# Performance Index for Water Distribution Networks under Multiple Loading Conditions

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**Abstract:** Previous studies have naturally related water distribution network performance to the ability to deliver sufficient pressure and flow. The present paper emphasizes that performance also depends on the efficiency of delivering these requirements. Accordingly, an efficiency-based performance index is proposed. It is the geometric average of four performance metrics: reliability, vulnerability, resilience, and connectivity. These are themselves based on the energy efficiency, hydraulic capacity, and structural ability of the system to deliver water under a range of conditions. The metrics are applied to two example networks and variations of these, enabling the assessment of their relevance, their sensitivity to system changes, and permitting a comparison to existing metrics. Variations represent different redundancy increasing strategies, recognized for improving performance. The proposed performance index generally follows a similar trend as the previous indices, increasing with network pressure. Nevertheless, it varies differently and penalizes networks with unnecessarily high pressures. Because the index is based on energy and demand efficiency metrics, it automatically complies with the energy and mass balances of the network. Moreover, the new metric is easily interpreted and can be applied to various systems, whether complex or involving multiple scenarios. **DOI:** **10.1061/(ASCE)WR.1943-5452.0000564.** *© 2015 American Society of Civil Engineers.*

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## Introduction

The performance of water distribution networks is multiobjective and dependent upon complex interactions between infrastructure components as well as external conditions. This can be compared to ecosystems, which must balance population requirements against outside pressures. Indeed, previous authors have found that ecosystems function according to principles that increase network sustainability, such as resilience and reliability (Biomimicry 3.8 Institute 2011; Ho and Ulanowicz 2005; Katifori et al. 2010).

The classic study by Holling (1973) argues that evolution finds a balance between two related system characteristics, namely resilience and stability, with resilience being a term coined for ecosystems to indicate a system's ability to absorb changes of state variables. Thus, resilience is related to the concept of persistence, while stability indicates the ability of these systems to return to an equilibrium state after a temporary disturbance. Therefore, a stable system would not fluctuate greatly, and a resilient system might undergo significant fluctuations. Klein et al. (2003) note that despite the continuous debate since the seminal work by Holling (1973), a consensus on how to operationalize this concept has not been reached. For instance, Timmerman (1981) links resilience to vulnerability and defines the first as the measure of a system's capacity to absorb and recover from a hazardous event. Pimm (1984) connects resilience with stability: resilience is the speed with which a system returns to its original state after a temporary disturbance. This definition concerns engineering resilience, which considers ecological systems to exist close to a single stable steady state (Holling 1996). Ecological resilience, on the other hand, emphasizes instabilities, which can lead the system to still function but in another state.

Fiering (1982a) introduces several indices to measure the resilience of water resource systems. These are related to various system attributes including the probability of the system being in an acceptable state, the probability of failure, the costs of being in each state, as well as expected time to change states. Each of these represent different properties of the system, all of which favorably indicate a system's performance, and are highly correlated (Fiering 1982b).

Hashimoto et al. (1982) instead develop a single concept for evaluating water supply system resilience, and two additional concepts, vulnerability and reliability, to assess system performance. In their work, resilience is the probability of recovery from failure within a specified time interval. As applied to water supply, this is calculated as the probability of quickly meeting demand after an instance of insufficient supply (Hashimoto et al. 1982; Moy et al. 1986; Solis et al. 2011). Reliability is the probability of water supply meeting demand during the period of the simulation (Klemes et al. 1981; Hashimoto et al. 1982; Moy et al. 1986; McMahon et al. 2006; Solis et al. 2011). Vulnerability introduces another consideration, being a measure of the significance (or consequences) of failure (Hashimoto et al. 1982). This is often calculated as direct surrogate of costs, such as the average demand deficit during failure events (Loucks and van Beek 2005; Solis et al. 2011) or the largest deficit during the period of operation (Moy et al. 1986).

For the analysis of water distribution networks, resilience has largely acquired another meaning, more related in earlier work to the concept of robustness. Ostfeld (2004) compares two extremes in water network reliability simulation models: a lumped supply-lumped demand model (Ostfeld 2001) and a general stochastic framework for both quantity and quality reliability indices (Ostfeld et al. 2002). While the first is a simple bespoke methodology for systems that can be lumped, the second is a general *black box* framework, which although applicable to any network, provides little insight into system behavior. This underlines an inherent

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trade-off between simplicity and precision. Ultimately, the choice of the model depends upon the problem, as well as the modeler's experience and preferences (Ostfeld 2004).

Todini (2000) proposes a resilience index, Eq. (1), as a surrogate measure of network reliability. Resilience is defined as the ability of the network to provide more power than required at each node in order to have a sufficient surplus to be dissipated internally in case of failure

$$\mathrm{RI} = \frac{\sum_{j=1}^{n} q_j(ha_j - hr_j)}{(\sum_{r=1}^{R} Q_r H_r + \sum_{b=1}^{B} P_b) - \sum_{j=1}^{n} q_j hr_j} \tag{1}$$

where $n$ = number of demand nodes; $q_j$ = demand at node $j$; $ha_j$ = head available at node $j$; $hr_j$ = minimum head required to meet constraints at node $j$; $R$ = number of reservoirs; $Q_r$ = flow being supplied to the system by reservoir $r$; $H_r$ = head at reservoir $r$; and $P_b$ = power introduced in the system by pump $b$.

Todini's resilience index has been widely adapted and applied to water distribution system studies (Todini 2000; Prasad and Park 2004; Jayaram and Srinivasam 2008; Baños et al. 2011; Greco et al. 2012; Atkinson et al. 2014; Di Nardo et al. 2014). Prasad and Park (2004) combine the resilience index with a diameter uniformity coefficient [Eq. (2)] in order to better represent the reliability of loops. The resulting network resilience index (NRI) is given in Eq. (3)

$$c_j = \frac{\sum_{j=1}^{np} D_j}{np \cdot \max(D_j)} \tag{2}$$

$$\mathrm{NRI} = \frac{\sum_{j=1}^{n} c_j q_j(ha_j - hr_j)}{(\sum_{r=1}^{R} Q_r H_r + \sum_{b=1}^{B} P_b) - \sum_{j=1}^{n} q_j hr_j} \tag{3}$$

where $np$ = number of pipes connected to node $j$; and $D$ = diameter of these pipes.

Prasad and Park (2004) argue that reliable loops are achieved if the pipes connected to a node are not widely varying in diameter. However, the proposed uniformity coefficient does not fully represent the advantage of loops; indeed, the coefficient is equal to 1 if all pipes connected to a node have the same diameter even if there is only one connection. If a pipe bursts, however, a one-pipe-node would obviously be less reliable.

Jayaram and Srinivasan (2008) moreover show that Todini's resilience index does not adequately represent the reliability of networks with multiple reservoirs. Because the power supplied by reservoirs depends on pipe diameter and roughness, a network with a large surplus power at the demand might also have a large input power, undesirably decreasing the resilience index. Thus, Jayaram and Srinivasan (2008) propose a modified resilience index (MRI), as shown in Eq. (4)

$$\mathrm{MRI} = \frac{\sum_{j=1}^{n} q_j(ha_j - hr_j)}{\sum_{j=1}^{n} q_j hr_j} \tag{4}$$

Baños et al. (2011) compare these three resilience indices through a cost versus reliability study. The modified indices are found to only marginally improve upon the original index by Todini (2000). Baños et al. (2011) also note that none of these indices consider the issue of overdemand, and thus do not accurately determine the capability of the network to deliver demand under uncertainty.

Since these indices do not fully consider the connectivity of a network, and cannot identify critical areas in the system, Yazdani et al. (2011) focus on nonhydraulic statistical and structural metrics for assessing water distribution network resilience. The connectivity pattern between nodes and links is used to calculate reliability, efficiency, and robustness of the networks. Graph theory principles have also been applied recently in improving water network sectorization (Di Nardo et al. 2014). Tanyimboh and Templeman (2000) evaluate network performance according to nonhydraulic metrics as well. The authors introduce the concept of entropy in water networks, entropy being defined as the probability of a node receiving demands given the availability of adequate alternate flow paths.

Greco et al. (2012) and Creaco et al. (2014) compare the resilience and entropy metrics as indirect measures of network reliability. The demand satisfaction rate is assumed to be a natural performance indicator and a direct measure of reliability; it is calculated as the ratio of demand delivered to demand required, based on a pressure-driven simulation. The maximum reliability is reached by just meeting the minimum pressure required to satisfy demands. Pressures above this level do not alter the assessment of reliability of the network. Given this definition, the resilience indices showed a much stronger positive correlation with network reliability. Zhuang et al. (2013) and Di Nardo et al. (2014), in fact, apply the demand satisfaction rate directly to support the assessment of water distribution networks. Although entropy is a surrogate measure of topological reliability, it was found to not represent the network's capability to perform after failure (Greco et al. 2012).

