Detecting Accidental Contaminations in Municipal Water Networks

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Abstract: A methodology for finding the optimal layout of a detection system in a municipal water network is formulated and demonstrated. The detection system considered consists of a set of monitoring stations aimed at detecting a random external input of water pollution. The level of service provided to the consumers is defined by the maximum volume of consumed polluted water prior to detection. The methodology involves the establishment of an auxiliary network that represents all possible flow directions for a typical demand cycle, an "all shortest paths" algorithm to identify domains of pollution, and a "set covering" algorithm to optimally allocate the monitoring stations. The algorithm outcome is a minimal set of monitoring stations that satisfies a given level of service. The methodology is demonstrated on a small illustrative case and on a midsize water network.

INTRODUCTION

The quality of drinking water is a growing concern, and so is its list of substances of interest. Monitoring and treatment costs for accomplishing the new Safe Drinking Water Act regulations in the United States are estimated at $4.1 billion annually, and ultimately might rise to $8.5 billion (Neukrug et al. 1995). While the Safe Drinking Water Act regulations describe the sampling frequency and the list of water quality parameters to be monitored, only limited guidelines are provided as for the layout and number of the monitoring stations.

Water quality in a distribution system deteriorates as a consequence of two main reasons: (1) a decay or growth of nonconservative constituents that takes place during the transport process (Boulos et al. 1994); and (2) an accidental intrusion of pollutants.

The behavior of nonconservative constituents can be approximated using dynamic water quality simulation models such as EPANET (Rossman 1994; Rossman and Boulos 1996). For this case, monitoring stations are primarily designed to detect undesirable levels of chlorine concentration (Hunt and Kroon 1991; Sharp et al. 1991) and to provide the needed data for a model calibration (Clark et al. 1993; Rossman et al. 1995).

In the case of an external intrusion of pollutants, monitoring stations should be designed to provide an "alarm signal" within an acceptable time limit. This task is difficult to address, as the episode of a pollution intrusion can happen at any part of the system at any time. In addition, the acceptable time limit between the pollution intrusion and its detection implies that the monitoring systems should maintain a specified level of service.

A previous study that is directly related to the selection monitoring stations is that of Lee and Deininger (1992). Its objective was to allocate monitoring stations that will provide maximum information about the water quality state within the distribution system. Their solution is based on the general feature that water quality parameters decrease with time and distance from the source. That is, if the water quality at a sampled node is good, then it must be good at an immediate upstream node. The term "covered node" was used to denote that the water quality at a particular node can be inferred by the water sampling at some downstream nodes. Using pathway analysis and integer programming, the location of monitoring stations is found to achieve a maximum coverage.

The methodology proposed by Lee and Deininger (1992) is most suitable for an internal or gradual deterioration of water quality. It is less appropriate for a rapid deterioration of water quality due to an external source of contamination. For example, in the case of a very long pipe with many consumption outlets, Lee and Deininger's methodology will result in a single monitoring station at the downstream pipe end. This is true regardless of the location of the intrusion, or its time-to-detection (the time elapsed until the pollutant has been detected). Obviously, in the case of an external pollution, the time-to-detection is most important and should be considered in the design process.

The paper presents a design methodology for detecting accidental contamination in municipal water networks. The methodology is aimed at identifying the best selection of monitoring stations, which allows capturing an accidental intrusion of contamination within a given level of service. The level of service, in this context, is the maximum volume of contaminated water that is consumed prior to detection.

The next section describes the basic concepts upon which the methodology is based. A step-by-step description of the proposed methodology is given and is further illustrated by a simple example. An application for a midsize water network is introduced with special considerations regarding system invulnerability.

CONCEPTS AND ASSUMPTIONS

The development of the methodology for an optimal layout of a detection system is based on the following concepts.

