Reliability analysis of water distribution systems

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ABSTRACT

Reliability is an integral part of all decisions regarding water distribution system layout, design, operation and maintenance. Providing reliability for water distribution systems is complicated due to the many factors that affect reliability, the inherent nonlinear behavior of the system and its consumers, and due to the different conflicting objectives facing a water distribution system utility. Although the reliability of water distribution systems has received considerable attention over the last two decades, there is still no common, acceptable, reliability measure or reliability assessment methodology. This paper describes the classification and reliability analysis methodologies of water distribution systems and compares two previously published algorithms for reliability evaluation of water distribution systems: a tailor-made 'lumped supply–lumped demand' approach used most commonly in regional water distribution systems and a general stochastic (Monte Carlo) framework suitable for any generic network.

Key words | EPANET, RAP, RAPTOR, reliability, stochastic simulation, water distribution system

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INTRODUCTION

Reliability is an inherent attribute of any system, referring to its ability to perform a mission adequately under stated environmental conditions for a prescribed time interval. No system is entirely reliable. In every system, undesirable events, i.e. failures, can cause decline or interruptions in the system performance. Failures are of a stochastic nature and are the result of unpredictable events that occur in the system itself and/or at its surrounding environment.

This paper describes the reliability analysis of water distribution systems and compares two different algorithms for reliability evaluation of water distribution systems: Ostfeld (2001)—a tailor-made methodology for regional water distribution systems based on RAPTOR (Carter *et al.*, 1997) and Ostfeld *et al.* (2002)—a general stochastic simulation framework based on EPANET (USEPA, 2002).

Reliability in general, and that of a water distribution system in particular, is a measure of performance. A system is said to be reliable if it functions properly for a specified time interval under prescribed environmental conditions. While the question 'is the system reliable?' is usually understood and easy to answer, the question 'is it reliable enough?' does not have a straightforward response, as it requires both the quantification and calculation of reliability measures.

Reliability considerations for water distribution systems are an integral part of all decisions regarding the planning, design and operation phases. A major problem in the reliability analysis of water distribution systems is to define reliability measures that are meaningful and appropriate, while still being computationally feasible. Traditionally, reliability is provided by following certain heuristic guidelines, like ensuring two alternative paths to each demand node from at least one source, or having all pipe diameters greater than a minimum prescribed value. By using these guidelines, it is implicitly assumed that reliability is assured, but the level of reliability provided is not quantified or measured. Therefore, only limited confidence can be placed in these guidelines, as reliability is not considered explicitly.

LITERATURE REVIEW

A review of the literature reveals that there is no single universally acceptable measure for the reliability of water distribution systems. This is because reliability analysis requires both the quantification of reliability measures that are meaningful and appropriate, while still being computationally feasible—an attribute which is system-dependent. Reliability assessment methods can be categorized into (1) connectivity/topological, (2) hydraulic and (3) entropy as a reliability surrogate.

Connectivity/topological reliability refers to measures associated with the probability that a given network remains physically connected; given its component reliabilities (i.e. the probability that a component remains operational over a given time interval under prescribed environmental conditions). Wagner *et al*. (1988*a*) applied analytical methods using the algorithms of Satyanarayana & Wood (1982) and Rosenthal (1977) for computing (1) connectivity—the probability that a given demand node in the system is connected to a source—and (2) reachability—the probability that all demand nodes in a system are connected to a source. Shamsi (1990) and Quimpo & Shamsi (1991) used node pair reliability (NPR) as the system reliability measure. The NPR is defined as the probability that a specific source and demand nodes are connected. This definition corresponds to the probability that at least one path is functional between the source node and the demand node considered. The NPR values were used to draw a contour map for establishing a maintenance strategy, giving priorities to areas with low NPRs. Goulter (1987) noted that network reliability is, in fact, defined, or more specifically constrained, by the fundamental layout of the network. Networks with better shapes (i.e. with more redundancy in terms of interconnections, etc.) will be more reliable. Jacobs & Goulter (1988) have shown that the optimally reliable network for a specified number of links in a set of nodes is regular (i.e. has an equal number of links incident on each node). Jacobs & Goulter (1989) have explored the impacts of using the regular graph target for the layout of water distribution networks. Measures used within this category do not consider the level of service provided to the consumers during a failure. The existence of a path between a consumer and a node is only a necessary condition for supplying its required demands. The motivation for using such measures is in providing initial screening for identifying parts of the system with low topological reliabilities.

Hydraulic reliability is the probability of supplying the consumer's demands. It thus refers directly to the fundamental task of a water distribution system: conveyance of desired quantities and qualities of water at required pressures to the appropriate locations at the appropriate times. Since the system is subject to random failures, component reliability and connectivity/topological reliability aspects must be explicitly considered.

