Water Distribution Reliability: Simulation Methods

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Abstract: Following a companion paper on analytical methods, this paper presents simulation as a complementary method for analyzing the reliability of water distribution networks. For this simulation, the distribution system is modeled as a network whose pipes and pumps are subject to failure. Nodes are targeted to receive a given supply at a given head. If this head is not attainable, supply at the node is reduced. Pumps and pipes fail randomly, according to probability distributions with user-specified parameters. Several reliability measures are estimated with this simulation. Confidence intervals are also supplied for some of these reliability measures. Simulation results are presented for a small network (ten nodes) and a larger network (sixteen nodes). Simulation enables computation of a much broader class of reliability measures than do analytical methods, but it requires considerably more computer time and its results are less easy to generalize. It is therefore recommended that analytical and simulation methods be used together when assessing the reliability of a system and considering improvements.

Introduction

Reliability of water distribution systems is becoming of increasing concern to water system designers and operators. Reliability is a probabilistic phenomenon and depends on the occurrence of random pipe and pump failures. Thus, reliability of water distribution systems should be assessed with probabilistic measures.

As shown in a companion paper (Wagner et al. 1988), a number of reliability measures (indices) for general networks can be calculated analytically. These analytical methods can provide a fast initial assessment of the reliability of a simple system. However, all of the analytical methods developed thus far involve fairly stringent assumptions that can restrict the applicability of analytical results to understanding real-life systems. Also, the measures that can be calculated analytically are few and do not provide a comprehensive coverage of reliability considerations. Stochastic simulation methods can incorporate more complicated features of these systems, allow calculation of any desired set of reliability measures, and thus can provide a more realistic analysis.

Once an initial assessment of the reliability of a water distribution system has been performed analytically and alternative improvement

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options proposed, a simulation of these options should be done to gain a better understanding of how the proposed alternative systems will be likely to behave under real-life conditions.

This paper presents an event-oriented, discrete simulation program developed to assess the reliability of water distribution networks subject to failure due to pipe breaks and pump outages. This program can be used to calculate a variety of reliability measures relating to the number, location, duration, and effects of failures. The measures of connectivity and probability of sufficient flow calculated simulation can also be checked by analytical measures reported in our other paper (Wagner et al. 1988).

This simulation approach allows great flexibility in the types of network elements that can be included for analysis, and of the failure time and repair time distributions employed. Additionally, changes in the operation of the system in response to pipe and pump failures can be simulated. Evaluation of options for improving the system reliability can also be performed with this program.

Simulation Formulation

In this analysis, the water distribution system is represented by a network model. This model depicts the pipeline system and facilities, such as sources, pumping stations, storage reservoirs, valves, and other control equipment. The level of detail captured in the model must be compatible with the problem being analyzed. For example, if one is studying the connectivity, density, sizing, and location of valves in a distribution system from the point of view of reliability, it may be necessary to include in the model every pipe down to the small sizes. On the other hand, for studying the reliability of supply to whole zones of the system, it should be adequate to model only the facilities and the major transmission system. In this paper, we shall not dwell on how to select the most appropriate model. Our emphasis is on showing how simulation can be used to evaluate reliability for the selected model.

Shortfalls in supply result from failures at the sources, pipe breaks, pump failures, and power outages. We shall concentrate on pipe and pump failures. Water from storage reservoirs can help reduce, or even eliminate, shortfalls during such events, provided that there is a sufficient quantity in storage and that the water can be delivered to the consumers with the failed components out of service. Storage reservoirs (tanks) are included in this analysis.

The simulation program for analyzing system reliability consists of two parts: (1) The simulation section, which generates failure and repair events according to specified probability distributions; and (2) the hydraulic network solution section, which gives the flows throughout the network and the heads at each node for a specified demand in the completely or partially failed system. The simulation program was designed to provide considerable flexibility in the failure probability distributions employed. The forms of the probability distributions used for pipe and pump break and repair times were chosen to fit available data for these processes or, for processes where such data were not available, "reasonable" distributions. The parameters for these distributions are input variables.

The hydraulic network was solved using SDP8, a program by Charles

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Howard and Associates, Ltd. (1984), which is based on the method of Shamir and Howard (1968). SDP8 was used as a subroutine in the simulation to solve for flows and pressures based on the configuration of the operating elements in the water distribution network.

Data needed for the simulation include:

1. Network information: (1) Topology; (2) length, diameter, and roughness (Hazen-Williams) coefficient for each pipe; (3) pump curve for each pump; (4) geometry for each water tank; and (5) valves (if any) on/off.
2. Demands and boundary conditions: (1) Demands at nodes; and (2) given heads at sources and tanks.
3. Failure and repair probabilities: (1) Form and parameters for inter-failure time probability distribution function for each component that is subject to failures; and (2) form and parameters of repair duration probability distribution function for each such component.
4. Total duration of the simulation time period.

