

# Assessment of Groundwater Contamination, In Situ Treatment, and Disposal of Treatment Residuals in the Vicinity of Lubbock, Texas

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Prepared by

Texas Bureau of Economic Geology,  
University of Texas, Austin Texas



**CH2MHILL**

12301 Research Boulevard  
Building 4, Suite 250  
Austin, Texas 78759



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# Executive Summary

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This report presents an assessment of groundwater contamination, potential in situ treatment technologies for drinking water supply, and assessment of injecting ex situ treatment residuals into the source aquifer in the vicinity of Lubbock, Texas. The study area surrounding Lubbock includes the following nine counties: Lubbock, Lamb, Hale, Floyd, Crosby, Garza, Lynn, Terry, and Hockley Counties. Many public water supply wells in the region exceed the maximum contaminant levels (MCLs) for the following water quality constituents of concern (COCs): nitrate (NO<sub>3</sub>), arsenic (As), fluoride (F), selenium (Se), uranium (U), and radium-226 (Ra-226), and radium-228 (Ra-228).

The study was divided into three main tasks: (1) stratification of naturally occurring contaminants in groundwater; (2) potential for in situ treatment; and (3) potential for disposal of treatment residuals in drinking water. Task 1 was conducted by the Bureau of Economic Geology, and tasks 2 and 3 were conducted by CH2M Hill under subcontract to the Bureau of Economic Geology.

Task 1 was accomplished by using GIS analysis of available groundwater quality data and well depth and evaluation of geophysical logs to determine potential sources of contaminants. The Ogallala aquifer in the study area (Southern HighPlains) was subdivided into a northern segment (Ogallala-N), which is characterized by water with low (< 500 mg/L) total dissolved solids (TDS), and a southern segment (Ogallala-S), which is characterized by water with high TDS (> 500 mg/L). A third aquifer category, termed Other, was assigned to all aquifers except the Ogallala. Arsenic concentrations exceed the EPA MCL of 10 µg/L in 31% of wells in the Ogallala-S aquifer, 6% in the Ogallala-N, and 8% in the Other category. Arsenic concentrations are stratified and are highest in the upper 100 - 200 ft in the Ogallala-S aquifer. Nitrate contamination (≥ 10 mg/L nitrate-N) was also highest in the Ogallala-S aquifer (20% of wells) and much lower in the other two categories (0 - 1%). Nitrate concentrations are stratified and are highest (> 10 mg/L) in the upper 200 ft and much lower below this zone. Correlations between nitrate and percent cultivated land suggest an anthropogenic source of nitrate. Fluoride contamination (> 4 mg/L) is highest in the Ogallala-S aquifer (49% of wells), followed by the Other category (18% of wells), and is very low in the Ogallala-N category. Depth stratification in the Ogallala-S aquifer is similar to that for arsenic and nitrate. Selenium contamination is relatively minor: 4% of wells in Ogallala-S aquifer, 2% in Other category, and 0% in Ogallala-N aquifer. Selenium concentrations are also highest in the upper 200 ft in the Ogallala-S aquifer. Information on uranium distribution is primarily available from the eastern part of the study area from the National Uranium Resource Evaluation (NURE) database and indicates high levels of contamination in the Ogallala-S (19% of wells) and Other (14% of wells) aquifers and none in the Ogallala-N aquifer. Uranium contamination is generally restricted to the upper 100 to 200 ft depth zone. Information on the distribution of radium is too limited to make a reliable assessment. In summary, most contaminants display strong vertical stratification, with highest levels in the upper 100 - 200 ft in the Ogallala-S aquifer. Therefore, drilling deeper wells may reduce contamination in PWS wells.

Geophysical well logs (~ 700) from the Bureau of Economic Geology Well Log Library and the TCEQ Surface Casing Unit were examined to map the distribution of high gamma

zones in the region as these indicate radioactive shales that might source many of the COCs. Approximately 110 of 250 logs have anomalously elevated gamma ray values. The most areally extensive region is in Andrews, Gaines, and Yoakum Counties. These high gamma regions are generally not collocated with the areas of high groundwater contamination; therefore, other sources of arsenic and radionuclides are likely. Mass balance calculations also indicate that the mapped distributions of volcanic ash are insufficient to account for the widespread contamination in the Ogallala aquifer.

Various approaches were investigated to conduct multilevel sampling of wells. The USGS well-bore flow and depth-dependent sampler provides many advantages over traditional approaches of conducting multilevel sampling such as multilevel wells and packer systems. The term Stratified Aquifer Sampling is being used to describe this system. The advantages of the system are the small diameter, which allows multilevel sampling in existing PWS wells, and the ability to measure variations in flow with depth and to sample water at various depth intervals. The system should allow stratification of contamination to be accurately defined and would help determine if contamination is restricted to specific depth intervals that could be excluded from future wells to minimize contamination. The Bureau of Economic Geology will build a Stratified Aquifer Sampling system, and 50% of the system will be funded by the Jackson School of Geosciences. Equipment for the system has been purchased, and the system will be built in the fall of 2005.

Additionally, a Quality Assurance Plan has been developed for well sampling and laboratory analysis of the previously listed contaminants.

Tasks 2 and 3 were conducted by CH2M Hill, a subcontractor to the Bureau of Economic Geology. While not historically practiced, an assessment of the potential impacts of injection of ex situ treatment residuals re-injection into Class V wells was also conducted as part of this study. Groundwater modeling was performed to represent general conceptual conditions in the study area. Modeling of residuals injection into a hypothetical section of the Ogallala aquifer using a Class V well demonstrates that over a typical 50-year project life, the injected concentrate remains relatively close to the injection well. Simulations show that even after 50 years (with the regional gradient) the concentrate front migrates approximately 7,600 feet from the original injection point, becoming more dilute with time. The concentration of COCs is less than two times background levels at a distance greater than 1,800 feet from the Class V well after 50 years of injection. Further field evaluation would be required to fully assess this approach. Site specific test drilling, pump testing, and additional modeling should be used to develop the concept further.

Ex situ treatment is the most common form of treatment for drinking water supply. These ex situ technologies generally include ion exchange, reverse osmosis, filtration and chemical reduction. In the future, in situ treatment may be used as a stand-alone treatment method or an enhancement to ex situ technology treatment. In situ technology selection and evaluation for this study were based primarily on treatment for those regulated COCs that are above EPA MCLs. Most in situ technologies were developed for remediation purposes, and using them for treatment of public water supply would be a new application. A number of these in situ technologies were evaluated as part of this study including: zero valent iron (ZVI) permeable reactive barriers (PRBs); injectable nano-scale ZVI (Ferox™ Process); phosphate and phosphate PRBs; in situ chemical reduction using dithionite and calcium polysulfide and in situ biological treatment. Evaluation of in situ technologies was conducted using a modified feasibility study framework defined in Guidance for

Conducting Remedial Investigation and Feasibility Studies Under CERCLA (USEPA, 1999), as outlined in Appendix A.

Although a number of in situ technologies could be beneficial for water supply, some appear to have greater potential for in situ treatment of water supply. ZVI in a PRB or using the Ferox™ process may prove to be beneficial because they have the capability to treat a large number of the water quality COCs. In situ chemical and in situ biological treatments tend to be less expensive to implement, but tend to be more expensive to operate and do not treat as many COCs compared with the ZVI technologies. Further technology efficacy testing and groundwater modeling would be needed to further develop the use of in situ technologies for water supply purposes. Groundwater flow modeling could be used to assist with calculations of treatment needs and final site-specific design. Bench-scale and field pilot testing are recommended to assist with the development of in situ technologies and to test the configurations and designs given site-specific conditions.



**Task 1**  
**Assessment of Groundwater Contamination in**  
**the Vicinity of Lubbock, Texas**

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## SECTION 1

# Introduction

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The University of Texas, Bureau of Economic Geology (BEG) is evaluating the distribution of groundwater contaminants in a nine-county area surrounding Lubbock, Texas. The study area includes the counties of Lubbock, Lamb, Hale, Floyd, Crosby, Garza, Lynn, Terry, and Hockley in the Southern High Plains in the Texas Panhandle (Figure 1). The following contaminants exceed the EPA maximum contaminant levels (MCLs): nitrate (NO<sub>3</sub>), arsenic (As), fluoride (F), selenium (Se), uranium (U), and radium-226 (Ra-226) and radium-228 (Ra-228). The origin of these contaminants is uncertain.

## 1.1 Study Objectives

The objective of this study was to evaluate stratification of naturally occurring contaminants in groundwater using available information. The study is located in the nine-county region surrounding Lubbock, Texas, where public water systems are out of compliance with respect to the following contaminants: arsenic, fluoride, nitrate, selenium, uranium, and radium. Subtasks included:

- 1a. Assess stratification of contaminants in groundwater using
  - GIS analysis with available groundwater quality data and well depth
  - Existing geophysical logs to determine potential sources of contaminants
  - Limited groundwater sampling of existing wells to evaluate vertical zonation
- 1b. Evaluate different approaches to conduct multilevel water sampling in existing wells

## SECTION 2

# GIS Analysis of Groundwater Quality Using Available Data

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The study area consists of Lubbock County and the surrounding eight counties (Figure 1). The aquifers were subdivided into three designated Ogallala-South (Ogallala-S), Ogallala-North (Ogallala-N), and Other for aquifers underlying the Ogallala aquifer and for aquifers outside the Ogallala aquifer, mostly in Garza, southern Crosby, and northeastern Floyd Counties (Figure 1). The Ogallala-S and Ogallala-N aquifers were delineated based on Ogallala Aquifer water quality: the Ogallala-S region has generally high ( $> 500$  mg/L) total dissolved solids (TDS), mostly in Lamb, Hockley, Lubbock, Terry, Lynn, and Garza Counties, whereas the Ogallala-N region has generally low ( $\leq 500$  mg/L) TDS, mostly in Hale, Floyd, and Crosby Counties. The line separating the two zones trends diagonally across Lubbock and Lamb Counties.

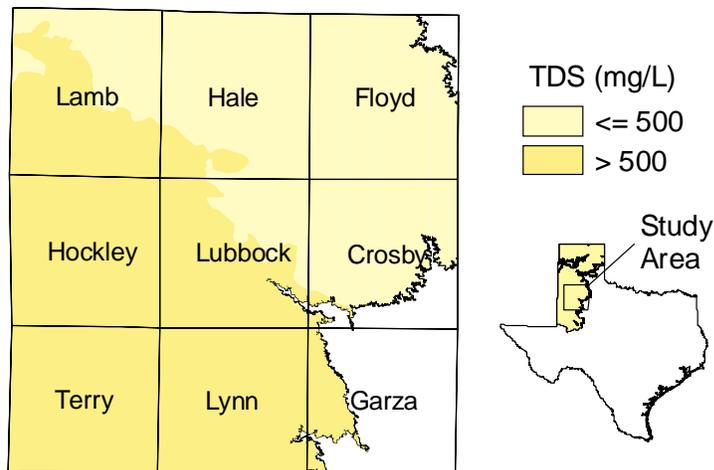


Figure 1. Study area location showing Ogallala aquifer (shaded) separated into two: 1) southern (Ogallala-S) aquifer with groundwater TDS  $> 500$  mg/L and 2) northern (Ogallala-N) region with TDS  $\leq 500$  mg/L.

## 2.1 Data Sources

The types of information required for different aspects of this study and that were variously available for individual wells in the study area include the aquifer(s) in which a well is completed, well depth, and analytical results for the various contaminant(s) of interest. Information for a total of 4817 individual wells located in the study area was obtained from three sources:

- 1) Texas Water Development Board (TWDB) database available at [http://www.twdb.state.tx.us/DATA/waterwell/well\\_info.asp](http://www.twdb.state.tx.us/DATA/waterwell/well_info.asp)
- 2) National Uranium Resource Evaluation (NURE) database available for the State of Texas at [http://pubs.usgs.gov/of/1997/ofr-97-0492/state/nure\\_tx.htm](http://pubs.usgs.gov/of/1997/ofr-97-0492/state/nure_tx.htm)

- 3) Texas Commission on Environmental Quality (TCEQ) Public Water System (PWS) database not publicly available (<http://www.tceq.state.tx.us/> )

The largest source was the TWDB database that includes 4169 wells in the study area. The second largest source is the USGS National Geochemical Database (Smith, 2001) based on the National Uranium Resource Evaluation (NURE) program, which included information on 600 wells in the study area. The Texas Commission on Environmental Quality (TCEQ) Public Water Supply (PWS) database included information on 48 wells that was used for this study.

The TWDB conducts ambient groundwater monitoring. All the major and selected minor aquifers are sampled on a 5-yr rotating basis. Water quality data are available for 55,000 groundwater sites (wells, springs) resulting in a total of 104,000 analyses. The earliest water chemistry data available are from the late 19<sup>th</sup> century. Groundwater quality information includes state well number, date of sampling event, time, collection remarks, reliability of sampling method remarks, collecting agency, indication of whether the sample is balanced or unbalanced, lab-calculated pH, phenol and total alkalinity, hardness, specific conductance, total dissolved solids, and major cations and anions (SiO<sub>2</sub>, Ca, Mg, K, Na, Sr, SO<sub>4</sub><sup>2-</sup>, HCO<sub>3</sub><sup>-1</sup>, CO<sub>3</sub><sup>2-</sup>, Cl<sup>-1</sup>, F<sup>-1</sup>, NO<sub>3</sub><sup>-1</sup>). In some instances, analyses are performed for infrequent constituents (metals), organics, nutrients, and radioactive constituents. Approximately 501,000 infrequent constituent analyses have been entered in the database. Additional well information is provided in the database, including well depth, aquifer, and groundwater level. The TWDB database includes some but not all the water quality data in the USGS database. The database is provided as a Microsoft Access file and can be downloaded from the TWDB website.

The NURE hydrogeochemical and stream sediment reconnaissance includes data from stream sediments, soils, groundwater, and surface water over the entire United States. The reconnaissance survey began in 1975 and ended in 1980 under the responsibility of four DOE national laboratories: Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Oak Ridge Gaseous Diffusion Plant (ORGP), and Savannah River Laboratory (SRL) (Smith, 2001; USGS, 2004). The purpose of the program was to explore for undiscovered uranium. This database provides chemical data for Ag, Al, As, Au, B, Ba, Be, Bi, Br, Ca, Cd, Ce, Cl-, Co, Cr, Cs, Cu, Cy, Eu, F, Fe, Ga, He, Hf, Hg, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Pt, Rb, Sb, Sc, Se, Si, Sm, Sn, Sr, Ta, Tb, Th, Ti, U, V, W, Y, Yb, Zn, Zr, PO<sub>4</sub> (phosphate), NO<sub>3</sub> (nitrate), SO<sub>4</sub> (sulfate), methane, ethane, propane, and butane in samples of stream sediment, spring sediment, lake or pond sediment, soil, rock, well water, stream water, and spring water. In addition, the database provides location and descriptive information for each sample. The NURE database covers only the eastern half of the southern High Plains. The database is provided as text files that were consolidated and imported into Microsoft Access and Excel.

The TCEQ PWS database includes water quality data for all public water systems in the state. Water sources of public water systems include surface water, groundwater, and/or mixed sources. Water chemistry data in the PWS database represent the water entry points, which may represent a blend of groundwater from different wells, or groundwater and surface water, or surface water. For this study, we are only interested in raw groundwater chemistry data; therefore, we selected water quality samples that can be associated with a single well and included raw and entry point data. The database obtained from TCEQ is a subset of the larger PWS database that includes only inorganic chemical constituents of concern, including arsenic.

The list of constituents in this modified database is as follows: specific conductance, TDS, alkalinity, total hardness, pH, Al, An, Be, N, NH<sub>3</sub>, As, Ba, Ca, Cd, Cl, Cr, Cu, Fl, Fe, Pb, Mg, Mn, Hg, Ni, NO<sub>3</sub>, NO<sub>2</sub>, K, Se, Ag, Na, SO<sub>4</sub>, Th, Zn, gross alpha, U, Rd, radium 226 and radium 228, gross beta, tritium, gross alpha, and Sr90. Additional well information in the database includes well depth, screened interval, aquifer designation, and geology. Well depth is available for most of the wells, but screen depth and geologic descriptions are not available for all the wells in the database. TCEQ PWS has limited spatial coverage because it excludes rural areas. The database is provided as a Microsoft Access file.

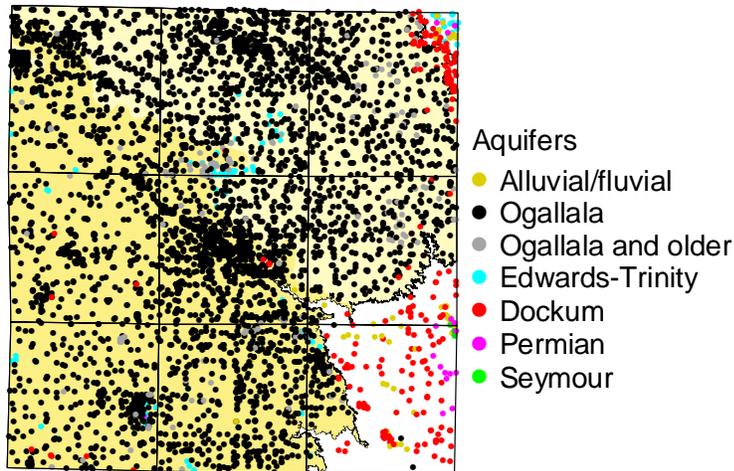


Figure 2. Well locations showing completion aquifers in the study area.

The main aquifer in the study area is the Ogallala aquifer (Figure 2) of early Tertiary age. A total of 4260 wells in the study area are completed solely in the Ogallala (Table 1), representing 88% of all wells in the study and 94% of all wells located within the Ogallala outcrop area. Other aquifers that are also present and that may locally be hydraulically connected to the Ogallala include younger alluvial/fluvial deposits of Quaternary age and underlying older aquifers, including the Edwards-Trinity High Plains Aquifer system of Cretaceous age, the Dockum Group of Triassic age, and undifferentiated Permian aquifers (Figure 2). A small pod of the Seymour Aquifer is also present in southern Crosby County and northern Garza County.

For the purposes of this study, wells were grouped into three main categories based on the completion aquifer and region. All wells located within the southern region (Figure 1) that are completed solely in the Ogallala are designated as “Ogallala-S” (2333 wells). All wells located within the northern region and completed solely in the Ogallala are designated as “Ogallala-N” (1927 wells). The remaining category, designated as “Other” (557 wells), includes all wells in the study area that are completed wholly or partially in aquifers other than the Ogallala.

Well depth information was available for 3751 wells in the study area (78% of all wells). Well depths are generally < 250 ft in southern and > 250 ft in the northern regions (Figure 3). Average Ogallala-S well depth (144 ft) is much shallower than Ogallala-N well depth (267 ft) (Table 1).

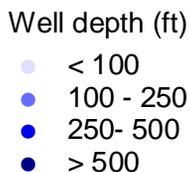
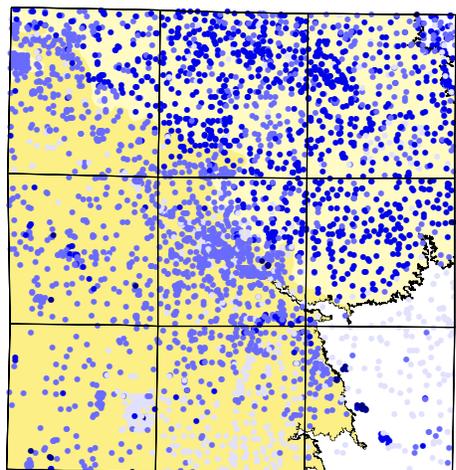


Figure 3. Spatial distribution of well depth in the study area.

Table 1. Region, aquifer, and depth information available for wells in the study area. Aquifers are listed in order of increasing age within each region, except the (Quaternary) Seymour.

Region	Aquifer	# of wells	Depth known	Depth (ft)			
				Average	Median	Minimum	Maximum
South	Alluvial/Fluvial	3	3	44	40	26	75
	Ogallala-S	2333	1744	144	140	11	420
	Ogallala-S and older	78	68	212	201	60	360
	Edwards-Trinity	54	50	167	125	20	415
	Dockum	15	14	1550	1600	390	2350
	Permian	2	2	-	-	2500	2600
North	Ogallala-N	1927	1517	267	291	10	500
	Ogallala-N and older	72	66	340	358	66	503
	Edwards-Trinity	37	37	216	220	125	336
	Dockum	23	17	245	237	55	517
Other	Alluvial/Fluvial	59	40	88	51	13	279
	Edwards-Trinity	22	18	303	281	120	673
	Dockum	168	157	203	115	10	750
	Permian	15	15	61	49	26	223
	Seymour	9	3	70	70	74	77
Total		4817	3751	-	-	-	-

Land use information was derived from the National Land Cover Data (NLCD) database, available at <http://landcover.usgs.gov>. The dominant land use in the study area is cultivated (72%), consisting of row crop, small grains, pasture/hay, and fallow areas (Figure 4, Table 2). Most of the remaining land use is rangeland (26%), consisting of shrublands and grasslands. Approximately 1% of the area is urban.

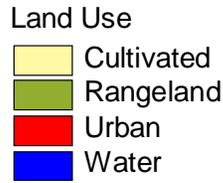
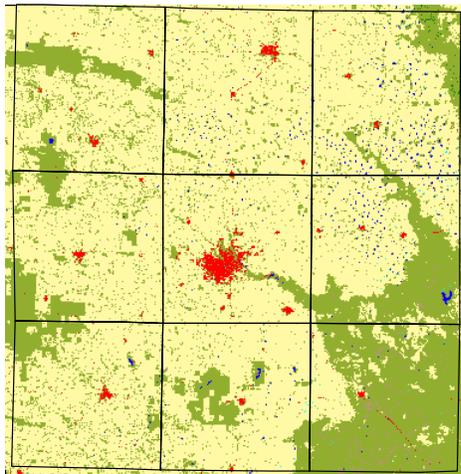


Table 2. Approximate land use areas and percentages in the study area.

Land use	Area	
	(mi <sup>2</sup> )	(%)
Cultivated	6274	71.6
Rangeland	2311	26.4
Urban	88	1.0
Water	39	0.4
Other	55	0.6

Figure 4. Spatial distribution of land use in the study area.

## 2.2 Distribution of Contaminants

The contaminants evaluated in this analysis include arsenic, fluoride, nitrate, selenium, uranium, and radium. The data have been tabulated according to the aquifer the wells have been completed in. Depth stratification of contaminants was evaluated by plotting contaminant concentrations versus well depths for the different aquifer categories (Ogallala-S, Ogallala-N, and Other) and by plotting the distribution of contaminants (10<sup>th</sup>, 25<sup>th</sup>, median, 75<sup>th</sup>, and 90<sup>th</sup> percentiles) versus the median of the 20<sup>th</sup> percentile well-depth increments.

### 2.2.1 Arsenic

Arsenic concentrations exceed the EPA Maximum Contaminant Level of 10 µg/L in 14% of the wells in the study area (Figure 5, Table 3). Arsenic contamination is highest in the Ogallala-S aquifer (31% of wells exceed the MCL) and is much lower in the Ogallala-N aquifer (6% of wells) and in the other aquifers (8% of wells).

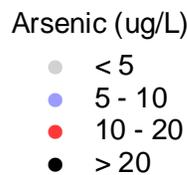
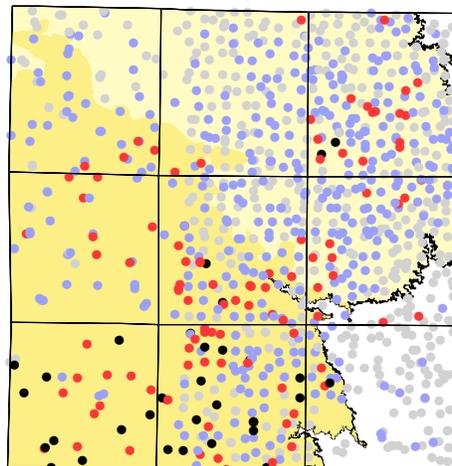


Table 3. Arsenic results summary

Aquifer	Total # wells	Arsenic > 10 µg/L	
		# wells	%
Ogallala-S	296	91	31
Ogallala-N	468	27	6
Other	171	14	8
Total	935	132	14

Figure 5. Spatial distribution of arsenic concentrations in the study area.

Most of the high arsenic concentrations are found in the Ogallala-S aquifer (Figure 6a). High arsenic concentrations are distributed throughout the Ogallala-S aquifer. Arsenic concentrations are related to well depth and are highest near the surface and decrease with depth (Figure 6c), with the 75<sup>th</sup> and 90<sup>th</sup> percentile concentrations decreasing sharply in the upper 200 ft in the Ogallala-S aquifer. High arsenic concentrations in the Ogallala-N aquifer are deeper than the Ogallala-S aquifer. The highest arsenic concentrations in the Ogallala-N aquifer are found at depths of 400 – 500 ft. Highest arsenic concentrations in the Other aquifer category occur at depths of 150 – 300 ft. The distribution of arsenic concentrations in the Ogallala-N aquifer does not vary greatly with depth. And there is no systematic variation in arsenic concentration distribution in the Other aquifer category. Arsenic concentrations in the study area are correlated with other oxyanions, including vanadium ( $r^2 = 0.75$ ) and molybdenum ( $r^2 = 0.20$ ) (Figure 7). Correlations between arsenic and fluoride are also high ( $r^2 = 0.41$ ), whereas correlations with nitrate are low ( $r^2=0.07$ ) (Figure 7). The high correlation of arsenic with vanadium and fluoride, both generally considered as naturally occurring rather than of anthropogenic sources, indicates a geologic source for arsenic.

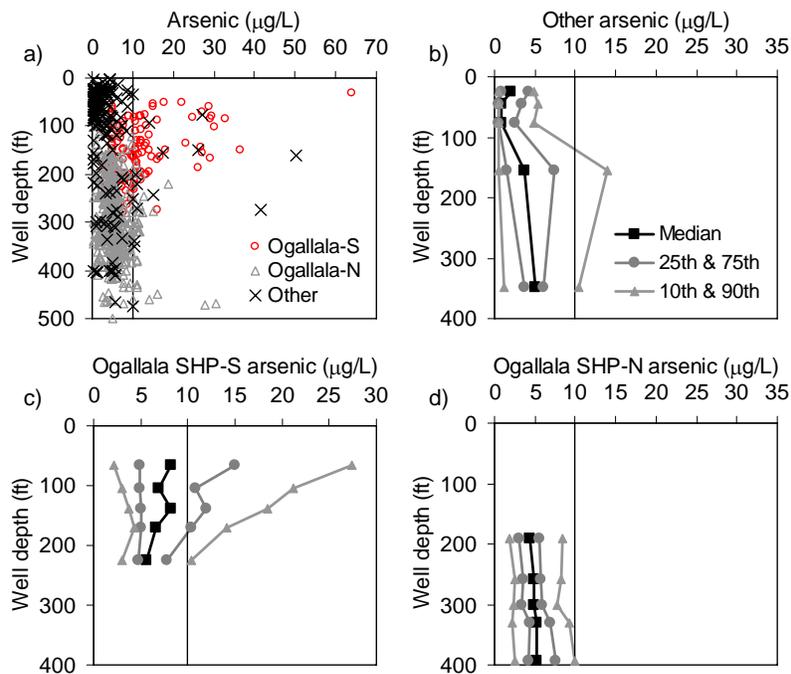


Figure 6. Distribution of arsenic concentrations with total well depth for a) individual wells in the study area and of arsenic concentration percentiles for b) wells completed solely or partially in aquifers other than the Ogallala, c) wells completed solely in the Ogallala-S aquifer, and d) wells completed solely in the Ogallala-N aquifer. Plotted well depth values for b), c) and d) represent medians of 20<sup>th</sup> percentile intervals.

