Groundwater

Performance Assessments of a Novel Well Design for Reducing Exposure to Bedrock-Derived Arsenic

by Richard B. Winston[1] and Joseph D. Ayotte[2]

Abstract

Arsenic in groundwater is a serious problem in New England, particularly for domestic well owners drawing water from bedrock aquifers. The overlying glacial aquifer generally has waters with low arsenic concentrations but is less used because of frequent loss of well water during dry periods and the vulnerability to surface-sourced bacterial contamination. An alternative, novel design for shallow wells in glacial aquifers is intended to draw water primarily from unconsolidated glacial deposits, while being resistant to drought conditions and surface contamination. Its use could greatly reduce exposure to arsenic through drinking water for domestic use. Hypothetical numerical models were used to investigate the potential hydraulic performance of the new well design in reducing arsenic exposure. The aquifer system was divided into two parts, an upper section representing the glacial sediments and a lower section representing the bedrock. The location of the well, recharge conditions, and hydraulic properties were systematically varied in a series of simulations and the potential for arsenic contamination was quantified by analyzing groundwater flow paths to the well. The greatest risk of arsenic contamination occurred when the hydraulic conductivity of the bedrock aquifer was high, or where there was upward flow from the bedrock aquifer because of the position of the well in the flow system.

Introduction

Arsenic in groundwater is a problem for domestic well owners both in the United States and worldwide and can be difficult to remediate (Zheng and Ayotte 2015). In New England, more than 10% of domestic wells drilled into fractured crystalline bedrock are at risk for concentrations of arsenic higher than the maximum contaminant level of 10 μg/L (Flanagan et al. 2012). In parts of eastern New England, the percentage can range from 20% to 30%, making arsenic a significant issue for domestic well owners (Ayotte et al. 2003; Yang et al. 2009). There are significant barriers to testing and treating domestic well water to make it safe for human consumption, such as cost, understanding, and optimism bias (Flanagan et al. 2012). As a result, as long as domestic well owners are responsible for testing and treating their well water, there will always be significant exposure to arsenic from groundwater used for drinking water (Zheng and Ayotte 2015).

One potential solution to reducing risk of arsenic exposure would be to manage the sources of well water. In New England, this can be done by increasing the use of glacial aquifers that overlie much of the region for drinking water. Water from the glacial aquifer is generally oxic with a low pH conditions that cause arsenic to adsorb to aquifer materials and be removed from groundwater. In contrast, the bedrock aquifer is generally anoxic with a high pH: conditions that enhance arsenic solubility in the groundwater (Smedley and Kinniburgh 2002; Stollenwerk 2003).

The glacial aquifer is seldom used for domestic drinking water wells today in New England because pumping combined with low water levels during dry periods frequently causes loss of well water. Such wells are also vulnerable to surface-sourced bacterial contamination (New Hampshire Department of Environmental Services 2010). In Bangladesh, concerns for lack of sanitary well conditions drove wells deeper over time, which not unlike New England, resulted in greater exposure to inorganic arsenic in drinking water (Joya et al. 2006). More than 90% of new wells are currently installed in bedrock aquifers (Flanagan et al. 2012). Problems associated with wells installed in glacial aquifers are the result of the well design. For example, sectional concrete casings can shift

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in a freeze-thaw environment and open up entry points for bacteria and rodents. In addition, water enters shallow glacial wells through a relatively small flux face (at the bottom of the well), so little water is available for use during periods of drought.

