Long Time-series Simulation of Water Quality in Distribution Systems

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Abstract

Dynamic models have largely replaced steady-state models for simulation of water quality in distribution networks. Dynamic models provide a better representation of the time-variant behavior of contaminants in distribution networks, particularly that arising from flow reversal in pipes. Dynamic modeling generally has been limited to periods of a day or a few days. This paper describes three modeling studies that used long time series analyses to characterize contamination in the water distribution system of a major city. The use of long time-series analysis provides a continuous representation of the persistence of contaminants in reservoirs. It also facilitates the understanding of transient operational conditions that may influence the way contaminants are transported within the pipe network. The technique also lends itself well to statistical analyses of exposure. As described in this paper, the methodology is practical for researchers and practitioners using readily available hardware and software.

Introduction

Modeling water quality in water distribution systems has become a widely-accepted tool in support of water supply planning, operations and research. Much of the impetus for development and application of water quality modeling tools and techniques has come from new regulatory frameworks that specify standards for the quality of water at the point of use, rather than at the point where it enters a water distribution system. Additional applications of water quality modeling have come in forensic studies which have the objective of reconstructing historical patterns of water quality for epidemiological studies or as part of litigation.

Real-world Systems

Water quality models are used to simulate real-world systems that operate under highly variable conditions. Water distribution systems are driven by water use, which, because it is the result of human behavior and is influenced by weather, is by its nature stochastic. In response to variations in water use, sources are dispatched dynamically and various highly non-linear automatic controls influence system operation. Changes in water use, control responses and dispatch of sources all can affect flow direction and thus the spatial distribution of contaminants. Because different water sources often have different quality, source dispatch can also cause dramatic changes in the quality of water entering the system. All of these conditions can change rapidly.

Tanks are used to meet the diurnal variation of water use in a water distribution system. For approximately one-half of a day tanks will be filling; during the remainder of the day they will be emptying. Thus, tanks serve as the "memory" of water quality conditions. Tanks are also the only place from which volatile but otherwise conservative compounds can escape from the water being carried in the system.

Requirements for Simulation

The requirements for water quality analyses depend on the type of application. Broadly speaking, the application of water quality models falls into three general categories:

- Planning/Design--These studies define system configurations, size or locate facilities, or define long-term operating policies. They adopt a long-term perspective but, under current practices, utilize short, hypothetical scenarios based on representative initial conditions and operating conditions. In principle, the statistical distribution of system conditions should be an important consideration, but in practice variability is considered only by analyses intended to represent worst-case conditions.

- Operations--These short-term studies analyze a scenario that is expected to occur in the immediate future so as to inform immediate operational decisions. These are based on current system conditions and expected operating conditions. These analyses are often driven by regulations.

- Forensics--These studies are used to link presence of contaminants to the risk or actual occurrence of disease. Depending on whether the objective is cast in terms of acute or chronic exposures, the study may adopt a short- or long-term perspective. Aral, et. al. (1996) define some of the objectives of forensic studies. 1) identify populations at risk from environmental hazards, 2) conduct exposure assessments of sensitive populations, 3) identify areas for the focus of public health education or community outreach and 4) identify target and control populations for health studies. Because there are often dose/response relationships and issues of latency in the etiology of disease, explicit consideration of the spatial distribution, timing, frequency, duration and level of contamination is important to these studies. However, published studies have primarily focussed on defining the spatial extent of contamination, and have often relied on rules of thumb, steady state models or short-term dynamic models (Rodenbeck and Maslia, 1998; Aral, et. al., 1996; Webler and Brown, 1993).

Evolution of Modeling Techniques

Water quality models have evolved to meet these requirements. The first water quality models worked from output from steady-state hydraulic models (Wood, 1980). Increasingly sophisticated codes, including stand-alone water quality models were developed in the 1980's (Males, et. al., 1985; Clark, et. al., 1984) with the first models able to simulate time-varying conditions introduced in the late 1980's (Grayman, et. al., 1988; Clark, et. al., 1986). Most of these models used the "extended-period simulation" (EPS) approach, which is a series of sequential steady-state solutions, each representing a time step and utilizing the results of the previous solution as its initial conditions. These models are quasi-dynamic, as they do not simulate the inertial effects due to rapid changes in velocity. They do, however, simulate flow reversal and the reactivity of constituents, and track conditions in tanks. Fully dynamic models and models that account for dispersion have been developed (Axworthy and Karney, 1996; Islam and

Chaudry, 1998), but extended-period simulation is at present the most advanced technique that is widely deployed for practical applications.