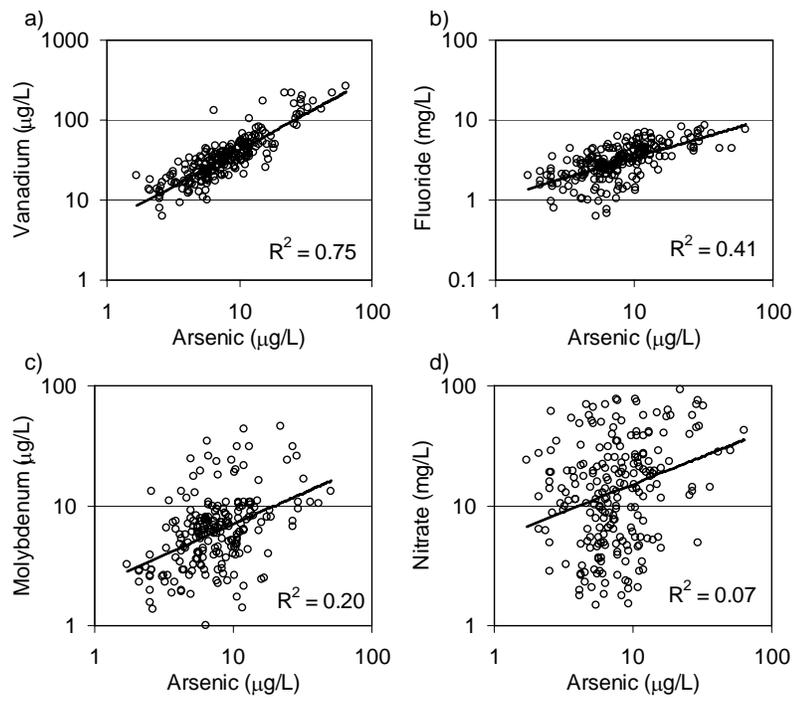


Figure 7. Relationship between arsenic concentrations and a) vanadium, b) fluoride, c) molybdenum, and d) nitrate in the study area.

## 2.2.2 Nitrate

Nitrate contamination (> 10 mg/L nitrate-N, EPA MCL) is widespread, particularly in the Ogallala-S aquifer (Figure 8, Table 4). Nitrate contamination is highest in the Ogallala-S aquifer (20% of wells exceed the MCL). There is very little nitrate contamination in the Ogallala-N aquifer (1% of wells exceed the MCL), and nitrate contamination is also very low in the Other aquifer category (3% of wells exceed the MCL).

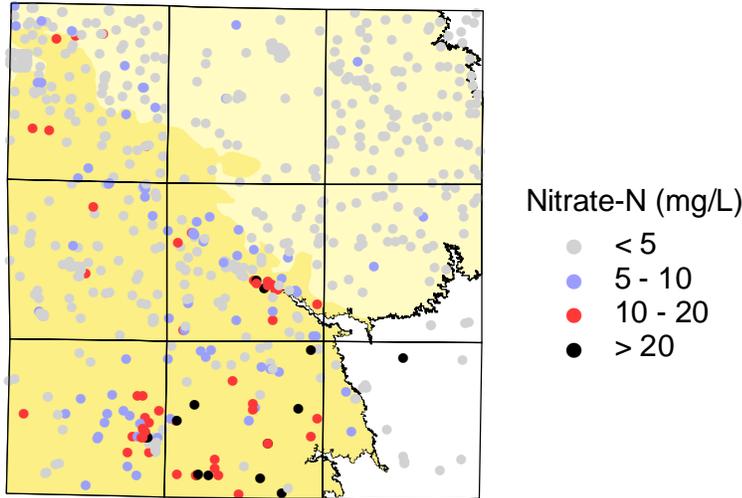


Table 4. Nitrate results summary

Aquifer	Total # wells	Nitrate > 10 mg/L	
		# wells	%
Ogallala-S	307	62	20
Ogallala-N	238	2	1
Other	91	3	3
Total	636	67	11

Figure 8. Spatial distribution of nitrate concentrations in the study area.

Nitrate contamination is stratified with depth with the highest nitrate concentrations found in wells shallower than about 200 ft (Figure 9a). The distribution of nitrate concentrations generally decreases and becomes less variable with depth for each of the three well categories in the study area. These results are consistent with our understanding of a dominant near-surface source of nitrate.

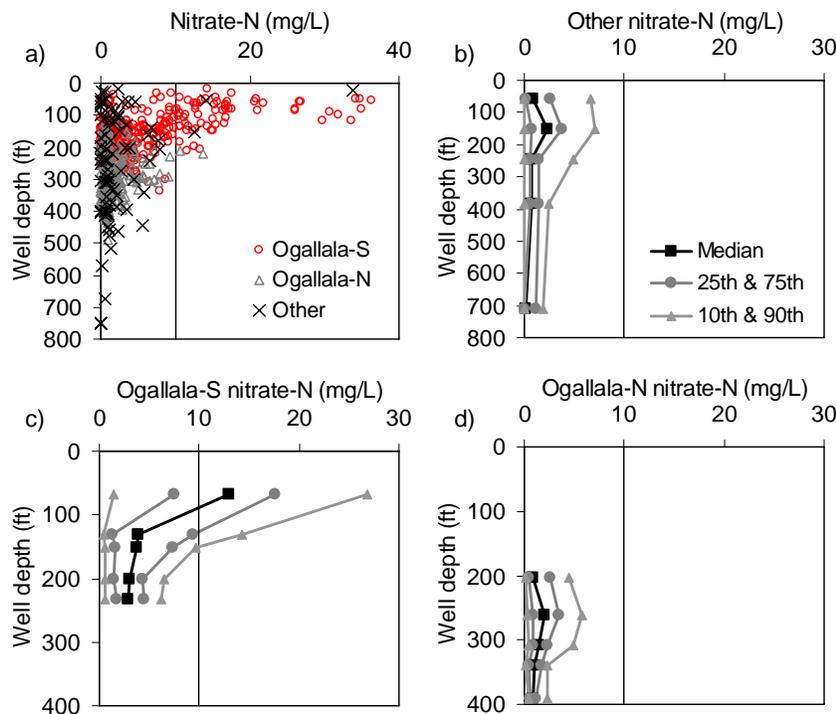


Figure 9. Distribution of nitrate concentrations with total well depth for a) individual wells in the study area and of nitrate concentration percentiles for b) wells completed solely or partially in aquifers other than the Ogallala, c) wells completed solely in the Ogallala-S aquifer, and d) wells completed solely in the Ogallala-N aquifer. Plotted well depth values for b), c) and d) represent medians of 20<sup>th</sup> percentile intervals.

Nitrate concentrations were correlated with land use in the study area (Figure 4). Median nitrate-N concentrations were compared with the percentages of cultivated and rangeland land use categories within a 500-m radius around wells within each of the aquifer categories. The results indicate that nitrate-N concentrations generally increase as the percentage of cultivated land increases and as the (complementary) percentage of rangeland decreases (Figure 10). This is particularly evident in the Ogallala-S aquifer.

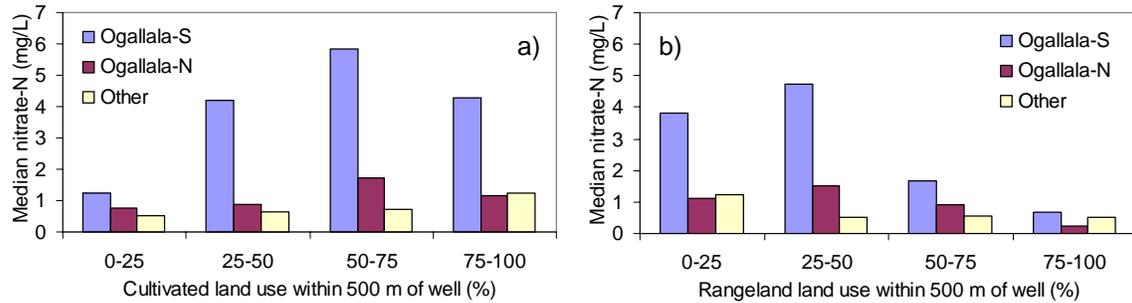


Figure 10. Relationship between nitrate-N concentrations and a) cultivated and b) rangeland land uses for the different aquifer categories in the study area.

Soil clay content within a 500-m radius of wells was compared with nitrate-N concentrations. Increasing clay content generally results in increasing nitrate-N levels in the Ogallala-S aquifer, which is difficult to explain.

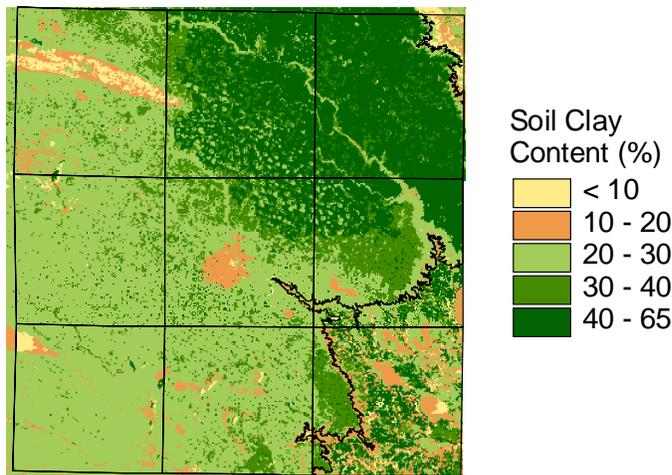


Figure 11. Average soil clay content in the study area.

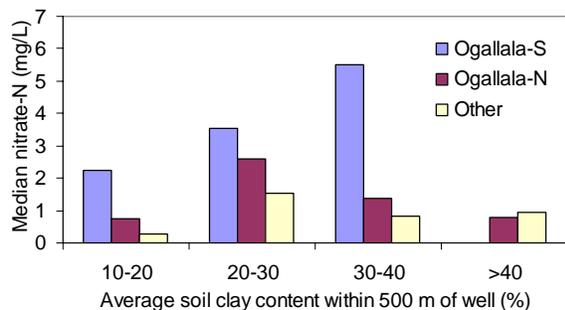


Figure 12. Relationship between average soil clay content and nitrate-N concentration for the different aquifer categories in the study area.

### 2.2.3 Fluoride

Fluoride contamination (> 4 mg/L, EPA MCL) is widespread in the Ogallala-S aquifer (49% of wells) and also in the Other aquifer category (18% of wells) and is extremely low in the Ogallala-N aquifer (2% of wells) (Figure 13, Table 5). Fluoride concentrations are stratified with depth, particularly in the Ogallala-S aquifer where the distribution of fluoride decreases sharply with depth, particularly in the shallowest median depth intervals (Figure 14). The distribution of fluoride concentrations decreases gradually at most percentiles shown in the upper 400 ft in the Other aquifer category.

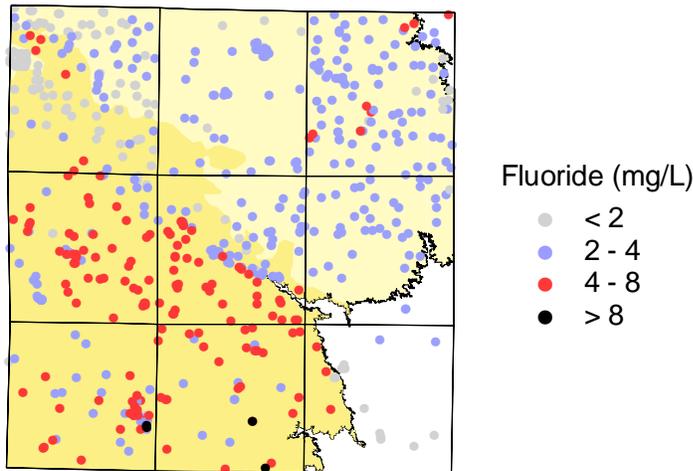


Table 5. Fluoride results summary.

Aquifer	Total # wells	Fluoride > 4 mg/L	
		# wells	%
Ogallala-S	284	139	49
Ogallala-N	237	5	2
Other	83	15	18
Total	604	159	26

Figure 13. Spatial distribution of fluoride concentrations in the study area.

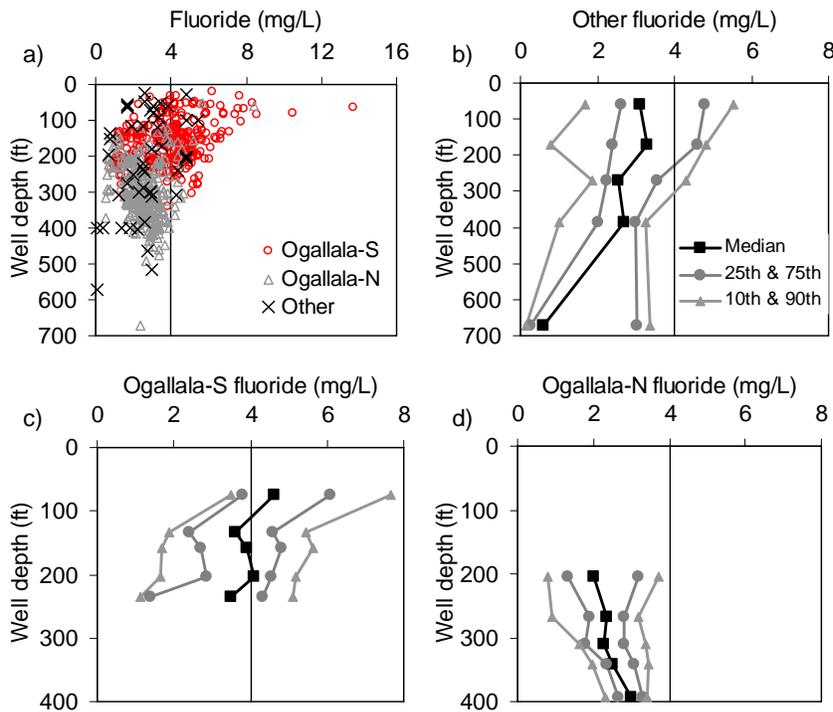


Figure 14. Distribution of fluoride concentrations with total well depth for a) individual wells in the study area and of fluoride concentration percentiles for b) wells completed solely or partially in aquifers other than the Ogallala, c) wells completed solely in the Ogallala-S aquifer, and d) wells completed solely in the Ogallala-N aquifer. Plotted well depth values for b), c) and d) represent medians of 20<sup>th</sup> percentile intervals.

## 2.2.4 Selenium

Selenium contamination ( $> 50 \mu\text{g/L}$ , EPA MCL) is generally limited in the study area, with only 4% of the wells being contaminated in the Ogallala-S aquifer, 2% in the Other aquifer category and 0% in the Ogallala-N aquifer (Figure 15, Table 6). Depth stratification of selenium concentrations in the Ogallala-S aquifer is similar to that of arsenic and nitrate, with a sharp decrease in selenium levels in the upper 100 to 200 ft depths (Figure 16). There is no systematic variation in selenium levels with depth in the Other aquifer category and the 90<sup>th</sup> percentile shows a large increase at the deepest interval, suggesting a deep source of selenium.

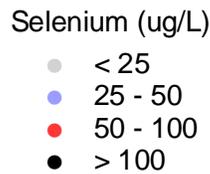
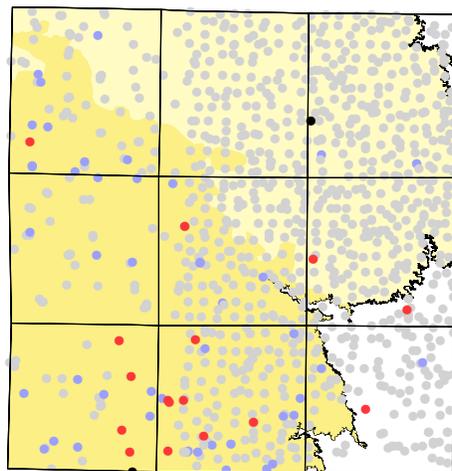


Table 6. Selenium results summary

Aquifer	Total # wells	Selenium $> 50 \mu\text{g/L}$	
		# wells	%
Ogallala-S	307	13	4
Ogallala-N	470	1	0
Other	171	4	2
Total	948	18	2

Figure 15. Spatial distribution of selenium concentrations in the study area.

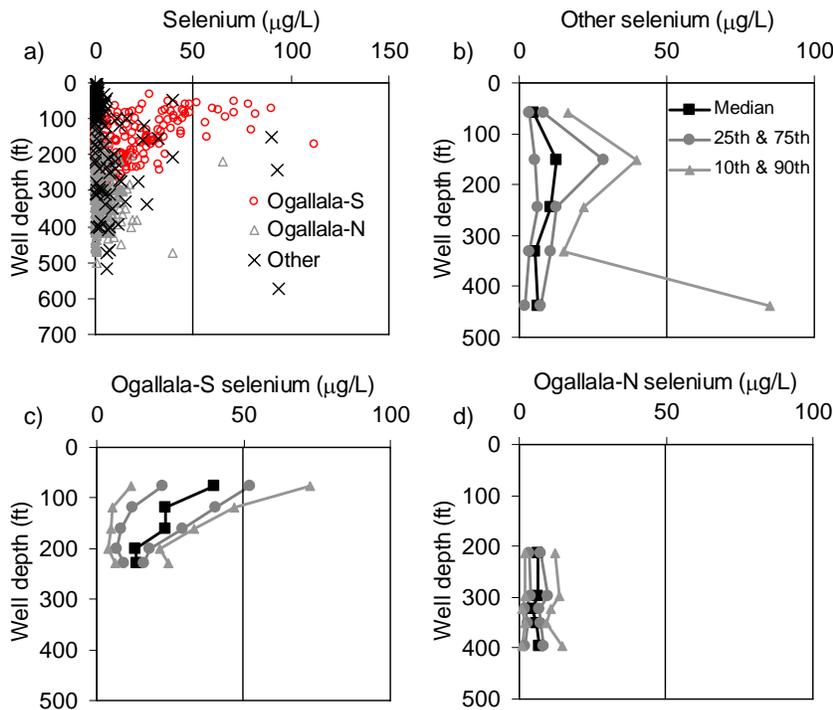


Figure 16. Distribution of selenium concentrations with total well depth for a) individual wells in the study area and of selenium concentration percentiles for b) wells completed solely or partially in aquifers other than the Ogallala, c) wells completed solely in the Ogallala-S aquifer, and d) wells completed solely in the Ogallala-N aquifer. Plotted well depth values for b), c) and d) represent medians of 20<sup>th</sup> percentile intervals.

## 2.2.5 Uranium

Contamination with uranium is limited in the study area. The data source for uranium is the NURE database, which is restricted to the eastern half of the study area (Figure 17). These data indicate that uranium contamination ( $U > 30 \mu\text{g/L}$ ) is restricted to the Ogallala-S aquifer and Other aquifer category and there is no uranium contamination in the sampled area of the Ogallala-N aquifer (Table 7). Uranium concentrations are stratified with depth, particularly the 75<sup>th</sup> and higher percentile categories in the Ogallala-S aquifer. There is no systematic variation in uranium levels in the Other aquifer category.

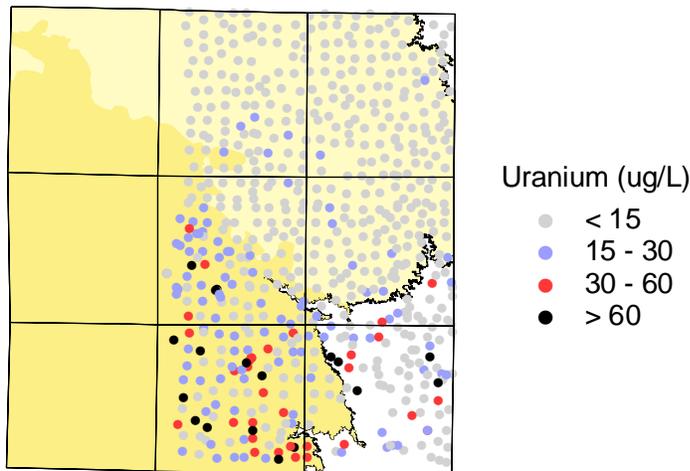


Table 7. Uranium results summary

Aquifer	Total # wells	Uranium > 30 $\mu\text{g/L}$	
		# wells	%
Ogallala-S	183	35	19
Ogallala-N	324	0	0
Other	115	16	14
Total	622	51	8

Figure 17. Spatial distribution of uranium concentrations in the study area.

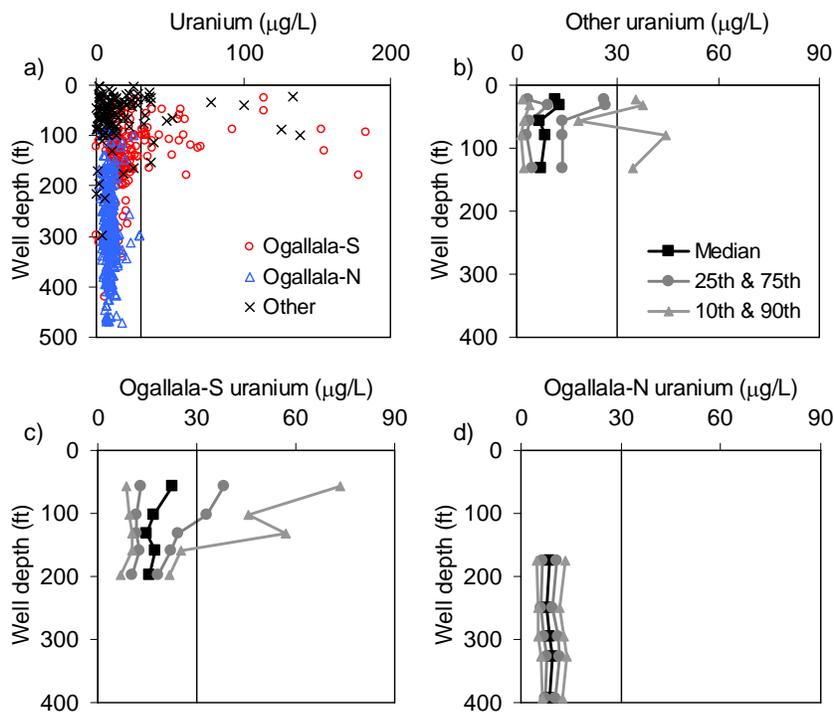


Figure 18. Distribution of uranium concentrations with total well depth for a) individual wells in the study area and of uranium concentration percentiles for b) wells completed solely or partially in aquifers other than the Ogallala, c) wells completed solely in the Ogallala-S aquifer, and d) wells completed solely in the Ogallala-N aquifer. Plotted well depth values for b), c) and d) represent medians of 20<sup>th</sup> percentile intervals.

## 2.2.6 Radium

Contamination with radium is limited in the study area. The TWDB data source for radium in the study area provided information only on Radium-228 (Figure 19, Table 8). Radium-228 levels > 5 ug/L were found only in the Other aquifer category at depths > 400 ft. The amount of data available on Radium 226 + 228 from the PWS database was insufficient to assess aquifer distribution and/or vertical zonation (Figure 21, Table 9).

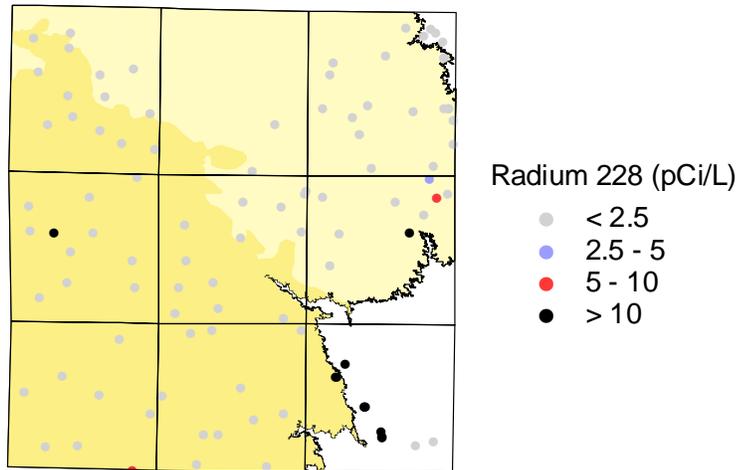


Table 8. Radium 228 results summary

Aquifer	Total # wells	Radium 228 > 5 pCi/L	
		# wells	%
Ogallala-S	42	0	0
Ogallala-N	29	0	0
Other	33	13	39
Total	104	13	13

Figure 19. Spatial distribution of radium 228 activity in the study area.

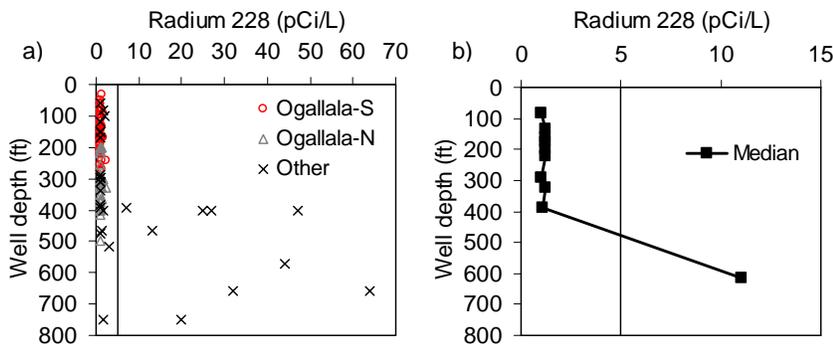


Figure 20. Distribution of radium-228 activity with total well depth for a) individual wells in the study area and b) median radium-228 activity for all wells in the study area.

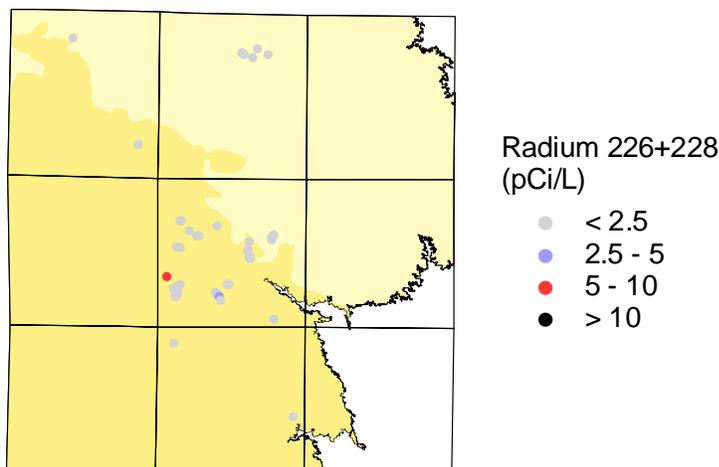


Table 9. Radium 226+228 results summary

Aquifer	Total # wells	Radium 226+228 > 5 pCi/L	
		# wells	%
Ogallala-S	38	1	3
Ogallala-N	10	0	0
Total	48	1	2

Figure 21. Spatial distribution of radium 226+228 activity in the study area.

In summary, contamination with respect to arsenic and nitrate occurs predominantly in the Ogallala-S aquifer, which is characterized by high TDS. Uranium contamination generally occurs in both the Ogallala-S aquifer and Other aquifer category. The occurrence of selenium contamination is much lower in the study area. Insufficient information was available on radium levels to assess its distribution. Most contaminants display strong vertical stratification, with highest levels in the shallowest zone and decreasing with depth in the Ogallala-S aquifer. The latter suggests that drilling deeper wells may reduce contaminant levels in groundwater.