Effective use of the glacial aquifer for domestic supply will require a well design or designs that can ameliorate the problems that have caused shallow dug wells to go out of favor. Many methods have been used worldwide with variable results. One of the most common is the infiltration gallery—a shallow collector system that takes advantage of many horizontal wells screens (collectors) that allow for greater infiltration of groundwater to a larger well (Verstraeten et al. 2002a; Sterrett 2007). In many cases, these are located adjacent to or under surface water bodies to increase well yield; but this may cause other problems such as the unanticipated introduction of anthropogenic contaminants (Verstraeten et al. 2001; Verstraeten et al. 2002a, 2002b; Warner and Ayotte 2014). Others include collector wells (Sterrett 2007), adits, qanats, and karezes (Macpherson et al. 2015), all of which seek to collect water in horizontal shafts, pipes, and tunnels. Although these methods can provide substantial water to users, they may have limitations in terms of cost of installation and (or) sanitation and, therefore, may not be practical for use as private domestic wells. It is, however, possible to combine the best features of many of these systems, along with other features, to design a modern alternative that is cost effective, easy to install, and can provide ample water in a sanitary manner and mitigate geogenic arsenic contamination. In Bangladesh, for example, shallow groundwater has been re-examined because it can be lower in arsenic than underlying deep groundwater resources (Joya et al. 2006) but more sophisticated targeting of deeper aquifers may also be warranted (McArthur et al. 2016).

Thus, an alternative well design could mitigate these problems and greatly reduce arsenic exposure through drinking water (Ayotte 2017) by allowing for reconsideration of the glacial aquifer as a viable domestic well water source, as has been proposed and demonstrated in other parts of the world (Joya et al. 2006). The proposed design increases flux of water into the well by adding large vertical flux faces resulting from excavation. The excavated space is subsequently filled with high-transmissivity crushed stone that is free of geogenic arsenic. A small diameter well casing with horizontal collectors facilitates removal of the water from the spaces between the stone for domestic use. The top of the stone is covered by a geotextile and is capped with low-transmissivity silt or clay (Figure 1). The well casing is then sealed with bentonite or similar materials at land surface (Ayotte 2017). This well design will minimize the risk of surface contamination while increasing inflow of water from the glacial aquifer, thereby reducing the exposure to arsenic-laden bedrock water.

The high-transmissivity (nearly infinite at domestic well pumping rates) crushed stone acts as a constructed aquifer containing a large volume of water available for immediate use. The large surface area in contact with the till allows for a large flow of water into the constructed aquifer. It also reduces drawdown in the vicinity of the well in comparison with a traditional dug well. The required length of the constructed aquifer depends on the anticipated water usage and the hydraulic properties of the till.

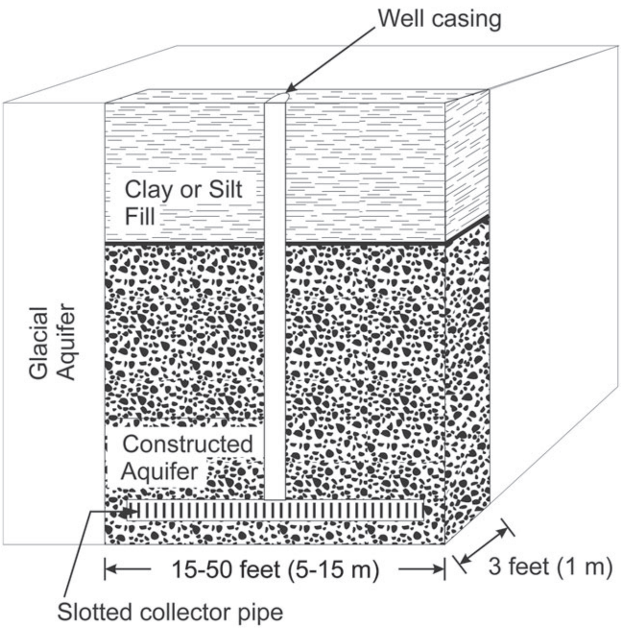

Figure 1. Simplified schematic diagram of the proposed well design (Ayotte 2015).

The potential operation of this well design in New England was assessed by estimating the fractions of glacial-aquifer and bedrock-aquifer water that would enter the well under different hydraulic conditions. Numerical simulations were conducted using MODFLOW-NWT (Niswonger et al. 2011) and MODPATH (Pollock 2012) to delineate flow paths of waters produced by the well. MODFLOW-NWT is a Newton-Raphson formulation for MODFLOW, a three-dimensional, finite difference, groundwater model. The uncalibrated simulations were used to identify the hydraulic parameters that are most important in determining the effectiveness of the well design in reducing the possibility of arsenic and bacterial contamination, and water loss during drought. To simulate a worst-case scenario, any water that passed through bedrock was assumed to be contaminated with arsenic.

