COMPARISON OF SURFACE AND GROUND WATER AS RECHARGE IN AQUIFER STORAGE AND RECOVERY WELLS

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ABSTRACT: Surface water treated to drinking water standards offers several important advantages over treated groundwater as a source of recharge to Aquifer Storage and Recovery (ASR) wells screened in confined, sandy aquifers. In confined aquifers comprised of a quartz sand matrix, pore water chemistry is often controlled by metal bearing-, and clay minerals. Successful ASR operations are often dependent on stabilizing these minerals in situ.

Surface water typically exhibits a relatively neutral pH that can be easily adjusted according to the geochemistry of the storage aquifer. In fresh surface waters away from coastal areas, calcium is the predominant cation, and is beneficial for stabilizing clay minerals in the storage aquifer. Surface water typically contains near saturation concentrations of dissolved oxygen (DO) which is beneficial for initiating the oxidation of common reduced-state, iron bearing minerals like pyrite and siderite. With the addition of sodium hydroxide (NaOH) to oxygenated recharge water to control pH, iron-bearing mineral minerals can be rapidly stabilized by the formation of ferric hydroxide precipitate coatings. These coatings isolate the mineral from further reaction with the aquifer environment and are highly sorptive of metal ions migrating in the aquifer environment. In the absence of DO, oxidation reactions are not initiated, and dissolved iron concentrations in the stored water reach equilibrium with the surrounding mineralogy.

Drawbacks to the use of treated surface water as a source of recharge include elevated concentrations of total organic carbon (TOC), total trihalomethanes (THM), and haloacetic acids (HAA). In confined storage aquifers, THM concentrations decline to 20 to 50 percent of their original concentration after several weeks of storage, with the degradation of brominated forms preceding chlorinated species. However, these rapid reductions in concentration moderate over several operational cycles, as the aquifer matrix is repeatedly oxidized.

INTRODUCTION

Surface water treated to drinking water standards offers important economic and geochemical advantages over treated groundwater as a source of recharge to Aquifer Storage and Recovery (ASR) wells. This paper will focus on advantages and disadvantages of treated surface water as a source of recharge to ASR wells, with discussion of several case studies. Although ASR wells are installed in a number of geologic terrain (glacial sand and gravel, limestone, sandstone, fractured basalt), all of the examples discussed in this paper involve wells screened in confined, clayey sand aquifers of the Atlantic Coastal Plain Physiographic Province.

ECONOMIC ADVANTAGES

ASR wells can substantially increase the peak period capacity of surface water treatment plants with no actual modification to the internal treatment processes at the plant. In a growing system, implementation of ASR wells can delay costly increases to treatment plant expansion until average day system demands, (not peak day demands) roughly equal the daily treatment capacity of the plant. Thus, plants can be run at a more economical base load throughout the year, while ASR wells are brought into service to meet peak day demands. When

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treatment plant expansion is finally necessary, the magnitude of modifications can be moderated so the plant is sized to meet future average day demands, as opposed to peak day demands. ASR wells can be used in conjunction with the plant to meet peak period/day demands.

Unit costs for the expansion to surface water treatment plants presently range from $2,000,000 to $4,000,000 per million gallons per day of capacity, while unit costs for ASR wells range from $250,000 to $500,000 per MGD of capacity. Thus, increasing peak period capacity with ASR wells is roughly 4 to 16 times less expensive than conventional treatment plant expansion. Table 1 presents numerous examples of capital costs of surface water treatment plant expansions in comparison to the installation cost for ASR facilities. In all examples, total capital costs for surface water treatment plant expansions are over 2 times the cost of ASR facility expansion.

Table 1. Comparison of Surface Water Treatment Plant Costs with ASR

<table>
<thead>
<tr>
<th>Location</th>
<th>Expansion Cost ($ million)</th>
<th>With ASR</th>
<th>Without ASR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wyoming, MI</td>
<td></td>
<td>9</td>
<td>31</td>
</tr>
<tr>
<td>Peace River, FL</td>
<td></td>
<td>46</td>
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</tr>
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<td>Manatee County, FL</td>
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<td>Florida Keys, FL</td>
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<td>5</td>
<td>35</td>
</tr>
<tr>
<td>Kerrville, TX</td>
<td></td>
<td>3</td>
<td>30</td>
</tr>
</tbody>
</table>

GEOCHEMICAL ADVANTAGES

In confined aquifers comprised of relatively inert, quartz sand, framework grains, pore water chemistry is often controlled by a minute percentage of interstitial, reactive metal bearing minerals, and clay minerals. Successful ASR operations, as defined by no post-recovery treatment, are dependent on stabilizing metal-bearing and clay minerals in situ. The inherent chemistry of surface water (elevated dissolved oxygen concentrations, calcium bicarbonate chemistry), even after treatment, offers certain advantages for stabilization of minerals within the storage zone matrix.

