Glacial Sediment Causing Regional-Scale Elevated Arsenic in Drinking Water

by Melinda L. Erickson¹,²,⁴ and Randal J. Barnes³

Abstract
In the upper Midwest, USA, elevated arsenic concentrations in public drinking water systems are associated with the lateral extent of northwest provenance late Wisconsin-aged drift. Twelve percent of public water systems located within the footprint of this drift (212 of 1764) exceed 10 µg/L arsenic, which is the U.S. EPA’s drinking water standard. Outside of the footprint, only 2.4% of public water systems (52 of 2182) exceed 10 µg/L arsenic. Both glacial drift aquifers and shallow bedrock aquifers overlain by northwest provenance late Wisconsin-aged sediment are affected by arsenic contamination. Evidence suggests that the distinct physical characteristics of northwest provenance late Wisconsin-aged drift—its fine-grained matrix and entrained organic carbon that fosters biological activity—cause the geochemical conditions necessary to mobilize arsenic via reductive mechanisms such as reductive desorption and reductive dissolution of metal oxides. This study highlights an important and often unrecognized phenomenon: high-arsenic sediment is not necessary to cause arsenic-impacted ground water—when “impacted” is now defined as >10 µg/L. This analysis also demonstrates the scientific and economic value of using existing large but imperfect statewide data sets to observe and characterize regional-scale environmental problems.

Introduction
Arsenic exposure from drinking water poses a significant environmental cancer risk, similar to cancer risks from environmental (second hand) tobacco smoke (Smith et al. 1992). In West Bengal, India, and Bangladesh alone, >40 million people are estimated to drink high-arsenic (over 50 µg/L) ground water (Smedley and Kinniburgh 2002). Worldwide, a number of different mechanisms have been shown, or postulated, to cause arsenic contamination in ground water. Some examples of arsenic-release mechanisms discussed in the literature include oxidation of arsenic-rich pyrite in mining areas (Williams 2001) or in an oxidized aquifer (Schreiber et al. 2000), desorption of arsenic from clays and reductive dissolution of metal oxides in alluvial aquifers (Kinniburgh and Smedley 2001) and in buried glacial aquifers (Kim et al. 2002), and discharge of arsenic-rich thermal water (Langner et al. 2001). Welch et al. (2000) reported that ~10% of 30,000 ground water samples, primarily from the USGS’s National Water Information System, exceed 10 µg/L arsenic. Ten micrograms per liter is the U.S. EPA’s arsenic drinking water standard, or maximum contaminant level (MCL), which was adopted in 2001. The 10 µg/L arsenic MCL will be enforced as of January 2006. Ryker (2003) reports that, nationwide, 8.9% of 4390 public drinking water systems and 11.5% of 7530 private drinking water supplies exceed 10 µg/L arsenic. An even larger percentage of wells in the upper Midwest have arsenic concentrations exceeding 10 µg/L. A study of arsenic occurrence and exposure in western Minnesota, USA, found that over 50% of the 900 sampled private drinking water wells had arsenic exceeding 10 µg/L. The study postulated that high arsenic in ground water in Minnesota may be linked to Des Moines lobe till, a subset of the late Wisconsin-aged glacial till regionally deposited by ice that advanced from a northwesterly direction (Minnesota Department of Health 2001).
This paper examines the proposed relationship between elevated arsenic concentrations in ground water used for public water systems to supply drinking water in the upper Midwest and the extent of northwest provenance late Wisconsin-aged glacial sediment. The conjectured relationship is examined and tested using statistical comparisons of averages, proportions, correlations, and geostatistical methods. An extensive database of measured ground water arsenic concentrations in public water systems was compiled for this study.

Data Compilation and Statistical Methods

Public water systems in the United States (U.S. EPA 2004) are required to test for arsenic and other regulated parameters. As such, each state has data available for measured arsenic concentrations in its public water systems. The agencies responsible for regulating drinking water in Iowa, Minnesota, North Dakota, and South Dakota provided the public water system water quality databases and the approximate locations of the public water systems (Iowa Environmental Protection Division 2003; Minnesota Department of Health 2002; North Dakota Department of Health 2003; South Dakota Drinking Water Program 2003). Surface water samples were excluded from the database.

