Aquifer Storage and Recovery Case Study

Site: Green Bay, Wisconsin

Highlights

"In the later 1990s and early 2000s, ASR was investigated as an option to enhance municipal water supply capacity in Green Bay, Wisc by injecting treated surface water during low-demand periods and recovering the water during times of high demand… ASR was ultimately determined to be infeasible at the site due to high levels of arsenic in the recovered water."

-Meghan Dickoff in her Master's Thesis

- In the latter half of the 20th century, the City of Green Bay, Wisconsin was struggling to meet high municipal water demand during the summer months.
- An ASR pilot study was undertaken in Green Bay from 2002-2003 in which treated surface water was injected into three hydrostratigraphic units. The upper and lower units, consisting of the Prairie du Chien Group and the Elk Mound Group were assumed to be aquifers that the injection water would occupy. The middle unit, the Tunnel City Group, was assumed to be an aquitard.
- Upon injection and recovery, elevated concentrations of arsenic were observed and ultimately determined full scale ASR would not be feasible..

Background

Through population growth and water-intensive lifestyle changes, annual water consumption by the City of Green Bay, Wisconsin increased dramatically throughout the 20th century (Figure 1) displays this trend, depicting the annual water pumping by the city towards their municipal supply. Until the late 1950s, Green Bay used groundwater as the sole source for their municipal water supply. Increased pumping by Green Bay and other cities along Lake Michigan, namely Milwaukee and Chicago created a regional cone of depression in eastern Wisconsin still present after more than 40 years of rebound (as shown in Figure 2). In the Green Bay area, water levels declined over 340 feet before the city switched to Lake Michigan as their municipal water supply in 1957.

However,even after the city switched, demand continued to increase until in the 1990s, Green Bay reached an upper limit of production during the high-demand summer months (Figure 3) . Water treatment facilities are generally designed to meet peak demand in the summer.In the early 2000s, the City was faced with the tough decision of either investing in an expensive expansion of their water treatment infrastructure leading to an investigation of the applicability of ASR to augment water supply in the summer.

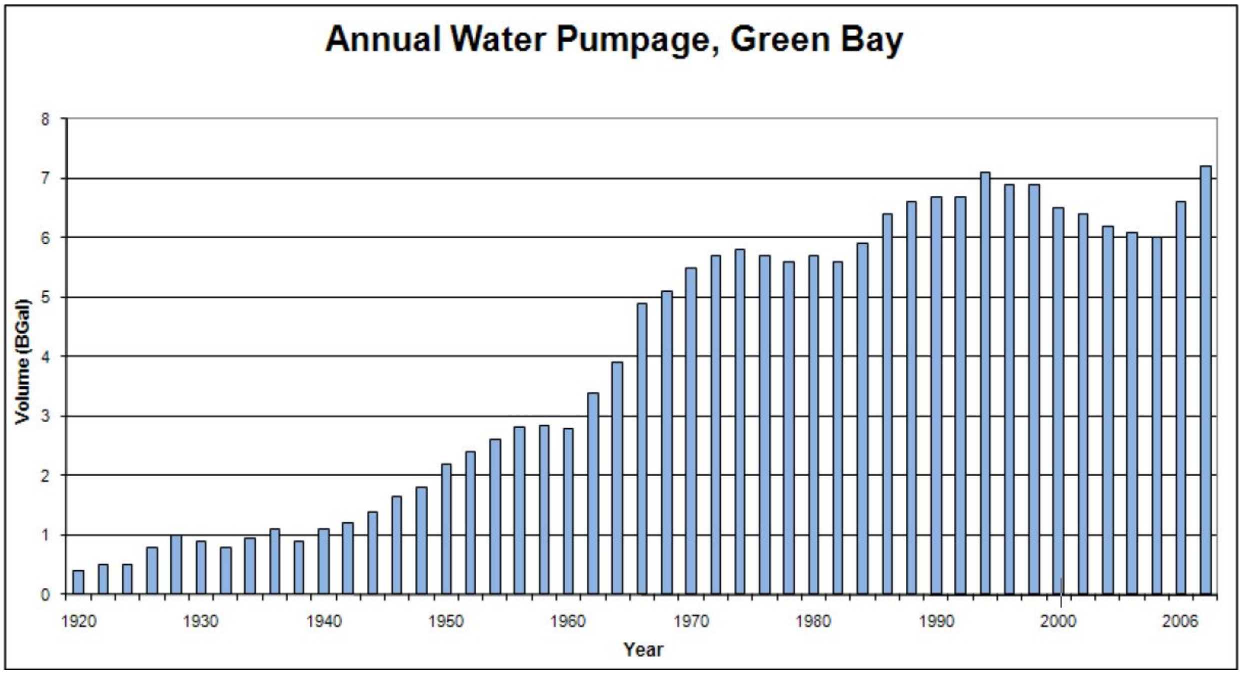


Figure 1: Annual rate of municipal water consumption in Green Bay, Wisconsin, over the majority of the 20th-century. (Source: [1])