Heads and flows throughout the system, with no failures, are obtained by solving the network with SDP8. The simulation proceeds by randomly generating failure times of the pipes and pumps according to the specified failure time distributions. When a link fails, it is removed from the system. The new heads at the demand nodes in the reduced network are determined by solving it with SDP8. It is assumed that link failures leave the demands unchanged. The new heads at the demand nodes are used to tell how the system is performing.

As discussed in the first paper (Wagner et al. 1988), a set of demands at nodes is selected for the reliability analysis. In the simulation study, the quantity actually supplied was allowed to depend on the head at the node. For each node, two head limits are given: (1) A minimum head H_m; and (2) a service head H_s.

The system is said to be performing normally only when, for each node, all the imposed demands can be met with heads above the service limit. If, however, at some node in the reduced system, the head is below the service limit, it is assumed that at that node the system cannot supply the full demand. The actual withdrawals will then be as follows: (1) Nodes with heads below the minimum head will be completely shut off; (2) nodes with heads above the minimum head but below the service head will be supplied at a reduced level; and (3) nodes with heads above the service head will be fully supplied.

As a simple but reasonable approximation, supply for a node in reduced mode will be reduced according to the following equation (see Fig. 1):

$$Q = \left(\frac{H - H_s}{H_m - H_s}\right)^{1/2} \cdot C \quad \text{(1)}$$

where Q = supply at node; H_s = service head; H_m = minimum head; H = calculated head ($H_s \leq H \leq H_m$); and C = full demand at the node.

The rationale for this formula is that hydraulic laws for flows through devices show that flow is proportional to the square root of head (relative to zero head at the device outlet). Thus we assume the supply reduction from normal supply to no flow will be related to the square root of the

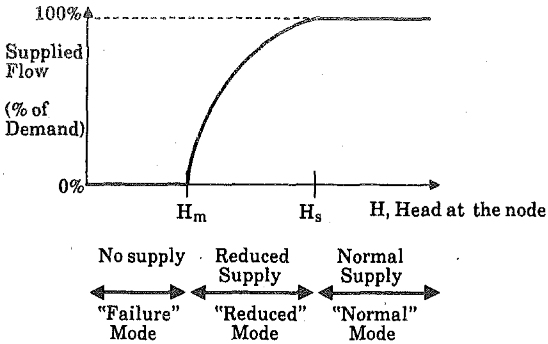

FIG. 1. Supply Response to Head Loss

computed head level. Any other law of flow reduction could be used. Alternatively, one could simplify the simulation by assuming withdrawals are independent of head.

Each node can thus be in a normal, reduced-service, or failure mode. The system will be said to be in normal mode if *all* nodes are receiving normal supply, in failure mode if supply to *any* node has been shut off, and in reduced mode if *some* node or nodes are receiving reduced supply but *no* nodes are completely shut off.

Once a link has failed, a random repair time is generated, and the system is assumed to operate in the reduced state until the repair time is reached, another link fails, or the reservoir empties. The simulation program records the total duration of reduced service and failure periods at each node, the shortfall at each node, and various other measures as listed in Appendix II.

In this analysis, pipes are assumed to fail independently. However, it would not be difficult to add to the simulation analysis pipes that fail dependently or in groups. For example, due to the location of the valves in a system, several pipes may have to be shut down to isolate a break.

Networks Analyzed

Two sample systems were analyzed with this simulation method. Network A (Fig. 2) is a small network with nine demand nodes, ten pipes, one reservoir, one pump, and two pressure-reducing valves. Note that in this network, water must be pumped up from the reservoir (node 1 at 100 ft) to a higher elevation zone (nodes 3, 4, 5, and 6 at 200–350 ft), and then pressure must be reduced to a zone of lower elevation (nodes 7, 8, 9, and 10 at 10–50 ft). Thus we expect the pump will be crucial to the reliability of this network, and reliability at the higher nodes will be less than at the lower ones.

Data for network A are given in Tables 1 and 2. Additional data required are:

1. Pipe and pump interfailure times; exponential distribution with mean times given in Table 2.
2. Pipe repair durations, uniform from 3–72 hr for all pipes.

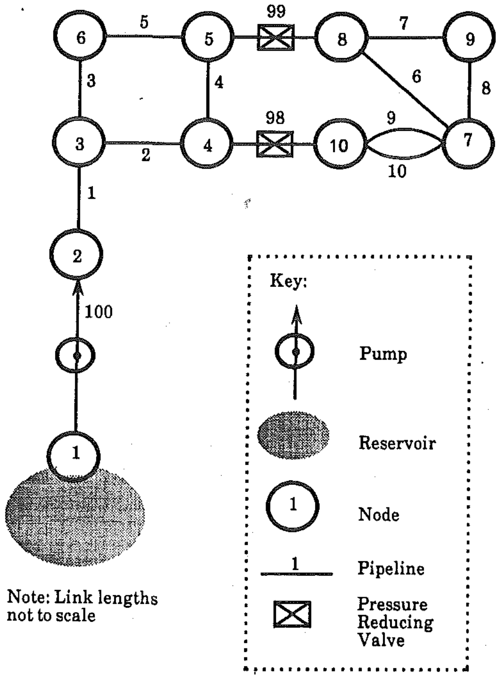

FIG. 2. Network A

3. Pump repair duration, log-normal with $\mu = 3.93$ and $\sigma = 0.2$ (corresponding to a mean repair time of 52 hr with a standard deviation of 10 hr).
4. Pump curve: discharge head = 475–0.015 (flow in mgd)$^{4.58}$.
5. Service head H_s = 40 psi; minimum head H_m = 20 psi.

