability surrogate measures, supported by illustrative examples, highlighting their pros and cons to help in deciding which one to use for design purposes. A new reliability index is proposed and used to design an example network, its advantages are highlighted, and the above question answered.

Keywords: Entropy, Modelling, Pressure-driven analysis, Reliability, Resilience index, Water distribution network design

1 Introduction

Water distribution systems provide an essential service to society. This kind of infrastructures involves huge investments, so it is necessary to optimize their costs in the design phase, trying to identify solutions that provide good service levels at the lowest cost. However, these two criteria (cost minimization and increased reliability) are opposed, that is, more reliability implies higher cost and minimum cost solution correspond to low reliability. Given this scenario, designers should seek solutions with reasonable compromises between both criteria.

The least cost design of a water distribution network (WDN) is a long-time study problem for scientific community. Several approaches have been proposed based on different methodologies, from traditional optimization methods to modern heuristics, such as simulated annealing [1]. However, since cost minimization tends to eliminate redundancies, this type of approach generally leads to solutions of reduced reliability.

The WDN reliability refers to the ability to satisfy the required consumptions with enough pressure, and the ideal would be achieving reasonable service levels even when facing critical scenarios. However, reaching this would imply unbearable funds. So, the question arises: to what extent will it be feasible to increase investment to reduce risk?

On the other hand, the WDN reliability is something that is not easy to assess. One way would be to simulate all potential critical scenarios and, based on the results, compute the level of reliability. However, such kind of procedure is computationally unacceptable, and this gave rise to the use of surrogate measures of reliability. These indirect measures have some weaknesses, but their simplicity and computation speed make them quite attractive. However, are they reliable to be used in the design of water distribution networks?

In the next section, after a brief review of common surrogate measures, a new one is introduced. In the methodology section, these surrogate measures (reliability indexes) are used to build an optimization model that is solved with a simulated annealing algorithm to identify the most reliable solution subject to a maximum budget. The methodology is implemented on WaterNetGen [2] ─ an EPANET extension. The results section presents a comparison of the reliability indexes performances, and some pros and cons are highlighted. The conclusion section draws some conclusions.

2 Reliability indexes – a brief review

In the context of WDN design, reliability has traditionally been achieved through the application of some empirical rules, namely: including redundant pipes to form meshes, assign pipe diameters greater than the minimum required diameter and maintain some equilibrium on the diameters within each loop. In the context of optimal design, several approaches have emerged, resulting in a set of methodologies whose objective is to obtain solutions that represent good trade-offs between economy and reliability.

The entropy index [3] can be computed by expression:

$$\frac{E}{K} = -\sum_{ij\in\{TF\}} \frac{Q_{ij}}{QT_0} \times ln\left(\frac{Q_{ij}}{QT_0}\right) + \sum_{n=1}^{N} \frac{QS_n}{QT_0} \times ln\left(\frac{QS_n}{QT_0}\right) \qquad (1)$$

where E is the entropy, K is a positive constant, N is the number of network junctions, QT_0 is the network total consumption, QS_n is the outflow of node n (including consumption), TF is the quantity of network flows, and Qij is the flow in pipe between nodes i and j, if $i \neq j$, Q_{ij} is the external flow into node j, if $i = 0$ and $j \neq 0$, else Q_{ij} is the external flow that outflows from node j.

A new formula has been proposed for calculating diameter-sensitive entropy [4]:

$$\frac{E}{K} = -\sum_{j\in NR} \frac{Q_j}{QT_0} \times ln\left(\frac{Q_j}{QT_0}\right) - \frac{1}{QT_0} \sum_{i=1}^{N} QT_i \left[\frac{Q_i}{QT_i} \times ln\left(\frac{Q_i}{QT_i}\right) + \sum_{i\in ND_i} \frac{C}{V_{ij}} \times \frac{q_{ij}}{QT_i} \times ln\left(\frac{q_{ij}}{QT_i}\right)\right] \qquad (2)$$

where Q_j is the outflow of tank j, NR is the number of tanks, QT_i is the inflow to node i, Q_i is the consumption at node i, ND_i is the number of pipes out from node i, C is an arbitrary velocity constant (for example, 1 m/s), V_{ij} is the flow velocity in pipe i,j, and q_{ij} is the flow in pipe i,j.