Figure 2: Regional cone of depression network in eastern Wisconsin as of 2000 due to groundwater pumping in the 20th century. (Source: [1])

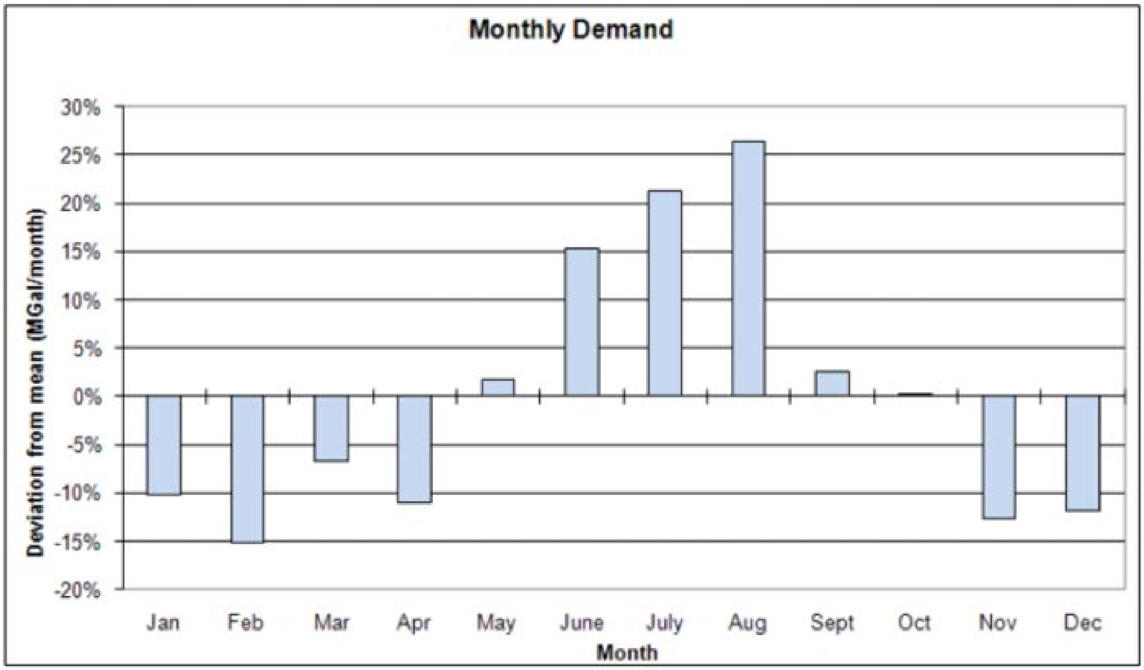
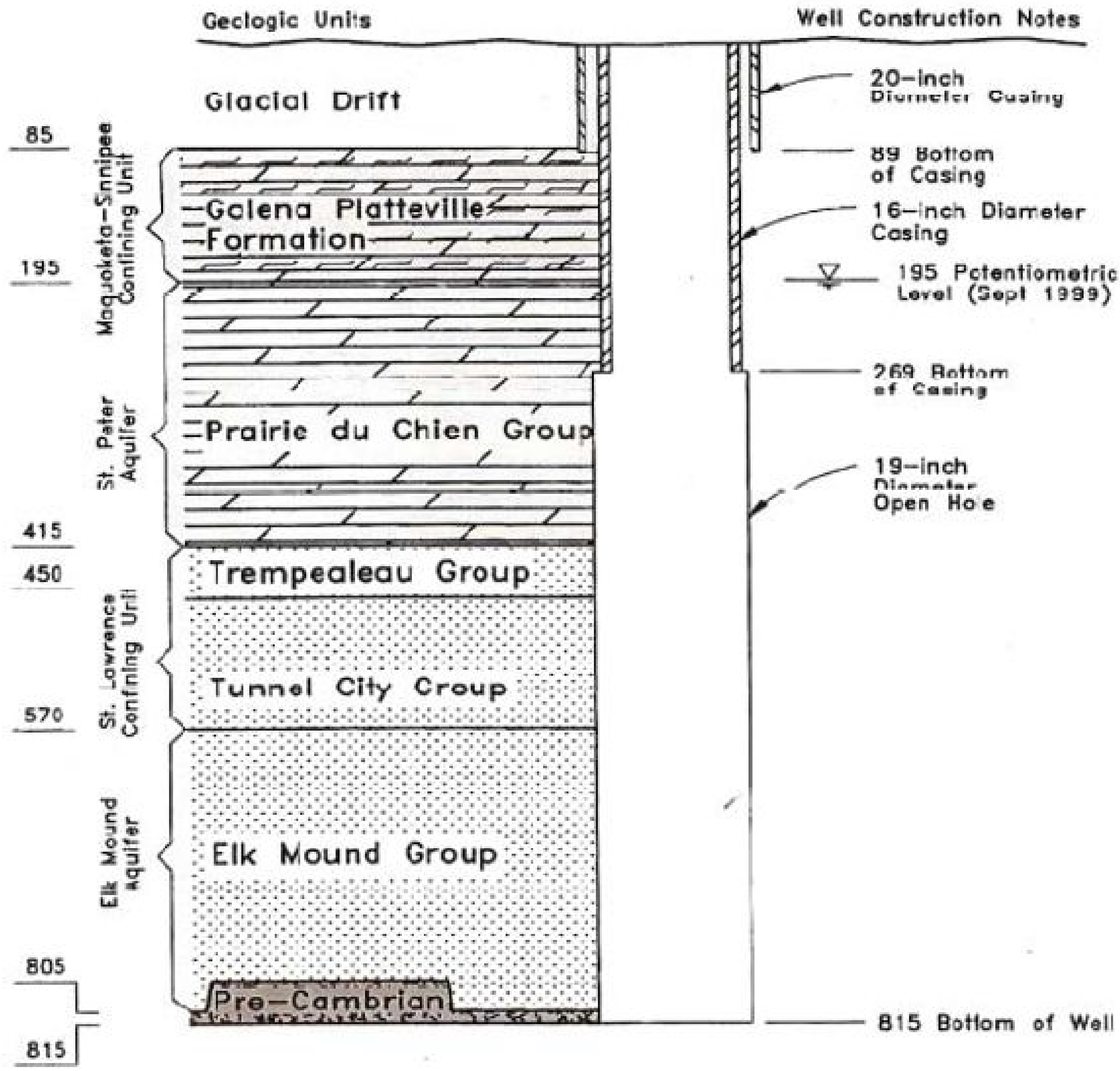