Considerable insight into the water quality behavior of a water distribution system can be gained through the use of steady state analyses. However, steady state models fall short of meeting the requirements set out above. EPS analyses more nearly meet the requirements. Still, as currently practiced, they fall short by not fully capturing the results of cyclic and random variability in water use and operational decisions.

Long time-series analyses of water quality are simply an extension of the quasi-dynamic EPS analysis to cover a period of weeks, months or years. Making such analyses requires only modest changes to the model codes. More substantial, but still within the realm of feasibility for practitioners, is the additional effort required to assemble input data sets and process output into meaningful and accessible information about the system.

Case Studies

Three case studies are described below that illustrate the application and benefits of long time series analyses. The three case studies of forensic analysis involve parts of the water distribution systems of Scottsdale and Phoenix, Arizona. The analyses were undertaken as part of litigation over the contamination of wells first detected in the fall of 1981 (Walski and Harding, 1997a, 1997b). The primary contaminant was trichloroethylene (TCE).

Objective

The objective of the analyses was to reconstruct the spatial and temporal patterns of contamination in the water distribution systems over a study period that covered more than 20 years. Water quality conditions were to be summarized on an annual basis, but their calculation had to consider the variability inherent in the subject systems.

Overview of Approach

The operations of the water distribution systems were simulated using pipe network models. Separate analyses were used to define the response of each system to a unit input of contamination at a source. The results of water quality model runs were used to define the A matrix (for a system with m sources and n water use nodes):

$$[A]\, w = c$$

Where [A] is an $n \times m$ matrix in which a_{ij} is the factor that converts concentration at source j to concentration at user node i. If $a_{ij} = 0$ source j does not supply node i; if $a_{ij} = 1$ all of the water at node i comes from source j; $0 <= a_{ij} <= 1$; the sum of any row in A is 1 for conservative constituents. W is an $m \times 1$ vector of concentration at water sources and c is an $n \times 1$ vector of concentrations at user nodes. The A matrix is developed using the results of runs of the water quality model using a unit input of contaminant at each source. In these case studies, each A matrix was developed based on one year of daily model analyses.

The results from these unit response analyses were then used in combination with source TCE concentrations to calculate TCE concentrations at points within the distribution system. The data necessary to formulate each model, pipe configurations, facilities characteristics, water use and operating practices, were determined by reference to historical documents, personal testimony or aerial photographs.

Water use data were calculated in three steps. First the parcels of land were identified and their land use established, after which they were split up according to which node in the pipe network model delivered water to each part of a parcel. Then, the average day water use for each of the parcels was calculated based on the land use of the parcel and its area. More intensive uses, such as high-density residential developments, use more water per acre than lower intensity uses.

Average daily water use was converted into a pattern of 365 daily water use values by applying for each day a factor that converted the average-day use to the actual use on that day. This factor was the same for each parcel in the system and was developed from actual daily production records. Finally, the daily water use was broken down into twelve 2-hour periods by applying another set of factors that are characteristic of the hour-to-hour (diurnal) pattern of water use for the particular land use of the parcel.

Land use data were obtained from maps and by interpreting aerial photographs. Average-day water use for each land parcel was calculated by applying areal water use factors, in gallons-per-minute per acre, to land use data. These coefficients, along with the diurnal patterns of use, were obtained from engineering studies performed for one or both of the municipalities.

Pipe networks, how the pipes were connected, their size and length and other characteristics, were formulated from old maps, aerial photographs and documents. The types of facilities--pumps, tanks, valves and the like--and their capacities, settings and operational procedures, were collected from old documents. A first-order approximation of the loss of TCE from storage tanks was developed. (Walski, 1999)

Data sets were assembled on a yearly basis. Simulation of hydraulic and water quality conditions was done using a modified version of EPANET (Rossman, et.al. 1994). The primary modifications allowed the software to read a time-series data file of arbitrary length and retain the results of each daily simulation as the initial conditions for the next day. Modifications were also made to streamline reporting and provide statistical summaries of time-series variables. Utilities were developed to handle the more voluminous output.

Model analyses were undertaken on computer hardware that was at the commercial standard of semi-obsolescence (desktop computers with 100 MHz processors). Performance in all cases was well within practical limits.

Scottsdale Zone 1 System

Scottsdale Zone 1 supplied an area of approximately 11.4 sq km (4.4 sq miles), and had an average day water use of approximately 220 L/s (5 mgd) in 1981. In 1981 the zone was supplied almost entirely by wells. The zone had no elevated storage so all pressurization was accomplished by boosters, which were automatically controlled.

In October, 1981 some of the wells serving Zone 1 were determined to be contaminated with TCE. A water distribution quality model was developed to reconstruct historical contamination levels in the system over the years prior to the discovery of contamination. Figure 1 shows Scottsdale Zone 1, identifies the water sources and other features, and shows the predicted annual average concentration of TCE across the zone in 1981. Wells 6 and 31 were contaminated with TCE.