Although different analytical methods were used in different states to measure arsenic concentrations in drinking water, each method had a detection limit of 10 μg/L or lower, which conveniently coincides with the MCL for arsenic. Many measurements are reported as “not detected” at a detection limit of 10 μg/L, so the regional analysis presented in this paper is presented as an indicator analysis (Barabas et al. 2001; Juang and Lee 1998; Oh and Lindquist 1999; Saito and Goovaerts 2000). The indicator variable is created based on measured arsenic concentration: a “1” is assigned to each measurement that is 10 μg/L or more, and a “0” is assigned to each measurement of <10 μg/L, including measurements that were not detected at a reporting limit of 10 μg/L (Berry and Lindgren 1990).

The public water supply wells are open to a variety of different aquifers, and all data were included in this analysis. Well depth and aquifer information were available for ~50% of the reported sample locations. The wells for which there is depth information are, in most cases, the same wells for which the aquifer at the open interval of the well has been characterized. Well depth is used as an indicator of the depth of the open interval. The final data set is based upon ~4000 public water system sample locations. The study area, sampling points, and simplified geologic setting are shown in Figure 1.

Due to increased security concerns related to public water system locations, the locations released by the states were not exact latitude and longitude locations. The locations are instead the centroid of the zip code in which the public water system is located. Because this paper examines the potential influence of a geologic feature that is of a scale of hundreds of square kilometers and zip code areas are on the order of kilometers to tens of square kilometers, the sample location accuracy is acceptable for this regional analysis.

Each of the states has mapped important geologic features, such as various glacial tills. Therefore, maps representing the extent of late Wisconsin-aged till in each state were available and obtained electronically.

A key component of the success of this analysis is accessing and screening existing results that were collected for other purposes. Although the cost of conducting this type of analysis is relatively small, the impact of the analysis can be large. A regional-scale environmental problem may be identified and characterized, and significant knowledge gaps that inhibit planning, such as the lack of information tying sampling results to a specific well, may be identified. Appropriate statistical analyses of the data, as described next, are fundamental to examining large and imperfect data sets.

Proportions of sample locations with As ≥ 10 μg/L are compared to test null hypotheses of differences in proportions in specified groups of data. For example, the null hypothesis that the proportion of As ≥ 10 μg/L is the same both inside and outside of the footprint of the sediment of interest is tested: $P_{\text{inside}} - P_{\text{outside}} = 0$ (Berry and Lindgren 1990). The null hypothesis is rejected if the proportions are sufficiently different (z ≥ 1.96) at the 95% confidence level ($P \leq 0.05$). The same criteria are used to evaluate whether the means of well depths for different groups of wells are different from one another.

Geostatistical analysis is performed using a directional indicator variogram. The directional indicator variogram reveals anisotropic spatial continuity by analyzing the variance of groups of sample points segregated by separation vectors (separation distance and direction). Spatial continuity is revealed when samples near one another are more alike. Anisotropy is revealed when samples lying along different directional vectors are more or less alike (Isaaks and Srivastava 1989). The spatial distribution of elevated arsenic concentrations was tested for randomness using a nearest-neighbor analysis (Cressie 1991) and a binomial distribution (Berry and Lindgren 1990).

Geologic Setting: Northwest Provenance

Late Wisconsin–Aged Drift

The geologic setting of the study area is composed of heterogeneous glacial sediments overlying bedrock in most locations. The exceptions are the southwestern part of North Dakota, the western part of South Dakota, and the southeastern part of Minnesota, which were either never glaciated or have no preserved glacial sediment (Soller 1997). The recent geologic history of the upper Midwest is complex. The area has been subject to numerous glacial advances and retreats. The glacial advances of most relevance to this study are the multiple late Wisconsin-period glacial advances (16,000 to 12,000 years ago) from the Kewatin ice center in central Canada, north-northwest of the study area. From west to east, the ice advances of interest and their associated glacial sediments include the Souris lobe, the James lobe, the Red River lobe, and the Des Moines lobe (Clayton et al. 1980; Fullerton et al. 1995; Lusardi 1997; Meyer 1997). Clayton et al. (1980), Fullerton et al. (1995), Lusardi (1997), Meyer
(1997), and Soller (1997) are all in general agreement regarding the approximate footprint of the northwest provenance late Wisconsin-aged sediment. This drift (the till and the associated melt water features [Bates and Jackson 1984]) is the glacial drift of particular interest to this study. Superior lobe sediments, also of late Wisconsin age, were deposited over northeastern Minnesota and areas north and east of the study area by ice traveling from the northeast, the Labrador ice center. Superior lobe till is distinctly different in texture, pebble composition, and color; it has a larger fraction of sand, and it is red (Boerboom 2002; Lusardi 1997; Wright 1972). Other glacial sediments also exist in the upper Midwest, either underlying the late Wisconsin-aged sediments or as the uppermost glacial unit. Older sediments are not of specific interest to this study. A generalized map of the glacial sediment in the study area is presented in Figure 1.