TABLE 1. Network A Node Data

Node (1)	Elevation (ft) (2)	Demand for fully working system[a] (mgd) (3)	Head for fully working system (ft) (4)	Service head (ft) (5)	Minimum head (ft) (6)
1 (Res.)	100	−6.625	100	—	—
2	100	1.6	388.48	192.28	146.14
3	200	1.2	386.43	292.28	246.14
4	210	0.6	376.80	302.28	256.14
5	230	0.4	377.54	322.28	276.14
6	250	0.825	380.05	342.28	296.14
7	10	0.6	173.57	102.28	56.14
8	10	0.8	170.31	102.28	56.14
9	50	0.4	160.87	142.28	96.14
10	25	0.2	181.37	117.28	96.14

[a]Supply appears as a negative value.

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TABLE 2. Network A Link Data

Link (1)	Length (ft) (2)	Diameter (in.) (3)	Hazen-Williams coefficient (4)	Mean time to failure (hr) (5)
1	200	16	120	231,000
2	1,500	12	120	30,800
3	1,800	14	120	25,700
4	2,000	10	120	23,100
5	1,900	14	120	24,300
6	1,000	8	120	46,300
7	2,500	10	120	18,500
8	3,500	8	120	13,200
9	1,500	10	120	30,800
10	1,500	6	120	30,800
98 (valve)	500	6	65	92,500
99 (valve)	500	4	65	92,500
100 (pump)	—	—	—	1,000

The second network, network C, (Fig. 3) is a larger, more connected network with 16 demand nodes and 34 pipes. This network is taken from Walski et al. (1987). Network C has a single source, one pumping station with three pumps in parallel, and two storage tanks. Node and link data are given in Tables 3 and 4. Additional data are:

1. Pipe and pump interfailure times; exponential distribution with mean times given in Table 4.

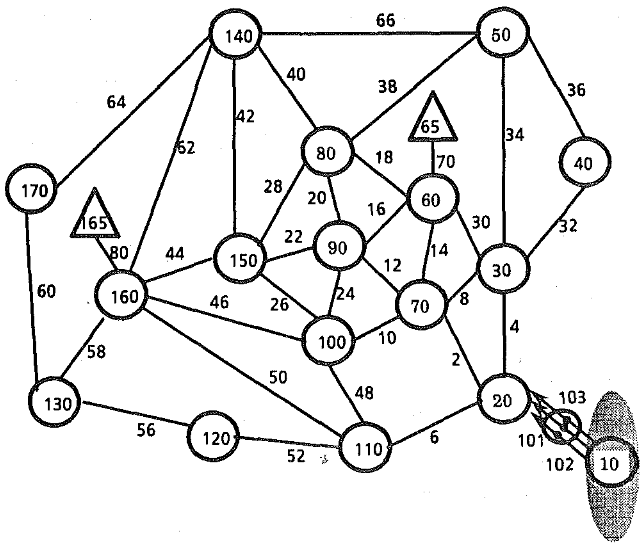

FIG. 3. Network C

TABLE 3. Network C Node Data

Node (1)	Elevation (ft) (2)	Demand for fully working system[a] (gpm) (3)	Head for fully working system (ft) (4)	Service head (ft) (5)	Minimum head (ft) (6)
10 (river)	10	−4,428	10	—	—
20	20	500	305.61	122.28	43.07
30	50	200	242.40	142.28	73.07
40	50	200	234.41	142.28	73.07
50	50	200	232.16	142.28	73.07
60	50	500	234.96	142.28	73.07
65 (tank)	235	−342	235	—	—
70	50	500	242.40	142.28	73.07
80	50	500	228.33	142.28	73.07
90	50	1,000	225.88	142.28	73.07
100	50	500	229.33	142.28	73.07
110	50	500	243.50	142.28	73.07
120	120	200	228.67	212.28	143.07
130	120	200	228.69	212.28	143.07
140	80	200	228.34	172.28	103.07
150	120	200	228.32	212.38	143.07
160	120	800	234.27	212.28	143.07
165 (tank)	235	−1,630	235	—	—
170	120	200	226.10	212.28	143.07

[a]Supply appears as a negative value.