# Evaluation of Geophysical Logs to Determine Potential Sources of Contaminants

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## 3.1 Introduction

A preliminary survey of geophysical well logs recorded in the Ogallala Formation in the Southern High Plains indicated potential occurrences of locally extensive, anomalously radioactive shale beds. These beds were interpreted to record local accumulations of volcanic-ash-rich shales, probably in lacustrine (lake) environments. Volcanic ash contains potassium-40 (a radioactive isotope that decays to argon), as well as uranium. Radioactive decay of these and associated isotopes allows volcanic ash to be used for geologic-age-dating. Volcanic ash has been observed in the Ogallala section in Potter County, Texas (Capeda, 2001) and Nebraska (Rose and others, 2003). Younger volcanic ashes also occur. There is a 10-my record of volcanic ash in the High Plains, the source of which has been suggested to be in the Yellowstone area of northern Wyoming (Izett, 1977). It was observed during this investigation that greater numbers of these beds occurred in the southern parts of the study area than in the north and that, coincidentally, greater relative numbers of water wells with elevated arsenic levels also occurred in the south. Volcanic materials have been shown to be a natural source for arsenic. Therefore, it was decided to further investigate the apparent correspondences between groundwater arsenic concentrations and presumed volcanic ash distribution in the Ogallala of the Southern High Plains.

## 3.2 Data and Methods

Over 700 geophysical well logs procured from the well log library of the Bureau of Economic Geology and the Surface Casing Unit of the Texas Commission on Environmental Quality were reviewed. These logs represented geologic sections from 21 counties (Fig. 1). Approximately 250 of these logs had gamma ray responses recorded for sufficiently thick portions of the Ogallala for the purposes of evaluating presence or absence of elevated gamma ray values. The criteria for usefulness of a given well log were 1) an anomalously elevated gamma ray value was generally defined as one that exceeded 100 API units; 2) that logging began within 8 m (25 ft) of the ground surface for logs that showed no anomalously elevated gamma ray values; and 3) that logging began within 30 m (100 ft) of the surface for logs that did show anomalously elevated values.

The gamma-ray value criterion was applied somewhat subjectively because it was obvious that not all of the well logs had been calibrated to the same standards. Not all logs were of the same vintage. In the end a gamma ray value was deemed to be anomalous if it exceeded values for other shale beds in the upper 300 m (1000 ft) of geologic section, which also included Cretaceous and Triassic strata. Also, ash-rich beds less than 2 ft thick may not have produced gamma-ray-log responses that achieved full expression of their actual radioactivity. The second

criterion assured that most of the Ogallala was measured prior to judging it free of volcanic beds. Most of the Ogallala is overlain by varying thicknesses of overburden, including the Blackwater Draw Formation and other alluvial material. The third criterion recognized that it was important only that a volcanic bed was observed in the Ogallala, not that it occurred in any pre-defined part of the section.

An attempt was made to provide as spatially consistent data coverage as was possible. Some counties have hundreds of hydrocarbon-prospective boreholes, while others have few. The distribution of well data that was collected should be adequate to detect local concentrations of volcanic ash of such extent as to justify further investigation to determine the boundaries of the deposits.

### 3.3 Results

The presence of anomalously elevated gamma ray values for strata within the Ogallala Formation was observed in logs from approximately 110 of the 250 locations for which data were gathered (Fig.23). The most areally extensive occurrences are in Andrews, Gaines, and Yoakum Counties, based on contour mapping of data that was classified according to bed thickness. Three bed-thickness classes were defined: greater than 5 ft thick, 1-5 ft thick, and 0 ft thick (no ash bed present). Contour mapping, in this instance, suggests lateral continuity of the geologic setting between data points. For example, if two data points show indications of the presence of an ash bed then any point between them (if data were available for the point) would also show presence of an ash bed. There is no implication that individual ash beds are laterally continuous between locations, although this is more likely between closer-spaced data locations. In other words: contours envelop areas within which ash beds are expected to have been deposited, but not necessarily at the same time in all places within the contour envelope. If ash beds are a source of arsenic, then the areas within contour envelopes are suggested to mark areas within which potential arsenic sources occur.

Groundwater arsenic generally is more concentrated in the south than in the north parts of the Southern High Plains (Fig. 23). For the comparison of inferred volcanic-ash-accumulations and groundwater-arsenic concentrations a three-tiered classification of arsenic concentrations was devised: 1) less than 10 ppb, 2) 10-30 ppb, and 3) greater than 30 ppb. Arsenic concentrations of 30 ppb or greater are most prominent at well locations in Yoakum, Terry, Lynn, Gaines, Dawson, Andrews, Martin, and western Howard Counties. Locations marked by arsenic concentrations between 10 and 30 ppb are closely associated with the > 30 ppb values but are more widespread. The overall impression is that there is a higher concentration of Ogallala groundwater arsenic in areas south of the tier of counties that include Lubbock and counties to its east and west, and north of central Midland County and counties to its east and west. There are occurrences of elevated arsenic northeast of Lubbock County; however, there are also a much greater number of locations for which values less than 10 ppb occur, so the relative number of wells with elevated arsenic is not high compared with areas to the south and west where arsenic data are more sparse.

There appears to be some association between estimated accumulations of interpreted volcanic ash and occurrences of elevated arsenic beneath them and down hydraulic gradient toward the southeast. These associations may indicate that arsenic-bearing constituents may have been extracted from ash deposits and are being transported by groundwater advection.

Sparcity of volcanic-ash indicators (elevated gamma-ray responses) in more northern areas and coincident overall with lower levels of arsenic is strongly suggestive that the volcanic deposits and elevated groundwater-arsenic in the south are interrelated. The following paragraphs will test this hypothesis.

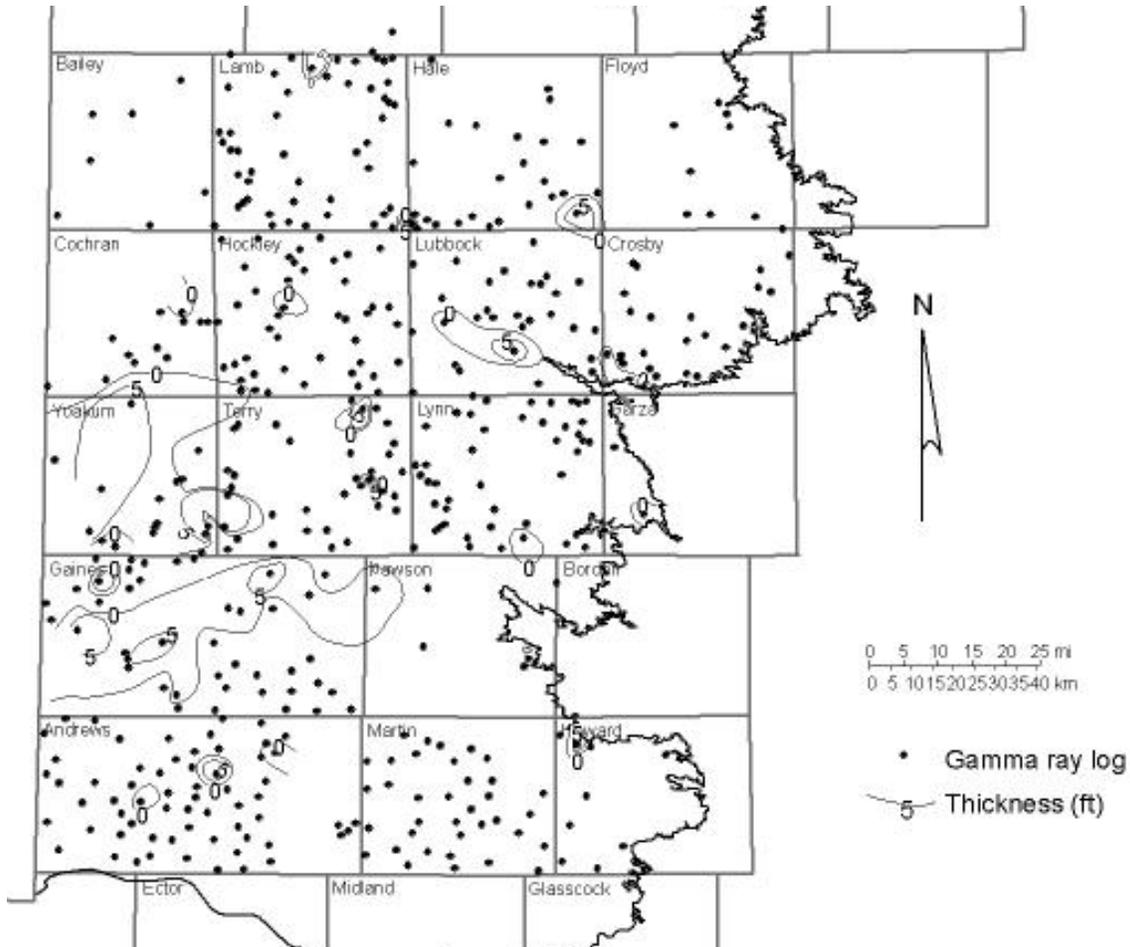


Figure 23. Thickness map of Ogallala-age ash beds based on geophysical logs

### 3.4 Mass Balance Computation

In order to assess the possibility of arsenic leaching from Ogallala-age ash beds, a crude mass balance was performed. The total mass of arsenic currently contained in the southern region of the southern High Plains is  $1.2 \times 10^6$  kg. This calculation assumes an average saturated thickness of 15 m with a porosity of 0.15 and an average arsenic concentration of 20  $\mu\text{g/L}$  over an approximate area of 25,000  $\text{km}^2$ . If the reasonable value of 500 for the number of pore volumes that went through the aquifer in the past 5 millions years, and the assumption that the average arsenic concentration has stayed constant since sediment deposition are used, approximately  $0.57 \times 10^9$  kg of arsenic have exited the aquifer through seeps and springs on the escarpment. The footprint of the operationally defined ash beds (mainly in Gaines and Yoakum

counties) is approximately 4,900 km<sup>2</sup>. The beds are assumed continuous with an average thickness of 1 m. A total volume for the ash beds of  $4.9 \times 10^9$  m<sup>3</sup> follows. Assuming arsenic content of 6 mg/kg and that half of it is leached, the total mass released is  $0.033 \times 10^9$  kg. This mass falls short by one order of magnitude of the amount required. It can, however, almost be matched if one assumes that the arsenic was leached when the ash covered the whole area (most of it would have washed away to the Gulf of Mexico and only relicts remained within the Ogallala Fm.) and that upgradient areas in New Mexico also provided arsenic.

### 3.5 Conclusions

The apparent association between distribution of groundwater arsenic and anomalously elevated radioactivity in Ogallala strata is intriguing and merits additional investigation. More stratigraphic and hydrochemical data should be analyzed than was allowed within the scope of this work. Hundreds of additional well logs are available that may allow more detailed stratigraphic and geographic mapping of interpreted volcanic ash deposits. A lower cutoff of gamma ray values for inclusion in the thickness map would more completely capture the geographical extent of lake deposits that contain ash material at presumably lower concentrations than were mapped for this survey. Stratigraphically controlled hydrochemical surveys may allow precise identification of Ogallala strata that convey arsenic-bearing groundwater. Use of stable isotopes may clarify the actual geologic source of arsenic, which conceivably could be Cretaceous (Edwards-Trinity aquifer) or Triassic (Dockum aquifer) strata.

## SECTION 4

# Evaluation of Different Approaches for Conducting Multilevel Sampling in Wells

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## 4.1 Introduction

Various approaches can be used to conduct multilevel water sampling in existing wells.

(1) Multilevel wells have been installed for previous studies such as a study related to perchlorate conducted by Texas Tech Water Resources Center (Jackson et al., 2004) and the National Water Quality Assessment study conducted by the USGS (McMahon et al., 2004). These wells can be sampled to obtain information on variations in water quality with depth.

(2) Traditionally packers can be used to isolate portions of a well for sampling. Inflatable packers have been developed for depth sampling. Such sampling cannot be conducted under pumping conditions. In addition, packers may leak providing misleading results.

(3) USGS combined well-bore flow and depth-dependent sampler: the following describes the USGS well bore flow and depth-dependent sample collection tool based on USGS Fact Sheet 196-99. The advantages of this system over those described previously are that it can be deployed in existing production wells having limited access and clearances as small as one inch. The combined system provides information on changes in well yield and groundwater quality with depth under operating conditions.

This tool would allow depth-dependent sampling of groundwater to evaluate stratification of flow, water ages, and water quality. The depth profile sampler consists of a high-pressure hose that includes valves for dye injection and sample collection. The hose is stored on a reel on a trailer. The hose is used to collect velocity-log data by injecting dye at different depths and measuring the travel time for the tracer to reach the surface where it is measured using a commercially available fluorimeter to measure dye concentrations. The flow velocity in a depth zone is estimated by calculating the difference in travel times between adjacent depths. A velocity profile is developed using a series of injections at different depths. The approach is termed the "tracer-pulse method". Dyes such as Rhodamine are typically used. Groundwater samples can be collected from a particular well depth by pressurizing the hose to greater than the hydrostatic value at that depth and lowering it into the well. Samples are collected by venting the hose at the surface allowing water to enter the hose at depth. A water-quality profile can be developed by sampling at varying depths. Water quality data and flow velocity data are used to estimate the water quality associated with each depth zone between sample collection points.

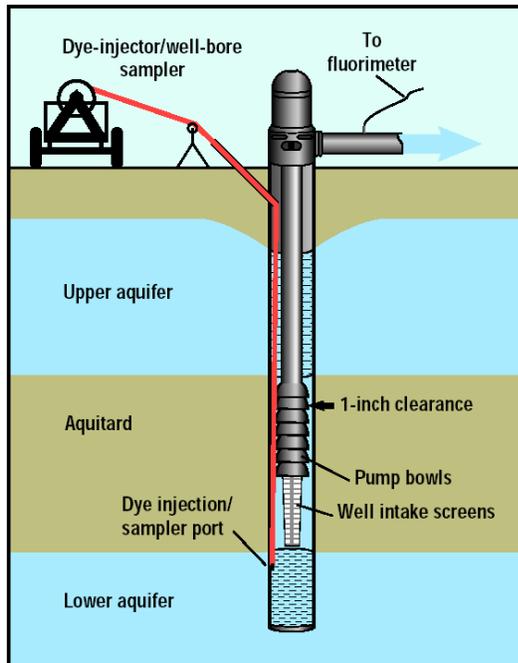


Figure 24. Schematic of depth profile sampler deployed in a typical well (USGS Fact Sheet 196-99).

The small diameter of the sampler allows collection of groundwater samples in existing production wells that have limited access and clearance (~ 1 inch). It is critical to be able to quantify the relative flow contribution of different aquifer depths to water in the well and to analyze water quality in these different zones under actual operating conditions. Commercial tools are too large to measure flow and sample water in existing wells.



Figure 25. View of sampling system for well bore flow and depth-dependent sampler used in field studies. There are two Bennet pump reels with hoses: one for dye injection and the other for sample collection. A generator is required for the pump. All equipment is mounted on a flat trailer.

The purpose of the Stratified Aquifer Sampling (SAS) system is to expand the capabilities of the Jackson School for both research and teaching in hydrogeology. Currently there are two of these systems in the US owned by the USGS. Developing this relatively unique capability would significantly enhance our ability to do groundwater research. Examples of the types of research that can be addressed using this system include:

- estimating groundwater recharge rates by age dating groundwater at different depths
- evaluating distribution of nutrients related to biogeochemical cycling (nitrogen),
- assessing distribution of naturally occurring contaminants in aquifers, such as arsenic, radionuclides etc and being able to relate them to specific geologic units
- quantifying variations with depth in geochemical processes, such as denitrification
- characterizing depth variations in groundwater salinity for brackish water resources development
- delineating depth distributions of point source contaminants
- and relating flow in aquifers to stratification of geologic units

This system is a fundamental tool for characterizing stratification of groundwater. Delineating depth distribution of naturally occurring contaminants, such as arsenic and radionuclides, will be essential to linking naturally occurring contaminants to specific geologic units. The information provided by the SAS can be used to assess the potential for producing from different depth zones and screening out different geologic units to reduce levels of these contaminants in their water.

The immediate need for the SAS system is to evaluate relationships between geologic units and zones of high arsenic, selenium, fluoride, nitrate, and uranium in public water system wells in the Southern High Plains. If we can isolate the geologic zones producing these contaminants, these public water systems will be able to design their wells to minimize contamination from these units.

## 4.2 Comparison of Different Approaches for Conducting Multilevel Sampling in Wells

The proposed system represents significant advances on traditional wireline tools provided by commercial logging companies which generally have large diameters (~ 3 in) and cannot function in existing pumping wells. Setting up packers to test different intervals is much more expensive to conduct and would require removal of the pump prior to testing, which is not always feasible. Drilling multilevel wells is extremely expensive and generally not feasible adjacent to existing pumping wells. Therefore, this system offers many advantages over traditional approaches with respect to costs, feasibility, and number of intervals that can be examined.

**Tasks 2 & 3**  
**Assessment of In Situ Technologies for Small  
Public Water Systems Near Lubbock, Texas**

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# Introduction

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The University of Texas Bureau of Economic Geology (BEG) is currently evaluating the potential use of in situ treatment technology approaches for public water systems that do not meet the U. S. Environmental Protection Agency (EPA) maximum concentrations limits (MCLs) for a number of water quality constituents of concern (COCs). This report presents an assessment of a number of potential in situ technologies for treatment, removal and/or precipitation of metals present in the vicinity of groundwater supply wells. Also included is an assessment of injecting ex situ treatment residuals into the source aquifer in the vicinity of Lubbock, Texas. The study area included the counties of Lubbock, Lamb, Hale, Floyd, Crosby, Garza, Lynn, Terry, and Hockley Counties in the northwestern portion of Texas.

Figure 26 shows the study area. Historic water quality monitoring within these counties has indicated that the most common COCs that do not meet MCLs include: nitrate ( $\text{NO}_3$ ), arsenic (As), fluoride (F), selenium (Se), uranium (U), and radium-226 (Ra-226), and radium-228 (Ra-228). With the exception of nitrate, these COCs are naturally occurring within these counties.

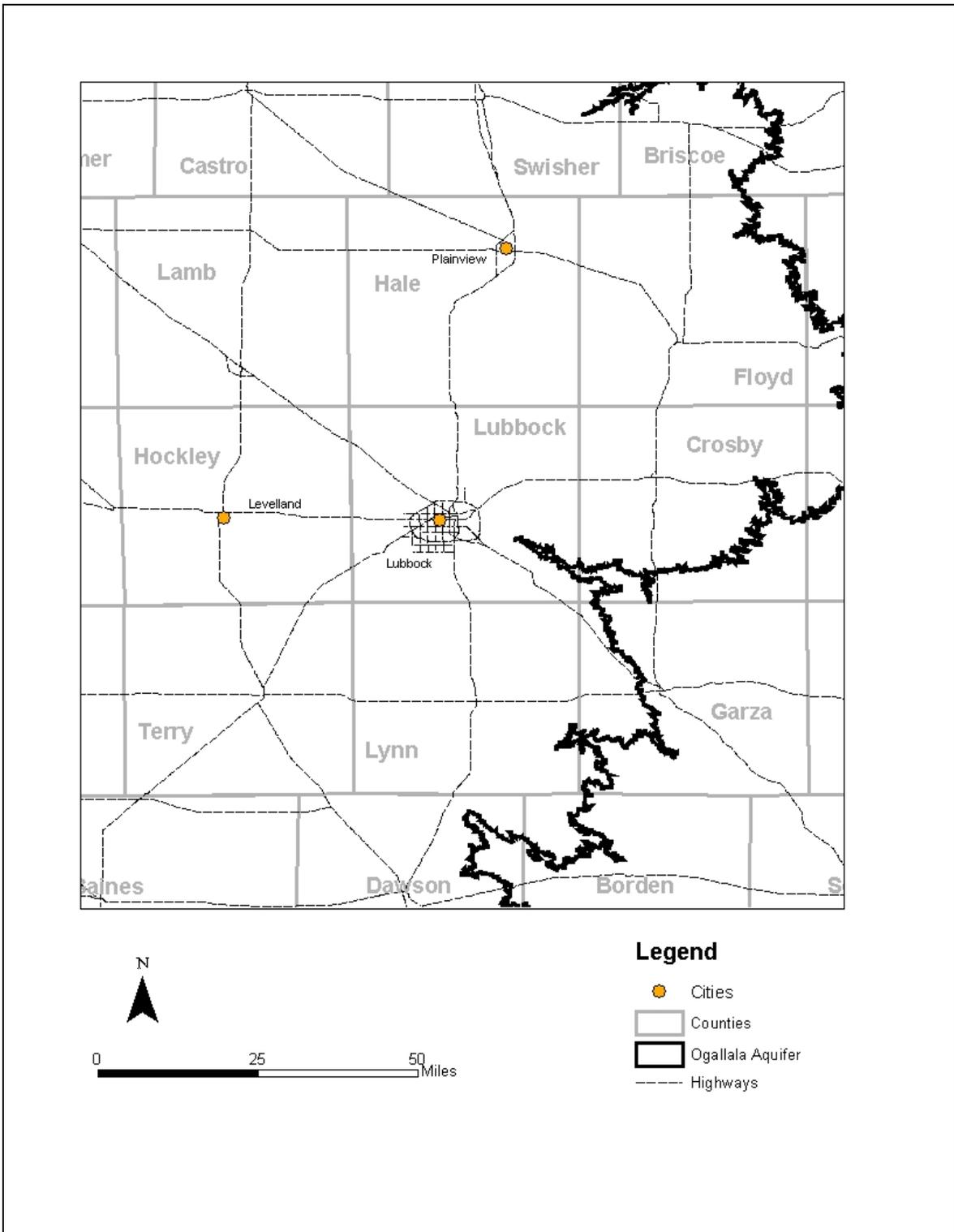
The information presented in this in situ technology screening assessment (TSA) will be used to help decision-makers select from a number of potential in situ technologies that may be used as a single, stand alone technology, or combined with ex situ treatment technologies to provide the necessary treatment required to meet drinking water quality standards.

## 5.1 Purpose and Approach

Traditional water supply treatment is conducted using ex situ treatment technologies such as ion exchange, reverse osmosis, filtration and chemical reduction. While it is anticipated that these ex situ technologies will be used for most large-scale drinking water treatment, other methods and technologies, such as in situ treatment, are being evaluated to support, enhance and potential reduce the costs of providing drinking water that meets EPA, state and local water quality standards. This report presents an evaluation of the potential benefits and use of in situ treatment technologies for water supply aquifers. Additionally, an evaluation of fate and transport of treatment residuals (from ex situ treatment technologies) injected back into the source aquifer will provide decision makers with another method for management of these residuals.

The completion of the technology evaluation and modeling of residuals injection will be used specifically to assist with:

- A) Determination of the potential for in situ treatment for exclusion of contaminants from the water produced by wells.
- B) Determination of potential impacts of injection of concentrated treatment residuals into the source aquifer (Class V injection) in the vicinity of the supply well.



**FIGURE 26**  
 Site Study Area near Lubbock, Texas  
 University of Texas, Bureau of Economic Geology, Austin, Texas

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The TSA develops and evaluates remedial technologies for mitigating COCs that exist in groundwater within the investigation area (Lubbock, Lamb, Hale, Floyd, Crosby, Garza, Lynn, Terry, and Hockley Counties). The TSA will be used to assist with a comprehensive evaluation of methods and techniques to meet water quality supply standards in aquifers that contain COCs. The TSA uses the site conceptual model, which was generated using information gathered from water quality monitoring conducted in these counties.

As part of the evaluation, the BEG is also evaluating the potential use and impacts, if any, of injection of treatment residuals using Class V wells in the vicinity of the source water supply well. Treatment residuals are produced from several ex situ treatment methods such as ion exchange, reverse osmosis, and chemical reduction. Typically, anions (chloride [Cl], NO<sub>3</sub>, sulfate [SO<sub>4</sub>], etc) and cations (sodium [Na], calcium [Ca], potassium [K], etc.) are removed via these treatment technologies producing concentrated residuals requiring disposal. Traditional residuals handling methods for these residuals includes disposal at an approved landfill site.

## 5.2 Study Objectives

The specific objectives of the in situ technology evaluation are to:

- Summarize common site conditions where the COCs occur.
- Identify in situ technologies that are used to treat or remove nitrate, As, Se, U, F, Ra-226 and Ra-228 in groundwater.
- Evaluate these technologies based on a range of site conditions present in the vicinity of Lubbock, Texas.
- Identify conceptual design factors needed to conduct the cost evaluation.
- Prepare a range of costs to implement each technology.

The specific objectives for assessment of treatment residuals injection are to:

- Estimate the distribution of concentrated residuals in the area of the injection well over various periods of operation.

Based on input from the BEG, evaluation of residuals injection targeted the Ogallala aquifer versus injection into deeper, more costly aquifers.

## 5.3 Report Organization

The remainder of the report is organized as follows:

- **Section 5.0 - Introduction:** Presents the purpose, objectives of the report and the report organization.
- **Section 6.0 - Background and Conceptual Model.** This section presents a summary of typical site conditions based on data from the counties included in this study.
- **Section 7.0 - Results Evaluation of Residuals Injection.**

- 
- **Section 8.0 - Technology Assessment.** Presents the identification and screening of remedial technologies for well head protection. Presents the analysis of the technologies using modified CERCLA evaluation criteria.
  - **Section 9.0 - Further Evaluation and Testing.** Describes additional steps required to design and implement a selected in situ technology.
  - **Section 10.0 - Summary and Conclusions.** Presents a summary of Tasks 2 & 3.

# Background and Conceptual Model

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## 6.1 Study Area Description and History

### 6.1.1 Physiography

The nine county area surrounding Lubbock, Texas, is located within the High Plains Section of the Great Plains physiographic province, which extends from central West Texas north to Canada. Underlain by primarily Tertiary sediments, the High Plains forms a gently rolling prairie traversed by rivers, creeks, and playas (shallow surface depressions resulting from solution of Permian evaporites underlying the Ogallala Formation). In general, there is little topographic relief, except in the southeastern portion of the study area along the Caprock Escarpment. The Caprock Escarpment forms a natural boundary line between the High Plains and the lower rolling plains of West Texas. It stretches from the Panhandle into Central Texas and is most prominent in Briscoe, Floyd, Motley, Dickens, Crosby, Garza, and Borden counties, where it reaches its highest elevations, rising abruptly above the plains at 200, 500, or as much as 1,000 feet. Large areas within the High Plains have poorly developed drainage systems. Most precipitation drains into the thousands of playa basins that range in size from a few hundred feet to more than a mile in diameter.

### 6.1.2 Climate

The climate in the region is characterized by large variations in daily temperatures, relatively low humidity, and infrequent precipitation. The mean annual daily temperatures in the study area range from 58 to 62 degrees Fahrenheit (° F). Summer temperatures often exceed 100° F and drop below freezing during the winter. Average yearly rainfall ranges from 15 to 21 inches per year. May and September are generally the wettest months of the year.

## 6.2 Summary of Study Area Conditions

### 6.2.1 Regional Geologic Framework

In the area surrounding Lubbock County, the surficial geology above the Caprock Escarpment is predominantly Quaternary alluvial deposits and Tertiary Ogallala Formation. Only portions of Floyd, Crosby, and most of Garza counties lie below the Caprock Escarpment. In these areas, the surficial geology consists of the Triassic aged Dockum Group. The Blackwater Draw Formation, comprised of unconsolidated clay, silt, sand, gravel, and caliche, is the most widespread unit that overlies the Ogallala to a depth of up to 80-feet. Table 11 presents a stratigraphic column for the region.

The Ogallala Formation is present in thicknesses up to 800-feet and is composed of gravels, sand, and silt deposited in fluvial and eolian environments. Unlike areas north of Texas, the

Ogallala in the study area is not formally subdivided into several smaller members. The uppermost section of the Ogallala Formation contains several extensive calcretes which form an erosion-resistant caprock.