Methods

The setting for the hypothetical aquifer system discussed herein is based on a hydrogeologic study of the Mirror Lake area in Grafton County, New Hampshire (Tiedeman et al. 1997). Glacial deposits are mostly from 16 to 66 feet (5–20 m) thick with a maximum thickness of 165 feet (50 m). Surface gradients in the area range from 0.05 to 0.4. Tiedeman et al. (1997) constructed a groundwater flow model of the glacial deposits and the upper 492 feet (150 m) of bedrock. The estimated hydraulic conductivity $K_{\text{glacial deposits}}$ of the glacial deposits ranged from 5.6×10^{-6} to 8.9×10^{-6} ft/s (1.7×10^{-6} to 2.7×10^{-6} m/s). Estimated bedrock hydraulic conductivities ranged from 10^{-6} to 2×10^{-7} ft/s (3×10^{-7} to 6×10^{-8} m/s). The calibrated recharge rate in the model ranged from 0.0023 to 0.0025 ft/d (26–28 cm/year).

The estimated $K_{\text{glacial deposits}}$ values of Tiedeman et al. (1997) compare favorably with values summarized by Melvin et al. (1992), who compiled the results of tests of hydraulic properties of tills. The results included 184 measurements of horizontal hydraulic conductivity, 81 measurements of vertical hydraulic conductivity, and 15 measurements of specific yield. Cumulative frequency distributions of horizontal and vertical hydraulic conductivity and specific yield are shown in Figure S1, Supporting Information. The values were measured through permeameter tests, slug tests, and aquifer tests. All the measurements of vertical hydraulic conductivity were made with permeameter tests. Specific yields were measured in laboratory tests. The median horizontal hydraulic conductivity from Melvin et al. (1992) is 4.6×10^{-6} ft/s (1.4×10^{-6} m/s). The median vertical hydraulic conductivity is 2.6×10^{-6} ft/s (7.8×10^{-7} m/s). The median specific yield is 20.3% (Figure S1).

Numerical simulations representing flow to the well utilized a rectangular model domain 500 feet (152 m) wide and 1000 feet (305 m) long, with a surface gradient of 0.1. The model represented one-half the flow field to the well, which was assumed symmetric about the long model axis (Figure 2). Two materials were simulated: bedrock and glacial deposits. The bedrock was 450 feet (137 m) thick and the glacial deposits were 30 feet (9 m) thick. The glacial deposits were represented by 10 model layers and the bedrock by 24 layers. In the glacial deposits, the top five layers were each 4 feet (1.2 m) thick and the bottom five layers were each 2 feet (0.61 m) thick. The top 10 layers in the bedrock were all uniformly 4.5 feet (1.37 m) thick. The layer thickness increased downward to a maximum thickness of 45 feet (13.7 m). A downgradient specified head boundary was placed along the short model axis in the till unit. The specified head boundary represents a stream or lake at the base of a hill slope. Recharge was applied to the uppermost active cell in the model. All other edges of the boundary were no-flow boundaries. The upgradient boundary (Figure 2A, top) was considered a groundwater divide. The lateral boundaries (Figure 2A, left and right) were considered flow lines. A pumped well was represented by five cells in layer 9: 2 feet above the base of the glacial deposits. In the vicinity of the well, the grid size was set to 2×2 feet (0.61×0.61 m). The grid size was expanded gradually away from the well to a maximum size of 10×10 feet (3×3 m). There were 90 columns and 180 rows in the model.

Most of the simulations were steady-state models. These were used to assess the effects of variations in aquifer properties and well design on well performance. Transient simulations were used to assess the effects of seasonal variation, drought, and near-surface contamination.

