RECONSTRUCTING LIFETIME EXPOSURE TO ARSENIC IN DRINKING WATER USING SPATIOTEMPORAL INFORMATION

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Abstract

Arsenic exposure from drinking water is generating continued regulatory and scientific debate, as the health risks associated with arsenic concentrations observed in groundwater of the United States remain unclear. Concentrations of arsenic exceeding World Health Organization (WHO) and US Environmental Protection Agency (EPA) guidelines (10 µg/L) have been identified in ground-water supplies of 11 counties in southeastern Michigan. These findings have prompted an epidemiological investigation of the relationship between arsenic in drinking water and bladder cancer in the region. We have gathered lifetime residential mobility and water consumption behaviour data for 660 cases and their matched controls in the area, as well as information detailing changes in public water supplies (serving populations greater than 1000) and private wells over time. Using new Space Time Information System (STIS) software that handles spatio-temporal datasets, we have created an exposure history for each participant based on their residential history, drinking water consumption patterns, and arsenic databases. This paper highlights the first step in the exposure assessment – assigning an arsenic concentration to each participant at each residence. The spatial-temporal GIS automates the process of assigning an arsenic concentration depending on a participant's primary drinking water source as well as other factors. These arsenic concentrations are critical for future efforts to estimate lifetime exposure to arsenic in this study population.

1. Introduction and Background

Arsenic in drinking water is a global phenomena, and in the United States an estimated thirteen million Americans drink water with arsenic levels above 10 µg/L. Concentrations of arsenic exceeding World Health Organization (WHO) and US Environmental Protection Agency (EPA) guidelines (10 µg/L) have been identified in ground-water supplies of 11 counties in southeastern Michigan: Genesee, Huron, Ingham, Jackson, Lapeer, Livingston, Oakland, Sanilac, Shiawassee, Tuscola, and Washtenaw (Kim et al. 2002; Kolker et al. 2003; Slotnick et al. 2003). These findings have prompted an epidemiological study of the relationship between arsenic exposure from drinking water and bladder cancer risk in the 11-county region.

In general, studying exposure involves two factors: the location of populations and the daily human activities that influence how often people come into contact with the chemical (Risk Assessment Forum USEPA, 1992). Exposure assessments have been completed to varying levels of detail, and often depend on the health outcome and exposure time frame of interest, as well as the data and methods available. Traditionally exposure assessments lack data on the individual level. Risk assessment, a component of exposure assessment has also historically focused on the hazard as the object of interest – such as the locations of industrial sites of high concentration in pollutants that are known to be human carcinogens – instead of the individual (Mark et al, 1999). More recently exposure assessment has targeted individuals in their present homes and activities but relatively little attention has been placed on individual exposure reconstruction involving residential histories and past activities particularly for diseases with long latencies such as cancer. As part of this case control study we reconstruct individual exposures by incorporating spatiotemporal data such as a residential history (where people have lived throughout their lives), changing boundaries and arsenic values of drinking water supply systems, and drinking water habits that fluctuate over the years. The residential histories account for the location of study participants and primary drinking water source, through which a measurement of arsenic concentration is obtained. The drinking water supply data provide information on arsenic concentration, and the telephone interviews quantify water consumption and other behaviours mediating arsenic exposure. From arsenic concentration and daily water consumption, an estimate of exposure to arsenic is achieved. This paper focuses on the first piece of the exposure assessment– attaining an arsenic concentration at each residence by using a novel STIS.

The STIS provides an innovative approach to visualizing and analyzing change spatially and through time – making it an ideal choice for our analysis. Where geographic information systems fail to handle multi temporal geographic information and the movement of individuals, STIS takes advantage of the opportunity. The STIS and some of its visualization and statistical functions have been explained previously in more detail. (AvRuskin et al.,2004, and Meliker et al., 2004). This paper describes a method specific to the arsenic and bladder cancer study which does not come packaged with the software. The following section explains the *arsenic method* in detail including an explanation of the datasets. In Section 3 we present the results followed by discussion and the conclusion.