TABLE 11

Generalized Stratigraphic Sequence in the Texas Panhandle  
*University of Texas, Bureau of Economic Geology, Austin, Texas*

System	Series	Group	Formation	Description	Hydrostratigraphic Units
Quaternary			Cenozoic Pecos Alluvium	Unconsolidated to partially consolidated sand, silt, gravel, clay, and caliche.	Local zones of perched groundwater
Tertiary	Late Miocene to Pliocene		Ogallala	Silty to coarse-grained sand alternating with silty clay and variable sized gravel.	Ogallala Aquifer
Cretaceous		Washita			Edwards-Trinity Aquifer
		Fredericksburg	Kiamichi	Thinly laminated shale with beds of thin, argillaceous limestone.	
			Edwards	Thick bedded to massive, fine to coarse-grained limestone	
			Comanche Peak	Irregularly bedded argillaceous limestone and thinly bedded shale.	
Trinity	Antlers	Fine to medium-grained, loosely cemented sandstone and conglomerate with beds of siltstone and clay.			
Triassic		Dockum	Cooper Canyon	Siltstone and mudstone with lenses of sandstone and conglomerate.	Dockum Aquifer
			Trujillo	Fine to coarse-grained sandstone and sandy conglomerate with thin interbedded shale.	

			Tecovas	Variegated sandy mudstone with interbedded fine to medium-grained sandstones.	
			Santa Rosa	Sandstone and conglomerate.	

In most instances, the Ogallala Formation in the areas surrounding Lubbock County unconformably overlies rocks of the Cretaceous (Trinity Group) and Triassic (Dockum Group). In the southwest portion of the study area, encompassing Hockley, Lubbock, Terry, Lynn, and part of Lamb counties, Cretaceous rocks unconformably underlie the Ogallala Formation. Triassic rocks underlie the Ogallala in the remainder of Lamb and a majority of Hale, Floyd, and Crosby counties. Most of Garza County, southeast of Lubbock, is below the Caprock Escarpment.

The sediments comprising the Ogallala have been interpreted as being sourced from the Rocky Mountains to the northwest (Seni, 1980). Typical sequences are composed of coarse-grained fluvial deposits that grade upward into fining sequences of fine-grained eolian sands and clays (Hopkins, 1993). Depositional environments for the Ogallala Formation range from alluvial valley fill or coalescing alluvial fans to eolian in nature (Seni, 1980; Gustavson and Winkler, 1988). In general sediments were alluvially deposited into the pre-existing erosional valleys within the underlying Triassic and Cretaceous rocks. The lower part of the Ogallala contains coarse fluvial deposits along major paleovalleys and finer eolian sediments concentrated between the channel axes.

Distribution of sand and gravel within the Ogallala has been previously mapped based on interpretation of drillers' logs from both Texas and New Mexico (Seni, 1980; Blandford, et.al., 2003). The variable thickness of sand and gravel within the Ogallala is related to the presence of paleochannels within the underlying stratigraphy. Thicker sequences of Ogallala sediments appear to be concentrated along the axes of these channels. In the area being investigated, the thickest sequences (greater than 200-feet) of sand and gravel are located in Lamb and Hale counties north of Lubbock (Blandford et al., 2003, Fig. 17). West of Lubbock in Hockley County, the thickness ranges between 50-feet to 200-feet. South of Lubbock, the thickness of gravel and sand comprising the Ogallala generally ranges from 0 to 150-feet.

### 6.2.2 Hydrogeologic Framework

The Ogallala is the primary water producing unit in the study area and consists of heterogeneous layers of clay, silt, sand, and gravel. It is considered to be unconfined with primary recharge occurring through direct infiltration of precipitation. To a much lesser extent, additional recharge may also occur through leakage caused by differing potentiometric pressure gradients between the Ogallala and underlying Cretaceous and Triassic aquifers. Low annual precipitation coupled with high evapotranspiration and low infiltration rates result in a small percentage of precipitation reaching the water table.

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Regional groundwater flow within the Ogallala aquifer is generally from the northwest to the southeast. Typical groundwater velocities are less than 1-ft/day (Ashworth, et. al., 1991). However, higher velocities are possible in coarser grained deposits. Regional groundwater gradients are on the order of  $10^{-3}$ ft/ft, although local pumping can create small localized areas with increased gradients.

Hydraulic conductivity is the volume of water capable of being transmitted under a unit hydraulic gradient, through a cross-section of unit height and width. Hydraulic conductivity of the Ogallala aquifer is influenced by the depositional environment in which sediments were deposited. Layering of fluvial and eolian sediments results in vertical anisotropy, and to a slightly lesser extent, horizontal anisotropy. Generally, in the study area, the thickness of the Ogallala water supply aquifer ranges from approximately 50 feet to over 200 feet thick in places. Hydraulic conductivity in the counties surrounding Lubbock ranges from less than 5 to over 500 ft/day. However, a majority of the area is less than 20 ft/day. The computed mean of hydraulic conductivity in the Ogallala aquifer is approximately 6.8 ft/day (Blandford et al., 2003). Approximately 98-percent of the hydraulic conductivity data from which these estimates were obtained, comes from specific capacity tests compiled from driller's well completion reports in Texas and New Mexico (Seni, 1980; Blandford, et.al., 2003). Other data was obtained from long term pump tests, laboratory analysis of core samples, and geophysical logging. Previous modeling of the Ogallala aquifer (Blandford, et.al., 2003) used a storage coefficient of 0.15, although other investigations provide further values ranging from 0.04 to 0.25 (Mullican et al., 1997; NMOSE, Musharrafieh and Chudnoff, 1999; Musharrafieh and Logan, 1999).

### 6.2.3 Nature of Groundwater Quality

A summary of water quality statistics for all counties evaluated as part of the study are presented in Tables 12 and 13. Concentrations in excess of the MCL are indicated in red text.

Groundwater samples from the Ogallala aquifer in Crosby County, exceeded the maximum contaminant level (MCL) for all seven of the chemicals of concern (COC) in at least one sampling analysis (i.e., the highest sampling value exceeded the MCL). However, neither the average nor the median value exceeded the MCL for any of the COCs.

Floyd County samples exceeded the MCL for the COCs in at least one analysis each of arsenic, fluoride, and nitrate. However, neither average nor median values exceeded the MCL for any of the COCs.

In Garza County, the maximum value measured for all of the seven COCs exceeded the MCL. Moreover, the average and median values measured for radium exceeded the MCL by an order of magnitude, indicating that radium is a significant concern in Garza County water. Also, the median fluoride concentration was slightly above the MCL.

In Hale County, the maximum value of arsenic and nitrate exceeded the MCL, but none of the average or median values of the COCs exceeded the MCL in Hale County.

In Hockley County, the maximum values of all seven COCs exceeded the MCL. Also, the median value of fluoride and mean value of nitrate slightly exceeded the MCL.

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In Lamb County, the maximum measured values of the non-radioactive COCs exceeded the MCLs. Also, the mean value for nitrate slightly exceeded the MCL.

In Lubbock County, the maximum values for all COCs except radium exceeded the MCL. Also, the mean value of nitrate exceeded the MCL.

In Lynn County, the maximum measured value of all COCs except radium exceeded the MCL. Moreover, the maximum value for uranium exceed the MCL by more than an order of magnitude, which indicates that certain areas in Lynn County have dangerous levels of uranium. Also, average values for arsenic, fluoride and nitrate exceeded the MCL.

TABLE 12

Summary Statistics For Constituents of Concern

University of Texas, Bureau of Economic Geology, Austin, Texas

Chemical (Units)	MCL	Statistic	County								
			Crosby	Floyd	Garza	Hale	Hockley	Lamb	Lubbock	Lynn	Terry
Arsenic (µg/L)	10 <sup>a</sup>	Analyses	193	201	138	167	53	91	213	162	43
		Detects	180	186	101	131	43	70	200	156	38
		Max	18.7	30.5	30	16	25.6	11	42.8	170	64
		Min	0.5	0.699	0.5	0.799	3.14	2.1	0.5	0.5	2.5
		Mean	5.08	6.08	5.35	4.78	8.6	5.23	9.23	12.7	21.3
		Median	4.75	5.48	3.5	4.39	7.77	5.04	8.00	8.65	15.95
		Fluoride (µg/L)	4000 <sup>b</sup>	Analyses	101	205	85	154	194	319	412
Detects	94	171		81	150	192	312	340	94	140	
Max	5400	6400		9200	3800	8200	8000	7900	22000	13700	
Min	1400	500		100	500	100	400	100	1700	100	
Mean	3035	3020		3871	2557	3885	2235	3579	5145	4505	
Median	2960	3000		4600	2530	4000	1960	3445	4915	4300	
Selenium (µg/L)	50	Analyses		192	201	137	176	53	90	198	168
		Detects	154	165	103	96	47	71	177	149	40
		Max	65	39.299	93.7	17.5	69.1	66.5	93.4	112	113.6
		Min	0.199	0.199	0.199	0.199	3	2	0.199	0.199	5.13
		Mean	3.05	3.77	3.5	2.68	15.6	16.8	10.3	9.71	35.4
		Median	0.599	0.799	0.500	0.599	11.0	13.0	4.00	0.599	26.6
		Radium 226 (pC/L)	5 <sup>c</sup>	Analyses	15	25	10	10	12	16	56
Detects	10			17	10	6	5	10	30	7	7
Max	6.6			1.9	105	0.3	17.6	0.9	2.8	1.6	4.6
Min	0.1			0.2	1.4	0.2	0.2	0.2	0.2	0.2	0.2
Mean	1.07			0.537	36.97	0.233	3.88	0.39	0.463	0.729	1.00
Median	0.35			0.4	31.55	0.2	0.5	0.35	0.3	0.6	0.4
Radium 228 (pC/L)	5 <sup>c</sup>			Analyses	14	24	10	10	12	16	55
		Detects	6	7	9	0	7	1	7	3	4
		Max	7	1.7	64	--	52	1	2.3	1.6	9
		Min	1	1	2	--	1.2	1	1	1	1.1
		Mean	2.64	1.33	33.1	--	8.79	1.00	1.53	1.3	3.13
		Median	1.8	1.3	27	--	1.4	1	1.6	1.3	1.2

TABLE 12

Summary Statistics For Constituents of Concern

University of Texas, Bureau of Economic Geology, Austin, Texas

Chemical (Units)	MCL	Statistic	County									
			Crosby	Floyd	Garza	Hale	Hockley	Lamb	Lubbock	Lynn	Terry	
Uranium (µg/L)	30	Analyses	144	124	115	118	0	145	113	133	0	
		Detects	143	124	112	118	--	145	98	130	--	
		Max	60.679	29.379	138.399	29.739	--	16.02	175.4	411.299	--	
		Min	0.779	2.649	0.539	1.62	--	0.32	0.199	0.459	--	
		Mean	11.3	7.91	21.4	8.23	--	4.54	5.62	29.6	--	
		Median	10.0	7.63	13.0	7.42	--	4.19	0.399	20.0	--	
Nitrate (mg/L as N)	10	Analyses	112	228	97	183	213	338	482	285	195	
		Detects	109	205	96	180	211	336	416	282	147	
		Max	31.079	56	150	53.12	83.23	75.1	148.7	283	161	
		Min	0.04966	0	0.01	0	0.04	0.09	0.04	0.3	0.04	
		Mean	2.41	5.15	12.4	6.15	12.1	13.5	15.9	40.0	30.5	
		Median	1.25	2.88	6.00	3.22	8.54	10.0	7.79	31.0	15.5	

Units:

µg/L = micrograms per liter

pC/L = picocuries per liter

mg/L as N = milligrams per liter as nitrogen

a: The MCL for arsenic is 50 µg/L until January 2006 at which time it changes to 10 µg/L.

b: The secondary standard for fluoride is 2000 µg/L

c: The MCL for Ra226 and Ra228 combined is 5 pC/L. The gross activity MCL for all radionuclide combined (excluding radon and uranium) is 15 pC/L.

TABLE 13

Summary Statistics For Dissolved Ions and General Chemistry Parameters

*University of Texas, Bureau of Economic Geology, Austin, Texas*

Chemical (Units)	Secondary Standard	Statistic	County								
			Crosby	Floyd	Garza	Hale	Hockley	Lamb	Lubbock	Lynn	Terry
Calcium (mg/L)	--	Analyses	229	331	200	273	194	318	509	401	196
		Detects	229	331	200	273	194	318	509	401	196
		Max	230	298	1760	93	6753	780	380	4010	770
		Min	2	10.399	0.899	8.399	10.8	22	4.71	2.229	3.2
		Mean	50.72	43.96	139.4	48.97	130.1	77.53	69.89	139.2	134.2
		Median	42	40	61	47.749	63.9	65.5	56.95	84.3	88
		Iron (mg/L)	<b>0.3</b>	Analyses	146	128	116	125	7	0	177
Detects	16			6	33	21	4	--	50	42	1
Max	<b>0.366</b>			0.054	<b>0.389</b>	0.354	0.039	--	1.96	<b>0.375</b>	0.055
Min	0.01			0.01	0.01	0.01	0.017	--	0.01	0.01	0.055
Mean	0.0641			0.0233	0.0348	0.0367	0.0298	--	0.142	0.0369	0.055
Median	0.013			0.0205	0.017	0.012	0.0315	--	0.02	0.017	0.055
Magnesium (mg/L)	--			Analyses	229	331	200	273	194	318	509
		Detects	227	319	188	246	194	311	492	355	174
		Max	150.399	125	1570	76.799	2153	599	340	1620	30004
		Min	0.899	6.599	0.199	5	13	8	3.55	1.089	1.52
		Mean	37.7	34.5	84.3	37	104	50.1	66.7	133	1960
		Median	33	34	54	36	72	40	60	91	102
		Potassium (mg/L)	--	Analyses	218	244	199	257	187	317	430
Detects	218			244	199	257	187	317	430	400	195
Max	30.799			12	69	21.899	88	31.92	32	139	11491
Min	0.399			2.3	0.299	2.299	0.6	2	6	1	1.08
Mean	9.19			8.06	10.2	9.51	14.64	10.92	14.28	19.43	407.9
Median	9.799			8.005	6.1495	9	12.4	8.48	13.699	17	19.65
Sodium (mg/L)	--			Detects	229	330	200	271	193	318	509
		Detects	227	307	188	243	193	311	495	362	162
		Max	1000	303	19216	196	21300	907	790	12100	58990
		Min	4.899	6	0.509	8	18.2	17	5	0.409	39
		Mean	105	55	1191	43	325	76	97	335	2249
		Median	54	43	165	38	81	43	86	176	152

TABLE 13

Summary Statistics For Dissolved Ions and General Chemistry Parameters

*University of Texas, Bureau of Economic Geology, Austin, Texas*

Chemical (Units)	Secondary Standard	Statistic	County										
			Crosby	Floyd	Garza	Hale	Hockley	Lamb	Lubbock	Lynn	Terry		
Chloride (mg/L)	250 <sup>c</sup>	Analyses	220	248	200	272	194	318	509	401	196		
		Detects	215	245	180	187	194	313	500	354	194		
		Max	2192	615	28000	223	33900	2733	2560	28000	104417		
		Min	5.7	3.54	19	5	19	6.65	5	1	36		
		Mean	132	39.1	1920	43.4	676	115	146	609	5270		
		Median	24.1	20	208	31	122.5	60	105	287	258		
		Sulfate (mg/L)	250 <sup>c</sup>	Analyses	245	329	200	272	194	318	509	401	196
Detects	242	326		194	246	194	313	509	300	190			
Max	1026	930		3140	202	2550	2184	1008	10400	184946			
Min	2	2		5	5	8	14	3	18	49			
Mean	113	48.6		435	36.7	236	153	165	462	12100			
Median	39	31		143	30	173.5	84	135	254.5	350			
pH (unitles)	6.5 - 8.5	Analyses		245	329	200	271	194	465	509	401	196	
		Max	9	8.5	10.599	8.4	8.6	8.5	8.899	8.6	9		
		Min	4.899	4.699	5.299	3.5	6.6	6.5	5.7	6	4.1		
		Mean	7.54	7.55	7.48	7.55	7.79	7.59	7.63	7.47	7.71		
		Median	7.5	7.599	7.5	7.5	7.8	7.6	7.6	7.399	7.6		
		Conductivity (not specified)	--	Analyses	146	128	115	132	7	148	178	132	1
				Max	7680	2500	12500	1600	2214	2700	3040	10907	2352
Min	395			380	310	500	869	450	46	330	2352		
Mean	1250			772	2600	753	1460	810	1270	2450	2350		
Median	780			710	1690	727.5	1500	700	1206	1790	2352		
Alkalinity (mg/L)	--			Analyses	146	127	115	116	7	1	178	131	0
				Detects	146	127	115	108	7	1	177	131	--
		Max	1441	498	713	612	317	224	714	1735	--		
		Min	134	210	90	194	203	224	7	75	--		
		Mean	342	281	341	296	256	224	300	312	--		
		Median	317	278	320	290	248	224	298	295	--		

TABLE 13

Summary Statistics For Dissolved Ions and General Chemistry Parameters

*University of Texas, Bureau of Economic Geology, Austin, Texas*

Chemical (Units)	Secondary Standard	Statistic	County								
			Crosby	Floyd	Garza	Hale	Hockley	Lamb	Lubbock	Lynn	Terry
TDS (mg/L)	500 <sup>d</sup>	Analyses	101	205	85	153	192	318	410	269	196
		Detects	99	188	84	152	192	312	409	159	163
		Max	3004	1944	50784	832	59292	7326	4463	45621	256421
		Min	244	209	321	167	446	242	30	451	508
		Mean	586	442	6910	442	1710	681	797	2030	10400
		Median	426	397	858.5	421.5	760.5	512	706	963	1187

Units:

mg/L = milligrams per liter

c: The Texas secondary standard is 30 mg/L for chloride and sulfate

d: The Texas secondary standard is 1000 mg/L for TDS

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In Terry County the maximum value of all COCs except uranium exceeded the MCL. Moreover, average values for arsenic, fluoride, and nitrate exceeded the MCL in Terry County.

Notable exceedances of secondary standards included sulfate and chloride in Terry and Lynn Counties. Also, average values for TDS exceeded the secondary standard in all but Floyd and Hale counties.

### 6.3 Residuals Injection Evaluation Methodology

In addition to evaluating potential in situ technologies, this report provides an assessment of the potential for injecting treatment residuals (Class V) into underlying geologic units. Typically, Class V wells are shallow wells used to inject a number of non-hazardous fluids directly below land surface or into formations that contain a drinking water source (an underground source of drinking water [USDW]). Class V wells would generally be defined as wells that inject at depths above the 10,000 mg/l TDS interface.

The scenarios evaluated in this study involved injecting treatment residuals into a portion of the same aquifer supplying water to the PWS, but in locations remote from the supply wells. If favorable geologic conditions were present, the concentrate could also be injected into zones within a USDW above or below the production zone, relying on confining properties of the intervening geologic strata to protect the source water. Because the effectiveness of this method would depend on the site specific properties of the confining layers, groundwater modeling was not conducted to evaluate this alternative.

A numerical groundwater model was constructed using Groundwater Modeling System (GMS) 5.1 software. This version of GMS utilizes MODFLOW 2000 (Harbaugh, et. al., 2000) as the groundwater hydraulic model. GMS utilizes MT3DMS (Zheng, 1999) as a solute transport package. The solute transport simulations were run under steady-state groundwater solutions.

The modeling was intended to represent general conditions in the study area but was not calibrated to match any specific site. A model domain was created three miles square and 200 feet (ft) thick. The model grid was set up as a single layer. Horizontal grid spacing ranged from a minimum of 10 ft to a maximum dimension of 200 ft with finer grid spacing around the production and injection well. This resulted in a total of 166 rows and 123 columns.

No chemical reactions were simulated in the solute transport modeling. Interaction of the treatment residuals with the formation matrix or native groundwater could increase or decrease the concentrations of dissolved COCs. These reactions would depend on the site specific properties of the aquifer, local groundwater, and treatment residuals. For the purposes of this study, it was considered that simulation of advective and dispersive transport mechanisms would provide a reasonable estimate of the distribution and relative concentration of injected treatment residuals.

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## 6.4 In Situ Technology Assessment Approach

This section presents the methodology used to identify, evaluate, and compare remediation technologies or a combination of technologies that could be used to for well head protection programs. The *Remediation Technologies Screening Matrix and Reference Guide*, Version 4.0, was used as a reference for several of the remedial technologies and process options (Federal Remediation Technologies Roundtable, 2002).

A variety of technically feasible treatment technologies exist for the COCs that are present in the water supply aquifers. Each technology must, however, be evaluated for site-specific conditions and considerations to identify the optimum technology configuration. For this study, evaluation of treatment technologies was conducted using a modified feasibility study framework defined in *Guidance for Conducting Remedial Investigation and Feasibility Studies Under CERCLA* (USEPA, 1999b).

Technologies were developed for a generic set of site conditions to provide a range of options that can be used to help select technologies that:

1. Can provide stand alone treatment, removal or management of COCs in aquifer water to meet MCLs for all COCs; or
2. Can provide treatment, removal or management of COCs in aquifer water that can be used with other ex situ technologies to meet MCLs.

In this phase of the evaluation, technologies are developed based on site conditions and are evaluated in detail against the decision criteria that are used to evaluate the technologies. The criteria used in the detailed analysis are listed below:

1. **Overall protection of water supply (including protection to human health and the environment).** This criterion includes an assessment of how well the technologies protect the surrounding environment once implemented. Some technologies change the subsurface conditions which can create ancillary water quality or soil degradation.
2. **Reduction of toxicity, mobility, or volume of impacted media through in situ treatment, removal or precipitation.** Technologies modify the physical or geochemical conditions to reduce toxicity of COCs, decrease the mobility of COCs, decrease the size of volume of impacted space or alter the state of the constituent to a non-regulated compound or element.
3. **Short- and long-term effectiveness and permanence of each alternative.** A key aspect of the technology evaluation is the effectiveness of each technology in meeting desired drinking water MCLs or alternative treatment limits to be used with other technologies. Each technology is evaluated in terms of its effectiveness in providing protection and the reductions in toxicity, mobility, or volume that it will achieve. Short-term and long-term effectiveness is evaluated. In this context, short-term refers to the construction and implementation period for the technology and long-term refers to the period after the technology has been implemented.
4. **Challenges with implementability.** Implementability is evaluated in terms of both the technical and administrative feasibility of constructing, operating, and maintaining the technology. Technical feasibility refers to the ability to construct, reliably operate, and

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comply with regulatory requirements during implementation of the technology. Technical feasibility also refers to the future operation and maintenance (including monitoring) of the technology after implementation. Administrative feasibility refers to the ability to obtain approvals and permits from regulatory agencies; the availability and capacity of treatment, storage, and disposal services; and the requirements for and availability of specialized equipment and technicians.

5. **Cost.** The primary purpose of the cost screening criterion is to permit comparative estimates between technologies. Although these estimates are only order-of-magnitude, the costs are acceptable for use in the screening as a relative measure of costs to compare the different alternatives.

Each in situ technology is evaluated individually against each criterion, and then the different technologies developed for an affected medium are compared to determine specific strengths and weaknesses that must be balanced. Technologies that are not effective or less effective in protecting the environment, that cannot be implemented because of the physical characteristics of the site or contaminants, or have a cost that is an order of magnitude greater than a similar technology, were not considered for this evaluation.

In situ technologies, considered viable given the site conditions and COCs present in the aquifers in the study area included:

1. Iron based technologies:
  - Zero valent iron (ZVI) permeable reactive barriers (PRBs)
  - Injectable nano-scale ZVI (Ferox™ Process)
2. Phosphate and or limestone based technologies:
  - Phosphate permeable reactive barriers (PRBs)
  - Limestone permeable reactive barriers (PRBs)
3. Sulfur based technologies:
  - Dithionite
  - Calcium polysulfide
4. Bioremediation:
  - Enhancement of geochemical conditions for treatment/removal of COCs
5. Innovative in situ natural treatment technologies (these technologies were not evaluated using the evaluation criteria because they rely on extraction to near surface and would be comparable to ex situ technologies).
  - Phytoremediation
  - Engineered Wetlands

# Results Evaluation of Residuals Injection

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Increasing water demands for potable water, combined with decreasing supplies, will necessitate utilization of groundwater that requires advanced treatment processes to meet federal and state drinking water standards. The treatment processes will result in a waste stream of concentrated treatment residuals that will need to be managed. While not permitted under current regulations, a cost-effective method for handling these residuals would be injection back into the source aquifer.

This report provides an assessment of the transport of treatment residuals injected into the same aquifer where a production well is pumping, but at a location remote from the production well. The primary objective of this study was to estimate the distribution of treatment residuals in the area of the injection well over 50 years of operation. Additionally, distribution of treatment residuals following shut down of the wells at the end of the theoretical project life of 50 years was modeled.

Because the modeling was conceptual in scope and aquifer parameters were not site-specific but represented general conditions in the study area, a sensitivity analysis was performed to evaluate the effects of varying aquifer parameters on the movement of injected fluids over a range of values consistent with the study area.

It should be noted that no chemical reactions have been modeled. Interaction of the concentrate with the formation matrix or native groundwater could increase or decrease the mass of dissolved COCs. However, it is anticipated that simulation of advection and dispersion provides a reasonable estimate of the distribution and relative concentration of injected treatment residuals since chemical reactions and dissolution are not expected to substantially affect the concentration of treatment residuals during transport in the Ogallala aquifer.

## 7.1 Current Regulations

Injection of concentrates falls under the jurisdiction of the Texas Commission on Environmental Quality (TCEQ) Underground Injection Control regulations (UIC). Generally, UIC regulations are designed to protect USDWs from contamination which would render the sources unusable. In Texas, a USDW is defined as an aquifer or portion of an aquifer that:

- Supplies any public water system or contains a quantity of ground water sufficient to supply a public water system
- Currently supplies drinking water for human consumption
- Contains less than 10,000 mg/L total dissolved solids and is not an exempted aquifer.

Currently, regulations do not allow Class V wells to inject water which would result in degradation of the water quality that exists in the USDW. However, it is possible that exceptions to the rule may be allowed in the future.

## 7.2 Conceptual Model

Based on the information presented by Blandford, et. al. (2003), a conceptual model of the Ogallala aquifer was developed for the purpose of assessing groundwater movement in the study area. The conceptual model includes a production well and an injection well, both completed in the Ogallala aquifer. The zone in the area of interest is approximately 200 feet thick with 75 feet of saturated thickness. The regional groundwater gradient was estimated at 9.8 ft/mile toward the east-southeast (66 degrees east of south). The injection well is modeled 4,000 feet down gradient of the production well to avoid capture of the injected fluid by the production well.

The volume of groundwater production, and associated volume of treatment residuals, was determined based on representative public water system capacity and water treatment method. The size of a typical public water system experiencing difficulties with the COCs was estimated at 60,000 gallons per day (gpd). This corresponds to a system with approximately 100 service connections.

To develop an understanding of the potential impacts of residuals disposal in the source aquifer, an estimate of the volumetric rate and concentration of the residuals was required. The inorganic COCs in this investigation include nitrate, arsenic, fluoride, selenium, uranium, and radium (226 and 228). The treatment processes commonly available to treat the inorganic COCs include coagulation (conventional or as part of a lime softening process), cation ion exchange, anion ion exchange, activated alumina, and reverse osmosis. Many of these treatment processes can be used to treat one, but not all, of the contaminants of concern and in some cases can only be used to treat specific forms of the contaminant. Of all the treatment technologies, only reverse osmosis can be used to treat all of the contaminants of concern in a single process. Table 14 summarizes the treatment options available for each contaminant.