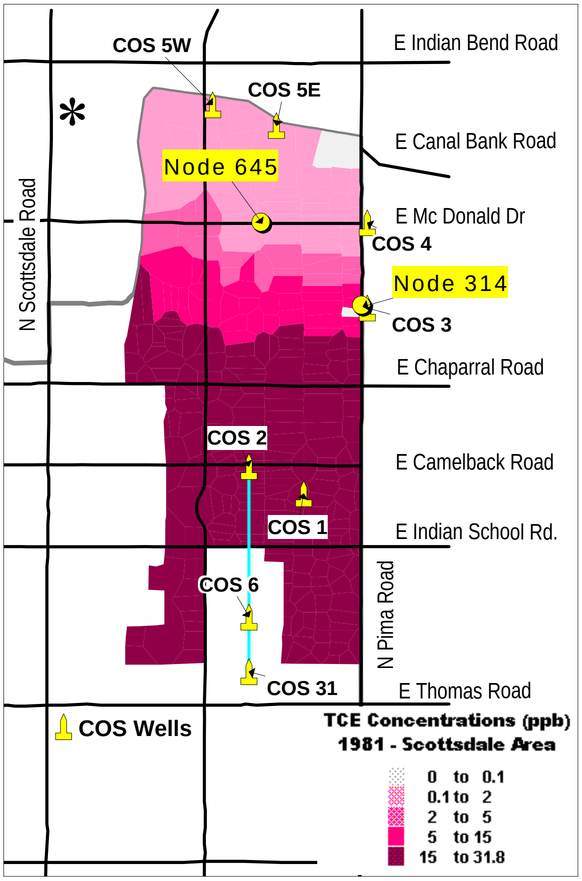

Figure 1 – Scottsdale Zone 1 Schematic

Figure 2 shows the model predictions of hourly variation in TCE concentration at Node 314, which is located on the east perimeter of the zone, approximately midway between the north and south boundaries. Node 314 had an annual average TCE concentration of approximately 7.5 ppb in 1981. The time-series concentration data show that contamination at that node was very episodic, with concentrations varying significantly from day to day and within a day. Two episodes, at about 800 and 1500 hours exhibited consistent TCE concentrations for several days. Another episode with a duration of about 40 days exhibited TCE concentrations that varied daily between approximately 40 ppb and zero.

Figure 3 shows the predicted hourly variation in TCE concentration at Node 645, which is located slightly north of the center of the zone. Node 645 had an annual average TCE concentration of approximately 1 ppb in 1981.

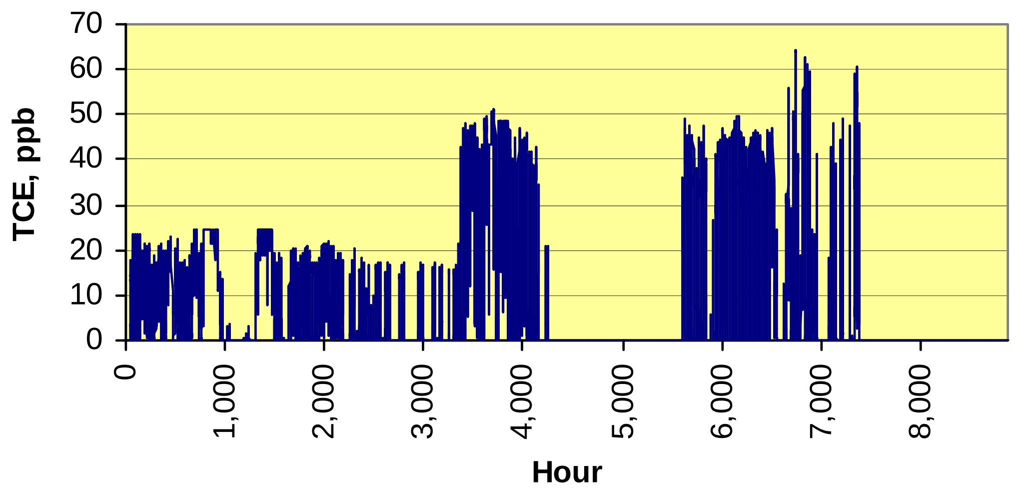

Figure 2 – Hourly TCE Concentrations, Node 314, Scottsdale Zone 1, 1981

The time-series concentration data show that like Node 314, contamination at Node 645 was episodic with concentrations ranging as high as 50 ppb. Node 645 shares with Node 314 a distinct episode at about 800 hours. Other contamination episodes correspond with those at Node 314, but with lower intensity. But node 645, which is farther from the contaminated sources than Node 314, shows contamination between about 4500 hours and 5500 hours, a time when Node 314 shows no contamination. This is a result the pattern of operation of the several uncontaminated wells in the system.