Even the demand satisfaction rate, although dependent upon pressure as well, clearly does not fully represent the performance of water networks. Delivering pressures above the minimum requirement to meet full demands does not affect this rate, but does alter both costs and how the network operates. The resilience metrics account for all pressures, but are partial to higher network pressures, which despite inducing the supply of surplus power might lead to higher leakage and burst rates. The present paper argues that the performance of the network should depend not only on the ability to deliver adequate flows and pressures, but also on its efficiency in doing so.

As argued when introducing previous resilience indices, power is an attractive measure in assessing networks since it is proportional to pressure and flow, the main products of the system. Cabrera et al. (2010) propose energy indicators to evaluate the efficiency of networks, defined according to ratios between energy supplied, energy lost, and useful energy or minimum required useful energy. These are calculated at a system level for a long-term period in order to represent its energy balance. Dziedzic and Karney (2013) propose water distribution system energy metrics that are computed for each component at each time step. This facilitates both the identification of areas for improvement and the comparison of operational efficiency in different scenarios.

The current study proposes efficiency-based performance metrics for evaluating and comparing water distribution networks. These metrics accommodate varying loads and multiple network components in order to represent network connectivity, capacity to deliver demand under uncertainty, and ability to recover after emergencies. The metrics are applied to two example networks and variations of these, enabling and provisionally validating their use in as network assessment tools.

## Performance Index

Four metrics are herein defined for evaluating water network performance: reliability, resilience, vulnerability, and connectivity. The first three are conceptually based on definitions used in water basin management as described in the previous section (Klemes et al. 1981; Hashimoto et al. 1982; Moy et al. 1986; Loucks and van Beek 2005; McMahon et al. 2006; Solis et al. 2011).

Because the performance of water networks depends on the efficient delivery of sufficient demand and pressure, energy efficiency is applied instead of demand to compute the metrics. Furthermore, unlike in water basin studies where a minimum demand is established, or the network resilience indices where a minimum pressure is determined, a minimum efficiency constraint has not been established. Accordingly, the proposed metrics do not evaluate the probability of the network meeting a minimum efficiency, but rather the efficiency of the network under various conditions. Failure events, in which demand and pressure requirements are not met, are also characterized by a reduction in energy efficiency. Nevertheless, to evaluate a wide range of conditions, the metrics naturally require an extended period analysis.

Energy efficiency, as represented by Eqs. (5) and (6), is herein defined as the ratio between total energy delivered $E_{\mathrm{delivered}}$ and energy supplied $E_{\mathrm{supplied}}$. The first represents energy available at nodes, through the demand supplied and the head delivered, in various scenarios. The second is the sum of energy supplied at tanks, reservoirs, and pumps, through gravity or pumped flow. Unlike previous resilience indices, the total energy consumed by the pumps, rather than the energy introduced to the network after the initial dissipation at the pumps, is considered. This integrates the efficiency of the pumps in the analysis of the network

$$e = \frac{E_{\mathrm{delivered}}}{E_{\mathrm{supplied}}} \tag{5}$$

$$e = \frac{\sum_{j=1}^{n} q_j h a_j}{\sum_{r=1}^{R} Q_r H_r + \sum_{b=1}^{B} P_b^*} \tag{6}$$

Reliability $P_{\mathrm{rel}}$, related to the system's performance under all conditions, is defined as the average energy efficiency over all scenarios, as given by Eq. (7), where $h$ is the number of simulation hours in one scenario and $s$ the number of scenarios. These scenarios should represent the normal and emergency conditions of the network. In this way, a long-term analysis of the network is progressively accomplished. In the present study, for an initial evaluation of the metrics, only three scenarios are run, representing scenarios with normal flow, a fire flow, and a pipe burst. These are important design scenarios and emergency events for water distribution systems in general. Future studies can easily be extended to include other cases such as pump breakdown and valve failure, or even a stochastic analysis of the lifecycle of the network

$$P_{\mathrm{rel}} = \sum_{i=1}^{s} \sum_{t=1}^{h} \frac{e_{t,i}}{s\,h} \tag{7}$$

Vulnerability $P_{\mathrm{vul}}$ is used here to represent a measure of the severity of failure. It is the minimum efficiency reached by the system during emergency events or normal operation [Eq. (8)]. Together with the other metrics ,it is indicative of the range of system efficiency

$$P_{\mathrm{vul}} = \min(e_{t,i}) \tag{8}$$

Similar to reliability, resilience $P_{\mathrm{res}}$ [Eq. (9)] is calculated as the average efficiency, but after a failure event. It implicitly reflects the system's capacity to adapt to change. This postemergency period $h^*$ should be long enough to represent recovery. For the example networks modeled, a period of 4 h was used

$$P_{\mathrm{res}} = \sum_{i=1}^{s^*} \sum_{t=1}^{h^*} \frac{e_{t^*,i^*}}{s^* h^*} \tag{9}$$

These energy-based metrics describe system performance under different conditions. However, because total pipe failure was not modeled but only burst-induced leakage, the measures do not fully represent the advantage of loops creating alternate flow paths. Yazdani et al. (2011) used statistical measurements of water distribution networks to analyze robustness and redundancy. They are based on the structural patterns and building blocks of the network. Herein, this concept was extended and a structural metric was related to demands. Network connectivity was defined as the minimum percentage of demand $Q$ delivered given a pipe $p$ break [Eq. (10)]. Herein, only one pipe break at a time was considered

$$P_{\mathrm{con}} = \min(Q_{\mathrm{delp}}/Q_{\mathrm{req}\,p}) \tag{10}$$

The connectivity of the network could be calculated by hydraulically modeling all of the potential bursts, yet a structural surrogate is proposed to estimate connectivity. The connectivity vector, given in Eq. (11), indicates if nodes are connected to a source of water. The network is represented as an adjacency matrix, $A$, of order $n \times n$, where $n$ is the number of nodes. The elements of the matrix represent the network connections. As usual, lines and columns indicate specific nodes with values of 1 indicating that a pipe directly connects the respective nodes, and 0 otherwise. The location of the sources is represented in a vector, $c_0$, where elements are either 1 if the node is a source or 0 if not. The elements of the resulting connectivity vector, $c$, are 0 if the particular node is not connected to any source of water, and different from 0 if it is

$$c = \sum_{j=1}^{n} c_0 A^j \tag{11}$$

For the purposes of this study, the demand-based connectivity, Eq. (10), was thus estimated assuming that a network connection between a source of water and a node would suffice for water to be delivered.

In order to evaluate these metrics collectively, an aggregate performance index is proposed. As shown in Eq. (12), this aggregate measure is taken as the geometric average of the performance metrics ($P_m$): reliability, resilience, vulnerability, and connectivity. Because these are ratios of either *energy delivered to supplied* or *demand delivered to required*, they all range between 0 and 1. The upper limit indicates the best situation. Other properties of this type of index are attractive: (1) if one of the metrics is zero, the index will be zero; (2) if the metrics are all equal, so is the overall measure; (3) there is an implicit weighting, through which the *worst* metrics are given more importance; and (4) each metric is considered essential and irreplaceable. In accordance with the second property, results from a geometric average are similar to those from an arithmetic average if efficiencies are consistent. However, for systems with a wider range of performance, because the worst metrics are given more importance, the geometric average represents this inconsistency better

$$\mathrm{PI} = \left[\prod_{m=1}^{M} P_m\right]^{1/M} \tag{12}$$

## Case Studies

In order to assess the performance and usefulness of the metrics, two example networks are assessed, with each having a range of pipe redundancy increasing strategies, as well as pumping and storage scenarios. Increasing network redundancy, whether through adding pipes or other components, is a recognized strategy for increasing network performance, especially resilience (Awumah et al. 1990; Goulter et al. 2004; Walski 2004; National Research Council 2006; USBR 2006; Yazdani et al. 2011). The proposed metrics were also compared to the resilience indices developed by Todini (2000), Prasad and Park (2004), and Jayaram and Srinivasam (2008), as well as the average pressure of the network.

The two example networks modeled are based on examples distributed with EPANET (Rossman 2000). They were selected because both are not only well known but have at least one reservoir, tank, and pump, as well as hourly varying demands. This allows for the analysis of storage and multiple loading conditions not evaluated by other authors (Todini 2000; Baños et al. 2011; Atkinson et al. 2014). The demand patterns were altered to better represent urban demand, with two peaks, in the morning and the evening (Blokker et al. 2010). Demand, however, was set to fluctuate more than would be expected during normal operations, varying between minimum (0 h), average (3 h), maximum (6 h), and peak demand (17 h) throughout the day, shown in Fig. 1. Peaking coefficients were based on recommendations from MEA (1977) and Ysusi (1999). This not only enables the analysis of different extreme scenarios, but also of system response to wide variations in demand. Further network modifications were made in order to maintain normal operations within standard pressure ranges. Pressure ranges were verified for the original looped configurations of the networks. However, in other configurations, pressures were found to be below operational standards, leading to greater vulnerability $P_{\mathrm{vul}}$. Network characteristics are described in the following sections.