TABLE 14

Process Suitability for Removal of Constituents of Concern  
*University of Texas, Bureau of Economic Geology, Austin, Texas*

Contaminant	Removal Technique				
	Lime Softening	ION Exchange (Cation)	ION Exchange (Anion)	Activated Alumina	Reverse Osmosis
Nitrate	N	N	Y	N	Y
Arsenic	Y <sup>1</sup>	N	Y <sup>1,2,3</sup>	Y <sup>1</sup>	Y
Fluoride	N	N	N	Y	Y
Selenium	Y	N	Y <sup>4</sup>	Y <sup>5</sup>	Y
Uranium	Y	N	Y <sup>3</sup>	N	Y
Radium (226 & 228)	Y	Y <sup>2,3</sup>	N	N	Y

1. Requires oxidation to As<sup>5+</sup>
  2. Significantly Impacted by High TDS levels.
  3. Significantly Impacted by High Sulfate levels.
  4. For Selenate Form (Se(VI))
  5. For Selenite Form (Se(IV))
- Y = Suitable  
 N = Not Suitable

The effectiveness of many of the treatment options shown is impacted by interferences with other COCs which may be in the water. For example, the anion ion exchange process can be significantly impacted by the presence of high levels of sulfate or total dissolved solids in the water, which will result in shorter run times and increased regeneration costs. Reverse osmosis recovery can be negatively impacted by high levels of barium or silica.

Treatment efficiency can be expected to be very high for all of the options listed as suitable in Table 14. Removals of over 90 percent can be anticipated. The waste stream generated will vary with the process selection and the interferences from other COCs in the water. In general, coagulation with iron salts will result in a sludge quantity of between 0.5 and 1 percent of the total plant flow. Lime softening residual production will be higher and depend on the amount of lime required. In either case, the solids content of the residual stream will make groundwater injection infeasible. Further treatment would be required to separate the solids from the water resulting in a clarified wastewater and a solids stream, which would contain the bulk of the COCs. The ion exchange and activated alumina processes will result in a concentration factor of about 60, meaning the waste stream will be about 1/60<sup>th</sup> of the influent stream and the concentration of the COCs will be about 60 times that of the raw water. The reverse osmosis process will have a recovery of about 70 percent resulting in a concentration factor of about 3.3 times that of the raw water and a waste stream volume of 30 percent of the incoming flow.

### 7.3 Groundwater and Solute Transport Model

Model parameters representative of the study area near Lubbock, Texas were chosen for the analysis. Dispersivity and hydraulic conductivity were varied as part of a sensitivity analysis. Selected model parameters used during the study are included in Table 15.

TABLE 15.			
Selected Model Parameters			
<i>University of Texas, Bureau of Economic Geology, Austin, Texas</i>			
	Low	High	Representative
Hydraulic Conductivity	4 ft/day	15 ft/day	7 ft/day
Longitudinal Dispersivity	25 ft	100 ft	50 ft
Transverse Dispersivity	5 ft	20 ft	10 ft
Vertical Dispersivity	5 ft	20 ft	10 ft
Effective Porosity	-	-	20%

A block-centered grid, with a 10-foot dimension at the production and injection well, increasing to a maximum dimension of 200 feet, was used in the model. Constant-head boundary conditions were specified perpendicular to the regional gradient. In order to prevent boundary effects parallel to the gradient, general head boundaries were selected with the regional gradient held at a distance of one mile from the model domain.

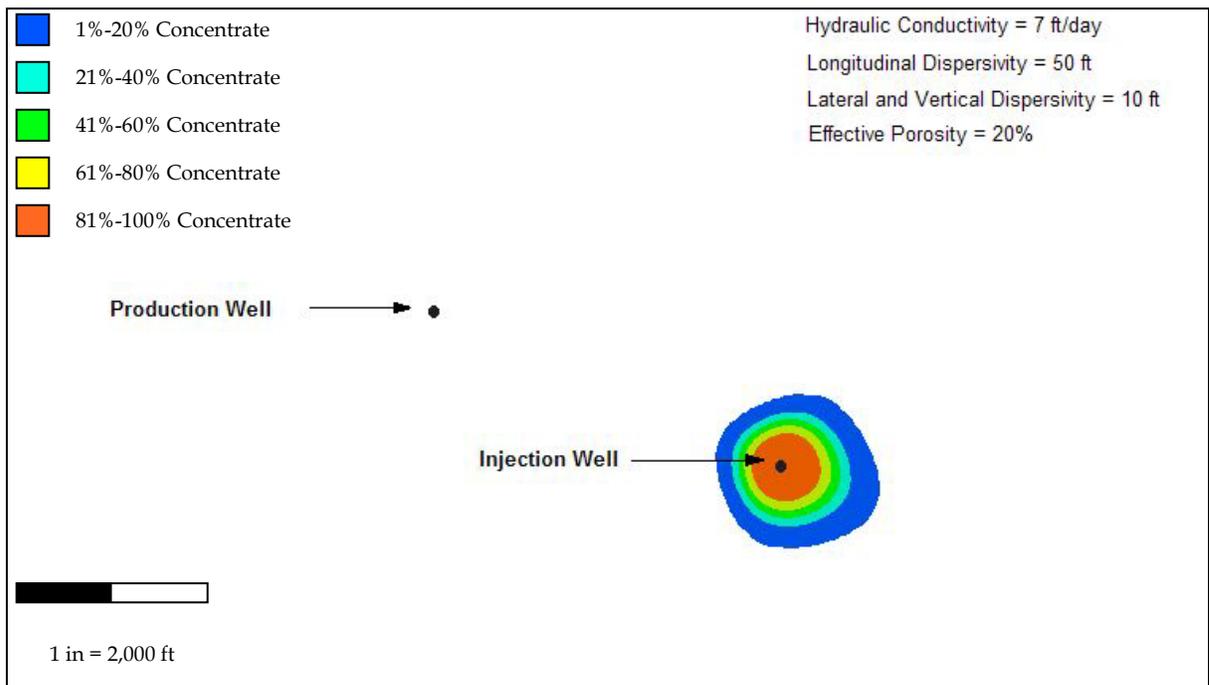
## 7.4 Results

The model results, with representative aquifer parameters, show that concentrate injected 4,000 feet down gradient of the production rate travels in the direction of the regional gradient, away from the production well. Figures 27, 28, and 29 show the distribution of concentrate, as a percentage, after 10 years, 20 years, and 50 years of system operation, respectively. Dispersion reduces the concentrations at a distance from the injection well, but results in more of the total aquifer volume being affected by the injection operations.

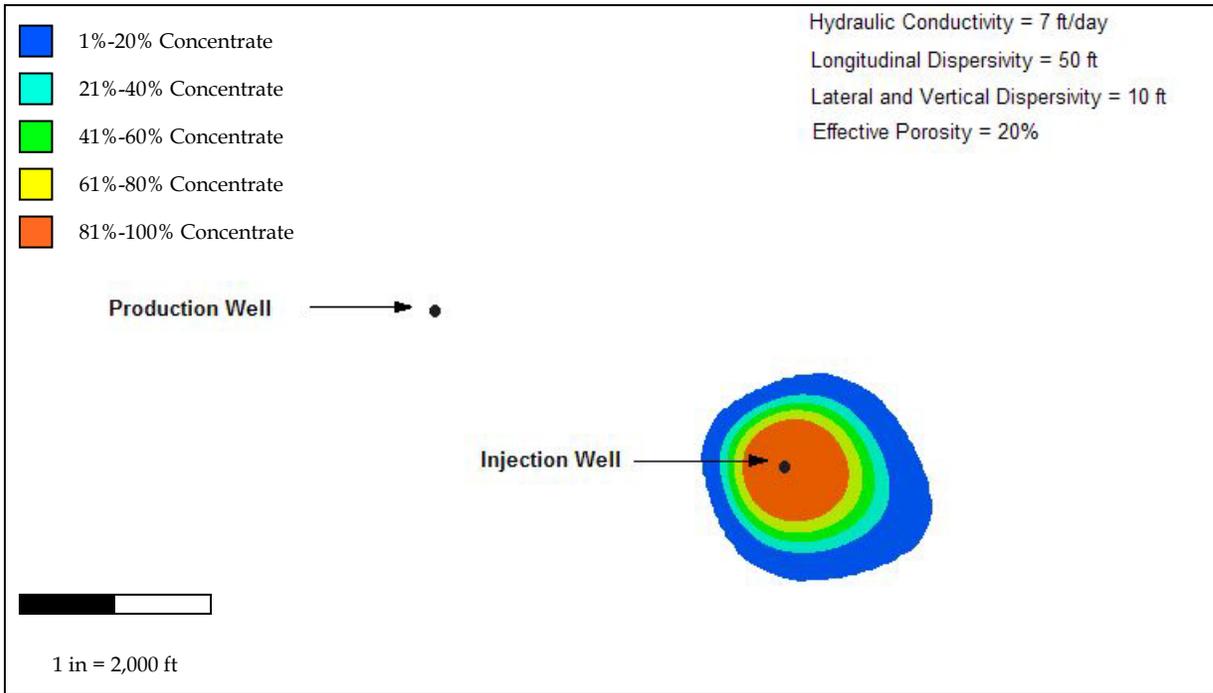
**FIGURE 27**

Concentrate Distribution After 10 Years of Injection

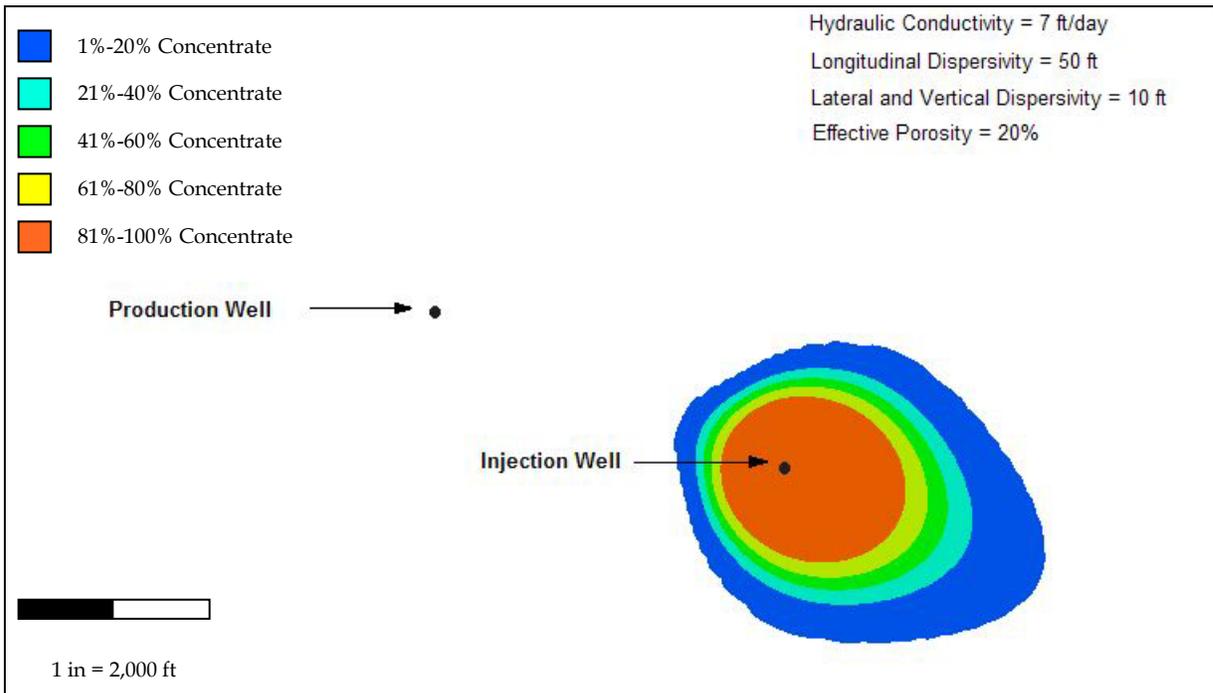
*University of Texas, Bureau of Economic Geology, Austin, Texas*



**FIGURE 28**  
 Concentrate Distribution After 20 Years of Injection  
 University of Texas, Bureau of Economic Geology, Austin, Texas



**FIGURE 29**  
 Concentrate Distribution After 50 Years of Injection  
 University of Texas, Bureau of Economic Geology, Austin, Texas

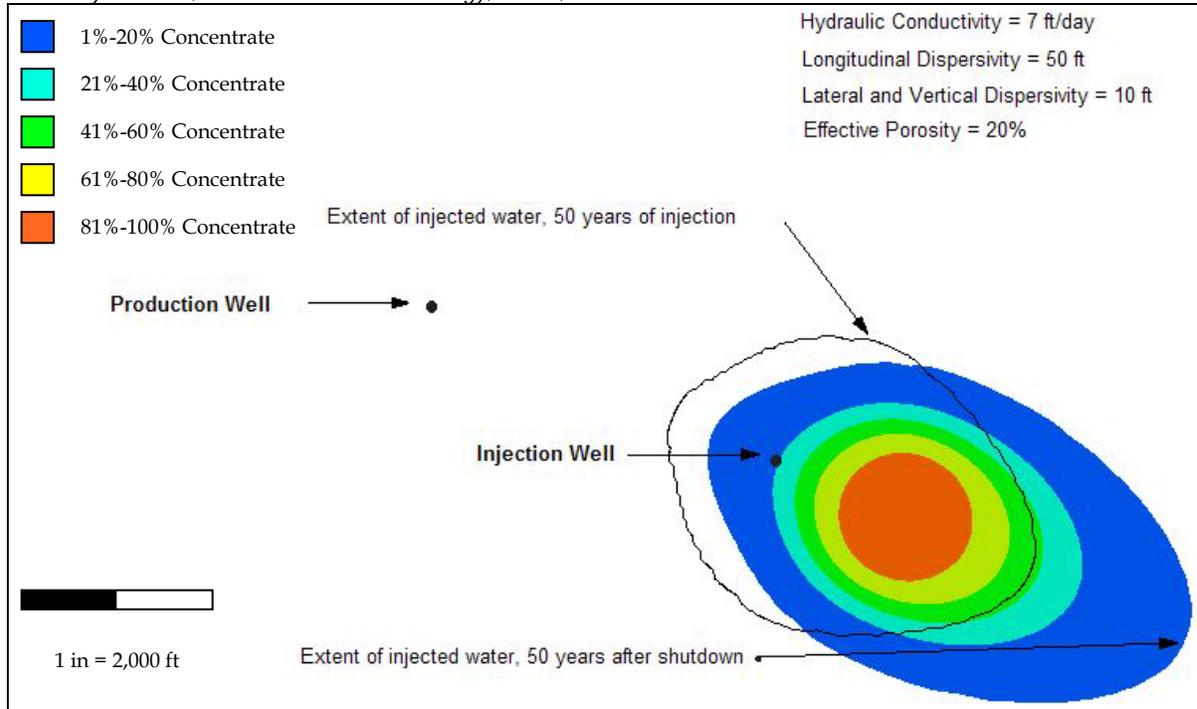


Simulated production and injection well operations result in a flattening of the local gradient. This reduction in gradient generally inhibits concentrate migrating and results in a relatively radially symmetric distribution. In order to illustrate transport, after system operations are discontinued and regional flow is restored, a second model run was performed with no production or injection.

Figure 30 presents the results of the shut-in simulation. Over the 50-year periods, the center of the concentrate distribution moved approximately 1,500 feet down gradient of the injection well. The distribution also became noticeably elongated along the axis of regional flow, lengthening from 4,000 feet after 50 years of operation to 5,500 ft, 50 years after system shut-in.

Generally, variation in the dispersivity had a relatively minor effect on the concentrate distribution, presumably due to the low groundwater velocities in the area around the injection well. Variations in hydraulic conductivity had a more significant effect with the higher values of hydraulic conductivity resulting in a distribution that was more affected by the regional gradient. The low end of the range for hydraulic conductivity would not support continuous pumping from the production well at the design rate. For the purpose of the assessment, the production rate was reduced. Even with the reduction in pumping rate, the local gradient is almost flat, resulting in a very symmetrically shaped distribution.

**FIGURE 30**  
Concentrate Distribution 50 Years After Shut-In  
*University of Texas, Bureau of Economic Geology, Austin, Texas*



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## 7.5 Summary and Recommendations

The preliminary modeling demonstrates that over a typical 50-year project life, the injected treatment residuals, remains relatively close to the injection well. Even after 50 years of movement with the regional gradient, the concentrate front migrates approximately 7,600 feet from the original injection point, becoming more dilute with time. Based on a concentration factor of approximately 3.3 for the COCs, the concentration of COCs is less than two times background where the simulated blend is less than 60 percent injectate. Using this criterion, the concentration of COCs is less than two times background levels at a distance greater than 1,800 feet from the Class V well, even after 50 years of injection.

Although the results of dispersivity do not appear to significantly influence the results of concentrate migration, hydraulic conductivity does affect the distribution of concentrate. Additionally, site specific test drilling, pump testing, and modeling should be performed prior to development of an actual system. A detailed monitoring plan to document and track movement of the concentrate should also be considered.

Application of Class V disposal must be coupled with long-term land use controls. These controls would be legal or administrative mechanisms to restrict access to contaminated groundwater associated with disposal activities.

# Technology Assessment

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## 8.1 Identification and Description of Technologies

Table 16 presents a list of promising technologies that can provide the basis for the in situ technology evaluation.

Many of the technologies listed in Table 16 are in the developmental stages and have not been tested under field conditions for water supply purposes. As many technologies have not been fully evaluated for water supply protection, CH2M HILL cannot recommend any technology without proper evaluation, testing, and design. Nonetheless, some technologies such as the permeable reactive barriers and in situ bioremediation can likely be used effectively to remove, treat or precipitate those COCs evaluated as part of this study. Other technologies identified in this study have merit based on treatment efficacy, but may not function as desired due to site or design limitations.

The remainder of this section provides an introduction and description of technologies and their principle of operation.

### 8.1.1 In Situ Chemical

#### 8.1.1.1 Permeable Reactive Barriers

Permeable reactive barriers (PRBs) make use of a granular reactive media to treat or alter the geochemistry to enhance degradation, precipitation or removal of contaminants. Several PRBs have been installed, using zero-valent granular iron (ZVI) for treatment of groundwater containing metals, chlorinated organic compounds and nutrients. Other reactive media include solid organic materials for treatment of chlorinated volatile organic compounds (CVOCs); nutrients (nitrate, phosphate, sulphate) and metals (uranium [U]); carbonate rock (limestone) to treat metals (such as lead, arsenic zinc copper and cadmium); and granular phosphate rock (U) (Blowes et al., 1999a; Blowes et al., 1999b; USEPA, 1999a; DOE, 2000; Felton, 1997). Table 17 presents a list of reactive media and COCs that have been treated.

A PRB is created by installing a wall of reactive media to intercept the flow of groundwater containing contaminants. Once the granular media is installed in the subsurface, groundwater flows through the PRB under natural gradients and no pumping or other above ground operations are required (Gavaskar, et. al., 2002). The reactive media is permeable and creates geochemical conditions or the reactive surfaces that remove, precipitate or treat (alter the state of the compound or element).

**Table 16 Summary and Screening of In situ Technologies for Wellhead Protection**

Treatment Technology	Technology Description	Typical Configuration	Effectiveness and Applicability for Sites Containing	Predominant removal mechanism						Implementation Feasibility	Treatment Residual Waste	Typical Time Needed to Implement	Cost		Screening and Selection for Further Assessment
				As	NO3	F	U	Se	Ra				Capital	O&M	
<b>In Situ Chemical</b>															
<b>Injectable Iron-based Technologies</b>															
Permeable Reactive Barriers (PRBs)	Zero Valent Iron corrodes to release hydrogen ions which chemically reduce many soluble constituents.	Conventional - trenching equipment used to install PRB to maximum of 60 ft bgs	Arsenic, fluoride, nitrate-N, uranium, selenium, radium 226 and radium 228	P	CR	Un	CR, P	CR, P	Un	PRBs can be installed using conventional trenching systems to approximately 60 ft bgs	None	1.5 to 2 years	High	None	Retained for detailed assessment
		Deep Installations - proprietary (GeoSierra) directional fracturing used to create void space for ZVI	Arsenic, fluoride, nitrate-N, uranium, selenium, radium 226 and radium 228	P	CR	Un	CR, P	CR, P	Un	Fracturing and injection of substrate is used to install PRB to depths greater than 60 ft bgs	None	1.5 to 2 years	Very High	None	Retained for detailed assessment
Fracturing and Injection of Zero Valent Iron (Ferox Process)	Subsurface fracturing is used to provide void space for injection of powdered ZVI	A series of wells are drilled to provide for treatment in a target area. Usually used for source remediation purposes.	Arsenic, fluoride, nitrate-N, uranium, selenium, radium 226 and radium 228	P	CR	Un	CR, P	CR, P	Un	Has been implemented successfully at several sites with Cr, and chlorinated solvents.	None	1 year	High	None	Retained for detailed assessment
<b>Phosphate Based Technologies</b>															
Permeable Reactive Barriers (PRBs)	Phosphate rock is ground into fine reactive material for placement into a PRB. Constituents react with phosphate and precipitation as insoluble phosphate compounds.	Conventional - trenching equipment used to install PRB to maximum of 60 ft bgs	Fluoride, uranium, radium 226 and radium 228	Un	Un	Un	P	Un	P	PRBs can be installed using conventional trenching systems to approximately 60 ft bgs	None	1.5 to 2 years	Moderate	None	Not retained due to limited number of water quality constituents treated

Treatment Technology	Technology Description	Typical Configuration	Effectiveness and Applicability for Sites Containing	Predominant removal mechanism						Implementation Feasibility	Treatment Residual Waste	Typical Time Needed to Implement	Cost		Screening and Selection for Further Assessment
				As	NO3	F	U	Se	Ra				Capital	O&M	
<b>Injectable Sulfur-based Technologies</b>															
Chemical Reduction using Dithionite	Dithionite reduces the Fe(III) to Fe(II). Sufficient natural Fe(III) is need in aquifer materials. This ferrous iron reduces U(VI) chemically to less soluble U(IV).	Dithionite is injected into aquifer using wells to provide for reduction of constituents	Arsenic, uranium, selenium	CR	Un	Un	CR, P	CR, P	Un	Evaluation of geochemistry/flow to define dithionate demand required	None	1.5 to 2 years	Very High	High due to the need to dose frequently	Retained for detailed assessment
Chemical Reduction using Calcium Polysulfide	Calcium Polysulfide is a sulfide-based reducing agent	Calcium polysulfide is injected into aquifer using wells for reduction of constituents	Arsenic, uranium	CR, P	Un	Un	CR, P	Un	Un	Evaluation of geochemistry/flow to define polysulfide demand required	None	1.5 to 2 years	Moderate	High due to the need to dose frequently	Retained for detailed assessment
<b>Electro-chemical Processes</b>															
Electrokinetic Processes	Constituents are removed using a electrical current	Anodes and cathodes are placed within the treatment zone.	Arsenic, nitrate-N, uranium, selenium, radium 226 and radium 228	ES	ES	ES	ES	ES	ES	Typically used for contaminated sediments and shallow groundwater.	Spent Cathode and Anode Rods	1.5 to 2 years	High	Moderate to High depending on electrical and oversight costs	Not retained due uncertainties with technology efficacy and cost
<b>In Situ Bioremediation</b>															
Biologically Enhanced Reduction (Soluble and Semi-Soluble Injectable Substrates)	Simple carbon substrates (injected using wells) are used to create a anaerobic biologically active zone.	Wells are used to deliver substrates such as alcohols, lactate (lactose), acetate, HRC, emulsified vegetable oil	Nitrate-N, uranium, arsenic, selenium	BR,P	BR	Un	BR	BR	Un	Microcosm, pilot-scale test, and evaluation of groundwater flow system required	None	1.5 to 2 years	Moderate	Moderate	Retained for detailed assessment

Treatment Technology	Technology Description	Typical Configuration	Effectiveness and Applicability for Sites Containing	Predominant removal mechanism						Implementation Feasibility	Treatment Residual Waste	Typical Time Needed to Implement	Cost		Screening and Selection for Further Assessment
				As	NO3	F	U	Se	Ra				Capital	O&M	
<b>Innovative In Situ Natural Treatment</b>															
Phytoremediation	Phytoremediation is a plant based technology that can be used to treat, remove and sequester metals and organic compounds	Phytoirrigation system would be used. Water is extracted and conveyed to a subsurface irrigation system with under drains to capture treated water.	Arsenic, fluoride, nitrate-N, uranium, selenium, radium 226 and radium 228	PU, BR	PU, S	PU	P, PU	CR, PU	PU	Well established technology and effective for many of the water quality constituents (F removal may be limited)	usually none	1.5 to 2 years	Moderate to high	Low	Not retained
Engineered Wetland	Engineered wetlands have the capability to remove, precipitate and sequester metals, organic compounds and pathogens	Subsurface vegetated wetlands are used to remove and precipitate metals and nitrate.	Arsenic, fluoride, nitrate-N, uranium, selenium, radium 226 and radium 228	S, P, CR	S, PU	PU	P, PU	CR, PU	P, PU	Very well established technology and proven to be effective for most (excluding F) of the water quality parameters	sediments	2 years	Moderate	Low	Not retained

Notes: OM&M - Operation, maintenance and monitoring, NA - not applicable, ft bgs - ft below ground surface, PRB - permeable reactive barriers, CR - chemical reduction, P - precipitation, BR - biological reduction, PU - plant uptake, S - sequestration (microbial), ES - Electrical sequestration

**TABLE 17**

Permeable Reactive Barrier Reactive Media

*University of Texas, Bureau of Economic Geology, Austin, Texas*

<b>Reactive Media</b>	<b>Contaminants</b>	<b>Number of Field Applications (including Full- and Pilot-Scale)</b>
Zero valent iron (ZVI) and surface modified zeolite (SMZ)	Chlorinated ethenes, chlorinated ethanes, arsenic, uranium, hexavalent chromium, nitrate, selenium	more than 150
Limestone (including high calcium limestone)	Arsenic, cadmium, copper, lead, and zinc	2
Phosphate	Uranium	1
Sodium dithionite	Hexavalent chromium	1
Organic materials and iron-organic mixtures	Chlorinated ethenes, chlorinated ethanes, uranium, hexavalent chromium, nickel, sulfate, nitrate, selenium	3

Notes:

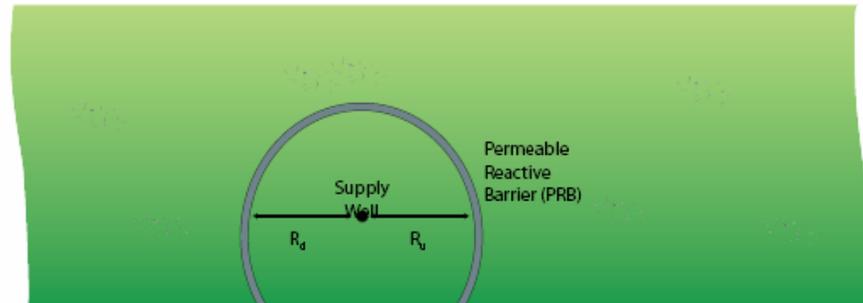
Source: National Technical University of Athens and USEPA

Commercial PRBs installed to date, have employed either a funnel and gate, continuous wall configuration or are injected into fractures using hydro-fracturing or pneumatic fracturing. Conventional installation involves continuous trenching or digging a trench to install the reactive media. Equipment to do this is limited to a depth of approximately 60 feet below ground surface (ft bgs). However, GeoSierra LLC (PRB installation contractor) has developed methods to inject ZVI to depths greater than 120 ft bgs. The technique is called azimuth controlled vertical hydrofracturing. ZVI is injected using a gel-based slurry. Several boreholes are used to install the PRB at approximately 15 ft apart. A special vertical fracturing tool, with pre-aligned fracturing shields, is used to direct water in a plane to create a contiguous barrier three inches thick. Multiple fracturing is conducted to produce walls up to 9 inches thick, which has proven to be very effective for most site conditions.

