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Assessing the Impact of Chlorinated-Solvent Sites on Metropolitan Groundwater Resources

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Abstract

Chlorinated-solvent compounds are among the most common groundwater contaminants in the U.S.A. The majority of the many sites contaminated by chlorinated-solvent compounds are located in metropolitan areas, and most such areas have one or more chlorinated-solvent contaminated sites. Thus, contamination of groundwater by chlorinated-solvent compounds may pose a potential risk to the sustainability of potable water supplies for many metropolitan areas. The impact of chlorinated-solvent sites on metropolitan water resources was assessed for Tucson, AZ, by comparing the aggregate volume of extracted groundwater for all pump-and-treat systems associated with contaminated sites in the region to the total regional groundwater withdrawal. The analysis revealed that the aggregate volume of groundwater withdrawn for the pump-and-treat systems operating in Tucson, all of which are located at chlorinated-solvent contaminated sites, was 20% of the total groundwater withdrawal in the city for the study period. The treated groundwater was used primarily for direct delivery to local water supply systems or for reinjection as part of the pump-and-treat system. The volume of the treated groundwater used for potable water represented approximately 13% of the total potable water supply sourced from groundwater, and approximately 6% of the total potable water supply. This case study illustrates the significant impact chlorinated-solvent contaminated sites can have on groundwater resources and regional potable-water supplies.

Introduction

Chlorinated-solvent compounds such as trichloroethene, tetrachloroethene, and carbon tetrachloride are among the most common groundwater contaminants in the USA due to their prior widespread use for numerous military, industrial, and commercial applications. These compounds are classified as known or suspected human carcinogens, and hence their regulatory standards for groundwater are in the range of a few $\mu\text{g/L}$. The toxicity of these compounds is of continuing concern. For example, the U.S. Environmental Protection Agency recently completed a toxicological review for trichloroethene (EPA, 2011), and the results may lead to more stringent screening levels and regulatory limits. Given their toxicity, widespread occurrence, and persistence, groundwater contaminated by chlorinated solvents continues to pose a significant risk to human health.

Extensive dissolved-phase groundwater contaminant plumes typically form at sites contaminated by these compounds because of their relatively high aqueous solubilities (in comparison to regulatory standards), limited retardation, and generally low (or very site dependent) transformation potential. In many cases, the plumes are hundreds of meters to several kilometers long. These large plumes are very expensive to contain and remediate, and present difficult challenges to the long-term management and closure of the sites.

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The majority of the many sites contaminated by chlorinated-solvent compounds are located in metropolitan areas, and most such areas have one or more chlorinated-solvent contaminated sites. Thus, contamination of groundwater by chlorinated-solvent compounds may pose a potential risk to the sustainability of potable water supplies for many metropolitan areas. The objective of the analysis presented herein is to assess the impact of chlorinated-solvent contaminated sites on metropolitan water resources, using Tucson, AZ, as a case study. This assessment includes the application of a novel metric, the fraction of total regional groundwater withdrawal represented by the aggregate groundwater extraction for all pump-and-treat systems in the region. While the assessment is focused on chlorinated-solvent compounds, the approach, results, and implications apply to other contaminants prone to forming large, persistent plumes, such as 1,4-dioxane, methyl tertiary-butyl ether, and perchlorate.

Materials and Methods

The City of Tucson, AZ, is used as the case study for the assessment. Until recently, Tucson was one of the largest municipalities in the U.S.A. whose potable water supply was sourced almost entirely from groundwater. Beginning in the early 2000's, the Central Arizona Project, which supplies water from the Colorado River, has provided an additional source of potable water through aquifer recharge and recovery activities conducted at facilities located on the city perimeter. Currently, it provides approximately 60% of all potable water for Tucson, with groundwater providing the remainder.

Chlorinated-solvent compounds are the primary contaminants of concern at 44 of the 50 current State and Federal Superfund sites located in Arizona. These sites comprise billions of liters of contaminated groundwater that are not available for direct potable use, hence posing a significant and long-term risk to the sustainability of water resources in Arizona. There are nine major Superfund sites located in Tucson, with seven State of Arizona Water Quality Assurance Revolving Fund sites, one Federal National Priorities List site, and one Department of Defense site (see Figure 1). Note that the Tucson International Airport Area (TIAA) site located in the south of Tucson comprises seven individual sub-sites, as delineated in the figure. Data for the sub-sites are aggregated for this analysis. The presence of contaminated groundwater has caused some potable-water supply wells to be removed from operation for some of the sites.

