Comparing performance indicators for assessing and building resilient water distribution systems

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Abstract

Water distribution systems (WDSs) are critical infrastructures that need to be resilient to cope with and quickly recover from exceptional conditions in an uncertain and challenging future. To build resilience in the design of WDSs, it is essential to explore indicators that can effectively quantify the level of system resilience. On the basis of the optimization of rehabilitation designs of three benchmark WDSs, four resilience related indicators are investigated, i.e. Todini’s index, which is a surrogate and indirect performance indicator, and three direct performance indicators - failure duration, failure magnitude and a severity-based resilience index. These indicators are widely used in literature yet have not been comprehensively examined and compared. Results show that strong correlations exist between the four resilience-related indicators, indicating that optimization using any one indicator is likely to improve system resilience measured by other indicators. Nevertheless, they have distinctive advantages and disadvantages. In particular, the severity-based resilience index is effective in identifying nodes susceptible to the occurrence of failures and slow in recovery. Todini’s index can be assessed without the need of setting up failure scenarios, which is an advantage compared to the other three resilience indicators; however, its correlations with direct resilience indicators are weaker in WDSs with tanks.

Keywords

Many-objective optimization, rehabilitation, resilience, Todini’s index, water distribution system

Introduction

Water distribution systems (WDSs) are critical infrastructures of our society for the safe and secure provision of drinking water (USEPA 2005). These are complex systems consisting of a large number of diverse and interconnected components such as pumps, pipes, valves and storage facilities and they span over long distances (National Research Council 2006). As such, WDSs are susceptible to a wide range of acute or chronic threats and failures are reported to be reoccurring (Gheisi et al. 2016). The magnitude and frequency of failures in WDSs are likely to increase under the pressure of rapid urbanization and climate change (Zimmerman et al. 2008; Basupi 2013).

To address the challenges posed to WDSs, there is a paradigm shift in water management where system capacity to rapidly recover from failures is increasingly being valued (USEPA 2014; Minsker et al. 2015; Zhang et al. 2017; Walski 2019). In the conventional design of WDSs, reliability is the primary goal so that a system can maintain the desired level of service, i.e. meeting consumers' water demand with sufficient pressure and water quality, even under threats (Ostfeld et al. 2002; Shinstine et al. 2002; Chung et al. 2009; Wu et al. 2009). However, incidents that lead to unsatisfied water demand are often unavoidable and unpredictable, hence it is essential to design resilient WDSs which can minimize the negative effects of system failures and recover quickly (Zhuang et al. 2013; Diao et al. 2016). This can be achieved by conventional measures without entailing excessive costs. For example, Diao et al. (2016) found that the addition of a pump at the water source in the studied WDS can shorten the maximum failure duration by 12 hours in the firefighting scenarios and the duplication of 9 pipes can reduce water supply deficit by about 40% in the pipe break scenarios. Software platforms such as WaterGEMS and InfoWater can support decision-making by simulation of how the level of service is affected under component failures to prioritize intervention strategies such as pipe renewal and to assess fire-fighting capacity (Bentley 2018; Awe et al. 2019; Innovyze 2020).

A prerequisite for building resilience in system design is to identify representative indicators for measuring resilience. It can be based on direct measurement of resilience performance (e.g. failure duration, magnitude and severity) under scenarios where a WDS is stressed leading to failures (Fu et al. 2013; Aydin et al. 2014; Hwang et al. 2015; Diao et al. 2016; Roach et al. 2018). As such, direct resilience assessment is dependent on the set up of failure scenarios, the number of which is usually limited. To address this, indirect approaches of evaluating resilience without performing failure analysis have been proposed. For example, the hydraulic or water quality-related capability of WDSs, measured by water pressure or the level of residual disinfectant, etc., is strongly influenced by innate system properties (Meng et al. 2018) and affects how a system behaves under adverse conditions (Raad et al. 2010; Liu et al. 2017a). Todini's index, which describes the global surplus hydraulic power above the minimum required nodal water head (Todini 2000), is such a surrogate performance indicator widely used in assessing system reliability (Farmani et al. 2005b; Saldarriaga and Serna 2007; Reca et al. 2008; Raad et al. 2010) and perceived as a resilience indicator in some studies though its relationship with resilience is not clear (Banos et al. 2011). As such, the representativeness of Todini's index for resilience of WDSs needs to be examined by comprehensive studies.