2. Estimating Arsenic Concentration at Past Residences in STIS

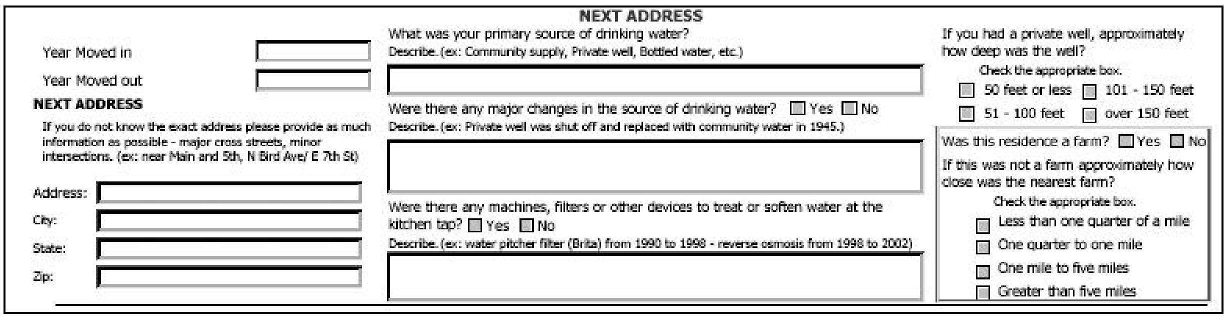
The *arsenic method* is a method written in C++ as an external dynamic linked library (dll) specifically for the purpose of this project. The goal of the procedure is to assign an arsenic value to each participant based on residential history, water source geography and arsenic concentration in the different water sources. These data vary in space and through time, further complicating exposure reconstruction. For example, participants change geographic locations whenever they move residences, and these relocations are largely asynchronous. Some participants move frequently, others less often or not at all. One must therefore employ exposure reconstruction methods that trace the residential history of each individual, and integrate exposure based on duration of residence and daily arsenic exposure at each place of residence. The data used by this method are described in Section 2.1 and the arsenic method is explained in Section 2.2.

2.1 Spatiotemporal and Raster Data Sets

Data for this study comes from a case-control study of bladder cancer in southeastern Michigan. The data presented here, for 660 participants are a subset of this larger study which will ultimately include information from a targeted 700 cases (people diagnosed with bladder cancer) and 700 controls frequency matched to cases on age, race, and gender. To be eligible for inclusion in the study, participants must have lived in the eleven county study area for at least the past five years and had no prior history of cancer (with the exception of non-melanoma skin cancer). Participants complete a written questionnaire describing their residential mobility history. Community water supply data and private well raster data are other datasets that will be discussed in detail. This is an ongoing five year project and only preliminary data are described here.

2.1.1 Residential History Dataset

As mentioned above residential history information is provided by each participant through a written questionnaire. Participants are asked to include each address that they lived at for at least one year. For each place of residence participants must provide information about the following: address, drinking water type, home water treatments (e.g. water softener, carbon filtration, etc), depth of private well (if on a private well), and proximity to a farm (Figure 1). In addition, participants indicate any changes in the source of drinking water or water treatment at each residence.



NEXT ADDRESS

Year Moved in

Year Moved out

NEXT ADDRESS

If you do not know the exact address please provide as much information as possible - major cross streets, minor intersections. (ex: near Main and 5th, N Bird Ave/ E 7th St)

Address:

City:

State:

Zip:

What was your primary source of drinking water?

Describe. (ex: Community supply, Private well, Bottled water, etc.)

Were there any major changes in the source of drinking water? Yes No

Describe. (ex: Private well was shut off and replaced with community water in 1945.)

Were there any machines, filters or other devices to treat or soften water at the kitchen tap? Yes No

Describe. (ex: water pitcher filter (Brita) from 1990 to 1998 - reverse osmosis from 1998 to 2002)

If you had a private well, approximately how deep was the well?