The horizontal hydraulic conductivity (K_x) of the glacial deposits and bedrock were set at 0.57 and 0.028 ft/d, respectively (2×10^{-6} and 10^{-7} m/s) (Melvin et al. 1992; Tiedeman et al. 1997). The vertical hydraulic conductivity of the glacial deposits was set to one-tenth its horizontal hydraulic conductivities. The vertical hydraulic conductivity of the bedrock was set equal to its horizontal hydraulic conductivity. The recharge rate was set to 0.002 ft/d (6.1×10^{-4} m/d). The pumping rate for the well was based on a per-capita water usage of 100 gal/d and a family of 4 (http://water.usgs.gov/edu/qa-home-percapita.html, accessed April 28, 2016). Because the model represents only half of the flow field, only half of the pumping was applied in the model resulting in an applied pumping rate of 26.7 ft^3/d (0.75 m^3/d). The well length within the model domain was 10 feet (3.05 m). The hydraulic conductivity of horizontal laterals attached to the well was set to 100 times the hydraulic conductivity of the glacial deposits. The models were generated using ModelMuse (Winston 2009, 2014).

Bedrock was assumed to be the source of arsenic-laden water. The proportion of bedrock water produced by the well was estimated through advective transport using backward particle tracking. The porosity used in the models for particle tracking was 0.25. The median porosity in till samples reported by Melvin et al. (1992) was 0.26. The porosity of the bedrock was irrelevant for the simulations discussed here. A total of 134,400 of particles were placed in a uniform 80×80 pattern on the external faces of the cells representing the well and its collectors. The fraction of the flow assigned to each particle was based on the total flow through the cell face where the particle originated. The flow path of each particle was traced to determine whether the particles had passed through a bedrock layer.

The water produced by the well is a mixture of bedrock and till water. The resulting arsenic concentration in the mixture can be calculated if the initial concentrations in each source are known. Assuming that the arsenic concentration of bedrock-water (C_{bedrock}) is 50 μg/L and that the concentration of glacial-deposit water ($C_{\text{glacial deposits}}$) is 0, the concentration of the resulting mixture C_{final} is given by

$$C_{\text{final}} = \left(C_{\text{glacial}} \times P_{\text{glacial}} + C_{\text{bedrock}} \times P_{\text{bedrock}}\right)/100,$$

where $P_{\text{glacial deposits}}$ and P_{bedrock} are the percentages of glacial-deposit and bedrock water produced by the well, respectively.

Therefore, if 10% of the flow to the well is from bedrock water, the resulting arsenic concentration would be 5 μg/L. Adsorption to aquifer materials as the water passes through the glacial deposits could be significant under typical geochemical conditions. Thus, these calculations are intended to represent a worst-case scenario.

Several variations on steady-state simulations were conducted to assess the potential for arsenic hazard under differing conditions (Table 1). Parameters that were varied