The resilience index [5] can be computed by the expression:

$$I_r = \sum_{i=1}^{N} Q_i \times \left(H_i - H_i^*\right) / \left(\sum_{j=1}^{NR} Q_j \times H_j + \sum_{k=1}^{NP} Q_K \times H_K - \sum_{i=1}^{N} Q_i \times H_i^*\right) \qquad (3)$$

where H_i is the head at node i, H^*_i is head at minimum delivery pressure at node i, NR is the number of tanks, H_j is the head at tank j, NP is the number of pumps, Q_k is flow flow at pump k, H_k is the power introduced into the network by pump k.
The network resilience index [6] can be computed by the expression:

$$I_n = \sum_{i=1}^{N} C_i \times Q_i \times \left(H_i - H_i^*\right) / \left(\sum_{j=1}^{NR} Q_j \times H_j + \sum_{k=1}^{NB} Q_K \times H_K - \sum_{i=1}^{N} Q_i \times H_i^*\right), C_i = \sum_{j=1}^{NC_i} D_j \,/\, \left(NC_i \times máx\left\{D_j\right\}\right) \tag{4}$$

where C_j is the diameter uniformity coefficient for node j, and D_j is the diameter of pipe j.
Expression (1) can be easily inserted in optimization models but does not consider the pipe diameters which may lead to solutions with balanced flow rates but large discrepancy of confluent diameters in the same node. The correction introduced in (2) only affects nodal outflow rates, which does not seem to make much sense, since the objective is to ensure the nodal supply, and this only improves with a uniformization of diameters in to the node not those out from the node.
Expression (3) does not consider the network topology or the pipe capacity and this weakens it as a measure to indirectly assess network reliability. The uniformity diameter expression (4) does not seem to be the ideal way to proceed with the desired correction, since the reliability of a WDN is related to the diameters uniformity within each loop and not to the uniformity of diameters of the pipes connected to a node (mainly those out from the node).
So a new index is designed, here called WNG Index, that takes into account the importance (I_i) of each node i and a coefficient (w_i) that represents the available flow to deal with a pipe failure at node i (a detailed description will be presented in the full paper). *NPipes*, *NValves*, *NPumps* and *NJunctions* are the number of pipes, valves, pumps and junctions, respectively:

$$WNG_{index} = \sum_{i=1}^{NJunctions} I_i \cdot w_i \,/\, \left(NPipes + NValves + NPumps\right) \tag{5}$$

3 Methodology

WaterNetGen was adapted to work with reliability indexes in two ways: 1) evaluation of reliability indexes; 2) optimized design considering the maximization of any reliability index subject to a maximum budget. In the first case, it is enough to simulate the network model to obtain the required hydraulic quantities and then request the calculation of the reliability indexes. For designing, it is necessary to choose the reliability index for the objective function and the maximum allowable cost limit (budget).
The simulation has been executed by the WaterNetGen's pressure-driven simulation module, so the ratio of the required consumptions that is effectively satisfied can be computed. To evaluate the global reliability of the WDN, all possibilities of only one closed pipe are simulated (as many simulations as the number of pipes). In each simulation, the consumption satisfaction ratio is computed and the overall reliability of the WDN is given by the average of these ratios.

4 Results

The WDN used in the case study has 1 tank, 16 junctions, 24 pipes, an instantaneous peak flow of 93.750 L/s and a minimum pressure of 30,592 m. The first step is finding the least cost solution (1,614,670€). The next step is to maximize a reliability index, subject to a certain budget (10% over the least cost = 1,776,137€). Table 1 shows the reliability indexes for each solution obtained, showing that maximize one index does not necessarily imply the improvement of the others, and the global reliability computed considering the one pipe fault scenario.