The aim of this study is to investigate the performance and relationships of three direct and one indirect resilience indicators (i.e. failure duration, magnitude and a severity-based resilience index, and Todini's index) widely used for guiding resilient design of WDSs. This is achieved by formulation of a resilience enhance problem, whereby different types (e.g. adding pipes, pumps and/or storage tanks and duplication/cleaning/lining of pipes) and amounts (e.g. adding one to several pumps) of rehabilitation measures are applied to a WDS to obtain larger resilience. Each rehabilitation strategy, if not meeting the full level of service under normal operating conditions, can also be viewed as a failure scenario of a well-established network. Hence, the addition of a pump/pipe/tank to a WDS can be deemed as the failure of the pump/pipe/tank in the well-established WDS. Resilience indicators and cost are defined as objectives for the optimization and a wide range of Pareto optimal solutions, i.e. high performing, resilient rehabilitation strategies at various levels of cost, are obtained for analyzing the relationships of the four resilience indicators. Three case studies are examined in this work so that findings are not limited to a single WDS. The sensitivity of the research results to water demand assumptions (a key source of uncertainty) is also examined. Note that isolation valves, which are key to the performance of WDSs under pipe failures, are not represented and accounted in this work. Also, network resilience could be affected by many internal and external factors and operational issues, which are not considered in this study, such as transients, valve failure, water contamination, natural hazards (e.g., drought, flooding and earthquake) and social-economic factors (e.g., human errors and strikes) (Khatavkar and Mays 2019; Walski 2020; Zhang et al. 2020).

Direct resilience indicators

Resilience refers to the degree to which a system minimizes the magnitude and duration of failure in service provision over its design life when subject to exceptional conditions (Hashimoto et al. (1982). It can be assessed by failure duration, failure magnitude, and severity which is a combination of the former two (Casal-Campos et al. 2015; Mugume et al. 2015a; Mugume et al. 2015b; Ward and Butler 2016; Meng et al. 2018; Sweetapple et al. 2018; Ayala-Cabrera et al. 2019). Failure duration indicates how quickly a system recovers from a failure. It is commonly measured by the average time at all nodes in a WDS that the quantity/quality of the supplied water is below the required level of service. Failure magnitude suggests how badly a system can fail and it can be quantified as the average drop in system service at all nodes at all time steps in a simulation. Severity describes the deficit in the quantity/quality of water supply compared to the total demand of the entire WDS; it is an aggregation of the failure impacts within the simulation and is not a simple multiplication of failure duration and magnitude. For the ease of understanding and analysis, the severity indicator is normalized and modified in this work as illustrated in Figure 1 and is hereinafter referred to as the ‘resilience index’. The dashed line represents the required level of service (e.g. nodal pressure, water quality) and the solid line represents the actual level of service. Severity is the area between the dashed and solid lines (i.e. *A*). The resilience index is one minus the ratio between severity and the total need (i.e. *A*+*B*). As such, the value of the resilience index is in the range of 0 to 1, which allows for direct comparison between different networks - the higher the index value, the greater the resilience of a WDS. The equation of the proposed resilience index is presented as

$$r = 1 - \frac{A}{B} = \frac{\sum_{i=1}^{n}\sum_{t=1}^{N} SW_{i,t} \times l_t}{\sum_{i=1}^{n}\sum_{t=1}^{N} D_{i,t} \times l_t} \tag{1}$$

where *r* is the resilience of system, $D_{i,t}$ is the nodal water demand at node *i* at the *t*th time step, $SW_{i,t}$ is the water supply to node *i* at the *t*th time step, *n* is the number of nodes in a WDS, *N* is the number of total time steps, and l_t is the duration of the *t*th time step.

