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Linking groundwater, contaminant transport, and water distribution models to determine the uncertainty of drinking water contaminant exposure

S. D. NORMANI, J. F. SYKES & W. C. LENNOX

Department of Civil Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
e-mail: sdnorman@uwaterloo.ca

Abstract Contaminant transport and water distribution models can be linked to assess the historical risk and uncertainty of drinking water contaminant exposure from a water distribution system that has been contaminated at a well head. A 1000 trial Monte Carlo analysis using distributed computing was performed with a transient groundwater flow and contaminant transport model. The resulting stochastic concentration breakthrough curves at the wells were used as concentration sources in the transient water distribution system model. Several water distribution models were created to account for network growth, and changing seasonal demand. Stochastic concentration breakthrough curves were then developed for each consumer node over a 17 year period. Contaminant exposures differ depending on the consumer node location, the time of year and the time of day. Uncertainty in groundwater modelling has been linked to a water distribution system to determine the uncertainty of contaminant exposure at a consumer node.

INTRODUCTION

Concerns over potential consequences for public health and the environment from exposure to hazardous and toxic wastes have led the United States Congress to enact legislation on hazardous waste sites. The resulting "Superfund" legislation led to the creation of the National Priorities List (NPL) of the most contaminated sites in the United States. In 1990, the NPL consisted of approximately 1200 sites of which 85.2% had groundwater impacts, and 73.1% had drinking water impacts (NRC, 1991).

Approximately 50% of urban Americans and 95% of rural Americans depend on groundwater as their source of drinking water (NRC, 1991). Due to the large percentage of the population that depends on groundwater, the large number of contaminated sites, and the fact that most sites have groundwater impacts, there exists a need to couple groundwater models of contaminant transport to drinking water distribution models to aid in assessing the historical risk of exposure to contaminated drinking water.

Water distribution exposure studies completed to date have not considered the transient behaviour of a groundwater flow system and its effects upon the concentrations at a well head. Transient water distribution models are required to assess the migration of contaminants for different periods during the day due to fluctuating consumer demand, while most current exposure studies use steady state models. Large-scale Monte Carlo analyses to assess the uncertainty of concentrations at wells are rarely performed due to the large computational burden of modelling an actual site.

As a result of the limitations in current approaches used to assess contaminant exposure, the objective of this research is to develop a methodology and a set of tools that can be used to assess the uncertainty of drinking water contaminant exposure from a water distribution system as the result of uncertainty in groundwater flow and contaminant transport.

Illegal dumping of drums of industrial wastes at a site during the 1970s resulted in the contamination of a surficial unconfined aquifer and a well field that supplies drinking water to a community of 85 000 residents. During the 1980s, an air stripper was installed to remove solvents which were discovered in the groundwater. Subsequent testing in 1996 revealed the presence of a *new* contaminant.

GROUNDWATER SYSTEM

A two-dimensional integrated depth transient triangular finite element groundwater flow and contaminant transport model was developed. Manual calibration was used to refine the values of hydraulic conductivity, areal recharge and leakage from rivers for steady state groundwater flow. The resulting calibrated heads were found to be very sensitive to the values chosen for areal recharge and hydraulic conductivity. Although a steady state analysis can be used to adequately characterize the current state of the groundwater flow system, a transient analysis is required to describe the evolution of the flow system from the 1970s to the present. During this time, Wellfield B (see Fig. 1) was constructed and placed into operation, resulting in significant changes to the groundwater flow directions, and the piezometric heads in the aquifer.