Iron and Manganese

At equilibrium, reduced-state iron bearing minerals like pyrite (FeS₂) and siderite (FeCO₃) can release large amounts of dissolved iron into the surrounding pore water. As manganese ions occupy a percentage of iron sites in these minerals, at a ratio ranging from 1/10 to 1/100 of the iron sites, dissolved manganese is often also present in pore water chemistry with iron. At the proper physiochemical conditions, dissolution of iron/manganese bearing minerals also occurs in water stored in aquifers containing these minerals.

Two examples of sites where water is stored in an aquifer containing elevated iron and manganese concentrations have been selected to demonstrate the advantage of surface water in stabilizing reactive metal bearing minerals in situ. The ASR sites lie in adjacent municipalities in New Jersey. Both systems use the sand units comprising the Potomac-Raritan-Magothy (PRM) Aquifer System as a storage zone.

At one site, the owner (Moorestown Township Department of Public Works-MTDWP) purchases surface water from an adjoining water purveyor to augment an internal groundwater source of supply. The interconnection between the two systems lies adjacent to the ASR facility, thus a significant percentage of the water used for recharge originates from the interconnection. Typical of surface water, the recharge water contains near saturated concentrations of dissolved oxygen (6.0 to 12.0 milligrams per liter), and is a calcium-bicarbonate type. Iron concentrations in the native groundwater of the Middle PRM Aquifer range from 8 to 9 mg/L.

At the second site (Mount Laurel Township Municipal Utilities Authority-MTLMUA) recharge water originates from a water treatment facility that handles strictly groundwater. Water is treated by filtration in a totally pressurized system. Treated effluent from the plant is anoxic with dissolved oxygen (DO) concentrations less than 1.0 mg/L. Iron concentrations in the native groundwater of the Lower PRM Aquifer are around 10 mg/L, and manganese concentrations range around 0.1 mg/L.
ASR wells at both facilities are screened in the Middle (MTDPW) and Lower (MTLMUA) Aquifers of the PRM system. Core samples of aquifer sands from these units describe a typical mineralogy consisting of 90 to 95 percent quartz, 1 to 3 percent feldspar, 1 percent lignite, and trace percentages of pyrite and siderite. Pyrite and siderite are typically associated with accumulations of organic debris, clay minerals, and generally finer-grained portions of the aquifers. However, both pyrite and siderite occasionally occur as authigenic growths in the pore spaces of coarser grained portions of the aquifer. In these zones, the minerals line major flowpaths in the aquifer.

MTDPW

At the MTDPW site, the pH of oxygenated recharge water is adjusted with sodium hydroxide (NaOH) to increase the pH from around 7.2 to 8.3. At 8.3, the pH of the recharge water is above the solubility limits of iron/manganese bearing minerals. With the addition of the OH-ion to recharge water containing DO, iron bearing minerals in the Middle PRM Aquifer are rapidly stabilized through the formation of ferric oxyhydroxide coatings on pyrite and siderite. Iron concentrations in recovered water from three ASR Test Cycles were less than laboratory method detection limits (MDL) even after up to 100 percent of the recharge water was recovered (Figure 1).

The pH of the recovered water was around 1.0 standard unit lower than the native groundwater, ranging from 5.5 to 6.5. Concentrations of DO ranged from 6.0 mg/L at the beginning of a recovery cycle to less than 1.0 mg/L at the end. The last water recovered typically travels the greatest distance from the ASR well and undergoes the longest storage period in the aquifer. With time and travel in the storage aquifer, DO is depleted through reactions with aquifer mineralogy.

Sulfate concentrations in the recovered water were more elevated than the recharge water or native groundwater. Elevated sulfate concentrations are indicative of pyrite oxidation. In the presence of DO, pyrite releases ferrous iron and the bisulfide ion. With abundant OH-ions, ferrous iron is precipitated as a ferric oxyhydroxide. The bisulfide ion oxidizes to sulfuric acid, lowering the pH of the stored water and increases sulfate concentrations.