A conceptual PRB configuration for wellhead protection is presented in Figure 31. Figure 31 shows a deep PRB in a circular configuration completely surrounding the supply well. It may be necessary to offset the PRB so that the radius on the upgradient ( $R_u$ ) portion of the supply well is greater than downgradient radius ( $R_d$ ), to account for slightly greater flow velocities (due to gradient) which affect residence time within the PRB.

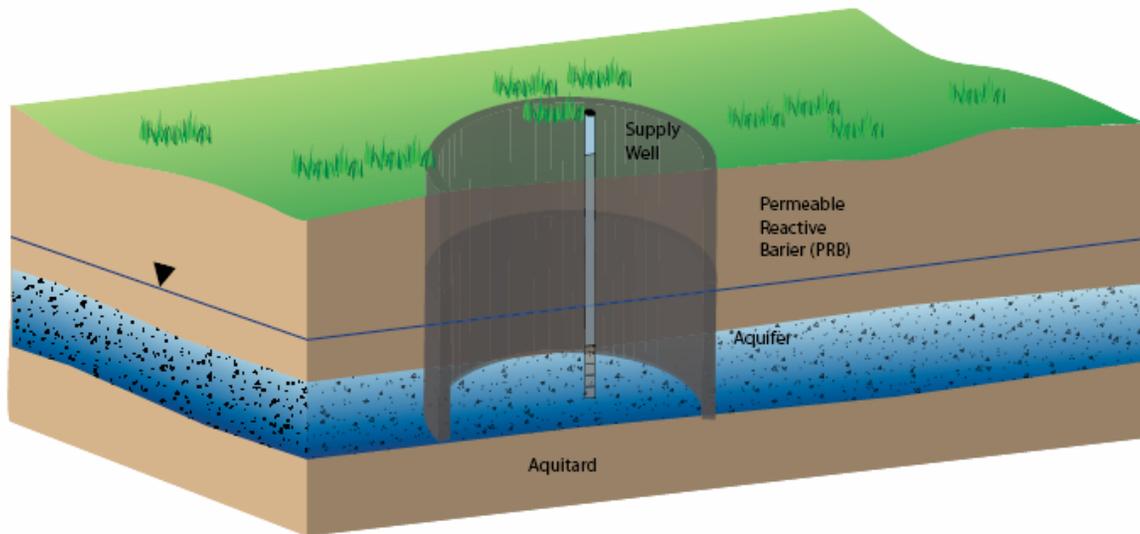
Circular Permeable Reactive Barrier alternative designs include:

- 1) full encompassing square PRB
- 2) partial upgradient and transgradient PRB



← Groundwater Flow

$R_u$  = Upgradient radius  
 $R_d$  = Downgradient radius



Notes:

- Reactive material placed at least 5 ft above high water level
- PRB can be comprised of zero valent iron, organic materials, carbonate, and phosphate-based materials



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Figure 31  
 Permeable Reactive Barrier Conceptual Configuration

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Alternative PRB configurations include:

- A square PRB configuration (construction may be more efficient). Construction and installation of PRBs tends to be less expensive when wall alignments are straight.
- A partial circular or u-shaped (with straight sides) PRB on the upgradient and transgradient side of the supply well.
- A combined slurry wall-PRB system that funnels (funnel and gate design) groundwater through the PRB section containing reactive material. As water quality COCs are not present at concentrations much greater than MCLs, the high-cost PRB sections of this system can be optimized and can likely still provide adequate treatment

The partial PRB or slurry-wall PRB can be used when constituent concentrations are very near the MCLs and only partial treatment is sufficient to treat extracted water to below MCLs.

### Advantages

Some of the benefits of the use of a PRB over more conventional approaches to groundwater remediation include:

- ZVI can degrade or immobilize contaminants, within a subsurface target treatment zone, to lower concentrations of COCs.
- ZVI is effective for nitrate, As, Se, U, cadmium (Cd), chromium (Cr<sup>6+</sup>), nickel (Ni), copper (Cu), lead (Pb) and radioactive elements, such as uranium, strontium, and technetium and possibly Ra-226 and Ra-228. It is also effective for treatment of select chlorinated solvents and potentially effective for some pesticides and herbicides.
- Requires no external energy once installed.
- The process does not require above ground structures or equipment.
- The process provides long-term passive treatment.
- No waste materials requiring treatment or disposal are generated.
- PRBs have low operation and maintenance costs.
- System configuration can accommodate the use of other less costly materials like a slurry wall.

### Disadvantages

Some of the potential issues with PRBs that need to be considered include:

- The initial capital cost and its installation schedule.
- Potential difficulties with construction to significant depths and in difficult geological settings.
- The potential for long-term (i.e., over 5 to 10 years depending on reactive material) fouling (due to precipitation of minerals or due to biofouling) of the PRB.

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This technology has proven to be highly effective for treatment of CVOCs, chromium and other compounds such as As, nitrate and U. ZVI reactive media has the greatest potential to treat the wide range of COCs present in the study area.

### Relative Cost

The costs for installing a conventional ZVI PRB (less than 60 ft bgs) generally range from \$30 to \$60 per face foot (length X depth). GeoSierra costs range from \$80 to \$110 per face foot depending on depth and thickness of the PRB. These are installation costs only and do not include engineering and design and maintenance. Therefore, the relative cost just for construction of the ZVI PRB (does not including engineering and permitting) for a circular ZVI PRB 50 ft bgs (saturated thickness) around a water supply well, would be approximately  $400 \times 50 \times \$50 = \$1,000,000$ . A ZVI PRB to a depth of 100 ft bgs installed by GeoSierra with the same saturated thickness would be approximately double (\$2,000,000).

#### 8.1.1.2 Ferox™ Process

The Ferox™ process utilizes zero valent iron (ZVI) powder, injected under high pressure into the subsurface, either as a slurry or as dry material, to create a permeable reaction zone, which may be used for both dehalogenation of organic compounds and reduction of heavy metals (Chen and Markesic, 2001). Nitrogen is used as the carrier gas to delay premature surficial iron oxidation (Chen et al., 2002).

The mechanism for chromium removal with the Ferox™ process is identical to that for other ZVI applications, such as in situ permeable reactive barriers and ex situ ZVI vessels; the reduced iron and oxidized chromium undergo a redox reaction in, which the iron is oxidized and the chromium is reduced, forming  $\text{Cr}(\text{OH})_3$ . As with other iron-based redox reaction technologies, secondary constituents such as dissolved oxygen can decrease the reactivity and hydraulic performance of the treatment zone.

The technology has been implemented at some sites and has been effective to depths 80 to below 100 ft bgs. The number of injections required to create a continuous reactive wall is uncertain and would be determined in the field through sampling and monitoring. The cost of implementation could be moderate to high, depending on the number of injection points, iron demand, and depth of injection.

### Advantages

- ZVI to degrade or immobilize contaminants, within a subsurface target treatment zone, to lower concentrations of COCs.
- ZVI is effective for nitrate, As, Se, U, cadmium (Cd), chromium ( $\text{Cr}^{6+}$ ), nickel (Ni), copper (Cu), lead (Pb) and radioactive elements, such as uranium, strontium, and technetium and possibly Ra-226 and Ra-228. It is also effective for treatment of select chlorinated solvents and potentially effective for some pesticides and herbicides.
- Requires no external energy once installed.
- Pneumatic fracturing is usually completed prior to injection to facilitate distribution of the injected materials, especially in low-permeability media.

- 
- A major advantage of this technology is the technology's flexibility. It is minimally disruptive to facility operations, less constrained by site physical features than trenching, and not constrained by depth or geologic media.

#### Disadvantages

- Heterogeneities in the subsurface can affect the configuration in the subsurface. Injection configuration cannot be controlled and therefore a contiguous wall with a uniform thickness can not be constructed.
- It is difficult to determine the volume and distribution of injected ZVI (compared to trenching).
- Site-specific conditions may affect applicability of the technology and/or cost-effectiveness with respect to conventional permeable reactive barriers (PRBs).

#### Relative Cost

- Costs for a typical application of the Ferox™ process (exclusive of site characterization and monitoring and engineering costs) are estimated to be on the order of \$5 to \$8 per pound of ZVI powder injected. Doses of ZVI may range from a few hundred to several thousand pounds per pound of contaminant. Larger applications of the technology can reach up to several hundreds of thousands or even millions of dollars.

#### 8.1.1.3 Phosphate and Limestone Reactive Barriers

Phosphate and limestone reactive barriers have been used for As, Cd, Cu, U, Pb and zinc (Zn). As presented in Table 17, a total of 3 known barriers have been constructed for treatment of shallow groundwater containing these metals. Limestone and or phosphate rock media is installed in the subsurface, so that groundwater containing COCs flows through the PRB under natural gradients or for water supply purposes under active pumping. The reactive media is semi-permeable and the water quality COCs react with the limestone or phosphate and precipitate into the surface media of the PRB.

A phosphate rock or limestone PRB is constructed by trenching and installing a wall of reactive media to intercept the flow of groundwater containing contaminants. Conventional installation involves continuous trenching or digging a trench to install the reactive media. Installation of deep PRBs could be conducted using the azimuth controlled vertical hydrofracturing pioneered by GeoSierra LLC (PRB installation contractor). As with the ZVI PRB, multiple boreholes are used to fracture and inject reactive materials.

A conceptual PRB configuration is presented in Figure 31 (same configuration as ZVI PRB). As with ZVI PRB, alternative PRB configurations include a square PRB configuration (construction may be more efficient) and a partial circular or u-shaped PRB on the upgradient and transgradient side of the supply well. The partial PRB can be used when constituent concentrations are very near the MCLs and only partial treatment is sufficient to treat extracted water to below MCLs.

#### Advantages

The benefits of the limestone and phosphate PRBs would be very similar to the ZVI PRB and include:

- 
- Phosphate and limestone reactive barriers that have been used to treat/remove As, Cd, Cu, U, Pb and Zn.
  - Requires no external energy once installed.
  - The process does not require above ground structures or equipment.
  - The process provides long-term passive treatment.
  - No waste materials requiring treatment or disposal are generated.
  - PRBs have low operation and maintenance costs.

### Disadvantages

Some of the potential issues with PRBs that need to be considered included:

- The initial capital cost and its installation schedule.
- Potential difficulties with construction to significant depths and in difficult geological settings.
- The potential for long-term (i.e., over 5 to 10 years depending on reactive material) fouling (due to precipitation of minerals or due to biofouling) of the PRB.

### Relative Cost

The costs for installing a conventional limestone or phosphate PRB (less than 60 ft bgs) would be similar or slightly less than a ZVI PRB, due to costs of reactive materials. A conventional system would range from \$25 to \$55 per face foot (length X depth).

#### 8.1.1.4 Injectable Sulfur Based Technologies

In situ chemical reduction using sulfur based compounds involves the injection of chemical reductants such as calcium polysulfate, dithionite or other sulfur based materials. Sulfites and sulfides such as sodium hydrosulfite (dithionite), ferrous sulfate, and calcium polysulfide have been used at several sites to remediate chromium contaminated groundwater (Jacobs et al, 2001). Sodium hydrosulfite functions by reducing Fe(III) in the aquifer matrix to Fe(II) which then reduces Cr(VI) to Cr(III). A large percentage of the reductant is consumed by the aquifer matrix to generate Fe(II).

Dithionite reduces iron (III) to iron (II) releasing electrons for reduction of reducible such as hexavalent chromium. It may be applicable for U and Se. Calcium polysulfide precipitates soluble oxidized metals such as arsenic, chromium, lead, copper, zinc, cadmium, uranium and molybdenum.

The choice of reductant should be partially based on the ability of the reductant to form reactive solids within the aquifer without plugging the pore spaces. The groundwater can then be reduced as it flows through the treated zone as a result of active pumping or as a result of the natural hydraulic gradient. Chemical reductants are injected into the subsurface using pressurized injection wells, or jetting.

Mixing of the substrate can occur using the natural hydraulic gradient in a Passive Flow System or using a recirculation system consisting of injection well/extraction wells.

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Polysulfate and dithionite are less soluble than the biological substrates which present challenges to mixing in the aquifer. This can be overcome through the use of several injection wells or a more substantial recirculation system. The equipment and installation techniques are well established and are considered conventional technologies and little regulated wastes are produced with this technology.

The half life of these sulfur based substrates is very short (days to week) necessitating the need for frequent injections. A permanent injection system may be required to facilitate substrate dosing during the functional life of the supply well. Considerable engineering would be needed to accomplish this for substrates that are not miscible in water and require pressurized injection to create desired subsurface conditions to make the technology viable.

A conceptualized well configuration for in situ chemical delivery is presented in Figure 32. Figure 32 shows a series of wells placed away from the supply well at a radius that is determined by the hydraulic properties of the supply well under normal high range pumping rates. The radius must be sufficient so that ample time is allocated for the treatment kinetics (i.e. sufficient time for treatment of COCs given concentrations and flow velocity). As flow velocities on the upgradient portion of the supply well can be greater, the upgradient radius ( $R_u$ ) needs to be slightly greater than the downgradient radius ( $R_d$ ).

An alternative configuration for well orientation is to place wells on the upgradient and transgradient sides of the supply well. This will not provide treatment for all extracted water, but the treatment configuration may be sufficient to lower COCs to below MCLs in extracted water.

### Advantages

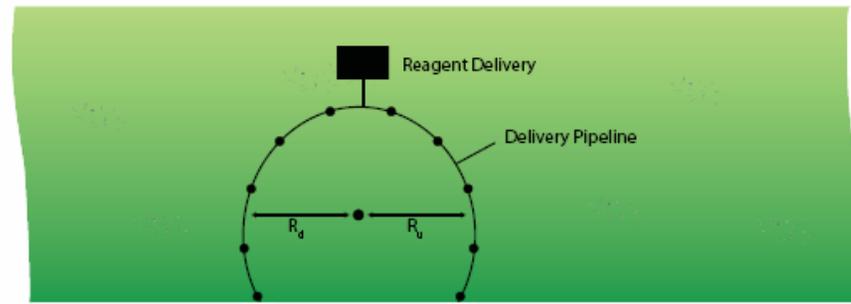
- Established technology.
- Injection wells can be used to distribute chemicals to subsurface to create a target treatment zone.
- Injections can be accomplished with portable delivery equipment.
- Modular approach can create treatment zone to any size required.
- Little to no surface disturbance or infrastructure needed to operate system.

### Disadvantages

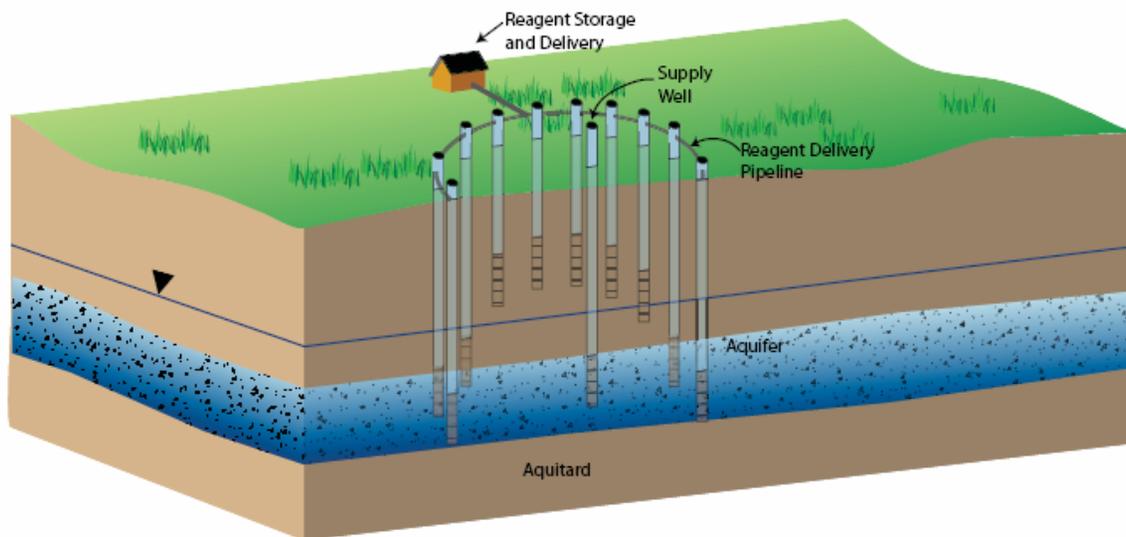
- Treats only a select number of reducible COCs.
- Requires frequent or continuous injection of chemicals to maintain conditions need for removal/treatment.
- Increases sulfur content in aquifer resulting in potential high sulfate groundwater.
- Secondary mineralization can occur reducing permeability and treatment effectiveness.
- Costs can be high compared to other in situ and ex situ technologies due to chemical demand

Substrate injection wells for:

- 1) chemical delivery
- 2) biological reagent delivery



$R_u$  = Upgradient radius  
 $R_d$  = Downgradient radius



Notes:

- Wells placed 15 – 20 ft apart
- Well screens fully penetrate aquifer
- For thicker aquifers (>25 ft), multi-depth injection wells may be needed
- $R_u$  greater than  $R_d$



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Figure 32  
In Situ Chemical and Biological reagent Injection  
Well Conceptual Configuration

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## Relative Cost

The costs for in situ chemical reduction technologies is highly dependant on the number of injection wells and the amount of substrate needed given the treatment zone size. Typical installations can range between \$250,000 and \$750,000, but can reach millions of dollars for larger applications.

### 8.1.1.5 Electrochemical

Electrochemical Remediation Technologies (ECRTs) and Induced Complexation (IC) process have been tested for sites containing both metals and organic compounds (Agronne National Laboratory, 2002). These technologies use electrical current to either immobilize or degrade contaminants in sediments or water. The ECRTs and IC technologies utilize DC/AC current passed between an electrode pair (anode and cathode) placed in the subsurface. Remediation of the sediment was to be accomplished by either the mineralization of organic contaminants through the oxidation process, or by use of the IC process to complex, mobilize, and remove metal contaminants on the electrodes. The sediment or aquifer matrix acts as a capacitor, discharging and charging electricity resulting in redox reactions, resulting in desorption of the both metals and organic compounds. Electrodes can be placed either vertically (most common) or horizontally at a spacing of about 30 feet. A direct electric current is connected to both electrodes which induces a preferential flow of ionized metals and compounds.

Research to date indicates that reaction rates are inversely proportional to grain size, and therefore treatment can be more rapid in finer-grained materials.

The aquifer materials-groundwater system is considered an electrochemical cell. Redox reactions occur simultaneously at the cathode (reduction) and anode (oxidation) and at any and all interfaces within the aquifer materials-water system at the pore scale. The reaction partners for oxidations and reductions are simultaneously generated by water hydrolysis.

Figure 33 shows a conceptualized configuration of an electrochemical remediation technology system. Anodes (positive charge) rods are placed opposite cathode (negative charge) rods to facilitate preferential transport of ions (metals). Negatively charge metals ions will gravitate to the anode and positively charge metal ions to the cathode. Transfer of metal ions from the aquifer water supply must be sufficient to overcome physical flow transport mechanisms for the technology to be viable for metal removal. Considerable engineering and testing may be required to determine the viability of the technology for water supply purposes.

### Advantages

- Can be used in saturated and unsaturated media.
- Applicable for most ionizable compounds and elements.
- ECRTs and IC can be used in often difficult to treat fine-grained sediments and aquifers
- Can be used for metals, radionuclides and organic compounds.
- Little to no impact occurs on the environment.
- Surface disturbance is limited.

- 
- Only waste generated in spent anodes and cathodes.

### Disadvantages

- Soil and aquifer material properties such as organic matter content, nature of ligands, moisture content, and competing ions affect the efficacy of the technology.
- Contaminants concentrations often increase before decreases are observed. This is due to desorption and mobilization mechanisms.
- Can not be used effectively in frozen environments.
- Some metals and radionuclides (cesium) will not bind to the electrodes.
- The technology is under development and has not been used for water supply production wells.

### Relative Cost

The cost of implementing this technology is dependent on the size of the treatment zone. Research to date indicates that small treatment zones of about 10,000 cubic yards can be treated for about \$100 per cubic yard and large zone of 100,000 cubic yards for about \$35 per yard. Costs increase as a function of surface area. The cost increases as a function of depth are not significant, as the only increase in costs are associated with electrode material, small increases in electrical demand and installation costs.

## 8.1.2 In Situ Biological Treatment

Biological reduction occurs under anaerobic reducing conditions (negative oxidation-reduction potential). Soluble organic carbon substrates such as food grade lactate, ethanol, acetic acid (vinegar), molasses, emulsified vegetable oil or hydrogen releasing compounds (HRC™) can be injected into the groundwater to stimulate microorganisms to create the reducing conditions to reduce soluble COCs such as arsenic, chromium, nitrate, selenium and uranium (USEPA, 1999a; Jones, et al., 2001; Groudev et al., 2001; Lutze et al., 2001). Solid organic substrates can also be used to provide a substrate that will last up to several months to years. The solid organic substrates break down via microbial metabolism into more soluble organic compounds. The soluble organic carbon is used by natural anaerobic microorganisms in the subsurface as an electron donor for energy production. The carbon substrates are supplied to the subsurface via active or passive injection wells. Solid organic substrates are injected into the subsurface under pressure.

Mixing in the subsurface can occur via natural hydraulic gradient (Passive Flow System) or via a recirculation system consisting of injection well/extraction wells. Extracted water is amended with the carbon substrates and injected and drawn through the target treatment zone using extraction wells. The re-circulation system provides for containment and re-injection of any excess electron donor, but uses more energy than the passive flow-injection system. The equipment and installation techniques are well established and are considered conventional technologies.

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In situ bioremediation treatment technologies do not produce any waste products that require management or disposal, but can reduce iron and manganese which are soluble and mobile in reduced states. These metals are readily oxidizable and can be removed either in the subsurface or with above ground treatment.

Figure 32 shows the conceptualized well configuration for both in situ biological and chemical delivery. The same design considerations for in situ chemical must be considered for the in situ biological treatment such as flow velocities, treatment times and distance to the treatment zone from the supply well (radius  $[R_u, R_d]$ ) must be factored into the design. Reaction time for biological reagents tend to be slightly slower than chemical and therefore the distance to the treatment zone from the supply well (radius  $[R_u, R_d]$ ) may need to be large for biological substrates.

An alternative configuration for well orientation is to place wells on the upgradient and transgradient sides of the supply well. This will not provide treatment for all extracted water, but the treatment configuration may be sufficient to lower COCs to below MCLs in extracted water.

### Advantages

- In situ biological treatment can be used to treat As, Se, U, Cr<sup>6+</sup>, and nitrate.
- In situ biological treatment is an established technology
- Injection wells can be used to distribute organic substrates to subsurface to create a target treatment zone
- Injections can be accomplished with portable delivery equipment
- Modular approach can create treatment zone to any size required
- Little to no surface disturbance or infrastructure needed to operate system

### Disadvantages

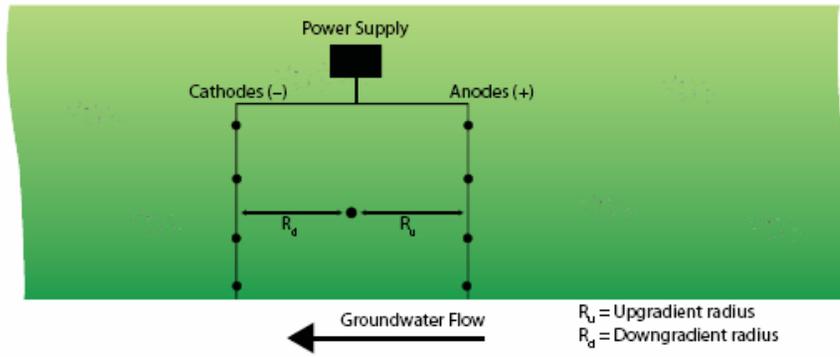
- Treats only a select number of reducible COCs
- Requires frequent or continuous injection of organic substrates to maintain conditions need for removal/treatment (unless long-term substrates are used)
- Can reduce other compounds/elements such as iron and manganese which may require secondary treatment.
- Costs can be moderate to high compared to other in situ and ex situ technologies due to chemical demand

### Relative Cost

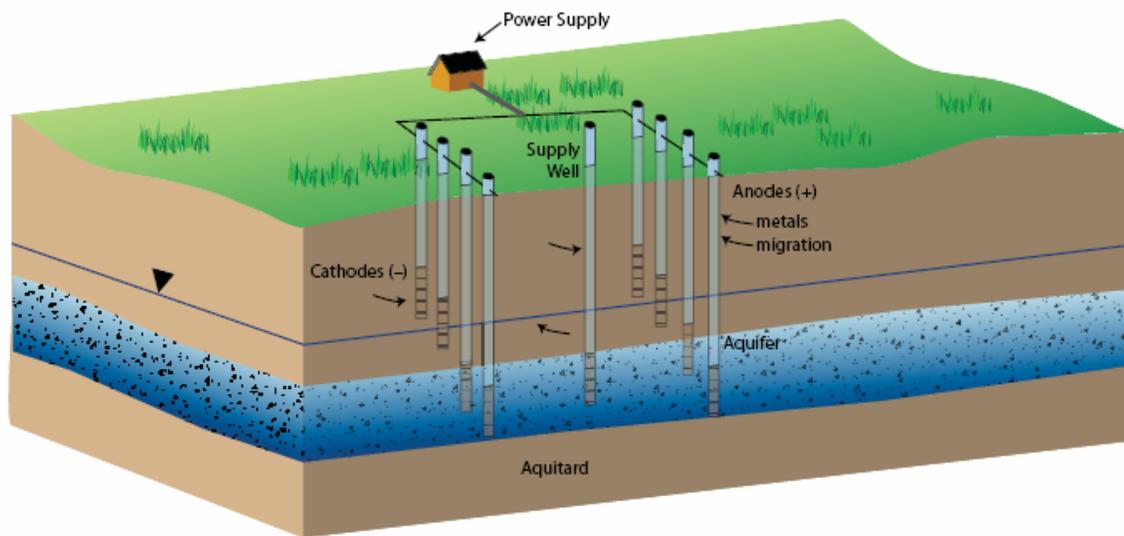
Costs associated with the implementation of in situ biological treatment technologies are very similar to in situ chemical. Total costs are dependant on the number of injection wells and the amount of substrate needed for treatment volume. Typical installations can range between \$250,000 and \$750,000, but can reach millions of dollars for larger applications.

Electrochemical alternative designs:

- 1) Cathode upgradient anode downgradient
- 2) Cathode and anode transgradient to flow



$R_u$  = Upgradient radius  
 $R_d$  = Downgradient radius



Notes:  
 • Spacing of anodes and cathodes dependent on flow velocities under pumping

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	Figure 33 Electrochemical Remediation System Conceptual Configuration

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### 8.1.3 Innovative In Situ Natural Treatment

#### Phytoremediation

Phytoremediation is a remediation technology that has generated considerable interest in the North America over the past few years. Phytoremediation makes use of selected plant species to remove, contain, accumulate or degrade a variety of chemicals in soil, surface water and groundwater environments. Several plant species have the ability, through their natural metabolic processes, to extract and directly uptake various inorganic and organic chemicals from soil and water media. Once within the plant, chemicals can either accumulate (as with metals) and/or be transformed (as with many organic compounds) through normal plant metabolic processes. In cases where chemicals accumulate in plant tissues, plant harvesting and disposal may provide a remediation alternative similar to traditional excavation and disposal techniques (Salt et al., 1995). In cases where chemicals are transformed, the potential exists to use phytoremediation to destroy the chemicals in situ. Plants also enhance or are responsible for biotic and abiotic reactions which can be manipulated to assist in degrading and or precipitating a variety of organic and inorganic chemicals in the rhizosphere (Schnoor et al., 1995).

