

# Exposure Assessment for Trichloroethylene in Drinking Water Using a Geographic Information System

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## Abstract

The Agency for Toxic Substances and Disease Registry's (ATSDR's) baseline survey of its Trichloroethylene (TCE) Subregistry found that there were excess speech and hearing problems among Subregistry children 10 years old and younger compared with national data. In the project described in this paper, drinking water analyses were used to assess TCE exposure of 318 children listed in the Subregistry. Geographic information system (GIS) models were used in conjunction with mathematical interpolation to explore the spatial and temporal variation of TCE exposure. Yearly and cumulative exposures were estimated. The subjects were categorized into subgroups in terms of exposure level, exposure duration, cumulative exposure, and geographic location. The potential confounding exposures were identified and characterized. At one of the six sites in the Subregistry—a site in Rockford, Illinois—GIS detected a contaminant plume spreading in an east-west direction. The estimated cumulative exposures were significantly associated with subject's geographic location and age at the time of remediation. No major changes in the geographic distribution pattern of TCE were observed at the Rockford site over a six-year period, except that the concentration generally increased. The subjects at this site could be categorized into two geographic subgroups: inside the plume area and outside the plume area. It was found that the cumulative exposure ranged from 0 to 59,210 parts per billion (ppb) per year, with a mean of 700 ppb per year. Four subgroups were created based on cumulative exposure levels. The mean exposure duration was  $5.5 \pm 2.9$  years. Of the 198 households in the study, 118 had water with measured TCE concentration exceeding 5 ppb, the EPA maximum allowable level for TCE in drinking water. The TCE exposure was significantly correlated with the potentially confounding exposures at the Rockford site, but not at another site, in Elkhart, Indiana.

Keywords: trichloroethylene, water, exposure

## Introduction

Trichloroethylene (TCE) is an organic chemical that has been widely used as a dry cleaning agent, a metal degreaser, a rubber solvent, and an ingredient in printing ink, paper, lacquer, and varnish (1). It also is a frequent contaminant of both untreated and treated drinking water in the United States. Various surveys conducted by the US Environmental Protection Agency (EPA) showed that about 38% of cities sampled had TCE in their drinking water (2). Spills and leaking storage tanks readily contaminate groundwater. The TCE released into soil can also migrate to groundwater, where the chemical remains for months to years (3). High-dose TCE exposure causes central

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nervous system depression, and trigeminal nerve toxicity was among the most often reported adverse effects in case studies (4,5,6).

To facilitate studying the effects of environmental exposure to TCE, the Agency for Toxic Substances and Disease Registry (ATSDR) established a subregistry of people exposed to TCE through their water supplies as part of the National Exposure Registry (7). At the sites covered by the TCE Subregistry, groundwater was contaminated by local industries—wastes containing TCE and other volatile organic compounds were disposed of on site in lagoons or injected into surface soil, resulting in contamination of soil, sediment, and groundwater. To be included in the Subregistry, a person must have used a private well as a water source, and TCE must have been detected in at least one water sample from their home water supply.

ATSDR's baseline survey of the TCE Subregistry revealed excess self-reported speech and hearing problems among the Subregistry population 10 years old and younger compared with National Health Interview Survey (NHIS) data for the same age group. However, these data cannot be used to establish a causal relationship between TCE exposure and impairment of speech and hearing.

To explore the association between speech and hearing impairment and TCE exposure, an ongoing study is evaluating the speech and hearing of the children in the Subregistry who were 10 years old or younger when the Subregistry was established. Results are to be compared with speech and hearing data from control children, matched by age and race, who have not been exposed to TCE or other relevant risk factors. Because a preliminary examination of well water data revealed a wide range of TCE concentrations in the exposed communities, categorizing Subregistry children by exposure level was highly desirable.

TCE has been shown to cause hearing deficits in laboratory animals (8,9). In one study, young animals were much more sensitive than older animals, indicating that the developmental stage may be an important factor in assessing toxicity (8). Estimating exposure as a function of age was therefore an important objective, because it would allow participants to be categorized by exposure during specific age ranges. Thus, an important objective was to assess TCE exposure as a function of participant age, because it would make it possible to investigate the impact of human TCE exposure on speech and hearing during vulnerable developmental stages.

The Subregistry consists of 814 households in six towns—Albion, Michigan; Byron, Illinois; Elkhart, Indiana; Rockford, Illinois; Roscoe, Illinois; and Verona, Michigan. Of the 814 households, the 198 that had children 10 years and younger were selected for the speech and hearing study. The home water TCE measurements available for exposure assessment numbered 248 for the households to be studied and 1,069 for the entire Subregistry (7). Only 20% of the households had more than one sample from their water supplies analyzed (7). This sparseness of data meant that, unless results could be spatially and temporally interpolated, accurate assessment of exposure over a child's life would have been impossible. Thus, the purpose of this effort was to explore new methods for dealing with sparse exposure data, using the data from all the Subregistry households to estimate exposure for the households in the study.

