Groundwater Research Report
WR14R002

ASSESSMENT OF ENVIRONMENTAL IMPACTS OF GEOTHERMAL SOURCE HEAT EXCHANGE

Christopher Y. Choi
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James M. Tinjum
Matthew K. Harper

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Christopher Y. Choi
Biological Systems Engineering
University of Wisconsin – Madison

David J. Hart
Wisconsin Geological and Natural History Survey
University of Wisconsin – Extension

James M. Tinjum
Engineering Professional Development
University of Wisconsin – Madison

Matthew K. Harper
Biological Systems Engineering
University of Wisconsin – Madison

University of Wisconsin Water Resources Institute
State of Wisconsin Groundwater Research and Monitoring Program

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Project Summary

Title:	Assessment of Environmental Impacts of Geothermal Source Heat Exchange
Project ID:	PRJ84QU
Committee:	Christopher Y. Choi, Advisor, Professor, Department of Biological Systems Engineering, University of Wisconsin-Madison David J. Hart, Hydrogeologist, Wisconsin Geological and Natural History Survey; Professor, Department of Environmental Sciences, University of Wisconsin-Extension James M. Tinjum, Associate Professor, Department of Geological Engineering, University of Wisconsin-Madison
Period of Contract:	July 1, 2014 – June 30, 2016
Background/Need:	A growing number of large-scale public institutions and corporations have begun to rely on ground-source heat exchangers (GSHE), used in combination with heat pumps, to heat, cool, and ventilate their interior spaces. Essentially, these systems transfer heat to and from the ground as needed by circulating a fluid through a loop of polyethylene pipe. GSHE systems rely on ground temperatures, which remain relatively stable year round, to provide an efficient heat source in the winter and serve as a heat sink in the summer. Geothermal energy is considered clean, renewable, and sustainable, thanks to the Earth's nearly unlimited thermal storage capacity. Most recently, large-scale GSHEs have been installed at West Madison High School, the Wisconsin Institutes of Discovery (at the University of Wisconsin-Madison), and Epic Systems Corporation. Epic's system relies on one of the largest GSHE fields in the nation, with more than 5,000 bore shafts drilled as of 2015. There is a growing need for research to monitor whether additional levels of arsenic may be released from the bedrock, as Epic's field adds heat to the ground adjacent to the borefield. As a number of recent studies have demonstrated, temperature increases might raise the rate of scorodite ($FeAsO_4 \cdot 2H_2O$) dissolution by up to a half of magnitude. Field data collected at the Brinton site in Floyd County, Virginia, also show that arsenic concentrations in groundwater are positively correlated with temperature. In Wisconsin, the zone of highest arsenic is near Lake Winnebago where the St. Peter sandstone forms most of the bedrock, but high arsenic concentrations have also been found in the Prairie du Chien, the bedrock layer into which Epic's geothermal boring shafts have been drilled. If in fact enhanced scorodite dissolution occurs at higher temperatures, thereby affecting arsenic mobility, there exists a potential for harmful groundwater contamination in the geothermal field and in downstream wells, wetlands and streams.
Objectives:	The purpose of this study is to address the research need associated with the potential release of arsenic into groundwater due to temperature increases in a ground-source heat exchange field. Based on the study's outcomes, we will determine the best design and operation practices that take potential environmental impacts into account and develop a set of recommendations. The study is also designed to provide mitigation strategies that large-scale GSHE

installations could use to minimize potential health risks and environmental impacts.

Methods: Investigations were conducted at Epic Systems' Borefield #4. A borefield-scale Computational Fluid Dynamics (CFD) model was developed using borefield design heating and cooling loads and estimated groundwater velocities. Groundwater flow-model parameters were varied. A borehole-scale CFD model was developed to investigate local heating and cooling effects. A borefield temperature mitigation strategy was developed and tested. Groundwater-monitoring wells were drilled and sampled for background levels of contaminants at 3 locations at the Field #4 site. These, along with an additional network of temperature monitoring wells, were instrumented with distributed temperature sensing (DTS) devices capable of generating continuous temperature profiles of the borefield's temperature.

Results & Discussion: Model results indicate that operation based on the design parameters can be sustainable. That is, applying a proposed mitigation strategy that involves venting excess heat from the ground to the atmosphere during the winter has been modeled and found to be an effective solution. Results from water sampling on site indicate that arsenic levels are, in general, under the EPA Maximum Contaminant Level (MCL). Sample results also indicate a positive relationship between aqueous arsenic concentration and temperature.

Conclusions & Recommendations: The proposed strategy has already implemented using a storm-water retention pond on site. Results from water sampling on site indicate that arsenic should not be a significant drinking-water concern at this time. While current data does indicate a positive relationship between aqueous arsenic concentration and temperature. These results are suggestive enough to warrant continued study. Therefore, it is the recommendation of this report that this site be monitored for the foreseeable future or until environmental concerns can be ruled out.

Keywords: Water quality, heat exchange, dissolution, arsenic, ground temperature, groundwater, thermal pollution

Funding: University of Wisconsin System through the Groundwater Coordinating Council

Introduction

The use of geothermal energy to heat and cool homes and buildings has become increasingly common because of public concerns about rising energy costs, geopolitical implications, and global climate change related to carbon emission. In Wisconsin, the use of ground source heat exchangers (GSHE) to run geothermal heat pumps has become especially popular. GSHE relies on wells drilled into the ground to take advantage of a nearly constant ground temperature, with the temperature difference between the water entering and exiting the ground heat exchangers driving geothermal heat pumps. These wells are typically around 300 to 500 ft (90 to 150 m) deep and contain polyethylene, closed-loop pipes that circulate the water or water fixed with antifreeze as a coolant. In general, geothermal heat pump systems are expensive to install because of the cost of the heat exchangers and drilling/excavation. However, in Wisconsin, energy savings range from 8% for single residential houses up to 17% for large-scale installations such as schools, and the payback period is 9-10 years when the systems are used for offices and schools, with a reduction in CO_2 emission of between 6 and 15% (Energy Center of Wisconsin, 2009). These favorable factors have been the main driver behind the rapid regional growth of geothermal energy systems in recent years and the development of large-scale geothermal fields. Epic Systems Corporation has a geothermal heat exchange system that has grown from 564 boreholes in 2006 to more 5,000 today, and the system has been successfully operated, with energy savings the facility's manager has determined are significant. In many other places besides Wisconsin, these large-scale geothermal fields are a relatively new land use. The Wisconsin Department of Natural Resources (WDNR) is currently considering how to regulate the systems in its state and monitor the impacts that the bore fields are likely to have on Wisconsin's surface waters and groundwater geochemistry. Wisconsin is not alone in lacking the data needed to make such assessments. At present, for example, there is also little empirical data available for the site at Ball State's geothermal field in Indiana, which has been cited as one of the largest fields in North America (Dowling et al, 2013). Sound judgments concerning the impacts and regulatory needs of these systems will depend on conducting additional research to gather and analyze sufficient data.

Geothermal Fields and Potential for Overheating

The efficiency the geothermal system's heat pump depends on maintaining a constant temperature. Doing so is neither easy nor to be assumed. The temperature differential between the fluid inside the GSHE loops and the geologic substrate outside of the loops can become substantially reduced over the years, and, too, there have been many episodes of temperature increase in geothermal fields. For example, the ground temperature in the center of the field used in Ball State's GSHE system has increased more than 10°C from November 2011 to October 2013 (initially, the system included 1,803 geothermal boreholes drilled 400ft (~120m) deep in a 15x15ft grid in two large fields in 2009; an additional 600 500ft (~150m) deep boreholes were completed in the subsequent year). During that same time, temperatures rose in the monitoring wells that surround the site (Dowling, Dunn, Neumann, Florea, & Samuelson, 2013). In December 2010, the Wisconsin Institute for Discovery (WID) at the University of Wisconsin-Madison opened a ground-coupled heat pump system with 385-ton heat pumps connected to 75 closed-loop boreholes 300ft (~90m) deep and spaced approximately 20 feet apart around the perimeter of the building. Knudson (2013) reported that during the summer months the temperature of the water entering the condenser after returning from the borefield exceeded 100°F (38°C), which was much higher than expected, and that such high temperatures greatly reduced system's coefficient of performance. Reportedly, the geothermal field's temperature in 2013 was well over 110°F and possibly as high as 120°F (43-49°C). Epic's first system, which originally included 564 boreholes 300ft (~90m) deep and was installed in 2006, has experienced similar problems. Over the years, however, Epic's facility management has mitigated the overheating problem and installed new systems (approximately 1,000 boreholes in 2008, an additional 2,000 boreholes in 2010, an additional 2500 boreholes in 2014-2015) that were designed on the basis of what Epic learned from operating its initial system. At present, the system works efficiently, and as a result of proper management, there are no indications of overheating; the geo-water entering the system ranges in temperature from 60°F to 70°F (15.5-21°C).