During Test Cycle 1, sulfate concentrations were greatest at the beginning of recovery (35 mg/L), and declined to 18 mg/L at the end. During Test Cycles 2 and 3, sulfate concentrations reached maximum concentrations near the middle of the cycle. As test volumes increased with progressive cycles, the elevated sulfate concentrations reflected water quality of greater volumes recovered, and thus from greater distances in the storage aquifer from the ASR well. Sulfate concentrations in regard to recovery volume are a useful indicator in the progress of pyrite oxidation in the storage aquifer.

MTLMUA

Using anoxic recharge water with the pH adjusted to 8.3 with NaOH, total iron concentrations in the recovered water increased from 0.296 mg/L during the early portion of the cycle to 5.3 mg/L at 78 percent of the recharge water recovered (Figure 2). Dissolved iron concentrations increased from 0.28 mg/L to 5.2 mg/L. The relative equivalence in total and dissolved iron concentrations suggests that the recovered water was in equilibrium with some mineral phase in the aquifer. Iron concentrations during the recovery portion of Test Cycle 1 appear to track closely with iron concentrations predicted by mixing between recharge water and native groundwater.

During Test Cycle 1, the pH of the recovered water declined from 7.5 at the beginning of the cycle to 6.8 at 78 percent of the recharge water recovered; the pH of the native groundwater. In the absence of DO in the recharge water, the oxidation/reduction potential (Eh) of the recovered water declined rapidly during the recovery portion of Test Cycle 1 from 400 millivolts (mv) at the beginning of the cycle to 120 mv after 20 percent of the recharge water was recovered. The Eh of the recovered water stabilized around 100 mv for the rest of Test Cycle 1.

Examination of thermodynamic equilibrium relationships of pH and Eh and output from the geochemical model MINTEQA2 (Allison, et. al. 1991) suggests that in addition to mixing with the native groundwater, the low Eh and equilibrium with the iron carbonate mineral, siderite in the storage aquifer, influenced iron concentrations in the recovered water. Other water quality parameters including sulfate and alkalinity suggest that iron concentrations in the recovered water from Test Cycle 1 were controlled by equilibrium with siderite. During Test Cycle 1, sulfate concentrations tracked closely between the concentrations of recharge water and the concentrations of the native groundwater. Alkalinity concentrations tracked in a similar manner during Test...
Cycle 1. If iron bearing minerals in the storage aquifer were oxidized, sulfate concentrations in the recovered water would increase, and with the formation of acids, pH, and alkalinity would decline.

With the introduction of DO to the recharge water during Test Cycles 2 and 3, the iron chemistry of the recovered water changed significantly in comparison to Test Cycle 1. Despite significant amounts of mixing between the recharge water and native groundwater during Test Cycle 2, total iron concentrations ranged from less than 0.1 mg/L to 0.18 mg/L at the end of the cycle (89 percent recovered). During Test Cycle 3, iron concentrations remained below 0.1 mg/L until after 80 percent of the recharge water was recovered, and slowly increased to 0.7 mg/L at the end of the cycle (141 percent recovered).

Although DO concentrations in the recovered water from Test Cycles 2 and 3 declined rapidly to near zero, Eh of the recovered water was relatively oxic ranging from around 400 to 210 mv. The pH of the recovered water during Test Cycles 2 and 3 declined from around 7.5 at the beginning of the cycles to 6.1 at the end of both cycles. Sulfate concentrations in the recovered water were elevated above concentrations in the recharge water at the beginning of recovery and declined to concentrations equivalent to the native groundwater at the end. Thus, the progressive oxidation of iron bearing minerals is apparent in the recovered water chemistry of Test Cycles 2 and 3.

**Clay Minerals**

Mobilization of clay minerals through mechanical or chemical mechanisms during recharge operations is a concern for successful ASR operations. Mobilized clay minerals can migrate into pore throats, brush piling in narrow interstices occluding flow, and eventually reducing the intrinsic permeability of the aquifer. In addition, disaggregation of clay minerals can increase the turbidity of the recovered water. In certain areas of the New Jersey Coastal Plain, aquifers naturally produce water with elevated turbidity. Native groundwater from these units typically exhibits a sodium-bicarbonate chemistry. In the absence of treatment with a stabilizing, concentrated salt solution rich in divalent or trivalent cations, a well can be pumped from 48 to 72 hours before turbidity levels decline to less than 5 NTUs. Recharge operations can increase turbidity in the recovered water even when the recharge water and native groundwaters exhibit nearly identical ionic strengths.