2. Pipe repair durations, uniform from 3–72 hr for all pipes.
3. Pump repair duration, log-normal with $\mu = 3.93$ and $\sigma = 0.2$ (corresponding to a mean repair time of 52 hr with a standard deviation of 10 hr).
4. Pump curve: discharge head = $310–2.06 \times 10^{-6}$ (flow in gpm)$^{1.974}$.
5. Service head $H_s = 40$ psi; minimum head $H_m = 20$ psi.
6. Storage tanks, cylindrical, 100-ft diameter, initial depth = 10 ft, initial volume = 587,000 gal.

The source (node 10) is at a low elevation, so water is pumped uphill from the river to downtown nodes (around node 70, at 50 ft), to the new part of town (node 140, at 80 ft), and to the other town areas (nodes near 160, at 120 ft).

The hydraulic behavior of this network was examined using SDP8. This preliminary investigation showed that even with only one pump, at every node the demand can be met at a head greater than or equal to the service head limit. However, when both tanks have failed, every node is below the minimum head limit, implying that when both water tanks are empty, none of the demands can be met. Thus, the pumps are not likely to be as crucial to the reliability of this network as they were to the smaller network. The volume and operation of the water tanks is expected to have a large effect upon the reliability of the entire network.

TABLE 4. Network C Link Data

Link (1)	Length (ft) (2)	Diameter (in.) (3)	Hazen-Williams coefficient (4)	Mean time to failure (hr) (5)
2	12,000	16	70	3,855
4	12,000	12	120	3,855
6	12,000	12	70	3,855
8	9,000	12	70	5,140
10	6,000	12	70	7,710
12	6,000	10	70	7,710
14	6,000	12	70	7,710
16	6,000	10	70	7,710
18	6,000	12	70	7,710
20	6,000	10	70	7,710
22	6,000	10	70	7,710
24	6,000	10	70	7,710
26	6,000	12	70	7,710
28	6,000	10	70	7,710
30	6,000	10	120	7,710
32	6,000	10	120	7,710
34	6,000	10	120	7,710
36	6,000	10	120	7,710
38	6,000	10	120	7,710
40	6,000	10	120	7,710
42	6,000	8	120	7,710
44	6,000	8	120	7,710
46	6,000	8	120	7,710
48	6,000	8	70	7,710
50	6,000	10	120	7,710
52	6,000	8	120	7,710
56	6,000	8	120	7,710
58	6,000	10	120	7,710
60	6,000	8	120	7,710
62	6,000	8	120	7,710
64	12,000	8	120	3,855
66	12,000	8	120	3,855
70	100	12	120	46,260
80	100	12	120	46,260
101 (pump)	—	—	—	1,000
102 (pump)	—	—	—	1,000
103 (pump)	—	—	—	1,000

Failure and Repair Time Probability Distributions

Data about probability distributions of failure times and repair times for pipes and pumps are usually not readily available. No failure or repair time data specific to the two networks analyzed exist. Thus, for this simulation, "reasonable" distributions with "reasonable" parameters were chosen.

A few studies have looked at quantifying the number of pipe breaks/unit time/pipe length, based on pipe qualities such as age, material, etc. Walski (1984) and O'Day (1982) present some data on pipe break interarrival times and qualitatively examine factors affecting these interarrival times. Shamir

TABLE 5. Pipe Break Data [Source: U.S. General Accounting Office (1980)]

City (1)	Year (2)	Pipe breaks/1,000 mi/yr (3)
Boston	1969–70	36
Chicago	1973	54
Denver	1973	156
Houston	1973	1,290
Indianapolis	1969–78	83
Los Angeles	1973–74	43
Louisville	1964–76	123
Milwaukee	1973	234
New Orleans	1969–78	680
New York City	1976	75
San Francisco	1973	106
St. Louis	1973	106
Troy, N.Y.	1969–78	167
Washington, D.C.	1969–78	116

and Howard (1979) developed an exponential model describing the increase of pipe breaks with pipe age. Walski and Pelliccia (1982) added corrections to this model for the factors of pipe size and number of previous breaks. However, neither of these models looks specifically at the

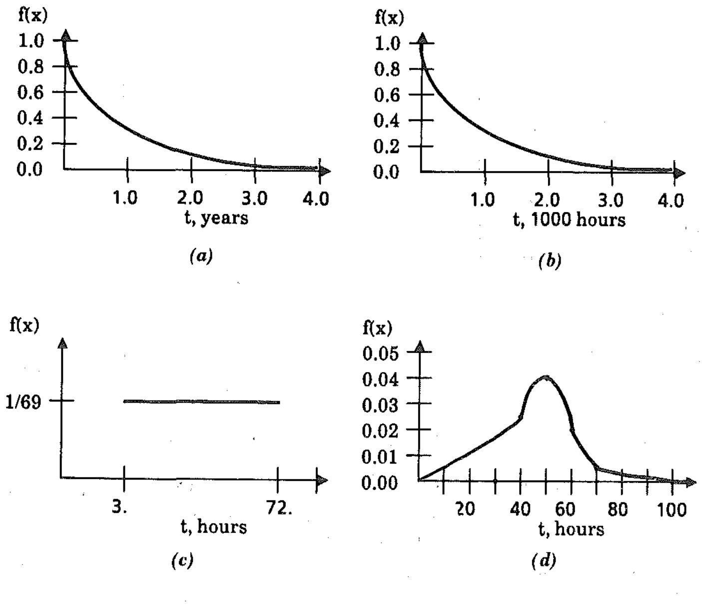

FIG. 4. Break and Repair Time Probability Distributions: (*a*) Time-to-Failure Distribution for 1-mi Pipe; (*b*) Time-to-Failure Distribution for Pumps; (*c*) Pipe Repair Distribution; (*d*) Pump Repair Distribution