The historical exposure was modeled using a geographic information system (GIS) and a mathematical approach for temporal interpolation. Specific questions addressed were whether spatial and temporal trends exist in the measured TCE concentration data and whether the exposure to potentially confounding environmental contaminants is

correlated with the TCE exposure. Exposure information for each household included household ID, subject ID, street address, city, state, chemical name and concentration in parts per billion (ppb), and sampling date. The data were checked for invalid entries, such as negative concentrations, extremely high values, missing values, or invalid time data. Questionable data were verified from ATSDR documentation.

## Methods

Total human exposure to a contaminant is the product of contributions from all environmental media (water, soil, air, and food) that contain the contaminant and all routes of entry to the human body (dermal contact, ingestion, and inhalation) (10). Ingestion and inhalation are thought to be the major routes of exposure for people in these communities who have no occupational contact. McKone and Knezovich (11) investigated the potential inhalation exposure resulting from vaporization of TCE from water in homes. They showed that TCE inhalation exposure is approximately proportional to the chemical's concentration in water; because ingestion exposure is also proportional to the chemical's concentration in water, this means that inhalation exposure to TCE is proportional to ingestion exposure. McKone and Knezovich's experiments revealed that the transfer efficiency of TCE from shower water to air has an arithmetic mean value of 61%. We have assumed that total exposure is proportional to the concentration in well water. Groundwater TCE values were therefore used as an index of total exposure.

Total human exposure by ingestion may be defined by Equation 1:

$$E = \int_{t_1}^{t_n} C(t) dt \quad (1)$$

where  $E$  is the cumulative exposure,  $C(t)$  is the time-varying concentration of a contaminant (TCE in this case),  $t$  is time, and  $t_1$  and  $t_n$  are the beginning and end times of the period of interest.

An approximate solution for Equation 1 is the application of the trapezoid method, which is illustrated in Equation 2:

$$\int_{t_1}^{t_n} C(t) dt = \frac{1}{2} (C_0 + C_1) \Delta t_1 + \frac{1}{2} (C_1 + C_2) \Delta t_2 + \dots + \frac{1}{2} (C_{n-1} + C_n) \Delta t_n \quad (2)$$

where  $\Delta t_n$  is the time increment from  $t_{n-1}$  to  $t_n$ . The TCE concentrations at each time must be determined when solving the above equation.

### GIS Modeling

The general functions of the GIS include data input and geocoding, geographic visualization, geographic editing and querying, and spatial analysis. When assessing exposure, one must combine geographic, demographic, and environmental databases to describe temporal and spatial characteristics of exposure. This is very difficult to do using a routine numerical approach. GIS, however, makes it easy to manipulate layered, spatially distributed data, thereby significantly simplifying the database management, visualization, and spatial analysis involved in exposure assessment (12).

This paper uses the Rockford site as an example to describe the methods and results obtained in this study because that site contains more than 50% of the study subjects and almost 50% of the households in the study. The first step in analyzing the Rockford site was to geocode subject households and match them with the digital map extracted from the US Bureau of the Census TIGER/Line census file (13). The Rockford samples were collected in four periods over six years: June to November 1984, January to November 1985, August 1988 to September 1989, and October 1989 to February 1990. Most households, however, had samples for only one of the four periods. For each sampling period, the TCE concentrations for households in the study that were not sampled were estimated by GIS spatial interpolation using data from neighboring households that were in the Subregistry (14).

There are several interpolating methods available in GIS, including inverse distance weighting (IDW), spline, and kriging (15). The two most frequently used methods, IDW and kriging, were applied to interpolate surface data in this study. In IDW interpolation, each input point has a local influence that diminishes with distance; points closer to the location of the estimate are weighted more heavily than those farther away. Kriging regards the statistical surface to be interpolated as a regionalized variable that has a certain degree of continuity. The kriging algorithm minimizes the variance of error.