Northwest provenance late Wisconsin-aged till, which is the uppermost glacial till in much of the study area, has several distinct features important to this study. This sediment has significant fractions of both carbonate and shale, it is generally gray, and it has a large fraction of fine-grained material (Fullerton et al. 1995; Harris et al. 1995; Harris 1999; Matsch 1972; Patterson 1999).

Simpkins and Parkin (1993) noted that the Des Moines lobe till near Ames, Iowa, has organic entrainment, active anaerobic biological activity documented by the presence of methane in ground water samples, and pyrite disseminated within the till matrix. The presence of methane in ground water and pyrite disseminated within the till are indicative of reducing conditions in the aquifer. Arsenic was not measured in the study.

In North America, regional-scale Quaternary aquitards, which include the northwest provenance late Wisconsin-aged sediment of interest to this study, have elevated levels of solid and aqueous organics when compared to coarser materials (Rodvang and Simpkins 2001). The organics entrained in the aquitard sediment derive from Quaternary forests, soils, and lakebeds. Simpkins and Parkin (1993) discuss the existence of a periglacial, coniferous forest that was incorporated into the Des Moines lobe sediment. Patterson (1999) remarks on the presence of wood in Des Moines lobe sediments. Soller (1997) comments that patchy, organic-rich sediments in Minnesota are primarily associated with poorly drained, late Wisconsin-aged sediments.

An internal Minnesota Department of Health report indicates that carbon sources such as wood, peat, lignite,

![Figure 1. Generalized geologic setting of the upper Midwest study area.](image-url)
and coal are often mentioned in well logs in locations that are consistent with the mapped extent of northwest provenance late Wisconsin-aged till in Minnesota (Soule 2003). Correlations between ground water arsenic concentration and redox are noted in the literature, as is a correlation between elevated ground water arsenic concentration and the general presence of organic material in the sediment (Holm and Curtiss 1988; Kim et al. 2002; Kinniburgh and Smedley 2001; Korte 1991; Schreiber et al. 2000; Sukop 2000; Warner 2001). Soule (2003) also notes a relationship between the thickness of a clay layer in a well log, as described by a driller, and the probability of having elevated arsenic in the well.

Geochemical Background

The Pierre and similar Cretaceous shales in North Dakota and Canada were entrained and later deposited as a significant fraction of the Des Moines lobe and other northwest provenance late Wisconsin-aged glacial sediments (Hobbs and Goebel 1972; Schultz et al. 1980; Wright 1972). The arsenic concentration in the Upper Cretaceous Pierre Shale has been measured at 1 to ~50 mg/kg (Rader and Grimaldi 1961), and a significant portion of the arsenic is present in iron sulfide minerals (USGS 1962). Arsenic is often present in iron sulfide minerals, such as pyrite, as an impurity. Pyrite can act as either an arsenic source, in oxidizing environments, or as an arsenic sink, in reducing environments (Schreiber et al. 2000; Welch et al. 2000). Mineral formation/dissolution has been identified as an important arsenic-trapping and -releasing mechanism in a number of environments (Schreiber et al. 2000; Smedley and Kinniburgh 2002; Thornton 1996). Processes, such as carbonate dissolution and biological activity, which control pH and redox states of fluids infiltrating through glacial tills or clay, have been well documented for numerous localities (Keller et al. 1991; Lawrence et al. 2000; Simpkins and Parkin 1993; Yan et al. 2000).

A Minnesota Department of Health (2001) report suggested that elevated arsenic concentrations in western Minnesota ground water are likely due to oxidation of pyrite present in the glacial sediment and an arsenic “sweeping” mechanism similar to classic “roll front” uranium deposits (Harshman 1968). The report also notes that ground water samples collected during the study often had a sulfurous smell, indicating a reducing environment.

Kanivetsky (2000) conjectured that arsenic adsorption/desorption mechanisms control arsenic concentrations in Minnesota ground water. Kanivetsky (2000) summarized arsenic concentrations measured in some of Minnesota’s Quaternary sediments, including the northwest provenance late Wisconsin-aged sediment of interest to this study. Reported mean sediment arsenic concentrations range from 2 to 26 mg/kg in the western part of the state, and 4 to 11 mg/kg in the eastern part of the state. Although categorized as “eastern” and “western,” all of the sample locations are within the footprint of the northwest provenance late Wisconsin-aged drift. Samples of northeastern provenance late Wisconsin-aged sediment have measured arsenic concentrations that range from 1.3 to 17.3 mg/kg, with averages of 4.2 mg/kg in rotasonic core samples specifically collected for the study and 5.1 mg/kg in archived core samples (Woodruff et al. 2003). The total arsenic concentration ranges in northwestern and northeastern provenance late Wisconsin-aged sediments are similar.