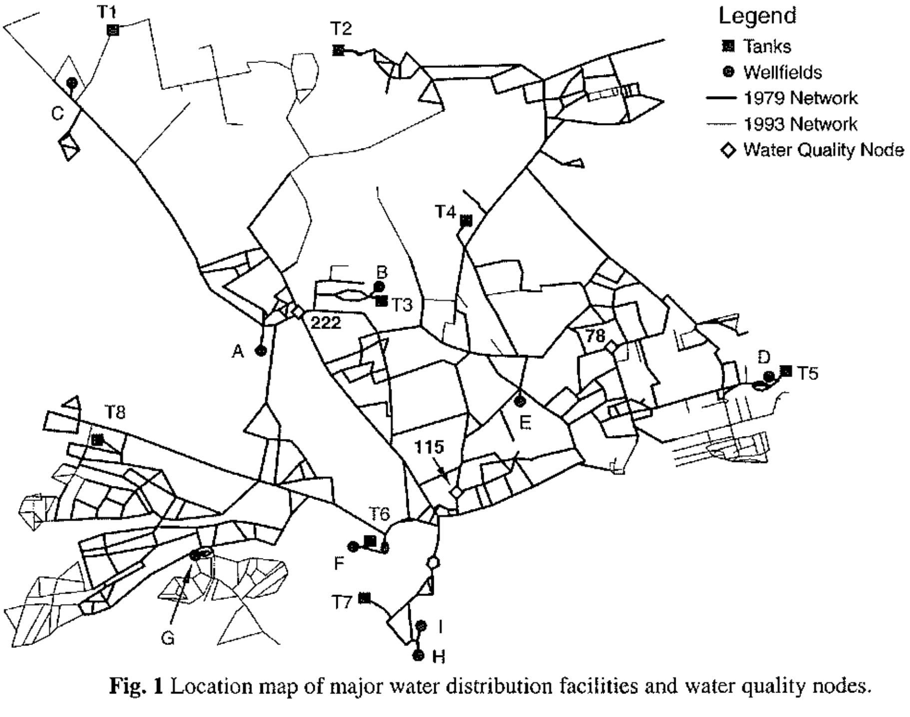

Fig. 1 Location map of major water distribution facilities and water quality nodes.

Contaminant transport analysis

The waste drums were removed within a few years of being discovered. Once removed, the buried waste is no longer a direct source of contamination, but the soil below the waste continues to be a source of contamination. Since a finite contaminant mass exists in the source zone, possible leaching caused by infiltration will deplete this mass. An exponential decay model is used to describe source mass depletion.

Once contamination was confirmed at Wellfield B, the wellfield was removed from service while an air-stripper was installed. The contaminated wells were routed through the air-stripper once the wellfield was returned to service. Water samples have been collected from the air-stripper influent since its installation. The measured TCE concentrations for the influent to the air-stripper were used to calibrate the parameters of the contaminant transport model. Simulated and observed air-stripper influent breakthrough concentrations are shown in Fig. 2.

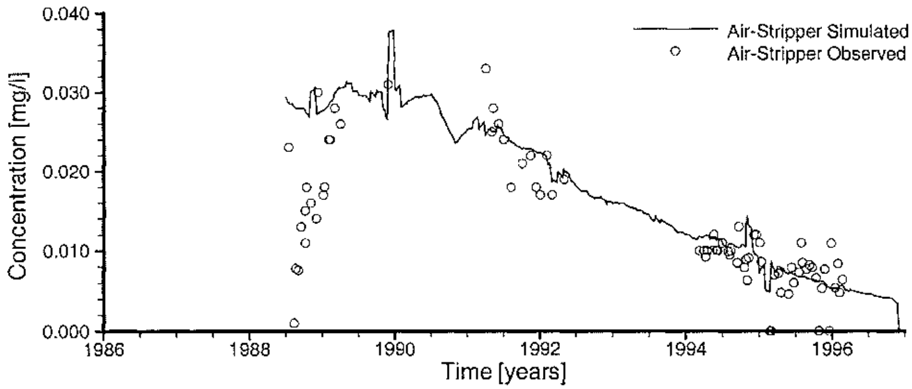

Fig. 2 Simulated and observed air-stripper influent concentrations.