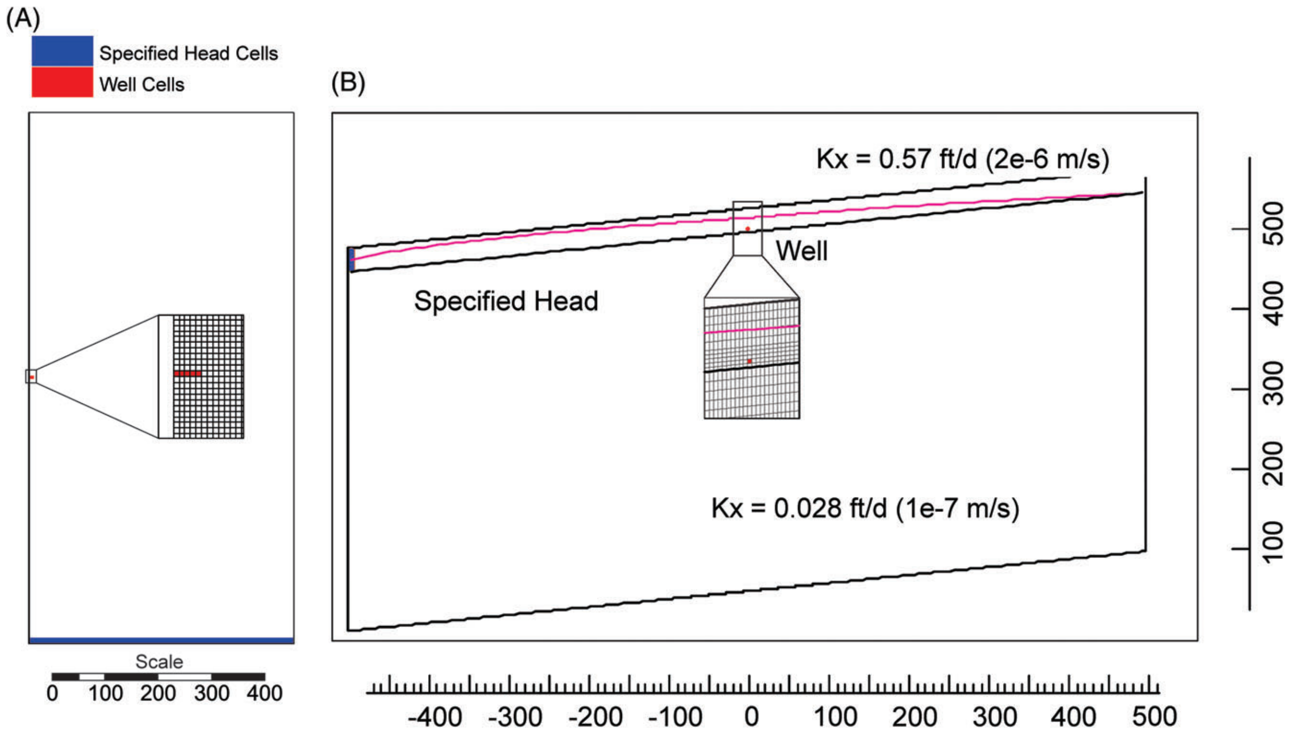

Figure 2. Diagram of the base case simulation showing the dimensions of the model, the position of the well and specified head boundaries, and the hydraulic conductivity of the bedrock and glacial deposits. Insets show expanded view of the model in the vicinity of the well. (A) Plan view. (B) Cross-sectional view along column 1. The red line represents the water table.

include the recharge rate, the position and orientation of the well screen, the vertical position of the well, the location of the well within the flow system, the well length, and the hydraulic conductivity of glacial deposits and bedrock. Some of these simulations are discussed here whereas others are in the Supporting Information (Appendix 1).

Transient simulations were also conducted to assess the potential for contamination under seasonal recharge and from near surface sources following an extreme recharge event. The results of these simulations are included in the Supporting Information (Appendix 1).

Five MT3DMS (Zheng and Wang 1999) solute transport simulations were used to assess the effects of dispersion on arsenic concentration in the well. The flow model in each case was the base case simulation. Longitudinal dispersivities of 0.01, 0.1, 1, 10, and 100 feet were used. The latter two dispersivity values are believed to be unrealistically high because they exceed the distance from the source of the arsenic to the well. In all the models, the ratio of transverse to longitudinal dispersivity was 0.1 and the ratio of vertical dispersivity to longitudinal dispersivity was 0.01. The simulation period was 20 years. The numerical simulations are fully available in Winston and Ayotte (2017).

Results

In the base case simulation, 11.6% of the flow passed through bedrock at some location along the travel path (Table 1). The capture zone for the well was approximately 265 feet (81 m) long and 60 feet (18 m) wide and extended from 245 feet (75 m) upgradient of the well to 18 feet (5 m) downgradient of the well (Figure 3A). The maximum travel time for any of the particles was 34,071 d (93 years) (Figure 3B). The maximum travel time for any particle that did not pass through the bedrock was 2639 d (7.2 years). The median travel time for particles that passed through the bedrock was 14,606 d (40 years). The median travel time for particles that did not pass through the bedrock was 467 d (1.5 years). Assuming that the bedrock-aquifer water had 50 μg/L of arsenic and the glacial-deposit-aquifer water had 0, the maximum possible arsenic concentration in the resulting mixed water in the well would be 5.8 μg/L (Table 1).

MT3DMS Simulations

In all the MT3DMS simulations, the calculated arsenic concentrations at the well cells had reached a plateau concentration by the end of the simulation. The calculated average arsenic concentrations in the well cells were 5.9, 5.9, 7.1, 17.0, and 38.4 μg/L for dispersivity values of 0.01, 0.1, 1, 10, and 100 feet. The latter two dispersivity values are believed to be unrealistically high because they exceed the distance from the source of the arsenic to the well. The first three values are comparable to the values calculated from the MODPATH simulations assuming no dispersion. The other two simulations show much higher concentrations.

