

Article

Improved Groundwater Arsenic Contamination Modeling Using 3-D Stratigraphic Mapping, Eastern Wisconsin, USA

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Abstract

Dissolved arsenic in private bedrock drinking water wells is a problem in eastern Wisconsin. Previous studies have identified bedrock sources of arsenic as discrete intervals within the local Paleozoic sedimentary section and have also identified release mechanisms causing arsenic to enter well boreholes. However, widespread contamination modeling is hindered by a lack of 3-D knowledge constraining the depth of the arsenic-bearing units in the subsurface. The growth and improvement of 3-D geologic mapping provides an opportunity to improve predictive models. This study in eastern Wisconsin, USA, uses a multivariate binary logistic regression analysis combined with 3-D geologic mapping to both assess various geologic and well construction factors that impact arsenic occurrence, and improve the ability to predict contamination risk. We find well construction characteristics, the stratigraphic unit within the open interval of a well, and the proximity to fold axes/fault zones are all statistically significant variables that impact the probability of a well exceeding either 2 or 10 $\mu\text{g/L}$ dissolved arsenic. We apply these results by using 3-D mapping to determine the geologic unit present within the open interval of thousands of untested wells and use the logistic regression results to calculate contamination probability. This allows arsenic risk to be rapidly estimated for thousands of individual groundwater wells, and models of potential casing regulations to be assessed.

Keywords: arsenic; 3-D geologic mapping; sulfide cement horizon; Wisconsin; logistic regression; groundwater contamination



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1. Introduction

Geologic units on 2-D geologic maps have long been used as variables in statistical models that increase or decrease arsenic contamination risk in bedrock groundwater wells [1–3]. This is due to the natural variation in abundance of arsenic in different geologic units, and variation in the mineral phases hosting the arsenic. However, many continental interiors contain thin (<10–80 m), nearly horizontal stratigraphic units, and groundwater wells are commonly open to a different stratigraphic unit than is present on the map surface. Thus, direct correlation of groundwater quality with a geologic unit on a map is not always possible. The growth and acceleration of the field of 3-D geologic mapping [4,5] provides new opportunities to rapidly determine the depth of geologic units in the subsurface, and determine what units are present within the open interval of bedrock groundwater wells. In continental interior settings where thin stratigraphic units are common, predictions about arsenic contamination risk for new or existing but untested groundwater wells require a comparison between the subsurface geology and the open interval of the wells.

Eastern Wisconsin, USA is an area that contains high levels of arsenic in bedrock groundwater wells and contains relatively flat, thin (<10–80 m) sedimentary units. In a previous study of groundwater wells in parts of Brown, Outagamie, and Winnebago counties in eastern Wisconsin (location given on Figure 1), around 4% of wells contained arsenic values greater than 50 µg/L [6], which is five times the current Environmental Protection Agency Maximum Contaminant Level (MCL) for safe drinking water in the United States. Parts of Outagamie and Winnebago counties were later classified as an arsenic advisory area by the Wisconsin Department of Natural Resources (WDNR), and new wells are required to have special construction characteristics to reduce risk.

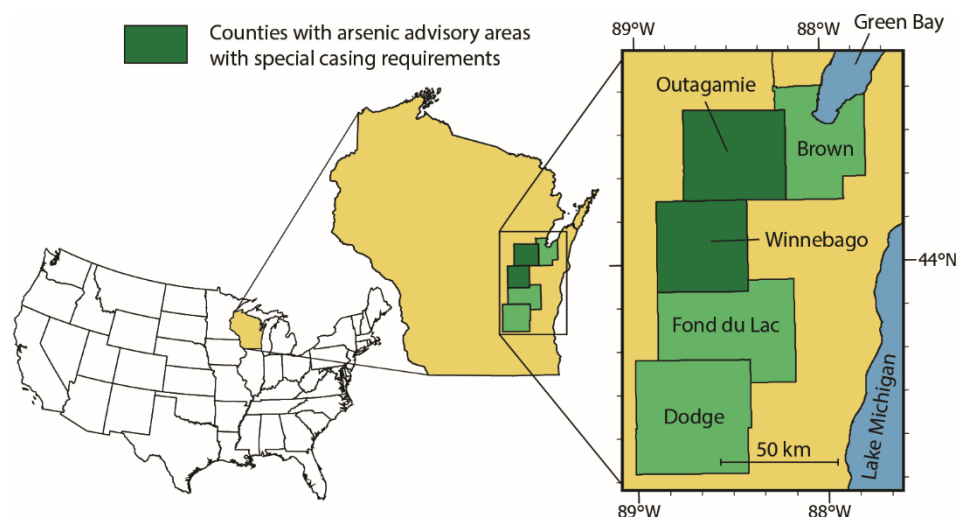


Figure 1. Location map for study area (Fond du Lac and Dodge counties, Wisconsin, USA). Counties that contain special casing requirements are highlighted in dark green.

This paper compiles historic groundwater arsenic analyses from wells in Dodge and Fond du Lac counties, immediately south of the arsenic advisory area (Figure 1). We use a stepwise multivariate binary logistic regression to quantitatively assess the contribution of different variables. We show how the results of the regression combined with 3-D geologic mapping can be used to predict the contamination risk for new wells drilled in the study area, and we model the effects of hypothetical casing regulations on arsenic detection for existing wells. This study shows the importance of combining traditional detailed arsenic release characterization and the growing field of 3-D geologic mapping. It shows that when both are integrated into statistical models, practical and useful predictions of risk can rapidly be made for new groundwater wells and for thousands of existing but untested wells. These results provide baseline information needed for future groundwater management and regulation, and provide a pathway for individuals to assess risk for their own private wells.

2. Regional Setting

2.1. Geologic and Hydrogeologic Setting

Bedrock units in Dodge and Fond du Lac counties include Silurian carbonates and Cambrian and Ordovician sandstones, shales, and dolostones that unconformably overlie Precambrian igneous and meta-sedimentary rocks (Figure 2). Individual formations and groups vary in thickness from less than 3 m to more than 80 m. Quaternary till and lacustrine sediment overlie bedrock units across most of the area, with thicknesses generally varying from 5 to 100 m (Figure 2). Quaternary units are known to be sources of elevated dissolved arsenic in groundwater wells in parts of Wisconsin [7] and across the

Midwest [8,9], but relatively few groundwater wells utilize this as a water source in Dodge and Fond du Lac counties.

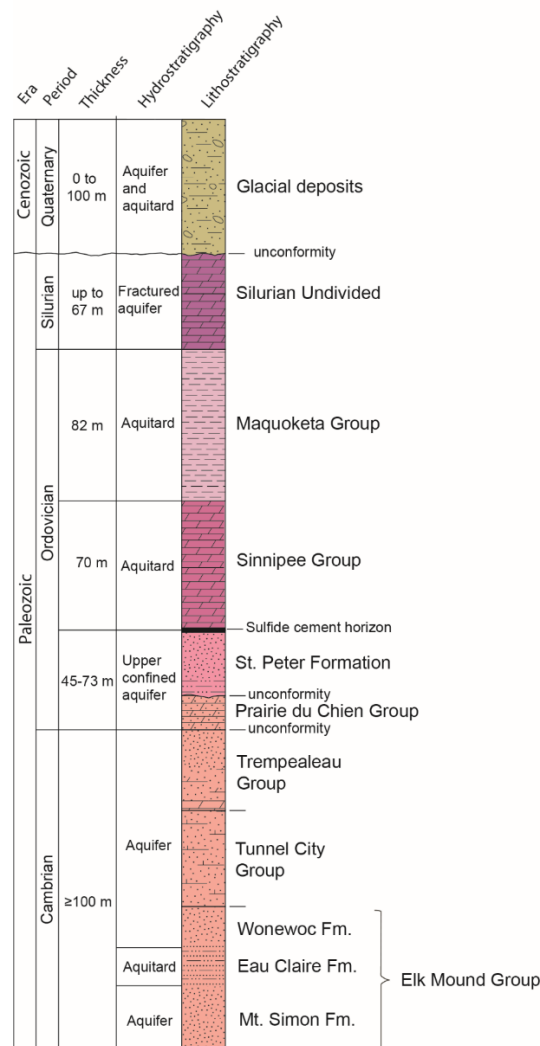


Figure 2. Stratigraphic and hydrostratigraphic column for eastern Wisconsin.

Dodge and Fond du Lac counties lie along the western edge of the Michigan Basin, a regionally significant Paleozoic basin which imparts a gentle east dip on the Paleozoic sequence of approximately 3.5 m per km. Small gentle folds with amplitudes of 15 to 60 m are superposed onto the regional eastward dip [10]. Some of these small folds are cored at depth by faults, but limited spatial resolution from subsurface well data precludes certainty in many cases.