With the objective of assessing the systems as well as the applicability and sensitivity of the performance metrics, the aforementioned strategies were applied to the example networks. For each example network, three variations were modeled: the original design (with loops), the network with fewer loops, and the network with fewer loops yet larger pipe diameters. In the last case, all pipe diameters were increased by 100 mm.

Furthermore, for each of these configurations, three 1-day scenarios were analyzed: normal demand pattern (Fig. 1), fire flow during maximum demand, and pipe burst during peak demand. The last scenario, unlike the former, is usually not considered in the design of water distribution systems even though it constitutes a significant emergency caused by system failure. Fire flow was set at a critical (low pressure) point in each network, and water loss due to a pipe burst was located in an area with high energy dissipation, which would possibly be more prone to cracking or failure.

The additional demands due to fire and leakage, each with a duration of 2 h, were assigned to dummy nodes, connected to the network by short pipes with insignificant head loss. The fire flow was determined based on the demands in the system and

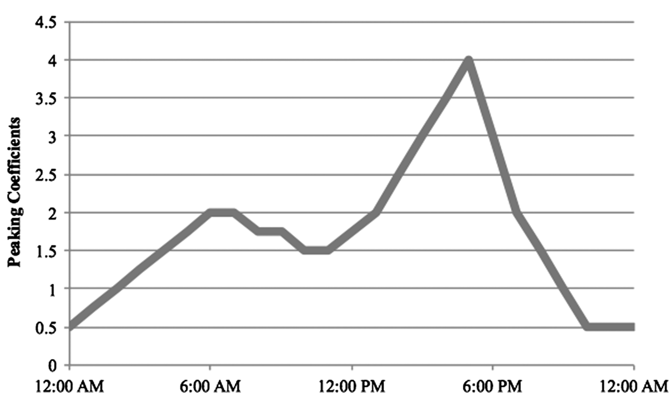


**Fig. 1.** Peaking coefficients for Networks 1 and 2

the ISO (2008) recommendations for residential dwellings. In Network 1, the fire flow is 63 $\mathrm{L\,s^{-1}}$, and in Network 2, 126 $\mathrm{L\,s^{-1}}$. Lambert et al. (2000) compared seven North American water distribution systems. Their leakage rates represented between 15 and 33% of total system input volume. In the present models, the leakage due to breakage in the pipe burst scenario was set to 20% of total demand. Although this is clearly a significant flow at a single node, it is less than many consistent leakage rates, and allows for the assessment of critical leakage on network performance. Bursts were defined as emitters in EPANET, with a pressure exponent of 1, as suggested by Lambert (2001). This resulted in a discharge coefficient of 0.7 for Network 1 and 2.9 for Network 2.

### Example Network 1

Network 1 is a simple 3-loop network, shown in Fig. 2. It has one reservoir and one tank, both at higher elevations than the remaining nodes. The initial level of the tank is 36 m, while the minimum and maximum level are 31 and 46 m, respectively. Although gravity flow does play a role in supplying flow, pumping is still required. The pump curve is defined by one head versus flow coordinate, 76.2 m for 94.6 $\mathrm{L\,s^{-1}}$.

Three network configurations were modeled: the original (looped) system, the same system with fewer loops, and with increased diameters. The basic node characteristics are the same for all three and are given in Table 1. Pipe characteristics of the looped network are listed in Table 2. In the second configuration, three pipes were removed, indicated by an asterisk in Table 2, and all other characteristics were maintained. In the third configuration, the same pipes are removed yet all other diameters are increased by 100 mm.

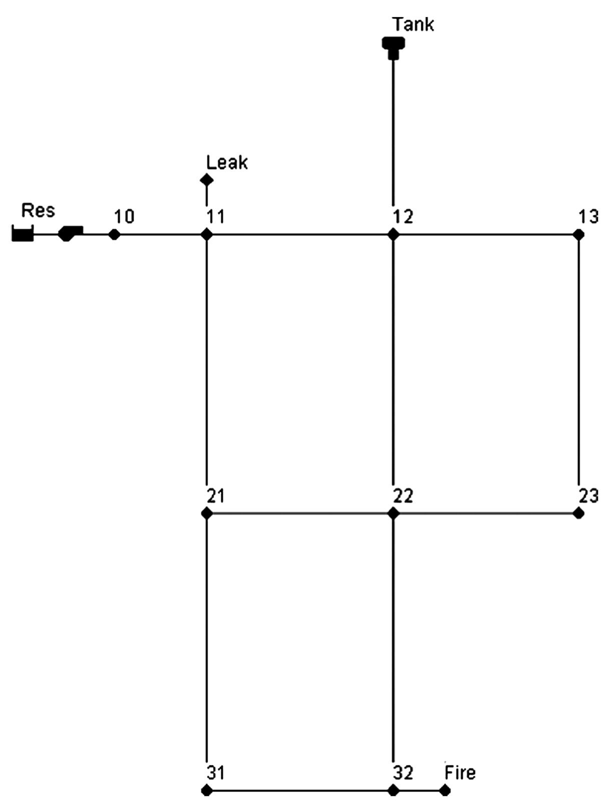


**Fig. 2.** Schematic representation of Network 1 with node IDs

**Table 1.** Elevation and Demand Values for Network 1 Nodes

| Node identifier | Elevation (m) | $Q$ (L s$^{-1}$) |
|---|---|---|
| Res | 243.8 | — |
| Tank | 259.1 | — |
| 10 | 216.4 | 0.0 |
| 11 | 216.4 | 9.5 |
| 12 | 213.4 | 9.5 |
| 13 | 211.8 | 6.3 |
| 21 | 213.4 | 9.5 |
| 22 | 211.8 | 12.6 |
| 23 | 210.3 | 9.5 |
| 31 | 213.4 | 6.3 |
| 32 | 216.4 | 6.3 |

**Table 2.** Length, Diameter, and Roughness Coefficient Values for Network 1 Pipes

| Pipe identifier | Start node | End node | Length (m) | Diameter (mm) | Roughness coefficient $C$ |
|---|---|---|---|---|---|
| 10 | 10 | 11 | 3,209.5 | 457.2 | 100 |
| 11 | 11 | 12 | 1,609.3 | 355.6 | 100 |
| 12 | 12 | 13 | 1,609.3 | 254.0 | 100 |
| 21[a] | 21 | 22 | 1,609.3 | 254.0 | 100 |
| 22 | 22 | 23 | 1,609.3 | 304.8 | 100 |
| 31 | 31 | 32 | 1,609.3 | 152.4 | 100 |
| 110 | Tank | 12 | 61.0 | 457.2 | 100 |
| 111 | 11 | 21 | 1,609.3 | 254.0 | 100 |
| 112[a] | 12 | 22 | 1,609.3 | 304.8 | 100 |
| 113 | 13 | 23 | 1,609.3 | 203.2 | 100 |
| 121 | 21 | 31 | 1,609.3 | 203.2 | 100 |
| 122[a] | 22 | 32 | 1,609.3 | 152.4 | 100 |

[a]Pipes not included in the configuration with fewer loops.

**Table 3.** Average Energy Metrics of the Alternative Configurations of Network 1

| Network | Pump $E_{supplied}$ (kWh) | $E_{dissipated} + E_{lost}$ (kWh) |
|---|---|---|
| Net 1 | 91.4 | 25.7 |
| Net 1 L | 91.4 | 36.8 |
| Net 1 L, D | 91.4 | 26.7 |

Note: D = larger diameters; L = fewer loops.

The average pumping energy varies minimally between the three modeled configurations of Network 1, original (looped), fewer loops, and increased diameters, as shown in Table 3. Therefore, operational energy costs are stable despite structural differences. The energy dissipated, however, varies significantly. The configuration with fewer loops consistently presents lower pressures and energy efficiency. Consumers would be receiving an inferior service in this case, and utilities would be spending more money on overcoming friction. Risks associated with pipe breaks or low pressures would also be higher.

The daily energy efficiency profiles of the alternative configurations of Network 1 are shown in Fig. 3. The percentage of energy delivered, equivalent to $e$, in the original looped configuration of Network 1 varies between 80 and 84%. The additional demands during peak hours as well as during fire events increase system efficiency [Fig. 3(a)]. Despite the increased energy dissipation in the pipes due to larger flows, tanks supply more water during this period. This allows pumps to operate at the same level, at similar dissipation rates as during normal operations, momentarily increasing efficiency. Obviously, this efficiency cannot be sustained but shows how storage can be used to maintain the reliability of the system. This is also true in the configuration with increased diameters [Fig. 3(c)], but not in the case with fewer loops [Fig. 3(b)]. In the latter, the additional flow during fire events and peak hours causes excessive pipe dissipation, reducing energy efficiency. In all three cases, then, the burst occurs during peak flow, the energy lost through leakage causes efficiency to plummet.