Figure 3: Seasonal demand for municipal water in Green Bay, Wisconsin – captured in 2006-2007. (Source: [1])

Summary of proposed ASR project

ASR would operate in annual cycles; in the fall, winter, and spring, when water demand was low, the water treatment plant would overproduce. The excess production volume would be injected through an ASR well, displacing native groundwater and to form a volume of treated water around the well. Treatment of the injection water to municipal water supply standards would occur so that the injection volume could be recovered and placed directly into the distribution system in the summer to satisfy peak demand. This would also prevent clogging from corrosion and would protect the water quality of the receiving aquifer(s).

An appropriate site for ASR was chosen on the north side of the City. A 815-foot deep well was drilled into the Cambrian-Ordovician aquifer system (Figures 4 and 5) and a nearby nested set of monitoring wells installed 50 feet away. They were separated by packers placed at 450 feet and 570 feet to create three intervals. The two suspected receiving aquifers, the Prairie du Chien and the Elk Mound Groups, were divided by the St. Lawrence confining unit consisting of the Trempealeau Group and the Tunnel City Group. Initial conceptual modeling suggested that most of the injected water would flow through the sandstones of the Elk Mound Group (Figure 6). The Tunnel City Group, owing to its high clay content and low vertical hydraulic conductivity, was expected to store negligible quantities of injected water. However, during the first pilot ASR cycle, oxidation-reduction potential, chloride levels, and dissolved oxygen levels changed at nearly the same time across all three intervals suggesting that flow occurred at roughly the same rate across all three layers. In addition, significant arsenic concentrations were observed in the monitoring well upon injection and recovery (Figure 7). Levels were highest in the middle layer suggesting that the Trempealeau and Tunnel City groups were the likely source for the majority of the arsenic contamination.



Well #10 (Injection well)

Figure 4: Geological strata penetrated by the ASR well in Green Bay. (Source: [1])

Core samples of the Tunnel City Group were taken on the ASR site in order to improve understanding of the layer. While the vertical hydraulic conductivity was confirmed to be quite low, the samples were heterogeneous and anisotropic. Geophysical testing performed at the monitoring well demonstrated that the Tunnel City Group is highly conductive in the horizontal direction. The injected flow was likely carried through bedding-plane fractures and other heterogeneities that gave rise to preferential flow paths. The implication of these findings was that the groundwater system did not act like two distinct aquifer layers separated by a confining unit, but rather as a single, heterogeneous aquifer. Revised conceptual modeling, which took into account the presence of preferential flowpaths and the heterogeneity of the aquifer was conducted (Figure 8).