Bedrock geologic units can be divided into several aquifer and aquitard hydrostratigraphic units (Figure 2). Silurian dolostones at the top of the stratigraphic sequence act as a fractured carbonate aquifer [11]. The Late Ordovician Maquoketa Group acts as a regional aquitard [12,13]. The Maquoketa Group overlies the Sinnipee Group, a collection of dolostones and minor shales which are generally treated as an aquitard but can act as an aquifer when fractured. Beneath the Sinnipee Group are the St. Peter Formation sandstone and the Prairie du Chien Group dolomite, which together represent the upper confined Cambro-Ordovician aquifer. Below are Cambrian sandstones and carbonates which comprise the lower Cambro-Ordovician confined aquifer. In the eastern portion of the two counties, private wells are generally cased through the Quaternary sediment and are open to Silurian carbonates. In the west, wells are generally cased through the Quater-

nary sediment and are open to the Sinnipee Group and St. Peter sandstone. Few wells are open to the Maquoketa Group. Municipal wells are generally much deeper and are cased through the Ordovician section and are open to the Cambrian lower confined aquifer.

2.2. Arsenic Release Mechanisms and Geologic Sources of Arsenic in Eastern Wisconsin

Arsenic sources and release mechanisms have been well studied in Wisconsin and across the upper Midwest of the USA [7,8,14–16]. The cause of high levels of arsenic in eastern Wisconsin bedrock groundwater wells ($>100\text{ }\mu\text{g/L}$) is thought to result from the oxidation of sulfide minerals in bedrock aquifers. High arsenic was found when well casing in groundwater wells ended at or above the static water level in the well, and the static water level was close to the contact between the St. Peter Formation and the overlying Sinnipee Group dolomites (Figure 2) [14,15]. This contact is characterized by a <2 to 30 cm thick arsenic-bearing iron sulfide horizon known as the sulfide cement horizon (SCH; Figure 2) [14,17]. The SCH oxidizes and breaks down as a result of exposure to oxygen within the well borehole, releasing arsenic from sulfides.

In addition to sulfide oxidation, the reduction of iron (hydr)oxides is thought to be an important cause of low to moderate arsenic contamination in eastern Wisconsin groundwater wells [16]. Iron (hydr)oxides strongly adsorb aqueous arsenic to their surface and can release arsenic under reducing conditions when the iron (hydr)oxides break down. Locally reducing conditions occur within the well borehole due to biogeochemical processes related to the presence of iron- and/or sulfate-reducing bacteria.

Small bedrock folds and faults (~ 15 – 100 m structural offset) may also increase the risk of arsenic in groundwater wells, though the mechanisms are complex and inadequately understood. In northwestern Dodge County, a correlation exists between detectable levels of arsenic in groundwater wells and proximity to the Beaver Dam anticline [18]. Increased mineralization due to higher fracture density and focused fluid flow was believed to have led to systematic changes in the amount of arsenic-bearing mineral hosts, causing more arsenic detections in well water. Recent geologic map-related studies in southwest Wisconsin have added details to this model, finding that arsenic-rich sulfide mineralization can be absent along the main portions of folds and faults, but can be focused adjacent to St. Peter Formation paleovalleys [19] or relay/transfer zones [20]. Relay and transfer zones are areas where displacement is transferred from one fault segment to another (Figure 3). These areas may act as local conduits with elevated hydraulic conductivity [20,21], acting to localize fluid flow and mineralization as flow is diverted from faults with low horizontal hydraulic conductivity (Figure 3) [22].

To reduce risk in the arsenic advisory area, the Wisconsin Department of Natural Resources (WDNR) introduced casing regulations for new groundwater wells. Well casing is a solid pipe that helps support the upper portion of the well and prevents the well from drawing water from potentially contaminated portions of an aquifer. Casing extends from the surface down to the open portion of the well, where water can enter the well borehole. New groundwater wells in the arsenic advisory areas with special casing requirements must have casing that extends through the problematic St. Peter sandstone and the underlying Prairie du Chien Group (Figure 2), allowing the well to draw water from the less contaminated underlying Cambrian section.

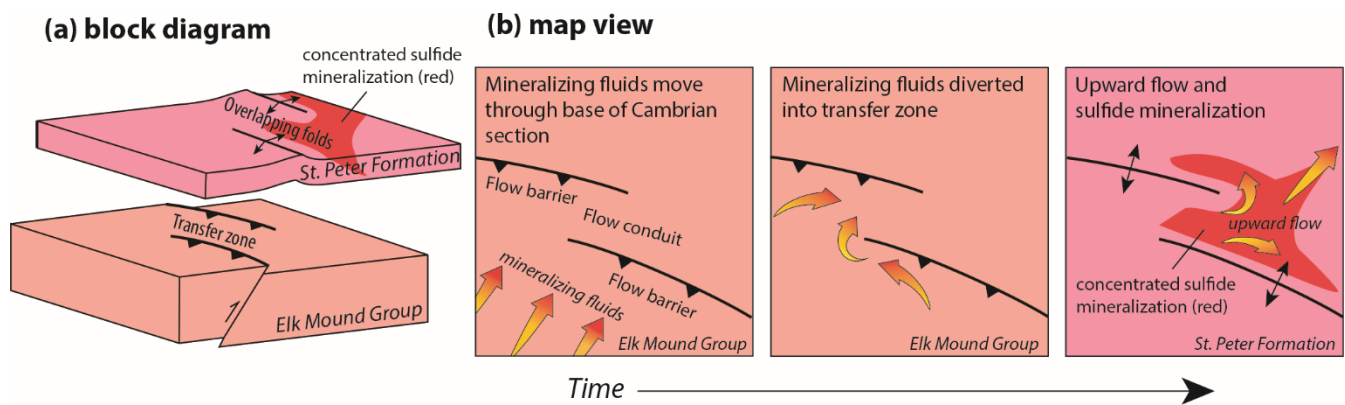


Figure 3. Conceptual model showing one example of how small faults and folds can locally increase arsenic-bearing sulfide mineralization. **(a)** Block diagram showing two thrust faults at depth, and two fault-propagation anticlines overlying the faults. Transfer zones form between thrust faults when slip is transferred from one fault segment to another. **(b)** Map view depicting mineralizing fluids being diverted by low horizontal hydraulic conductivity fault zones into higher hydraulic conductivity transfer zones. Upward flow of mineralizing fluids leads to concentrated arsenic-bearing sulfide mineralization adjacent to the overlying anticlines.

3. Materials and Methods

3.1. Construction of 3-D Geologic Surfaces

Rasters (surfaces) of the base of the Sinnipee Group and base of the St. Peter Formation were compiled and constructed in ArcGIS ArcMap (version 10.8) to determine where folds and faults are located, and to help model risk in untested wells. These rasters contain elevation values for each raster cell and so represent 3-D surfaces of the unit contacts. They can be used to help model risk because the surfaces provide an estimate of the elevation of lithologic contacts across the study area and can be compared to the elevation of the open interval of thousands of untested wells to rapidly predict which geologic units provide water to the well.

Rasters were compiled and constructed in a variety of ways. The base of the Sinnipee Group for Dodge County is from the bedrock geologic map of Dodge County [10]. Rasters for the base of the Sinnipee Group in Fond du Lac County, and the base of the St. Peter Formation for both counties are new, but previous geologic maps provided the input data. Base St. Peter Formation contact lines from [10] and base St. Peter and Sinnipee contact lines from [23] were converted into points in ArcGIS. The elevation of the bedrock surface (land surface minus depth to bedrock) at each point, derived from mapping by [24] and [23], was used as the elevation of the contact. Formation picks from well construction reports used by [10,23] were also included. Preliminary rasters were constructed using the TopoToRaster tool in ArcGIS. Drainage enforcement in TopoToRaster was not used, allowing the interpolation algorithm to keep surface irregularities and complex geometries typical of geologic contacts. Contours derived from the preliminary rasters were hand edited to produce a geologically plausible map interpretation. The final rasters were constructed using the edited contours in the TopoToRaster tool, also without drainage enforcement. A 100 m cell size was used for the base Sinnipee Group surface, and a 50 m cell size was used for the base St. Peter surface. Folds were assumed to contain vertical axial planes. Axial plane dip direction was difficult to determine due to a decrease in the number of deep contacts recorded in well construction reports and geologic logs.

3.2. Well Data

Well data were compiled to test for potential variables that might influence the probability of detecting arsenic, such as the open (uncased) geologic units in the well, well construction parameters (casing depth minus static water level in well, casing depth minus depth to bedrock), and the distance to fold axes and faults. A total of 526 arsenic analyses from 526 unique groundwater wells in Fond du Lac and Dodge counties were compiled from two sources: the Wisconsin Department of Natural Resources (WDNR) online well quality database [25]; and pump works tests conducted by the WDNR [26] (Table S1). Samples were tested between the 1980s and 2021. Arsenic analyses in the pump works data set are required by Wisconsin code when a property sale occurs and during certain well inspection work. Lithologic logs, well casing depth, and depth to bedrock were compiled from well construction reports for each analysis that could be tied to a well construction report. When wells were tested more than once, only the highest concentration was used (worst-case scenario). Of the 526 analyses compiled, 515 had concentrations of less than 100 µg/L.