- A water quality detection system is a distributed set of monitoring stations that constantly monitor water quality parameters. Its purpose is to provide an "alarm signal" in case water quality deteriorates to an unacceptable level due to an accidental intrusion of pollutants.
- A level of service of a detection system is measured by the consumed volume of contaminated water prior to detection. A high of service corresponds to a small volume of consumed contaminated water, and vice versa. For example, a "1,000 ft^3 level of service" means that the detection system has the capability to detect external pollution before 1,000 ft^3 of contaminated water has been consumed.
- Pollution due to an external intrusion is propagated by the immediate flow pattern and the flow patterns that follow. Since a pollutant entry can occur at any given time and place, its propagation is possible by an infinite number of

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flow combinations. To handle this uncertainty, a single hypothetical flow pattern is established. This pattern, termed a representative flow pattern, is defined by the time-averaged flow in each pipe and in each flow direction. The time averaging is made with respect to a typical demand cycle such as a day or a week. The distinction between flow directions is made on an auxiliary network, where each pipe of alternated flow direction is replaced by two parallel pipes, one in each direction. For example, assume a 24-hr flow cycle of three different scenarios, 8 hr each, with corresponding flows at a particular pipe of +1,000, −700, and +1,500 units. The pipe is represented on the auxiliary network by two unidirectional and parallel pipes. The first pipe, assigned with a positive flow direction, has a representative flow of (1,000 × 8/24) + (1,500 × 8/24) = 833.3 units. The second pipe, assigned with a negative flow direction, has a representative flow of (700 × 8/24) = 233.3 units. The pollution propagation is therefore made possible in both flow directions, each with its corresponding time-averaged flow value.

- The domain of detection for a particular node includes all nodes that are subject to contamination following an accidental pollution at that node. The pollution is therefore detectable by any given monitoring station within this domain. A dual term is the domain of coverage (or covering domain), which includes all possible sources of pollution that are detectable by a particular monitoring station. The size of both domains depends on the representative flow pattern and on the given level of service. A special case is a polluted node with only inflow arcs directed to it. Such a node, named a singular node, has a detection domain of one node only, which is the source of pollution.
- A path in a network is any sequence of arcs where the final node of one is the initial node of the next. Associating a value with each arc, the length of a path is the sum of the arc values along the path. The shortest path is the path of minimum length between two nodes on the auxiliary network. Assuming that each arc length equals its averaged travel time (the pipe's physical length divided by its average flow velocity), the minimum propagation time from a source of pollution to any other node, is equal to the shortest path between the source and the node considered.
- It can often happen that there is more than one minimal set of monitoring stations that "covers" the entire network—that is, several sets with the same number of stations but of different locations. In this case, an additional criterion is required to fully identify the optimal detection system. Such a criterion might be system invulnerability, which evaluates the system performance under a failure in one of its components. In this study, the invulnerability of the detection system is measured by the extent of overlapping between the covering domains. Such an overlapping means that a particular source of pollution can be detected by more than one monitoring station at a time. In other words, a failure in one of these monitoring stations will not exclude the system's ability to detect a pollution out of that source.

The following assumptions are made in developing the proposed methodology.

1. External water pollution might occur at any place and time. That is, every node in the network is a possible source of pollution, starting at any time.
2. Given a polluting node, all the water that passes through that node is considered contaminated regardless of the pollutant concentration.
3. The pollution particles are carried downstream with a velocity that equals the mean cross-sectional water velocity (i.e., a "piston flow," neglecting the pollutant dispersion).
4. An intrusion of a pollutant into the distribution network is made in a continuous mode.
5. The detection system provides real-time monitoring measurements. For example, both continuous turbidimeters and conductivity meters can be used to detect contamination caused by wastewater or surface runoff intrusions.
6. The probability of each node to become a source of external pollution is equal. Only one node acts at a time as source of pollution.

The second assumption, regarding the substance concentration, ignores the dilution processes that take part throughout the network. Such an assumption is justified for certain substances like microbial contamination and toxic pollutants, but does not fit others such as salts and nitrates. The latter have acceptable threshold levels that can be rapidly reached through dilution processes.

METHODOLOGY

A methodology for finding the best set of monitoring stations, subjected to a given level of service, is presented in this section. The methodology is later demonstrated, step by step, in an illustrative example.

Step 1: Hydraulic Simulation

An extended-period simulation of the water distribution network is carried out using a hydraulic simulator. The extended period covers a typical demand cycle, usually one day or one week. The output of the hydraulic simulation to be used includes the time history of the flow velocities for each pipe in the network.

Step 2: Auxiliary Network

The auxiliary network is built as a directed graph, which consists of a set of nodes and a set of directed arcs. The set of nodes equals the network's original set of nodes. The set of arcs is assigned, based on the simulation results, as follows.

- A single directed arc, $e(i,j)$, is assigned if there exists a pipe between node i and node j and if flow occurs only from node i to node j.
- Two parallel directed arcs of opposite directions, $e(j,j)$ and $e(j,i)$, are assigned between nodes i and j if there exists a pipe between nodes i and j and if flow occurs in both directions.