An 'accurate' calculation of the hydraulic reliability of a given system requires data on its entire component reliabilities and their associated failures' impacts on the consumer's demands. This is a computationally infeasible task. Hydraulic reliability is thus evaluated using stochastic (Monte Carlo) simulation. Wagner *et al*. (1988*b*) used stochastic simulation through (1) a simulation section generating failure and repair events for pipes and pumps, according to specified component probability distributions and (2) a hydraulic network solver simulating the distribution of flow and pressure. The model is used to calculate a number of reliability measures, such as the percentage of failure time for each pump and pipe, or the total unmet demand at the consumer nodes. Bao & Mays (1990) used stochastic simulation to calculate (1) nodal reliabilities defined for each node as the probability of receiving a sufficient flow rate at a required pressure head and (2) system reliability defined as the mean of the nodal reliabilities. Su *et al*. (1987) used the cut-set approach to measure hydraulic reliability, involving simulations of all the combinations of pipe failures and their impacts on consumers' demands. The reliability of the system is defined as the complement of the probability of no minimum cut-set. Cullinane *et al*. (1992) incorporated availability as a reliability constraint in an overall optimal design problem of a water distribution system, with availability defined as the percentage of time for which the demand can be supplied at or above the required minimum pressure. Fujiwara & Ganesharajah (1993) expanded the Markov chain approach, proposed by Biem & Hobbs (1988) for assessing the reliability of water supply systems with bulk supply and bulk demand to water distribution systems. The system modeled includes a treatment plant, ground level storage, pumps and a distribution network. The model considers failures of the pumping stations, the pipes and demand fluctuations. The reliability measure employed is the ratio of the expected maximum total water supplied to the total water demanded. Xu & Goulter (1998) developed a probabilistic model for water distribution reliability recognizing uncertainties in nodal demands, pipe capacity, reservoir/tank levels and availability of system components. The methodology comprises derivations of the probability distribution functions of the nodal heads, using a linearized hydraulic model based on known probability distribution functions of the nodal demands, pipe roughnesses and reservoir/tank levels, and combining these probabilities with the probabilities of different system configurations and demand levels. The outcome is a reliability measure for the entire system, or for a specific portion of it. Shinstine *et al.* (2001) applied an existing reliability model (Su *et al.*, 1987), based on a minimum cut-set method linked to a steady-state simulation model, that implicitly solves the continuity and energy equations for two large-scale municipal water distribution networks in the Tucson Metropolitan Area. The measure of reliability was defined as the probability of satisfying nodal demands and pressure heads for various possible pipe failures (breaks) in the water distribution system at any given time. Weintrob *et al.* (2001) used an accelerated Monte Carlo method (Lieber *et al.*, 1999) to reduce the number of simulations required in a conventional stochastic (Monte Carlo) algorithm. The model is based on iteratively solving a Linear Programming (LP) model that approximates the water distribution system behavior, recording unfeasible solutions as system failures instances. The model was applied to two networks taken from the research literature.

Entropy, as a surrogate measure for reliability, has been used by several researchers during the past 15 years (Awumah *et al.*, 1990, 1991; Awumah & Goulter, 1992; Tanyimboh & Templeman, 1993, 2000). The fundamental idea is to use Shannon's (1948) entropy measure of uncertainty that quantifies the amount of information contained in a finite probability distribution, to measure the inherent redundancy of a network (i.e. if a particular component is out of service, are there other paths through the network to supply the affected nodes?). In this regard, entropy is more related to the category of connectivity/topological analysis than to that of hydraulic reliability. It is assumed that distribution systems, which are designed to carry maximum entropy flows, are generally reliable. Awumah *et al.* (1990, 1991) used entropy to quantify the reliability of a single-source gravitational water distribution system under one loading condition. Entropy criteria were calculated and compared to the NPR measure suggested by Shamsi (1990) and Quimpo & Shamsi (1991). Awumah & Goulter (1992) maximized the entropy measures suggested by Awumah *et al.* (1990, 1991) in an overall optimal design model for water networks. Tanyimboh & Templeman (1993) suggested algorithms for maximizing entropy flows for single-source networks and Tanyimboh & Templeman (2000) summarized the existing attempts to explore the relationships between reliability and entropy. Although more than a decade of research has passed, it is still an open question of what a given level of entropy means in terms of reliability for a particular system. Table 1 summarizes the literature review.

An excellent reference, summarizing methods for assessing the reliability of water distribution systems, was published by the ASCE Task Committee on Risk and Reliability Analysis of Water Distribution Systems (Mays, 1989).

Currently, the quality of the water supplied is a growing concern and 'water' is no longer considered a single commodity; water distribution systems are becoming multi-commodity systems. Waters of different qualities are taken from sources, possibly treated, mixed in the system and supplied as a blend. Such systems are termed Multi-quality Water Distribution Systems (MWDS), serving all three types of consumers: municipal, industrial and agricultural.

The remainder of this paper compares the methodologies of two different reliability simulation models and approaches: the first (Ostfeld, 2001) is a tailor-made methodology suitable for 'lumped supply–lumped demand' water distribution systems, commonly representing regional water distribution systems; the second (Ostfeld *et al.*, 2002) is a general stochastic simulation framework for both quantity and quality reliability indices suitable for any generic network.

Table 1 | Literature review summary

Category	Authors	Reliability measure (s)	Methodology	Applications
Connectivity/ topological	Goulter (1987)	General overview/trends.	Overview.	Overview.
	Jacobs & Goulter (1988)	Enumeration of all possible combinations of working/ non-working system components	State enumeration, filtering and heuristic procedures	Six small illustrative examples
	Wagner *et al.* (1988*a*)	Connectivity–the probability that a given demand node is connected to a source; and, Reachability–the probability that all demand nodes in a system are connected to a source	Graph theory algorithms (Satyanarayana & Wood 1982; Rosenthal 1977)	'Lumped supply–lumped demand', small illustrative series-parallel systems and small illustrative looped networks
	Jacobs & Goulter (1989)	Redundancy measures arising from system layout	Integer goal programming	AnyTown USA (Walski *et al.* 1987)
	Shamsi (1990)	NPR = node pair reliability–the probability of two nodes been connected	Minimal path-sets/minimal cut-sets	Small illustrative looped network
	Quimpo & Shamsi (1991)	NPR = node pair reliability–the probability of two nodes been connected	Minimal path-sets/minimal cut-sets	Small illustrative looped network, and City of Norwich, State of New-York Hydraulic
Hydraulic	Su *et al.* (1987)	The probability of satisfying nodal demands and pressure heads for various possible pipe failures	Minimum cut-set	Small illustrative looped network
	Wagner *et al.* (1988*b*)	List of: Even-Related, Node-Related, Link-Related, System-Related (see appendix I in Wagner *et al.* (1988*a*))	Stochastic (Monte Carlo) simulation	Small illustrative, and AnyTown USA (Walski *et al.* 1987)
	Bao & Mays (1990)	Probability of providing demand flowrate at required pressure head	Stochastic (Monte Carlo) simulation	Small illustrative looped network
	Cullinane *et al.* (1992)	Availability = the proportion of time the system satisfactory fulfils its function–minimum pressure at consumer nodes	Hydraulic simulation linked with non-linear optimization	Small illustrative looped examples
	Fujiwara & Ganesharajah (1993)	Expected served demand	Markov chain approach	Small illustrative two-looped system, with a treatment plant, pumping units and a ground-level storage