Check the appropriate box.

50 feet or less | 101 - 150 feet

51 - 100 feet | over 150 feet

Was this residence a farm? Yes No

If this was not a farm approximately how close was the nearest farm?

Check the appropriate box.

Less than one quarter of a mile

One quarter to one mile

One mile to five miles

Greater than five miles

Figure 1. Portion of Residential History Form. This information is solicited each time a participant moved to a new residential location.

Each residence in the study area is geocoded and assigned a geographic coordinate in ArcGIS. For the 660 cases and controls in this paper participants resid e at a total of 2830 homes, and spend an average of 65% of their lifetime within the study area. Out of these 2830 residences, 35% were successfully matched using ArcGIS settings of spelling sensitivity equal to 75, minimum candidate score equal to 10, and a minimum match score of 60. 53% of the addresses were rematched manually. The remaining addresses were manually matched using cross streets with the assistance of internet mapping services (6%). When exact street address cannot be recalled, participants are requested to provide the nearest cross streets. If cross streets are not provided, best informed guesses place the address on the road or as a last resort, residenc e is matched to town centroid (6%). Residences outside the study area are not geocoded. However, their data are still useful and are used by the *arsenic method*. Participants reside at 1165 homes within the state of Michigan, averaging 22% of their lifetime. Participants who live d abroad or in any other state spent an average of 10% of their lives outside the study area with a total of 1073 residences. The remaining 3% did not live in one location for longer than a year, thus no information was collected. The spatial location of each participant at each residence inside the study area is accounted for in the *arsenic method* as described in Section 2.2.

Each participant also reports the primary source of their drinking water. Responses include bottled water, community supply, private well, and unknown. A few participants report a mix of two types of drinking water such as community supply and bottled water or private well and bottled water. A blank field or no response is treated as an unknown type in the method. Many participants experience a change in drinking water source without an address change. For instance, a person might be drinking private well water for 20 years and then connect to a community water supply. They remain in their home but the source of their primary drinking water has changed and this change is noted. Table 2 summarizes the source of primary drinking water for all study participants in 1999.

Table 2. Source of drinking water in 1999.

Source of Water	Code (for source)	Total Number of Participants
Bottled	1	11
Community Supply (CS)	2	346
Private Well (PW)	3	283
Unknown	4	3
CS and Bottled	5	6
PW and Bottled	6	6

For each current residence, drinking water samples are collected and an arsenic value is assigned to the primary source of drinking water. Water samples are generally taken from the kitchen tap unless another primary drinking water source is specified. The samples are analyzed for arsenic concentration at the University of Michigan using an inductively coupled plasma mass spectrometer (ICP-MS, Argilent Technologies Model 7500c). Participants who have not changed their primary source of drinking water while residing at that location use the arsenic concentration from that sample as input to the arsenic method, and it remains constant for the duration at that residence. When water supply sources have changed the arsenic concentration in drinking water is set to the concentration for that supply source, and is then used by the arsenic method for the corresponding period of time. Historical information on these alternative supplies is thus required by the arsenic method, as described below.

2.1.2 Public Water Supply Dataset

Historical data were collected for each community in the study area served by a public water supply. . The public water supply might come from surface water (directly from a la ke), it might come from a few deep water wells (groundwater), or it might be purchased from another system that is either surface or groundwater. Michigan Department of Environmental Quality (MDEQ) maintains a database of arsenic measurements (1993-2002) in public well water supplies (N=1675 arsenic measurements) analyzed in a state laboratory with graphite furnace atomic absorption spectrometry (GF/AAS) (1993-1995), hydride flame (quartz tube AAS) (1993-1995), and an ICP-MS (1996-2002). This information becomes part of the public water supply dataset. In addition, each public water supply serving a population greater than 1000 was contacted by telephone. Information was collected relating to source of supply (ground water wells versus surface water), treatment (carbon filter, reverse osmosis), the geographic extent of the public supply, and how this extent and the chararacteristic s of the source of supply changed through time. If a change occurred the year of the change was noted. For example the town of Ypsilanti used a ground water system (using wells) from 1940-1972. In 1972 it started mixing ground water with purchased surface water from Detroit. Finally in 1996 it switched entirely to surface water and closed its ground water wells. Arsenic concentration estimates associated with these alterations in supply changed accordingly The overall result is a dataset for all public water supplies in the study area from serving populations greater than 1000 with arsenic concentrations that reflect changes in supply source and geographic extent. Missing values exist and are discussed in more detail in section 2.2