interarrival time between individual breaks of the same pipe. Marks et al. (1985) present a hazard failure model giving the probability, at any small interval dt, that a pipe will break based on several factors including the age of the pipe, the number of previous breaks, and the time since the last break. It is commonly assumed, by these and other studies, that failures of different pipes occur independently.

For this study, an exponential distribution was chosen for the pipe break distribution. A listing of the rate of pipe breaks for various U.S. cities, obtained from a U.S. General Accounting Office report to Congress (1980), is presented in Table 5. A figure of one break/one mile/year was picked for use for all pipes. This figure is in the high range so as to fully exercise the simulation system. Fig. 4(*a*) shows the probability distribution for the time until breakage for a 1-mi long pipe.

There is even less data available on pump breaks than on pipe breaks. In a simulation of a water distribution system with only pump failures, Damelin et al. (1972) used some field data and fitted an exponential distribution for pump break interarrival times. Their data were based on interarrival times of working hours, not including times when the pumps were inoperative due to scheduled outages for maintenance. A representative time of 1,000 hr was chosen as the mean time between pump failures from their paper. This pump break time distribution is shown in Fig. 4(*b*).

Pump repair times can be represented by a log-normal distribution. Parameters were chosen for the model based on the 50-hr mean repair duration given in Damelin et al. (1972) but with more variability, again so as to fully exercise the program. Fig. 4(*d*) shows the distribution used (μ = 3.93, σ = 0.2).

No data were found for pipe repair time distributions. A uniform distribution between 3–72 hr was chosen as a first estimation of this process [Fig. 4(*c*)]. For an analysis of an actual system, data on these times should be available from maintenance and payroll records of many urban public works departments.

Simulation Details

As shown in Appendix II, a number of reliability measures are calculated by this simulation program. Since these measures are based on a finite number of random events, the calculated values are only approximate. Confidence intervals were calculated for the reliability measures of annual shortfall (gallons), the percentage of time spent in emergency mode (for every node), and the percentage of time spent in failure mode (for every node). These measures are felt to be some of the most important measures for assessing the reliability of an urban water supply system. The shortfall measure is a good overall indicator of the reliability of the system. However, a low shortfall for some systems could be obtained by disconnecting, at any sign of emergency, one node of moderate demand so as to supply the others. Thus the percentages of time spent in the non-normal conditions for each node were also examined in evaluating alternative systems. Examination of these measures also allows the identification of nodes markedly more or less reliable than average.

Confidence intervals were calculated using the regenerative method [see, e.g., Law and Kelton (1982)]. The regenerative method involves measurements within a "cycle," which in this case can be defined as the time between successive times when the system returns to being fully operational. Within each individual cycle, the shortfall, and the time spent in each mode, for that cycle are tabulated. The n cycle times and measurements are statistically independent and therefore can be used with methods from classical statistics to calculate the required reliability estimates and the associated confidence intervals. After n cycles, n cycle times ($c_1, c_2, \ldots, c_n$) and n shortfall measurements ($s_1, s_2, \ldots, s_n$) are obtained. The best estimate for the time-average shortfall S is given by

$$S = \frac{\sum_{i=1}^{n} s_i}{\sum_{i=1}^{n} c_i} \qquad (2)$$

We can calculate an estimated annual average shortfall S_i for each cycle i by (note c_i in hours):

$$S_i = (s_i - S \cdot c_i) \cdot 8{,}760 \qquad (3)$$

The variance σ^2 of these cycles estimates is given by

$$\sigma^2 = \frac{1}{n}\left[\sum_{i=1}^{n} (S_i - S)^2\right] \qquad (4)$$

The 95% confidence interval is then given by

$$\mathrm{CI} = S \pm \frac{\left[1.96 \cdot \left(\frac{\sigma^2}{n}\right)^{1/2}\right]}{\left[\frac{\left(\sum_{i=1}^{n} c_i\right)}{n}\right]} \qquad (5)$$

A general flow chart of the simulation program is shown in Fig. 5. Early simulation runs turned out to take considerable computer time. As a means for reducing this time, the following method was developed. Many different network configurations, with one link at a time in failure, were analyzed with SDP8, and the results stored. Thus, during the simulation, only unusual failure modes, e.g., more than one failed link, had to be analyzed hydraulically, while for the rest the hydraulic status could be read