Potential Arsenic Release in Groundwater due to Geothermal Overheating

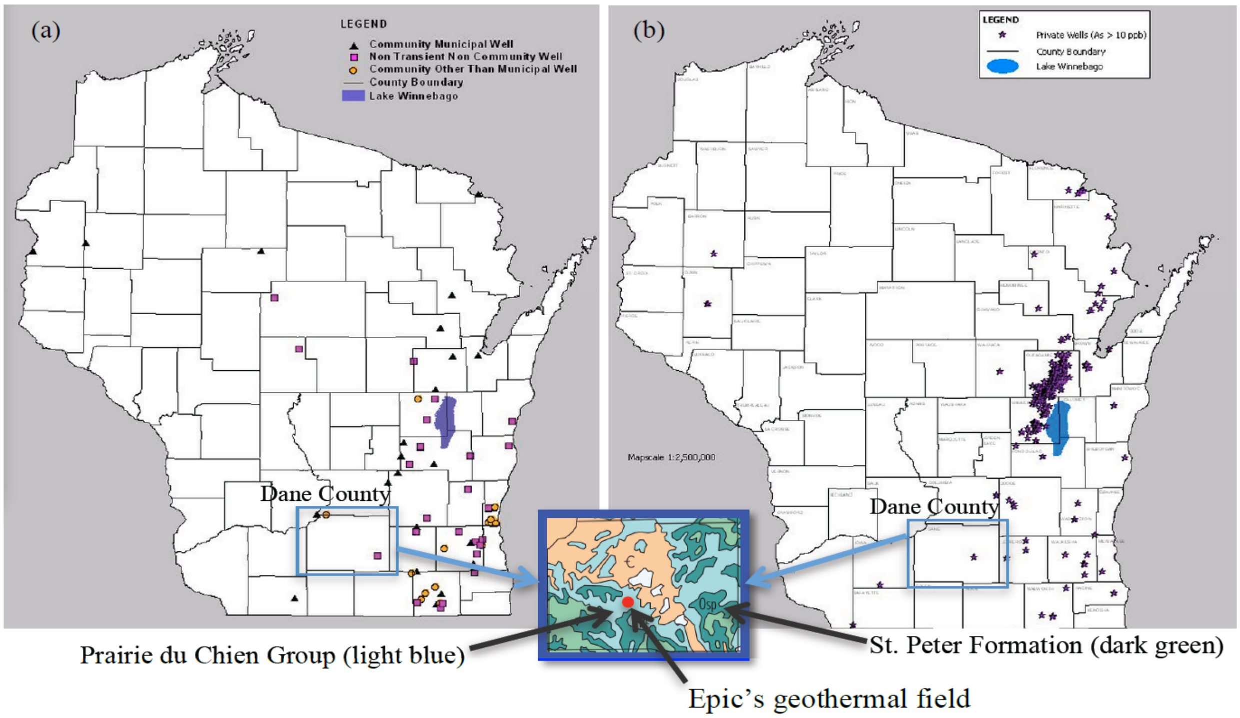


Figure 1: Maps displaying (a) public and (b) private wells with a concentration of arsenic greater than 10 ppb. (Wisconsin Department of Natural Resources, 2012)

Arsenic is a naturally occurring element found in bedrock throughout eastern Wisconsin. Anthropological alteration of the pumping-induced hydraulic gradient, geochemistry, and temperature can cause the bedrock to release its arsenic into groundwater, and at high enough concentrations to be harmful to humans. The immediate health effects include high blood pressure, nerve damage, and diabetes, to name a few, and a long-term exposure can increase the risk of liver, lung, and kidney cancers. As shown in Figure 1, arsenic has been detected frequently in drinking water drawn from public and private wells near Lake Winnebago, where the St. Peter sandstone is common. High arsenic concentrations have been also found in the Prairie du Chien (dolomite with some sandstone and shale) Formation in Dane county.

Harvey et al. (2006) investigated the dissolution kinetics of a common arsenic-bearing mineral as a function of pH and temperature and found that increases in temperature had a significant effect on the solubility of arsenic. As Figure 2a shows, after only four hours of exposure the concentration of arsenic nearly doubled to an elevated temperature of 50°C.

Bluteau and Demopoulos (2007) expanded upon this work by applying elevated temperatures for a matter of weeks rather than hours. This allowed them to capture the long-term effects beyond the initial increase in arsenic concentration and in so doing achieve a logarithmic response curve of the arsenic concentration versus time, a thus affording an insight that could not be gleaned from the earlier work (Figure 2b).

Additionally, this research showed that arsenic concentrations were still increasing after 43 weeks of experimentation for those cases wherein the 50°C and >7 pH (Bluteau & Demopoulos, 2007). In a subsequent field study, a positive correlation was found between temperature and arsenic concentration at a site in Floyd County, Virginia (Brown et al., 2007). Each of these studies clearly indicates that an increase in soil temperature could increase groundwater arsenic concentrations.

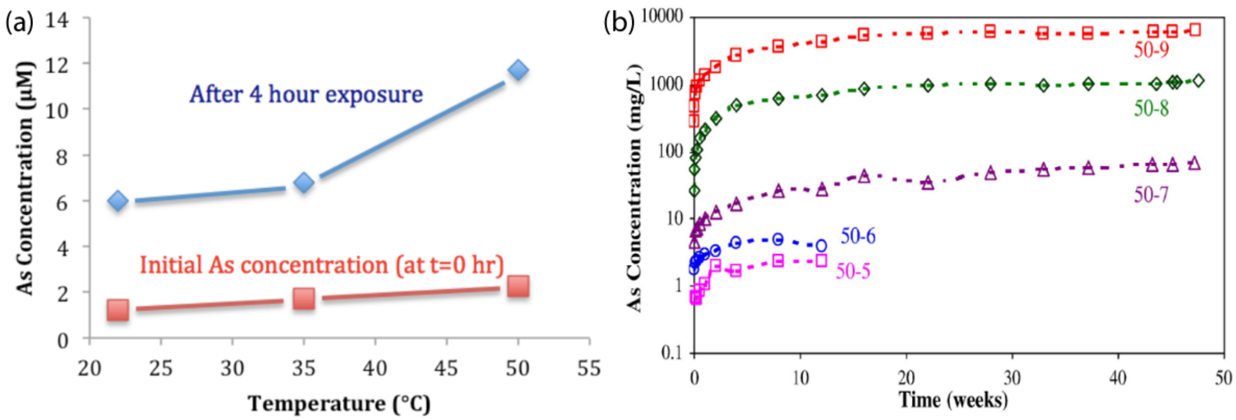


Figure 2: (a) Arsenic (As) concentration as a function of temperature at pH = 6. Values taken from Harvey et al. (2006) and (b) As concentration as a function of time for T=50°C and varying pH. Figure from Bluteau and Demopoulos (2007).

Epic Systems Corporation's geothermal fields are located on the Prairie du Chien Formation (Figure 1), a formation that has yielded high arsenic concentrations. In response, concerns have been raised about impacts to groundwater quality due to increased temperatures in the bedrock within geothermal fields.