Table 1
Results of Model Simulations on Percent of Flow by Aquifer and Hypothetical Resulting Worst-Case Concentrations of Arsenic

Simulation and Model Feature That Was Varied	Percent of Flow and Assumed Arsenic Concentration: Bedrock (Assumed Arsenic Concentration = 50 μg/L)	Percent of Flow and Assumed Arsenic Concentration: Glacial Deposits (Assumed Arsenic Concentration = 0 μg/L)	Concentration of Arsenic in Well Water (μg/L)
Base case	11.6%	88.4%	5.8
Well orientation[1]	11.8%	88.2%	5.9
Decreased slope and recharge[1]	11.5%	88.5%	5.7
Vertical position of well deeper[1]	13.8%	86.2%	6.9
Increased localized bedrock hydraulic conductivity	67.1%	32.9%	33.5
Well moved 300 feet (91 m). downslope	17.4%	82.6%	8.7
Well 300 feet (91 m) downslope and shallower	10.9%	89.1%	5.4
Both aquifers isotropic[1]	11.2%	88.8%	5.6
Well length[1]	10.9%	89.1%	5.4
Enhanced bedrock hydraulic conductivity near top[1]	17.8%	82.2%	8.9

[1] Discussed in Supporting Informations (Appendix 1, Figures S4–S6).

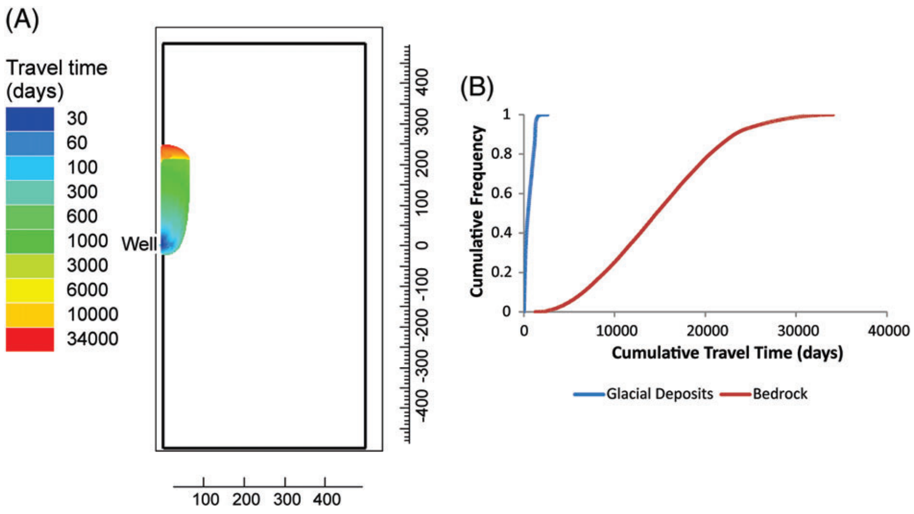

Figure 3. Capture zone and travel times for base-case simulation. (A) Capture zone, plan view color represents travel time in days. (B) Cumulative frequency distribution of travel times through glacial deposits and bedrock.

Localized High Hydraulic Conductivity

To investigate the effect of a localized zone of higher hydraulic conductivity in the bedrock in the vicinity of the well on the amount of bedrock-aquifer water that would enter the well, a modified version of the base model was made in which the horizontal and vertical hydraulic conductivity of the bedrock was increased in the area surrounding the well. The zone of higher hydraulic conductivity was circular in plan view with a diameter of 100 feet (30 m) and extended from the top of the bedrock to half the thickness of the bedrock. Within this zone, the horizontal and vertical hydraulic conductivity were set to a value close to the maximum measured value from Tiedeman et al. (1997), -2.0×10^{-4} ft/s (6×10^{-5} m/s). In this model, the percentage of flow to the well through bedrock was 67.1% (Table 1). Using the assumed concentrations of arsenic in each aquifer, this would result in a maximum potential well-water arsenic concentration of 33.5 μg/L.