Very little is known about the new contaminant, or about its physical and chemical properties. A 1000 trial Monte Carlo analysis was performed whereby various transient groundwater flow and contaminant transport parameters were represented by probability density functions. Since each trial required between one and two hours to complete on a high performance PC, distributed computing across a PC network was used to perform the 1000 Monte Carlo trials over a four day period during evenings. Thirty six computers were used for a total CPU time of 57.48 days.

An arbitrary source concentration of 100 mg l^{-1} was used. The resulting concentration breakthrough curves are calculated for the wells at wellfields A and B for each of the Monte Carlo trials. The concentration values for each breakthrough curve across all trials were evaluated at the same points in time. Thus, for a chosen well, each time step contains 1000 concentration values, one for each Monte Carlo trial that was performed.

The stochastic breakthrough curves are calculated by determining the 5th, 25th, 50th, 75th and 95th concentration percentiles for each time step once the 1000 concentration values are sorted from smallest to largest. This process is repeated for each time step to yield a concentration breakthrough curve based on the concentration percentiles for each time step. The percentile at a point in time represents the probability of the concentration being less than indicated.

During 1996, several samples were taken from Wellfield B once the new contaminant was first detected. The sample at one well showed a concentration of approximately 8 ppb. Since the actual source zone concentration is unknown, this information at Wellfield B can be used to determine what the source concentration could have been during the 1970s to obtain a concentration of 8 ppb in 1996. The contaminant source concentration can be linearly scaled by a factor calculated as the ratio of the measured and simulated contaminant concentrations for the measured well during 1996. Each trial will have a different scaling factor, resulting in each trial having a different contaminant source concentration. The appropriate scaling factor is applied to each breakthrough curve to yield adjusted concentration breakthrough curves for each trial. Water from each well in Wellfield B is blended together before entering the water distribution system. The stochastic concentration breakthrough curves for Wellfields A and B which represent sources to the distribution system are shown in Figs 3 and 4.

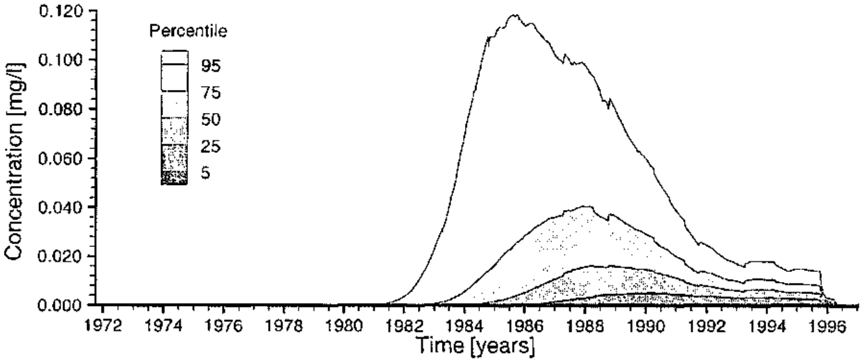

Fig. 3 Simulated stochastic contaminant concentration breakthrough curves for Wellfield A with an 8 ppb contaminant concentration at a Wellfield B well in 1996.

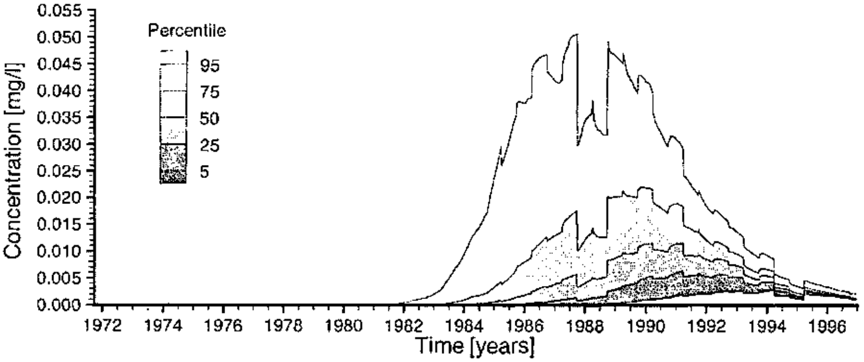

Fig. 4 Simulated stochastic contaminant concentration breakthrough curves for blended Wellfield B with an 8 ppb contaminant concentration at a Wellfield B well in 1996.