Procedures and Methods

Well Construction and Instrumentation

Three boreholes, each approximately 500 ft. (152.4m) deep, have been drilled for temperature and water quality monitoring of Epic's Borefield #4. Locations can be seen in blue within Figure 3. The first is on the north edge of the field and roughly centered relative to the field. The second is on the east edge of the field and located slightly north of center; both were installed in August 2014. Original plans did not call for a water quality monitoring well within the borefield, but with a planned temperature monitoring well already drilled and an interest in observing a worst-case temperature scenario effect, it was decided to move forward with a third monitoring well located within the north-east quadrant of the field; this was installed in May 12th, 2015.

Each borehole is equipped with two piezometers: one installed in the shallow bedrock, which consists of mainly the Prairie du Chien, Trempealeau, and Tunnel City Groups and is screened from 130-140 feet (39.6-42.6 m) below the surface; the second installed in the deep bedrock, which consists of mainly the Wonewoc Formation and is screened from 490-500 feet (149.4-152.4m) below the surface. This arrangement allowed for separate sampling of both the upper and lower aquifers, which are separated by the leaky confining layer of the Tunnel City Group. In addition, these piezometers were instrumented with leveloggers to monitor the groundwater level fluctuations and resulting groundwater gradients.

The boreholes were also instrumented with fiber optic cables for distributed temperature sensing (DTS). More information on the calibration of this system can be found in McDaniel, et al., 2016.

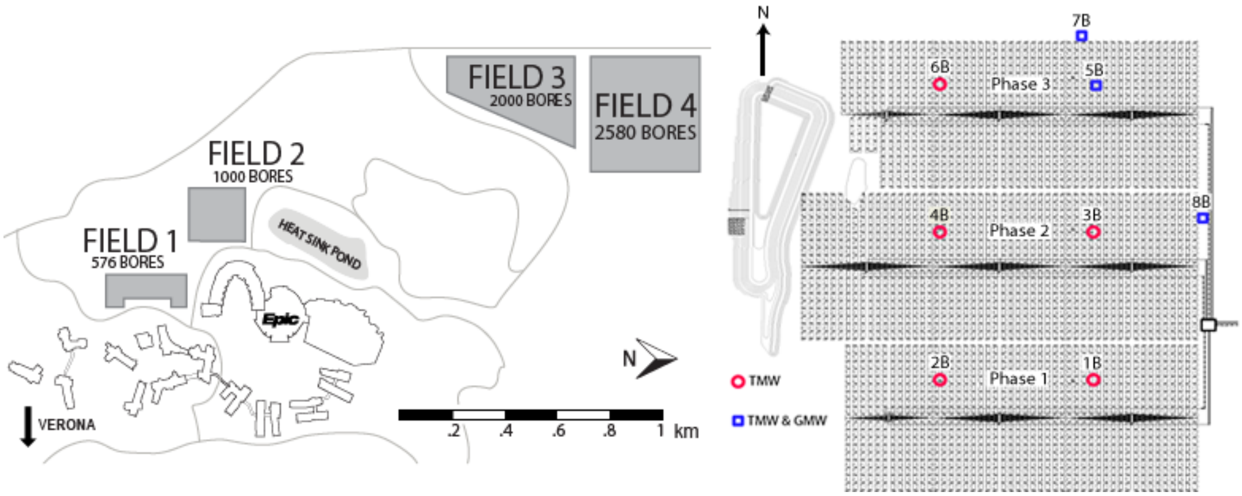


Figure 3: Specific Epic geothermal site layout in Verona, Wisconsin.

Testing and Monitoring

Geophysical and temperature logs were performed on site. To establish a baseline level of geochemical components, water samples were taken before field activation. The field was constructed and subsequently activated in three phases: Phase 1 was activated in January 2015, Phase 2 in June 2015, and Phase 3 in October 2015. Our piezometers were located in Phase 3 by design to allow sufficient time to establish baseline levels of aqueous chemistry. Additional samples were taken as the wells were being installed and over time for monitoring purposes. In each case, a minimum of 3 well volumes were evacuated before sampling; in the case of TMW-5B, 10 well volumes were evacuated for the first sample as the well had very recently been drilled and grouted. Samples were field filtered through a .45 µm sterile filter unit. All samples were analyzed by UW-Steven's Point Water & Environmental Analysis Lab (DNR Cert. No. 750040280). Values below the detection limit were handled using a simple substitution method of $Value = DL/2$ for plotting and analysis purposes. In additon to water sampling, we have also performed XRF measurements on drilling samples taken from the site to assess likely sources of arsenic within the formations. These measurements influenced our choice of piezometer installation depth, as we are interested in evaluating a worst-case scenario.

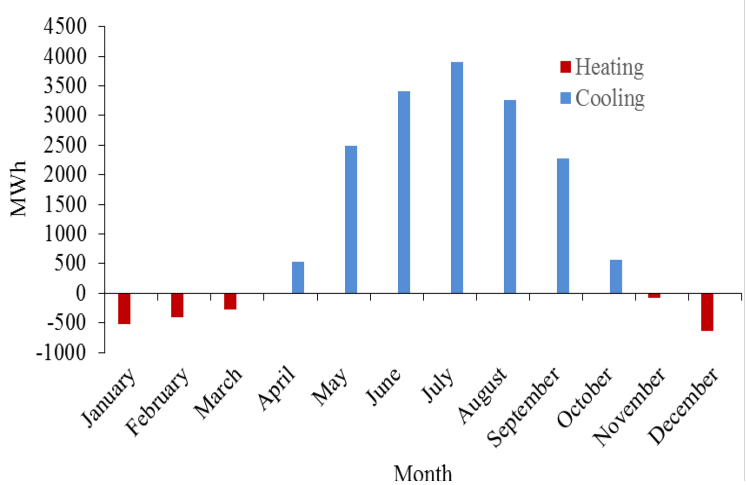


Figure 4: Design thermal loads used for simulation

Computational Models

Initial computational work focused on benchmarking numerical results against analytical solutions. The use of 2D "slices" to reduce computational time was validated by comparing the 2D and 3D model results (which matched to within error tolerances). From this point on, we worked on creating a 2D borefield-scale model (Figure 5), based on the design heating/cooling loads (Figure 4) provided by the design firm MEP

Associates, for a completed Epic geo-exchange field (Borefield #3).

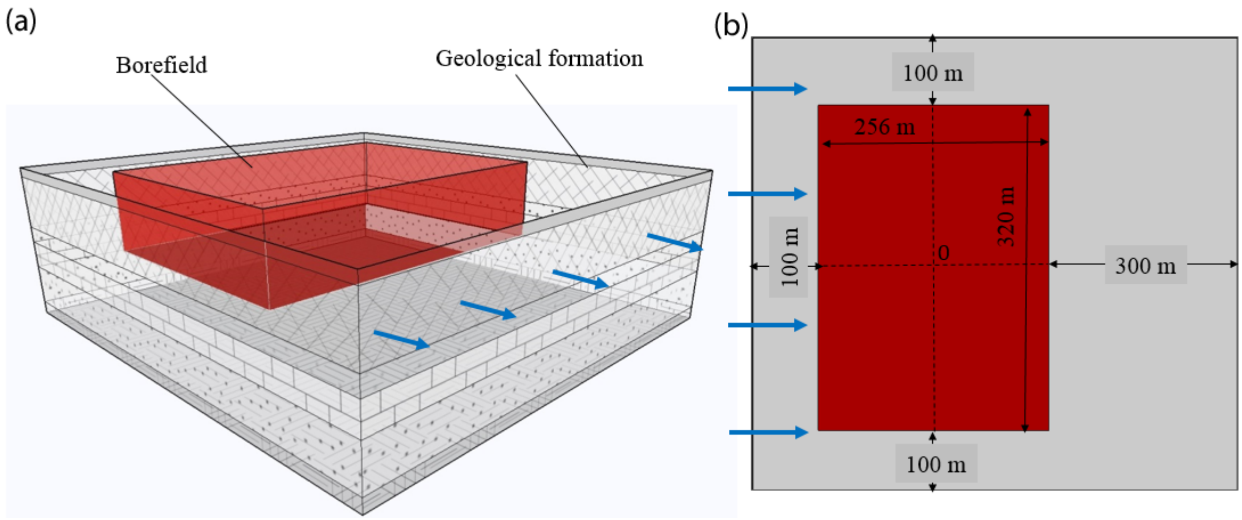
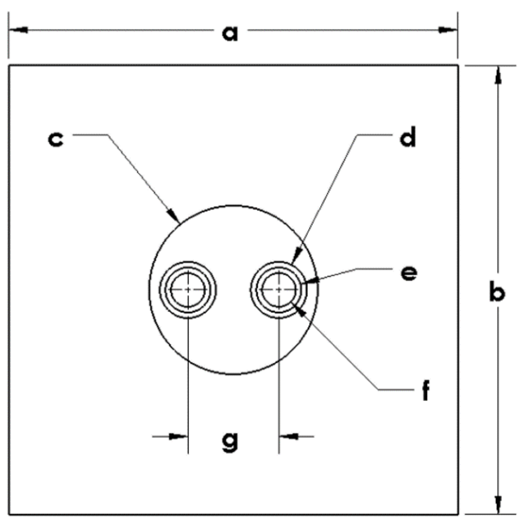


