

# Water quality monitoring records for estimating tap water arsenic and nitrate: a validity study

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# **Abstract**

## **Background**

Tap water may be an important source of exposure to arsenic and nitrate. Obtaining and analyzing samples in the context of large studies of health effects can be expensive. As an alternative, studies might estimate contaminant levels in individual homes by using publicly available water quality monitoring records, either alone or in combination with geographic information systems (GIS).

## **Methods**

We examined the validity of such records-based methods in Washington State, where arsenic and nitrate contamination is prevalent but generally observed at modest levels. Laboratory analysis of samples from 107 homes (median 0.6 µg/L arsenic, median 0.4 mg/L nitrate as nitrogen) served as our “gold standard.” Using Spearman’s rho we compared these measures to estimates obtained using only the homes’ street addresses and recent and/or historical measures from publicly monitored water sources within specified distances (0.5-10 miles).

## **Results**

Agreement improved as distance decreased, but the proportion of homes for which we could estimate summary measures also decreased. When including all homes, agreement was 0.05-0.24 for arsenic (8 miles), and 0.31-0.33 for nitrate (6 miles). Focusing on the closest source yielded little improvement. Agreement was greatest among homes with private wells. For homes on a system, agreement improved considerably if we included only sources serving the relevant system ( $\rho=0.29$  for arsenic,  $\rho=0.60$  for nitrate).

**Conclusions**

The feasibility of using historical water quality databases for epidemiologic studies varies by contaminant, and may require a combination of exposure estimation methods.

## **Background**

Tap water may be an important source of arsenic and nitrate exposure, but obtaining and analyzing water samples from epidemiologic study participants is expensive and time-consuming. Further, tap water samples may not be available for all participants or reflect levels during the relevant time period, yet inferences about the relationship between disease and exposure are frequently based on present-day contaminant levels from only those who still live at a relevant residence and agree to water testing.

Exposure assessment methods that address these shortcomings are needed.

Many developed countries routinely monitor drinking water quality. For example, in the U.S. water purveyors serving >15 residences or >25 people have monitored their sources (e.g. wells and rivers) under the federal Safe Drinking Water Act (SDWA) since 1976. Currently there are standards for >90 contaminants. Levels measured in specific water sources may be available to reconstruct historical exposure estimates in epidemiologic studies. Typically participants' purveyors or water sources are determined, and respective records used to estimate contaminant levels in individuals' tap water, alone or in combination with other exposure information. This type of approach has been frequently used in parts of North America, Europe and Asia, including in recent years for a variety of contaminants and outcomes in adults and children (for example [1-8]). Although this method has been validated for nitrate [9], some participants may rely on private water sources for which public data are not available. In addition, participants may not know their source of water. A residential history or an address at birth, diagnosis or death may be easier to obtain. Within one region of the U.S. (Washington State), we examined how accurately residents report

their water purveyor, and the extent to which street address is sufficient to identify purveyors.

We also explored whether tap water levels of selected contaminants could be estimated for individual homes, including those not served by publicly monitored water systems, by using geographic information systems (GIS) to link residence locations to publicly available, geographically referenced water monitoring data. We focused on arsenic and nitrate because they tend to be regionally dispersed, are prevalent in our region, are often the focus of etiologic studies of environmental contaminants, and have been regulated since the inception of the SDWA.

Finally, because one advantage of using public water monitoring data is the possibility of conducting records-based studies, we examined the potential for misclassification of exposure due to residential use of bottled water and filtration devices. Prior research indicates this might be important [10].

## **Methods**

**Participant selection, interview and water collection.** Methods have been described [11]. Briefly, we used an added-digit technique [12] to identify, via telephone, a sample of 156 residences with children in regions of Washington State with varying levels of arsenic and nitrate. These homes represented 98% of eligible residences (72% of reached residences were screened). We asked whether the home was on a water system, the purveyor's name, and about use of bottled water and filters. Most (95%) survey participants agreed to provide a tap water sample; 107 (72%) did. Participants collected the samples themselves. We requested they run the cold tap for 2 minutes prior, and to circumvent filters. The majority of samples (77%)

arrived at the study lab (North Creek Analytical, Bothell, WA) the day after collection and at  $<6^{\circ}$  C. Institutional Review Board approval was received from Fred Hutchinson Cancer Research Center prior to study conduct, and consent was obtained via telephone (survey respondents) and in writing (participants providing water samples).