Horizontal Well Position

To investigate the effects of the location of the well relative to the constant head boundary on the amount of bedrock-aquifer water that would enter the well, a modified version of the base model was made in which the well was displaced 300 feet (91 m) south. In the model, the percentage of flow to the well through bedrock was 17.4% (Table 1) and the hypothetical maximum arsenic concentration was 8.7 μg/L. The shape of the capture zone varied depending on the position of the well (Figure 4). In the model, the well was located in an area where flow is upward from the bedrock into the glacial deposits even without the well (Figure S2). In the base case simulation, there would be no upward

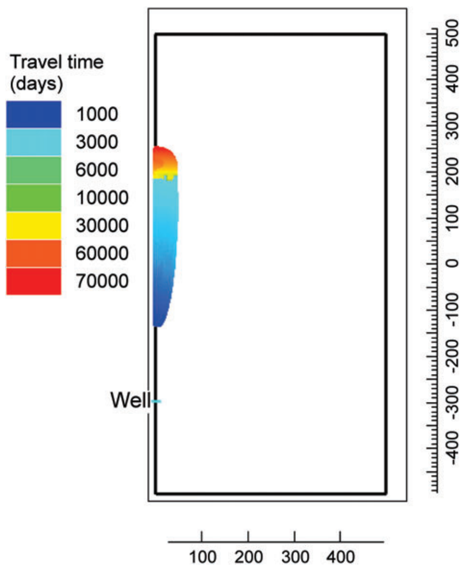

Figure 4. Effect of well position on capture zones. Color represents travel time in days. Well moved 300 feet downgradient. Compare with Figure 3A.

flow from the bedrock where the well is located if no well were present (Figure S2). An additional simulation was performed in which the well was not only moved south by 300 feet (91 m) but also moved from layer 9 to layer 8. In that model, the percentage of flow to the well through bedrock was 10.9% (Table 1).

Transport Time for Bedrock-Aquifer Water

To investigate how long it takes for bedrock-aquifer water to reach the well, a modified version of the base model was created in which particles were tracked backward until they reached the bedrock. It took 11 d for the first arsenic-containing water to reach the well. By 250 d, most of the bedrock-aquifer water that would reach the well had reached it (Figure S3). Because the particles stopped when the bedrock was reached, the porosity of the bedrock is irrelevant. If the porosity were increased, the travel time would increase proportionally. Thus for a porosity of 0.5, the first arsenic-containing water would reach the well in 48 d and most of the bedrock-aquifer water would reach the well by 500 d.

Discussion

The modeling exercises in this article are based on generic and uniform hydraulic properties of till and bedrock in the northeast United States; in reality, till and bedrock properties vary greatly perhaps even over a particular site. The results from this modeling were used to generally assess the effects of bulk changes in hydraulic properties of aquifers, well orientation and position in the groundwater flow field, hydraulic gradient and length of well, not to model a specific site or conditions.

In most of the simulations, the fraction of bedrock-aquifer water reaching the well varied little from the base-case simulation. Two models were notable exceptions.

In the simulation in which the well was moved 300 feet (91 m) downgradient relative to the base case, the fraction of arsenic-containing water reaching the well was increased 17.4% compared to 11.6% in the base simulation. In the absence of the well, groundwater flow is from the bedrock into the glacial deposits in the southern 350 feet (107 m) of the aquifer whereas in the northern 650 feet (198 m) of the aquifer groundwater flow is from the glacial deposits into the bedrock. When the well is moved south, it is moved from a zone where groundwater flow is naturally downward to one where it is naturally upward. In areas where arsenic is present in bedrock-aquifer water, this upward flow may introduce arsenic into the lower part of the glacial-deposit-aquifer, potentially resulting in greater flow of arsenic to the well than in the base case (Table 1). Thus, locating the well in places where the flow is naturally downward may reduce the chances of arsenic entering the well. Upward flow from bedrock to glacial deposits could also be identified by measuring head differences in wells screened in the bedrock and glacial deposits.