#### **Temporal Interpolation by Lagrange's Formula**

With data from GIS interpolation included, each household in Rockford had TCE values for 1984, 1985, 1989, and 1990. Exposures occurring between 1985 and 1989, however, still needed to be determined to solve Equation 2. To account for these periods without TCE samples, we applied Lagrange's interpolation formula (16). Let  $c(t)$  be the polynomial of degree  $n$ , which, for values  $t_1, t_2, \dots$ , and  $t_n$  of the argument  $t$ , has the values  $c_0, c_1, c_2, \dots$ , and  $c_n$ , respectively. Lagrange's formula is shown in Equation 3:

$$c(t) = \frac{(t-t_1)(t-t_2)\dots(t-t_n)}{(t_0-t_1)(t_0-t_2)\dots(t_0-t_n)} c_0 +$$

$$\frac{(t-t_0)(t-t_2)\dots(t-t_n)}{(t_1-t_0)(t_1-t_2)\dots(t_1-t_n)} c_1 +$$

$$\dots\dots\dots +$$

$$\frac{(t-t_0)(t-t_1)\dots(t-t_{n-1})}{(t_n-t_0)(t_n-t_1)\dots(t_n-t_{n-1})} c_n \quad (3)$$

where  $t_n$  is the  $n$ th time period,  $c_n$  is the TCE value corresponding to the  $n$ th time period, and  $c(t)$  is the TCE value to be interpolated at time  $t$ .

Equation 4 was used to account for exposure in utero, under the assumption that subjects were exposed to TCE since their conception:

$$E_0 = E_1 \times 0.75 \quad (4)$$

where  $E_0$  is the in utero exposure level and  $E_1$  is the exposure level for the first year after birth.

According to the time when a subject entered and left the exposed group, an exposure duration in years was computed for each subject. The starting and ending times for each site were different, so the exposure of each subject was calculated individually. The cumulative exposure in ppb per year was estimated by integrating the exposure level over the exposure duration. GIS and repeat measure analysis (taking multiple measurements of the same observational unit) were used to explore temporal trends visually and statistically.

### ***Confounding Exposure***

The four other chemicals most frequently found in the water supply of people in the Subregistry—trichloroethane (TCA), dichloroethane (DCA), dichloroethene (DCE), and perchloroethylene (PCE)—were included in an analysis of confounding exposures. Although a literature search did not find any direct evidence that these chemicals cause speech and hearing impairment (17–24), they have central nervous system effects, including depression, irritability, and dementia, at high exposure levels. Therefore, chronic exposure to these chemicals may have some as yet undetected effects on speech and hearing.

Correlation analysis was conducted using SAS software (SAS Institute, Inc., Cary, NC) and GIS to detect the relationship between TCE and the potentially confounding exposures. The subjects were stratified into subgroups according to their levels of potential confounding exposures.

## **Results**

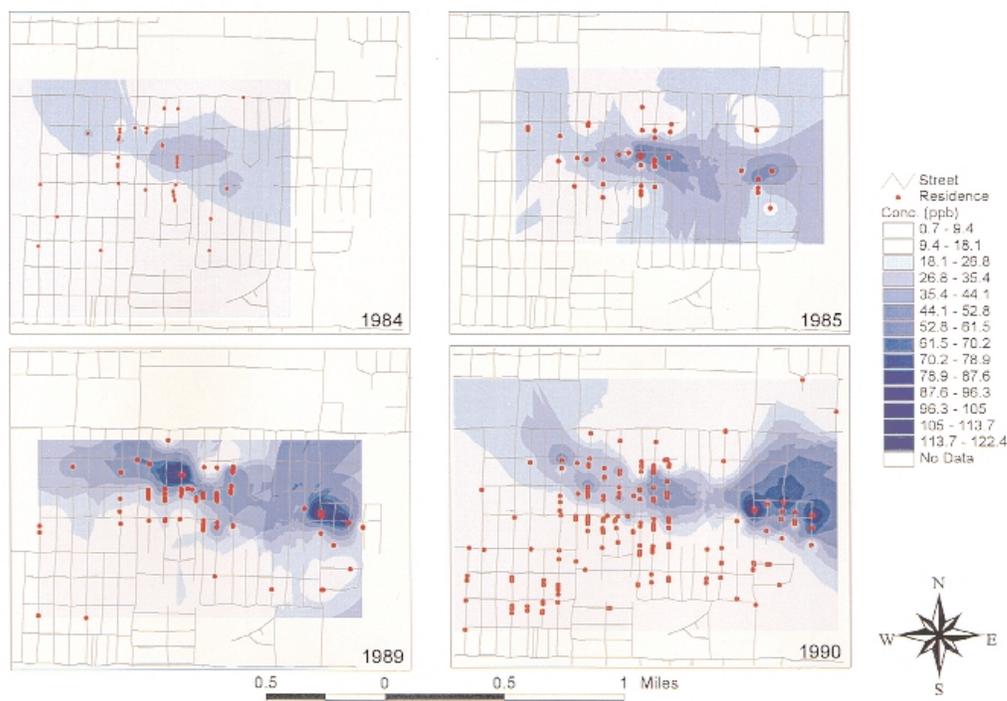
### ***The Rockford Site***

There were 330 Subregistry households at the Rockford site, including 98 subject residences. The number of samples collected during each sampling campaign is listed in Table 1. The four maps in Figure 1 were created by interpolating surfaces (using IDW) from samples collected in 1984, 1985, 1989, and 1990, respectively.