2.1.3 Private Well Raster Dataset

The final dataset in the *arsenic method* is a geostatistically generated raster representing arsenic concentrations in groundwater for the entire study area. This dataset is used to estimate arsenic concentrations in water from private wells for those wells that were not assayed during the sampling procedure described earlier. Data originates from an MDEQ database of 9,188 records of arsenic measurements from over 8,000 private wells. These data were collected at private wells sampled between 1993 and 2002. Fewer than 10% of the measurements (737 observations) are below the detection limit and these are reset to half the value of the detection limit for the time they were collected; that is 0.15 µg/L for 12 wells (in 1996), 0.5 µg/L for 670 wells (1998-2003), and 1.0 µg/L for 55 wells (1993-1996). Goovaerts et al (in press) describe the geostatistical model of arsenic concentration in ground water, and how it changes spatially and as a function of geology in this study area.

2.2 The Arsenic Method

The result of the *arsenic method* is an estimate of daily arsenic consumption from drinking water for each study participant. As noted earlier, this estimate accounts for residential history and for changes in drinking water source and characteristics. The datasets described above are imported into STIS as a shapefile, raster, and/or database file (dbf). The import procedure of the software and other data handling features are explained in detail in AvRuskin et al (2004). This *arsenic method* is written in C++ as a DLL to be used with STIS software. The method uses the following as input parameters (Figure 2):

- A dataset ("Residential History") containing arsenic concentrations in the drinking water at each current place of residence ("Current Arsenic"), from tap water collected during field visits and analysed in the University of Michigan School of Public Health laboratory for each study participant, and as described in section 2.1.1 "Residential History Dataset". The variable is a decimal value corresponding to µg/L .
- A dataset ("Residential History") containing a categorical variable ("drinking water source") describing water source (ex: bottled=1, community supply=2, private well=3, etc.). These water supply codes were also described in section 2.1.1.
- A dataset ("Public Water Supply") describing mean arsenic values from the public water supply dataset. This decimal variable ("MEAN_(AS)") is associated with the geographic extent and water supply characteristics as described earlier for the public water supplies in section 2.1.2.
- A raster dataset ("raster") with a decimal variable ("Private Well Raster") describing arsenic concentration in groundwater as estimated by the geostatistical model of groundwater arsenic concentrations, as described in section 2.1.3.