These differences are clear in the performance metrics shown in Table 4. While reliability and resilience are similar for the configurations with greater redundancy, they are lower in the configuration with fewer loops. The greater connectivity and lower vulnerability in the looped network lead to a higher performance index, setting it apart from the configuration with larger diameters.

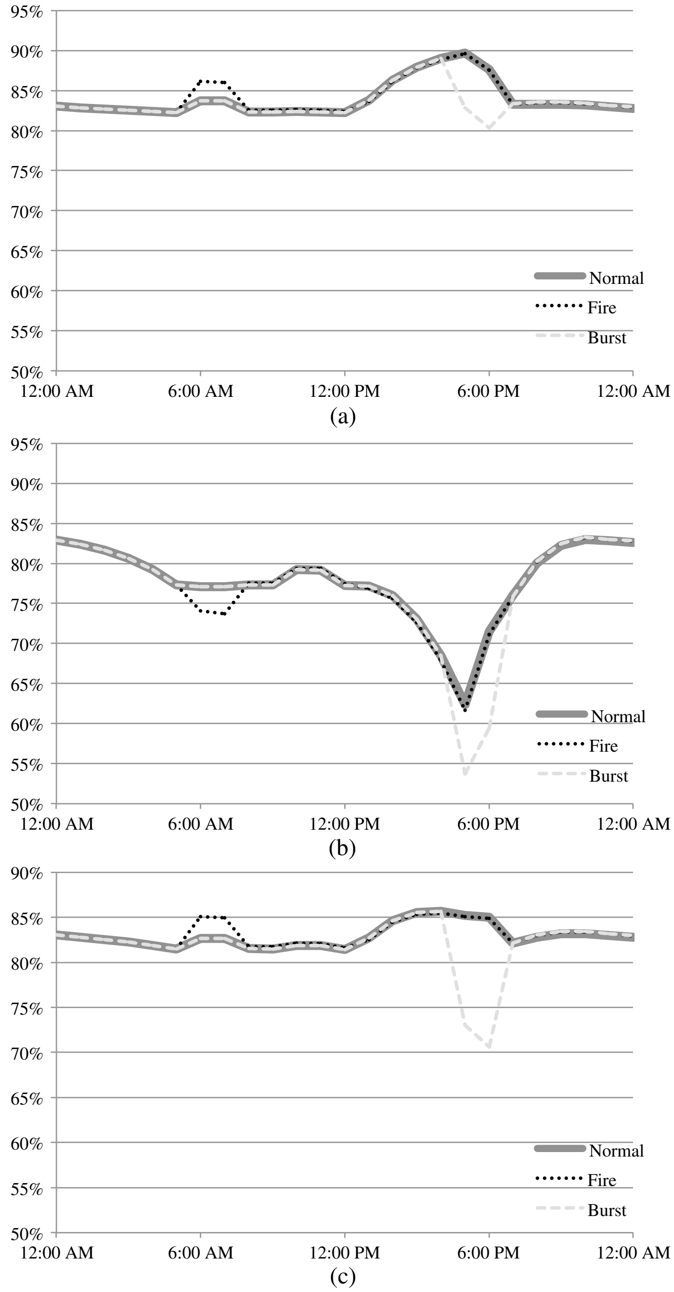


**Fig. 3.** Energy efficiency profile over 24-h simulation for Network 1: (a) original network; (b) fewer loops; (c) larger diameters



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**Table 4.** Proposed Performance Metrics, Resilience Index (Todini 2000), Network Resilience Index (Prasad and Park 2004), Modified Resilience Index (Jayaram and Srinivasam 2008), and Average Pressure of the Alternative Configurations of Network 1

| Network | Rel | Vul | Res | Con | PI | RI | NRI | MRI | Avg P |
|---|---|---|---|---|---|---|---|---|---|
| Net 1 | 0.84 | 0.80 | 0.83 | 1.00 | **0.86** | **0.99** | 0.80 | **1.15** | **83.94** |
| Net 1 L | 0.77 | 0.54 | 0.79 | 0.59 | 0.66 | 0.87 | 0.76 | 0.97 | 78.60 |
| Net 1 L, D | 0.83 | 0.71 | 0.82 | 0.59 | 0.73 | 0.97 | **0.87** | 1.12 | 83.14 |

Note: D = larger diameters; L = fewer loops; the best performing networks according to each index are indicated in bold.

The proposed performance index follows the same trend as the resilience index by Todini (2000) and the modified resilience index by Jayaram and Srinivasam (2008). All indicate that the looped configuration has the best performance. Nevertheless, the difference between the looped and the larger diameter configuration is small according to the resilience indices. Because these are proportional to the power surplus, they vary similarly to the average pressure of the networks. The inclusion of vulnerability and connectivity into the proposed performance index helps to distinguish the real performance differences of the networks.

The index defined by Prasad and Park (2004) is the only metric that is more partial to the configuration with no loops and larger diameters. Removing pipes or increasing diameters has a greater effect on node uniformity in smaller networks, such as the given example. Thus, an advantage is given to branched networks with more nodes reached only by a single pipe.

### Example Network 2

Network 2 is more complex and better represents many systems. It has two reservoirs, three tanks, and two pumps, shown in Fig. 4. In

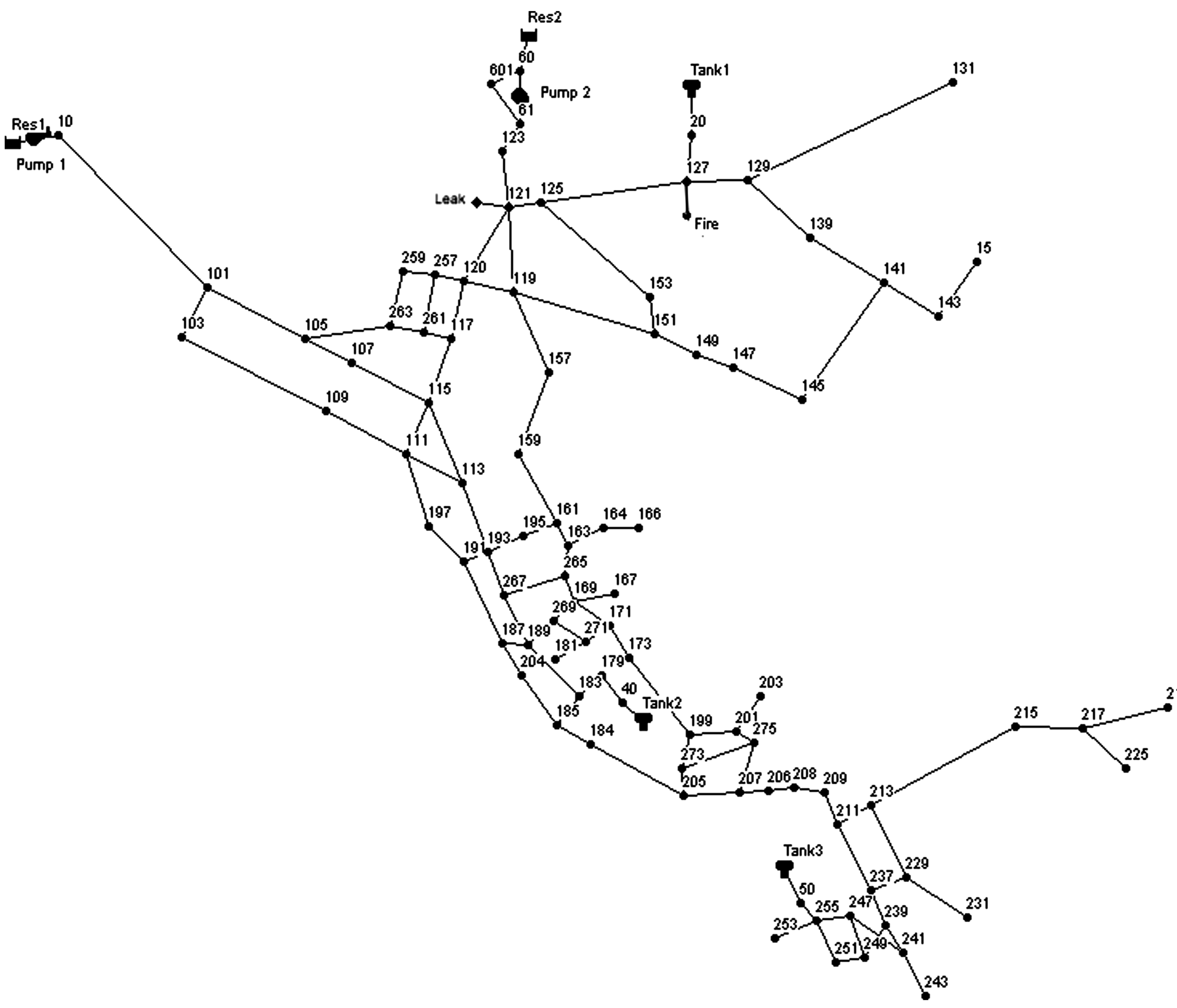


**Fig. 4.** Schematic representation of Network 2 with node IDs



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**Table 5.** Pump Curve Coordinates, Flow and Head, for Network 2

| Pump 1 | | Pump 2 | |
|---|---|---|---|
| $Q$ (L s$^{-1}$) | H (m) | $Q$ (L s$^{-1}$) | H (m) |
| 0 | 63 | 0 | 60 |
| 126 | 56 | 504 | 42 |
| 252 | 38 | 883 | 26 |