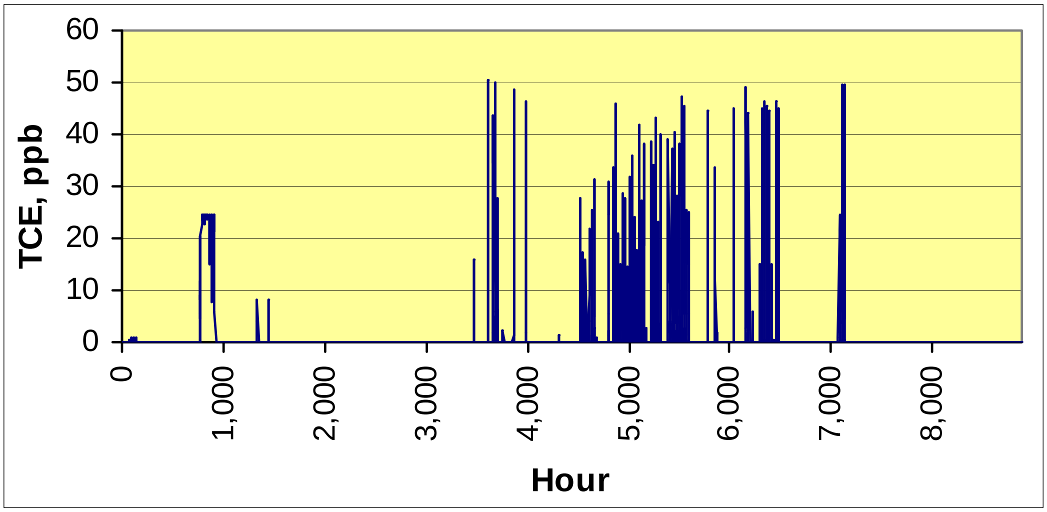

Figure 3 – Hourly TCE Concentrations, Node 645, Scottsdale Zone 1, 1981

East Phoenix Zone 2C and 3B

Phoenix Zones 2C and 3B were adjacent to Scottsdale Zone 1 in 1981. These zones received water from several sources, each with differing quality. Together they served an area of approximately 57 sq km (22 sq miles) with an average day water use of about 875 L/s (20 mgd). The predominant source of water was the Thomas Street