Table 1 | Continued

Category	Authors	Reliability measure (s)	Methodology	Applications
	Xu & Goulter (1998)	Probability of meeting nodal demands, at or above a minimum prescribed pressure	Two-stage stochastic assessment method based on a linearized hydraulic model	Illustrative example
	Shinstine *et al.* (2001)	The probability of satisfying nodal demands and pressure heads for various possible pipe failures	Minimum cut-set (Su *et al.* 1987)	Two large-scale municipal water distribution networks, Tucson, AZ
	Weintrob *et al.* (2001)	Required demands at acceptable pressures	Fast stochastic simulation (Lieber *et al.* 1999) + a linear optimization model	EPANET Example 3 (Rossman 2002)
	Ostfeld (2001)	Probability of zero annual shortage	'Lumped supply–lumped demand' analysis + stochastic simulation	The regional water supply system of Nazareth, Israel
	Ostfeld *et al.* (2002)	Probability of Fraction of Delivered Volume (FDV), Fraction of Delivered Demand (FDD), and Fraction of Delivered Quality (FDQ)	Stochastic (Monte Carlo) simulation	EPANET Examples 1 and 3 (Rossman 2002)
Entropy	Awumah *et al.* (1990, 1991)	Surrogates for redundancy using entropy measures of flow in pipes and consumptions at nodes	Simple entropy reliability expression calculations.	Illustrative examples
	Awumah & Goulter (1992)	Entropy based measures based on flow and consumption	Entropy measures as constraints in optimal design of water distribution systems; use of non-linear optimization	Illustrative example
	Tanyimboh & Templeman (1993)	Entropy based measures based on flow and consumption	Tailored maximum entropy flow algorithm for single-source networks	Small illustrative
	Tanyimboh & Templeman (2000)	Entropy based measures based on flow and consumption—summarizing previous work.	Tailored maximum constrained approach	Small illustrative

MODEL I: REGIONAL WATER DISTRIBUTION SYSTEMS RELIABILITY SIMULATION (OSTFELD, 2001)

Regional water distribution systems serve as the hydraulic connections (supplying quantities of water at minimum pressures) between sources (wells, reservoirs) and inlets to municipal regions. As such, these systems usually consist of a few hydraulic control elements and may be categorized as ‘lumped supply–lumped demand’ (Wagner *et al.*, 1988*a*). A ‘lumped supply–lumped demand’ system is one that can be modeled as a single aggregated consumer, fed by a single aggregated storage reservoir and a single aggregated source.

The methodology, described in detail in Ostfeld (2001), consists of two interconnected stages: (1) storage–analysis of the trade-off between storage capacity, water delivery capacity and annual durations of shortfall and (2) stochastic simulation using the outcome of stage 1 through the use of the American Air Force Rapid Availability Prototyping for Testing Operational Readiness (RAPTOR) software (Carter *et al.*, 1997). Descriptions of these two stages follow.

Stage 1: storage conveyance analysis

For a given water delivery capacity and storage pair, a sequence of consumer demands is to be met from the aggregated source and the aggregated storage. If, at a specific time, the consumer demand is fully met by the water delivery capacity, then the difference between the water delivery capacity and the consumer demand feeds the aggregated storage; if the water delivery capacity is less than the consumer demand, then the difference needed to fulfil the consumer demand is supplied from the aggregated storage; if the aggregated storage plus the water delivery capacity fail to meet the consumer demand, then a shortfall (and its duration) is recorded.

Running the consumer demand sequence through a grid of storage capacity versus water delivery capacity pairs results in a graph of isoreliability lines (or isolines of shortfall durations) for the system considered. Such a graph for the Nazareth regional water distribution system is shown in Figure 1. Point A in Figure 1 shows the regular water delivery capacity versus storage (i.e. no component failure), while point B, the water delivery capacity versus storage after a failure occurred, that is approximately at an isoline of four hours of annual shortfall.

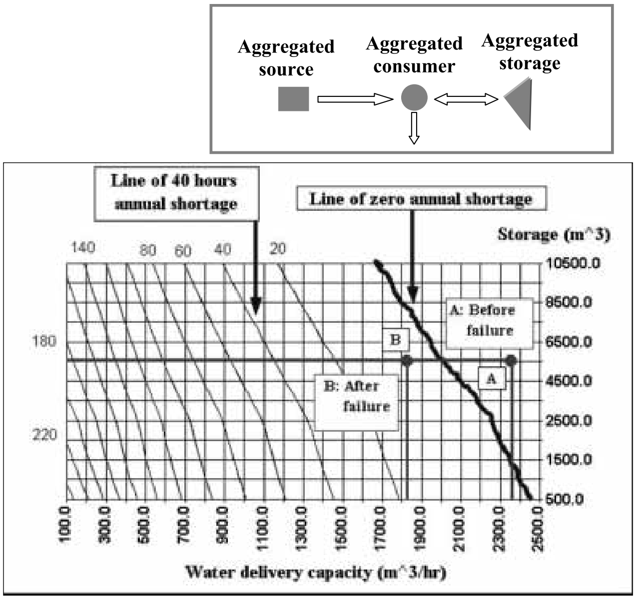


Figure 1 | Shortages analysis—storage versus water delivery capacity.