X-ray diffraction analysis of filtrate samples of turbid water from several different sites, involving different aquifers reveals a remarkably similar clay mineral suite, despite the clay mineralogy defined by core samples from each storage aquifer. Filtrate samples of turbid water were collected at the MTDPW site, Monroe Municipal Utilities Authority in Gloucester County, New Jersey, and the United Water Toms River site in Ocean County, New Jersey.

The clay mineralogy of filtrate samples is dominated by kaolinite which comprises over 50 percent of sample by volume, followed by illite/micas, illite/smectite, and chlorites. By comparison clay mineralogy of core samples at these sites is dominated by from greatest to least: illite-smectite, illite/mica, kaolinite and chlorite. Percentages of kaolinite and chlorite are typically 1/4 to 1/2 of illite/smectite, or illite/ mica assemblages. Only core samples from the MTDPW site exhibit a clay mineral suite dominated by kaolinite. Comparison of the clay mineralogy of filtrate samples from turbid water, and core samples suggests kaolinite is less well attached than other clay minerals in the aquifers of the New Jersey Coastal Plain, and prone to mobilization from mechanical or geochemical mechanisms during recharge operations.

At sites where turbidity is caused by recharge operations, the calcium-bicarbonate chemistry of surface water appears beneficial for stabilizing clay minerals in situ, and mitigating turbidity in recovered water. Testing at the UWTR site reveals that recharging water with a calcium bicarbonate chemistry results in recovered water with significantly less turbidity than a groundwater exhibiting sodium bicarbonate chemistry, or groundwater adjusted to a sodium bicarbonate chemistry with NaOH (Figure 3). Initial turbidity is less and declines more rapidly than with other water types. Similar testing at the MTDPW site displays a similar, yet less severe pattern (Figure 4).

**DISADVANTAGES OF SURFACE WATER AS A SOURCE OF RECHARGE WATER**

Treated surface water can also exhibit properties that are disadvantages for use as recharge water. Treated surface water nearly always contains significantly greater total THM's, HAA's, and other disinfection byproducts than treated groundwater. Further, treated surface water typically contains greater total suspended solids than
treated groundwater. Suspended solids exhibit a tendency to accumulate in the screen, gravel pack, and at the borehole wall, occluding pore spaces and reducing the specific capacity of the well. The frequency of backflushing during recharge and well rehabilitation, is increased with water containing elevated suspended solids concentrations.

The behavior of THM's in storage aquifers is well documented in recent literature (Brothers, et. al., 1993; Pyne, et. al., 1993). In confined aquifers exhibiting reduced conditions, THM concentrations and formation potential decline as a function of storage time. THM concentrations are often reduced by nearly 100 percent depending on storage time and aquifer conditions. Concentrations of brominated forms (bromoform, bromodichloromethane, and dibromochloromethane) decline more rapidly than chlorinated forms (chloroform). Mechanisms for THM attenuation are poorly understood, but are believed to occur through the action of anaerobic bacteria, or sorption reactions with natural organics contained in the aquifer matrix (Pyne, et. al. 1993).

However, long term ASR operations in a confined aquifer with oxygenated recharge water are typified by gradual, yet progressive, oxidation of the aquifer mineralogy. Thus, conditions favorable to THM reduction are progressively degraded. After several operational cycles, reduction of THM concentrations is moderated, and longer periods of storage time are required to achieve the same reduction as previous cycles.

CONCLUSIONS

Surface water treated to drinking water standards offers several important advantages over treated groundwater as a source of recharge water to ASR wells screened in confined sandy aquifers.

- Use of ASR wells at surface water treatment plants to delay treatment plant expansion, typically offers the greatest economic advantages of any use of ASR.
- As surface water typically contains nearly saturated levels of DO, it is beneficial in the progressive oxidation and stabilization of iron and manganese minerals in the storage aquifer. Drinking quality water can be recovered from aquifers containing native groundwater with dissolved iron concentrations greater than 10 mg/L.
- DO must be added to anoxic, treated groundwater through specialized engineering measures to achieve the same degree of effectiveness in stabilizing iron bearing minerals in situ.
- Surface water exhibiting a calcium bicarbonate type chemistry is beneficial in reducing turbidity in recovered water from aquifers where clay minerals are mechanically or geochemically unstable during recharge operations.
- Surface water typically contains significantly higher concentrations of THMs than surface water. THM reduction is significant in confined aquifers and is strongly correlative to aquifer storage time. However, with successive cycles and oxidation of the aquifer mineralogy, THM reduction moderates.

REFERENCES