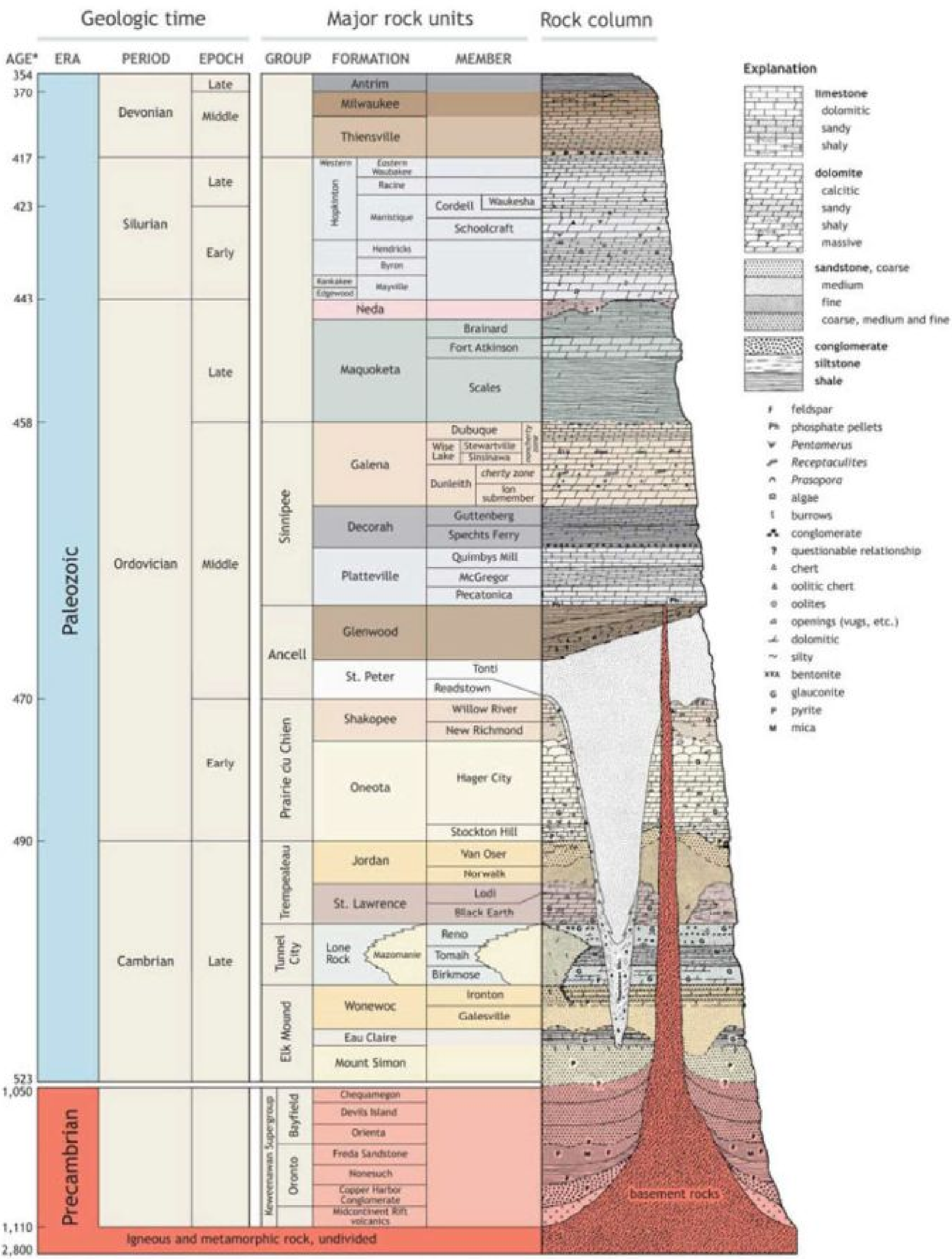


Figure 5: Bedrock stratigraphy of Wisconsin. (Source: [1])