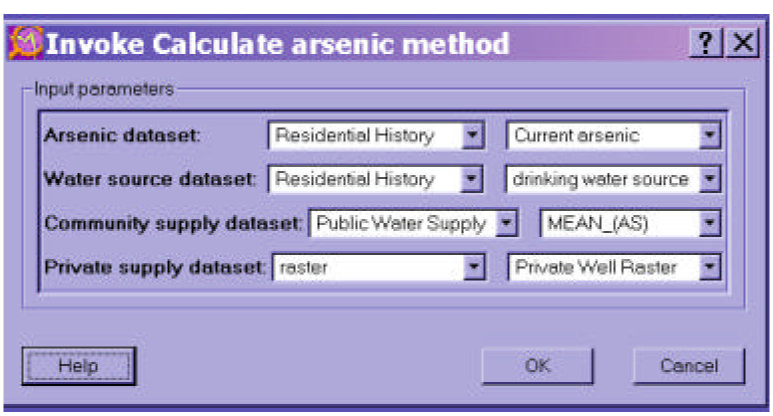


Figure 2. Input Parameters for the arsenic method

The arsenic method loops successively through each person in the residential history dataset and retrieves their water source history and associated time periods of consumption (years drinking tap water at each residence or years drinking from an alternative primary water source). If a current arsenic value is found (from the arsenic dataset) the procedure continues through the source water history dataset. If the participant stated that he or she drank bottled water as their primary source of water the procedure automatically assigns a value of 0.17µg/L. Otherwise the geographic coordinates of this participant are retrieved and stored for future calculations. At this point, arsenic values exists for every individual who ever stated that they drank bottled water and for the home currently occupied by the participant.

The method then evaluates arsenic concentration at all past residences. It is important to remember that arsenic values as well as geographic coordinates are both changing through time. First the method evaluates participants whose source water is a public water supply. The x,y location of the address is retrieved for each time interval and the method proceeds to the same time interval for the community supply dataset. For instance Person A lived at location x, y between 1970 and 1991 and had a water source code of “2”. The method retrieves this location and finds the public water supply polygon surrounding it. If the participant’s community water polygon boundary changes within the stated time interval a message is sent to the STIS log window and the procedure internally considers this change. In this way the spatial location of the individual and the spatial extent of the public water supply system become an intrinsic part of the procedure. Next the method finds the arsenic value for the specified time period. If the value has changed between 1970 and 1991, this change is taken into account and Person A is assigned all arsenic values corresponding to changes in the database. The dll also takes into account missing values from the community supply dataset. Only recently in Michigan (1970s) were public supply systems tested for arsenic. Before this time arsenic concentrations were not measured. For this reason, the *arsenic method* actually uses the private well raster information as a surrogate for public supply systems where no other arsenic measurement is found. The values of the private well raster are aggregated by the polygon boundary of the public supply system to obtain one arsenic concentration for each public water supply system. As the public water supply boundary changes, so too does the aggregated arsenic value. For example Southfield, MI in 1953 has an aggregated arsenic value from the private well database as

0.169µg/L because its boundaries change in 1970 and still no recorded arsenic measurement exits, its aggregated arsenic value changes to 0.162µg/L. Only after 1975 does an actual public water supply value exist from the public water supply dataset. Again, the aggregation of private well arsenic measurements is only applied when no public supply arsenic measurement exists.

The final primary drinking water category awaiting an arsenic concentration is private wells. The method uses the raster dataset and captures the value of the pixel, at the x, y coordinate of the individual. Finally, if at any location a participant does not remember his or her primary drinking water source an unknown code – "4" is assigned to them. This occurs at 216 residences. The STIS compares the x,y, coordinates of the residence with community supply boundaries at the appropriate time interval. If the residence lies within a community supply boundary then an arsenic concentration is assigned from the community supply dataset. If not, then the raster is used to estimate an arsenic concentration, assuming the residence is served by a private well.

Of 660 participants and a total of 5195 primary drinking water source information (or residences) only 43 residences had a mix of two primary drinking water types. Twenty one mix community supply water and bottled water and the other half drink private well water and bottled water. Arsenic values for these participants are computed by hand by taking the average of the two values. In the future this process will also be automated. If any other code for drinking water occurs other than the six listed in Table 2, an error message is sent to the log and a missing value is assigned for the arsenic concentration for that participant during that time interval. A typing error, or other unhandled code will be reported to the log and will have to be corrected before an arsenic concentration can be assigned.