Figure 5: Borefield-scale model geometry

Given the unbalanced nature of Epic's heating and cooling loads, a strategy was proposed to balance energy inputs to the ground and limit ground temperate increases. Essentially, excess heat would be vented to the atmosphere during the winter months by using heat exchange coils located in surface waters and using the ground as short-term thermal storage rather than a long-term heat sink. To simulate this cold-water circulation, a borehole scale model was developed (as can be seen in Figure 6). The water was assumed to have a mean temperature of 3°C based on typical energy extraction rates for geo-exchange boreholes.



	Description	Borefield 3 model dimensions	2D single borehole model dimensions
a	Spacing, x	6.40	20.00
b	Spacing, y	6.40	20.00
c	Borehole	0.140	0.150
d	Pipe	0.042	0.061
e	Boundary layer	0.032	0.051
f	Water	0.025	0.040
g	Pipes distance	0.081	0.081

Figure 6: Detailed borehole-scale model geometry and corresponding dimensions

Results and Discussion

XRF measurement results performed in July 2014 showed a consistent presence of arsenic at approximately 20 and 40 meters below the surface (Figure 7), though much higher levels were found in Core #2 (a) than in Core #4 (b) (Clay and Hart, 2014). This confirmed, rather than merely assumed, presence of arsenic on site lends credence to the supposition that a contamination could result from the increased dissolution that will occur at elevated temperatures. It should also be noted that the arsenic-detection at 40 meters was particularly important, as it provided a basis for a screening depth within the shallow aquifer.

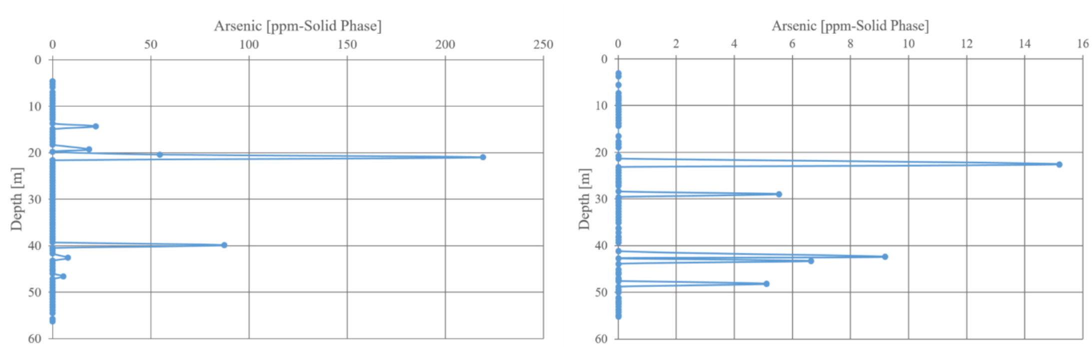


Figure 7: XRF measurement results for (a) Core 2 and (b) Core 4

Water samples were collected on Aug. 27th & 28th, 2014; April 30th, 2015; June 4th, 2015; November 3rd & 4th, 2015; and March 14th & 18th, 2016. Complete results, including field measurements, can be found in Appendix B-2. Samples taken from the shallow aquifer showed significantly more total dissolved solids, especially nitrates, chloride, and phosphorus at a greater than one order of magnitude higher than those taken from the deep aquifer. Nitrates in particular were found to be in excess of the EPA maximum contaminant level (MCL) of 10 mg-L^{-1}. Background levels of arsenic for both the shallow and deep aquifers were 0.0050 and 0.0044 mg-L^{-1}, respectively.

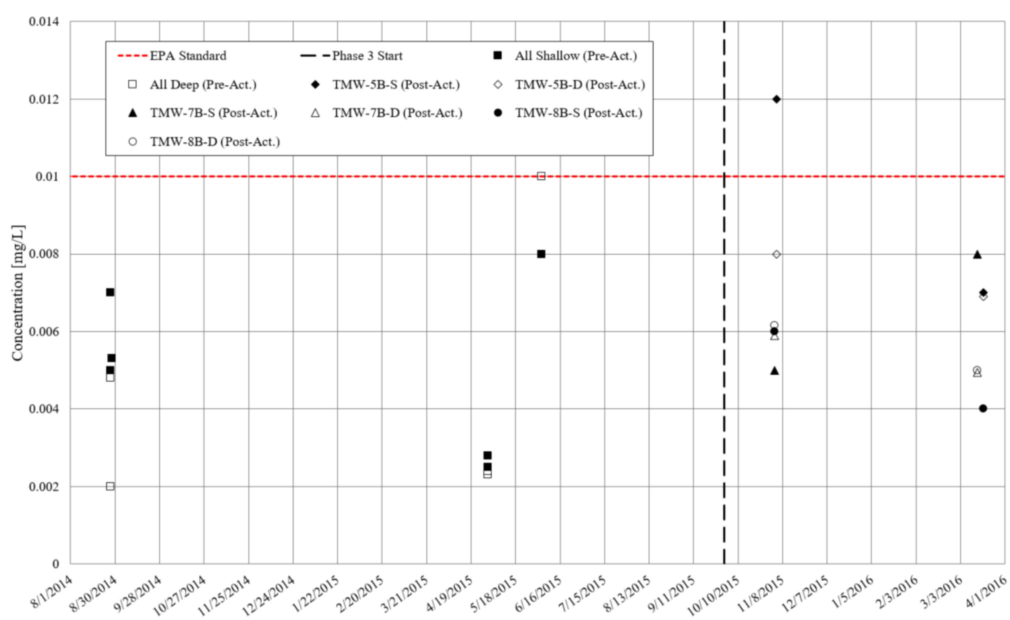


Figure 8: Arsenic concentration in groundwater samples over the experimental period

Figure 8 shows the evolution of arsenic concentration over time, with samples divided into either pre-activation (sampled before October 2015) or post-activation (sampled after October 2015). Out of all aquifer samples 8.3% (2 of 24) matched or exceeded the EPA MCL of 10ppb for arsenic; the highest concentrations were found at TMW-5B, which is located within Borefield 4. As mentioned previously, Phase 3 was not activated until October 2015; therefore, our monitoring area has not undergone significant temperature changes. This can be seen in Figure 9b, which shows that Phase 3 of the field only reached a maximum temperature of 13 °C, a deviation of at most 2.5 °C from the background temperature. However, this result, when contrasted with those obtained from a temperature monitoring location in Phase 1 (Figure 9a), shows an increase of approximately 5 °C over 5 months. Thus, Phase 3 has the potential to heat up over time.