Sediment analyses performed by the authors indicate that total arsenic concentrations in glacial sediment in western and central Minnesota range from 2 to 10 mg/kg. Sediment and ground water samples were collected and analyzed from the same well. These results, shown in Figure 2, indicate that water arsenic concentrations are not correlated to either till arsenic concentrations ($R^2 = 0.147, P = 0.309$) or aquifer sediment arsenic concentrations ($R^2 = 0.0032, P = 0.885$).

Arsenic is a common element, and its crustal average concentration is 1.8 mg/kg (Hem 1985). As pointed out by Hering and Kneebone (2002), mobilization of just 0.09% of the average crustal arsenic concentration in sediment, 1.8 mg/kg, yields water arsenic concentrations exceeding 10 µg/L. They assume sediment specific gravity of 2.6 g/cm$^3$ and porosity of 30%, which is consistent with the characteristics of the sediment of interest to this study. Hering and Kneebone’s example calculation illustrates that total arsenic concentration in sediment is less important than the availability of the arsenic to mobilization.

In related work conducted by the authors to quantify arsenic adsorbed to and coprecipitated with metal oxides coating sediment grains, selected sequential extraction steps were performed in an anaerobic environment following methods provided in Keon et al. (2001). Aquifer sediment samples were taken from two rotasonic cores obtained from northwest Minnesota. The results of the selected extraction steps are summarized in Table 1. The sediment extraction results show that 0.4 to 0.8 mg/kg of the arsenic present in northwest provenance late Wisconsin-aged aquifer sediment is arsenic adsorbed to or coprecipitated with metal oxides coating sediment grains. Arsenic that is adsorbed to or coprecipitated with metal oxides is labile arsenic. Labile arsenic is more

![Figure 2](image-url)
sensitive to redox conditions than arsenic minerals or arsenic coprecipitated with minerals other than metal oxides (Smedley and Kinniburgh 2002).

In summary, northwest provenance late Wisconsin-aged till has two distinct features important to this study: a large fraction of fine-grained material and organic entrainment that causes active anaerobic biological activity. Arsenic concentrations in northwest provenance late Wisconsin-aged sediment are neither particularly high nor significantly different from arsenic concentrations in sediment of northeastern provenance. Total arsenic concentrations in sediment are not related to arsenic concentration in ground water. Adsorbed arsenic, which is labile and sensitive to redox condition, has been measured at 0.4 to 0.8 mg/kg in northwest provenance aquifer sediment.

### Results

Figure 3 presents the compilation of arsenic concentrations in public water systems and the lateral extent of northwest provenance late Wisconsin-aged drift in the

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Depth (m)</th>
<th>Extractant</th>
<th>As (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>694217</td>
<td>18</td>
<td>1 M NaH$_2$PO$_4$, 1 N HCl, 0.2 M ammonium oxalate/oxalic acid</td>
<td>0.56 0.19 0.09 0.85</td>
</tr>
<tr>
<td>694217</td>
<td>19</td>
<td>1 M NaH$_2$PO$_4$, 1 N HCl, 0.2 M ammonium oxalate/oxalic acid</td>
<td>0.32 0.08 0.19 0.58</td>
</tr>
<tr>
<td>694218</td>
<td>21</td>
<td>1 M NaH$_2$PO$_4$, 1 N HCl, 0.2 M ammonium oxalate/oxalic acid</td>
<td>0.24 0.04 0.09 0.37</td>
</tr>
</tbody>
</table>

Figure 3. Arsenic concentrations in public water systems in the upper Midwest, USA. Within the footprint, 12.0% of public water system sample locations exceed 10 mg/L arsenic; outside of the footprint, only 2.4% of public water system sample locations exceed 10 mg/L arsenic.
upper Midwest, USA. Visual inspection of Figure 3 provides a compelling argument that there is a relationship between the presence of this sediment and elevated arsenic concentrations in ground water.