In the simulation in which the bedrock had a higher vertical hydraulic conductivity, the fraction of arsenic-containing water reaching the well was increased to 67.1% compared to 11.6% the base simulation (Table 1). It may be possible to use geophysical techniques to identify such locations.

In cases where a prospective well is to be installed where the bedrock is more permeable, or where upward flow from bedrock to glacial deposits exists, it is prudent to test the arsenic concentrations in the glacial deposits prior to well installation by use of a test pit or small monitoring well. If the groundwater is slightly acidic and oxic, then the likelihood that the dug well will have high arsenic is small. If the groundwater is slightly alkaline and anoxic in the glacial deposits, then the dug well may be at risk for containing high arsenic. If arsenic is found, there may be locations further up slope where conditions are more favorable.

Small concentrations of arsenic can be mitigated through dilution and (or) adsorption to clay minerals in the glacial deposits (Amirbahman et al. 2006) or iron oxides (Smedley and Kinniburgh 2002; Welch and Stollenwerk 2003). For example, if the concentration of arsenic in bedrock water is 50 μg/L and its proportion in well water is 1%, then the resulting arsenic concentration in drinking water would be diluted to 0.5 μg/L. Bedrock water with 50 μg/L arsenic could comprise up to 20% of the mixed water and still not cause the resultant water to exceed 10 μg/L. Thus, the likelihood that contributions from bedrock could cause the dug well water to exceed drinking water limits for arsenic is small and is part of the rationale for the novel dug well design.

To minimize the potential for contamination by events near the ground surface, the well design calls for materials of such low permeability (very fine clay loam) that the permeability of the capping material is lower than the surrounding glacial deposits. If the primary concern regarding surficial contamination is biologic contamination, determining the travel time to the well within the capture zone of the well may aid in properly citing the well. To minimize the chance of biological surface contaminants from reaching the well, the fill material needs to be selected such that its vertical hydraulic conductivity resembles that of the glacial deposits or lower. Care also should be taken that constructing the well does not cause the vertical hydraulic conductivity of the glacial deposits next to the fill material to increase through the formation of cracks in the glacial deposits.

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Disclosure

The U.S. Geological Survey has received a patent (Ayotte 2015, 2017) on the well design described in this paper. Because of the patent, royalties may apply when the design is being used.

Supporting Information

Additional Supporting Information may be found in the online version of this article. Supporting Information is generally *not* peer reviewed.

Appendix S1. Descriptions of additional simulations.

Figure S1. Cumulative frequency distributions of hydraulic conductivity and specific yield in till based on data from Melvin et al. (1992). The median values were used to justify the hydraulic properties used in the simulations.

Figure S2. Plan views showing upward specific discharge. The individual images show the specific discharge (ft/d) from the bedrock to the glacial deposits for the cases with (A) no well (Model = "NoWell"), (B) the base simulation (model name = "Base Case"), and (C) a model with the well moved 300 feet (91 m) south of its position in the base simulation (Model name = "WellMovedSouth"). Uncolored regions represent areas where the specific discharge is from the glacial deposits into the bedrock. Flow into the well from the bedrock is enhanced where flow from bedrock into the till would occur even without the well.

Figure S3. Cumulative flow of bedrock-aquifer water to well as a function of travel time from the bedrock. To investigate how long it takes for bedrock-aquifer water to reach the well, a modified version of the base model was created in which particles were tracked backwards until they reached the bedrock. It took 11 d for the first arsenic-containing water to reach the well. By 250 d, most of the bedrock-aquifer water that would reach the well had reached it.

Figure S4. Illustration of the well orientation. The blue line represents the well. (A) Perpendicular to flow (model BaseCase). (B) Parallel to flow (model RotatedWell).

Figure S5. Water table elevation (feet) showing a higher slope in the model with a higher surface slope and higher recharge. A. Higher slope (0.1) and recharge (0.002 ft/d) (ModelName = BaseCase). (B) Lower slope (0.05) and recharge (0.001 ft/d) (Model.name = LowerSlopeAndRecharge).

Figure S6. Four-hundred days capture zone of the well. Color represents the travel time to the well in days. Travel times longer than 400 d are not shown (Model simulation = Barrier).

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Authors' Note

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