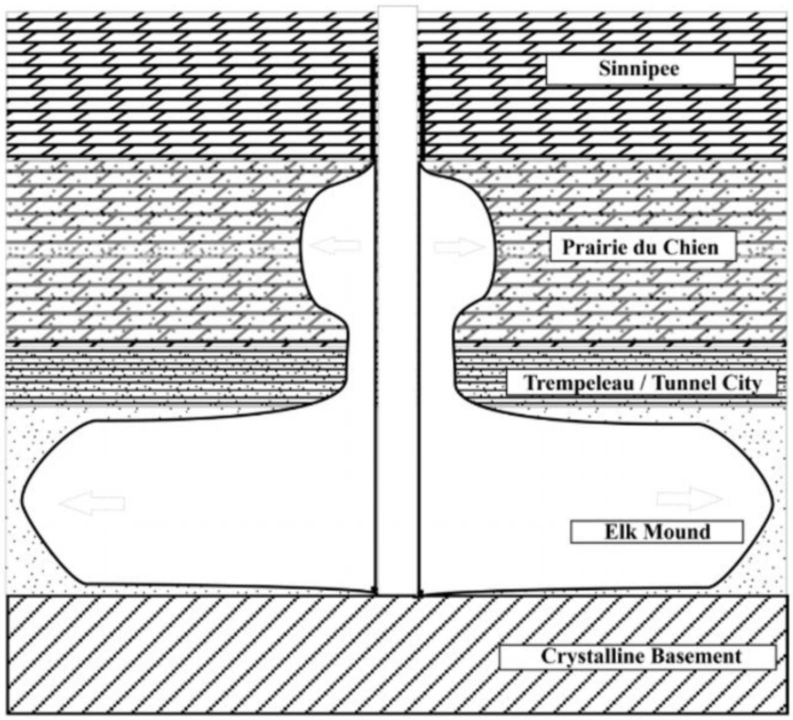


Figure 6: Original conceptual model of the Green Bay ASR flow system. (Source: [1])

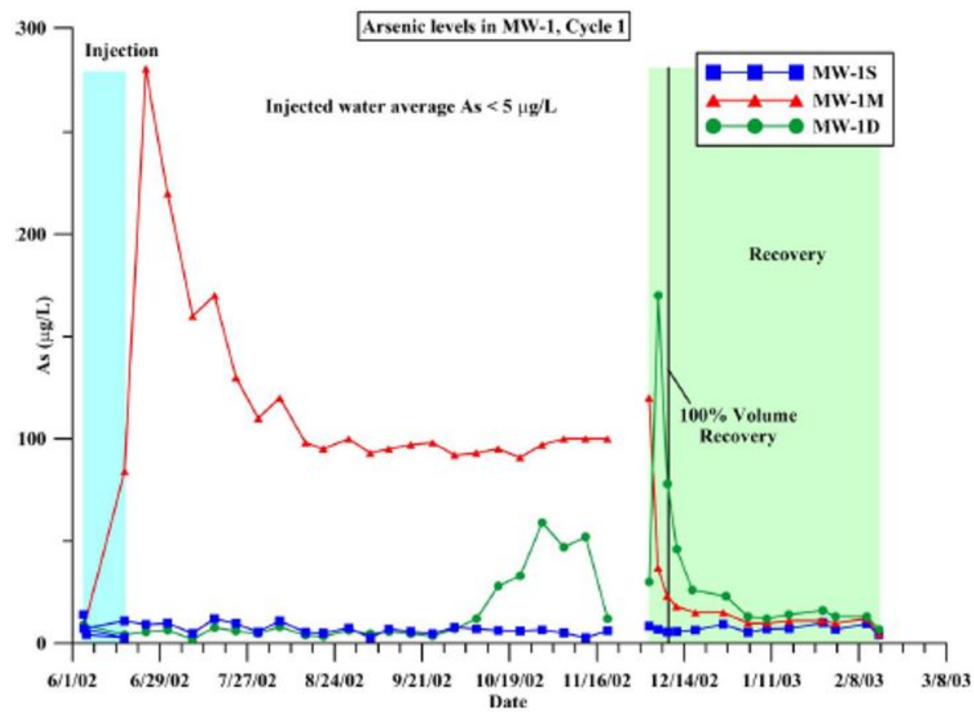


Figure 7: Arsenic levels found during Pilot Cycle 1 in the monitoring well in the Prairie du Chien (MW-1S), Trempealeau-Tunnel City (MW-1M), and Elk Mound (MW-1D) Groups. (Source: [1])