A length is associated with each arc of the auxiliary network. The length equals the average travel time along that arc—that is, the physical length of the corresponding arc divided by its average flow velocity.

Step 3: All Shortest Paths

Assuming that the pollutant particles move with a velocity equal to the flow velocity, the time of the pollutant's propagation from node i to node j equals the minimum travel time between these two nodes. Hence, the solution to the all-shortest-paths problem defines the propagation times from any given source of pollution to all other nodes. In this study, the Floyd algorithm (Floyd 1962) was implemented to find the all shortest paths in the auxiliary network.

Step 4: Pollution Matrix

A matrix, termed the pollution matrix, is constructed to represent the domains of detection and coverage of each node of the network. It is an $N \times N$ matrix of 0-1 coefficients, where N is the number of nodes and "1" and "0" correspond to contaminated and noncontaminated nodes, respectively. The ith row lists all contaminated nodes due to an accidental pollution in node i. The jth column lists all polluting nodes (sources of pollution) that can contaminate node j.

From a monitoring point of view, the ith row indicates the domain of detection due to an accidental pollution at node i. That is, a source of pollution at node i can be detected by all nodes having a "1" entry in the ith row. The jth column indicates the domain of coverage of node j. That is, a monitoring station at node j "covers" pollution intrusions at all nodes having a "1" entry at the jth column.

The pollution matrix is established using the following steps for each node (a possible source of pollution) in the network.

1. Assign a "0" entry for all nodes in the ith row of the pollution matrix.
2. Sort all reachable nodes from node i, on the auxiliary network, according to the shortest path length, in an increasing order.
3. Start from the first sorted node. Calculate the volume of polluted water that is consumed prior to the arrival of the pollution from node i to the current sorted node, j. If the volume exceeds the maximum allowed volume (i.e., the level of service), stop. Otherwise, assign "1" at row i and column j of the pollution matrix and repeat for the next sorted node.

Step 5: Minimum Covering Set

The minimum number of monitoring stations is equivalent to the minimal set of columns, such that every row in the pollution matrix has an entry of "1" under at least one column of the minimal set. In other words, it is the minimum number of columns (monitoring stations) that "cover" all the rows (possible sources of pollution). Finding the aforementioned minimum set is known in graph theory as the set covering problem.

Solution of the minimum set covering problem is achieved using the algorithm suggested by Christofides (1975). Following Christofides' algorithm, an initial cost is associated with each column of the pollution matrix. The outcome of the algorithm is a set of columns with a minimum cost that "covers" all rows in the matrix. In the present work, the initial cost of each column is used to fulfill an additional criterion of system invulnerability. It is equal to an arbitrary high value minus the number of "1" entries in each column. For example, the initial costs of columns with two and five entries of "1" are 998 and 995, respectively. The minimum cost solution is therefore the minimum set of columns that "covers" all rows with a maximum number of "1" entries. It follows that if there are two or more candidate sets of monitoring stations, the chosen set is the one with the maximum overlapping between the covering domains of its monitoring stations.

Following step 5, a minimum covering set of columns is selected in the pollution matrix. Each column corresponds to a particular node in the network for which a monitoring station is assigned.

ILLUSTRATIVE CASE

The proposed methodology is demonstrated in a small distribution system taken from the *EPANET user's manual* (example 1, Rossman 1994). It consists of three loops, a reservoir, a pumping station, and an elevated storage tank, as shown in Fig. 1. The system is subject to a 24-hour representative demand cycle, as shown in Table 1.

TABLE 1. Twenty-Four Hour Demand Pattern Characteristics for Illustrative Case

Time of day (1)	Multiplier of average demand (2)
24–02	1.0
02–04	1.2
04–06	1.4
06–08	1.6
08–10	1.4
10–12	1.2
12–14	1.0
14–16	0.8
16–18	0.6
18–20	0.4
20–22	0.6
22–24	0.8