**Table 1** Number of Samples for Each Sampling Period at the Rockford, Illinois, Site

<b>Sampling Period</b>	<b>Midpoint of Sampling Period</b>	<b>Years of Exposure<sup>a</sup></b>	<b>Number of Samples</b>
June 1984–November 1984	August 1984	4.67	39
January 1985–November 1985	June 1985	5.50	41
August 1988–September 1989	February 1989	9.17	82
October 1989–February 1990	December 1989	10.00	203

<sup>a</sup> Years of exposure were determined by calculating the time between January 1, 1980 (when exposure at Rockford is assumed to have begun), and the midpoint of the time period.



**Figure 1** Well water trichloroethylene plume at the Rockford, Illinois, site.

### Comparison of IDW and Kriging in Exposure Assessment

Fifty-seven households were covered by both IDW and kriging. The IDW and kriging exposure estimates were compared for the 89 subjects living in these households (Table 2). T-tests did not find a significant difference between the exposures estimated by the two methods ( $p=.0724$ ). Thus, the results of IDW interpolation were used in later analyses because the IDW algorithm was more stable than kriging for the GIS program used here.

**Table 2** Comparison of Inverse Distance Weighting and Kriging by Cumulative Exposure for the Rockford, Illinois, Site

Method	Number of Subjects	Mean $\pm$ SD <sup>a</sup>	Cumulative Exposure (parts per billion per year)						
			Maximum	95%	90%	75%	50%	25%	Minimum
IDW	89	173 $\pm$ 108	442	383	335	247	166	81	7
Kriging	89	184 $\pm$ 102	396	380	309	255	188	98	8

<sup>a</sup>SD=standard deviation

$p=.0724$  at  $\alpha=.05$

### Temporal Trends of TCE Contamination

The surfaces were interpolated from 396 samples collected at the four time periods covering 1984 through 1990. Although TCE levels were not completely the same in the four sampling periods, GIS spatial interpolation indicated that the overall geographic distribution of TCE contamination was similar. A ribbon-shaped contaminant plume extending in a southeast-northwest direction was first found in 1984, consistently appeared in 1985 and 1989, and became most apparent in 1990, when sampling coverage (203 households) was much denser than in previous years. The heavily contaminated area was always located between Road 1 and Road 2, with TCE concentration on the eastern side of the site higher than on the western side. No significant south or north movement of contamination was observed. For example, TCE levels in most areas south of Road 2 were always around 0 to 18 ppb over the six years covered by sampling. The more heavily contaminated area had TCE values ranging from 18 to 139 ppb. On the other hand, repeated measures analyses indicated the existence of time effect ( $p=.0001$ ). Therefore, even though GIS found no major qualitative changes in the TCE distribution pattern over the six years, comparison of the TCE plumes in Figure 1 suggests a trend of generally increasing concentration with time. Thus, it is unreasonable to assume that the TCE level in households was constant over the six years for which water was sampled.

### Geographic Variation of TCE Exposure

The ribbon-shaped plume flowed in an east-west direction and separated the site into three geographic areas: north of the plume, inside the plume, and south of the plume (see the 1990 map in Figure 1). The TCE exposure of the subjects living at these three areas was compared by the SAS General Linear Models (GLM) procedure, which analyzes variance. The model, including independent variables of area and age, was statistically significant ( $p=.0001$ ). A contrast test among the three areas indicated that the cumulative exposure of the subjects inside the plume area was significantly higher than that of the subjects north or south of the plume ( $p=.0001$ ). No statistically significant difference between the exposure of the subjects north of the plume and south of the plume was detected ( $p=.4491$ ). The GLM procedure also found that there was no significant difference between the areas in terms of subjects' age or exposure length ( $p>.1$ ). With the areas above and below the plume combined, exposure inside the plume was found to be significantly higher ( $p=.0001$ , Table 3) than exposures outside the plume. It was concluded that the TCE exposure inside the plume area was higher than exposure in the other areas at the Rockford site.