The storage conveyance analysis is accomplished assuming that all system components are operational and therefore constitutes an expression of the ability of the system to satisfy the consumers’ demand, where the only constraint is the required consumption quantities. As such, it provides only a deterministic indication of the reliability level of the system; it does not define the ‘probability distance’ from a given storage conveyance design point to a given isoline of shortfall duration once failures are considered. This ‘probability distance’, which is a function of the system redundancy, the system component reliabilities and the system maintenance level, is the reliability quantification of the system. It is ‘measured’ using stochastic simulation based on RAPTOR. This is stage 2 of the methodology.

Stage 2: stochastic simulation using RAPTOR

RAPTOR is a public domain stochastic modeling simulation environment for the creation of Reliability,

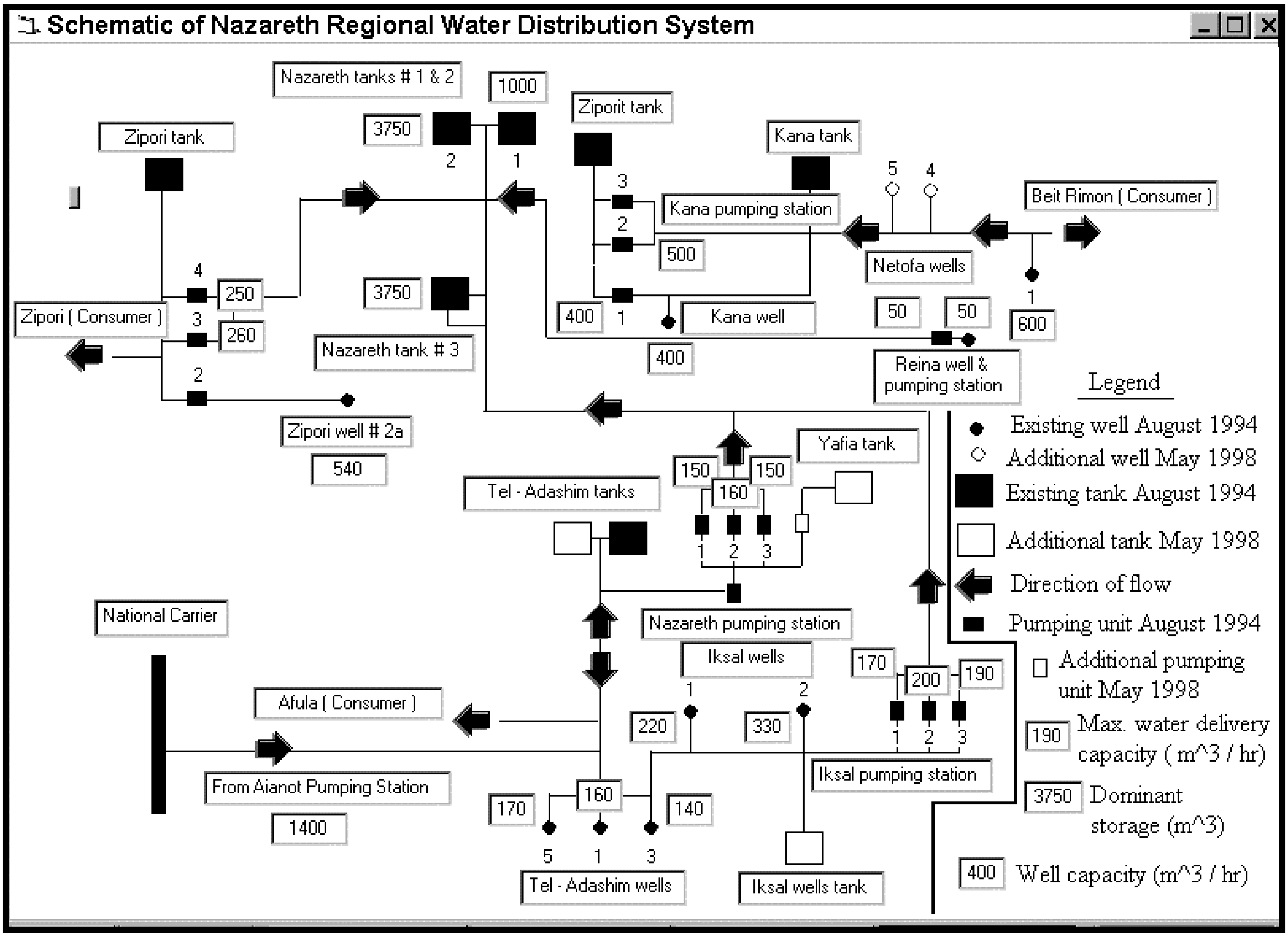


Figure 2 | Schematic of Nazareth regional water distribution system.

Availability and Maintainability (RAM) models. The user models his system graphically by drawing a Reliability Block Diagram (RBD), comprising reliability blocks connected through '*k*-out-of-*n*' nodes, where a '*k*-out-of-*n*' node is a node for which *k* (out of *n*) inlet paths are required in order for the node to be considered 'up' (i.e. in an operational mode). As the blocks fail and repair randomly during simulation, system-level reliability, maintainability and availability parameters are determined.

The definitions of the reliability blocks and the connecting '*k*-out-of-*n*' nodes comprise the entire Reliability Block Diagram (RBD). The RBD is the model representation of the system used for 'measuring' the 'probability distance' between an existing (or planned) water delivery capacity–storage point and an iso shortfall line. The 'probability distance', measured through running RAPTOR, serves as the system reliability quantification. The following is an example application.

Figure 2 is a schematic representation of the Nazareth regional water distribution system, showing its status as of August 1994 and expansions as of May 1998. The sources of the system are the National Water Carrier and regional wells (e.g. Tel-Adashim wells, Iksal wells). The system discharges to the elevated storage tanks of Nazareth (tanks 1, 2 and 3), from which water is supplied to the consumers.