Most analyses from the pump works subset of the data included a street address but not a well construction report unique identifier. To recover a well construction report for these analyses, the given addresses were compared to parcel addresses across each county in the Wisconsin Geological and Natural History Survey's well construction database [27]. Where matches occurred, the respective well construction report was used. Out of 1994 analyses in the pump works data set, this yielded 120 analyses with a matched well construction report. The percentage was low in part because many properties contain more than one well (such as a barn and residential well), and in those cases it was generally not possible to determine which well was tested. Pump works results over 100 µg/L were a minority of total analyses (~2%), and due to their elevated values were treated separately. Each of these analyses was located manually, and where possible was tied to a well construction report. A total of 32 results >100 µg/L were successfully located, either through the initial query or through manual location, and 13 results were tied to well construction information. To avoid biasing the results, all results over 100 µg/L that were manually located were not used in the logistic regression analysis but were considered separately.

3.3. Binary Logistic Regression

A stepwise binary logistic regression was run in the study area to test for potential explanatory variables in arsenic detection rate. Logistic regressions are a common tool used to predict arsenic contamination in groundwater settings, e.g., [1,3,28–30]. 70% of the input data was used as a training data set, and 30% was used as a testing data set. An amount of 30% of the total was needed in the testing data set to provide enough analyses for goodness-of-fit tests. The final model was constructed using both the training and testing data sets. For both the training and final models, individual variables were screened for statistical significance (univariate case), and significant variables were combined into a multivariate model. Individual variables were then tested for significance against the multivariate model.

A binary logistic regression calculates best-fit coefficients that can be used to calculate the probability of an event or outcome occurring based on the relation [31]:

$$p = \frac{e^{(b_0 + b_1x_1 + b_2x_2 + \dots)}}{1 + e^{(b_0 + b_1x_1 + b_2x_2 + \dots)}} \quad (1)$$

where p is the probability of the event or outcome occurring, x_i are independent explanatory variables, and b_i are the calculated coefficients.

Explanatory variables (x_i) tested are listed in Table 1 and were chosen based on recognized arsenic release mechanisms [14–16] on geologic units in the area, and to test the role of folding and faulting [18]. Arsenic release mechanisms in well water in eastern Wisconsin are related to well construction parameters. The difference between the casing depth and the static water level depth in a well was used to determine whether wells with bedrock exposed to borehole air tend to increase the probability of detecting arsenic. This is believed to be responsible for very high levels of arsenic ($>100 \mu\text{g/L}$) in wells in Outagamie and Winnebago counties (for location, see Figure 1) [14]. To avoid collinearity with other variables, such as the importance of deeper stratigraphic units, the difference was limited to wells with static water levels within 100 feet of the casing depth. Larger differences were excluded. The difference between casing depth in the well and the depth to bedrock was another variable tested that considered weathering and oxidation of the bedrock surface. Prior to the deposition of Pleistocene glacial till, the current bedrock surface was probably close to land surface. Arsenic in weathered bedrock is predominantly hosted in iron (hydr)oxides, which may change the probability of arsenic being released into borehole water. To test the significance of geologic units a well draws water from, categorical (yes/no) coding of each well was used. In this case, we used $x_i = 0$ when the well is not open to a particular unit, and $x_i = 1$ when the well is open to the unit. To determine the unit, the lithologic log on each well construction report was assessed individually and compared to existing geologic maps [10,23]. The SCH was not tested separately due to the concern about collinearity with the stratigraphic units above and below. All wells open to the SCH are also open to the units above and below, making it difficult to separate out its impact. Finally, the influence of folds and faults were assessed by considering the distance between each well analysis and the axis of the nearest mapped fold. Each distance was calculated using the NEAR tool in ArcGIS. If the axial plane on a fold is inclined, error could be introduced in the calculated distance for deeper stratigraphic units.

Table 1. Variables tested in univariate logistic regression.

Variable Tested	Variable Type
Distance to nearest fold axis	Continuous
Well open to the Sinnipee Group	Categorical
Well open to St. Peter Formation	Categorical
Well open to units below St. Peter	Categorical
Casing depth minus depth to bedrock	Continuous
Casing depth minus depth to static water level	Continuous

Coefficients for possible explanatory variables were computed in Microsoft Excel 2016 using the Solver add-in. Best fits for the coefficients were calculated by maximizing the sum of the log likelihood function (LL) for all the input well data:

$$LL_{max} = \sum y_i * \ln \frac{e^{(b_0 + b_1 x_1 + b_2 x_2 + \dots)}}{1 + e^{(b_0 + b_1 x_1 + b_2 x_2 + \dots)}} + (1 - y_i) * \ln \left(1 - \frac{e^{(b_0 + b_1 x_1 + b_2 x_2 + \dots)}}{1 + e^{(b_0 + b_1 x_1 + b_2 x_2 + \dots)}} \right) \quad (2)$$

where y_i reflects the 0 or 1 (yes/no) arsenic cutoff exceedance result for each input well analysis. Two separate logistic regressions were run using cutoff values of 2 and $10 \mu\text{g/L}$. A 0 (no) result is defined as a dissolved arsenic analysis that yielded $<2 \mu\text{g/L}$ for the $2 \mu\text{g/L}$ cutoff case and $<10 \mu\text{g/L}$ for the $10 \mu\text{g/L}$ cutoff case. A 1 (yes) result is defined as an arsenic analysis that met or exceeded the cutoff value for each respective case. The 95% confidence intervals for the final model coefficients were calculated using a nonparametric bootstrap analysis ($n = 1000$). A bootstrap analysis assumes the input data are representative of the whole and uses random selection of the input data with replacement to assess the range of

possible results. If the sign on the calculated best-fit variable coefficient changes within 95% confidence, then there is no confidence that the variable is responsible for the final result. Each run in the bootstrap analysis was solved using Equation (2) as described above.

The p values were calculated for both the univariate and multivariate cases to assess the statistical significance of each variable coefficient (b_i). Values below 0.05 were considered statistically significant. To calculate p values, a likelihood ratio was calculated by comparing the full model (LL_{max} , Equation (2) above) with a partial model ($LL_{partial}$) that sets the coefficient of interest (b_i) to 0 [31]:

$$Likelihood\ Ratio = 2 * (LL_{max} - LL_{partial}) \quad (3)$$

In both the univariate and multivariate cases, the likelihood ratio follows a Chi-Square distribution with 1 degree of freedom.

3.4. Model Fit and Assessment

One application of the logistic regression analysis is to apply the best fit solution towards modeling risk for untested wells and predicting the impact of hypothetical casing regulation on arsenic detection at 2 µg/L and 10 µg/L. Logistic regressions are simple but powerful tools for predicting outcomes, but only if the best fit solution accurately fits the data. It is possible for a best fit solution to contain statistically significant variables but be a poor predictor of a result. This happens when additional variables are important but were not tested for in the regression. For example, in the case of arsenic detection, it is possible that the pumping rate prior to sampling is important [16], but this is not a variable that is easily determined and so was not considered. The fit of a model can help determine if untested or unknown variables, such as pumping rate, are needed to predict the results.

In logistic regression, goodness-of-fit tests can determine if a model built from a training data set is able to predict results in a test data set and can also test the overall fit of a final combined model (training plus testing). The Hosmer–Lemeshow goodness-of-fit test [31,32] was used to assess goodness-of-fit. The Hosmer–Lemeshow goodness-of-fit test compares predicted positive results to observed positive results. A probability of exceeding the cutoff value was calculated for each analysis at both cutoffs using Equation (1). These were sorted from least to greatest probability and binned into subequal groups of 6 sets for the test data, and 6, 8, and 10 sets for the final combined (training plus testing) model. The predicted number of positive results in each bin, equaling the average probability of each set times the number of analyses in each set, was compared to the actual observed number of positive results in each bin. A test statistic was calculated using the relation [32]:

$$Test\ statistic = \sum_{i=1}^n \frac{(ob_i - ex_i)^2}{ex_i} \quad (4)$$

where n equals the number of bins, ob_i equals the observed number of positive results in each bin, and ex_i equals the predicted number of positive results in each bin. A p value was calculated since the test statistic follows a Chi-Square distribution with $n-2$ degrees of freedom. In this case, a low p value (<0.05) indicates a significant difference between the predicted positive probability and the observed positive probability. If the model yields a good fit and is a useful predictor of a result, the p value should be higher than 0.05. Since the number of geolocated arsenic analyses tied to well construction reports is modest, splitting the data set into a training and testing set was not ideal, particularly for the higher 10 µg/L cutoff. To prevent the expected number of positive results (ex_i) in the testing data set from being less than 1 for the lowest 10 µg/L cutoff probability bin, roughly twice the

number of analyses were included in the lowest probability bin (20) compared to the other bins (9 or 10).

ROC (receiver operating characteristic) curves and confusion matrices are additional tools for assessing logistic regression results. Like goodness-of-fit tests, they also compare predicted values to observed values. ROC curves plot true positive rate (sensitivity) against false positive rate (1-specificity) across a range of cutpoints or threshold probability values. Sensitivity and specificity were calculated on the testing data set at 0.025 percent cutpoint intervals from 0 to 1. Confusion matrices were chosen where sensitivity and specificity values were roughly equal.