**Table 6.** Tank Levels for Network 2

| Tank identifier | Initial level | Minimum level | Maximum level |
|---|---|---|---|
| 1 | 4 | 0.03 | 9.8 |
| 2 | 7.2 | 2 | 12.3 |
| 3 | 8.8 | 1.2 | 10.8 |

this case, nine configurations were modeled in order to assess modifications to storage and pumping, as well pipe redundancy. Three storage and pumping configurations were evaluated: the original, a scenario with reduced storage, and one with reduced storage and pumping. The head versus flow coordinates of the pump curves and tank levels of the original configuration are presented in Tables 5 and 6, respectively. In the second case, the maximum levels of the tanks were reduced to equal their initial levels. In the third case, in addition to reducing storage, head imparted at pump 2 was decreased by half.

Three pipe configurations were modeled for each case: original (looped), fewer loops, and increased diameters. The common node characteristics for all three systems are given in Table 7. Pipe characteristics of the looped network are listed in Table 8. In the second configuration, three pipes were removed, indicated by an asterisk in Table 8, and all other characteristics were maintained. In the third configuration, the same pipes are removed yet all other pipe diameters are increased by 100 mm.

Although energy supplied by pumps in the original Network 2 configuration (Table 9) is not much different from that in Network 1, energy dissipated changes dramatically, and his about four to five times higher in the former. This low efficiency is largely due to the high percentage of energy dissipated in the pipe leaving pump 2, which conveys most of the flow when reservoirs are supplying water. The original Network 2 experiences a wide variation in energy dissipated and consequently in energy efficiency $e$, which increases throughout the day from 45 to 70% [Fig. 5(a)]. These represent extremes of operation, with large flows in the pipes due to tank filling at the beginning of the simulation, and small flows at the end. The higher efficiency could, thus, not be sustained, and this 24-h period does not represent a full cycle of operation.

During the initial hours of the original Network 2 simulation, both tanks are being filled at a rate that is more than seven times greater than the total demand at junctions. However, less than 10% of the water stored is used during peak flow. Therefore, the rate of tank filling is inconsistent with the rate of draining, generating unnecessarily high flows and head loss. The effects of oversizing tanks go beyond water quality if they are not operated adequately. Tanks are generally filled when electricity prices are lowest, at night, which coincides with low water demand. Nonetheless, the rate at which they are filled must be carefully considered as indicated by the low energy efficiency of Network 2. The principal purpose of tanks is to provide pressure equalization, allowing the system to operate closer to a steady state. If tank demand is unnecessarily high, this is not achieved.

**Table 7.** Elevation and Demand Values for Network 2 Nodes

| Node identifer | Elevation (m) | $Q$ (L s$^{-1}$) |
|---|---|---|
| Res1 | 50.9 | — |
| Res2 | 67.1 | — |
| Tank1 | 39.3 | — |
| Tank2 | 40.2 | — |
| Tank3 | 35.5 | — |
| 10 | 44.8 | 0.0 |
| 15 | 9.8 | 0.1 |
| 20 | 39.3 | 0.0 |
| 35 | 3.8 | 0.1 |
| 40 | 40.2 | 0.0 |
| 50 | 35.5 | 0.0 |
| 60 | 0.0 | 0.0 |
| 601 | 0.0 | 0.0 |
| 61 | 0.0 | 0.0 |
| 101 | 12.8 | 12.0 |
| 103 | 13.1 | 8.4 |
| 105 | 8.7 | 8.5 |
| 107 | 6.7 | 3.4 |
| 109 | 6.2 | 14.6 |
| 111 | 3.0 | 9.0 |
| 113 | 0.6 | 1.3 |
| 115 | 4.3 | 3.3 |
| 117 | 4.1 | 7.4 |
| 119 | 0.6 | 11.1 |
| 120 | 0.0 | 0.0 |
| 121 | −0.6 | 2.6 |
| 123 | 3.4 | 0.1 |
| 125 | 3.4 | 2.9 |
| 127 | 17.1 | 1.1 |
| 129 | 15.5 | 0.0 |
| 131 | 1.8 | 2.7 |
| 139 | 9.4 | 0.4 |
| 141 | 1.2 | 0.6 |
| 143 | −1.4 | 0.4 |
| 145 | 0.3 | 1.7 |
| 147 | 5.6 | 0.5 |
| 149 | 4.9 | 1.7 |
| 151 | 10.2 | 9.1 |
| 153 | 20.2 | 2.8 |
| 157 | 4.0 | 3.3 |
| 159 | 1.8 | 2.6 |
| 161 | 1.2 | 1.0 |
| 163 | 1.5 | 0.6 |
| 164 | 1.5 | 0.0 |
| 166 | −0.6 | 0.2 |
| 167 | −1.5 | 0.9 |
| 169 | −1.5 | 0.0 |
| 171 | −1.2 | 2.5 |
| 173 | −1.2 | 0.0 |
| 177 | 2.4 | 3.7 |
| 179 | 2.4 | 0.0 |
| 181 | 2.4 | 0.0 |
| 183 | 3.4 | 0.0 |
| 184 | 4.9 | 0.0 |
| 185 | 4.9 | 1.6 |
| 187 | 3.8 | 0.0 |
| 189 | 1.2 | 6.8 |
| 191 | 7.6 | 5.2 |
| 193 | 5.5 | 4.5 |
| 195 | 4.7 | 0.0 |
| 197 | 7.0 | 1.1 |
| 199 | −0.6 | 7.5 |
| 201 | 0.0 | 2.8 |
| 203 | 0.6 | 0.1 |
| 204 | 6.4 | 0.0 |
| 205 | 6.4 | 4.1 |
| 206 | 0.3 | 0.0 |



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**Table 7.** (*Continued*.)

| Node identifer | Elevation (m) | $Q$ ($\mathrm{L\,s^{-1}}$) |
|---|---|---|
| 207 | 2.7 | 4.4 |
| 208 | 4.9 | 0.0 |
| 209 | −0.6 | 0.1 |
| 211 | 2.1 | 0.5 |
| 213 | 2.1 | 0.9 |
| 215 | 2.1 | 5.8 |
| 217 | 1.8 | 1.5 |
| 219 | 1.2 | 2.6 |
| 225 | 2.4 | 1.4 |
| 229 | 3.2 | 4.0 |
| 231 | 1.5 | 1.0 |
| 237 | 4.3 | 1.0 |
| 239 | 4.0 | 2.8 |
| 241 | 4.0 | 0.0 |
| 243 | 4.3 | 0.3 |
| 247 | 5.5 | 4.4 |
| 249 | 5.5 | 0.0 |
| 251 | 9.1 | 1.5 |
| 253 | 11.0 | 3.4 |
| 255 | 8.2 | 2.5 |
| 257 | 5.2 | 0.0 |
| 259 | 7.6 | 0.0 |
| 261 | 0.0 | 0.0 |
| 263 | 0.0 | 0.0 |
| 265 | 0.0 | 0.0 |
| 267 | 6.4 | 0.0 |
| 269 | 0.0 | 0.0 |
| 271 | 1.8 | 0.0 |
| 273 | 2.4 | 0.0 |
| 275 | 3.0 | 0.0 |

Because of its high localized head loss, the configuration with larger diameters produced the highest energy efficiency, as shown in Table 10. Accordingly, all of the performance metrics, except for connectivity are also higher in this configuration. Because connectivity is only marginally reduced by decreasing the number of loops, this is the best performing configuration according to the proposed performance index.

Given the failure of this case of Network 2 to maintain stable efficiencies, further modifications were made to the system in order to improve its performance and investigate the effects of tank and pump sizing on system operation. These are the reduced storage, and reduced storage and pumping cases, described before.