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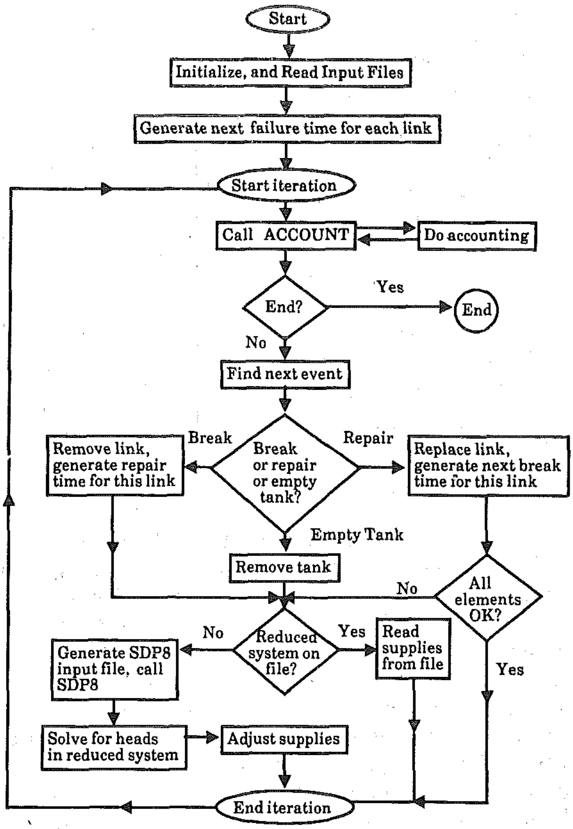

FIG. 5. Simplified Flowchart of Simulation Program

from the files. This modification reduced computer time significantly, obviously at the expense of more computer storage.

Results

The values calculated for a number of reliability measures are presented for all nodes and links in network A in Appendix III and Tables 6 and 7. The results for network C are summarized in the text. These results are discussed in the following.

Network A was simulated for a 200-yr period. Appendix III presents the system-wide results and the results for the pump. Table 6 contains the reliability measures for the nodes, and Table 7 the measures for the links. During the 200-yr simulation period, there were a total of 4,846 failure and repair events. The system cycled 2,350 times, i.e., returned this many times to fully operational condition. (The number of events is higher than twice the number of cycles because overlapping failures are counted as two events but only one cycle.) The average annual shortfall was 121,000,000 gal (with a ±5,500,000 gal 95% confidence interval), or 5.04%

TABLE 6. Network A Simulation Results: Nodes

Node (1)	Average Time in Reduced Service %[a] (2)	hr/yr (3)	Number/yr (4)	Average Time in Time in Failure %[b] (5)	hr/yr (6)	Number/yr (7)	Average Shortfall % (8)	Annual average (gal) (9)
1 (Res.)	0.0	0	0	0.0	0	0	—	—
2	0.0	0	0	4.98	436	8.4	4.97	29,000,000
3	0.0	0	0	4.99	437	8.4	4.99	22,000,000
4	0.0	0	0	4.99	437	8.4	4.99	11,000,000
5	0.15	13	0.4	4.99	437	8.4	4.99	7,000,000
6	0.15	13	0.4	4.99	437	8.4	5.03	15,000,000
7	0.14	13	0.3	5.07	444	8.6	5.10	11,000,000
8	0.14	13	0.3	5.07	444	8.6	5.10	15,000,000
9	0.28	25	0.7	5.21	457	8.9	5.27	8,000,000
10	0.0	0	0	5.07	444	8.6	5.07	4,000,000

[a]±0.05%.
[b]±0.23%.

of the 6.625 × 365 = 2.418 billion gallons annual demand. All failures were caused by breaks in single pipes and pump failures; two pipes never failed at the same time. All emergency conditions recorded in the simulation were caused by breaks in pipe 2 (connecting nodes 3 and 4) and pipe 5 (connecting nodes 5 and 6).

In this system, there is very little problem with reduced service. Node 9 endures reduced service most often, but this mode occurs on average only for about one day per year and less than once per year. Failure conditions do occur relatively frequently. Note that all of the node failure results are very close to those of the pump. This correspondence indicates pump failures are the major source of unreliability in this system, as expected. It should be noted that the probability distribution parameters were consciously chosen to be high, so fairly high failure occurrences are not surprising. Also note that although we might expect the nodes at the higher

TABLE 7. Network A Simulation Results: Links

Pipe (1)	Time in Failure % (2)	hr/yr (3)	Number/yr (4)
1	0.02	1	0.04
2	0.15	13	0.3
3	0.16	14	0.4
4	0.14	12	0.3
5	0.14	12	0.3
6	0.11	10	0.2
7	0.25	22	0.6
8	0.33	29	0.7
9	0.14	13	0.3
10	0.12	10	0.3
98 (valve)	0.03	3	0.9
99 (valve)	0.05	4	0.1