4. Results

Section 4.1 begins by presenting the results of the 3-D geologic mapping. Next, Section 4.2 examines the relationship between various well construction and geologic variables on arsenic contamination in wells. Section 4.3 quantifies the impact of these variables by presenting the results of the multivariate logistic regression. Later in the Discussion section, the 3-D geologic map surfaces are used to interpret the subsurface geology within the open interval of hypothetical and existing but untested groundwater wells in the study area. The results of the logistic regression are then applied to these scenarios, and the impact of well construction design and casing regulations are modeled.

4.1. Three-Dimensional Geologic Surfaces

Base Sinnipee and St. Peter surfaces dip shallowly east at around 3.5 m/km. Superposed on the east dip are a series of gentle folds, visible on the base Sinnipee surface (Figure 4a). The base St. Peter surface shows a much more complicated topography (Figure 4b), consistent with it occurring at an important erosional unconformity, as has been recognized elsewhere [33].

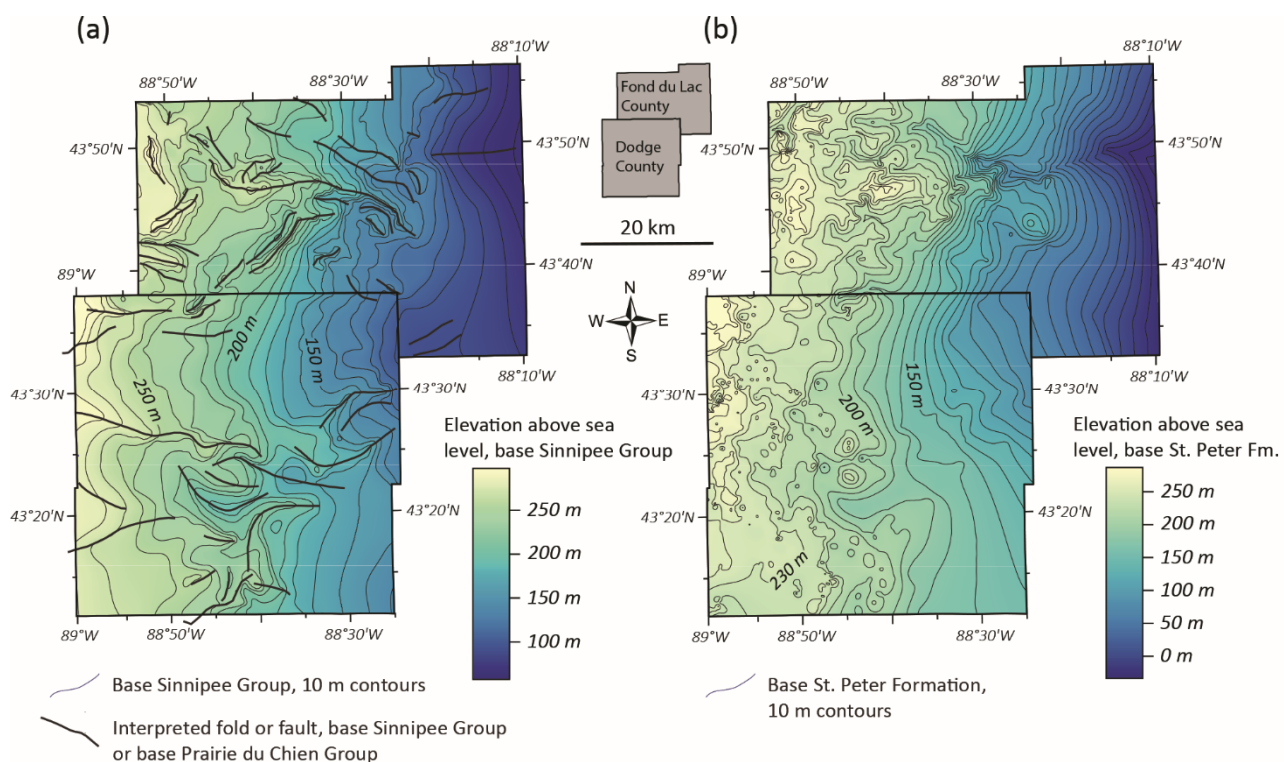


Figure 4. (a) Contoured base Sinnipee Group surface. Some folds in the far west were based on evidence for folding in stratigraphically lower units. (b) Contoured base St. Peter Formation surface. In both maps, the surfaces get smoother to the east due to a reduction in data density.

4.2. Well Data

Overall, 12.7% of geolocated Wisconsin Department of Natural Resources tests (67 of 526) exceeded the current EPA MCL of 10 $\mu\text{g/L}$ in Fond du Lac and Dodge counties (Figure 5). The percentage of wells over 10 $\mu\text{g/L}$ varied across the study area, with much higher percentages in the western and central portions where the St. Peter Formation and Sinnipee Group are near land surface (Figure 5).

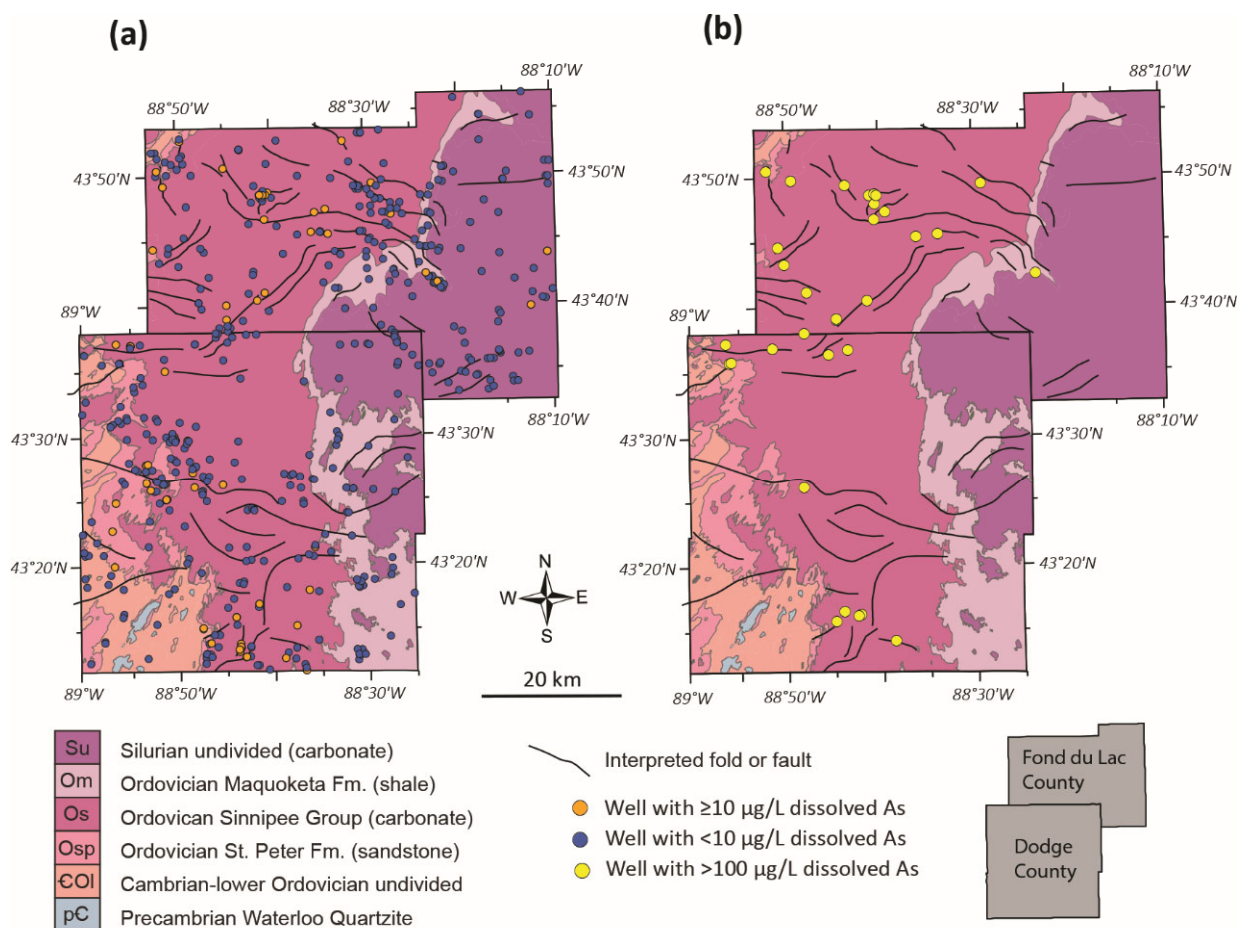


Figure 5. Geologic map of Fond du Lac and Dodge counties [10,23] showing distribution of wells with (a) ≥ 10 and $< 10 \mu\text{g/L}$, and (b) $> 100 \mu\text{g/L}$ dissolved arsenic. Wells with $> 100 \mu\text{g/L}$ were manually located from the pump works data set.

4.2.1. High Arsenic Values ($> 100 \mu\text{g/L}$)

A total of 32 arsenic analyses with results in excess of 10 times the EPA MCL ($> 100 \mu\text{g/L}$) were located in Dodge and Fond du Lac counties. Most of these high values fall in the western portions of those counties (Figure 5b).