Figures 3 and 4 present the pumping units' time to failure and time to repair probability cumulative

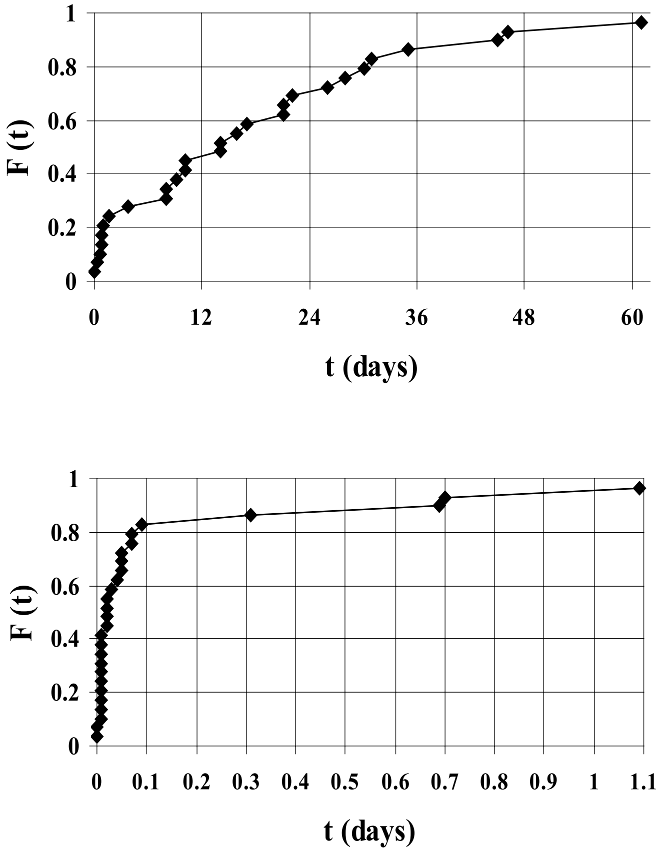


Figure 3 | Pumping units' time to failure (top) and time to repair (bottom) probability cumulative distribution functions.

distribution functions and the wells' time to failure and time to repair probability cumulative distribution functions, respectively, used in the analysis. The data are based on real-time field measurements of the system components.

Figure 5 illustrates the RBD schematic for the Nazareth regional water distribution system, including its design final stage expansions as represented in RAPTOR. The upper part of Figure 5 describes a 'Green' run of the system, resembling a situation in which all system components are functioning. The middle part shows a 'Red' run state during stochastic simulation, where a 'Red' state is one in which some blocks on the critical path in the RBD are failed, causing the overall system to be in a failure mode (the 'Yellow' node corresponds to a node in which some of the inlet paths are down, but still not causing the entire system to fail). The bottom part of Figure 5 shows the stochastic accumulated information on the system performance, gathered through the simulations: Ao (availability) = the percentage of time the system is in either 'Green' or 'Yellow' states; MTBDE = Mean Time Between Downing Events—the average time between events which bring the entire system down; MDT = Mean Down Time—the average amount of time the entire system is down; MTBM = Mean Time Between Maintenance—the total uptime of the system divided by the total number of failures of all blocks; MRT = Mean Repair Time—the average amount of time it takes to repair any block in the system; % Green Time = the percentage of time the system is in a Green state (i.e. no failures); % Yellow Time = the percentage of time the system is in a Yellow state (i.e. blocks are out of service but the entire system is 'up'); % Red Time = the percentage of time the system is in a Red state (i.e. the entire system failed) and System Failures = the number of times the entire system was 'down'.

Figure 6 shows the reliabilities (i.e. the probabilities of zero annual shortfalls) versus costs for the regional water distribution system of Nazareth. The system reliabilities obtained were: 0.864 as of August 1994, 0.923 for the expansions as of May 1998 and 0.993 for the final design stage. The additional costs for obtaining those reliabilities were: 7.53 million New Israeli Shekels (NIS) (NIS 1~US$0.25) for May 1998 and 43.61 million NIS for the final design stage.

MODEL II: RELIABILITY ANALYSIS PROGRAM (RAP) (OSTFELD *et al.*, 2002)

A detailed description of RAP can be found in Ostfeld *et al.* (2002). RAP quantifies through stochastic (Monte Carlo) simulation, using EPANET (USEPA, 2002), three water distribution reliability measures: the Fraction of Delivered Volume (FDV), the Fraction of Delivered Demand (FDD) and the Fraction of Delivered Quality (FDQ).

The Fraction of Delivered Volume (FDV) is the sum of the total volumes delivered to a consumer node in all