**Table 3** Descriptive Statistics of Trichloroethylene Exposure for the Rockford, Illinois, Site

Area	Number of Subjects	Mean $\pm$ SD <sup>a</sup>	Cumulative Exposure (parts per billion per year)						
			Maximum	95%	90%	75%	50%	25%	Minimum
Within plume	64	225 $\pm$ 137	768	434	383	276	229	124	7
Outside plume	111	47 $\pm$ 56	229	162	137	58	20	9	0

<sup>a</sup>SD=standard deviation

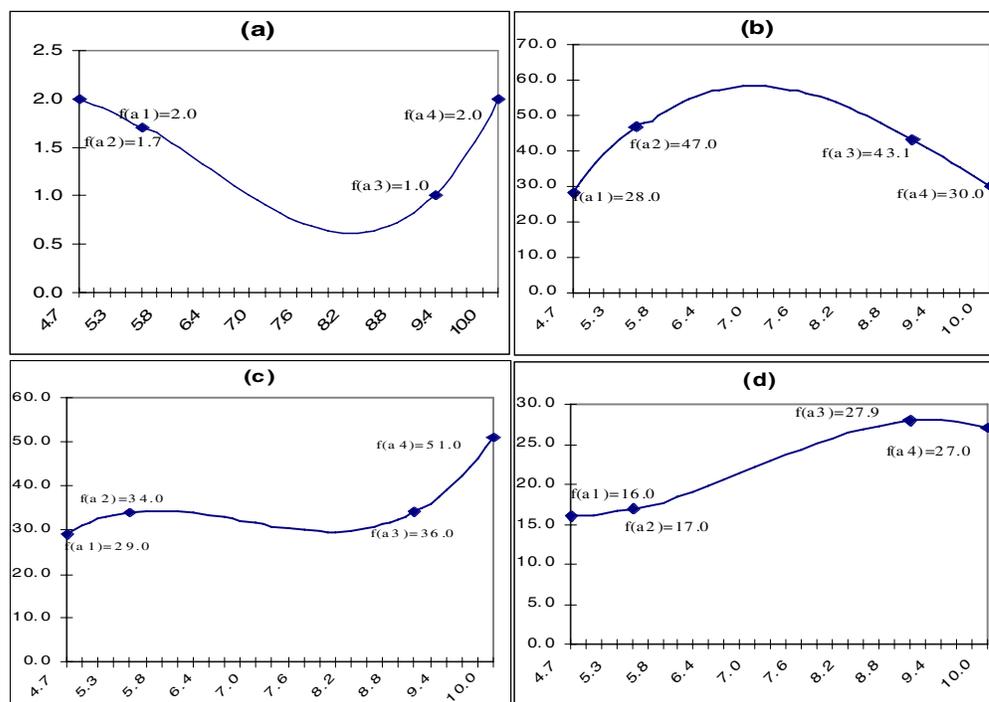
$p=.0001$  at  $\alpha=.05$

### Quantitative Exposure Assessment

The exposure between 1985 and 1989 was interpolated by Lagrange's formula rather than a regression model because each solution has only 4 degrees of freedom. The interpolated curves were developed for each of the 98 subject households in Rockford. Comparison of these curves indicated the following features of Lagrange's interpolation depending on the relationship of the known values.

- $c(t_1) > c(t_2)$  and  $c(t_3) < c(t_4)$ : a concave curve was generated, indicating that the interpolated values were lower than the four known values (Figure 2a).
- $c(t_1) < c(t_2)$  and  $c(t_3) > c(t_4)$ : a convex curve was generated, indicating that the interpolated values were higher than the four known values (Figure 2b).
- $c(t_1) < c(t_2)$  and  $c(t_3) < c(t_4)$ , or  $c(t_1) > c(t_2)$  and  $c(t_3) > c(t_4)$ : a sinusoidal curve was generated, indicating a trend of increase-decrease-increase or decrease-increase-decrease (Figures 2c and 2d).
- $c(t_1) < c(t_2) < c(t_3) < c(t_4)$ : a monotonically increasing curve was generated.

When the slope of a line between two sequential concentration points is very high or very low, Lagrange's interpolation can produce unrealistic concentration estimates. However, this happened only once in this dataset. This single unrealistic estimate—a negative value—was replaced with the average value of the samples from the five nearest neighboring points.



**Figure 2** Lagrange's interpolation curve.

### **Creation of Exposure Subgroups**

The subjects were categorized into subgroups to facilitate various types of comparison. The subgroups were generated from the following criteria: geographic location, cumulative exposure, length of exposure, and maximum TCE levels.

Table 4 illustrates the subjects' grouping by cumulative TCE exposure. This scheme considered both level of TCE contamination and length of exposure. The subjects were divided into four subgroups: 0 to 15 ppb per year, 15 to 100 ppb per year, 100 to 550 ppb per year, and more than 550 ppb per year. The mean cumulative exposure was 652 ppb per year.