Typically, the impact of a Superfund or other sites on groundwater resources is assessed based on the footprint of the groundwater contaminant plume (e.g., the expanse of the plume demarcated by the concentration contour for the regulatory limit). This approach (with knowledge of porosity and plume thickness) provides a determination of the volume of groundwater contaminated at the time of assessment. However, given the nature of these sites and the presence of contaminant mass in other phases in addition to that in groundwater, this metric greatly underrepresents the actual impact of the contamination on groundwater resources. This is clearly illustrated by the behavior of plumes at sites wherein pump and treat has been in operation for many years. It is commonly observed that, while significant quantities of contaminant mass have been removed (often greater than the mass estimated to be present initially in the (aqueous-phase) plume), the size of the plume does not decrease substantially. Such behavior has been observed, for example, for the TIAA site shown in Figure 1 (Brusseau et al., 2007, 2011).

An alternative metric is introduced to provide a more comprehensive assessment of the impact of groundwater contamination on water resources. This metric entails determining the aggregate volume of groundwater extraction for all pump-and-treat systems in the region of interest. This volume is compared to the total groundwater withdrawal for all uses in that

region. The data are indexed to groundwater withdrawals rather than total potable water supply to focus the analysis on groundwater resources. However, the impact in relation to total water resources can readily be examined by incorporating the relative fraction of total potable supply contributed by groundwater sources.

Information was obtained for all sites in Tucson for which pump and treat is being (or has been) used for groundwater treatment. Information concerning the total contaminant mass removed as of 2010 and volume of groundwater extracted is presented in Table 1. The data were obtained from performance reports submitted to the pertinent regulatory agencies. Information for total groundwater withdrawals in the City of Tucson was collected from several sources, primarily the water providers noted in Table 2, for 2010.

Results

As noted, there are nine state and federal Superfund sites in Tucson. Tetrachloroethene and/or trichloroethene are the primary contaminants of concern at all of these sites. The footprints of the groundwater contaminant plumes are shown in Figure 1. The aggregate area of the plumes represents a substantial fraction of the areal expanse of the city. Inspection of Table 1 shows that the TIAA site provides by far the greatest contribution to aggregate groundwater withdrawals and contaminant masses recovered.

Pump-and-treat systems are in operation at five of the sites (Table 1). Multiple systems are in operation at three of the five sites. For example, six separate systems were in operation at the TIAA site during the timeframe of the analysis. The operational data for the separate systems is aggregated for each site for the analyses reported herein. In total, there were 12 pump-and-treat systems in operation at the five sites during the timeframe of analysis. The total volume of groundwater withdrawn in 2010 for these systems was approximately 16.5 Million m³ [13,400 acre-ft].

The volumes and sources of groundwater withdrawn in the metropolitan area for 2010 are listed in Table 2. The total volume withdrawn, not including volumes associated with the pump-and-treat systems, is approximately 68.3M m³ [55,400 acre-ft]. Comparison of the two volumes reveals that the aggregate volume of groundwater withdrawn for the pump-and-treat systems is ~20% of the combined total groundwater withdrawal (84.8M m³ [68,800 acre-ft]), including both potable water supply and pump-and-treat systems. A similar analysis was conducted using data collected for year 2008, and the results were essentially identical.

The disposition of the extracted groundwater after receiving treatment is a critical factor for assessing the ultimate impact of groundwater contamination on water resources. There are four general types of applications for treated water. In many cases, the treated water is reinjected as part of the pump-and-treat system design. While this application may facilitate system operations, the water can be considered as lost to the metropolitan water resources supply. Treated water in some cases is used on-site for various applications. If this water replaces equivalent volumes that would be otherwise obtained from the potable water supply, it is not considered lost to the metropolitan water resources supply. For some sites, treated water is delivered directly to potable water supply systems, and thus provides a direct contribution to the metropolitan water resources supply. Finally, treated water may be disposed of by, for example, delivery to a sewer system or surface water body. The impact of this application to the metropolitan water resources supply will depend on the disposition and use of the source to which the treated water is delivered.

The disposition of the treated groundwater is noted in Table 1 for the pump-and-treat systems analyzed. The water is reinjected as part of the pump-and-treat system for some

sites. For other cases, the water is used on-site for various applications. For example, a portion of the treated water is applied to the land surface for dust control at the Los Reales Landfill site. Treated water was used in the manufacturing process for the Texas Instruments sub-site of the TIAA site. The treated water is delivered directly to potable water supply systems for some sites. For example, all of the treated water at the TARP sub-site of the TIAA site is delivered to Tucson Water's potable water supply system, and represents approximately 20% of their total groundwater withdrawals.

Approximately 9.9M m³ [8000 acre-ft] of the treated groundwater is used in a manner that contributes to the metropolitan water resources supply, with the vast majority being delivered directly to potable water supply systems. This volume represents approximately 60% of the total volume of groundwater withdrawn for all of the pump-and-treat systems. The remaining 40% portion is reinjected as designed for the pump-and-treat systems. This fraction, considered lost to the metropolitan water resources supply, represents approximately 8% of the aggregate total groundwater withdrawal for the city. However, this water can be considered to have beneficial use if reinjection is critical to operation of the system (e.g., enhances the rate of remediation, reduces risk).