At this juncture every participant in the study area has an arsenic concentration in their drinking water throughout their lifetime. Because the method is inherently spatial, only those residences with an x,y coordinate within the 11 county study area are assigned an arsenic value. However, in order to analyze lifetime exposure to arsenic, residences outside the study area also need to be assigned an arsenic value. For comparison, there are two disparate techniques for assigning arsenic concentrations for residences outside the study area. The simplest technique assigns an arsenic value of 0.3µg/L (the value for public surface water most commonly found in Michigan) to every address outside the study area (a total of 2238 addresses or 44%, but representing only 35% of total person years). The more complicated technique assigns a value of 0.3µg/L to all residences outside the United States. Data originating from the USEPA (1980-1998 database) is used for participants drinking from a community water supply system. If no data exists for a particular public system then the default 0.3µg/L is assigned. Participants who drink from a private well outside the study area are allocated values according to data from the United States Geological Survey (2001). County averages calculated from this dataset are used if no arsenic value appears for the city corresponding to the participant's residential history. If there are no measurements in the county then the default 0.3µg/L is assigned.

3. Results

Table 3 summarizes arsenic values for the 660 participants by primary drinking water source, maximum arsenic value, minimum arsenic value, and mean arsenic value for all the residences inside and outside the area. Table 4 summarizes the same information but uses the default value of 0.3µg/L for the participants outside the study area.

Table 3. Arsenic Concentration by Primary Drinking Water Source

Primary Drinking Water Source	Number of Residences	Mean (µg/L)	Min (µg/L)	Max (µg/L)
Bottled	28	0.17	0.17	0.17
Community Supply (CS)	3538	1.12	0.02	38.2
Private Well (PW)	1369	2.11	0.02	99.33
Unknown	216	0.82	0.2	25.62
CS and Bottled	28	0.95	0.02	9.71
PW and Bottled	15	2.97	0.02	10.62

Table 4. Arsenic Concentration by Primary Drinking Water Source using Default value (0.3µg/L) for Residences Outside of Study Area

Primary Drinking Water Source	Number of Residences	Mean (µg/L)	Min (µg/L)	Max (µg/L)
Bottled	28	0.17	0.17	0.17
Community Supply (CS)	3538	1.00	0.02	38.2
Private Well (PW)	1369	1.84	0.02	99.33
Unknown	216	0.80	0.2	25.62
CS and Bottled	28	0.89	0.02	9.71