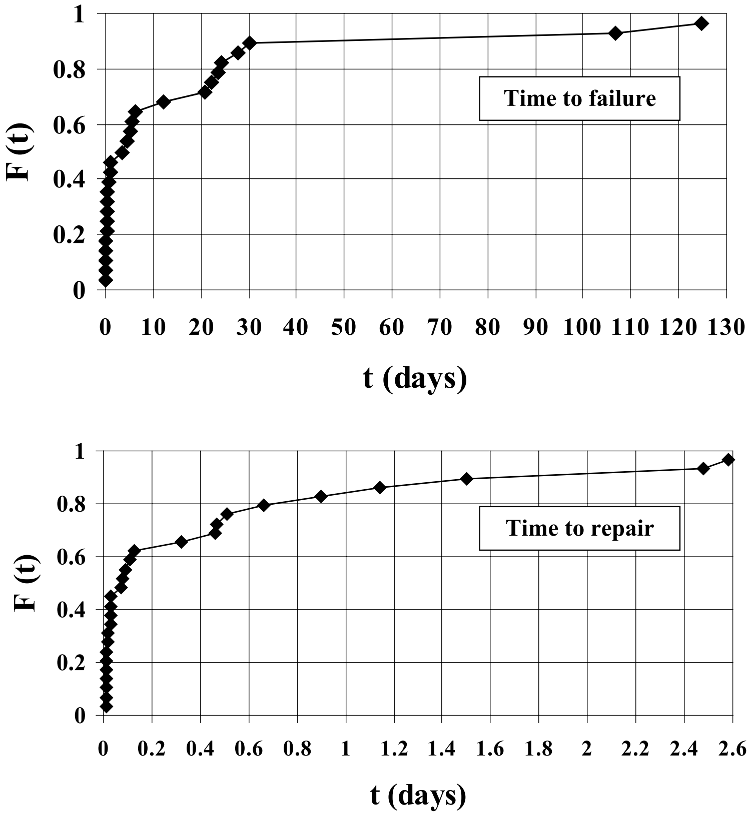
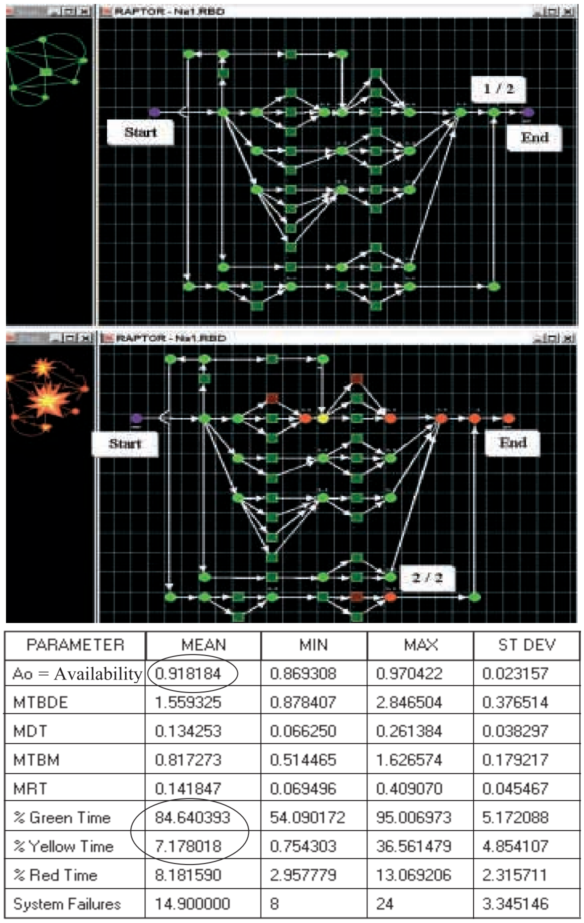


Figure 4 | Wells' time to failure and time to repair probability cumulative distribution functions.

simulation runs divided by the sum of the total volumes requested by the consumer over all the simulation runs; the Fraction of Delivered Demand (FDD) is the sum of all time periods in all simulation runs for which the demand supplied at a consumer node is above a demand factor (i.e. the system is 'up') divided by the total number of simulation runs multiplied by a demand cycle (e.g. 24 hours) and the Fraction of Delivered Quality (FDQ) is the sum of all time periods in all simulation runs for which the concentration supplied at a consumer node is below a threshold concentration factor divided by the total number of simulation runs multiplied by a demand cycle.

EPANET was developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the US Environmental Protection Agency's National Risk Management Research Laboratory. It is an extended-period simulator of hydraulic and water quality constituents within pressurized pipe networks. EPANET tracks flow and chemical concentrations in each pipe, the pressure at each node and the water level in each tank. In addition to chemical species, water age and source tracing can also be simulated. EPANET provides an integrated environment for editing network input data, running extended-period hydraulic and water quality simulations, and data display in a variety of formats, including color-coded network maps, data tables, time series graphs and contour plots. The EPANET Toolkit allows customization of EPANET for specific targets (e.g. development of RAP).

Figure 7 illustrates a snapshot of the RAP interface. Figure 8 shows the results of applying RAP to a moderate municipal water network (Example 3 of the EPANET User's Manual). The network consists of two sources, three elevated tanks, 117 pipes, 97 demand nodes and two pumps.



PARAMETER	MEAN	MIN	MAX	ST DEV
Ao = Availability	0.918184	0.869308	0.970422	0.023157
MTBDE	1.559325	0.878407	2.846504	0.376514
MDT	0.134253	0.066250	0.261384	0.038297
MTBM	0.817273	0.514465	1.626574	0.179217
MRT	0.141847	0.069496	0.409070	0.045467
% Green Time	84.640393	54.090172	95.006973	5.172088
% Yellow Time	7.178018	0.754303	36.561479	4.854107
% Red Time	8.181590	2.957779	13.069206	2.315711
System Failures	14.900000	8	24	3.345146

Figure 5 | Snapshots from RAPTOR.

The FDV, FDD and FDQ maps in Figure 8 represent domains of reliability values. These are the main outcomes of RAP, allowing for a visual identification of portions of a given network with low reliability values for easy comparisons and analysis.