**Table 4** Descriptive Statistics of Cumulative Exposure for All Six Study Sites

TCE Group (parts per billion per year)	Number of Subjects	Mean ±SD <sup>a</sup>	Maxi- mum	Cumulative Exposure (parts per billion per year)					Mini- mum
				95%	90%	75%	50%	25%	
0–15	101	6±5	15	14	12	10	6	2	0
15–100	86	44±24	99	95	80	56	39	23	6
100–550	98	244±103	527	442	402	307	223	162	101
>550	33	5,900±13,097	59,210	51,570	7,816	4,090	1,566	810	556
Total	318	701±4,524	59,210	1,829	573	229	51	10	0

<sup>a</sup> SD=standard deviation

Table 5 summarizes the length of exposure, including the adjustment for in utero exposure. The subgroups created were 0 to 2.75 years, 2.75 to 5.75 years, 5.75 to 7.75 years, and more than 7.75 years.

**Table 5** Descriptive Statistics of Exposure Length for All Six Study Sites

Exposure Length (years)	Number of Subjects	Mean ±SD <sup>a</sup>	Maxi- mum	Exposure Length (years)					Mini- mum
				95%	90%	75%	50%	25%	
0–2.75	81	1.8±0.9	2.75	2.75	2.75	2.75	1.75	1.00	0
2.75–5.75	108	4.8±0.8	5.75	5.75	5.75	5.75	4.75	3.75	0
5.75–7.75	65	7.3±0.5	7.75	7.75	7.75	7.75	7.75	6.75	0
>7.75	64	9.7±0.8	10.75	10.75	10.75	10.75	9.75	8.75	0
Total	318	5.5±2.9	10.75	10.75	9.75	7.75	5.75	2.75	0

<sup>a</sup> SD=standard deviation

Table 6 illustrates the TCE exposure grouping by site. The Roscoe site had the highest exposure among the six sites, with a mean of 2,128 ppb per year. The next highest exposure occurred at the Elkhart site, which had a mean of 1,564 ppb per year.

Exposures at the Albion and Verona sites were the lowest, with means of less than 100 ppb per year.

**Table 6** Descriptive Statistics of Trichloroethylene Exposure by Site

Site	Number of Subjects	Cumulative Exposure (parts per billion per year)							Minimum
		Mean $\pm$ SD <sup>a</sup>	Maximum	95%	90%	75%	50%	25%	
Albion	7	74 $\pm$ 137	357	357	357	153	0	0	0
Byron	8	682 $\pm$ 923	1,970	1,970	1,970	1,698	36	9	4
Elkhart	96	1,564 $\pm$ 8,041	59,210	3,048	1,163	366	37	8	0
Rockford	175	112 $\pm$ 127	768	352	263	200	53	13	0
Roscoe	22	2,126 $\pm$ 2,697	7,816	7,639	6,446	3,732	702	176	1
Verona	10	51 $\pm$ 71	195	195	162	124	16	0	0

<sup>a</sup> SD=standard deviation

### **Factors Affecting Exposure**

The variation in TCE exposure might be caused by a variety of factors, including household geographic location, hydrologic features, source of contamination, and years exposed. Each site had a different source of contamination and most sites were contaminated by multiple sources. It was not feasible to characterize the sources of contamination based on the available information. Likewise, hydrologic features and the depth of wells were not included for similar reason. The numbers of men and women at these sites were nearly equal (157/161). Men and women living in the same households received the same exposure for any specific time. Thus, it was reasonable to disregard the effect of gender on TCE exposure. The question that remains is how a subject's age and site affect cumulative exposure.

Subjects were classified into five levels according to their age in 1990: 0 to 2, 3 to 4, 5 to 6, 7 to 8, and 9 to 10. The GLM procedure detected that the full model was statistically significant ( $p=.0001$ ). The main effects of age and city (i.e., the effects of those two independent variables in the model) were statistically significant ( $p=.0001$ ). The interaction between age and city (the crossed effect), however, was not significant ( $p=.2717$ ). It was concluded that levels of cumulative TCE exposure were statistically different among age groups and sites. A contrast test (i.e., a test to determine how the level of one variable influences the affect of another) of the age groups indicated that TCE exposure of the 0-to-2 age group was significantly lower than that of any other age groups. The differences between the 3-to-4, 5-to-6, and 7-to-8 age groups were not statistically significant. The exposures of both the 3-to-4 and 5-to-6 age groups were significantly lower than that of the 9-to-10 age group. No significant difference between the 7-to-8 age group and the 9-to-10 age group was detected.

### **Analyses of Potentially Confounding Exposure**

More than 20 chemicals were found in the groundwater of the contaminated sites, including DCE, DCA, TCA, PCE, benzene, carbon tetrachloride, freon, toluene, xylene, and heavy metals. Other reported secondary contaminants were chemicals and

biological degradation products of TCE and the other chlorinated hydrocarbons (7). The available data, however, indicated that most of the chemicals were not detected often enough to make it possible to characterize exposure to them at any sites. Only the four most frequently detected chemicals, DCE, DCA, TCA, and PCE (whose concentrations varied from 0.7 to 400 ppb), were included in the analyses of potentially confounding exposures.