To date, researchers have documented the accumulation and/or transformation of a wide variety of organic and inorganic compounds, including many metals (Huang et al., 1997; Lawrence and David, 1997; Brown et al., 1995; Tossell, et al., 1997), radionuclides (Cornish et al., 1995).

A conceptual design for water supply would include a subsurface phytoirrigation approach. Most phytoremediation applications are designed for in situ treatment. Phytoirrigation is a phytoremediation technology that distributes water requiring treatment to a near-surface phytoremediation system. Water is conveyed to a subsurface irrigation system and the plant soil system removes and treats water as it filters through the soil-root zone. It is the soil-root system that acts an ion exchange, chemical reduction and filtering system to remove metals and some organic compounds. Phytoirrigation provides a relatively inexpensive means of moving the water to a zone where it can be effectively treated, expanding the ways in which phytoremediation can be used. Phytoirrigation systems can be used to apply water at the surface or below the surface to meet the requirements for treatment.

A major disadvantage is that some water is lost due to evapotranspiration (ET), especially with the high ET potential in the study area. In addition, release of groundwater to the near surface environment would require additional treatment processes, similar to those for surface water, substantially increasing the cost.

#### Engineered Wetlands

Engineered wetlands have been used for treated water reuse or for treatment of a variety of water COCs. The use of wetlands for stormwater and wastewater is an emerging technology in North America and worldwide. Treatment wetlands make use of physical and biological processes to remove, contain, and degrade these chemicals. Constructed surface flow (SF) treatment wetlands are shallow impoundments planted with emergent, rooted vegetation. Water flows primarily above the sediment surface through the wetlands.

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The use of wetlands for treatment stormwater and wastewater is an emerging technology in North America and worldwide. Engineered wetlands have been used to serve as mitigation for lost wetland habitat, to treat or improve water quality, create habitat and to provide opportunities for community recreation.

Treatment wetlands make use of physical and biological processes to remove, contain and degrade these chemicals. Treatment wetlands are engineered to enhance or provide optimum conditions for treatment of a number of chemicals including nutrients such as ammonia-nitrogen, nitrate-nitrogen, phosphates and sulfates, organic chemicals such as petroleum hydrocarbons and chlorinated solvents, metals (Kadlec and Knight, 1996).

Constructed SF or recharge wetlands are shallow impoundments planted with emergent, rooted vegetation. Water flows primarily above the sediment surface through the wetland. This wetland will be planted manually with mature plant communities. These are typically planted with a diverse plant community of native species, such as cattails (*Typha* spp.) and bulrushes (*Scirpus* spp.), sedges and grasses.

Treatment includes physical, chemical and biological mitigation processes such as sedimentation, chemical fixation and biological degradation/transformation. Microbial flora (bacteria and fungi) that attach to the plants have natural assimilative capacity to remove biodegradable organics and nitrogen while metals and phosphorus will be sequestered in plant materials and wetland sediments. Much of the treatment that occurs in wetlands is the result of sediment trapping and microbial action rather than plant uptake. Treatment wetland efficiency for several key water quality parameters is summarized in Table 18.

Most surface flow treatment wetlands attract significant wildlife populations (Kadlec and Knight, 1996). As a consequence of the diversity of wildlife attracted to treatment wetlands and their more general aesthetic qualities, many treatment wetlands provide public use functions. The use of treatment wetlands by wetland dependent wildlife and by humans is incidental to their water quality functions, but considerable design guidance is available to provide these ancillary benefits through careful project planning. Additional benefits of wetlands technology include:

- Wetlands may be relatively inexpensive to construct and operate. The primary costs consist of the land, grading, diking and planting. Properly designed and constructed treatment wetlands are essentially self-maintaining systems.
- Wetlands can be located at points within the landscape (remote and/or wet areas) that might otherwise present construction and management difficulties.
- Wetlands can be a long-term and self-sustaining, approach that requires little maintenance and capital input during operation and provides ecological benefits related to habitat creation and aesthetic value.

**TABLE 18**  
 Summary of Engineered Wetland Performance Characteristics  
*University of Texas, Bureau of Economic Geology, Austin, Texas*

<b>Parameter</b>	<b>Removal Efficiency</b>	<b>Achievable Water Quality Limit</b>
BOD	50-90%	2-10 mg/L
TSS	50-90%	2-10 mg/L
Total Nitrogen	40-90%	1-3 mg/L
Total Phosphorous	10-90%	<1 mg/L
Fecal Coliform	80-90%	<100-1,000 col/100 mL
Metals	50-90%	Below detection

*Notes:*

Compiled from Kadlec and Knight (1996) and various sources.

As with subsurface phytoirrigation, significant water is lost to ET. In addition, release of groundwater to the surface environment would require additional treatment processes, similar to those for surface water, substantially increasing the cost.

### 8.1.4 Screening of Technologies

Preliminary screening of technologies is conducted to help focus the development of site technology management system that has the greatest potential to meet treatment objectives. A summary of technologies and a preliminary screening is found in Table 16 and includes those technologies that were retained for further more detailed assessment in subsequent section of this report. A summary of the preliminary screening is presented in the following sections.

- PRBs using ZVI appear to be a very promising in situ technology for water supply. PRBs using ZVI or other iron materials have proven effective for treatment and/or precipitation of metals including: nitrate, As, Se, U, cadmium (Cd), chromium (Cr<sup>6+</sup>), nickel (Ni), copper (Cu), lead (Pb) and radioactive elements such as uranium, strontium, and technetium and possibly Ra-226 and Ra-228. This technology was selected for further analysis using the modified evaluation criteria.
- The Ferox™ process using ZVI has the potential to treat many of the water supply COCs. Although, the installation process can not be used to construct a PRB, treatment may be sufficient for reach MCLs for many COCs. The Ferox™ technology was selected for further analysis using the modified evaluation criteria.
- PRBs using limestone and phosphate based rock appear to be applicable for fewer water quality COCs compared to ZVI. Therefore, PRBs using limestone and phosphate based rock were not retained for further assessment.
- In situ chemical reduction using sulfur based compounds such as calcium polysulfate, dithionite or other sulfur based materials was retained for further evaluation and assessment.

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- The ECRTs and IC technologies have the potential to be effective for many of the water quality COCs, but due to concerns about technology development, efficacy and costs, electrochemical technologies were not retained for further detailed assessment.
  - Innovative technologies such as phytoremediation and engineered wetlands were not retained due to more applicable in situ technologies which do not require significant end-of-pipe treatment configuration.

## 8.2 Detailed Evaluation of Technologies for Groundwater Supply Aquifers

An evaluation of the most promising technologies identified in Section 8.1 is provided in this section, and the results of the technology assessment process are summarized.

To facilitate cost estimation that provides for a comparison across most if not all technologies, the configuration and physical size of the treatment zone and set-back from the supply well was standardized. Other variables such as depth to water table, depth to confining layer and general shape of the technology configuration were assumed to be the same for all technologies. The following standards were used for cost estimation purposes:

- Depth to water table: 60 ft bgs
- Depth to confining layer: 110 ft bgs
- Minimum set-back (radius) from supply well: 80 ft
- Assumed radius of influence for injected chemical and biological reagent: 30 ft
- Number of borings or wells to injection chemical or biological reagents: 13 (with 25 ft spacing provides treatment for approximately two thirds of the extracted water)
- Assumed percentage of extracted water to meet MCLs: 67%
- Number of new monitoring wells used to monitor performance: 4
- Number of Ferox injection borings: 7 (fracturing creates a larger radius of influence than pressurized injection)

A detailed evaluation summary of the retained in situ technologies is presented in Table 19.

Table 19. Detailed Evaluation of In situ Remediation Technologies

Technology	Description	Decision Criteria					Screening Results
		Protection of the Water Supply (Human Health and the Environment)	Treatment of Constituents Reduction of Toxicity, Mobility, Mass or Volume	Short and Long-term Effectiveness	Implementability	Order of Magnitude Cost (\$)	
<b>Iron Based Technologies</b>							
Zero Valent Iron (ZVI) Permeable Reactive Barriers (PRBs)	Zero Valent Iron corrodes to release hydrogen ions which chemically reduce many soluble constituents.	A; This technology has the potential to provide considerable protection as it removes or treats many of the identified water quality constituents	A: Has the potential to treat, remove or precipitate many constituents thereby reducing toxicity, mobility or volume of impacted aquifer water	A; Can be effective over short and long-term. Many PRBs have been in operation for years without significant decreased efficiency	A; Implementable as a conventional and deep PRB. Proven to depths of 120 ft bgs	\$4,770,000 for full circular barrier; \$3,192,000 for partial barrier	Very good candidate technology for in situ water supply treatment. Preferred technology.
Fracturing and Injection of Zero Valent Iron (Ferox Process)	Subsurface fracturing is used to provide void space for injection of powdered ZVI	A; as with ZVI PRB	B+; as with ZVI PRB, but can not be implemented as a contiguous wall and therefore not all water is treated	A; Can be effective over short and long-term.	B+; as with ZVI PRB, but can not be implemented as a contiguous wall and therefore not all water is treated	\$3,864,000 for a system with 13 Ferox injections	Very good candidate technology for in situ water supply treatment. Preferred technology.
<b>Sulfur-based Technologies</b>							
Chemical Reduction using Dithionite	Dithionite reduces the Fe(III) to Fe(II). Sufficient natural Fe(II) is need in aquifer materials. This ferrous iron reduces U(VI) chemically to less soluble U(IV).	B-; Technology can be used to treat a subset of water quality constituents (Ar, U, Se)	C; Technology will remove or treat some constituents but not all. Increases sulfur content (SO <sub>4</sub> ) content of aquifer.	C; Effective short and long-term, but requires considerable operation and maintenance of injection equipment and frequent dosing .	A; Implementable. Conventional wells and dosing equipment are used to delivery reagents to subsurface	\$4,066,000 for system with 7 injection wells	Technology is feasible, but due to considerable operation and maintenance and limited number of applicable constituents, this would be a challenge to maintain. Not recommended.
Chemical Reduction using Calcium Polysulfide	Calcium polysulfide is injected into aquifer to reduce As, U and other metals.	B-; Technology can be used to treat a subset of water quality constituents (Ar, U)	C; Technology will remove or treat some constituents but not all. Increases sulfur content (SO <sub>4</sub> ) content of aquifer.	C; Effective short and long-term, but requires considerable operation and maintenance of injection equipment and frequent dosing .	A; Implementable. Conventional wells and dosing equipment are used to delivery reagents to subsurface	3860000 for a system with 7 injection wells	Like the dithionite technology, is feasible. However, due to considerable operation and maintenance and limited number of applicable constituents, this would be a challenge to maintain. Not recommended.

Technology	Description	Decision Criteria				Screening Results	
		Protection of the Water Supply (Human Health and the Environment)	Treatment of Constituents Reduction of Toxicity, Mobility, Mass or Volume	Short and Long-term Effectiveness	Implementability		Order of Magnitude Cost (\$)
<b><i>In Situ Biological Treatment</i></b>							
Biologically Enhanced Reduction (Soluble and Semi-Soluble Injectable Substrates)	Simple carbon substrates (injected using wells) are used to create an anaerobic biologically active zone.	B+; In situ biological treatment has the potential to treat a number but not all constituents (Ar, U, Se, and nitrate)	C; Technology will remove or treat some constituents but not all. Increases solubility of naturally occurring iron and manganese. Can be removed via oxidation, in aquifer or with ex situ technologies	B; Can be effective both in the short and long term for mass removal. Requires dosing approximately every 2 years	A; Implementable. Conventional wells and dosing equipment are used to deliver reagents to subsurface	\$3,301,000 for a system with 7 injection wells	Technology is feasible, less operation and maintenance than chemical, but is considered a less feasible compared to ZVI-based technologies. Not recommended.

Notes: Letter symbols appearing before criterion explanation are a relative ranking of how well the alternative meets the specific criteria objectives. "A" is the highest rank, "B" is a medium rank, and "C" is the lowest rank. "+" and "-" symbols are modifiers to letter rank, with "+" representing "better satisfies criterion than no modifier" and "-" representing "satisfies criterion slightly poorer than no modifier."

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## 8.2.1 Permeable Reactive Barrier (PRB)

### Design Basis and Assumptions for Water Supply Purposes

Several PRB configurations and PRB materials could potentially be used for water supply purposes. However, none likely have more promise than a PRB with ZVI as it has the potential to treat most if not all COCs of this study including As, nitrate, U, Se and possibly F and Ra. The PRB would be approximately 320 ft long (circular orientation) and average 120 ft below ground surface (bgs) to the bottom of the aquifer. The PRB is created by installing a wall of zero-valent granular iron to intercept the flow of groundwater as it migrates to the supply well pumping at an average of 42 gpm (the assumed capacity of the typical PWS).

Typical installations consist of a continuous permeable barrier with ZVI or a mixture of sand and ZVI. An alternative is iron rich crushed slag which is much less expensive than ZVI. Due to the depth of the PRB, the installation would consist of azimuth controlled vertical hydrofracturing, the process that is used by GeoSierra LLC who developed and owns the rights to the technology. ZVI is injected using a HPG gel-based slurry. Several boreholes are used to install the PRB at approximately 15 ft apart. Once installed no maintenance is required for this system. However, performance monitoring would be required, which would be a going forward cost.

### Overall Protection of Water Supply (Human Health)

ZVI PRBs have a proven track record and has been in use for over 10 years at some sites. Application of the technology has proven to be effective for metals (As, U, F, Se) and nitrate. The technology has the potential to reduce mass and concentration over the long term and is protective of human health. The technology has the potential to be used for water supply treatment given the application and conditions in the subsurface aquifer.

### Reduction of Constituent Concentrations Through Treatment

A ZVI (or other PRB materials) PRB has the potential to reduce constituent concentrations and mass, and volume of extracted water via in situ treatment and precipitation of metals and nitrate. The reduction in constituent concentrations to below MCLs is possible given proper design.

### Short-term and Long-term Effectiveness

To date, over 40 full-scale PRB systems using granular ZVI to remediate groundwater chlorinated VOCs and/or chromium. This technology has proven to be highly effective in treating chlorinated VOCs, chromium, U, Se and nitrate. Recent research into the longevity of ZVI used in PRBs suggested that these installations might last up to 30 years or more without significant maintenance requirement or loss of significant permeability. The oldest PRB has been operating for 11 years without significant mineral or biofouling or a reduction in performance.

### Implementability

Conventional construction of PRBs using trenching or excavating equipment has been used since the first application of the technology. Therefore, conventional construction is well

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established. More recently, hydraulic and pneumatic injection of ZVI has been implemented successfully at over 15 sites. Injection wells/boreholes and injection equipment are required to implement this alternative. Based on the performance of these installations there does not appear to be major challenges to the implementation of the technology.

### **Cost**

The capital costs, annual costs, NPV, and total cost for implementation of the PRB technology is summarized in Table 20. Capital costs include construction and injection of the ZVI. Annual costs include groundwater/performance monitoring. Zero Valent Iron (Ferox™)

**Design Basis and Assumptions for Water Supply Purposes** The Ferox™ process involves the fracturing of the aquifer formation and injection of ZVI or mixture of organic and ZVI. Typically granular or nano-scale ZVI would be installed using pneumatic fracturing. For a supply well treatment application, the Ferox™ process would be implanted to provide treatment of aquifer water around the supply well. This could be conducted through multiple borehole injections around the entire supply well or upgradient and transgradient of the supply well. A series Ferox™ injection could potentially provide the treatment necessary to meet MCLs at the wellhead.

As with the PRB with ZVI, Ferox™ has the potential to treat most, if not all, COCs of this study including As, nitrate, U, Se and possibly F, and Ra. For conceptual design purposes, we assume that six Ferox™ injection wells would be needed to meet MCLs for COCs. Similar to the PRB conceptual design, the supply well would be pumped at an average of 42 gpm. Each of the Ferox™ boreholes would be drilled at 20 ft spacing. Once the Ferox™ system is installed no maintenance is required, other than performance monitoring.

### **Overall Protection of Water Supply (Human Health)**

The Ferox™ has been used for remediation purposes at over 10 sites. The subsurface use of ZVI has proven to be effective for metals (As, U, F, Se) and nitrate. Although the technology does not create a contiguous barrier or PRB, it has the potential to treat COCs to concentrations that could be below MCLs. Given the proper application of the technology (implemented upgradient of supply wells), the Ferox™ process has the potential to be used for water supply treatment purposes.

### **Reduction of Constituent Concentrations Through Treatment**

Injection of ZVI using the Ferox™ process has the potential to reduce constituent concentration, mass, and volume of COCs within the aquifer potentially resulting in meeting MCLs for most COCs. Although it is unlikely that a contiguous ZVI barrier could be constructed with the technology, the Ferox™ approach may be sufficient for the intended purpose of meeting MCLs in extracted drinking water supply.

Table 20, Summary of Costs for In Situ Technologies

Technology	Technology Description	Annual Costs	Number of years	NPV Annual Costs	Direct Capital Costs	Indirect Capital Costs	Total NPV Costs
ZVI PRB	Fully Encompassing ZVI PRB	\$ 80,097	10	\$ 666,132	\$2,647,935	\$ 1,456,364	<b>\$ 4,770,000</b>
	Slurry Wall-ZVI PRB	\$ 119,075	10	\$ 990,297	\$1,420,755	\$ 781,415	<b>\$ 3,192,000</b>
Ferox	ZVI Injection Around Supply Well	\$ 116,028	10	\$ 964,956	\$1,870,414	\$ 1,028,728	<b>\$ 3,864,000</b>
In Situ Chemical	Dithionite	\$ 275,479	10	\$ 2,291,050	\$ 957,295	\$ 817,866	<b>\$ 4,066,000</b>
	Calcium Polysulfide	\$ 251,306	10	\$ 2,090,013	\$ 953,672	\$ 815,946	<b>\$ 3,860,000</b>
In Situ Biological Treatment	Emulsified Vegetable Oil Biobarrier	\$ 187,260	10	\$ 1,557,365	\$ 936,595	\$ 806,895	<b>\$ 3,301,000</b>

Notes: Refer to Appendix C for a breakdown and itemized list of costs.

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## Short-Term and Long-Term Effectiveness and Permanence

To date, approximately 10 Ferox™ systems have been implemented used granular ZVI to remediate groundwater chlorinated VOCs and/or chromium. This technology has proven to be highly effective for providing the reducing conditions needed to reduce or precipitate many metals in the subsurface. Research has indicated that ZVI or other forms of iron can persist for some time in the subsurface providing the required conditions for treatment and precipitation. The system requires little to no maintenance and performance monitoring requirements are similar to any in situ system.

### Implementability

Pneumatic and hydraulic fracturing and injection of ZVI has been implemented successfully at more than 10 sites. Injection wells/boreholes and injection equipment are required to implement this alternative. No challenges are anticipated with this technology.

### Cost

The capital costs, annual costs, NPV, and total cost to implement the Ferox™ technology are summarized in Table 20. Capital costs include construction and injection of the ZVI. Annual costs include maintenance of groundwater use restrictions and groundwater monitoring.

## 8.2.2 In Situ Chemical Reduction

### Design Basis and Assumptions for Water Supply Purposes

In situ chemical reduction involves the injection and delivery of soluble or semi-soluble reducing substrates such as dithionite and calcium polysulfide. The basis of the conceptual design includes the drilling of several injection wells around the supply well to encompass the well entirely, or partially. The system would involve the drilling of several new injection wells placed in a circular pattern (Figure 32) within a 100 foot radius of the supply well. This produces approximately 13 to 14 injection/delivery wells. The treatment zone is needed for as long as the supply well operates (several years), and therefore, multiple injection of the chemical substrates is required because of the short half-life of these chemicals. It assumed that dosing occurs every 3 weeks over a 10 year life expectancy.

### Overall Protection of Water Supply (Human Health)

In situ chemical treatment has the potential to meet or partially meet MCLs for reducible metals such as U, Se and As (which reacts with sulfides). This technology would reduce contaminant mass through in situ treatment and subsequent precipitation. This technology has the potential to reduce mass and concentration of COCs over the long-term or for as long as the system is maintained as designed.

### Short-term and Long-term Effectiveness and Permanence

In situ chemical treatment and remediation has been implemented at multiple sites in the U.S. It is considered an established treatment/remediation technology however, the long-term effectiveness is not know as many of the applications met remediation objectives within 2 years of implementation. It's applicability for in situ treatment for water supply purposes may be limited to a short-time period due to the effectiveness of the technology over the long-term. Regulatory permitting time can be substantial. The in situ system would

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make use of passive treatment zone to reduce metals and may be sufficient to treat U, and Se, only.

### **Reduction of Constituent Concentrations Through Treatment**

In situ chemical reduction has the potential to treat U and Se in aquifer water. Therefore, treatment can reduce volume, and mass of these COCs, and thereby eliminate mobility of regulated compounds in the subsurface over the short-term (as long as the system operates as designed).

### **Implementability**

In situ chemical treatment system consists of injection wells, common equipment, and components and no challenges to implementation are anticipated.

### **Cost**

The capital costs, annual costs, NPV, and total cost to implement in situ biological treatment system are summarized in Table 20. Capital costs include installation of injection and extraction wells. Annual costs include maintenance of wells, groundwater or system performance monitoring, and dosing every 3 week and costs associated with the system.

## **8.2.3 In Situ Biological Treatment**

### **Design Basis and Assumptions for Water Supply Purposes**

In situ bioremediation includes adding soluble carbon substrates (lactate, alcohol, acetic acid), emulsified vegetable oil (EVO), or hydrogen releasing compounds (HRC) or solid carbon substrates (chitin, EHC [Adventus Americas product] and natural organic materials) to the subsurface via active injection wells or via pressurized injection.

This technology can be implemented using either a passive injection system or active groundwater recirculation system; however, due to pumping of the supply well a passive biobarrier approach was considered for water supply purposes. The passive system involves the drilling of several new injection wells placed in a circular pattern (Figure 32) within a 100 foot radius of the supply well. This produces approximately 13 injection/delivery wells. Because the treatment zone is needed for as long as the supply well operates (several years), a long term carbon substrate such as chitin or EVO is recommended to minimize the need for frequent injections. For cost estimating purposes we have assumed that EVO will be used over a 10 year lifespan. Dosing of EVO will occur ever 2 years. Injection/delivery wells are assumed to be 4 inch nominal diameter top a depth of 200 ft bgs and a well screen of 40 ft.

Total flow rate from the supply well is assumed to be 60,000 gallons per day (gpd) or an average of 42 gallons per minute (gpm).

### **Overall Protection of Water Supply (Human Health)**

In situ biological treatment has the potential to meet water quality MCLs for reducable metals such as U, Se and As (which reacts with sulfides) and nitrate. This technology would reduce contaminant mass through in situ treatment for as long as the system is operating as designed. This technology has the potential to reduce mass and concentration over the long-

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term. Iron and manganese can be mobilized in the treatment zone where reducing conditions predominate. However, overall protection of human health is not impacted significantly, as these metals will oxidize and become immobile once exposed to oxygen rich environments.

### **Reduction of Constituent Concentrations Through Treatment**

A functioning in situ biological treatment system has the capacity to treat and or precipitate chemicals over a short time frame. Therefore, in situ biological treatment has the potential to reduce toxicity. This technology has the potential to decrease toxicity, volume, and mass, and eliminate mobility of regulated compounds in the subsurface over the short and long term (as long as the system operates as designed).

### **Short-term and Long-term Effectiveness and Permanence**

In situ biological treatment is an established treatment/remediation technology for reducing volume and mass in the subsurface. This technology can be effective over the short term and long term provided that the system operates as designed. A full-scale system can be constructed and completed within 6 to 12 months following design and efficacy testing. Regulatory permitting time can be substantial. The proposed system would make use of passive treatment zone to reduce metals and nitrate present in aquifer water above MCLs. In situ biological treatment has proven effective at other sites and can be operated in perpetuity for as long as the system infrastructure can be maintained.

### **Implementability**

In situ biological treatment system consists of injection wells, common equipment, and components. Implementability would be similar to that of groundwater extraction without the issues of water disposal. Implementability is not expected to be a challenge for this technology.

### **Cost**

The capital costs, annual costs, NPV, and total cost to implement in situ biological treatment system are summarized in Table 20. Capital costs include installation of injection and extraction wells and additional monitoring wells. Annual costs include maintenance of wells, groundwater or system performance monitoring, and dosing every two years and costs associated with the system.

## **8.3 Summary of Technology Assessment**

This section presents a summary of the technology assessment. The technologies identified in this study all have strengths and weaknesses. This summary provides an assessment of how those strengths and weaknesses balance the overall effectiveness of the technology application.

Many of the in situ technologies were developed for remediation purposes and using them for protection of water supply is a new application. However, there are some common elements of the technology as applied to water supply treatment. These would be the technologies ability to treat or precipitate the COCs in the subsurface aquifer. Conceptually,

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these technologies could work for water supply purposes, but lacking the testing that is required for efficacy leads to challenges with developing designs.

Given the discussion on the technology application for water supply purposes, it appears that the technology that may have the greatest potential for this application is the use of ZVI, either as a PRB or using the Ferox™ process. Other technologies may be less expensive to implement, but tend to have greater operating expense and are only applicable for a few of the water quality COCs. In some cases, where water quality COCs are only marginally above drinking water MCLs, only partial in situ treatment may be required and therefore, technology design and implementation can be matched to treatment of portions of aquifer water rather than all water captured with the supply well. In this case, groundwater flow modeling would be used to assist with calculations on treatment needs and final site specific design.

Major factors affecting cost of in situ technology implementation include well drilling, costs of reagents or reactive materials, delivery of reagents and reactive materials and ongoing operation and maintenance costs. It is anticipated that advances in well drilling technology may help to reduce costs in the future. Methods for delivery and mixing of soluble reagents are a current area of research. The goal of the research is to find methods that provide better delivery mixing in the aquifer at a lower cost. This will result in the need for fewer delivery wells thereby reducing drilling costs; which was a major cost factor for this study. New materials to compete with ZVI are being evaluated which may result in lower iron costs for those technologies that relay on iron for treatment. Recent developments with pneumatic injection have helped to decrease costs for placement of ZVI in the subsurface. With additional refinements and use of this injection method, overall implementation costs may be more competitive in the future.

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SECTION 9

## Further Evaluation and Testing

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This section presents proposed additional testing and data requirements to establish performance, design and monitoring criteria required to further evaluate the efficacy of in situ treatment concepts for water supply purposes.

Bench-scale testing (treatability testing) and field pilot testing (pilot testing) are recommended to assist with the development of in situ technologies specifically for water supply. Bench scale treatability testing would be used to evaluate promising technologies ability to treat most, if not all, water quality COCs present in groundwater in the study area. The treatability testing would ideally be conducted using representative site groundwater geochemical conditions. The results of the treatability testing would be used to assist with selection of a technology that shows considerable promise and to provide parameters for the design of a pilot and ultimately a full-scale treatment system.

The goal of a field pilot test program is to collect in situ technology performance data and to generate design, operational and cost information for its full-scale use for this application.

# Summary and Conclusions

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This section presents a summary of the technology assessment for water supply treatment and the evaluation of the ex situ treatment residuals re-injection into Class V wells.

## 10.1 Study Background

The University of Texas' BEG is currently evaluating several in situ technology approaches for small public water systems using groundwater that do not meet the EPA MCLs for a number of water quality COCs. The study was limited to the Ogallala aquifer in the counties of Lubbock, Lamb, Hale, Floyd, Crosby, Garza, Lynn, Terry, and Hockley, in the northwestern portion of Texas.

Conventional water supply treatment is conducted using ex situ treatment technologies such as ion exchange, reverse osmosis, filtration and chemical reduction. While these ex situ technologies will be used for most drinking water treatment, other methods and technologies, such as in situ treatment, are being evaluated to support, enhance and reduce the costs of providing drinking water that meets EPA, state and local water quality standards.