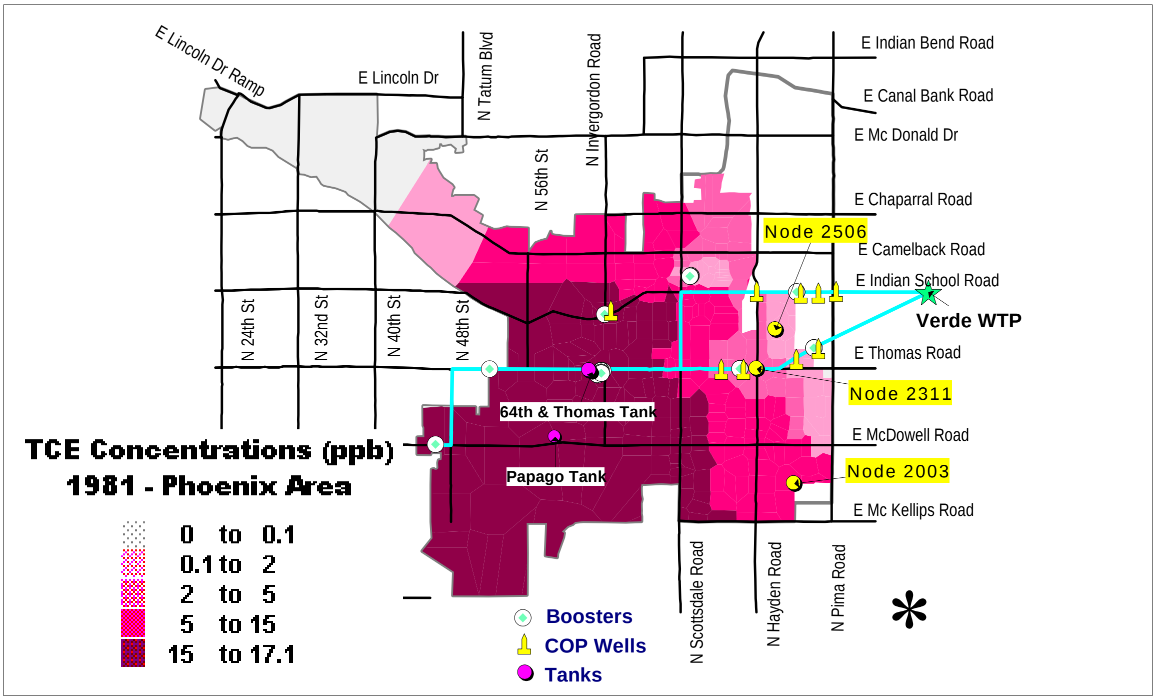

Figure 4 – Phoenix Zones 2C and 3B Schematic

Reservoir, which received contaminated water. The Papago tank, which received contaminated water from the Thomas Street Reservoir, floated on the zone. The largest boosters in the system drew water from the Thomas Street Reservoir and were controlled off of the Papago tank. Smaller boosters drew water from intermediate points on the pipelines supplying the Thomas Street reservoir and were controlled by local pressure. Figure 4 shows a schematic of the zone, identifies the water sources and shows the predicted annual average TCE concentrations across the area in 1981.

Operation of boosters in the eastern part of the zones reduced the average concentration of TCE in that area. These boosters drew water from unpressurized transmission lines that were in some cases free of contamination or had lower levels of contamination. Figures 5 through 7 show predicted TCE concentrations at three points in the system that illustrate the interplay between the different sources. During times of high demand, water from Thomas street extended farther into the zone. Nodes 2003, 2311 and 2506 are roughly equidistant from the Thomas Street Reservoir, but are progressively closer to the smaller boosters along the transmission lines and thus show more influence from these sources.