A correlation analysis was conducted to detect the association between TCE and the four chemicals. TCE concentrations were significantly correlated with the levels of the four chemicals at the Rockford site, but not at the Elkhart site (Table 7). Measurements of the four chemicals above their quantitation limits were too sparse at other sites to allow effective analysis, so only the Rockford and Elkhart sites were considered in the confounding analysis. Confounding contaminant plumes were detected at the Rockford site. These plumes showed geographic distribution patterns similar to that of the TCE plume presented earlier. This provides visual evidence of the correlation (Figure 3).

**Table 7** Correlation Analysis between Trichloroethylene and Other Contaminants (Pearson Correlation Coefficients) for the Rockford, Illinois, and Elkhart, Indiana, Sites

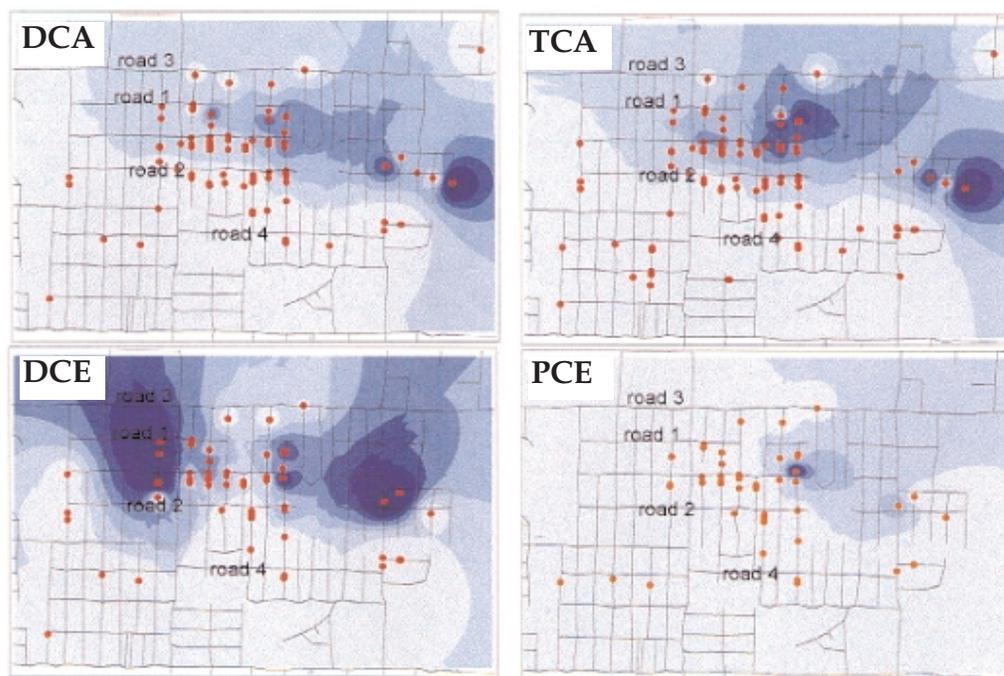
Chemical	Number of Subjects	Rockford	Elkhart
TCA	175	.7532 (.0001 <sup>a</sup> )	.1217 (.5219)
DCE	174	.5785 (.0001 <sup>a</sup> )	.1877 (.1873)
DCA	175	.7753 (.0001 <sup>a</sup> )	Sample size small
PCE	172	.3429 (.0197 <sup>a</sup> )	-.0286 (.8453)

<sup>a</sup> Statistically significant at  $\alpha=.05$ .

The cumulative exposure of the four potential confounders was computed for the subjects. The subjects were then stratified into subgroups by level of potential confounding exposure. The three subgroups formed were 0 to 10 ppb per year, 10 to 100 ppb per year, and more than 100 ppb per year for TCA, DCE, and DCA exposure and 0 to 1 ppb per year, 1 to 10 ppb per year, and more than 10 ppb per year for PCE exposure. The subjects within each subgroup were further categorized into sub-subgroups according to their TCE exposure levels.

## Discussion

In epidemiological studies and risk assessments, exposure assessment is often the most difficult task because it depends on factors that are hard to estimate and for which there are little data. As was discussed earlier, the environmental data in this study had limitations that increased the complexity of the retrospective exposure assessment. The samples were not taken to quantify exposure over time, but to verify contamination (7). Most of the environmental data consisted of single samples of well water from each household, reflecting exposure during small parts of the subjects' lives. Furthermore, TCE was not distributed uniformly within the study areas; it varied as a function of source characteristics and groundwater flow patterns. It was thus inappropriate to assume that the exposure of Subregistry children was constant over time and use the concentration of TCE in a single sample as the exposure level over the entire exposure



**Figure 3** Confounding contaminant plumes in well water at the Rockford, Illinois, site.

period. In addition, we assumed that each subject at each site had been born there and had lived there continuously until the baseline survey was conducted. When each subject's residential history becomes available, the results of this assessment will be adjusted to yield the final estimate of exposure profiles. Groundwater contaminant concentration and other geohydrologic features tend to be spatially correlated; that is, the agreement of contaminant concentration and geohydrologic features at points within an area increases as the distance between the points decreases. This made it possible to estimate the subjects' exposures by using their neighbors' exposures for the time periods when no samples were collected at the subjects' residences.