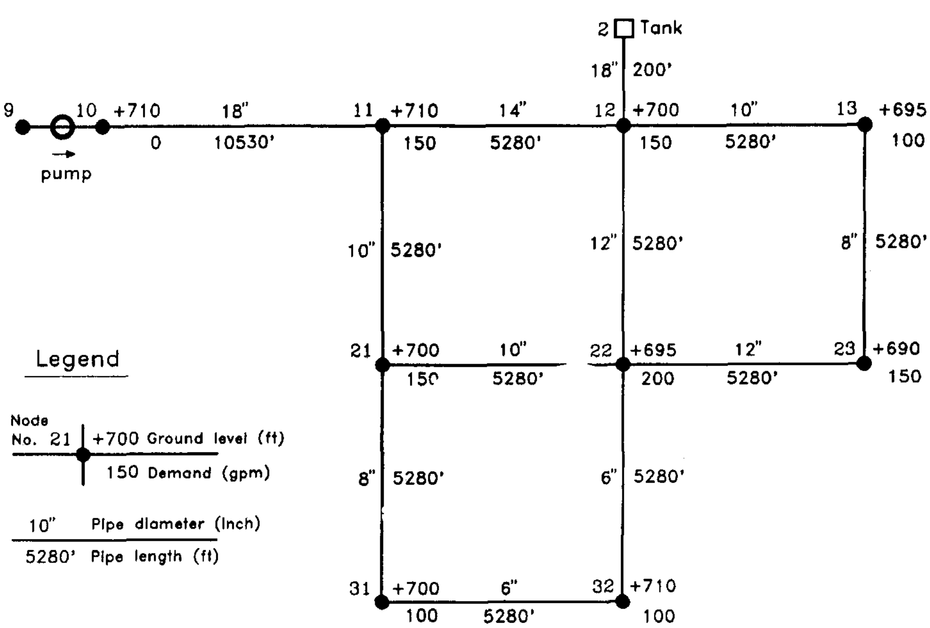

FIG. 1. Network Schematic for Illustrative Case

The pump takes water from a reservoir at node 9 that is at a constant water level of +800 ft. The characteristics of the pumping curve are a shutoff head of 332.5 ft, an intermediate point of 1,500 gal./min at 250 ft, and 3,000 gal./min at zero head. The operation of the pump is controlled by the water level in the tank; the pump is "on" below 110 ft, and "off" above 140 ft. The tank is 50.5 ft in diameter and +850 ft in elevation. The initial, minimum, and maximum water levels of the tank are 120, 100, and 150 ft, respectively.

The detection system required is for a 10,000 ft^3 level of service. That is, the system should be able to detect an external pollution prior to the consumption of 10,000 ft^3 of polluted water. Issues to be resolved are the minimum required number of monitoring stations, and their allocations in the network.

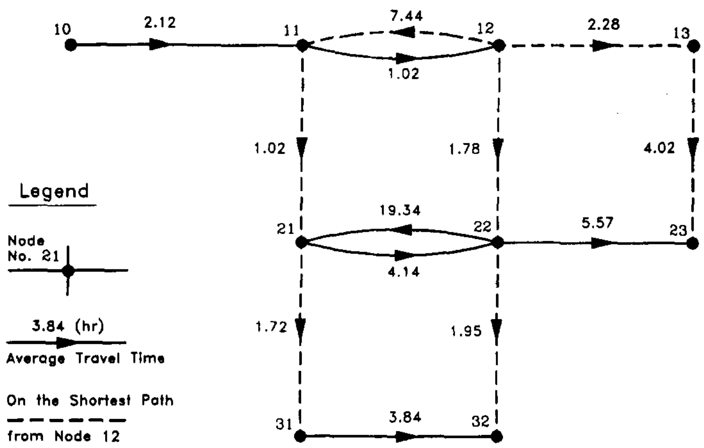

FIG. 2. Auxiliary Network for Illustrative Case

TABLE 2. Pollution Matrix for 10,000 ft^3 Level of Service

Source of pollution (1)	Polluted Nodes								
	10 (2)	11 (3)	12 (4)	13 (5)	21 (6)	22 (7)	23 (8)	31 (9)	32 (10)
10	0	1	1	0	1	1	0	1	0
11	0	1	1	0	1	1	0	1	0
12	0	0	1	1	0	1	0	0	1
13	0	0	0	1	0	0	1	0	0
21	0	0	0	0	1	1	0	1	0
22	0	0	0	0	0	1	0	0	1
23	0	0	0	0	0	0	1	0	0
31	0	0	0	0	0	0	0	1	1
32	0	0	0	0	0	0	0	0	1

In the first step, an extended-period simulation is carried out. The simulations were performed using the Environmental Protection Agency's hydraulic water quality simulator. The input file of these simulations is identical to the one used for example 1 in the *EPANET user's manual.*

In the second step, the auxiliary network is built on the results of the hydraulic simulations in the first step. The auxiliary network is shown in Fig. 2, along with its corresponding average travel times. The tank and the pump were excluded from the auxiliary network due to their immediate neighborhood to nodes 12 and 10, respectively. Parallel pipes were added between nodes 11–12, and 21–22, as these are the only arcs that exercise a change in the flow direction through the course of the simulation.