WATER DISTRIBUTION SYSTEM

The distribution network is comprised of pipes ranging in diameter from 5 to 40 cm. For this paper, a skeletonized hydraulic model was developed such that only pipes greater than or equal to 10 cm in diameter were included.

Consumer demand for water varies on an hourly basis (higher demand in the morning and early evening), a seasonal basis, and a yearly basis (population growth) (DeMoyer & Horwitz, 1975). On a seasonal basis, peak daily demand in the summer can be double the minimum day demand during the winter.

Two time periods were selected to accommodate the development of the distribution network: the 1979 network (1979–1985 inclusive), and the 1993 network (1986–1996 inclusive). A map of the 1979 and 1993 networks showing the locations of wellfields and tanks is shown in Fig. 1. A total of three models were developed for each time period to simulate the behaviour of the water distribution system during different seasons: average demand day during the spring and fall, peak demand day during the summer, and minimum demand day during the winter months. A summary of when the various models were used is shown in Fig. 5.

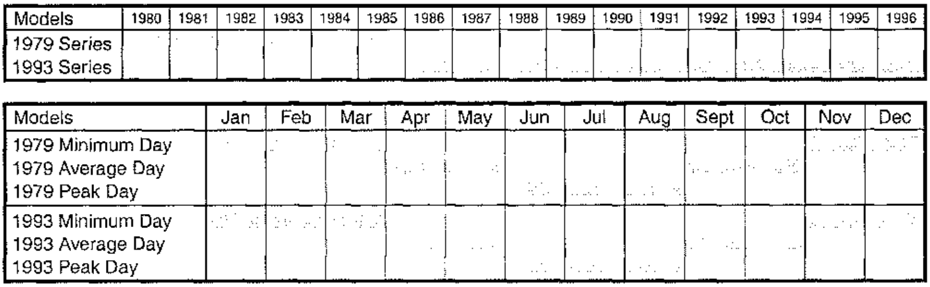

Fig. 5 Time periods for which the 1979 and 1993 seasonal models were used.

A transient hydraulic and contaminant transport simulation of the water distribution network was performed using EPANET, a model that simulates transient hydraulic and water quality behaviour within drinking water distribution systems (Rossman, 1994).

Contaminant migration

A seven day simulation was performed to provide insight into the transient behaviour of the distribution system. The initial 48 hours of the simulation are considered a "wind-up" period to allow the effects of the assumed initial conditions to dissipate. The final 24 hour period of the seven day simulation (144:00 to 168:00 hours) is subsequently used to represent a typical 24 hour period. A unit concentration is applied at Wellfield A and Wellfield B thereby resulting in normalized concentrations in the distribution system.

The contaminant was modelled as a conservative species within the distribution network. Since the contaminant source concentrations at Wellfield A and at Wellfield B are changing in time, the source concentration at a wellfield can be multiplied by the normalized concentration profiles to obtain the 24 hour contaminant concentration at a node due to Wellfield A and due to Wellfield B individually.

The contaminant concentration profiles due to each source can be added to obtain the final contaminant concentration profile at any node. The mean concentration value for the final profile is then calculated. This process is repeated for each consumer node and for each Monte Carlo trial. The stochastic contaminant concentration breakthrough curves for the mean concentration measure for the selected nodes is shown in Fig. 6. The contaminant concentration at the selected nodes depends upon the source concentration at the wells, the season, and growth in the network. The concentration that an individual would experience also depends upon their location and the time of day that they open their water tap. Concentrations are less during the summer period since the contaminated wells represent a smaller percentage of the total volume produced since other wellfields are brought into production to satisfy the increased demand.