The public water system arsenic concentrations were evaluated on the basis of location inside or outside of the footprint of the northwest provenance late Wisconsin-aged drift. The proportion of public water system sample locations with arsenic concentrations exceeding 10 μg/L was then calculated for each group. Table 2 presents a summary of this indicator analysis. The comparison rejects the hypothesis that these two proportions are equal ($z = 11.46$, $P < 0.001$); thus, the two populations are different.

Table 3 summarizes available information regarding well depth and aquifer type for sample locations. Many public water system sample locations are not associated with a particular well. Instead, the sample locations provide a sample of water blended from two or more sources. Many of the sample locations with unknown aquifer and well depth information are from such sample locations.

Table 4 presents additional arsenic concentration differences within well types for wells with known depths and located within the northwest provenance late Wisconsin-aged drift. Depth ranges were chosen based upon quartile ranges for the two different well types. The shallowest and deepest depth ranges represent the lower and upper quartiles, while the middle depth range represents the middle 50% of depth ranges.

The proportions of both bedrock wells and glacial drift wells exceeding 10 μg/L As within the footprint are different from their counterparts located outside of the footprint (bedrock $z = 4.13$, $P < 0.001$; glacial $z = 9.68$, $P < 0.001$). The shallowest bedrock wells located within the footprint are significantly impacted with arsenic, as are the glacial drift wells in the middle depth range. Glacial drift wells are significantly deeper within the footprint than outside of the footprint; the populations are different ($z = 7.09$, $P < 0.001$).

Figure 4 presents a directional indicator variogram of the upper Midwest region’s public water system arsenic measurements. The perpendicular directional variogram, not shown, has a similar sill, but the apparent nugget effect is more than three times larger. As illustrated by the variogram, public water system arsenic measurements are spatially correlated on a scale of 150 km; therefore, one or more of the variables governing the release of arsenic are correlated at this length scale, and this is a regional phenomenon. Additionally, nearest-neighbor analysis shows that elevated arsenic concentrations are clustered, not randomly distributed. Clustering of elevated arsenic concentrations is consistent with the small nugget effect in the directional variogram model relative to the variogram sill, a measure of total variance (Barnes 1991).

Figure 5 presents arsenic and iron measurements available for ~300 upper Midwest public water system sample locations. Arsenic and iron are very weakly correlated ($R^2 = 0.176$, $P \leq 0.001$).

### Table 2
**Summary of Upper Midwest Public Water System Arsenic Concentrations**

<table>
<thead>
<tr>
<th>Group</th>
<th>Total Count</th>
<th>Count Exceeding 10 μg/L</th>
<th>% Wells &gt;10 μg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside footprint</td>
<td>1764</td>
<td>212</td>
<td>12.0</td>
</tr>
<tr>
<td>Outside footprint</td>
<td>2182</td>
<td>52</td>
<td>2.4</td>
</tr>
</tbody>
</table>

### Table 3
**Summary of Upper Midwest Public Water System Well Depths, Aquifer Types, and Arsenic Concentrations**

<table>
<thead>
<tr>
<th>Well Type</th>
<th>Count</th>
<th>Known Depth (m)</th>
<th>Unknown Depth (m)</th>
<th>Median Depth (m)</th>
<th>% Wells &gt;10 μg/L As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside footprint of NW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedrock</td>
<td>583</td>
<td>526</td>
<td>57</td>
<td>130</td>
<td>7.2</td>
</tr>
<tr>
<td>Glacial drift</td>
<td>551</td>
<td>474</td>
<td>77</td>
<td>44</td>
<td>16.3</td>
</tr>
<tr>
<td>Unknown</td>
<td>630</td>
<td>57</td>
<td>573</td>
<td>49</td>
<td>12.7</td>
</tr>
<tr>
<td>Outside footprint of NW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedrock</td>
<td>642</td>
<td>601</td>
<td>41</td>
<td>129</td>
<td>2.2</td>
</tr>
<tr>
<td>Glacial drift</td>
<td>219</td>
<td>191</td>
<td>28</td>
<td>26</td>
<td>0.5</td>
</tr>
<tr>
<td>Unknown</td>
<td>1321</td>
<td>37</td>
<td>1284</td>
<td>62</td>
<td>2.8</td>
</tr>
</tbody>
</table>