**Laboratory analysis.** Arsenic [13-14] and nitrate and nitrite as nitrogen [13, 15] were quantified using established methods and 250 mL tap water for each analysis. For quality control, residents from 10 additional homes provided a sample, and within 24 hours study staff obtained a sample for comparison, and a duplicate sample for testing at the laboratory that certifies others in the state. Excellent agreement was observed ( $\rho=0.89-0.94$  for arsenic,  $\rho=0.997-1.0$  for nitrate, no nitrite).

**Linkage of residences to water purveyor.** We assigned a latitude-longitude coordinate to each street address and determined whether the home was located inside city/town boundaries using Maptitude (version 4.1, Caliper Corporation, Newton, MA; 83% geocoded automatically, 17% manually). We also compared each home's coordinate to online water purveyor maps. Some purveyors obtain water from sources managed by other water suppliers, and we used additional online information (mainly from the U.S. Environmental Protection Agency) to determine whether and from whom a purveyor's water was purchased, and whether groundwater or surface water predominantly served each supplier.

**Derivation of summary measures from water monitoring data.** The Washington State Department of Health provided water monitoring data for 24,856 drinking water

sources throughout the state. Included were quantitative laboratory results for arsenic (32,441 samples from the years 1975-2003) and nitrate (82,274 samples from 1975-2003). We excluded samples unlikely to reflect true values: 11 arsenic and 3 nitrate samples >10 times the respective federal maximum contaminant level (MCL) and at least an order of magnitude higher than any other samples from that water source; and 22,219 (68%) arsenic samples reported as 0.01 mg/l (the MCL at the time) while being the highest level ever reported for that source.

Records for each water source indicated its latitude-longitude coordinate and the supplier served. Coordinates within the water quality database had been obtained as follows: 22% by global positioning system (GPS), 64% by quarter-quarter-section, 11% by section, and 4% by other methods. We calculated the distance between each water source and study residence using the haversine great circle distance formula. We used water sample data from sources within selected radii 0.5-10 miles to estimate the home's tap water arsenic and nitrate. For each radius and contaminant we calculated the mean, identified the maximum, and noted the level obtained most recently. We repeated calculations using only samples from the closest water source. Lastly, irrespective of proximity, we calculated the mean using only samples from sources associated with the home's water purveyor (if any).

**Statistical analysis.** We compared each summary measure to respective contaminant levels in participants' tap water. Because levels were non-normal, we estimated precision (hereafter also "agreement") using the Spearman correlation coefficient, while keeping all measures on the same (continuous) scale [16].

## Results

**Reporting of water purveyor.** Among residents of homes on a water system, 74% reported the correct water purveyor. Thirteen (39%) who did not instead reported another type of utility, and another 10 (30%) rented the home. All survey respondents who reported having a private water source provided sufficient confirmatory detail (e.g. type and well maintenance).

**Use of bottled water and filters.** Three-quarters of surveyed homes used some bottled (53%) and/or filtered (38%) water, and 32% used these exclusively. However, only one home (<1%) had a device particularly well-suited for removing arsenic or nitrate (i.e. a reverse osmosis system). Other types of filters were more common: pitcher (15%), refrigerator (15%), kitchen tap (7%), and whole-house (5%).

**Characteristics of water-sampled residences.** Although only 52% of homes were within city/town limits, 83% were on a water system, most commonly a municipality (Table 1). A majority (62%) of on-system homes received groundwater. A private well served each off-system home.

Water-sampled homes were slightly more likely to be located within city/town limits than all surveyed homes (46%, not shown in table). They were similar with regard to the number of residents (2-8, median 4), type of water purveyor and source, and use of bottled water and filters.

Arsenic and nitrate were present in most tap water samples (91% and 72%, respectively), but levels were generally below the MCL (Table 1). No homes on a publicly monitored water system contained arsenic or nitrate near or above the MCL,

whereas one private well had 9.5 µg/L arsenic, and two had nitrate above the MCL (maximum 40.5 mg/L). Nitrite was not detected.