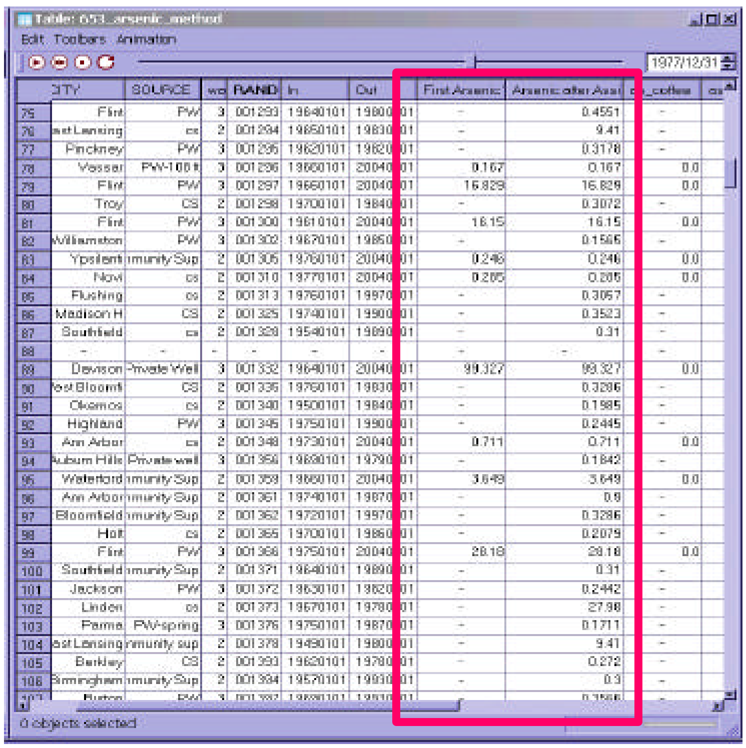
PW and Bottled	15	2.59	0.02	10.62

Arsenic concentration is quite variable both among the different primary drinking water sources and within each drinking water source. Although the mean value is greatest for those people drinking both private well and bottled water, the maximum value for the private well source is almost forty percent greater than any other maximum value. In all categories other than bottled water the mean values in Table 3 are greater than those in Table 4. Assigning 0.3µg/L to all people outside of the study area generates a smaller mean value for all of the primary drinking water categories. However, incorporating the two techniques for assigning arsenic outside the study area can shed light on how sensitive the arsenic exposure estimates are to different drinking water sources for those periods of a participant's life when they are outside of the study area.

4. Discussion

The *arsenic method* provides a computationally fast technique for reconstructing arsenic concentrations from drinking water that accounts for residential mobility, changes in municipal supply characteristics and geographic extent, and spatial variability in groundwater arsenic concentrations. The ability of the STIS to handle spatiotemporal dynamics such as polygon morphing, attribute change, and residential mobility makes implementation of complex techniques that are not feasible using conventional approaches possible. To illustrate, we attempted to perform this function by hand, using Excel software on only 40 participants with an average of five residences each. The process took more than 40 work hours. Assigning the bottled water value was simple but to properly assign the public water supply value we had to manually locate each participant on the public water supply map. We then had to review the public water supply database to see if that particular supplier changed its boundaries or arsenic value at any point in our participant's noted time interval. Finally, if the participant was on private well water, we had to query a raster map at that exact location and manually retrieve an arsenic concentration. The process was tedious, time-consuming, and was prone to data processing errors.

Execution of the *arsenic method* as currently implemented takes less than one minute, with the added feature of warning messages or error messages appearing in the log. Values are made available instantly in a table view and a time slider allows us to animate the residential histories and changing public water supply geography, and to see how arsenic exposure estimates change through time. Figure 3 is a screenshot of values before (First Arsenic) and after (Arsenic after Assign) the method is initiated. In the screen it is clear that out of 31 participants only ten had arsenic values before the estimation procedure. Recall that this is possible because these ten participants currently live at these addresses, and samples were taken from participants' current residences. Thus, the values come from the University of Michigan Laboratory, not the public water supply database or the private well raster. After completion of the method all the participants had an arsenic concentration assigned based on the techniques defined in Section 2.2.



	CITY	SOURCE	wo	RAND	In	Out		First Arsenic	Arsenic after Assi	c_coffee	cs
75	Flint	PW	3	001293	19640101	19800	01	-	0.4551	-	
76	ast Lansing	cs	2	001294	19650101	19830	01	-	9.41	-	
77	Pinckney	PW	3	001295	19620101	19820	01	-	0.3178	-	
78	Vassar	PW-100 ft	3	001296	19680101	20040	01	0.167	0.167	0.0	
79	Flint	PW	3	001297	19660101	20040	01	16.829	16.829	0.0	
80	Troy	CS	2	001298	19700101	19840	01	-	0.3072	-	
81	Flint	PW	3	001300	19610101	20040	01	16.15	16.15	0.0	
82	Williamston	PW	3	001302	19670101	19850	01	-	0.1566	-	
83	Ypsilanti	mmunity Sup	2	001306	19760101	20040	01	0.246	0.246	0.0	
84	Novi	cs	2	001310	19770101	20040	01	0.285	0.285	0.0	
85	Flushing	cs	2	001313	19760101	19970	01	-	0.3057	-	
86	Madison H	CS	2	001325	19740101	19900	01	-	0.3523	-	
87	Southfield	cs	2	001328	19540101	19890	01	-	0.31	-	
88	-	-	-	-	-	-		-	-	-	
89	Davison	Private Well	3	001332	19640101	20040	01	99.327	99.327	0.0	
90	West Bloomfi	CS	2	001335	19760101	19830	01	-	0.3286	-	
91	Okemos	cs	2	001340	19500101	19840	01	-	0.1985	-	
92	Highland	PW	3	001345	19750101	19900	01	-	0.2445	-	
93	Ann Arbor	cs	2	001348	19730101	20040	01	0.711	0.711	0.0	
94	Auburn Hills	Private well	3	001356	19630101	19790	01	-	0.1842	-	
95	Waterford	mmunity Sup	2	001359	19660101	20040	01	3.649	3.649	0.0	
96	Ann Arbor	mmunity Sup	2	001361	19740101	19870	01	-	0.8	-	
97	Bloomfield	mmunity Sup	2	001362	19720101	19970	01	-	0.3286	-	
98	Holt	cs	2	001365	19700101	19860	01	-	0.2079	-	
99	Flint	PW	3	001366	19750101	20040	01	28.18	28.18	0.0	
100	Southfield	mmunity Sup	2	001371	19640101	19890	01	-	0.31	-	
101	Jackson	PW	3	001372	19630101	19820	01	-	0.2442	-	
102	Linden	cs	2	001373	19670101	19780	01	-	27.98	-	
103	Parma	PW-spring	3	001376	19750101	19870	01	-	0.1711	-	
104	ast Lansing	mmunity sup	2	001378	19490101	19800	01	-	9.41	-	
105	Berkley	CS	2	001393	19620101	19780	01	-	0.272	-	
106	Birmingham	mmunity Sup	2	001394	19570101	19930	01	-	0.3	-	
107	Burton	PW	3	[illegible]	[illegible]	[illegible]	01	-	[illegible]	-	