COMPARING MODELS I AND II

Model I (Ostfeld, 2001) and Model II (Ostfeld *et al.*, 2002) represent two different extreme models and approaches for the reliability assessment of water distribution systems. To apply Model I, the system needs to be modeled as 'lumped supply–lumped demand' (i.e. an aggregated consumer fed from an aggregated source and/or an aggregated storage). The minimum total delivery capacity (assuming no component failures) required to be conveyed to the consumer, subject to a given annual shortage (i.e. the reliability measure), is quantified using a conventional conveyance storage analysis. Once this capacity is defined, a stochastic simulation commences for assessing the probability of providing that capacity, using the system components layout and their probability distributions to fail and repair. The outcome of that is the system reliability. This concept assumes that (1) the capacity needed will be delivered at the minimum required pressure, (2) system failures are caused only as a result of component outages, not as random demands exceeding system capacity, and (3) that flow direction is known *a priori*. The method is thus straightforward and very simple to apply, but limited to distribution systems that can be modeled as 'lumped supply–lumped demand' and whose reliability measure is the total annual shortage. At the other extreme, Model II employs a stochastic simulation, with no *a priori* assumptions of the system performance once failures occur. The system encounters random failures and random repairs, recording their impacts on the consumer nodes. Using this approach, any reliability measure can be quantified, since all statistics of consumer behavior are available. The main advantage of this concept is the ability to simulate the 'true' system behavior, enabling the calculation of any desired reliability measure. The shortcoming of this approach is

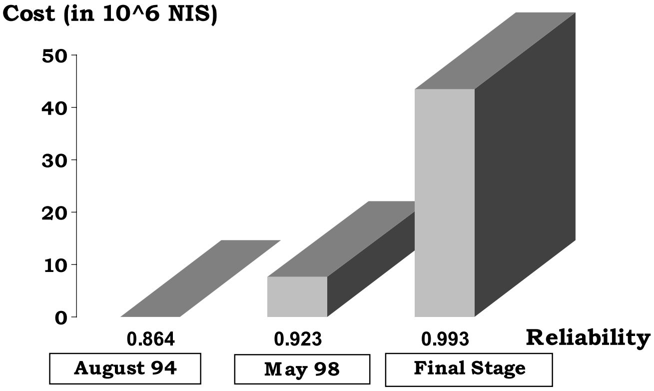
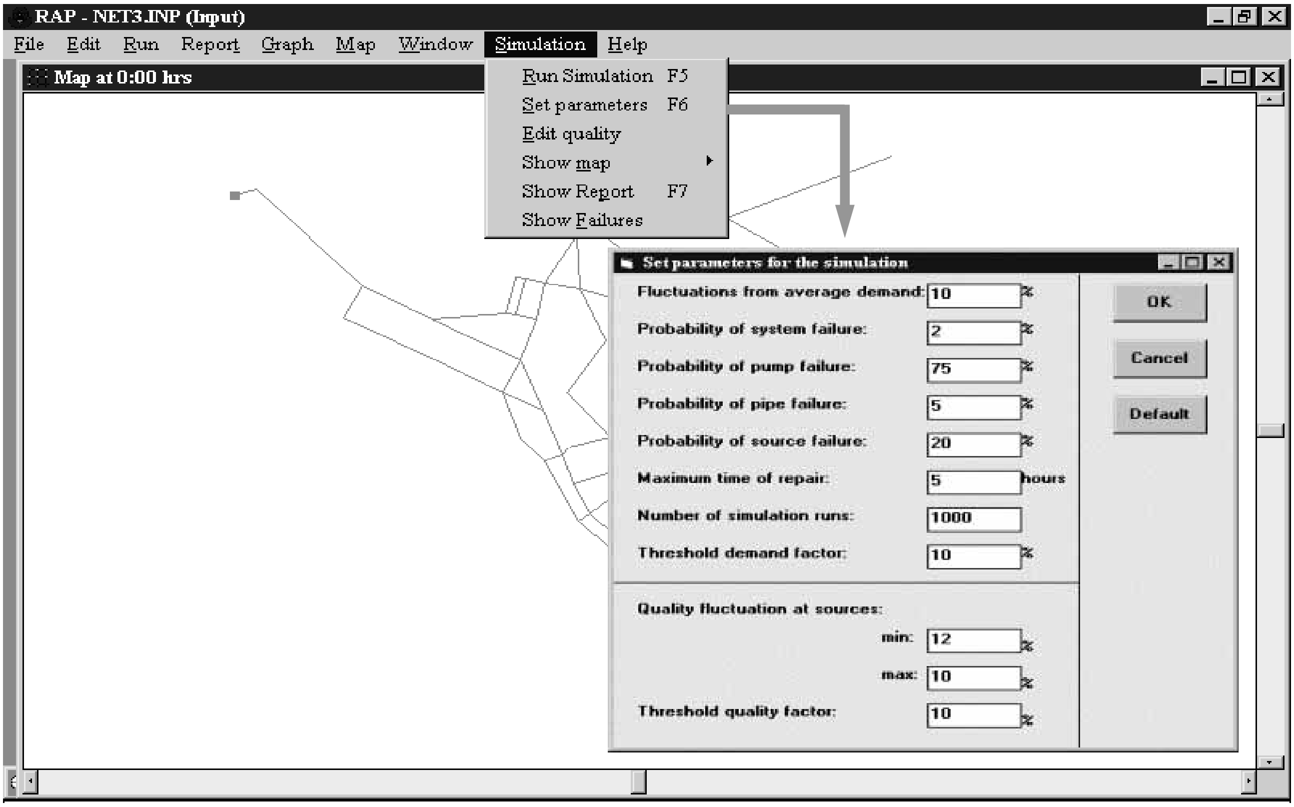


Figure 6 | Cost versus reliability for the Nazareth regional water distribution system.



Fluctuations from average demand: 10 %

Probability of system failure: 2 %

Probability of pump failure: 75 %

Probability of pipe failure: 5 %

Probability of source failure: 20 %

Maximum time of repair: 5 hours

Number of simulation runs: 1000

Threshold demand factor: 10 %

Quality fluctuation at sources:

min: 12 %

max: 10 %

Threshold quality factor: 10 %

Figure 7 | Main menu and input parameters for RAP.

the large number of runs needed for quantifying reliability, as failures are commonly a rare event. Typically thousands of runs are required.