1 All but four of these wells are >30 m deep.

### Table 4
**Public Water System Arsenic Concentrations, by Depth Range and Aquifer Type**

<table>
<thead>
<tr>
<th>Well Type</th>
<th>Count</th>
<th>Depth Range (m)</th>
<th>% Wells &gt;10 μg/L As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock</td>
<td>132</td>
<td>800–186</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>263</td>
<td>185–92</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>131</td>
<td>91–41</td>
<td>22.1</td>
</tr>
<tr>
<td>Glacial drift</td>
<td>120</td>
<td>157–65</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>236</td>
<td>64–28</td>
<td>27.0</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>28–7</td>
<td>7.4</td>
</tr>
</tbody>
</table>
Discussion

Visual inspection of the regional mapping of arsenic concentrations and the lateral extent of the northwest provenance late Wisconsin-aged drift provides a compelling argument that there is a relationship between the two; the statistical analyses provide undeniable evidence of a relationship. Within the footprint, significantly more sample locations exceed 10 \( \mu g/L \) arsenic compared to outside the footprint. Inside the footprint, a higher percentage of wells finished in glacial sediments have elevated arsenic concentrations compared with bedrock wells. Additionally, a higher percentage of the shallowest bedrock wells that are overlain by northwest provenance late Wisconsin-aged drift have elevated arsenic compared with other bedrock wells. Glacial drift wells within the footprint are significantly deeper than glacial drift wells outside of the footprint. The use of deeper wells implies that the northwest provenance late Wisconsin-aged drift is fairly continuous, thick, and not very permeable, which is consistent with the reported characteristics of this drift.

Elevated arsenic concentrations are not spatially random, as evidenced by their spatial correlation over lengths of 150 km as well as their geographic clustering. The directional variogram captures the fact that elevated arsenic concentrations mirror the ice flow direction of late Wisconsin ice advances from the northwest. The long-distance spatial correlation of the data eliminates localized phenomena, such as pyrite oxidation induced by the presence of a well or an arsenic roll front, as probable regional-scale arsenic mobilization mechanisms.

Northwest provenance late Wisconsin-aged sediment does not have particularly high arsenic concentrations when compared with sediment of northeastern provenance. Additionally, existing data suggest that sediment arsenic concentrations are not correlated to ground water arsenic concentrations. It is nonetheless conjectured that the presence of the northwest provenance late Wisconsin-aged drift is the cause of the widespread area of elevated arsenic concentrations in ground water in the upper Midwest study area. The physical characteristics of this drift—its fine-grained matrix, entrained carbon, and biological activity associated with consuming carbon—are consistent with sediment characteristics associated with reductive arsenic mobilization mechanisms, such as reductive dissolution and reductive desorption (reduction of As(V) to As(III) followed by desorption of As(III) species, or reduction of Fe(III) species to less adsorptive nonaqueous Fe(II) species). The presence of this significant geologic feature and its depositional history are consistent with the observation that elevated arsenic concentrations are spatially related in the direction of ice flow on a scale of 150 km.

Glacial drift wells constructed within the northwest provenance late Wisconsin-aged sediment are relatively deep. Age dating of glacial drift well water in west-central Minnesota indicates that most wells have water that is hundreds to thousands of years old (Ekman and Alexander 2002). Rodvang and Simpkins (2001) observe that ground water in aquifers beneath North American Quaternary till is older than the practice of intensive agriculture. The observed well depths and age dating results suggest that the water in the upper Midwest glacial drift wells is reduced. Limited water sampling results from glacial drift public water system wells in Minnesota, conducted in related work by the authors, suggest that the water is, indeed, reduced. These results are illustrated in Figure 6.

The oxidation state of arsenic is sensitive to the redox state of the solution. Processes within an aquifer influence the redox state not only of arsenic but also of iron and sulfur, which influence distributions of arsenic concentration.
Evidence suggests that the distinct physical characteristics of the northwest provenance late Wisconsin-aged drift cause the geochemical conditions necessary to mobilize arsenic. These fine-grained, comparatively organic-rich, biologically active sediments create a geochemical environment that is favorable to a regional-scale mobilization of arsenic in ground water via reductive mobilization mechanisms such as reductive dissolution and reductive desorption. This study highlights an important and often unrecognized phenomenon: high arsenic sediment is not necessary to cause arsenic-impacted ground water—when “impacted” is now defined as >10 μg/L.

Most of the data used in this analysis were collected for other purposes; therefore, the cost of conducting this analysis was relatively low. The results, however, have enormous value and consequences: identification of a regional-scale environmental problem and exposing significant knowledge gaps that inhibit planning, such as the lack of information tying sampling results to a specific well. A significant result of this analysis is demonstration of the value of finding and using existing statewide sampling results to cost-effectively observe and characterize regional-scale environmental problems.

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