For the 13 wells in Dodge and Fond du Lac counties with well construction reports and high arsenic values, most (9 of 13) have casing ending above the static water level or within 3 m below the static water level (gray transparent box, Figure 6a). In Figure 6b, the solid diagonal line reflects values where the SCH is equal to the static water level in the well. Values below and to the right of the solid diagonal line occur when the SCH is below the static water level in the well. The dashed diagonal lines illustrate where the SCH is 10 and 20 m below the static water level in the well. Most points (10 of 13) show the SCH is at least 10 m deeper than the static water level in the well. This indicates oxidation of the SCH from borehole air is unlikely to be the cause of high dissolved arsenic concentrations

in most, but not all, of the wells shown in Figure 6b. High arsenic values are clustered near mapped folds or faults (Figure 5b).

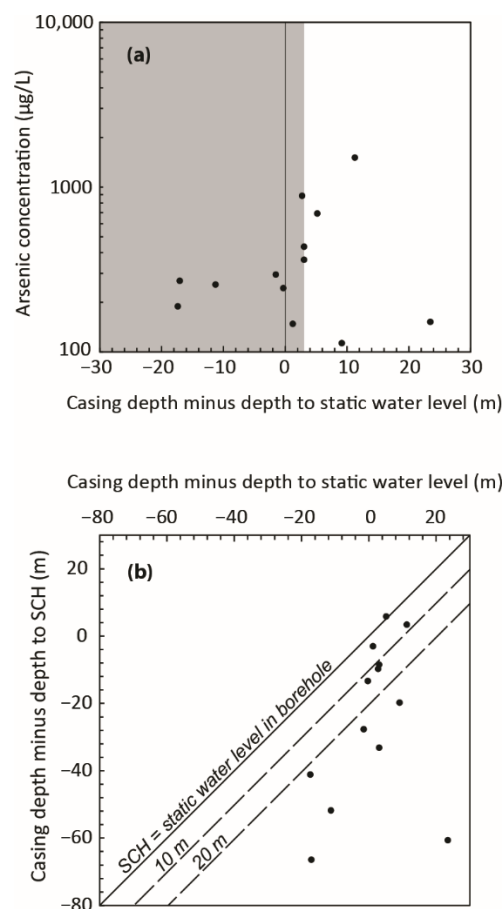


Figure 6. Well construction characteristics for wells with arsenic values exceeding 100 µg/L. (a) Arsenic concentration versus the difference between casing depth and static water level depth in meters. Values to the left of the vertical line indicate rock in the borehole is exposed to air. Values to the right of the line indicate the casing extends below the static water level in the well. The gray shaded box contains 9 of the 13 analyses with casing ending above the static water level or within 3 m below the static water level. Pumping may cause the water level to drop, exposing rock to borehole air when the casing is only marginally deeper than the static water level. (b) Plot of casing depth minus depth to the sulfide cement horizon (SCH) versus casing depth minus depth to static water level. The solid line shows where the SCH equals the static water level, and the dashed lines show where the SCH is 10 m and 20 m below the static water level.

4.2.2. Low to Moderate Arsenic Values (0 to 100 µg/L)

Low to moderate arsenic concentrations show weak relationships with well construction characteristics. Higher values tend to occur when the casing ends near or above the static water level (Figure 7a). Additionally, when the casing ends near the bedrock surface, values tend to be slightly higher (Figure 7b).

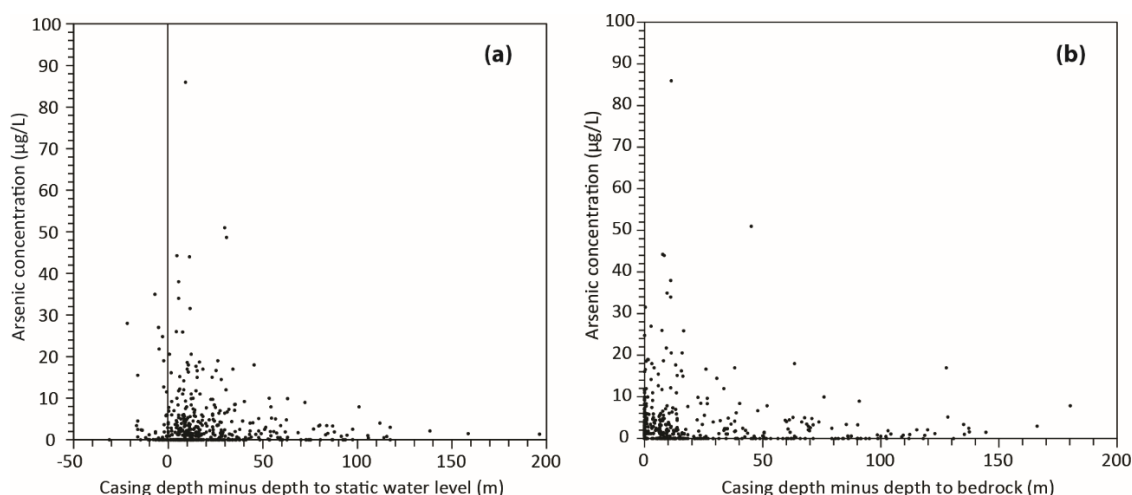


Figure 7. Well construction characteristics for wells with arsenic values between 0 and 100 µg/L. (a) Arsenic concentration plotted against the difference between casing depth and depth to the static water level ($n = 463$). (b) Arsenic concentration plotted against the difference between casing depth and depth to the bedrock surface ($n = 484$).

4.2.3. Role of Geologic Units in Arsenic Detection

Groundwater from wells open to different geologic units exhibit arsenic detection at different rates. Figure 8 shows the percentage of wells with arsenic greater than 2 and 10 µg/L for different geologic units. Many wells are open to more than one unit. Wells open to the Silurian section and the Maquoketa Group were least likely to have arsenic, while wells open to the St. Peter Formation were most likely to experience elevated arsenic. Wells open to units below the St. Peter Formation rarely have values above 10 µg/L. Additionally, wells from the western portions of the counties, where the St. Peter Formation and Sinnipee Group are near land surface, show higher rates of arsenic detection than the bulk average for the counties.

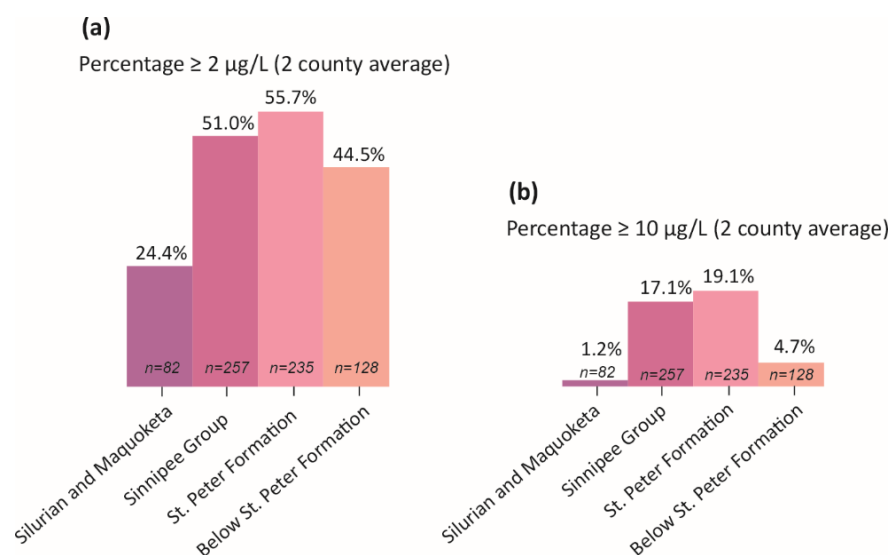


Figure 8. Percentage of wells across the entire two-county area with (a) more than 2 and (b) more than 10 µg/L dissolved arsenic open to different geologic units. Many wells are open to more than one unit.

4.3. Logistic Regression Results

Based on the well data results, a multivariate logistic regression was run for western and central Fond du Lac and Dodge counties. Figure 9 shows the area included in the regression analysis. Well data results showed that areas with wells open to the Maquoketa Group and Silurian strata were much less likely to contain arsenic compared to other units (Figures 5 and 8). Because the geologic section dips gently eastward into the Michigan Basin, the stratigraphically higher units tend to occur at the bedrock surface in the eastern portions of the county. The regression analysis focused on the western, higher-risk portion of the counties.