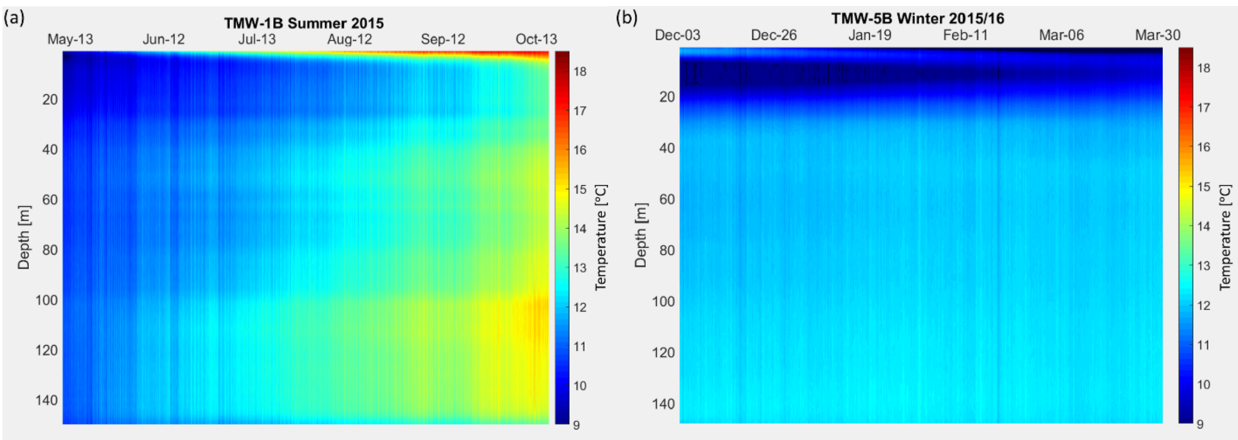


Figure 9: Color floods based on fiber optics temperature measurements

Using the design's heating/cooling loads as energy inputs into the borefield area, we were able to estimate the temperature plume's migration away from the field (Figure 10) and the temperature rise within the field (Figure 11a) under various groundwater flow conditions. These loads are imbalanced due to significant internal heat generated by employees and computer equipment inside the buildings and resulting in a net input to the ground of approximately 14,500 MWh per year without balancing efforts. Given the slow migration of heat in this system, it seems unlikely that the Sugar River would experience impacts due to warmer waters discharging into it. The heat is expected to dissipate into the atmosphere by the time the groundwater would reach the river.

Figure 11b shows that by using a two-borefield rotation (i.e. remediating one field by transferring excess stored energy to surface water while the other is heating buildings) a two-year energy imbalance could be corrected in approximately 4 months. While this strategy would not limit ground temperature increases during a specific cooling season, it would prevent the year-over-year temperature increases that pose more significant potential environmental issues.

Epic has implemented this remediation strategy by installing heat exchange coils in their storm-water retention pond. Net daily energy flows to the pond and borefields in 2015 were calculated using temperature and flowrate data and can be seen in Figure 12. The pond heat exchangers are essentially only active during the heating season (winter). During this period, the pond works contrary to the borefields; while the borefields are operated to extract energy to heat buildings (see Figure 12, Borefield 3), the pond is used to vent excess energy that has built up within the system. Figure 12 also shows the overall heat flows to Borefield 4 in 2015.

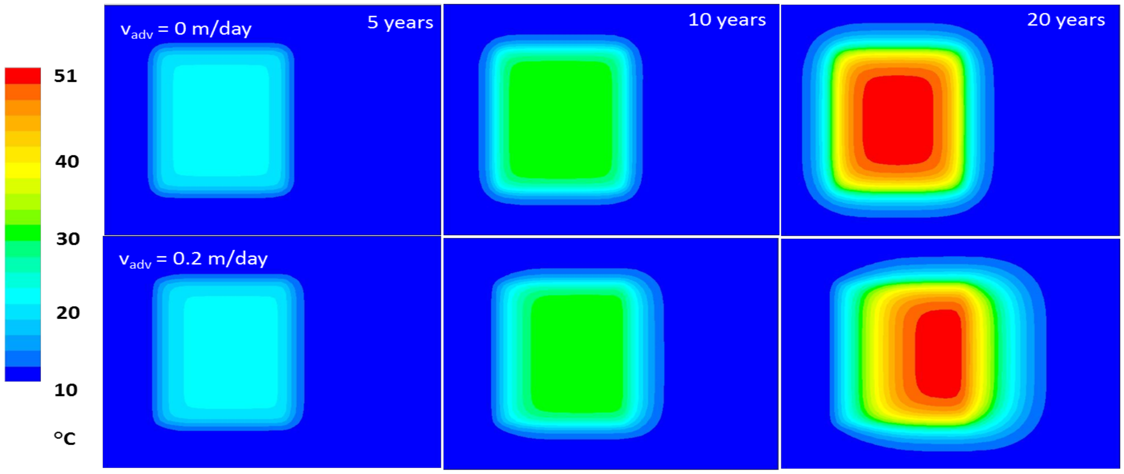


Figure 10: Temperature contours using borefield-scale computational simulations

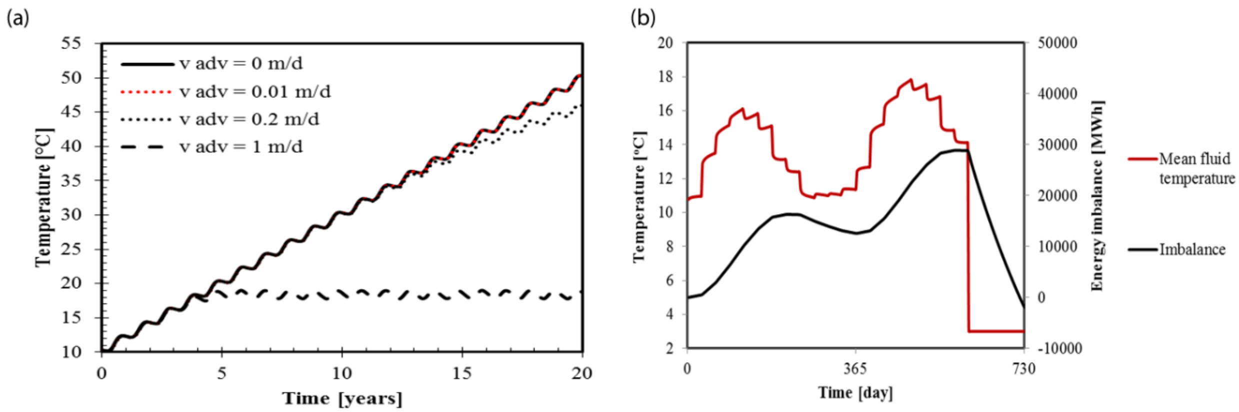


Figure 11: (a) Borefield temperature trends over time and (b) remediation strategy based on computational fluid dynamics outcomes

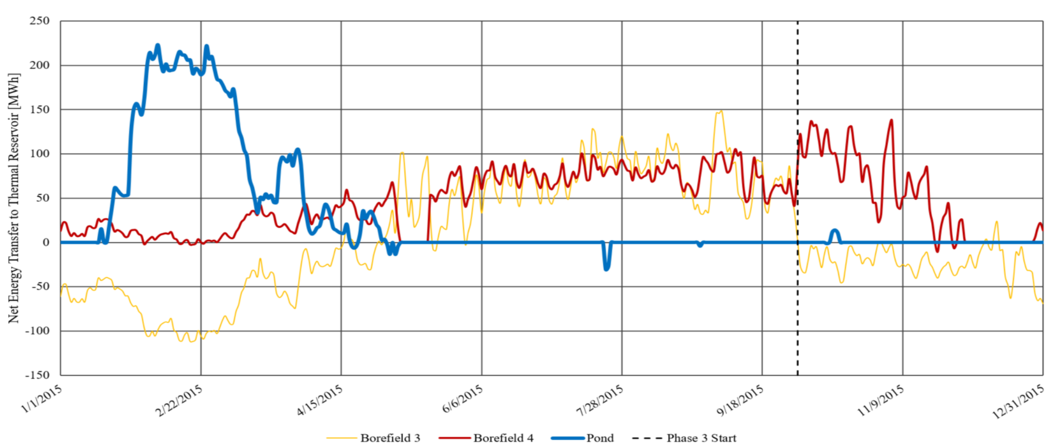


Figure 12: Measured daily net energy flows

It is premature to predict the general trend based on an *in situ* temperature and arsenic concentration relationship, as shown in Figure 13. Overall, results indicate a weak positive relationship between aqueous arsenic concentrations and temperature, but the correlation is not statistically significant. Groundwater should continue be monitored because of the potential for additional exceedances.