Methodology

As mentioned earlier, the three direct resilience indicators, Todini’s index and cost are set as objectives for the many-objective optimization of rehabilitation design of WDSs. It is in theory equal to but more efficient than performing 10 optimizations for each pair of the five optimization objectives; moreover, by doing the optimization in one run, the randomness of Genetic Algorithm in every run can be avoided to enable fair comparisons between the resilience indicators (Nicklow et al. 2010; Fu et al. 2013; Reed et al. 2013; Maier et al. 2014; Matrosov et al. 2015). WDSs that cannot provide full level of service (i.e. failing to meet water demand in the system) are studied and structural and/or operational rehabilitation measures (e.g. adding new pipes/tanks/pumps and duplicating or cleaning/lining of pipes) are applied to mitigate the failures. Based on the Pareto optimal solutions, the correlations between the resilience indicators are examined to reveal their relationships and the appropriateness of using one single indicator for resilient system design. As water demand is one of the key sources of uncertainty affecting system performance, the sensitivity of the research findings of this work to water demand assumptions is tested. This is achieved by repeating the optimization of rehabilitation for a case study WDS under different water demand scenarios, including fireflow, increased base demands, stochastic water usage behavior and leakage.

A pressure-driven hydraulic simulation model of WDSs developed by Morley and Tricarico (2008) is employed in this study. It is a modification of the demand-driven hydraulic simulation model EPANET2 (Rossman 2000; Morley and Tricarico 2008) so that the amount of water supply to a node is determined by nodal pressure (Wagner et al. 1988) rather than in full level of service regardless of water pressure. As such, the adopted model can produce more realistic simulation of water leakage and system behavior under abnormal conditions, such as involving excessively high water demands (e.g. for firefighting) or under component (pipes, pumps, etc.) failures leading to low pressures in a WDS.

Mathematical formulations of the four resilience indicators are provided in Equations (1) and (S1) to (S3) in the Supplemental Data. The cost of rehabilitation includes both the capital and operational costs. Capital costs are for new pipes (linking two nodes not connected before) and tanks, pipe duplication (linking two nodes already connected), and cleaning and lining of existing pipes. The costs for pipes are calculated by multiplying pipe length with unit costs for new pipes/cleaning/lining which are functions of pipe diameter. The cost for a new tank relates to the tank capacity. The operational cost refers to the energy cost for running pumps and is calculated by multiplying electricity tariff ($0.12/kWh in the case study) with the total energy consumption (in kWh, determined by pump efficiency and operational schedule). More details on the cost-related parameters can be found in Center for Water Systems (2004). Non-dominated sorting algorithm-II (NSGA-II) (Deb et al. 2002) is employed as it is a fast and popular evolutionary algorithm for multi-objective optimization (Farmani et al. 2005a; Atiquzzaman et al. 2006; Wang et al. 2014).

Case studies

Three benchmark WDSs (*New York Tunnel*, *Anytown* and *EXNET*) (Center for Water Systems 2004) are chosen as the case studies. They are widely used in system design-related studies with rehabilitation options defined and provided. The three WDSs vary in size, topology and system configurations as shown in Figure 2 and Table S1. *New York Tunnel* (*NYT*) (Figure 2a) is a gravity-fed water supply network that can be rehabilitated by duplication of any pipes. For each duplicating pipe, there are 15 options of pipe diameter and a 'do nothing' option (i.e. no duplication). *EXNET* (Figure 2b) is a much larger WDS where 567 pipes (highlighted in thick lines in Figure 2b) of the total 3032 pipes can be chosen for duplication with 10 diameter options or 'do nothing' as defined in the system file. *Anytown* (Figure 2c) is more complex than the former two WDSs in terms of operation as it has several pumps and tanks. The network needs to be reinforced to meet the projected water demand increase (Walski et al. 1987) and rehabilitation measures include duplicating or cleaning and lining of 35 selected pipes (in solid lines in Figure 2c), adding six new pipes between nodes not connected before (in dashed lines in Figure 2c), optimizing the operational schedules of all pumps, and building two new tanks at any nodes with no existing tanks connected (Basupi 2013; Atkinson et al. 2014). As such, the investigated rehabilitation measures are structural-related for *NYT* and *EXNET* and both structural and operational-related for *Anytown*.