**Precision of arsenic summary measures.** An 8-mile radius was required to link all homes to a publicly monitored water source with usable arsenic data. At this distance, the median number of arsenic samples was 105 (range 1-507) from 1-281 (median 48) water sources. At much shorter radii, the number of residences linking to arsenic-sampled water sources was modest, but precision improved greatly (Table 2). Using a half-mile radius, agreement was acceptable and similar across summary measures ( $\rho=0.47-0.51$ ), but only 30% of homes were included. Doubling the radius (1 mile) doubled the homes included (58%), but agreement dropped notably ( $\rho=0.26-0.36$ ). Agreement at larger radii was poor to modest ( $\rho=0.04-0.32$ ). At radii sufficient to include all homes, use of only the most recent monitoring records maximized agreement.

For most radii, agreement was substantially better for homes off rather than on a water system (Table 2). With an 8-mile radius agreement was 0.27 and 0.03, respectively. Agreement for on-system homes improved markedly ( $\rho=0.29$ ) when we used only samples from water source(s) serving the respective water system (not shown). Had we not excluded 0.01 mg/L arsenic reports, agreement would have been 0.04.

**Precision of nitrate summary measures.** A 6-mile radius was necessary to link all homes to a publicly monitored water source with nitrate data. At this radius, the median number of nitrate samples was 587 (range 3-2,797) from 1-550 (median 127)

water sources. For the most part, agreement decreased as the radius increased (Table 3). The summary measure based on mean nitrate in all sources within the respective distance was consistently most strongly correlated with homes' tap water nitrate. However, when agreement was maximized (half-mile radius,  $\rho=0.49$ ), only half of homes could be included, and agreement dropped to 0.32 when the radius was sufficient to include all homes.

Precision was somewhat better for homes off, rather than on, a water system. For example, when using a 6-mile radius, respective agreement was 0.47 and 0.29 (Table 3). For homes on a system, agreement was substantially improved by using only records pertaining to the respective water system ( $\rho=0.60$ , not shown).

## **Discussion**

Our results indicate that publicly available water quality monitoring data might be used to estimate drinking water contamination levels for participants in epidemiologic studies, but highlight several important limitations. In general, the approaches examined here worked better for nitrate than arsenic. This may have been due to the number and quality of records available. There were substantially more nitrate than arsenic records, and it was important to exclude arsenic records we believed to be reported as an upper bound. In addition, precision slightly improved by using only the most recent records. This may reflect variation in arsenic levels over time, which may occur in our region [17]. Elsewhere [10] correlation between residential tap water arsenic over a much shorter period of time was strong but imperfect ( $r=0.88$ ), confirming the plausibility of modest improvements when focusing on water records closest in time to water sampling. However, we expected [18] but did not observe this for nitrate. Thus, alternatively, perhaps more recent samples for arsenic only are

recorded with greater accuracy (the most recent arsenic samples included here followed the announcement of the lower MCL for arsenic, whereas there were no regulatory changes for nitrate). Thus, as new records accumulate, water quality monitoring databases may be increasingly useful for estimating arsenic. At the same time, our observations underscore the possibility that the validity of such methods may vary substantially by contaminant.

For both arsenic and nitrate we developed several summary measures. As expected, there was variation in how well each correctly ordered households with regard to actual levels. More important, however, were the radius (maximum distance) between the home and sampled water source, and whether the home was on a water system. Precision increased as the radius decreased, but ability to link homes to any sampled water source also decreased. This effect was sufficiently pronounced that if agreement became marginally acceptable ( $\rho > 0.40$ ), “participation” percentages ranged from unacceptable to marginal (30% for arsenic, and 50-72% for nitrate). Precision was also greater for homes off than on a water system. Perhaps for homes with private wells, the spatial relationship with its actual water source is more geographically based than for homes served by a water system. This may be particularly true for those relying on surface sources, which may be quite distant from their ultimate tap destinations. Regardless, it is encouraging that while using our GIS approach, precision is most acceptable for the subset of homes for which it would be impossible to apply the more traditional approach of linking water quality records according to which system served the home.

It is likewise encouraging that for homes on a water system, precision of the simple linkage-by-system approach is good, at least for nitrate. This approach yielded less acceptable agreement for arsenic, but was comparable to the GIS method.