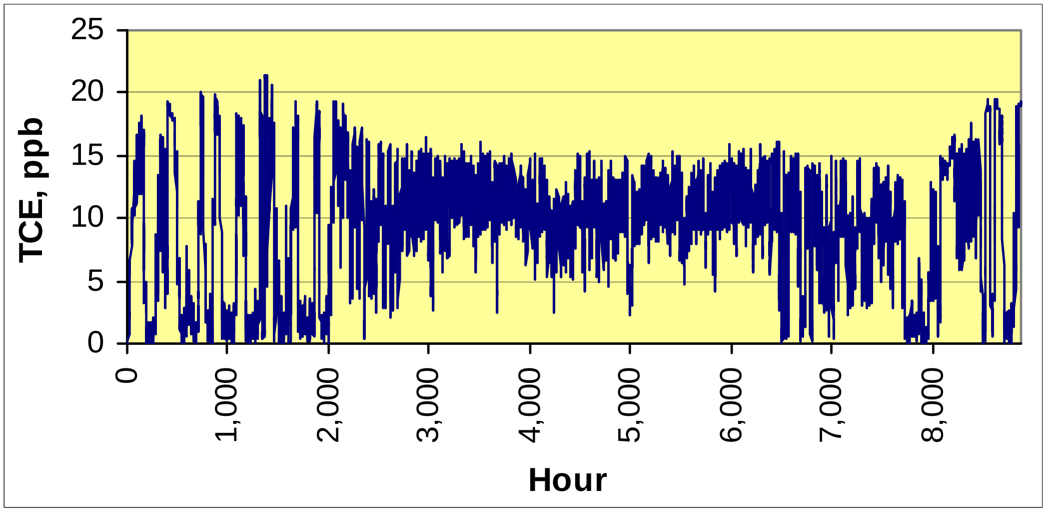

Figure 5 –Hourly TCE Concentrations, Node 2003, Zones 2C & 3B, 1981

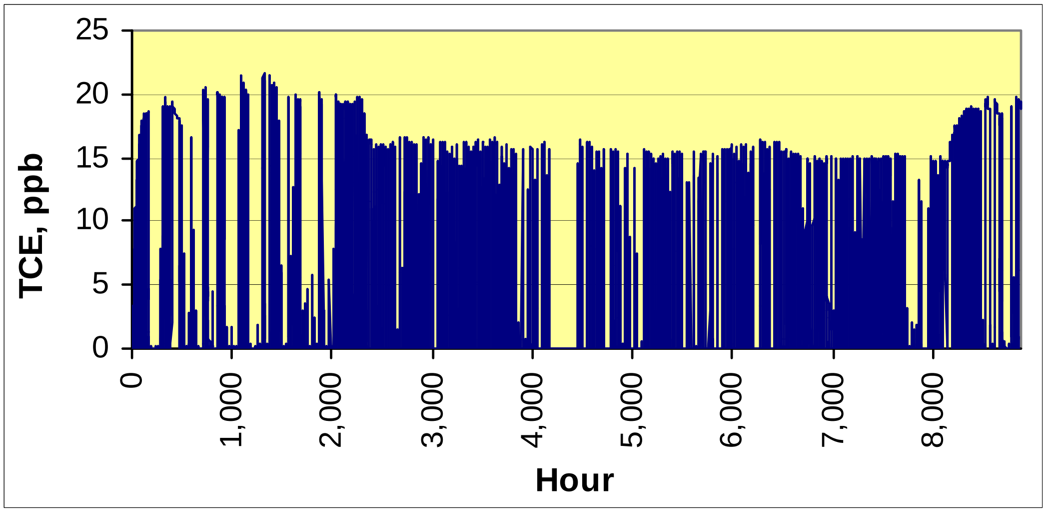

Figure 6 – Hourly TCE Concentrations, Node 2311, Zones 2B & 3C, 1981

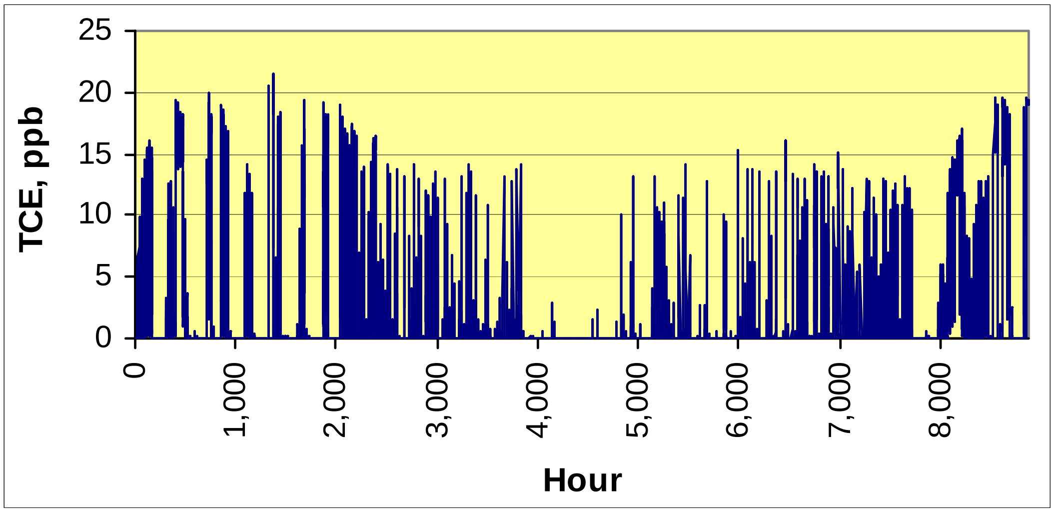

Figure 7 – Hourly TCE Concentrations, Node 2506, Zones 2B & 3C, 1981

Phoenix, Zone 1

Phoenix Zone 1 is the largest pressure zone in Phoenix, covering 360 sq km (140 sq miles) with an average day water use of about 4400 L/s (100 mgd) in 1981. It was supplied by four water treatment plants and more than 40 wells. Zone 1 received contaminated water from other sources, but this analysis addresses only contaminated water from the Thomas Street Reservoir, the same source that served Zones 2C and 3B.