Additional description or assumption of the three cases is presented in the Supplemental Data. As resilience is associated with dynamic performance of a system under failure, a water demand pattern (i.e. multiplying daily water demand with hourly coefficients, as presented in Table S2) is applied to enable extended period simulations. Results show hydraulic failures (i.e. insufficient water pressure exists at certain nodes) in all three WDSs. Some other commonly used measures to increase resilience such as adaptive pump operation during pipe failure (Zhuang et al. 2013), providing back-up pumps, adding isolation valves (Walski 1993a; b; Liu et al. 2017b) to reduce the impacts of pipe break, reduction in transients, emergency connections to neighboring water systems and improved communications, are not considered and can be examined in future studies (Murphy et al. 1994; Center for Water Systems 2004; Walski 2020).

The decision variables for the optimization are case-specific and include diameter for duplicated/added pipes, operational scheduling of pumps, if cleaning or lining is provided for pipes, and if and how (size and location) tanks are added. There are 21, 567 and 77 decision variables of the three case studies respectively. The optimization is performed with a population size of 500, which is found to be sufficiently large to produce satisfactory results according to a preliminary test. The optimization is run for 1000 generations, as the changes in the average objective values (among the optimal strategies) are less than 2% in the last 10 generations as shown in Figures S1 to S3.

The cross rate and mutation rate are set as the default values of 0.9 and 0.1 respectively.

Due to the diverse rehabilitation options in *Anytown*, this WDS is selected to perform the following scenarios with different water demand assumptions for the sensitivity analysis.

- S1 - 'Fireflow': A slightly modified demand pattern with two hours of excessively large water consumption (2.5 times as much as under normal condition) is applied to node 19 (one of the nodes with the highest water demands, defined as the point for fireflow analysis in the system file) to simulate fire flow conditions. The time and duration of the fire flow coincide with low water level at the tanks and one pump being out of service, which enable the appraisal of system resilience under extreme conditions. According to the definition of the network, the minimum required pressure in the firefighting scenario is set to be 20 psi (14.06 m) rather than the minimum pressure standard at normal conditions (28.13m).
- S2 – 'Increased base demands': The nodal base demand is 1.2 times of that in the normal condition scenario (Table S3) while other settings remain the same.
- S3 – 'Stochastic water usage behavior': Five different demand patterns are created and randomly assigned to different nodes (Tables S3 and S4). Other parameters and settings are the same as the normal condition scenario.

- S4 – ‘Leakage’: Additional modifications are made to S3 by adding water leakage randomly placed at different locations in the network. The total amount of leakage is about 10-20% of the customer water demand. The simulation of leakage is described in the Supplemental Data.

Results and discussion

Relationships between the optimization objectives

The Pareto optimal rehabilitation solutions obtained for the three WDSs are presented in Figure 3, where each line represents a solution plotted against the five objectives (i.e. the vertical lines). The arrows at the top of the vertical lines show the desirable direction of the objective value (i.e. lower cost and higher resilience). There is a clear trade-off between cost and resilience (i.e. cost increases with higher resilience). The cost of being more resilient is case specific; moreover, the marginal cost for improvement in resilience gets higher as the value of resilience increases. In *New York Tunnel*, the Todini’s index increases from 0.31 to 0.68 (120% increase) by rehabilitation measures that cost \$58 x10^6 (135% increase), yet the same amount of investment only improves the index value by 0.02 if the initial value is 0.82 (i.e. 2% of increase in Todini’s index by 30% increase in cost). The trade-off between cost and resilience, the desirable level of resilience and the affordable level of cost are key factors to consider in the selection of rehabilitation strategy to implement.

The linear correlation coefficients (*r*) between each pair of the five objectives based on all the optimal strategies are presented in Table 1. Strong correlations are observed between the four resilience indicators (except that between failure magnitude and other indicators in EXNET because the failure magnitude in this network is clustered around two values as explained in the next section). However, there are more lines crossing between Todini's index and resilience and between failure magnitude and failure duration in Figure 3c than Figures 3a and 3b. This may be caused by the existence of storage tanks in the network, which play a key role in enhancing system resilience against failures but is not well captured by the Todini's index. Similar relationships between the five objectives are observed in the other four scenarios of *Anytown* as presented in Table S5 and Figure S4.