Respondents had only moderate knowledge of their water purveyor, but we were able to assign each home to a water purveyor using online maps. Thus, it appears possible that by combining approaches examined here, one would be able to include all or most participants in a study, whether or not they were on a water system and could provide water purveyor information. Use of multiple approaches in one study is not novel, but inclusion of all study participants may reduce the potential for bias, assuming analyses account for the possibility that different exposure assessment methods imply different degrees of measurement error. We assessed one component of this, precision, and observed that it did differ between methods, as well as between homes on and off a water system.

Other studies that have examined reliability or validity of records-based methods for assessing tap water arsenic or nitrate observed fairly similar results. In southeastern Michigan, several spatial models of groundwater arsenic were developed using samples from 6050 private wells, and then validated [19] using samples from 371 private wells in a case-control study. A geographic model that secondarily took into account geologic formations and geographic boundaries of bedrock performed best ( $\rho=0.46$ ). Models more similar to our basic GIS linkage methods yielded precision closer in magnitude to what we observed for our small subgroup of homes on private wells. One model used mean arsenic within a township (typically 6 × 6 miles; 4.24 miles maximum from the centre), and when we focused on homes served by private wells and used a radius of 4 miles our results were nearly identical ( $\rho=0.35$  vs.

$\rho=0.36$ ). The authors repeated this model using a township section ( $1 \times 1$  mile; 0.7 miles maximum from the centre). As in our analysis, precision improved ( $\rho=0.42$ ) with this reduced “radius,” but data were unavailable for half of homes. Finally, as in our study, the authors observed little difference between this method and using only samples from the closest well ( $\rho=0.35$ ). The similarities between our results are especially interesting given that arsenic levels were greater in that study (median 2.30  $\mu\text{L}$ ; 90<sup>th</sup> percentile 22.73  $\mu\text{L}$ ).

In a German case-control study in which 591 participants lived at a home receiving water from one of 69 public authorities, tap water nitrate was assessed by semi-quantitative test strip and by historical water records [9]. Again water contamination levels were greater than in our region (>50% of controls’ tap water exceeded the U.S. MCL of 10 mg/L nitrate as nitrogen). Nonetheless, agreement ( $\rho=0.62$  for cases,  $\rho=0.59$  for controls) was nearly identical to our estimate using the most similar method (mean in all water sources supplying the relevant water purveyor,  $\rho=0.60$ ). It should be noted, though, that the German study implies a higher validity than ours because our “gold standard” (laboratory testing) was presumably better than theirs (test strips). Using 97% of our nitrate-sampled homes we estimated precision of such nitrate test strips to be 0.72 when used by study participants [11] (we did not examine the precision of field test kits for arsenic because they may contain or produce toxic substances [20]).

That the nitrate test strips are more precise than the best methods assessed in the present work deserves discussion. Attenuation of odds ratios would be substantial even when using the test strip (Table 4). Still, the test strip method relies on

subjective comparison of the moistened strip to a colour chart, and bias might occur if the outcome is already known to the person using the test strip [11], whereas linkage-based methods can be applied objectively. The test strip method also requires access to the water source of interest, which is not always feasible [21]. In addition, use of records might allow one to consider past nitrate levels, including those at past residences. The importance of this has been documented [22]. Finally, use of a records-based method might allow a quick and cost-effective study, perhaps without contacting participants. In such case, increasing sample size might be feasible and help compensate for the greater measurement error of this method, as well as any added error if one cannot ask participants how much water they consumed, or whether they used bottled water or filters.

Our results indicated that nearly a third of homes with children exclusively drink bottled/filtered water at home. Failure to take this into account during sample size calculations and analysis might substantially impair the ability to detect associations in studies in which the contaminant of interest is removed by the most common types of filters, and for which the main route of exposure is ingestion as opposed to absorption/inhalation during bathing, showering and swimming. For arsenic and nitrate, this might be less problematic if reverse osmosis devices are uncommon (as we observed), but their use should be taken into consideration if possible [10].

## **Conclusions**

Water quality monitoring records obtained for non-research purposes are potentially useful for exposure assessment in epidemiologic studies. However, these studies must be well powered; designed to minimize the potential for selection bias and

differential measurement error; and interpreted in light of the likely effect of substantial non-differential measurement error.

## List of abbreviations

GIS	geographic information systems
GPS	global positioning system
MCL	maximum contaminant level
$\mu\text{g/L}$	micrograms per litre
$\text{mg/L}$	milligrams per litre
OR	odds ratio
$r$	Pearson's correlation coefficient
$\rho$	Spearman's rho
SDWA	Safe Drinking Water Act

## **Competing interests**

The authors declare that they have no competing interests.