In the third step, the auxiliary network is solved for all shortest paths. An example of all shortest paths from node 12 is shown in Fig. 2.

In the fourth step, the pollution matrix is constructed for a 10,000 ft^3 level of service, as shown in Table 2. Assuming, for example, that node 12 becomes a source of pollution, its detection domain includes nodes 12, 13, 22, and 32, as indicated in the third row of the matrix. The domain of coverage of node 12 includes nodes 10, 11, and 12, as indicated in the third column of the matrix. Notice that node 10 has a "0" entry on the matrix principal diagonal since no water is withdrawn from this node.

In the fifth step, the minimum number of columns that "covers" all rows is solved by the set covering problem algorithm. Considering the pollution matrix in Table 2, it can be seen that the minimal set consists of three columns, with the following two possible sets: 21, 23, 32; and 22, 23, 32. The last two nodes in both sets are singular monitoring nodes that should take part in any solution under any level of service. The two sets present different degrees of invulnerability. Higher invulnerability is acquired by the set of 22, 23, 32 due to a higher degree of overlapping. The overlapping occurs between the covering domains of nodes 22 and 32, as shown in Fig. 3. The optimal solution for this example is thus a detection system of three monitoring stations located at nodes 22, 23, and 32.

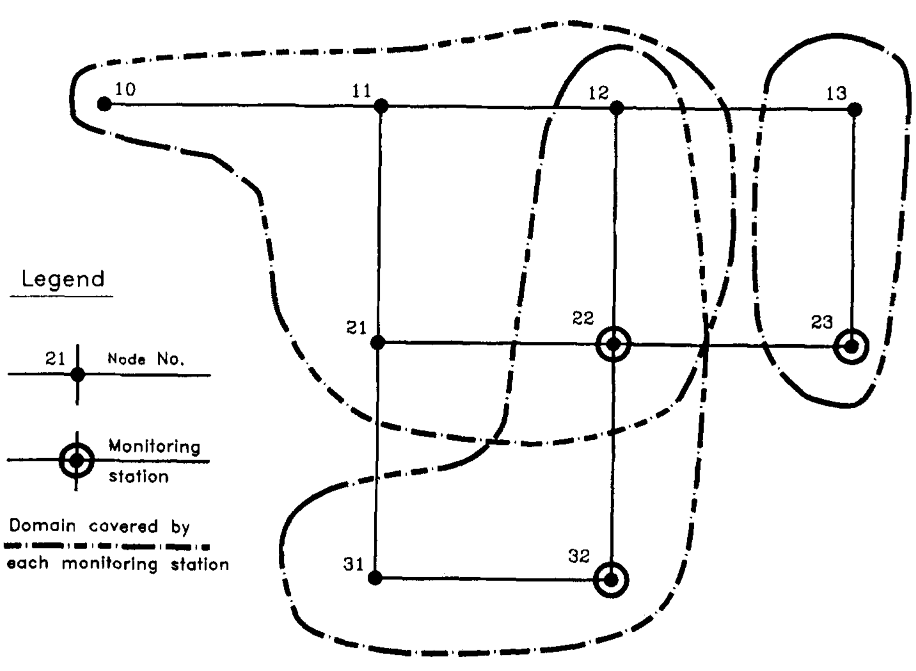

FIG. 3. Minimum Set of Monitoring Stations for 10,000 ft^3 Level of Service

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CASE STUDY

To demonstrate the capability of the proposed methodology on a more realistic case, the methodology is applied to Anytown U.S.A. (Walski et al. 1987). A schematic representation of the distribution system is shown in Fig. 4. The distribution system is made of 34 pipes, 16 nodes, two 56,832 ft^3 elevated storage tanks, one pumping station, and a single well. The tanks are assumed to be cylindrical between their minimum and maximum levels. The water level in the well is maintained at an elevation of 10 ft. The pipes, nodes, tanks, and pumping station characteristics are shown in Tables 3–6, respectively. The system is subject to the demand flow pattern shown in Table 7. The pumping station is assumed to operate at each one of the various flow patterns.