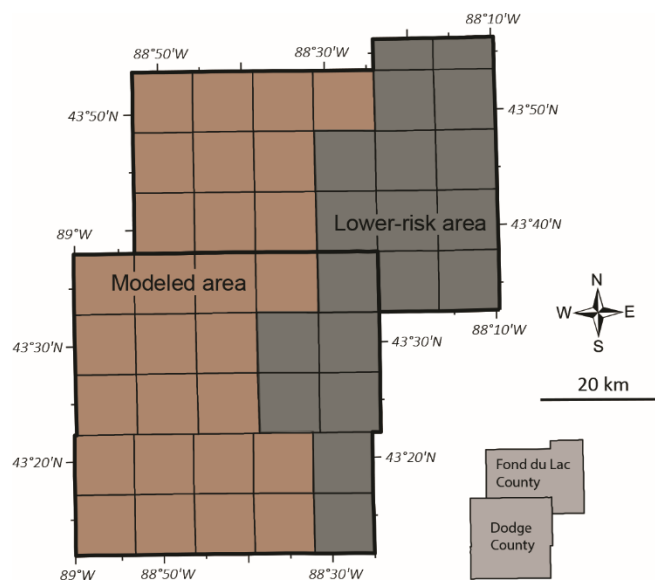


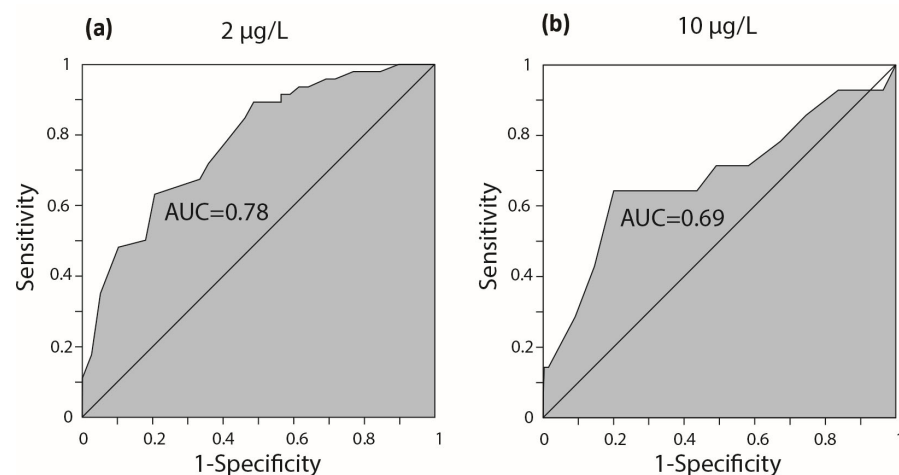
Figure 9. Area modeled using logistic regression (brown shaded region, left). Lower-risk parts of the study area (gray shaded region) were not included in the regression analysis. Squares on the map are local townships, part of the public land survey system used in the United States.

Regression results varied depending on cutoff value (Table 2). For a 2 µg/L cutoff, wells near fold axes were more likely to detect arsenic, wells open to the St. Peter Formation were more likely to detect arsenic, and wells with casing that ends near the bedrock surface were more likely to detect arsenic. At a 10 µg/L cutoff, wells near fold axes were also more likely to detect arsenic; however, other variables changed. Wells open to units below the St. Peter yielded a statistically significant reduction in the probability of detecting arsenic, and wells that were not cased far below the static water level yielded higher probabilities of arsenic detection. Goodness-of-fit *p*-values calculated for the testing data set based on comparison of predicted versus observed yielded values of 0.78 for the 2 µg/L cutoff and 0.24 for the 10 µg/L cutoff. The final combined model (training plus testing) had model fits that all exceeded 0.52 for all bin ranges. ROC curves and confusion matrices for 2 and 10 µg/L cutoffs are given on Figure 10 and Table 3. Both models contain an area under the curve (AUC) exceeding 0.5. The goodness-of-fit testing and ROC curves indicate that while both models have some predictive ability, the 2 µg/L model did a better job of predicting results in the testing data set.

Table 2. Final multivariate logistic regression model ¹.

Variable	Variable Type	2 µg/L Cutoff (<i>n</i> = 283)		10 µg/L Cutoff (<i>n</i> = 228)	
		Variable (<i>b_i</i>) Coefficient (Multivariate)	Odds Ratio	Variable (<i>b_i</i>) Coefficient (Multivariate)	Odds Ratio
Intercept	N/A	0.8398 (0.3556, 1.4274)	N/A	−0.3126 (−0.8671, 0.3436)	N/A
Distance to nearest fold axis ²	Continuous	−0.3454 (−0.5215, −0.2254)	0.7079 (0.5936, 0.7982)	−0.2689 (−0.5821, −0.0900)	0.7642 (0.5587, 0.9139)
Well open to St. Peter Formation	Categorical	0.6532 (0.1197, 1.2225)	1.9216 (1.1271, 3.3956)	N/A	N/A
Well open to units below St. Peter	Categorical	N/A	N/A	−1.0684 (−2.9185, −0.1396)	0.3436 (0.0540, 0.8697)
Casing depth minus depth to bedrock ³	Continuous	−0.0184 (−0.0302, −0.0085)	0.9818 (0.9703, 0.9915)	N/A	N/A
Casing depth minus depth to static water level ³	Continuous	N/A	N/A	−0.0409 (−0.0804, −0.0026)	0.9599 (0.9227, 0.9974)

Notes: ¹ 95% confidence intervals in parentheses; ² calculated using units of km; ³ calculated using units of m.

**Figure 10.** ROC curves. An area under the curve (AUC) of 0.5 indicates no predictive ability, while values over 0.9 indicate exceptionally high predictive ability. (a) 2 µg/L. (b) 10 µg/L.**Table 3.** Confusion matrices ¹.

2 µg/L ²	Actual Positive	Actual Negative	10 µg/L ³	Actual Positive	Actual Negative
Predicted Positive	31	13	Predicted Positive	9	18
Predicted negative	15	26	Predicted negative	5	37

Notes: ¹ Calculated on testing data set; ² calculated at a cutpoint of 57.5%; ³ calculated at a cutpoint of 20%.

5. Discussion

In this section, we begin by comparing the logistic regression results with previous arsenic research in eastern Wisconsin. We use this to interpret the main drivers for well contamination in the study area. Next, we provide examples showing the applications of combining 3-D geologic mapping with logistic regression results. We show how variations in well construction design can be used to quantitatively assess the impact of deeper (but more expensive) wells. We also apply the best-fit solution of the logistic regression analysis to existing groundwater wells with known location and well construction parameters. This

allows us to rapidly predict contamination risk for thousands of individual wells, which would not be possible without the 3-D geologic mapping. Finally, we model potential casing requirements on existing wells and calculate the reduction in contamination risk.

5.1. Causes of Arsenic in Groundwater in Fond Du Lac and Dodge Counties

We interpret the regression results to support previous studies on arsenic release in eastern Wisconsin, though with some important differences. In eastern Wisconsin, reduction of iron (hydr)oxides was found to be an important source of low to moderate concentrations of arsenic [16]. Our results indicate wells with casing that ends near the bedrock surface have a higher probability of detecting arsenic above 2 µg/L. A pre-Pleistocene oxidation front below the current bedrock surface is probably the cause. Prior to Pleistocene glaciation, the current bedrock surface was close to land surface, and an oxidation front likely developed in the bedrock [18]. Today, the oxidation front is buried by till and Quaternary sediment that can reach over 100 m. Modern groundwater wells that have casing that ends near the current bedrock surface are open to rocks that were oxidized prior to glaciation and have the potential to release arsenic via the reduction of iron (hydr)oxides.

Regression results and Figure 6a are also consistent with sulfide oxidation becoming more important at higher concentrations [14]. Wells with casing that ends above the static water level or near the static water level had an increased chance of detecting more than 10 µg/L arsenic (Table 2). This presumably reflects the increasingly importance of sulfide oxidation. However, unlike previous studies from the arsenic advisory area to the north (see Figure 1 for location) [14], oxidation of the SCH might not be driving the highest levels of dissolved arsenic. The dashed diagonal lines in Figure 6b show that most wells with >100 µg/L dissolved arsenic (10 of 13) have a static water level that is at least 10 m higher than the SCH in the well. While oxidation of sulfides is the likely release mechanism (Figure 6a), the source of the sulfides in most cases appears to be within the lower portions of the Sinnipee Group rather than the SCH.

Finally, folds and faults were also found to increase the probability of arsenic contamination, consistent with previous findings [18]. This presumably reflects the increase in abundance of arsenic-bearing mineral phases in portions of the folds due to concentrated fluid flow during sulfide mineralization.

5.2. Applications

5.2.1. Construction of new groundwater wells

Deeper groundwater wells in the study area have a lower probability of containing arsenic, but they are also more expensive to construct. Deciding how deep to drill and how deep to case bedrock groundwater wells is rarely clear, even if homeowners are aware of the benefits of deeper wells. Our regression results combined with the 3-D mapping provides a quantitative method of assessing the cost versus benefit of different well construction designs. The approach also requires water table and depth-to-bedrock maps for an area and assumes the static water level in a well can be reasonably approximated by water table maps. The approach is promising because it is fast, easy, and applicable at the individual well scale, and provides probability predictions readily digestible by non-specialists.

Figure 11 shows the location of a hypothetical planned groundwater well in Dodge County. Information needed to estimate the probability of arsenic contamination is easily acquired. The well has a surface elevation of 278 m. The bedrock surface, calculated by subtracting land surface from depth to bedrock [24], is estimated to be 263 m. The water level in the well is assumed to be 268 m and was estimated from water table mapping [34]. The elevation of the base Sinnipee Group (261 m) and base St. Peter Formation (237 m) were derived from the surface rasters (Figure 4), and were calculated using the Add Surface

Information tool in ArcGIS Pro (version 3.4.2). The distance to the nearest fold/fault was calculated at 4.7 km in ArcGIS Pro (version 3.4.2) using the NEAR tool. Table 4 illustrates how increasing the casing from 15 m to 45 m reduces the probability of the well exceeding 2 and 10 $\mu\text{g/L}$ of arsenic. The reduction in probability for the deeper casing scenario occurs due to the increasing distance between the base of the casing and the bedrock surface/static water level, and because the deeper well becomes open to units below the St. Peter Formation. These values are easily calculated and could be made available across the modeled area. Landowners could then make informed decisions that weigh contamination risk versus well construction bids and prices.