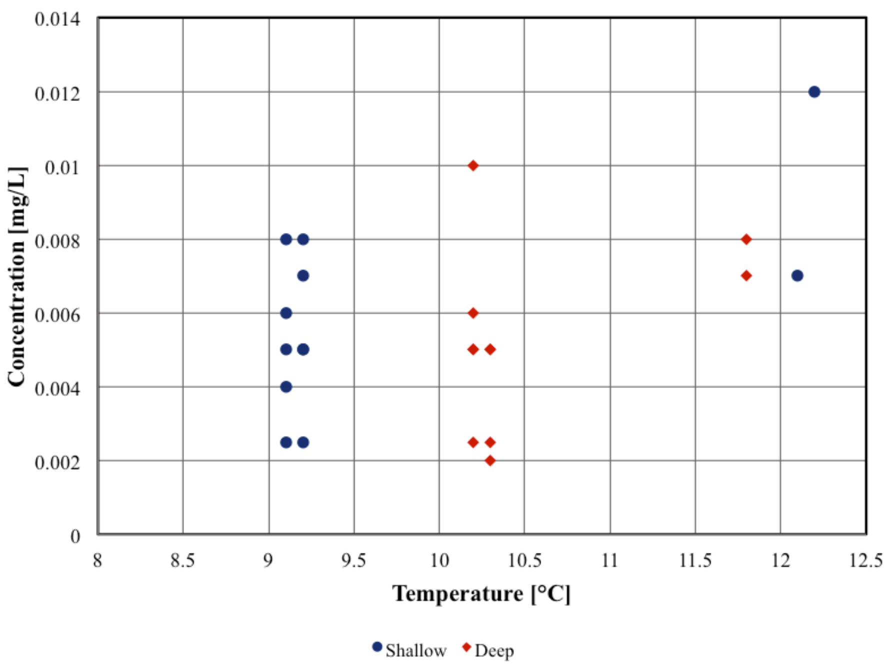


Figure 13: Relationship between aqueous arsenic concentration and temperature

Conclusions and Recommendations

Model results indicate that operation based on design parameters is unsustainable, even when operated under unrealistic advective heat flux conditions. However, applying a mitigation strategy that involves venting excess heat from the ground to the atmosphere during the winter is an effective solution as modeled. Implementation of this strategy has already begun using a storm-water retention pond (on site) that kept over 10,000 MWh of energy out of the borefields in 2015. However, given that several borefields are already at elevated temperatures and the sizable yearly imbalance within the system, the current surface water available is not enough to regulate the system. Additional surface water heat-exchange systems should be installed as soon as possible to prevent additional overheating.

While, as expected, current data does indicate a positive relationship between aqueous arsenic concentration and temperature, at this time there is not enough data from which to draw any meaningful conclusions or make reccomendations regarding borefield temperature regulation. However, preliminary results are suggestive enough to warant continued study. Therefore, it is the recomendation of this report that this site be monitored for the foreseeable future until envirenmental concerns can be ruled out.

While water-sampling data from the site shows that arsenic levels have varied over time, only two samples out of twenty-four exceeded the EPA MCL of 10 mg-L^{-1}. Due to the relatively long time it would take for groundwater to travel off site, at this time there seems no danger that drinking or surface water in other areas will occur as a result of current borefield operations from arsenic or warm groundwater discharge.

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McDaniel, A., Harper, M., Fratta, D., Tinjum, J. M., Choi, C. Y., & Hart, D. J. (2016). Dynamic Calibration of a Fiber-Optic Distributed Temperature Sensing Network at a Distric-Scale Geothermal Exchange Borefield. *GeoChicago 2016.*

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Appendix A: Papers, Presentations, and Posters

Harper, M. K., Choi, C. Y., Hart, D. J., and Tinjum, J. T. Preliminary Modeling and Monitoring Results from District-Scale Geothermal Fields. *American Water Resources Association-Wisconsin Section, 39th Annual Meeting,* Oconomowoc, WI, March 5-6, 2015.

Ozdogan-Dolcek, A., Atkins, I., Harper, M.K., Tinjum, J.M. and Choi, C.Y. Performance and Sustainability of District-Scale Ground Coupled Heat Pump Systems, *Journal of Geotechnical and Geological Engineering*. In review. 2016.

McDaniel, A., Harper, M., Fratta, D., Tinjum, J. M., Choi, C. Y., & Hart, D. J. Dynamic Calibration of a Fiber-Optic Distributed Temperature Sensing Network at a Distric-Scale Geothermal Exchange Borefield. Accepted. *GeoChicago 2016.*

Appendix B

B-1: Geophysical Logs

Figure 14 shows an amalgamation of the various geophysical logs that were performed at TMW-8B (WGNHS Well ID 13005726), including gamma, caliper, and temperature. Of note is the variation present in the caliper log in the Prairie du Chien dolomite, as well as the presence of the Tunnel City leaky confining layer at approximately 240-260ft, indicated by the SPR and Image logs.

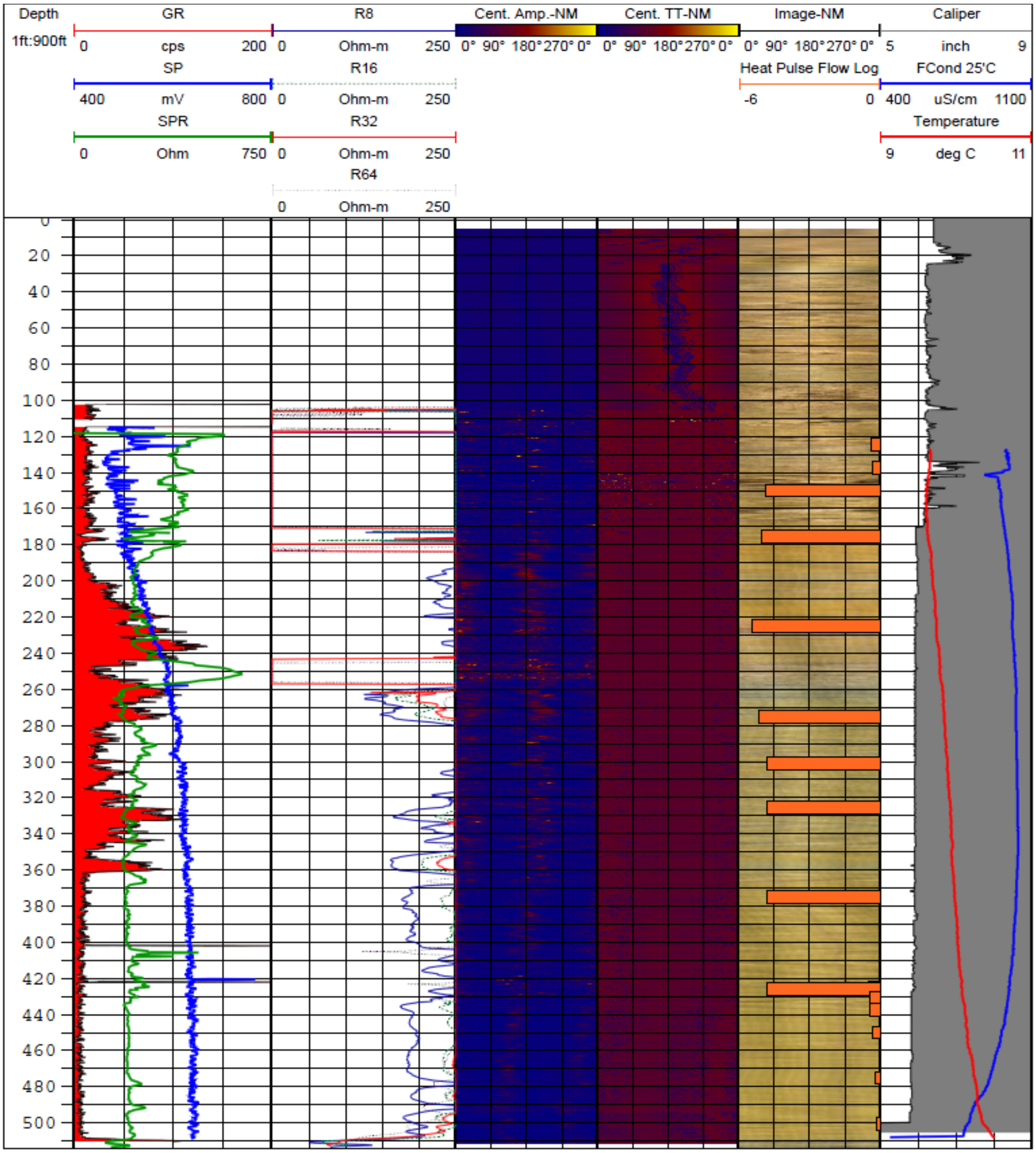

Figure 14: Collection of geophysical logs performed at PZE on 07/23/14. (Hart & Chase, 2014)