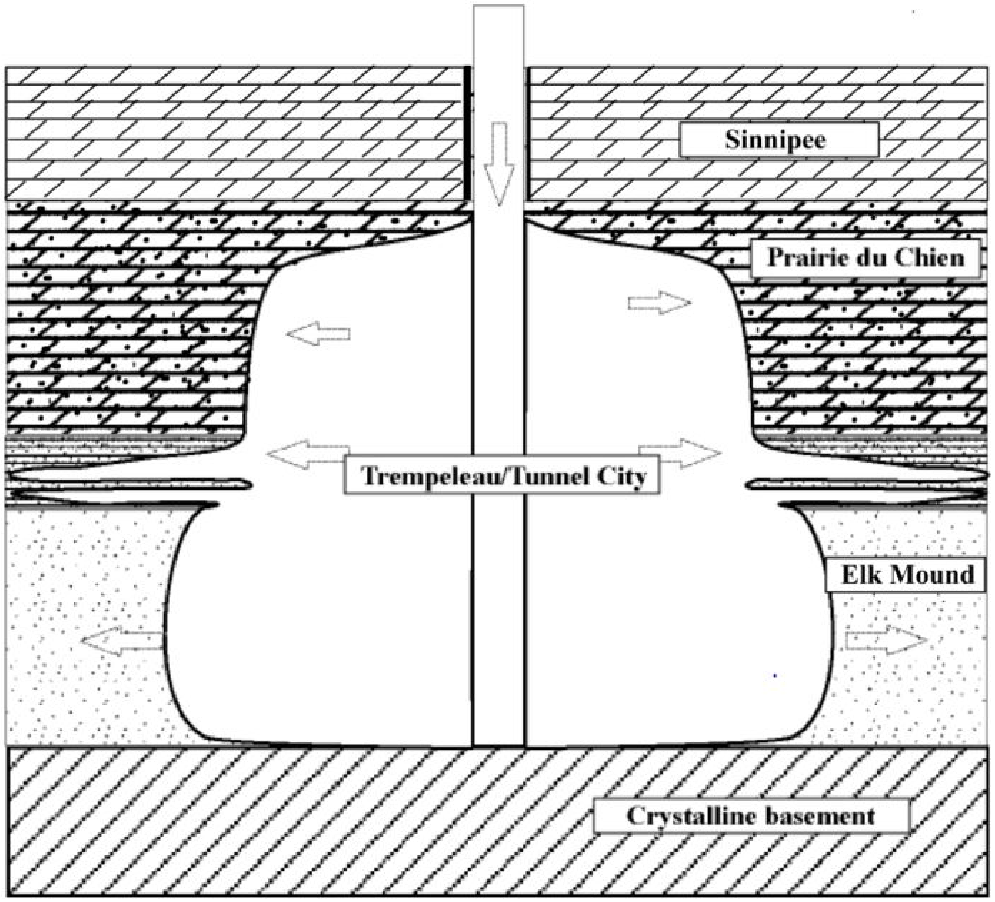


Figure 8: Revised conceptual model of the Green Bay ASR flow system. (Source: [1])

Arsenic levels in the first pilot cycle indicated that the Tunnel City Group was the main source of arsenic contamination. For the second pilot cycle, the well casing was extended in an attempt to restrict flow to only the Elk Mound Group. Unfortunately, this action was unsuccessful and arsenic concentrations still spiked during injection and recovery (Figure 9). Simultaneous water chemistry changes in the Prairie du Chien and Tunnel City groups indicated that the flow was not restricted to the Elk Mound System. This failure was attributed to the presence of vertical fractures in the vicinity of the ASR well as a result of blasting during well construction. While arsenic levels were lower in the second cycle, the variations in injection volume, injection time, and storage time between the two cycles precluded any significant conclusions about aquifer conditioning.