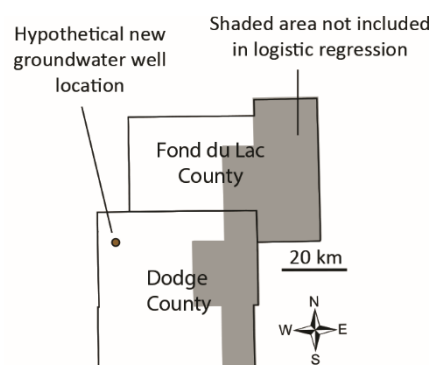


Figure 11. Map showing the location of a hypothetical planned groundwater well in Dodge County.

Table 4. Impact of well construction design on probability of arsenic exceedance.

	15 m Casing, 40 m Deep Well		45 m Casing, 80 m Deep Well	
	2 $\mu\text{g/L}$ Cutoff	10 $\mu\text{g/L}$ Cutoff	2 $\mu\text{g/L}$ Cutoff	10 $\mu\text{g/L}$ Cutoff
Probability of arsenic exceedance	46.7%	14.4%	20.9%	1.7%

5.2.2. Evaluation of Risk to Existing Groundwater Wells, and Impact of Casing Requirements

Casing regulations in the special arsenic advisory area of eastern Wisconsin (Figure 1) have helped reduce arsenic contamination in new groundwater wells. Within our study area immediately to the south, we first estimate the risk of arsenic contamination in current wells, then estimate the impact of hypothetical casing regulations. The regression solution (Table 2) was applied to all (3251) groundwater wells in the Wisconsin Geological and Natural History Survey database in western Dodge and Fond du Lac counties (modeled area of Figure 9) that contained a known location, a lithologic log, well casing information, and static water level. Our hypothetical casing regulations prohibited wells open to the St. Peter Formation and required at least 15 (case 1) or 30 (case 2) m of casing extending below the static water level. The geologic units within the open interval in each well were determined by comparing the elevation of the base Sinnipee Group (Figure 4a) and base St. Peter Formation (Figure 4b) at each well location to the elevation of the open interval in the well. We used the Add Surface Information tool in ArcGIS ArcMap (version 10.8) to extract the surface elevations of both contacts for each well location. To model the impact of the two cases, all wells open to the St. Peter were assumed to instead be open to units below the St. Peter, and wells with less than 15 or 30 m of casing beneath the static water level were given additional casing to meet the respective minimum amount for each case. Estimates of the reduction in arsenic probability due to casing regulations are considered minimum estimates. Some wells currently open only to the Sinnipee Group would be forced into the St. Peter due to the static water level casing requirement. In such cases,

additional casing (and expense) would be required to extend the well below the St. Peter to meet all hypothetical requirements. This was not included in the model in part due to the uncertainty in the base St. Peter for these wells. Finally, the distance to the nearest fold was determined in ArcGIS ArcMap (version 10.8) using the NEAR tool.

Under current conditions (without hypothetical regulations), an estimated 20.3% of wells are predicted to exceed the EPA limit for arsenic in the western modeled portions of Fond du Lac and Dodge counties (Figure 12; Table 5). Hypothetical regulations that require casing extend through the St. Peter Formation and at least 15 m below the static water level are estimated to reduce the percentage of wells that test positive at $\geq 10 \mu\text{g/L}$ to 7.3% (Figure 12; Table 5). Increasing the casing to 30 m below the static water level further reduces the predicted percentage of positive values to 4.3%. Values $\geq 2 \mu\text{g/L}$ are also predicted to drop if casing regulations were applied to all wells, though some risk remains (Table 5).

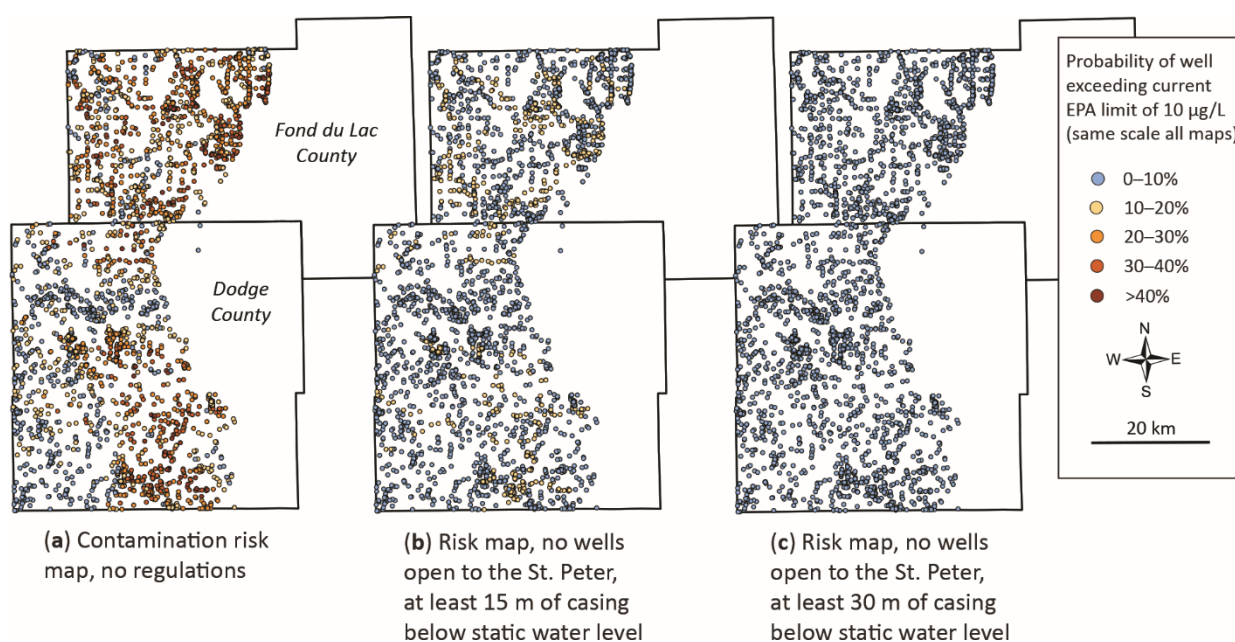


Figure 12. (a) Arsenic contamination risk map for individual but untested groundwater wells in the western portion of the study area (modeled area). (b) Arsenic risk map over the same area showing how casing requirements would lower the probability of wells exceeding the EPA MCL. (c) Arsenic risk map over the same area with deeper casing requirements than (b).

Table 5. Bulk average contamination risk for modeled areas and impact of hypothetical casing requirements.

	Probability $\geq 2 \mu\text{g/L}$	Probability $\geq 10 \mu\text{g/L}$
Current well construction design, no regulations	56.7%	20.3%
Hypothetical casing extends at least 15 m below static water level, well not open to St. Peter Fm.	46.2%	7.3%
Hypothetical casing extends at least 30 m below static water level, well not open to St. Peter Fm.	40.6%	4.3%

6. Conclusions and Future Work

Groundwater wells in continental interior settings with thin stratigraphic units often draw water from deeper geologic units than are present on traditional 2-dimensional geologic maps. This hinders the ability to apply predictive bedrock groundwater contamination models to new or untested groundwater wells. We use a multivariate binary

logistic regression to develop a predictive model of arsenic contamination in parts of eastern Wisconsin, and find that well construction characteristics, the stratigraphic unit within the open interval of a well, and the proximity to fold axes/fault zones are all statistically significant variables that increase or decrease contamination risk. We combine the statistical model with 3-D geologic maps to show arsenic contamination risk can be rapidly assessed for new groundwater wells and existing but untested wells. These results are useful for future groundwater management and potential regulation in eastern Wisconsin.

The field of 3-D geologic mapping in Wisconsin and elsewhere is still in its infancy despite the long-standing recognition of its importance [4]. In the future, the growth of this field along with the growth of machine learning in water quality studies [9,35] provides exciting future pathways to develop increasingly sophisticated arsenic models in the upper Midwest, USA.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w17132024/s1>, Dataset S1: Base Sinnipee raster and base St. Peter Formation raster; Table S1: Supplementary arsenic data.