The correlations can also be seen by plotting the optimal strategies against cost and each resilience indicator. Figure 4 shows the results on *Anytown*, with the Pareto optimal fronts against each pair of objectives (i.e. cost and one resilience indicator) highlighted in orange, yellow, purple and green respectively. Had the two-objective problems with each resilience index and cost been solved separately, the same Pareto fronts should have been obtained assuming that the influence of optimization algorithms is excluded. Similar figures for *NYT* and *EXNET* are presented in Figures S6 to S7. The strong correlations between the resilience indicators can be seen from the similar shapes between dots with different colors. The weaker correlations in *Anytown* than *NYT* and *EXNET* are obvious as the dots are not as close together in Figure 4 as Figures S6 and S7.

Performances of different resilience indicators

Despite the strong correlations between the resilience indicators, each indicator provides valuable perspectives on the resilience performance of WDSs. Figure 5 shows the results of the optimal strategies plotted against Todini’s index and failure duration/magnitude. It can be seen that failure duration can vary greatly for strategies with the same value of Todini’s index. For example, the failure duration ranges from 5.7 to 9.6 hours when Todini’s index is 0.39 for *Anytown* as shown in Figure 5c. In comparison, the variations in failure magnitude are smaller which is in agreement with the stronger correlations between failure magnitude and Todini’s index. Similar results are shown in the other four scenarios of *Anytown* as presented in Figure S5.

The examination of values of the direct resilience indicators at single nodes help identify the vulnerable places that may fail badly or cannot recover rapidly after failures. For example, the failure magnitude of *EXNET* clusters at two values (i.e. 1×10^{-6} and 1.2×10^{-5}) as is evident in Figure 5e. A detailed examination reveals that this is attributed to a few crucial nodes having greater impacts than others in influencing the result of failure magnitude which is an average value among all nodes. These critical nodes are clustered at three areas near the end of the network hence are subject to limited influence from most rehabilitation measures applied in the network. By contrast, Todini's index is a summation of surplus energy at all nodes in a network, hence cannot support the localization of vulnerable nodes in a WDS.

Todini's index is strongly correlated with the direct resilience indicators, suggesting that the surplus energy of a WDS measured under one scenario is indicative of its hydraulic capacity under other scenarios. However, it performs less satisfactory on WDSs with storage tanks as mentioned in the previous section. This finding agrees with discussions on the limitation of excess capacity indicators in representing resilience (Walski 2020). Moreover, its value is not indicative of the absolute resilience capacity of a WDS and should not be used to compare performance of different WDSs. For example, the failure duration and magnitude of *New York Tunnel* can be as low as zero if Todini's index is higher than 0.68. However, rehabilitation solutions that have the same value of Todini's index of *Anytown* still show high failure impacts, that is, failure duration can be as high as 3.5 hours.

Conclusions

The relationships between the Todini's index, a widely used surrogate performance indicator, and three direct indicators of resilience (failure duration, failure magnitude and a severity-based resilience index) are investigated in this study. This is achieved by the optimization of rehabilitation measures towards lower cost and higher resilience of three typical benchmark WDSs. Todini's index is a widely used indicator for system design and can be assessed without setting up failure scenarios. Results show that Todini's index is strongly correlated with the direct resilience indicators with the two networks without tanks, *NYT* and *EXNET*. However, the Todini's index should be used with caution for resilience design as its correlation with the direct resilience indicators are found to be weaker for WDSs with complex configurations containing water tanks such as the *Anytown* network. Moreover, the Todini's index value should not be used to compare the resilience of different WDSs.

Data Availability Statement

The rehabilitation network designs used for the analysis in this study are available from the corresponding author by request.

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Supplemental Data

Descriptions are provided in the Supplemental Data on 1) definition of the resilience indicators, 2) description of the case studies, 3) pressure driven hydraulic modelling, 4) pressure dependent leakage model, 5) correlation results of scenarios S1 to S4, and 6) optimal Results of *NYT* and *EXNET*. They are available online in the ASCE Library (www.ascelibrary.org).

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