The analysis of the global reliability values calculated for the solutions obtained seems to lead to the conclusion that the maximization of some indexes (diameter-sensitive entropy, resilience index and network resilience) has only a residual contribution to the reliability of the network (or even none contribution at all). Apparently, the reliability indexes whose maximization contributed to overall reliability were entropy and WNG Index. These indexes deserve a detailed study with more examples.

Table 1 Comparison of reliability indexes.

		Global Network Realibility Indexes					**Cost**	**Global Reliability**
		Entropy	**D.S. Entropy**	**Resilience**	**Net Resilience**	**WDN Index**		
Least Cost		2.9974	5.8142	0.3171	0.2234	0.8786	1 614 670 €	0.909
Maximize	**Entropy**	**3.3951**	6.4595	0.3626	0.2943	0.8986	1 772 530 €	**0.947**
	D.S. Entropy	2.9495	**9.8814**	0.3511	0.2443	0.8767	1 770 780 €	0.909
	Resilience	2.9546	6.5980	**0.6150**	0.4300	0.8758	1 774 610 €	0.909
	Net Resilience	2.9882	6.4953	0.5978	**0.4337**	0.8760	1 773 520 €	0.914
	WNG Index	3.2391	6.8508	0.2527	0.1994	**0.9035**	1 774 550 €	**0.939**

5 Conclusions

WDN reliability assessment is an important subject in the design of these infrastructures. However, since its full assessment is too complex, it is common to use indirect measures (reliability indexes) to do it expeditiously. However, as these indexes are empirical and do not always consider some aspects that effectively condition the reliability of WDN, some caution must be taken in its use. In this work, five reliability indexes (entropy, diameter-sensitive entropy, resilience index, network resilience, and a new one) were evaluated for a case study (hypothetical network) and it is concluded that apparently not all point in the same direction, that is, the maximization of one index does not necessarily imply the improvement of the others. For example, the analysis of global reliability values (average consumption satisfaction ratio when one pipe is out of service) for the solutions obtained seems to lead to the conclusion that the maximization of some indexes (diameter-sensitive entropy, resilience index and network resilience) has only a residual contribution to the global reliability of the network (or even no contribution at all). Apparently, the maximization of network entropy or the new index (WNG index) improves the overall network reliability. But it is obvious that this conclusion can't be drawn from a single example, so a larger sample of WDN will be tested and then the full paper will present more informed conclusions.

Reference

[1] M.C. Cunha, J. Sousa, Water distribution network design optimization: Simulated Annealing approach. Journal of water Resources Planning and Management, ASCE, 125(4) (1999) 215-221.

[2] J. Muranho, A. Ferreira, J. Sousa, A. Gomes, A. Sá Marques, WaterNetGen – an EPANET extension for automatic water distribution network models generation and pipe sizing, Water Science & Technology: Water Supply, IWA Publishing, 12(1) (2012) 117-123.

[3] G.A. Walters, Discussion of “Maximum entropy flows in single source networks” from T.T. Tanyimboh and A.B. Templeman, Engineering Optimization, 25 (1995) 155-163.

[4] H. Liu, D. Savic, Z. Kapelan, M. Zhao, Y. Yuan, H. Zhao, A diameter-sensitive flow entropy method for reliability consideration in water distribution system design, Water Resources Research, 50 (2014) 5597–5610.

[5] E. Todini, Looped water distribution networks design using a resilience index based heuristic approach, Urban Water Journal, 2 (3) (2000) 115–122.

[6] T.D. Prasad, H. Sung-Hoon, P. Namsik, Reliability based design of water distribution networks using multiobjective genetic algorithms, KSCE Journal of Civil Engineering, 7(3), (2003) 351-361.