Deciding for either model for a given case study is not unique nor easy. The governing leading principle should be the ability to provide a good balance between the reliability measure(s) adopted and the capability to calculate them accurately enough. In general, the 'lumped supply–lumped demand' approach is preferable if a system can be modeled as such: if it is a 'natural' 'lumped supply–lumped demand' system, or if it can be decomposed to sub-systems of 'lumped supply–lumped demand' whose reliability can be calculated separately and then assembled. The reasoning for that is that the 'lumped supply–lumped demand' approach is easier to implement than the general Monte Carlo approach and that the reliability measure calculated—'probability of annual shortage (or probability of annual shortage duration)'—is a transferable easy-to-communicate reliability measure. On the other hand, if a complicated municipal water distribution system reliability is to be assessed, then the Monte Carlo approach might be the only way. Still, one should try to avoid using the Monte Carlo approach as the only reliability assessment tool, as this is a 'black box' mechanism, whose outcome is, in most cases, difficult to infer.

CONCLUSIONS

Reliability analysis of water distribution systems is a complex task, as it requires the definition of reliability measures which are both meaningful and computationally feasible. This paper focuses on conceptual issues involved in analyzing the reliability of water distribution systems

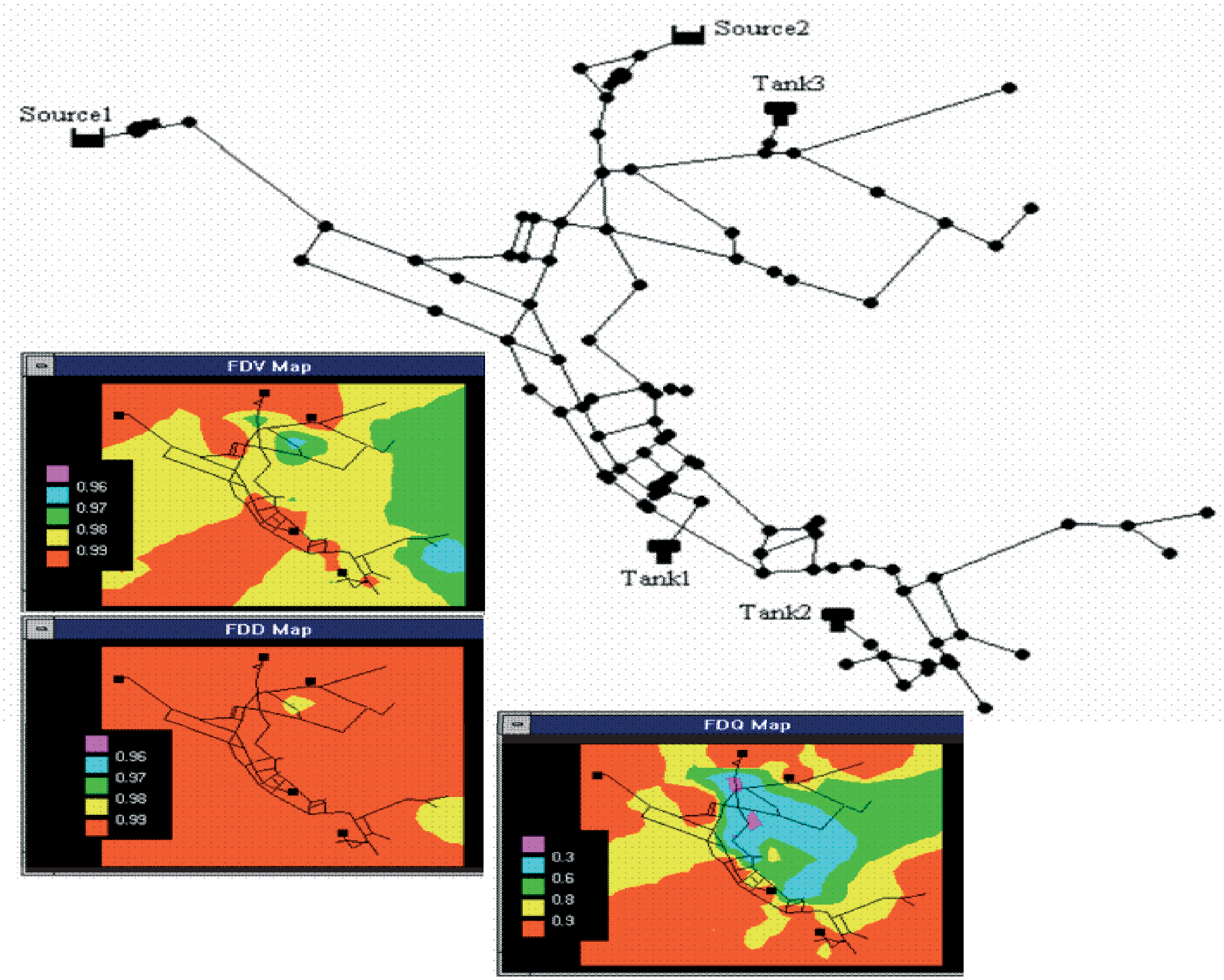


Figure 8 | Application of RAP to a municipal water distribution system.

and on comparing two different reliability assessment methods and approaches.

The first (Model I) is a tailor-made reliability methodology for the reliability assessment of regional water distribution systems that combines topological and hydraulic reliability in a single, simple, straightforward framework, but is limited to 'lumped supply–lumped demand' systems. The second (Model II) is a general stochastic simulation (Monte Carlo) program suited to 'any kind' of a network that can be modeled using EPANET, but requires intensive computational efforts.

Model I is tailored from the system layout and the reliability measure applied to the methodology developed. Model II provides a general 'black-box' framework, not dependent on the system layout or the reliability measure selected, but with almost no insight into the system behavior and on ways of improving reliability if found unsatisfactory.

In general, the 'lumped supply–lumped demand' approach is preferable if a system can be modeled as such. One should try to avoid using the Monte Carlo approach as the only reliability assessment tool, as this is a 'black box' mechanism whose outcome is, in most cases, difficult to infer. The selection of either concept is dependent on the problem in hand and on the modeler's intuition, experience and preferences.

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