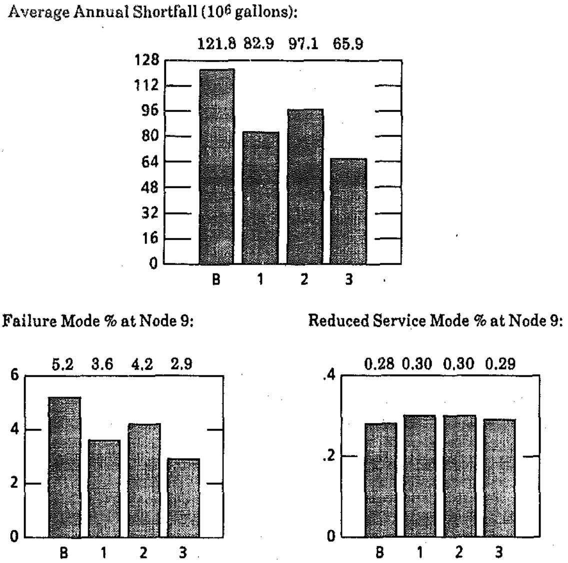

FIG. 6. Comparison of Results for Network A Pump Parameter Values

elevations to be the least reliable, for this system the least reliable nodes are those furthest from the source but at lower elevations.

On average then, the system appears to function fully about 95% of the time. The corresponding figures from the analytical methods (Wagner et al. 1988) are connectivity = 95.4% and probability of sufficient flow = 94.26%. The results of the methods agree closely for this system. However, it should be noted that in both cases these figures mainly reflect the reliability of the pump.

Since the pumps are the most important determinant of reliability in this system, a number of changes in the pump-related parameters were examined as options for system improvement. The alternatives simulated were: (1) Improvement of pump maintenance, resulting in an increase of mean time between failures from 1,000 to 1,500 hr; (2) improvement of pump repair, resulting in a decrease of mean time to repair from 50 to 40 hr; and (3) a combination of alternatives 1 and 2.

Fig. 6 shows, for the base case (B) and the improvement options (1, 2, and 3), the calculated values of annual shortfall and percentage of time in each mode for node 9. Node 9 was chosen for these comparisons because it is the node with the most severe reliability problems. Note that increasing the maintenance of the pump causes a larger decrease in shortfall and failure percentage at node 9 than does improving the pump repair time. The combination of these two options decreases shortfall and percentage of time in failure mode by approximately 45%. The option of adding a smaller backup pump in parallel with the existing pump was also explored. To be effective, the backup pump must be almost as large as the original—a costly alternative.

Network C is, in general, less reliable than network A, and the analysis was thus more difficult. This network is quite large, and frequently more

TABLE 8. Improvement Options for Network C

Option (1)	Initial volume in each tank (gal) (2)	Pipe Repair[a] (hr) (3)
1	587,000	3–72
2	1,320,500	3–72
3	587,000	3–48
4	1,320,000	3–48
5	587,000	3–24
6	1,320,000	3–24

[a]Uniform distribution.

than one link failed at the same time. Also, the tanks are frequently depleted. For both computer time and storage requirements, a simulation period of three years (140 regeneration cycles) was chosen. This period gave confidence intervals for network C to within 18% for shortfalls. Again the confidence intervals for the small percentages of time each node was in failure or reduced service mode were sometimes quite wide.

In the 140 cycles, 631 events were observed. The average annual shortfall was 248,680,000 gal (±44,700,000) for 7.39% of the 3.3638 billion gal annual demand. The pumps failed about 4% of the time, with approximately seven failures per year per pump and an average outage time of 364 hr/yr.

Node 20 (adjacent to the river) was completely supplied. The other nodes spend between 0.66–18.34% of the time in reduced service (nodes 30 and 90, respectively) and 1.39–20.02% (nodes 20 and 120, respectively) of the time in failure. All the nodes with high percentages of time in reduced service and failure modes (nodes 120, 130, 150, 160, and 170) are those that cannot be supplied by the pumps alone. These percentages correspond primarily to the 20% of the time both tanks have been depleted. Walski et al. (1987) report that the system has trouble filling tank 165, so it does not seem surprising that 20% of the time (about 1.5 days/week), there is some supply problem at the nodes at the higher elevations.

The links spent less than 1% of the time in failure. Link 40 was the most reliable in this simulation (0.05% of the time spent in an average of 0.3 events/year), and link 4 was the least reliable (1.02% of the time spent in an average of 2.3 events/year).

Studies made on this system (Walski et al. 1987), focused on finding a design to meet projected future water demand rather than on reliability. Lee et al. used 800,000-gal tanks that were not allowed to run dry. Gessler also used tanks with 800,000 gal each. These tanks are on the same order as the 587,000 gal of available water used in this simulation. However in both of these studies, the recommended expansion involved another tank added to the system.