The EPANET simulator was used for the establishment of the auxiliary network. The auxiliary network is shown in Fig. 5, along with the average travel times along the pipes, and an example of all the shortest paths from node 20. The shortest average travel time is 0.6 hr, between nodes 70 and 100, and the longest is 52.9 hr between nodes 150 and 80.

The decision for a detection system is, in most cases, gov-

TABLE 3. Pipe Characteristics for Anytown U.S.A.

Pipe number (1)	Length (ft) (2)	Diameter (in.) (3)	C-factor (4)
2	12,000	16	120
4	12,000	12	120
6	12,000	12	120
8	9,000	12	120
10	6,000	12	120
12	6,000	10	120
14	6,000	12	120
16	6,000	10	120
18	6,000	12	120
20	6,000	10	120
22	6,000	10	120
24	6,000	10	120
26	6,000	12	120
28	6,000	10	120
30	6,000	10	120
32	6,000	10	120
34	9,000	10	120
36	6,000	10	120
38	6,000	10	120
40	6,000	10	120
42	6,000	8	120
44	6,000	8	120
46	6,000	8	120
48	6,000	8	120
50	6,000	10	120
52	6,000	8	120
56	6,000	8	120
58	6,000	10	120
60	6,000	8	120
62	6,000	8	120
64	12,000	8	120
66	12,000	8	120
78	100	12	120
80	100	12	120

TABLE 4. Node Characteristics for Anytown U.S.A.

Node number (1)	Elevation (ft) (2)	Average demand (gal./min) (3)
20	20	500
30	50	200
40	50	200
50	50	200
60	50	500
70	50	500
80	50	500
90	50	1,000
100	50	500
110	50	500
120	120	200
130	120	200
140	80	200
150	120	200
160	120	800
170	120	200

TABLE 5. Tank Characteristics for Anytown U.S.A.

Tank number (1)	Elevation (ft) (2)	Initial level (ft) (3)	Minimum level (ft) (4)	Maximum level (ft) (5)	Diameter (ft) (6)
65	215	35	10	35	53.8
165	215	35	10	35	53.8

TABLE 6. Pump Characteristics for Anytown U.S.A.

Discharge (gal./min) (1)	Head (ft) (2)
0	358
12,000	270
24,000	190
33,000	0

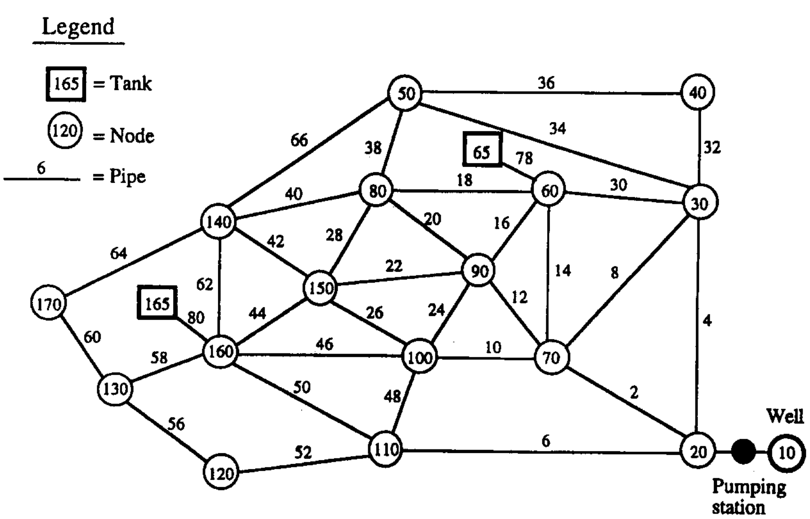

FIG. 4. Network Schematic for Anytown U.S.A.

TABLE 7. Twenty-Four Hour Demand Pattern Characteristics for Anytown U.S.A.

Time of day (1)	Multiplier of average demand (2)
06-09	1.2
09-12	1.3
12-15	1.2
15-18	1.1
18-21	1.0
21-24	0.9
24-03	0.7
03-06	0.6

erned by a budget limitation on the one hand, and by the level of service, on the other. To be able to decide on the appropriate detection system, the analysis of the trade-off between the number of monitoring stations versus the level of service is essential.