Reducing storage in Network 2 resulted in a more stable operation under normal conditions since less flow is being directed to tanks and dissipation is reduced. Nevertheless, vulnerability increased, as there is less storage to meet the extra demands during peak hours. Overall, the average efficiency of 78% is higher than in the original case with more storage, 70%. The energy supplied by pumps increased more than two-fold Table 9, yet the first case uses more tank supply and is not representative of a full cycle of operation. Pressures are also higher in the second case, yet less energy is dissipated.

Simply reducing storage increased energy requirements as less storage is available to meet demands. Furthermore, pressures almost doubled as pumps were now oversized for the given flow. Therefore, a third variation of the system, with reduced pumping capacity as well as reduce storage, was modeled. This significantly reduced pumping requirements and average network pressures, yet did not affect the reliability of the network (Table 10). Efficiencies remained stable and vulnerabilities (minimum efficiencies) even increased.

**Table 8.** Length, Diameter, and Roughness Coefficient Values for Network 2 Pipes

| Pipe identifier | Start node | End node | Length (m) | Diameter (mm) | Roughness coefficient $C$ |
|---|---|---|---|---|---|
| 20 | Tank1 | 20 | 30 | 2,515 | 199 |
| 40 | Tank2 | 40 | 30 | 2,515 | 199 |
| 50 | Tank3 | 50 | 30 | 2,515 | 199 |
| 60 | Res2 | 60 | 375 | 610 | 140 |
| 101 | 10 | 101 | 4,328 | 457 | 110 |
| 103 | 101 | 103 | 411 | 406 | 130 |
| 105 | 101 | 105 | 774 | 305 | 130 |
| 107 | 105 | 107 | 448 | 305 | 130 |
| 109 | 103 | 109 | 1,201 | 406 | 130 |
| 111 | 109 | 111 | 610 | 305 | 130 |
| 112[a] | 115 | 111 | 354 | 305 | 130 |
| 113[a] | 111 | 113 | 512 | 305 | 130 |
| 114 | 115 | 113 | 610 | 203 | 130 |
| 115 | 107 | 115 | 594 | 203 | 130 |
| 116 | 113 | 193 | 506 | 305 | 130 |
| 117 | 263 | 105 | 831 | 305 | 130 |
| 119[a] | 115 | 117 | 664 | 305 | 130 |
| 120 | 119 | 120 | 223 | 305 | 130 |
| 121[a] | 120 | 117 | 570 | 305 | 130 |
| 122[a] | 121 | 120 | 625 | 203 | 130 |
| 123 | 121 | 119 | 610 | 762 | 141 |
| 125 | 123 | 121 | 457 | 762 | 141 |
| 129 | 121 | 125 | 283 | 610 | 130 |
| 131 | 125 | 127 | 988 | 610 | 130 |
| 133 | 20 | 127 | 239 | 508 | 130 |
| 135 | 127 | 129 | 274 | 610 | 130 |
| 137 | 129 | 131 | 1,975 | 406 | 130 |
| 145 | 129 | 139 | 838 | 203 | 130 |
| 147 | 139 | 141 | 625 | 203 | 130 |
| 149 | 143 | 141 | 427 | 203 | 130 |
| 151 | 15 | 143 | 503 | 203 | 130 |
| 153[a] | 145 | 141 | 1,070 | 305 | 130 |
| 155 | 147 | 145 | 671 | 305 | 130 |
| 159 | 147 | 149 | 268 | 305 | 130 |
| 161 | 149 | 151 | 311 | 203 | 130 |
| 163 | 151 | 153 | 357 | 305 | 130 |
| 169[a] | 125 | 153 | 1,390 | 203 | 130 |
| 171 | 119 | 151 | 1,055 | 305 | 130 |
| 173 | 119 | 157 | 634 | 762 | 141 |
| 175 | 157 | 159 | 887 | 762 | 141 |
| 177 | 159 | 161 | 610 | 762 | 141 |
| 179 | 161 | 163 | 131 | 762 | 141 |
| 180 | 163 | 164 | 46 | 356 | 130 |
| 181 | 164 | 166 | 149 | 356 | 130 |
| 183 | 265 | 169 | 180 | 762 | 141 |
| 185 | 167 | 169 | 18 | 203 | 130 |
| 186 | 187 | 204 | 30 | 203 | 130 |
| 187 | 169 | 171 | 387 | 762 | 141 |
| 189 | 171 | 173 | 15 | 762 | 141 |
| 191 | 271 | 171 | 232 | 610 | 130 |
| 193 | 35 | 181 | 9 | 610 | 130 |
| 195 | 181 | 177 | 9 | 305 | 130 |
| 197 | 177 | 179 | 9 | 305 | 130 |
| 199 | 179 | 183 | 64 | 305 | 130 |
| 201 | 40 | 179 | 363 | 305 | 130 |
| 202 | 185 | 184 | 30 | 203 | 130 |
| 203 | 183 | 185 | 155 | 203 | 130 |
| 204 | 184 | 205 | 1,381 | 305 | 130 |
| 205 | 204 | 185 | 404 | 305 | 130 |
| 207 | 189 | 183 | 411 | 305 | 130 |
| 209[a] | 189 | 187 | 152 | 203 | 130 |
| 211 | 169 | 269 | 197 | 305 | 130 |
| 213 | 191 | 187 | 780 | 305 | 130 |
| 215 | 267 | 189 | 375 | 305 | 130 |
| 217[a] | 191 | 193 | 158 | 305 | 130 |

**Table 8.** (*Continued*.)

| Pipe identifier | Start node | End node | Length (m) | Diameter (mm) | Roughness coefficient $C$ |
|---|---|---|---|---|---|
| 219 | 193 | 195 | 110 | 305 | 130 |
| 221[a] | 161 | 195 | 701 | 203 | 130 |
| 223 | 197 | 191 | 351 | 305 | 130 |
| 225 | 111 | 197 | 850 | 305 | 130 |
| 229 | 173 | 199 | 1,219 | 610 | 141 |
| 231 | 199 | 201 | 192 | 610 | 141 |
| 233 | 201 | 203 | 37 | 610 | 130 |
| 235[a] | 199 | 273 | 221 | 305 | 130 |
| 237 | 205 | 207 | 366 | 305 | 130 |
| 238 | 207 | 206 | 137 | 305 | 130 |
| 239 | 275 | 207 | 436 | 305 | 130 |
| 240 | 206 | 208 | 155 | 305 | 130 |
| 241 | 208 | 209 | 270 | 305 | 130 |
| 243 | 209 | 211 | 369 | 406 | 130 |
| 245 | 211 | 213 | 302 | 406 | 130 |
| 247 | 213 | 215 | 1,306 | 406 | 130 |
| 249 | 215 | 217 | 506 | 406 | 130 |
| 251 | 217 | 219 | 625 | 356 | 130 |
| 257 | 217 | 225 | 475 | 305 | 130 |
| 261[a] | 213 | 229 | 671 | 203 | 130 |
| 263 | 229 | 231 | 597 | 305 | 130 |
| 269 | 211 | 237 | 634 | 305 | 130 |
| 271 | 237 | 229 | 241 | 203 | 130 |
| 273 | 237 | 239 | 155 | 305 | 130 |
| 275 | 239 | 241 | 11 | 305 | 130 |
| 277 | 241 | 243 | 671 | 305 | 130 |
| 281[a] | 241 | 247 | 136 | 254 | 130 |
| 283 | 239 | 249 | 131 | 305 | 130 |
| 285 | 247 | 249 | 3 | 305 | 130 |
| 287 | 247 | 255 | 424 | 254 | 130 |
| 289 | 50 | 255 | 282 | 254 | 130 |
| 291 | 255 | 253 | 335 | 254 | 130 |
| 293[a] | 255 | 251 | 335 | 203 | 130 |
| 295 | 249 | 251 | 442 | 305 | 130 |
| 297 | 120 | 257 | 197 | 203 | 130 |
| 299 | 257 | 259 | 107 | 203 | 130 |
| 301 | 259 | 263 | 427 | 203 | 130 |
| 303[a] | 257 | 261 | 427 | 203 | 130 |
| 305 | 117 | 261 | 197 | 305 | 130 |
| 307 | 261 | 263 | 107 | 305 | 130 |
| 309[a] | 265 | 267 | 482 | 203 | 130 |
| 311 | 193 | 267 | 357 | 305 | 130 |
| 313[a] | 269 | 189 | 197 | 305 | 130 |
| 315 | 181 | 271 | 88 | 610 | 130 |
| 317[a] | 273 | 275 | 680 | 203 | 130 |
| 319 | 273 | 205 | 197 | 305 | 130 |
| 321 | 163 | 265 | 366 | 762 | 141 |
| 323 | 201 | 275 | 91 | 305 | 130 |
| 325[a] | 269 | 271 | 393 | 203 | 130 |
| 329 | 61 | 123 | 13,868 | 762 | 140 |
| 330 | 60 | 601 | 0 | 762 | 140 |
| 333 | 601 | 61 | 0 | 762 | 140 |

[a]Pipes not included in the configuration with fewer loops.