GIS provided the platform in which spatial and temporal distribution of contaminants could be described, interpreted, and integrated. The strong data manipulation and visualization functions of GIS made exposure assessment rather straightforward and demonstrated the distinct advantage of GIS over routine numerical methods. The spatial interpolation performed by IDW and kriging methods identified a contaminated groundwater plume in Rockford extending in an east-west direction (Figure 1), which was consistent with ATSDR's finding (7). By using the GIS map query tool, a subgroup of 64 subjects living at the heavily contaminated area identified by GIS spatial analysis was created. It was found that their cumulative TCE exposures were significantly higher than those of subjects at the less-contaminated areas, provided that there were no statistical differences in age between the two groups.

GIS was also used to determine the exposure duration for the 103 subjects who lived in four different areas of Elkhart, each of which had a different time period of ex-

posure. The available information only provided a brief description of the exposure time for the areas, and the available geographic demarcation of the areas was not sufficient to permit assignment of a household to one of the four areas based on its address. The geocoding tool of GIS mapped each household to the corresponding location on a digital map. GIS thus made it possible to determine, and show, in which area each household was located.

Statistical and mathematical models, instead of groundwater models, were applied to explore spatial and temporal variation of TCE contamination. Groundwater models are often used to estimate the fate of contaminants that enter groundwater, but these models are usually complex, due to the many physical and chemical processes that can affect transport and transformation of contaminants in groundwater. Using groundwater models requires extensive knowledge of a site's geohydrology and geochemistry. In this retrospective study, many of the elements needed to establish groundwater models, such as sources of contamination and depth of wells, were unavailable. The statistical and mathematical approach presented here was not constrained by these limits. It fully utilized the available measured concentration data and allowed geostatistical inference. The kriging interpolation procedure can provide not only concentration estimates, but also the variance of these estimates. This can be used to establish confidence limits on estimates if needed.

Potential confounding exposure was a critical concern in the exposure assessment. Most of the subjects were exposed to multiple contaminants; more than 20 chemicals were detected in their well water. The typical contaminant sources for the sites were industrial processes that used a variety of common solvents in addition to TCE (7). At the Rockford site, exposure to TCE was significantly correlated with exposure to four other chemicals, TCA, DCA, DCE, and PCE. Spatial analyses found that the area with the highest concentrations of TCA, DCA, and DCE was also located between Road 1 and Road 2, similar to the pattern of TCE distribution. Because of this, caution must be exercised in interpreting results of speech and hearing tests in Rockford. It may be possible to distinguish between the effects of confounders by comparing Rockford results with those from Elkhart, where TCE exposure was not confounded.

Another issue should be kept in mind when interpreting this type of environmental data. Most of the samples were taken one time from households that were exposed over extended periods ranging from 4 to 10 years. These one-time samples might not be representative of the exposure for all of those periods. For instance, weather conditions might affect sample composition. Heavy rain might result in sediment loading to water bodies, which could increase contamination or affect the concentration of other contaminants through adsorption and settling in the water column. Ideally, monitoring should provide a full annual sampling cycle or at least encompass seasonal extremes such as conditions of high water/low water, high recharge/low recharge, and high suspended-solids/clear water (25).

## Conclusion

All of the six sites studied were contaminated with TCE. The cumulative exposures were significantly associated with geographic location. No major changes in the geographic distribution pattern of TCE were observed at the Rockford site, except that the TCE levels generally increased over a six-year period. The subjects at this site could be

categorized into two subgroups: within the contaminant plume and outside the plume. It was found that the cumulative exposure ranged from 0 to 59,210 ppb per year, with a mean of 701 ppb per year. The mean exposure length was  $5.5 \pm 2.9$  years. Of the 198 households in the study, 118 had water with measured TCE concentrations exceeding 5 ppb, the EPA maximum allowable level for TCE in drinking water. The TCE exposure was significantly correlated with the potential confounding exposures at the Rockford site. Correlation was not significant at the Elkhart site. The subgroups created by quantitative exposure assessment could be used for the epidemiological investigations of cause-effect and dose-response relationships between TCE exposure and adverse health outcomes. GIS was shown to be a powerful tool for environmental studies involving spatial and temporal data.

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