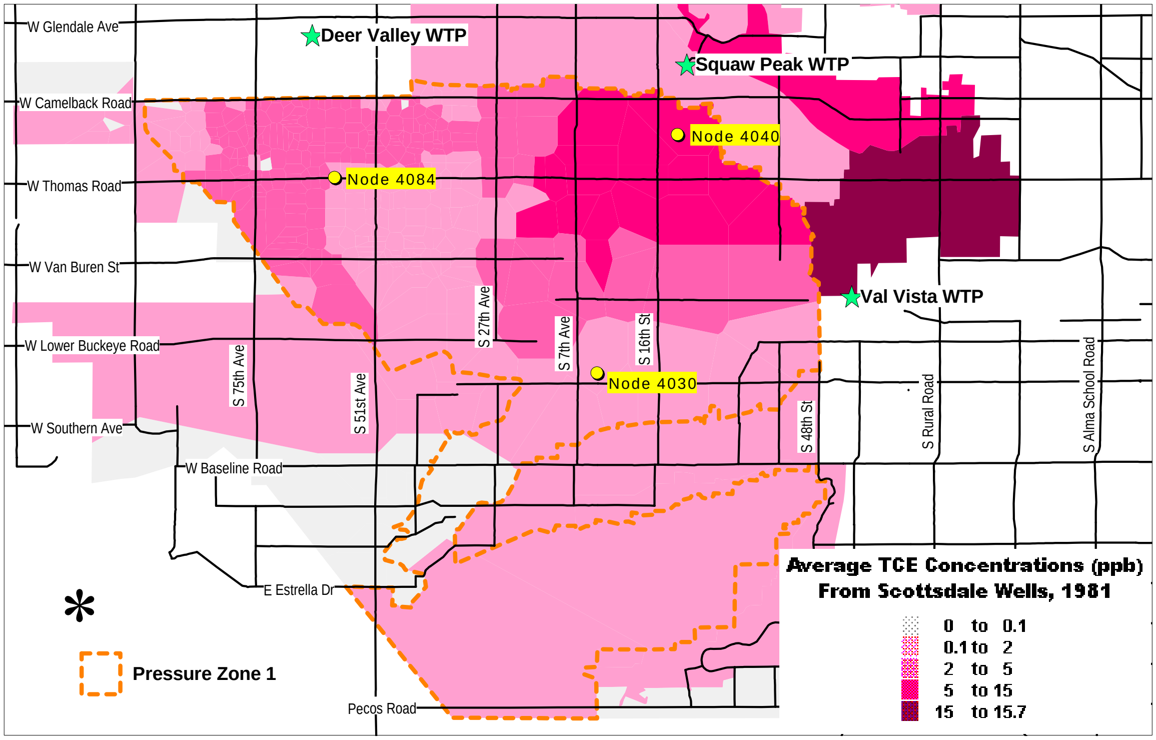

Figure 8 – Phoenix Zone 1 Schematic

The water treatment plants that served Zone 1 in 1981 in addition to the Thomas Street Reservoir drew raw water from irrigation canals. These canals are periodically shut down for maintenance, an activity called "canal dryup". During dryup, the water treatment plants along a canal are shut down and Zone 1 is served by local wells and other sources. Figure 8 shows a schematic of the zone, its water sources and the predicted average annual TCE concentrations across the zone in 1981.

Figures 9 through 11 show the predicted time series of hourly TCE concentrations at three locations identified on Figure 8. Node 4040 is located on the edge of an area that can be considered part of the normal service area of the Thomas Street Reservoir. It shows TCE concentrations that are characteristic of the reservoir, but with substantial variation as other, uncontaminated sources are used during higher demand periods. Node 4030 is located to the south of the normal service area of the Thomas Street Reservoir. This node is normally served by the Val Vista water treatment plant. Val Vista was taken off line in October of 1981 and its production was reduced in February and March, leading to the two contamination episodes evident from Figure 10.