Conclusion

The analysis presented above revealed that the aggregate volume of groundwater withdrawn for the pump-and-treat systems operating in Tucson, all of which are located at chlorinated-solvent contaminated sites, was 20% of the total groundwater withdrawal in the city in 2010. The treated groundwater was used primarily for direct delivery to local water supply systems or for reinjection as part of the pump-and-treat system. The volume of treated groundwater delivered to potable water supply systems represented approximately 13% of the total potable water supply sourced from groundwater. In addition, this volume represented approximately 6% of the total potable water supply (including all sources such as CAP). These results show that treated groundwater associated with the contaminated sites provides a substantial contribution to the regional water resources supply. Given that chlorinated-solvent contaminated sites are present in many metropolitan areas, the results obtained herein may reflect conditions at many other cities dependent upon groundwater for a substantial portion of their water supply.

Pump and treat has been the primary method used to contain and treat groundwater contaminant plumes at chlorinated-solvent sites. After approximately 30 years of experience gained, it is now clear that most sites with large plumes comprising these contaminants will require many more decades before cleanup will be achieved under current methods and standards (e.g., NRC, 2013). The continued use of pump and treat to manage plumes at these sites for the many additional decades anticipated will result in an enormous aggregate operations and maintenance cost. For example, it is estimated that the Department of Defense may spend more than \$100 million annually for hydraulic containment at chlorinated-solvent sites using pump-and-treat technologies, with total lifetime aggregate costs exceeding \$2 billion (SERDP, 2006). Furthermore, it has been estimated that aggregate annual pump-and-treat costs for the estimated 15,000 to 25,000 sites in the U.S. with chlorinated-solvent contamination could range from \$2.7 to \$4.5 billion dollars, with lifetime aggregate costs exceeding \$100 billion (EPA, 2003).

In light of this situation, great interest has developed in alternative methods that can be used to cost-effectively manage these plumes, such as permeable reactive barriers and monitored natural attenuation. Assessments of the implementation of such alternatives should consider the potential long-term impact on regional water resources. As illustrated herein, groundwater treated by pump-and-treat systems is often used for beneficial purposes that

contribute to metropolitan water resources supplies. Transitioning of the pump-and-treat system to an alternative such as monitored natural attenuation would generally eliminate the contribution of that source of water to the water supply, considering that contaminant concentrations within the plume would typically remain above the regulatory limit for an extended time. However, this could be addressed for example by using on-demand (e.g., wellhead) treatment of groundwater. It is important to note that the use of standard permeable reactive barriers is generally impractical for the large, deep contaminant plumes associated with sites in the southwest U.S.A., and that monitored natural attenuation is often not feasible due to site conditions. Hence, it is likely that pump and treat will continue to play a critical role in long-term management of contaminated groundwater at many chlorinated-solvent sites. Efforts to optimize the operational cost-effectiveness of such systems should include consideration of their impacts on local water resources.

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Figure 1.
Map of major contaminated sites in Tucson; developed by Arizona Department of Environmental Quality (public domain).

Table 1

Chlorinated-Solvent Contaminated Sites in Tucson with Pump-and-Treat Systems

Site	Plume Area (km ²)	PAT ^a Initiated	# PAT ^a Systems	Contaminant Mass Removed ^b (kg)	Groundwater Extracted 2010 (million m ³)	Disposition of Treated Groundwater
TIAA ^c	9	1987 ^d	6 ^e	15,000	13.4	Reinjection, potable supply, reuse
Shannon/ECC	1.6	1997	2	143	1.0	Potable supply, disposed
Miracle Mile	1.3	2007	1	3	0.95	Potable supply
Broadway/Pantano	1.3	2003	1	19	0.94	Reinjection
Los Reales Landfill	2.2	1999	2	17	0.27	Reuse, reinjection

^a PAT = pump and treat

^b Through 2010

^c TIAA = Tucson International Airport Authority

^d Start year for first PAT system; other systems started later

^e The PAT system for the Texas Instruments site of the TIAA complex has been shut down

Table 2

Groundwater Withdrawals in Tucson for 2010

Water Provider	Groundwater Withdrawal (million m³)
Tucson Water	40.1
Metro Water	10.2
Flowing Wells Irrigation District	2.0
Private Well Owners ^b	16.0
Total ^a	68.3
Total Withdrawal for Pump and Treat	16.5
Combined Total	84.8

^a Excluding withdrawals associated with the pump-and-treat systems listed in Table 1

^b Includes single homeowners, homeowner associations, commercial entities (e.g., hospitals, golf courses)