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Abbreviations

The following abbreviations are used in this manuscript:

SCH	Sulfide cement horizon
WDNR	Wisconsin Department of Natural Resources
EPA MCL	Environmental Protection Agency Maximum Contaminant Level

References

1. Ayotte, J.D.; Nolan, B.T.; Nuckols, J.R.; Cantor, K.P.; Robinson, G.R.; Baris, D.; Hayes, L.; Karagas, M.; Bress, W.; Silverman, D.T.; et al. Modeling the probability of arsenic in groundwater in New England as a tool for exposure assessment. *Environ. Sci. Technol.* **2006**, *40*, 3578–3585. [[CrossRef](#)]
2. Kim, D.; Miranda, M.L.; Tootoo, J.; Bradley, P.; Gelfand, A.E. Spatial modeling for groundwater arsenic levels in North Carolina. *Environ. Sci. Technol.* **2011**, *45*, 4824–4831. [[CrossRef](#)]
3. VanDerwerker, T.; Zhang, L.; Ling, E.; Benham, B.; Schreiber, M. Evaluating geologic sources of arsenic in well water in Virginia (USA). *Int. J. Environ. Res. Public Health* **2018**, *15*, 787. [[CrossRef](#)]
4. Berg, R.C.; Russell, H.A.J.; Thorleifson, L.H. Introduction to a Special Issue on Three-dimensional Geological Mapping for Groundwater Applications. *J. Maps* **2007**, *3*, 211–218. [[CrossRef](#)]
5. Pavlis, T.L.; Mason, K.A. The new world of 3D geologic mapping. *GSA Today* **2017**, *27*, 4–10. [[CrossRef](#)]
6. Burkell, R.S.; Stoll, R.C. Naturally occurring arsenic in sandstone aquifer water supply wells of northeastern Wisconsin. *Groundw. Monit. Remediat.* **1999**, *19*, 114–121. [[CrossRef](#)]

7. Root, T.L.; Gotkowitz, M.B.; Bahr, J.M.; Attig, J.W. Arsenic geochemistry and hydrostratigraphy in Midwestern US glacial deposits. *Groundwater* **2010**, *48*, 903–912. [CrossRef] [PubMed]
8. Erickson, M.L.; Barnes, R.J. Glacial sediment causing regional-scale elevated arsenic in drinking water. *Groundwater* **2005**, *43*, 796–805. [CrossRef]
9. Erickson, M.L.; Elliott, S.M.; Brown, C.J.; Stackelberg, P.E.; Ransom, K.M.; Reddy, J.E.; Cravotta, C.A., III. Machine-learning predictions of high arsenic and high manganese at drinking water depths of the glacial aquifer system, northern continental United States. *Environ. Sci. Technol.* **2021**, *55*, 5791–5805. [CrossRef]
10. Stewart, E.K. *Bedrock Geology of Dodge County*; Map 508, 7, 1 pl., scale 1:100,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 2021. Available online: <https://wgnhs.wisc.edu/pubs/000975> (accessed on 20 June 2025).
11. Muldoon, M.A.; Simo, J.A.; Bradbury, K.R. Correlation of hydraulic conductivity with stratigraphy in a fractured-dolomite aquifer, northeastern Wisconsin, USA. *Hydrogeol. J.* **2001**, *9*, 570–583. [CrossRef]
12. Hart, D.J.; Bradbury, K.R.; Feinstein, D.T. The vertical hydraulic conductivity of an aquitard at two spatial scales. *Groundwater* **2006**, *44*, 201–211. [CrossRef] [PubMed]
13. Eaton, T.T.; Anderson, M.P.; Bradbury, K.R. Fracture control of ground water flow and water chemistry in a rock aquitard. *Groundwater* **2007**, *45*, 601–615. [CrossRef] [PubMed]
14. Schreiber, M.E.; Simo, J.A.; Freiberg, P.G. Stratigraphic and geochemical controls on naturally occurring arsenic in groundwater, eastern Wisconsin, USA. *Hydrogeol. J.* **2000**, *8*, 161–176. [CrossRef]
15. Schreiber, M.E.; Gotkowitz, M.B.; Simo, J.A.; Freiberg, P.G. Mechanisms of arsenic release to ground water from naturally occurring sources, eastern Wisconsin. In *Arsenic in Ground Water: Geochemistry and Occurrence*; Welch, A.H., Stollenwerk, K.G., Eds.; Springer: Boston, MA, USA, 2003; pp. 259–280. [CrossRef]
16. Gotkowitz, M.B.; Schreiber, M.E.; Simo, J.A. Effects of water use on arsenic release to well water in a confined aquifer. *Groundwater* **2004**, *42*, 568–575. [CrossRef]
17. Luczaj, J.A.; McIntire, M.J.; Hunt, J.O. Geochemical characterization of trace MVT mineralization in Paleozoic sedimentary rocks of northeastern Wisconsin, USA. *Geosciences* **2016**, *6*, 29. [CrossRef]
18. Stewart, E.D.; Stewart, E.K.; Bradbury, K.R.; Fitzpatrick, W. Correlating bedrock folds to higher rates of arsenic detection in groundwater, southeast Wisconsin, USA. *Groundwater* **2021**, *59*, 829–838. [CrossRef]
19. Fitzpatrick, W.A.; Stewart, E.D. *Geologic map of the Highland East and West 7.5-minute Quadrangles, Grant and Iowa Counties, Wisconsin*; Map 510, 15, 1 pl., scale 1:24,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 2024. [CrossRef]
20. Stewart, E.D.; Mauel, S.W.; Batten, W.G. *Geologic Map of the Stitzer and Western Part of the Montfort 7.5-minute Quadrangles*; Open-File Report 2023–03, 1 pl., scale 1:24,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 2023. [CrossRef]
21. Stewart, E.D.; Mauel, S.W.; Bremmer, S.E.; Fitzpatrick, W.A. *Bedrock geology of Grant County, Wisconsin*; Bulletin 119, 33 p., 1 pl., scale 1:100,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 2025. [CrossRef]
22. Hadley, D.R.; Abrams, D.B.; Roadcap, G.S. Modeling a large-scale historic aquifer test—Insight into the hydrogeology of a regional fault zone. *Groundwater* **2020**, *58*, 453–463. [CrossRef] [PubMed]
23. Batten, W.G. *Bedrock geology of Fond du Lac County*; Map 505, 2 pl., scale 1:100,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 2018. Available online: <https://wgnhs.wisc.edu/catalog/publication/000963> (accessed on 20 June 2025).
24. Stewart, E.K. *Depth-to-Bedrock Map of Dodge County*; Open-File Report 2021–03, 13 p., 1 pl., scale 1:100,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 2021. Available online: <https://wgnhs.wisc.edu/catalog/publication/000981> (accessed on 20 June 2025).
25. Wisconsin Department of Natural Resources. Search Sample Analytical Data. Available online: <https://dnr.wisconsin.gov/topic/Groundwater/GRN.html> (accessed on 20 May 2020).
26. Wisconsin Department of Natural Resources. Pump Works Data. Available online: https://en.wikipedia.org/wiki/Wisconsin_Department_of_Natural_Resources?ysclid=mcpcynpcv2y334118609 (accessed on 8 March 2021).
27. Wisconsin Geological and Natural History Survey. Well Construction Report Database. Available online: <https://home.wgnhs.wisc.edu/> (accessed on 3 May 2021).
28. Yang, Q.; Jung, H.B.; Marvinney, R.G.; Culbertson, C.W.; Zheng, Y. Can arsenic occurrence rates in bedrock aquifers be predicted? *Environ. Sci. Technol.* **2012**, *46*, 2080–2087. [CrossRef]
29. Andy, C.M.; Fahnestock, M.F.; Lombard, M.A.; Hayes, L.; Bryce, J.G.; Ayotte, J.D. Assessing models of arsenic occurrence in drinking water from bedrock aquifers in New Hampshire. *J. Contemp. Water Res. Educ.* **2017**, *160*, 25–41. [CrossRef]
30. Cao, H.; Xie, X.; Wang, Y.; Pi, K.; Li, J.; Zhan, H.; Liu, P. Predicting the risk of groundwater arsenic contamination in drinking water wells. *J. Hydrol.* **2018**, *560*, 318–325. [CrossRef]
31. Hosmer, D.W.; Lemeshow Sturdivant, R.X. *Applied Logistic Regression*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
32. Hosmer, D.W.; Lemeshow, S. Goodness of fit tests for the multiple logistic regression model. *Commun. Stat.—Theory Methods* **1980**, *9*, 1043–1069. [CrossRef]

33. Mai, H.; Dott, R.H., Jr. *A Subsurface Study of the St. Peter Sandstone in Southern and Eastern Wisconsin*; Information Circular, v. 47, 26 p., 2 pls., scale 1:750,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 1985. Available online: <https://wgnhs.wisc.edu/pubs/000297> (accessed on 20 June 2025).
34. Devaul, R.W.; Harr, C.A.; Schiller, J.J. *Ground-Water Resources and Geology of Dodge County, Wisconsin*; Information Circular 44, 34 p., 1 plate, scale 1:125,000; Wisconsin Geological and Natural History Survey: Madison, WI, USA, 1983. Available online: <https://wgnhs.wisc.edu/pubs/000294> (accessed on 20 June 2025).
35. Knierim, K.J.; Kingsbury, J.A.; Belitz, K.; Stackelberg, P.E.; Minsley, B.J.; Rigby, J.R. Mapped predictions of manganese and arsenic in an alluvial aquifer using boosted regression trees. *Groundwater* **2022**, *60*, 362–376. [[CrossRef](#)] [[PubMed](#)]

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