## **Authors' contributions**

All authors read, edited and approved the final manuscript. BAM conceived the study design, supervised implementation, and contributed to the statistical analysis. SSN helped conceive the study design, conducted statistical analyses, and drafted the manuscript. CMK coordinated the field and laboratory components, and conducted field work and data management.

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## Tables

**Table 1: Characteristics of water-sampled homes, overall and by type of water supply**

	<b>All homes N=107</b>	<b>Public system* N=89</b>	<b>Private well† N=18</b>
	<u>n (%)</u>	<u>n (%)</u>	<u>n (%)</u>
Within city/town limits	56 (52)	55 (62)	1 (6)
Type of water supply			
Public system	89 (83)	89 (100)	--
Municipality	63 (59)	63 (71)	--
Utility district	12 (11)	12 (13)	--
Private utility/association	14 (13)	14 (16)	--
Private well	18 (17)	--	18 (100)
Shared	7 (7)	--	7 (39)
Individual	11 (10)	--	11 (61)
Water source			
Groundwater	73 (68)	55 (62)	18 (100)
Surface	34 (32)	34 (38)	0 (0)
Arsenic level			
Any detected	97 (91)	82 (92)	15 (83)
>MCL‡	0 (0)	0 (0)	0 (0)
	<u>µg/L</u>	<u>µg/L</u>	<u>µg/L</u>
Minimum	0	0	0
25 <sup>th</sup> percentile	0.35	0.35	0.41
Median (µg/L)	0.59	0.56	1.31
75 <sup>th</sup> percentile	1.24	0.97	1.94
Maximum (µg/L)	9.5	4.34	9.5
Nitrate level§			
Any detected	<u>n (%)</u> 76 (72)	<u>n (%)</u> 64 (74)	<u>n (%)</u> 12 (67)
>MCL‡	2 (2)	0 (0)	2 (11)
	<u>mg/L as N</u>	<u>mg/L as N</u>	<u>mg/L as N</u>
Minimum	0	0	0
25 <sup>th</sup> percentile	0	0	0
Median (mg/L)	0.37	0.35	0.39
75 <sup>th</sup> percentile	1.65	1.52	2.27
Maximum (mg/L)	40.5	4.48	40.5
	<u>n (%)</u>	<u>n (%)</u>	<u>n (%)</u>
Nitrite, any detected§	0 (0)	0 (0)	0 (0)

**Table 1: Characteristics of water-sampled homes, overall and by type of water supply (continued)**

\* Water system served by wells, surface sources or other sources with federally-mandated monitoring; represented systems served 95 to >600 000 homes; water came directly or via intermediate purveyors from one of 55 water suppliers, including 12 serving multiple ( $\leq 12$ ) sampled homes.

† Individual or shared (2-8 homes) private well, not subject to federally-mandated monitoring.

‡ Current U.S. federal maximum contaminant level (10  $\mu\text{g/L}$  arsenic and 10  $\text{mg/L}$  nitrate as nitrogen).

§ As nitrogen, among 105 for whom nitrate and nitrite values were determined.

**Table 2: Agreement\* between arsenic measures, overall and by type of water source**

	<b>Radius (maximum distance between residence and water source, miles)</b>										
	<b><u>0.5</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>3</u></b>	<b><u>4</u></b>	<b><u>5</u></b>	<b><u>6</u></b>	<b><u>7</u></b>	<b><u>8</u></b>	<b><u>9</u></b>	<b><u>10</u></b>
<b><u>All residences (N):</u></b>	32	62	83	95	98	100	105	106	107	107	107
<i>All sources in radius</i>											
Mean	0.49	0.30	0.32	0.20	0.18	0.15	0.12	0.04	0.05	0.08	0.09
Maximum	0.51	0.26	0.26	0.21	0.24	0.20	0.16	0.12	0.15	0.16	0.17
Most recent	0.49	0.33	0.13	0.10	0.17	0.07	0.20	0.17	0.24	0.25	0.31
<i>Closest source only</i>											
Mean	0.49	0.35	0.19	0.11	0.10	0.09	0.11	0.11	0.13	0.13	0.13
Maximum	0.47	0.36	0.19	0.11	0.10	0.09	0.10	0.10	0.12	0.12	0.12
Most recent	0.49	0.35	0.17	0.09	0.08	0.08	0.09	0.09	0.11	0.11	0.11
<b><u>Residences on a public system<sup>†</sup> (N):</u></b>	28	53	72	79	81	83	87	88	89	89	89
<i>All sources (mean)</i>	0.41	0.21	0.29	0.24	0.22	0.15	0.09	0.02	0.03	0.08	0.09
<b><u>Residences with a private well<sup>‡</sup> (N):</u></b>	4	9	11	16	17	17	18	18	18	18	18
<i>All sources (mean)</i>	1.0	0.68	0.67	0.22	0.32	0.32	0.35	0.25	0.27	0.29	0.32