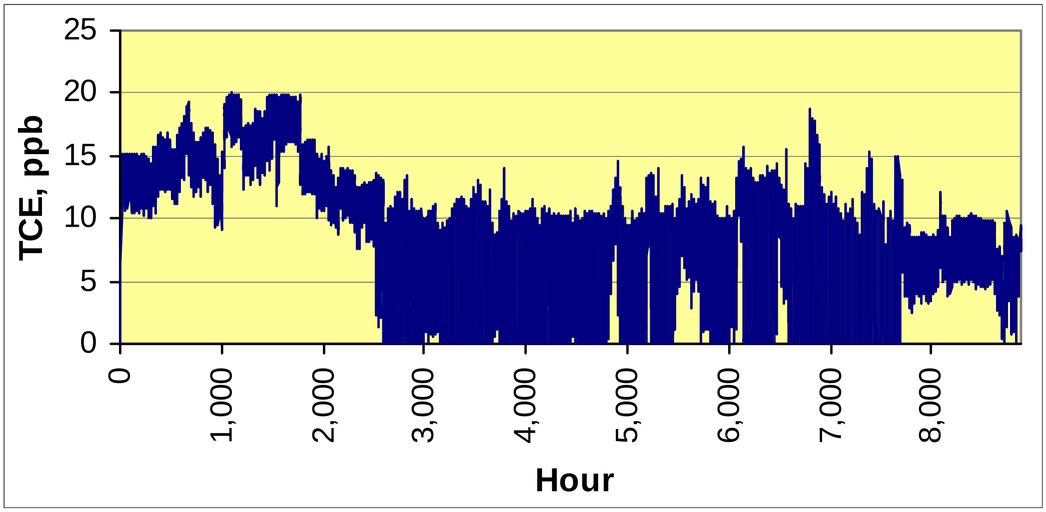

Figure 9 – Hourly TCE Concentrations, Node 4040, Phoenix Zone 1, 1981

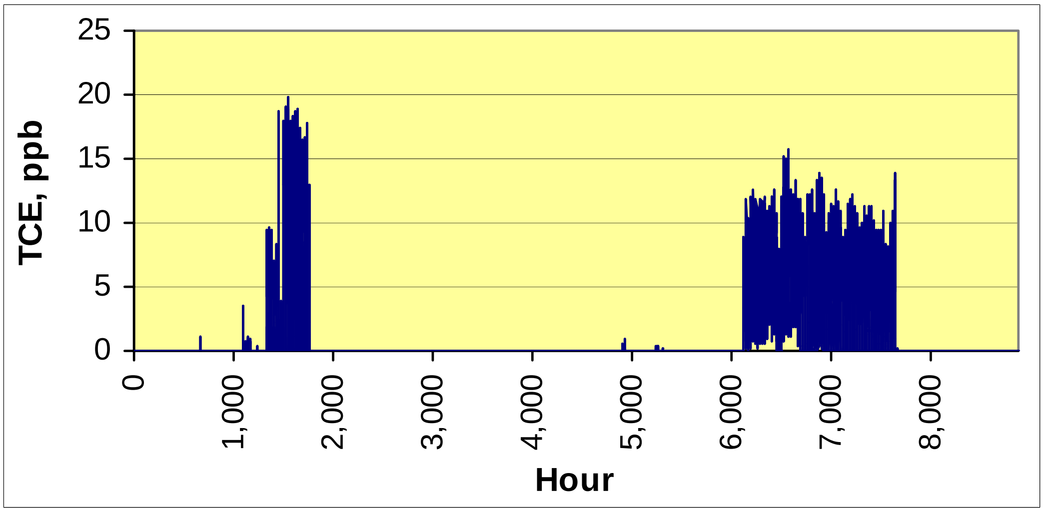

Figure 10 – Hourly TCE Concentrations, Node 4030, Phoenix Zone 1, 1981

Node 4084 is located approximately 22 km (14 miles) to the west of the Thomas Street Reservoir. Yet, the model predicts that TCE from the Thomas Street Reservoir reaches Node 4084 during canal dryup, when only that reservoir, the Val Vista water treatment plant and local wells serve Zone 1. The average annual TCE concentration predicted at Node 4084 during 1981 was approximately 2 ppb, but predicted TCE concentrations there were typically several times that amount during contamination episodes.

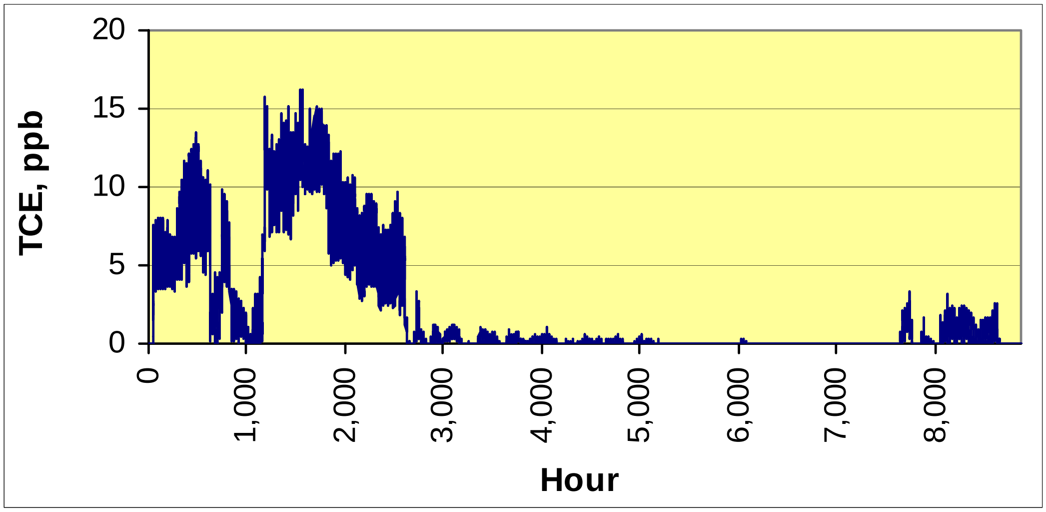

Figure 11 – Hourly TCE Concentrations, Node 4084, Phoenix Zone 1, 1981

Summary

Extended-period-simulation as is currently practiced does not meet all the requirements of many applications of water quality modeling. In particular, EPS does not, by itself, address the variability of water use and operational decisions over the long term. The analyst can overcome this deficiency by intelligently selecting several representative periods for EPS analysis, but there is the risk that important and unforeseen combinations of events could be missed and it is difficult to define frequency distributions of water quality conditions from selected periods.

Long time-series simulation improves on EPS by explicitly capturing the full variability in water quality conditions. The case studies presented here demonstrate some of the variability of water quality in typical water distribution systems and the feasibility of the approach for water quality practitioners.

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