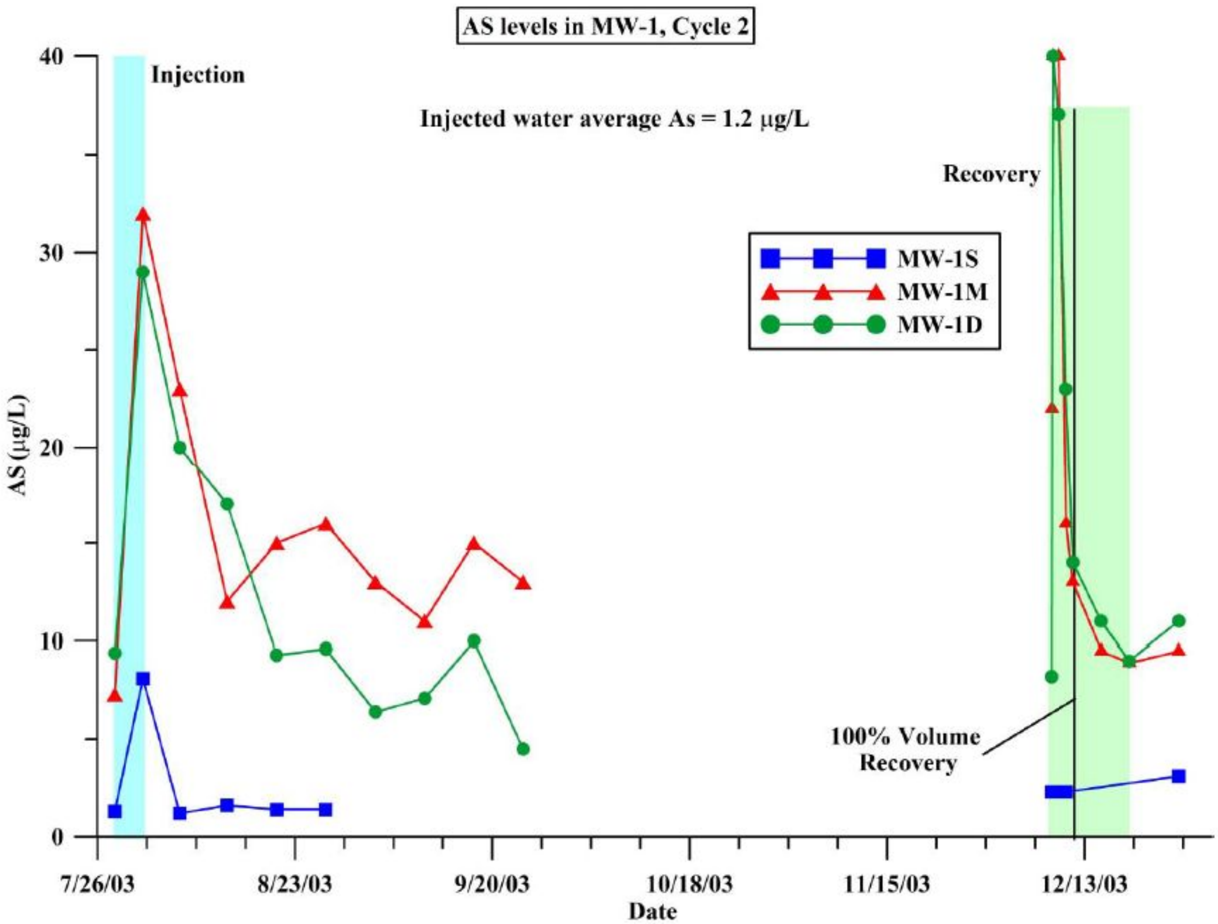


Figure 9: Arsenic levels found during Pilot Cycle 1 in the monitoring well in the Prairie du Chien (MW-1S), Trempealeau-Tunnel City (MW-1M), and Elk Mound (MW-1D) Groups. (Source: [1])

During the first cycle, strong positive correlations were observed between the concentrations of arsenic and sulfate in the injected, stored, and recovered water, implying that the release of arsenic and sulfate were mediated by the same mechanism. This mechanism is most likely the dissolution of arsenic-containing iron-sulfide minerals like arsenopyrite [FeAsS] or arsenian pyrite [$Fe(As,S)_2$]. Pyrite minerals can be destabilized through changes in either pH or reduction potential (E_h), or both. Throughout the test cycles pH in the water remained very stable, suggesting that changes in pH were not directly responsible for the arsenic release. E_h, on the other hand, varied widely during pilot cycles due to the injection of highly oxygenated surface water, which had an average dissolved oxygen concentration of 15.5 mg/L, and an average E_h of 635 mV. In contrast, the native groundwater on the site exists in a reduced state. Pyrite minerals are stable in this reduced state, when the contacting water has a negative E_h. At the pH of the water during injection and recovery, elevated E_h values caused the pyrite to become unstable, as shown in Figure 10. When E_h values dropped during storage, arsenic concentrations decreased as the conditions in the aquifer became amenable to pyrite stability. Increases in arsenic concentrations during injection and recovery can then be attributed to the oxidative dissolution of arsenic-bearing iron sulfides.