The trade-off between the number of monitoring stations versus the level of service is shown in Fig. 6. The trade-off graph was established using different model runs for increasing amounts of maximum consumed polluted water prior to detection (i.e., different levels of service). An initial cost of 1,000 units was assigned for each column in the pollution matrix, with a cost reduction of one unit for each "1" entry in each

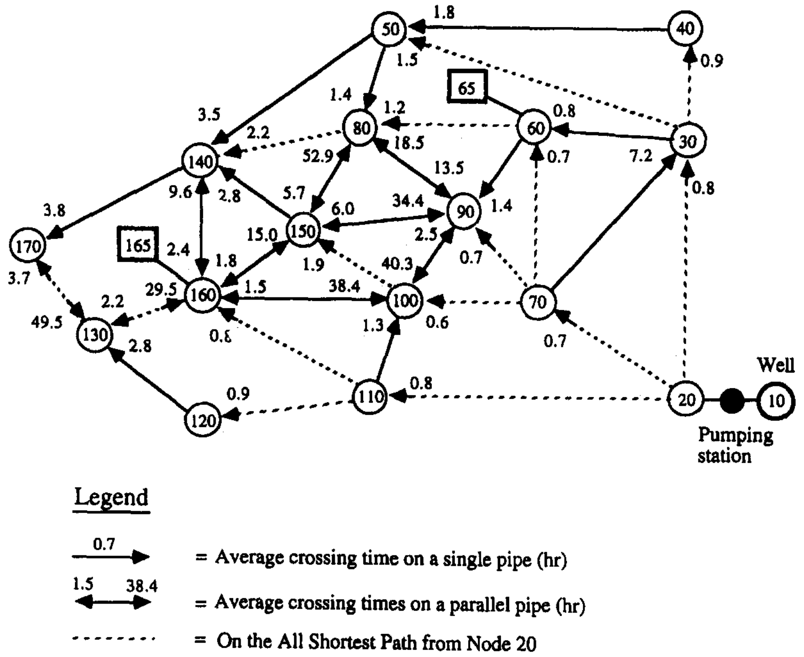

FIG. 5. Auxiliary Network for Anytown U.S.A.

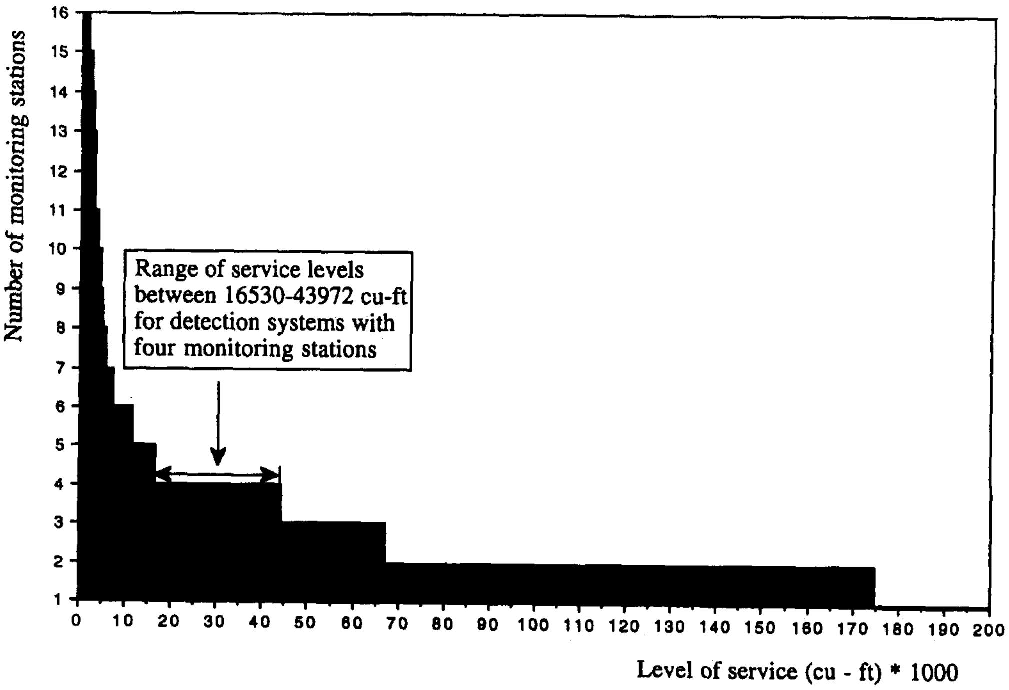

FIG. 6. Trade-Off between Number of Monitoring Stations and Level of Service for Anytown U.S.A.