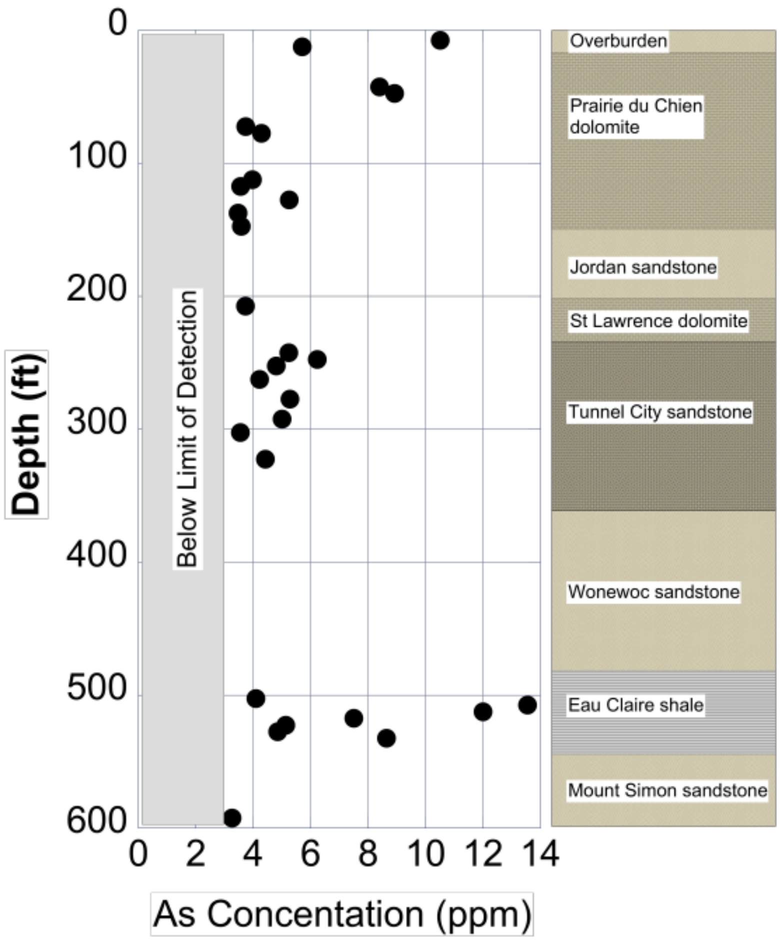

Figure 15. Arsenic concentration levels with the depth. The data was collected using a Niton™ XL3t XRF Analyzer using well bore cuttings from Verona well #5 located on the Epic campus. The elevation of the well is approximately the same as TMB-5B.

B-2: Groundwater Sampling Data

All values are in mg-L^{-1} unless otherwise specified. Conductivity, temperature, and pH vaules are from field measurements.

Table 1: Summary of lab results from sampling during the study period

Round	Name	Date	Nitrogen, Nitrate	Alkalinity	Chloride	Arsenic	Calcium
1	TMW-8B-D	8/27/2014	0.3	320	2.8	0.005	60.49
1	TMW-7B-S	8/27/2014	12.3	340	37.8	0.005	82.55
1	TMW-7B-D	8/27/2014	0.2	312	0.3	0.002	54.75
1	TMW-7B-S	8/27/2014	12.5	348	38.0	0.007	82.08
1	TMW-8B-S	8/28/2014	11.2	336	39.5	0.005	85.05
2	TMW-8B-D	4/30/2015	0.05	300	0.1	0.003	57.18
2	TMW-7B-D	4/30/2015	0.05	300	0.1	0.003	56.60
2	TMW-7B-S	4/30/2015	11.6	320	37.7	0.003	85.24
2	TMW-8B-S	4/30/2015	10.7	340	37.9	0.003	85.14
2	Sugar River	4/30/2015	4.7	264	31.7	0.003	64.94
3	TMW-5B-D	6/4/2015	0.05	308	1.6	0.010	56.38
3	TMW-5B -S	6/4/2015	11.8	344	48.1	0.008	81.69
4	TMW-8B-S	11/3/2015	10.9	316	37.9	0.006	83.24
4	TMW-8B-D	11/3/2015	0.05	180	1.8	0.006	56.29
4	TMW-7B-D	11/3/2015	0.5	304	3.5	0.005	56.00
4	TMW-7B-S	11/3/2015	12.3	312	41.8	0.005	87.52
4	TMW-5B-D	11/4/2015	4.1	308	14.6	0.008	60.00
4	TMW-5B -S	11/4/2015	11.4	336	48.5	0.012	83.67
4	Sugar River	11/11/2015	4.8	248	32.0	0.003	62.22
5	TMW-8B-D	3/14/2016	10.4	318	38.9	0.005	83.49
5	TMW-7B-S	3/14/2016	0.05	308	0.3	0.008	55.28
5	TMW-7B-D	3/14/2016	3.2	308	10.0	0.005	52.59
5	TMW-8B-S	3/18/2016	11.3	317	39.3	0.004	86.13
5	TMW-5B-D	3/18/2016	8.1	321	29.6	0.007	70.33
5	TMW-5B -S	3/18/2016	11.1	337	47.5	0.007	84.66
5	TMW-5B -S	3/18/2016	11.1	310	47.6	0.007	87.30
5	Sugar River	3/18/2016	3.5	211	25.6	0.002	49.23
6	TMW-8B-S	7/7/2016	10.6	308	37.6	0.003	82.32
6	TMW-8B-D	7/7/2016	0.0	308	1.7	0.003	55.14
6	TMW-7B-D	7/7/2016	3.3	310	11.3	0.003	58.28
6	TMW-7B-S	7/7/2016	11.7	319	44.9	0.003	87.27
6	TMW-5B-D	7/8/2016	3.6	304	13.1	0.003	60.35
6	TMW-5B -S	7/8/2016	11.7	327	49.3	0.004	88.34
6	TMW-5B –S Unf	7/8/2016	11.6	328	49.3	0.003	86.29
6	Sugar River	7/8/2016	5.3	281	32.4	0.003	69.03

Table 2: Summary of lab results from sampling during the study period (continued)