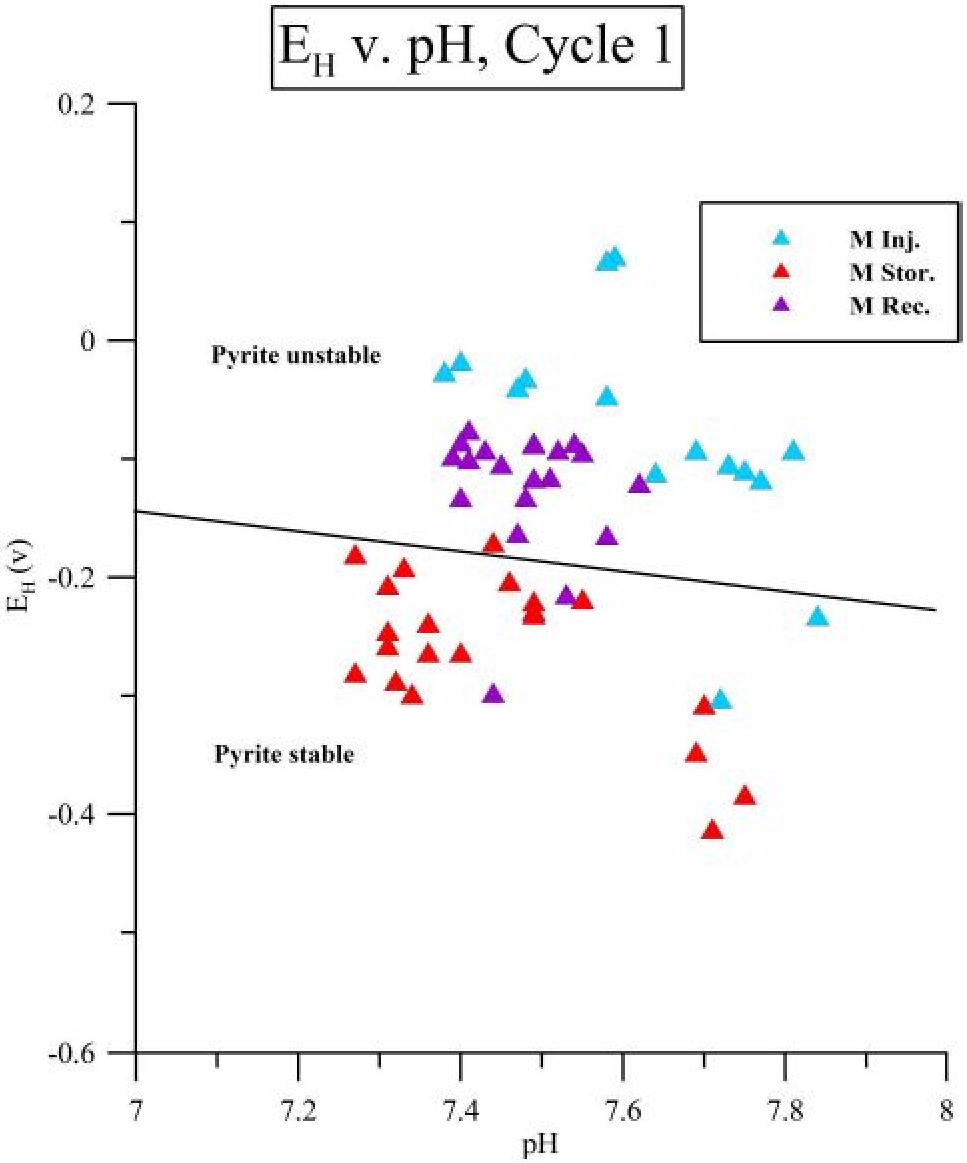


Figure 10: $E_{h \text{ vs.}}$ pH diagram of observations in the Tunnel City Group during injection (M Inj.), storage (M Stor.), and recovery (M Rec.). (Source: [1])

Future Projections

Overall, the ASR testing in Green Bay, Wisconsin yielded unexpected chemical changes that can be attributed to unfavorable interactions between the injected source water and the native groundwater as well as aquifer minerals. Due to the inability to restrict injected flow from entering the Tunnel City Group, which was deemed the major source of arsenic contamination, the project was abandoned and the City moved forward with an expansion of their drinking water treatment plant.

Policy Connections

The United States Environmental Protection Agency (EPA) has created National Primary Drinking Water Regulations (NPDWR). These regulations are legally enforceable limits on the levels of contaminant in drinking water in order to protect public health. One of the regulated contaminants is arsenic which has a maximum contaminant level (MCL) of 10 µg/L. The MCL is the highest value of arsenic that is acceptable in drinking water. States also have the authority to set more stringent limits. Arsenic is naturally present at low levels in groundwater, but during injection and recovery phases of the Green Bay ASR pilot study, concentrations of arsenic rose well above the MCL making the recovered water unsuitable for distribution to customers.

Economic Considerations

The Green Bay ASR project was explored in order to potentially avoid the cost of expanding the city's drinking water treatment facility. Expansion of these facilities are expensive, easily in the millions of dollars. A large amount of work has been done in the area of estimating the cost of drinking water treatment plant construction and expansion, which in and of itself is a testament to the significance of the associated costs. ASR is a method by which these exorbitant expansions can be avoided. While the construction and operation of ASR wells come with a price, the cost is minimal compared to expanding the capacity of a drinking water treatment plant.

References

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2. Wu, X., Bowers, B., Kim, D., Lee, B., & Jun, Y.-S. (2019). Dissolved Organic Matter Affects Arsenic Mobility and Iron(III) (hydr)oxides Formation: Implications for Managed Aquifer Recharge. *Environmental Science & Technology*, (Iii). https://doi.org/10.1021/acs.est.9b04873
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4. "National Primary Drinking Water Regulations." *EPA*, Environmental Protection Agency, 14 Feb. 2020, www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#one.