It seems reasonable that in designing storage for this system, the volume of the water storage tanks should take into account the amount of water needed to supply the system during failure events. The required tank volume should be related to the distribution of the pipe repair time. Thus for improvement alternatives, combinations of pipe repair time distributions and tanks sizes were examined. The options examined are given in

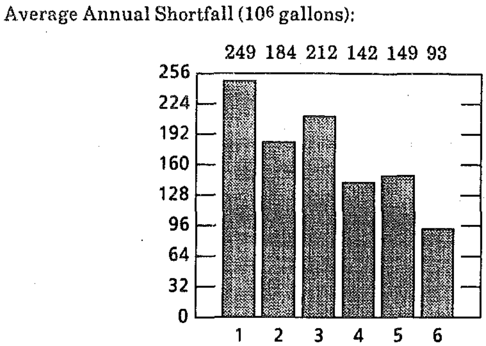

FIG. 7. Comparison of Results for Network C Options

Table 8. A summary of the shortfalls for each combination is shown in Fig. 7. The "best" alternative (large tanks and pipe repairs within 24 hr) gives an average annual shortfall of 93,000,000 ± 22,000,000 gal. For this case, the maximum time in reduced service mode is 7.3 ± 1.7% for node 110, and the maximum time in failure mode is 7.6 ± 1.7% for nodes 120 and 130.

Conclusions

As shown by the analysis of these networks, simulation can be a useful tool for reliability assessment. Although simulation seems a time-consuming task in comparison with the analytical methods presented in the companion paper (Wagner et al. 1988), simulation can provide three advantages.

First, with simulation a number of reliability measures can be calculated. As shown in Appendix II, this program already calculates a number of measures. With only minor modification, the program could record additional measures such as the duration of the longest period of failure at any node, the duration of the longest period of reduced service at any node, and the failure event in which the greatest total shortfall occurred. Only with simulation is such flexibility in reliability criteria possible.

Second, simulation allows the analysis of a system with complicated interactions. This program can include operational response to supply loss, water tanks with storage dependent on the state of the system, and fairly detailed modeling of the reliability of the individual pipes in the system. Analytical methods have been designed that handle, to some extent, some of these complexities. However, to analyze a system with all of these elements at once requires simulation. Simulation provides a level of realism available with no other method.

Third, simulation allows the detailed modeling of the hydraulic behavior of the system. In contrast, to remain tractable, most analytical methods require a simplified description of the water system. By using simulation with an accepted model of hydraulic behavior in a piping network, like SDP8, the risk of an incorrect response because of over-simplification of the hydraulic model can be lessened.

Simulation can, however, be time consuming, both in terms of computer time per analysis and in terms of time to set up and use such a program.

Also, simulation runs are hard to optimize and can be hard to generalize beyond a very specific system. Thus perhaps the best approach to performing a reliability assessment is to use both simulation and analytical methods.

The analytic methods developed in the first paper (Wagner et al. 1988) and the simulation method presented here can be used together, iteratively. Analytic methods are used first to look at reliability of an existing system and identify problem areas. Once additional components or other corrective measures are proposed, then simulation can be used to examine reliability in more detail. The simulation may again point to attractive alternatives, which are then screened by analytic methods.

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Appendix I. Units

To convert	*To*	*Multiply by*
inches (in.)	centimeters (cm)	2.54
feet (ft)	centimeters (cm)	0.3048
miles (mi)	kilometers (km)	1.609
gallons (gal)	meters^3 (m^3)	3.785×10^{-3}
million gallons/day (mgd)	meters^3/second (m^3/s)	0.0439
gallons/minute (gpm)	meters^3/second (m^3/s)	6.309×10^{-5}
pounds/inch^2 (psi)	Newtons/meter^2 (N/m^2)	6.895×10^3

Appendix II. Measures Calculated for Each Simulation Run

Measures

Event-Related

- Type of event (failure or repair).
- Interfailure times and repair durations.
- Total number of events in simulation period.
- System status during each event (normal, reduced service, or failure).

Node-Related

- Total demand during simulation period.
- Total demand during simulation period.
- Shortfall (total unmet demand).
- Average head.
- Number of reduced service events.
- Duration of reduced service events.
- Number of failure events.
- Duration of failure events.

Link-Related

- Number of pipe failures.
- Total duration of failure time for each pipe.
- Percentage of failure time for each pipe.
- Number of pump failures.
- Total duration of failure time for each pump.
- Percentage of failure time for each pump.

System-Related

- Total system consumption.
- Total number of breaks.
- Maximum number of breaks per event.

Appendix III. Network A Simulation Results; System and Pump

System

- Number of cycles = 2,350.
- Number of events = 4,846.
- Average annual shortfall 5.04% = 121,000,000 gal. (±5,500,000).

Pump

- Average time in failure 4.97% = 436 hr/yr, 8.4 failures/yr.

Appendix IV. References

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Appendix V. Notation

The following symbols are used in this paper:

C = demand at node;
CI = confidence interval;
c_i = time in cycle i;
H = head at node;
H_m = minimum head limit;
H_s = service head limit;
n = number of cycles;
Q = supply at node;
S = shortfall;
s_i = shortfall in cycle i;
σ = shape parameter for log-normal distribution;
σ^2 = variance; and
μ = scale parameter for log-normal distribution.

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