Figure 3. Arsenic Concentrations Before and After the *arsenic method* (December 31, 1977).

With an arsenic concentration now assigned for each residence or each primary source of drinking water we can proceed to calculate arsenic exposure for each participant. Another piece of data that has been collected is drinking water consumption, such as glasses of water consumed at home, glasses of tea/coffee consumed at home, and glasses of juice made with water at home. Using a built-in calculator in STIS a water consumption value that might change over the years is calculated for each participant. A crude exposure measure is achieved by simply multiplying the arsenic concentration by the total water consumption value that can change yearly. For this study data is generally collected on an annual basis thus exposure changes annually (although STIS has the ability to deal with temporal intervals of minutes and even seconds). Several different ways to calculate and analyze exposure such as cumulative, instantaneous, and time window specific exist in the STIS. These are discussed in detail in a forthcoming article. But without first arriving at an arsenic concentration using the *arsenic method*, exposure analysis is limited to current values of arsenic that do not change spatially or through time. This limitation is common in many epidemiological studies, and can result in misclassification of exposure, thus impacting the ability to accurately assess disease risk.

6. Conclusions

Typical GIS software can not readily handle spatiotemporal data such as that being collected in the arsenic and bladder cancer study. The advanced technology and capabilities of the STIS resolve this problem. The *arsenic method* efficiently and easily computes an arsenic concentration from various spatiotemporal datasets for each participant at each residence or primary drinking water source. The method is also flexible. In order to evaluate sensitivity of the results to the range of possible input values for arsenic concentration from public water supplies one might use the maximum arsenic value for the public water supply system rather than its mean value. The arsenic concentrations would then of course be higher for those participants on a public water supply system, and we would obtain, at each time point, the distribution of individual arsenic exposure estimates as reconstructed using these extreme values. We plan to use such an approach in the future for evaluating sensitivity of the exposure estimate to uncertainty in groundwater arsenic concentrations. The geostatistical model employed by Goovaerts et al. (in press) models not only mean value but also its uncertainty. How sensitive are the arsenic exposure estimates for the study participants to different sources of uncertainty? This will be investigated in the future when uncertainty maps (of private well data) and other information (new or other historical public water supply system data) are assembled. For current purposes, using the STIS to assign arsenic concentration to all participants in the study area is novel and, because it is computationally fast, makes exploration of the importance of the variables that are thought to be determinants of arsenic exposure possible.

5. Acknowledgements

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