Round	Name	Date	Copper	Iron	Potassium	Magnesium	Manganese
1	TMW-8B-D	8/27/2014	0.0010	0.090	1.89	42.581	0.0098
1	TMW-7B-S	8/27/2014	0.0010	0.100	1.77	43.711	0.0032
1	TMW-7B-D	8/27/2014	0.0010	0.066	1.18	40.376	0.0073
1	TMW-7B-S	8/27/2014	0.0010	0.517	1.78	42.955	0.0057
1	TMW-8B-S	8/28/2014	0.0330	0.889	6.15	44.592	0.0106
2	TMW-8B-D	4/30/2015	0.0004	0.006	1.49	41.308	0.0257
2	TMW-7B-D	4/30/2015	0.0004	0.006	1.27	40.712	0.0036
2	TMW-7B-S	4/30/2015	0.0004	0.003	2.18	45.147	0.0006
2	TMW-8B-S	4/30/2015	0.0004	0.005	2.48	44.767	0.0038
2	Sugar River	4/30/2015	0.0004	0.036	2.24	35.083	0.0372
3	TMW-5B-D	6/4/2015	0.0010	0.009	1.21	39.735	0.0101
3	TMW-5B -S	6/4/2015	0.0004	0.006	2.90	43.277	0.0061
4	TMW-8B-S	11/3/2015	0.0005	0.003	2.12	42.963	0.0005
4	TMW-8B-D	11/3/2015	0.0031	0.003	1.42	40.897	0.0207
4	TMW-7B-D	11/3/2015	0.0011	0.006	1.28	40.897	0.0036
4	TMW-7B-S	11/3/2015	0.0022	0.091	2.28	46.091	0.0026
4	TMW-5B-D	11/4/2015	0.0017	0.006	1.25	41.721	0.0043
4	TMW-5B -S	11/4/2015	0.0004	0.003	2.71	43.100	0.0016
4	Sugar River	11/11/2015	0.0014	0.047	2.07	32.086	0.0326
5	TMW-8B-D	3/14/2016	0.0008	0.015	1.46	41.286	0.0195
5	TMW-7B-S	3/14/2016	0.0010	0.014	2.64	45.219	0.0085
5	TMW-7B-D	3/14/2016	0.0010	0.116	1.90	35.890	0.1078
5	TMW-8B-S	3/18/2016	0.0026	0.007	7.22	43.935	0.0014
5	TMW-5B-D	3/18/2016	0.0003	0.009	2.11	44.467	0.0026
5	TMW-5B -S	3/18/2016	0.0007	0.029	2.96	44.792	0.0029
5	TMW-5B -S	3/18/2016	0.0010	0.008	3.07	46.041	0.0017
5	Sugar River	3/18/2016	0.0009	0.076	2.03	25.981	0.0341
6	TMW-8B-S	7/7/2016	0.0042	0.004	2.37	43.281	0.0007
6	TMW-8B-D	7/7/2016	0.0006	0.005	1.49	41.113	0.0143
6	TMW-7B-D	7/7/2016	0.0008	0.004	2.04	39.762	0.0042
6	TMW-7B-S	7/7/2016	0.0005	0.004	2.71	46.405	0.0004
6	TMW-5B-D	7/8/2016	0.0005	0.004	2.26	36.247	0.0029
6	TMW-5B -S	7/8/2016	0.0016	0.248	3.51	46.619	0.0436
6	TMW-5B –S Unf	7/8/2016	0.0005	0.003	3.43	45.956	0.0009
6	Sugar River	7/8/2016	0.0098	0.049	2.78	36.304	0.0244

Table 3: Summary of lab results from sampling during the study period (end)

Round	Name	Date	Sodium	Phosphorus	Lead	Sulfate	Zinc
1	TMW-8B-D	8/27/2014	3.2	0.043	0.0025	15.44	0.005
1	TMW-7B-S	8/27/2014	26.3	1.595	0.0025	22.74	0.002
1	TMW-7B-D	8/27/2014	3.5	0.126	0.0025	10.90	0.001
1	TMW-7B-S	8/27/2014	29.0	1.813	0.0025	23.10	0.003
1	TMW-8B-S	8/28/2014	34.3	0.736	0.0025	27.33	0.014
2	TMW-8B-D	4/30/2015	2.0	0.004	0.001	15.94	0.020
2	TMW-7B-D	4/30/2015	2.0	0.021	0.001	11.35	0.021
2	TMW-7B-S	4/30/2015	10.0	0.250	0.001	19.38	0.002
2	TMW-8B-S	4/30/2015	9.8	0.049	0.001	20.80	0.016
2	Sugar River	4/30/2015	10.7	0.046	0.001	13.51	0.001
3	TMW-5B-D	6/4/2015	4.1	0.040	0.001	9.90	0.031
3	TMW-5B -S	6/4/2015	32.6	1.027	0.001	26.17	0.002
4	TMW-8B-S	11/3/2015	8.9	0.034	0.001	19.67	0.011
4	TMW-8B-D	11/3/2015	2.6	0.004	0.003	16.15	0.012
4	TMW-7B-D	11/3/2015	5.4	0.007	0.001	14.04	0.008
4	TMW-7B-S	11/3/2015	9.3	0.133	0.002	21.65	0.027
4	TMW-5B-D	11/4/2015	15.4	0.005	0.002	21.95	0.042
4	TMW-5B -S	11/4/2015	24.5	0.746	0.003	23.69	0.008
4	Sugar River	11/11/2015	9.9	0.056	0.001	13.71	0.018
5	TMW-8B-D	3/14/2016	1.9	0.002	0.0008	15.50	0.023
5	TMW-7B-S	3/14/2016	10.1	0.139	0.0008	21.40	0.016
5	TMW-7B-D	3/14/2016	26.6	0.010	0.0008	21.80	0.013
5	TMW-8B-S	3/18/2016	9.2	0.046	0.0008	19.70	0.032
5	TMW-5B-D	3/18/2016	17.9	0.006	0.0008	22.90	0.029
5	TMW-5B -S	3/18/2016	24.5	1.041	0.0008	22.10	0.007
5	TMW-5B -S	3/18/2016	22.2	0.849	0.0008	192.50	0.010
5	Sugar River	3/18/2016	9.5	0.047	0.0008	23.90	0.008
6	TMW-8B-S	7/7/2016	9.1	0.032	0.002	19.1	0.009
6	TMW-8B-D	7/7/2016	1.9	0.003	0.002	14.7	0.009
6	TMW-7B-D	7/7/2016	17.8	0.014	0.002	18.6	0.003
6	TMW-7B-S	7/7/2016	10.8	0.104	0.002	20.1	0.003
6	TMW-5B-D	7/8/2016	21.9	0.004	0.002	17.4	0.019
6	TMW-5B -S	7/8/2016	18.8	0.615	0.002	19.4	0.009
6	TMW-5B –S Unf	7/8/2016	18.8	0.540	0.002	20.0	0.005
6	Sugar River	7/8/2016	12.6	0.051	0.002	12.8	0.032

Table 4: Summary of field measurements taken during sampling over the study period

Round	Name	Date	Conductivity [µS/cm]	Temperature [°C]	pH
1	TMW-8B-D	8/27/2014	608	10.8	7.43
1	TMW-7B-S	8/27/2014	872	10.0	7.39
1	TMW-7B-D	8/27/2014	578	10.7	7.44
1	TMW-7B-S	8/27/2014	872	10.0	7.39
1	TMW-8B-S	8/28/2014	819	12.4	7.45
2	TMW-8B-D	4/30/2015	614	11.4	7.20
2	TMW-7B-D	4/30/2015	590	11.5	7.20
2	TMW-7B-S	4/30/2015	858	11.0	7.30
2	TMW-8B-S	4/30/2015	858	10.2	7.40
2	Sugar River	4/30/2015	684	15.8	7.70
3	TMW-5B-D	6/4/2015	570	11.9	7.73
3	TMW-5B -S	6/4/2015	877	11.5	7.59
4	TMW-8B-S	11/3/2015	735	13.5	7.21
4	TMW-8B-D	11/3/2015	521	11.5	7.34
4	TMW-7B-D	11/3/2015	538	12.0	7.49
4	TMW-7B-S	11/3/2015	752	11.3	7.32
4	TMW-5B-D	11/4/2015	604	12.0	7.52
4	TMW-5B -S	11/4/2015	785	11.7	7.36
4	Sugar River	11/11/2015	684	9.6	7.91
5	TMW-8B-D	3/14/2016	628	11.1	7.37
5	TMW-7B-S	3/14/2016	920	10.3	5.48
5	TMW-7B-D	3/14/2016	715	11.3	7.00
5	TMW-8B-S	3/18/2016	865	10.0	7.76
5	TMW-5B-D	3/18/2016	812	11.7	7.62
5	TMW-5B -S	3/18/2016	927	11.5	7.55
5	TMW-5B -S	3/18/2016	927	11.5	7.55
5	Sugar River	3/18/2016	560	7.0	7.90
6	TMW-8B-S	7/7/2016	831	13.2	7.61
6	TMW-8B-D	7/7/2016	600	12.4	7.64
6	TMW-7B-D	7/7/2016	597	12.7	7.78
6	TMW-7B-S	7/7/2016	826	11.7	7.55
6	TMW-5B-D	7/8/2016	682	13.2	7.61
6	TMW-5B -S	7/8/2016	906	13.2	7.38
6	TMW-5B –S Unf	7/8/2016	906	13.2	7.38
6	Sugar River	7/8/2016	699	13.5	7.84