For each storage and pumping case, three pipe configurations were modeled, looped, fewer loops, and fewer loops with increased diameters. In every case, the proposed performance index and the resilience indices defined by Todini (2000), Prasad and Park (2004), and Jayaram and Srinivasam (2008) followed the same trend and assigned the configuration with fewer loops and increased diameters the best value. This trend is also observed by simply comparing network reliability, i.e., average energy efficiency, or even average network pressure.

**Table 9.** Average Energy Metrics of the Alternative Configurations of Network 2

| Network | Pump $e_{\text{supplied}}$ (kWh) | $e_{\text{dissipated}} + e_{\text{lost}}$ (kWh) |
|---|---|---|
| Net 2 | 96.0 | 135.1 |
| Net 2 L | 95.7 | 142.0 |
| Net 2 L,D | 77.3 | 99.6 |
| Net 2 S | 207.2 | 115.6 |
| Net 2 S,L | 208.1 | 125.1 |
| Net 2 S,L,D | 204.6 | 88.4 |
| Net 2 S,P | 135.4 | 96.6 |
| Net 2 S,P,L | 135.7 | 106.5 |
| Net 2 S,P,L,D | 135.0 | 70.5 |

Note: D = larger diameters, L = fewer loops; P = reduced pumping; S = reduced storage.

When comparing the different storage and pumping cases, the resilience indices are higher for the case with reduced storage, which experiences notably higher pressures. Because these indices are proportional to power surplus, they are partial to higher pressures, even if these are excessive. Even though the performance indices are similar for these three cases, the reduced storage and pumping case slightly outperforms the others. This is due to its higher resilience and reliability.

Overall, as expected, the performance and resilience indices confirm that networks with greater pipe redundancy perform better. The creation of loops or increase in pipe diameter not only decreases head loss but also reduces its variation. The standard deviation of head loss per kilometer of pipe was found to decrease in these configurations for both example networks. Redundancy at tanks and pumps can increase system efficiency, yet different from pipes, they must be controlled according to operational scenarios. Storage can be used to offset pumping during peak hours and maintain efficiency and pressure levels, as shown in the example Network 1. Nevertheless, tank inflow must be managed in order avoid high dissipation and low pressures, as in the original case of the example Network 2. Therefore, increasing storage and pumping might not necessarily increase performance.

## Discussion

The proposed performance index is based on the assumption that the performance of water distribution networks does not depend only on the ability to deliver adequate flows and pressures, but also on its efficiency in doing so. Previous measures equate demand satisfaction to performance and apply surrogate reliability measures that are proportional to pressure surplus. The present paper argues that above safe operating levels of pressure that ensure good water quality, higher pressures might not translate directly to higher performance.

The applications to the example networks in the previous section show that the resilience indices consistently follow the same trend and vary to a similar degree as the average network pressure. Although the performance index generally follows this same trend, it varies differently and can even be similar for networks with distinct average pressures, as observed in Network 2. Therefore, this enables the comparison of the performance of networks that maintain different, yet safe, pressures. Minimum pressure standards vary internationally, and operational standards can even vary locally according to utility practices.

The performance index integrates three energy efficiency metrics and a network demand connectivity metric. Because they represent the efficiency in delivering demand and pressure, they vary

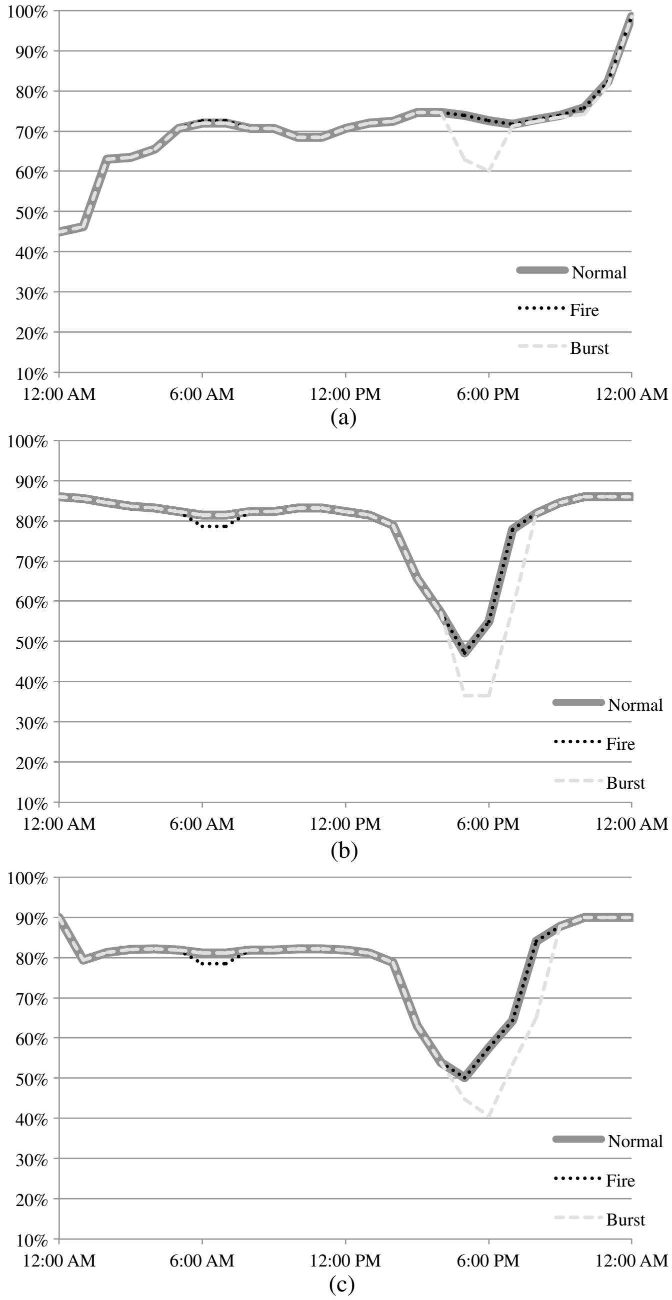


**Fig. 5.** Energy efficiency profile over 24-h simulation for Network 2: (a) original network; (b) reduced storage; (c) reduced storage and pumping

between 0 and 1 and have a physical interpretation, as does the aggregate index. The metrics capture the range of performance of the network. Furthermore, because these metrics comply with the energy and mass balance of the network, they can be applied to any system. Herein, the performance index was applied to two example networks in order to initially assess the method and compare it to previous studies. Nevertheless, the metrics can be applied to the analysis of real water systems with more scenarios, including potential simultaneous failure.

Even though the performance index consistently followed the same trend as the reliability and resilience of the example networks, the vulnerability and connectivity metrics helped distinguish between networks with similar average efficiency. In the present study, the metrics received equal weighting in the performance index. This can readily be altered to better reflect the priorities of decision makers and stakeholders. Using a single performance index can also be controversial if it oversimplifies system conditions. Nevertheless, it can facilitate comparisons and if used in decision making, this index would be part of a multiobjective analysis including other measures and constraints. Therefore, balancing four additional performance metrics instead of one adds unnecessary computational costs.

## Conclusions

An efficiency-based performance index is proposed. Unlike previous reliability and resilience metrics, which evaluate the network's ability to deliver a given set of flows and pressures, the new measure also emphasizes the efficiency of this delivery. The index integrates four submetrics: reliability, the average efficiency of the network under all conditions; vulnerability, the minimum efficiency of the network; resilience, average efficiency after a period of failure (vulnerability); and connectivity, minimum percentage of flow delivered despite a pipe burst.

This index was applied to the analysis of two example networks with different configurations and compared to previous resilience indices. All of the indices indicated, as expected, that increasing pipe redundancy, whether through larger pipe diameters or additional loops, increases performance. Not only does it increase efficiency, it also reduces its variability. The redundancy of pumps and tanks, however, must be controlled according to demands in order to maintain pressures and efficiencies.