\* Correlation (Spearman's rho) between arsenic levels measured in tap water of individual residences and selected summary measures estimated for that home using public water quality data and geographic information systems (GIS).

<sup>†</sup> Water system served by wells, surface sources or other sources with federally-mandated monitoring.

<sup>‡</sup> Individual or shared private well, not subject to federally-mandated monitoring.

**Table 3: Agreement\* between nitrate measures, overall and by type of water source**

	<b>Radius (maximum distance between residence and water source, miles)</b>										
	<b><u>0.5</u></b>	<b><u>1</u></b>	<b><u>2</u></b>	<b><u>3</u></b>	<b><u>4</u></b>	<b><u>5</u></b>	<b><u>6</u></b>	<b><u>7</u></b>	<b><u>8</u></b>	<b><u>9</u></b>	<b><u>10</u></b>
<b><u>All residences (N):</u></b>	52	76	91	97	99	103	105	105	105	105	105
<i>All sources in radius</i>											
Mean	0.49	0.44	0.39	0.34	0.34	0.30	0.32	0.32	0.31	0.32	0.34
Maximum	0.37	0.37	0.27	0.26	0.28	0.28	0.33	0.29	0.29	0.29	0.25
Most recent	0.38	0.17	0.31	0.32	0.25	0.27	0.31	0.30	0.28	0.21	0.18
<i>Closest source only</i>											
Mean	0.34	0.32	0.25	0.25	0.25	0.24	0.25	0.25	0.25	0.25	0.25
Maximum	0.19	0.26	0.19	0.20	0.19	0.21	0.20	0.20	0.20	0.20	0.20
Most recent	0.35	0.33	0.24	0.24	0.23	0.22	0.21	0.21	0.21	0.21	0.21
<b><u>Residences on a public system<sup>†</sup> (N):</u></b>	41	63	76	80	82	86	87	87	87	87	87
<i>All sources (mean)</i>	0.49	0.39	0.35	0.29	0.29	0.24	0.29	0.30	0.28	0.31	0.35
<b><u>Residences with a private well<sup>‡</sup> (N):</u></b>	11	13	15	17	17	17	18	18	18	18	18
<i>All sources (mean)</i>	0.14	0.60	0.40	0.51	0.47	0.44	0.47	0.46	0.43	0.41	0.40

\* Correlation (Spearman’s rho) between nitrate levels measured in tap water of individual residences and selected summary measures for that home estimated using public water quality data and geographic information systems (GIS).

<sup>†</sup> Water system served by wells, surface sources or other sources with federally-mandated monitoring.

<sup>‡</sup> Individual or shared private well, not subject to federally-mandated monitoring.

**Table 4: Observable odds ratios (ORs) given selected true ORs and non-differential measurement error for water nitrate\***

	<u>Observable OR<sup>†</sup></u>		
<u>Spearman's rho:</u>	<u>0.72</u> *	<u>0.60</u> *	<u>0.47</u> *
<u>True OR<sup>†</sup></u>			
<b>2.0</b>	1.43	1.28	1.17
<b>1.8</b>	1.36	1.24	1.14
<b>1.5</b>	1.23	1.16	1.09
<b>1.3</b>	1.15	1.10	1.06

\* Spearman's rho as a measure of precision: 0.72 for semi-quantitative test strips [11]; 0.60 for direct linkage to water supplier data (homes served by water systems); 0.47 for GIS linkage to water source data using a 6-mile radius (homes served by private wells).

† Per unit increase in water nitrate levels; derived from the attenuation equation [16].