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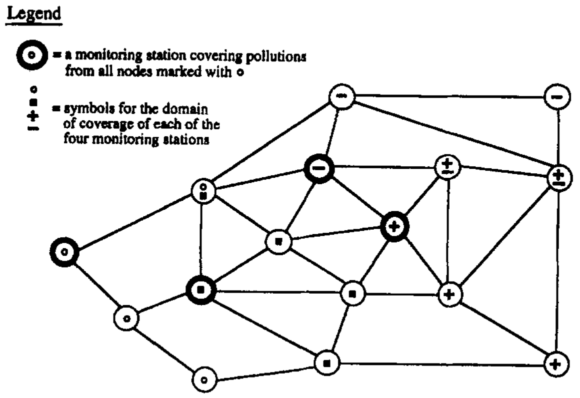

FIG. 7. Optimal Set of Monitoring Stations for 16,530 ft^3 Level of Service

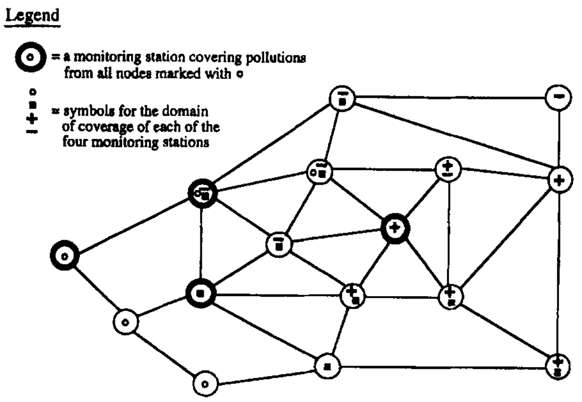

FIG. 8. Optimal Set of Monitoring Stations for 43,972 ft^3 Level of Service

column. These costs were selected to guarantee, in the first place, a minimum number of monitoring stations and, in the second place, the most invulnerable set of stations.

Analysis of Fig. 6 reveals the following.

1. The minimum number of monitoring stations decreases in an exponential manner, as the level of service decreases.
2. An equal number of monitoring stations does not necessarily provide a unique level of service. For example, four monitoring stations provide range-of-service levels between 16,530 and 43,972 ft^3 (see Fig. 6).
3. Within given range-of-service levels, which correspond to an equal number of monitoring stations, the system invulnerability increases as the level of service decreases.

The rationale for point three is that a decrease in the level of service results in a higher number of contaminated nodes, and thus a higher number of "1" entries in the pollution matrix. Consequently, the extent of overlapping among the matrix columns is raised, which leads to a higher level of system invulnerability. For example, a 16,530 ft^3 level of service results in four monitoring stations whose covering domains overlap at three nodes (see Fig. 7); a 43,972 ft^3 level of service results in the same number of monitoring stations, but with an overlapping at eight nodes (see Fig. 8).

To sum up, three conceptual steps are included in the planning procedure of a detection system.

1. Establishment of the relationship between the number of monitoring stations and the level of service. This relationship represents the trade-off that exists between cost investment and the associated health risk.
2. Selection of a minimum number of monitoring stations by the decision maker. The decision involves budget limitations on one hand, and the health risks on the other
3. Allocation of the minimum set of monitoring stations based on invulnerability considerations

CONCLUSIONS

A methodology for finding the optimal layout of a detection system in a municipal water network is formulated and demonstrated. The detection system is aimed at capturing any accidental contaminant entry within a prespecified level of service. A straightforward solution for a detection system is allocating a monitoring station at each of the network nodes. Obviously, such a solution is not economically feasible. The solution proposed in this study consists of the minimum set of monitoring stations that "covers" the entire network at a maximum degree of system invulnerability.

The detection and the coverage domains are evaluated for each node using the "all shortest paths" algorithm on the auxiliary network. The domains are given by their expected values, as defined by the time-averaged flow distribution. The deviation that exists between the actual and the expected value becomes smaller as the domains become larger, in terms of number of nodes and demand patterns. In large domains the actual length of the shortest path between two remote nodes approaches the sum of the arcs' expected lengths (similar to the fact that the variance of the sum of n random elements is reduced according to the variance of the sample divided by n). It is therefore concluded that the proposed methodology is favorable in the case of large and complex networks such as municipal water distribution networks.

Issues such as the consideration of nonconservative pollutants, for which the dilution in the network is important, or unequal probabilities for the system nodes to become sources of pollution need further research consideration.

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