Although the proposed index generally follows the same trend as the previous indices, such as generally increasing with network pressure, it varies differently in important ways. For instance, it is not unduly responsive to power surplus and is able to compare networks that efficiently maintain different, yet safe, levels of pressure. Furthermore, because it is based on efficiency metrics, it has a

**Table 10.** Proposed Performance Metrics, Resilience Index (Todini 2000), Network Resilience Index (Prasad and Park 2004), Modified Resilience Index (Jayaram and Srinivasam 2008), and Average Pressure of the Alternative Configurations of Network 2

| Network | Rel | Vul | Res | Con | PI | RI | NRI | MRI | Avg P |
|---|---|---|---|---|---|---|---|---|---|
| Net 2 | 0.70 | 0.45 | 0.66 | 0.94 | 0.66 | 0.45 | 0.41 | 0.48 | 52.38 |
| Net 2 L | 0.68 | 0.45 | 0.66 | 0.92 | 0.66 | 0.39 | 0.37 | 0.44 | 51.77 |
| Net 2 L,D | 0.77 | 0.50 | 0.72 | 0.92 | **0.71** | **0.62** | **0.59** | **0.66** | **55.79** |
| Net 2 S | 0.78 | 0.36 | 0.80 | 0.94 | 0.68 | 0.85 | 0.77 | 1.90 | 99.34 |
| Net 2 S,L | 0.77 | 0.28 | 0.80 | 0.92 | 0.63 | 0.82 | 0.77 | 1.86 | 98.53 |
| Net 2 S,L,D | 0.82 | 0.45 | 0.85 | 0.92 | **0.73** | **0.92** | **0.87** | **2.04** | **104.28** |
| Net 2 S,P | 0.78 | 0.41 | 0.78 | 0.94 | 0.69 | 0.79 | 0.72 | 1.32 | 78.10 |
| Net 2 S,P,L | 0.76 | 0.34 | 0.78 | 0.92 | 0.66 | 0.74 | 0.70 | 1.26 | 77.01 |
| Net 2 S,P,L,D | 0.83 | 0.45 | 0.86 | 0.92 | **0.74** | **0.88** | **0.84** | **1.45** | **82.96** |

Note: D = larger diameters; L = fewer loops; P = reduced pumping; S = reduced storage; the best performing networks according to each index are indicated in bold.

direct and simple physical interpretation. This also indicates that the index complies with the energy and mass balances of the network. It can thus be applied with reasonable confidence to real networks. Even though the index was provisionally applied to only three demand scenarios (normal, fire, and pipe burst), it can be easily adapted to multiple scenarios, including simultaneous failures.

## References


Atkinson, S., Farmani, R., Memon, F. A., and Butler, D. (2014). "Reliability indicators for water distribution system design: Comparison." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000304, 160–168.

Awumah, K., Goulter, I., and Bhatt, S. K. (1990). "Assessment of reliability in water distribution networks using entropy based measures." *Stochastic Hydrol. Hydraul.*, 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 Resour. Manage.*, 25(10), 2351–2366.

Biomimicry 3.8 Institute. (2011). *Life's principles: Design lessons from nature*, Missoula, MT.

Blokker, E. J. M., Vreeburg, H. G., and van Dijk, J. C. (2010). "Simulating residential water demand with a stochastic end-use model." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000002, 19–26.

Cabrera, E., Pardo, M. E., Cobacho, R., and Enrique, C., Jr. (2010). "Energy audit of water networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000077, 669–677.

Creaco, E., Fortunato, A., Franchini, M., and Mazzola, M. R. (2014). "Comparison between entropy and resilience as indirect measures of reliability in the framework of water distribution network design." *12th Int. Conf. on Computing and Control for the Water Industry: Procedia Engineering*, Vol. 70, Elsevier, 379–388.

Di Nardo, A., Di Natale, M., Santonastaso, G. F., Tzatchkov, V. G., and Alcocer-Yamanaka, V. H. (2014). "Water network sectorization based on graph theory and energy performance indices." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000364, 620–629.

Dziedzic, R. M., and Karney, B. W. (2013). "Energy metrics for water distribution assessment." *Proc., 46th Annual Stormwater and Urban Water Systems Modeling Conf.*, CHI Press.

Fiering, M. B. (1982a). "Alternative indices of resilience." *Water Resour. Res.*, 18(1), 33–39.

Fiering, M. B. (1982b). "Estimating resilience by canonical analysis." *Water Resour. Res.*, 18(1), 51–57.

Goulter, I., Walski, T. M., Mays, L. W., Sakarya, A. B. A., Bouchart, F., and Rung, Y. K. (2004). "Hydraulic design of water distribution storage tanks." Chapter 18, *Water distribution systems handbook*, L. W. Mays, ed., McGraw Hill, New York.

Greco, R., Di Nardo, A., and Santonastaso, G. (2012). "Resilience and entropy as indices of robustness of water distribution networks." *J. Hydroinf.*, 14(3), 761–771.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). "Reliability, resiliency and vulnerability criteria for water resource system performance evaluation." *Water Resour. Res.*, 18(1), 14–20.

Ho, M. W., and Ulanowicz, R. (2005). "Sustainable systems as organisms?" *BioSystems*, 82(1), 39–51.

Holling, C. S. (1973). "Resilience and stability of ecological systems." *Ann. Rev. Ecol. Syst.*, 4(1), 1–23.

Holling, C. S. (1996). "Engineering resilience versus ecological resilience." *Engineering within ecological constraints*, P. C. Schulze, ed., National Academy Press, Washington, DC, 31–44.

ISO (International Standards Organization). (2008). *Guide for determination of needed fire flow*, ISO Properties, Jersey City, NJ.

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.

Katifori, E., Szöllõsi, G. J., and Magnasco, M. O. (2010). "Damage and fluctuations induce loops in optimal transport networks." *Phys. Rev. Lett.*, 104(4), 048704.

Klein, R. J. T., Nicholls, R. J., and Thomalla, F. (2003). "Resilience to natural hazards: How useful is this concept?" *Environ. Hazards*, 5(1), 35–45.

Klemes, V., Srikanthan, R., and McMahon, T. A. (1981). "Long-memory flow models in reservoir analysis: What is their practical value?" *Water Resour. Res.*, 17(3), 737–751.

Lambert, A., Huntington, D., and Brown, T. G. (2000). "Water loss management in North America—Just how good is it?" *American Water Works Association Distribution Systems Symp.*, New Orleans.

Lambert, A. (2001). "What do we know about pressure: Leakage relationships in distribution systems?" *Proc., System Approach to Leakage Control and Water Distribution Systems Management*, IWA, London.

Loucks, D. P., and van Beek, E. (2005). "Water resources systems planning and management." United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.

McMahon, T. A., Adeloye, A. J., and Sen-Lin, Z. (2006). "Understanding performance measures of reservoirs." *J. Hydrol.*, 324(1–4), 359–382.

MEA (Municipal Engineers Association). (1977). "Water distribution system design." Chapter 4, *Municipal works design manual*, Municipal Engineers Association, Oshawa, ON.

Moy, W.-S., Cohon, J. L., and ReVelle, C. S. (1986). "A programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir." *Water Resour. Res.*, 22(4), 489–498.

National Research Council. (2006). *Drinking water distribution systems: Assessing and reducing risks*, National Academies Press, Washington, DC.

Ostfeld, A. (2001). "Reliability analysis of regional water distribution systems." *Urban Water*, 3(4), 253–260.

Ostfeld, A. (2004). "Reliability analysis of water distribution systems." *J. Hydroinf.*, 6(4), 281–294.

Ostfeld, A., Kogan, D., and Shamir, R. (2002). "Reliability simulation of water distribution systems—Single and multiequality." *Urban Water*, 4(1), 53–61.

Pimm, S. L. (1984). "The complexity and stability of ecosystems." *Nature*, 307(5949), 321–326.

Prasad, T. D., and Park, N. S. (2004). "Multiobjective genetic algorithms for design of water distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2004)130:1(73), 73–82.

Rossman, L. A. (2000). "EPANET 2 users manual." National Risk Management Research Laboratory, Cincinnati.

Solis, S. S., McKinney, D. C., and Loucks, D. P. (2011). "Sustainability index for water resources planning and management." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000134, 381–390.

Tanyimboh, T. T., and Templeman, A. B. (2000). "A quantified assessment of the relationship between the reliability and entropy of water distribution systems." *Eng. Optim.*, 33(2), 179–199.

Timmerman, P. (1981). *Vulnerability, resilience and the collapse of society: A review of models and possible climatic applications*, Institute for Environmental Studies, Univ. of Toronto, Canada.

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

USBR (U.S. Dept. of the Interior Bureau of Reclamation). (2006). "Potential water distribution system pressure zone layout and preliminary review of fireflow requirements." Washington, DC.

Walski, T. M. (2004). "Hydraulic design of water distribution storage tanks." Chapter 10, *Water distribution systems handbook*, L. W. Mays, ed., McGraw Hill, New York.

Yazdani, A., Otoo, R. A., and Jeffrey, P. (2011). "Resilience enhancing expansion strategies for water distribution systems: A network theory approach." *Environ. Model.*, 26(12), 1574–1582.

Ysusi, M. A. (1999). "Water distribution system design." Chapter 11, *Hydraulic design handbook*, L. W. Mays, ed., McGraw Hill, New York.

Zhuang, B., Lansey, K., and Kang, D. (2013). "Resilience/availability analysis of municipal water distribution system incorporating adaptive pump operation." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000676, 527–537.




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