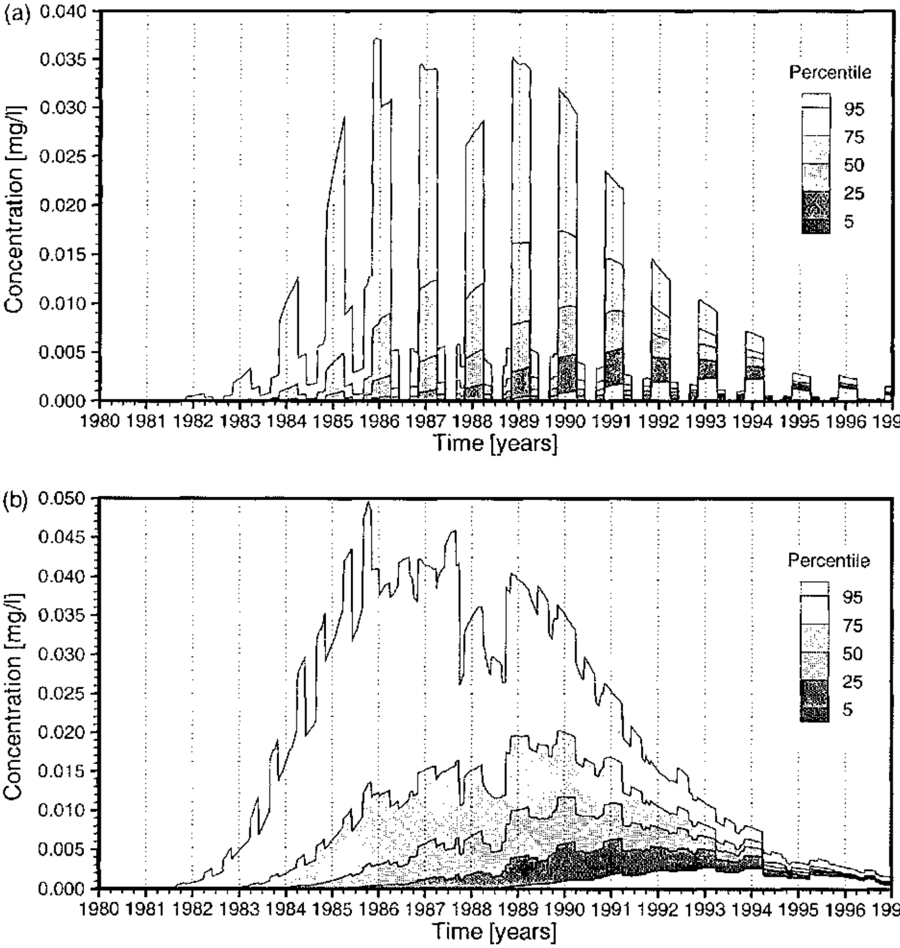

Fig. 6 Simulated stochastic contaminant concentration curves for (a) node 78, and (b) node 222 using an average daily concentration measure.

Node 78 (Fig. 6(a)) located in the eastern portion of the network sees very little concentration during the summer season beyond 1986 since its water primarily comes from Wellfield D which is typically operated during the peak demand periods. Node 222 (Fig. 6(b)) which is located directly between Wellfields A and B experiences the highest concentrations throughout the year with small fluctuations from season to season.

CONCLUSIONS

This paper has presented a methodology for estimating the uncertainty of contaminant migration in a water distribution system due to parameter uncertainty in a groundwater flow system. The stochastic concentration breakthrough curves consider the physical constraints and uncertainties associated with the entire contaminant pathway. The contaminant pathway begins at the dumping site and proceeds through the unsaturated zone, into a transient groundwater flow system, into the municipal wells and finally propagates through a transient water distribution system to a consumer, spanning a time period of nearly three decades. Ultimately, these stochastic concentration breakthrough curves can provide an epidemiologist with a better estimate for exposure to a contaminant.

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