An assessment of the potential impacts of injection of ex situ treatment residuals re-injection into Class V wells was also conducted as part of this study. Demands for potable water, necessitate utilization of groundwater that requires advanced treatment processes to meet federal and state drinking water MCLs. These ex situ treatment processes result in a waste stream of concentrated treatment residuals that will need to be managed. Class V wells generally include wells which inject fluids into or above an underground source of drinking water (USDW), defined as an aquifer with less than 10,000 mg/l total dissolved solids (TDS) (40CFR146.3). Groundwater modeling was performed to represent general conditions in the study area. A sensitivity analysis was performed to evaluate the effects of varying aquifer parameters on the movement of injected fluids over a range of values consistent with the study area.

## 10.2 Results of Residuals Injection

Modeling of residuals injection into a hypothetical section of the Ogallala aquifer using a Class V well demonstrates that over a typical 50-year project life, the injected concentrate remains relatively close to the injection well. Simulations show that even after 50 years (with the regional gradient) the concentrate front migrates approximately 7,600 feet from the original injection point, becoming more dilute with time. The concentration of COCs is less than two times background levels at a distance greater than 1,800 feet from the Class V well after 50 years of injection.

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Modeling results indicate that aquifer dispersivity does not appear to significantly influence concentrate migration. However, hydraulic conductivity and gradient does affect the distribution of concentrate. Further field evaluation would be required to fully assess this approach. Site specific test drilling, pump testing, and additional modeling should be used to develop the concept further.

Application of Class V disposal must be coupled with long-term land use controls. These controls would be legal or administrative mechanisms to restrict access to contaminated groundwater associated with disposal activities.

### 10.3 Results of In Situ Technology Assessment

Technology selection of was based on primarily on treatment for those regulated COCs that are above EPA MCLs in the study area groundwater. Most of the in situ technologies evaluated were developed for remediation purposes and using them for treatment of public water supply is a new application. The technologies principle mode of operation is the same for both remediation and water supply applications, but the configuration and mode of operation can be very different.

In situ technologies, considered viable given the site conditions and COCs present in the aquifers in the study area included:

- Zero valent iron (ZVI) permeable reactive barriers (PRBs)
- Injectable nano-scale ZVI (Ferox™ Process)
- Phosphate and phosphate PRBs
- In situ chemical reduction using dithionite and calcium polysulfide
- Innovative in situ treatment technologies such as phytoremediation and engineered wetlands

Technology evaluation was conducted using a modified feasibility study framework defined in *Guidance for Conducting Remedial Investigation and Feasibility Studies Under CERCLA* (USEPA, 1999). Each technology was evaluated for study area conditions and considerations to determine the optimum in situ treatment technology.

Based on the evaluation of the technologies using the modified assessment criteria, it appears that the technology that may have the greatest potential for in situ treatment for water supply is ZVI either, as a PRB or using the Ferox™ process. Depending on the water quality COCs, other promising technologies include in situ chemical and in situ biological treatment. These technologies tend to be less expensive to implement, but tend to be more expensive to operate. In addition, they are applicable for only a limited number of the water quality COCs present in the Ogallala near Lubbock, Texas.

Additional testing and groundwater modeling is needed to further develop the use of in situ technologies for water supply purposes. In this case groundwater flow modeling would be used to assist with calculations on treatment needs and final site specific design. Bench-scale and field pilot testing are recommended to assist with the development of in situ technologies and to test the configurations and designs given site specific conditions.

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Application of Class V disposal must be coupled with long-term land use controls, both legal and administrative, to restrict access to contaminated groundwater associated with disposal activities.

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## SECTION 11

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**Appendix A**  
**Geochemistry of Contaminants**

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# Geochemistry of Contaminants

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## Introduction

The elements that result in noncompliance of Public Water Systems in Lubbock and surrounding counties include nitrate, arsenic, fluoride, selenium, uranium, and radium.

### Nitrate

Nitrate contamination occurs when nitrate-N concentrations exceed 10 mg/L nitrate-N (MCL for nitrate-N). Nitrate is negatively charged and behaves conservatively; i.e. it does not sorb onto soils, volatilize, precipitate readily etc. Natural sources of nitrate include fixed nitrogen by shrubs such as mesquite in rangeland settings. Nitrate concentrations in soil profiles in most rangeland settings in the Southern High Plains are generally low (Scanlon et al., 2003; McMahon et al., 2005). Conversion of rangeland to agriculture can result in nitrification of soil organic matter. Anthropogenic sources of nitrate include chemical and organic (manure) fertilizers, nitrogen fixation through growth of leguminous crops, and barnyard and septic tank effluent. Nitrogen isotopes have been used to distinguish these various sources; however, such a study has not been conducted in the Southern High Plains. Nitrogen profiles measured in soils in Dawson County indicated that nitrate concentrations in soil pore water were generally low to moderate (Scanlon et al., 2003). The highest concentrations were found in irrigated areas because irrigation water contains higher nitrate concentrations than rain water and irrigation rates are low enough to result in evapoconcentration of nitrate in the soils.

### Arsenic

Arsenic exists naturally in three redox states (-III, III, V) It strongly interacts with soil particles, particularly iron oxides. The fully deprotonated arsenate  $\text{AsO}_4^{3-}$  is the expected form of arsenic in most soils under aerobic conditions only at high pH. At more neutral and acid pH's, the  $\text{HAsO}_4^{2-}$  and  $\text{H}_2\text{AsO}_4^{-1}$  forms, respectively, are dominant. The general understanding of arsenic mobility in soil and aquifers is that it increases with increasing pH and phosphate concentration and with decreasing clay and iron oxide content. As pH increases, the negative charge of the arsenate ion increases making it less likely to sorb on negatively charged soil particles. Phosphates have a chemical structure very similar to arsenates and sorb to soils preferentially to them in some conditions. Other structurally similar oxyanions, sulfate and selenate, are also weak sorbers. Under less oxidizing conditions, the arsenite ion  $\text{H}_3\text{AsO}_3$  is most stable. The lack of charge renders the ion more mobile and less likely to sorb to soil particles. Its pH stability spread ranges from very acid to alkaline. The first deprotonated form  $\text{H}_2\text{AsO}_3^{-1}$  exists at

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significant concentrations only above a pH of approximately 9. The redox processes seem to be mediated by microorganisms (Welch et al., 2000) and to take place next to mineral surfaces.

As(V) and As(III) minerals are fairly soluble and do not control arsenic solubility in oxidizing and mildly reducing conditions except maybe if barium is present (Henry et al., 1982a, p.21). This is in contrast to other companion oxyanions not as mobile under reducing conditions, except vanadium. In reducing conditions, As precipitates as arsenopyrite (FeAsS) but more commonly in solid solution with pyrite.

### Fluoride

Fluorine exists naturally in solution under one valence, F<sup>-</sup>, the fluoride ion. Fluoride tends to make complexes and ion pairs with trace elements. It can also sorb significantly to oxides, especially aluminum oxides, and clays (Hem, 1985, p.121). Its concentration is controlled by calcium as fluorite (CaF<sub>2</sub>) is the most common fluorine mineral. Apatite (a calcium phosphate) can also contain a significant amount of fluorine.

### Selenium

Selenium has a chemistry similar to that of sulfur, existing naturally in four redox states VI, IV, 0, and -II, with selenate, selenite and selenide ions occurring in Eh-pH conditions largely parallel to those of arsenic. In oxic conditions, the selenate ion, SeO<sub>4</sub><sup>2-</sup>, is the dominant species across all natural pHs. In slightly reducing conditions, the selenite ion exists from the fully deprotonated form, SeO<sub>3</sub><sup>2-</sup>, at alkaline pHs to the neutral H<sub>2</sub>SeO<sub>3</sub> at acid pHs and the HSeO<sub>3</sub><sup>-1</sup> form at neutral pHs. However, here are several differences with arsenic. The selenate ion is a weak sorber and its behavior resembles more that of sulfate than that of arsenate ion (White and Dubrovsky, 1994). Organo-selenium compounds and possibly native selenium are also more widespread. All selenate and selenite minerals are highly soluble. Native selenium or more likely ferroselite (pyrite with some Se substituted for S) can precipitate at relatively high Eh neutral pH. However, kinetics issues may keep selenium in solution even at reducing Ehs (Henry et al., 1982a, p.21).

### Radionuclides

Radionuclide impact on water quality is measured according to two scales: intrinsic measurement of radioactivity and impact on human beings. Activity or number of disintegrations per unit time is typically measured in pico Curies (pCi), whereas impact on living organisms is measured in mrem. Radioactive decay can generate alpha or beta particles, as well as gamma rays. Two radioactive elements with the same activity may have vastly different impacts on life, depending on the energy released during decay. Each radionuclide has a conversion factor from pCi to mrem as a function of exposure pathway. Activity is related to contaminant concentration and half-life. A higher concentration and a shorter half-life lead to increased activity. Given the ratio of the half-life of each (Table 1), it is apparent that radium is approximately 1 million times more radioactive than uranium. Concentrations of gross alpha and beta emitters take into account the whole decay series and not just uranium and radium, as well as other elements such as K40.

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Uranium is both a heavy metal and a radionuclide. Its geochemistry is complicated in the details but can be summarized by the following. Uranium(VI) in oxidizing conditions exists as the soluble positively charged uranyl ion  $\text{UO}_2^{++}$ . Solubility is higher at acid pHs, decreases at neutral pHs, and goes slightly back up at alkaline pHs. However, the uranyl ion, to the contrary of oxyanions, can easily form aqueous complexes, including with the hydroxyl, fluoride, carbonate and phosphate ligands. Hence in presence of carbonates, uranium solubility is considerably enhanced in the form of uranyl-carbonate ( $\text{UO}_2\text{CO}_3$ ) and other higher order carbonate complexes: uranyl-di- and uranyl-tri-carbonates ( $\text{UO}_2(\text{CO}_3)_2^{-2}$  and  $\text{UO}_2(\text{CO}_3)_3^{-4}$ ). Adsorption of uranium is inverse to its solubility and is the highest at neutral pHs (De Soto, 1978, p.11). Uranium(IV) is the other commonly found redox state. In that state, however, uranium is not very soluble and precipitates as uraninite,  $\text{UO}_2$ , coffinite,  $\text{USiO}_4 \cdot n\text{H}_2\text{O}$  (if  $\text{SiO}_2 > 60$  mg/L, Henry et al., 1982a, p.18), or related minerals.

Uranium and thorium both radium sources, are common trace elements. They are abundant in acidic rocks. Thorium exists naturally only in one redox state Th(IV).  $\text{Th}^{+4}$  forms complexes with most common aqueous anions. However, thorium solubility remains low except perhaps at higher pH when complexed by carbonate ions (EPA, 1999). Thorium sorbs strongly to metal oxides in a way similar to uranium.

Radium originates from the radioactive decay of uranium and thorium. Ra226 is an intermediate product of U238 (the most common uranium isotope >99%, Table A-1) decay, whereas Ra228 belongs to the Th232 (~100% of natural thorium) decay series. Ra226 has a much longer half life (1,599 yr) than Ra228 (5.6 yr). Both radium isotopes further decay to radon and, ultimately, to lead. Radon is a gas and tends to volatilize from shallower units. Radium is an alkaline Earth element and belongs to the same group as magnesium, calcium, strontium, and barium. It most resembles barium chemically, as evidenced by removal technologies such as ion exchange with Na and lime softening. Sorption on iron and manganese oxides is also a common trait of alkaline Earth elements. Radium exists only under one oxidation state, the divalent cation  $\text{Ra}^{+2}$ , similar to other alkaline Earth elements ( $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{Sr}^{+2}$ , and  $\text{Ba}^{+2}$ ).  $\text{RaSO}_4$  is extremely insoluble (more so than barium sulfate), with a log K solubility product of -10.5, compared with that of barium sulfate at ~-10. Radium solubility is mostly controlled by sulfate activity.

Table A-1. Uranium, thorium, and radium abundance and half-lives

Decay series	Uranium/thorium	Radium	Radon
U238	U238 - ~99.3% ( $4.47 \times 10^9$ yrs)	Ra226 - (1,599 yrs)	Rn222 - (3.8 days)
	U234 - 0.0055% ( $0.246 \times 10^9$ yrs)	Intermediate product of U238 decay	
U235	U235 - ~0.7% ( $0.72 \times 10^9$ yrs)	Ra223 - (11.4 days)	Rn219 - (4 seconds)
Th232	Th232 - ~100% ( $14.0 \times 10^9$ yrs)	Ra228 - (5.76 yrs) Ra224 - (3.7 days)	Rn220 - (~1 min)

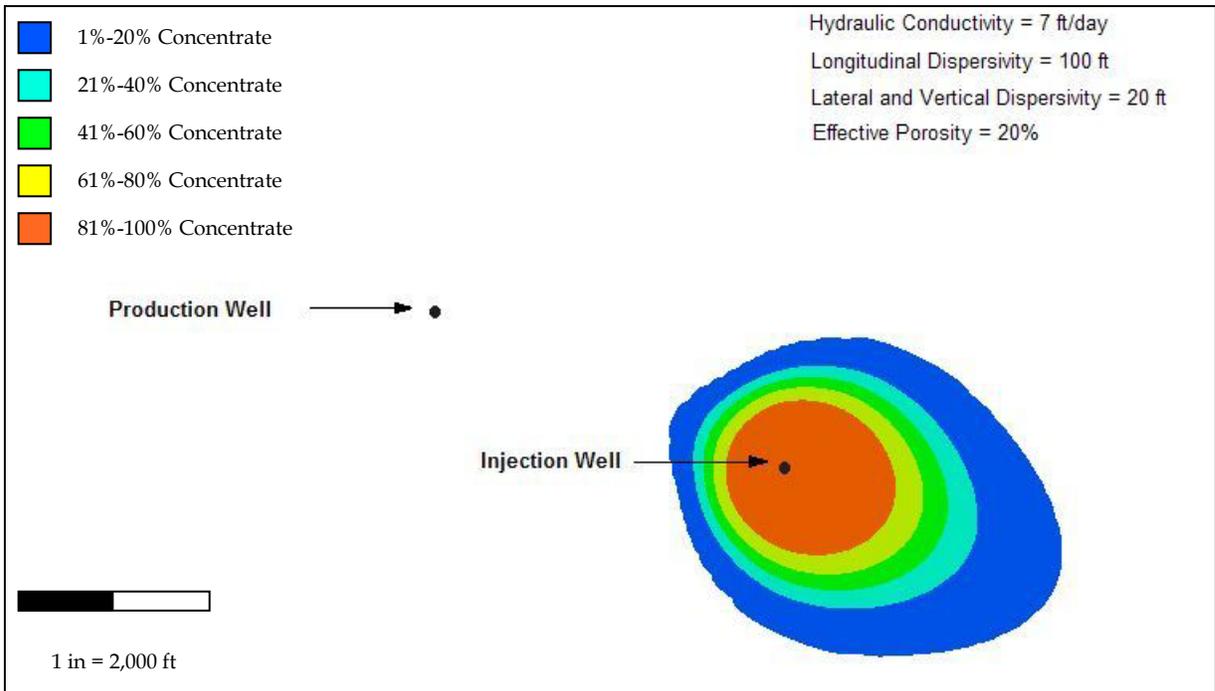
NOTE: half-life from Parrington et al. (1996)

**Appendix B**  
**Sensitivity Results: Residuals Injection**

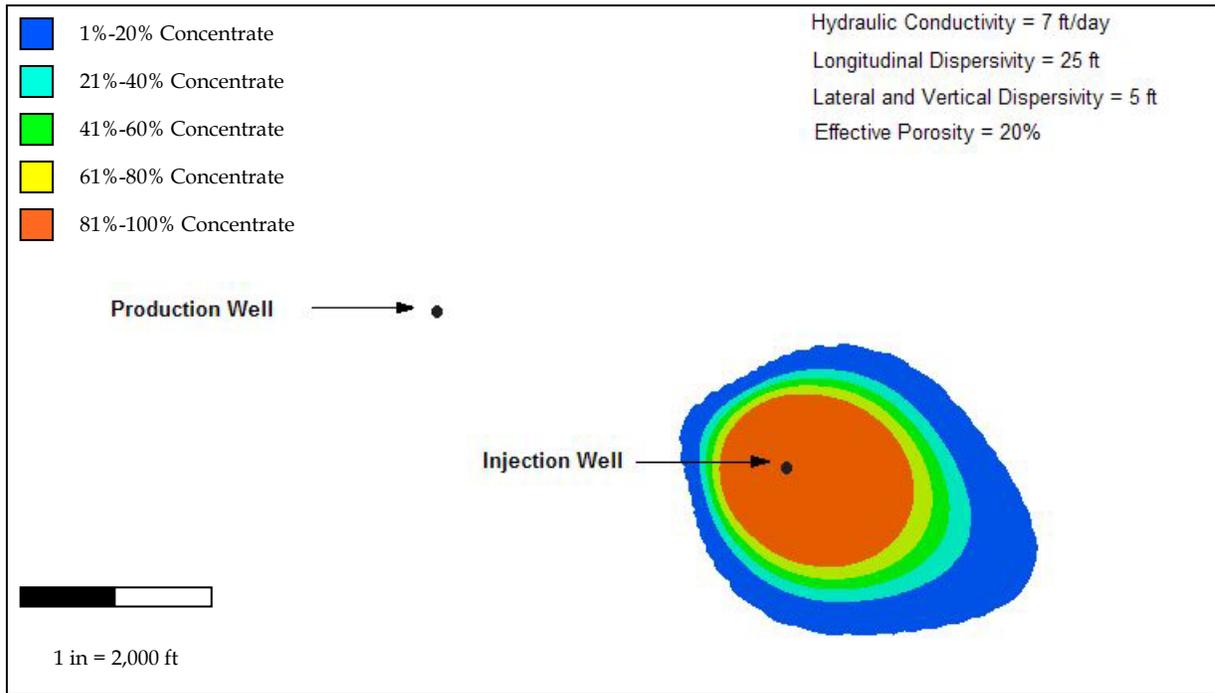
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# Sensitivity Results: Residuals Injection

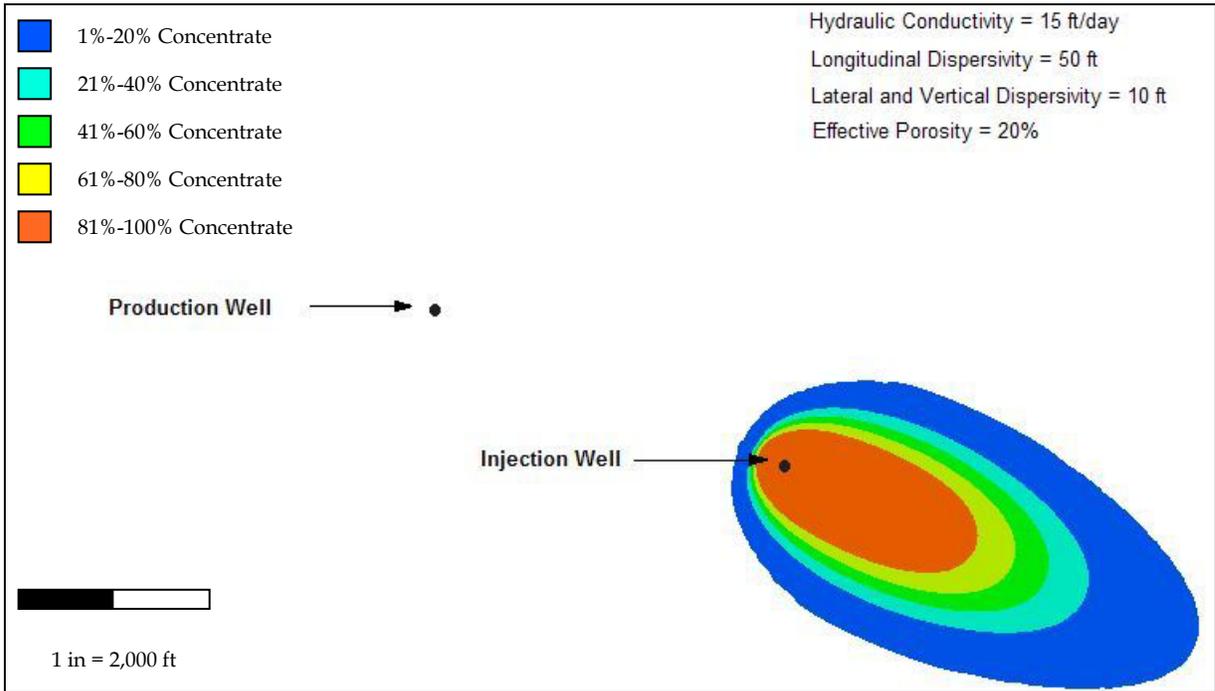
FIGURE B-1  
Sensitivity Analysis – High Dispersivity



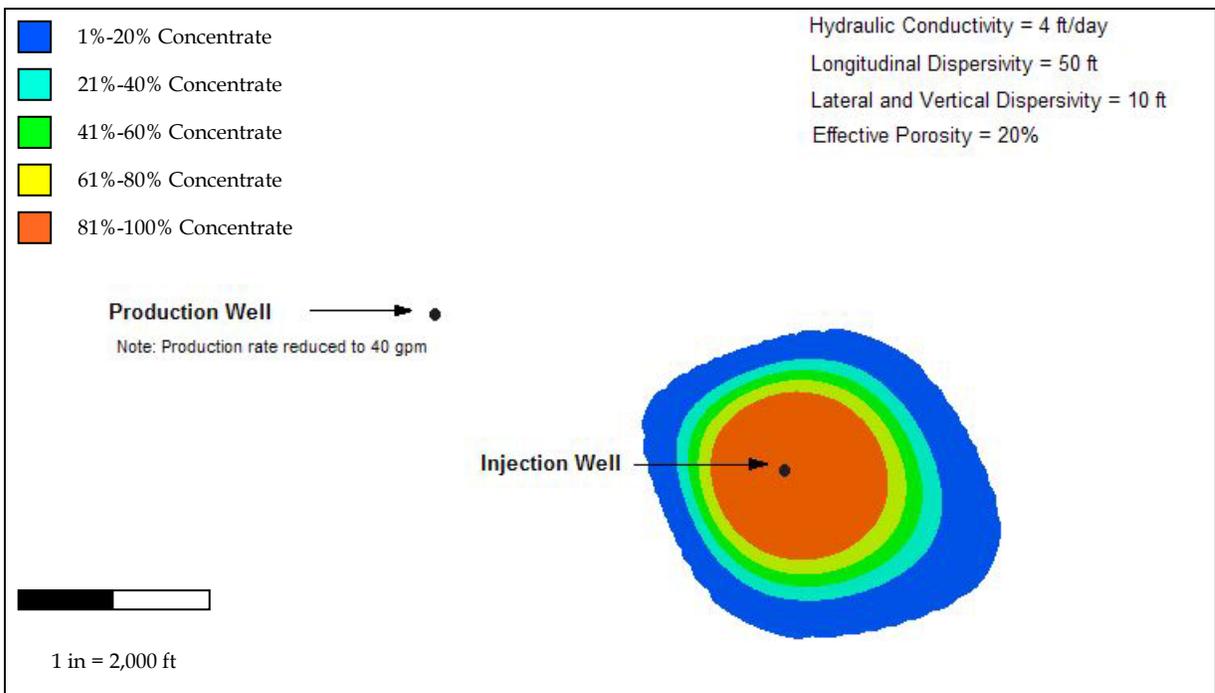
**FIGURE B-2**  
Sensitivity Analysis – Low Dispersivity



**FIGURE B-3**  
Sensitivity Analysis – High Hydraulic Conductivity



**FIGURE B-4**  
Sensitivity Analysis – Low Hydraulic Conductivity



**Appendix C**  
**Technology Evaluation Criteria**

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# Technology Evaluation Criteria

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Evaluation of treatment technologies was conducted using a modified feasibility study framework defined in *Guidance for Conducting Remedial Investigation and Feasibility Studies Under CERCLA* (USEPA, 1999). Each technology was evaluated for generic site conditions and considerations to determine the optimum remediation technology. A description of the modified evaluation criteria is provided in this section, along with the methods and considerations used to evaluate the effectiveness of treatment technologies in meeting each criteria.

## Criterion 1 - Overall Protection of Water Supply (Human Health)

This evaluation criterion assesses how each technology provides and maintains adequate protection of human health through treatment. Technologies are assessed to determine whether they can adequately protect against risks posed by COCs present in water supply aquifers at the site, in both the short- and long-term. This criterion is also used to evaluate how risks would be eliminated, reduced, or controlled through treatment, engineering, institutional controls, or other remedial activities. The considerations evaluated during the analysis of each technology for overall protection of the water supply are presented in Table C-1.

TABLE C-1

Criterion 1—Overall Protection of Water Supply (Human Health)

*BEG In situ Technology Evaluation*

<b>Analysis Factor</b>	<b>Considerations</b>
Human health protection	Likelihood that the technology reduces risk to human health resulting from in situ treatment of COCs
Chemical-specific Regulatory requirements	Likelihood that the technology will achieve compliance with chemical-specific Regulatory requirements. This criterion is related to federal, state and local drinking water quality limits.

## Criterion 2 – Short- and Long-Term Effectiveness and Permanence

This evaluation criterion addresses the short- and long-term effectiveness and permanence of maintaining the effective treatment/removal of COCs to protect of human health. The considerations evaluated during the analysis of each technology for long-term effectiveness and permanence are presented in Table C-2.

TABLE C-2  
 Criterion 2 — Short and Long-term Effectiveness  
*BEG In situ Technology Evaluation*

Analysis Factor	Considerations
Adequacy and reliability of controls	Likelihood that the technologies will meet required process efficiencies or performance specifications. Type and degree of short- and long-term management required. Short- and Long-term monitoring requirements. O&M functions that must be performed. Difficulties and uncertainties associated with short- long-term O&M functions. Potential need for technical components replacement. Degree of confidence that controls can adequately handle potential problems. Uncertainties associated with land disposal of residuals and untreated wastes.
Protection of the community during the remedial action	Risks to the community that must be addressed.  How the risks will be addressed and mitigated. Remaining risks that cannot be readily controlled.
Protection of workers during implementation	Risks to the workers that must be addressed.  How the risks will be addressed and mitigated. Remaining risks that cannot be readily controlled.
Environmental impacts	Environmental impacts that are expected with the construction and implementation of the technology.  Mitigation measures that are available, and their reliability to minimize potential impacts. Impacts that cannot be avoided, should the technology be implemented.
Time until remedial action objectives are achieved	Time to achieve protection against the threats being addressed.

**Criterion 3 - Reduction of Toxicity, Mobility, or Volume through Treatment**

This evaluation criterion addresses the anticipated performance of the technology’s treatment/removal technologies in permanently and significantly reducing toxicity, of regulated COCs in the produced groundwater. A preference is given to technologies where treatment is used to reduce the principal threats at a site through destruction of toxic contaminants, irreversible reduction in contaminant mobility, or reduction of total volume of contaminated media. The considerations evaluated during the analysis of each technology for reduction of toxicity, mobility, or volume of contaminants present at a given site are presented in Table C-3.

TABLE C-3

Criterion 3—Reduction of Toxicity, Mobility, or Volume through Treatment  
*BEG In situ Technology Evaluation*

<b>Analysis Factor</b>	<b>Considerations</b>
Treatment process and remedy	Likelihood that the treatment process addresses the principal threat (treatment/removal of COCs). Special requirements for the treatment process. Portion (mass) of contaminant that is treated.
Reduction in toxicity, mobility, or volume	Extent that the total mass of contaminants is reduced. Extent that the mobility of contaminants is reduced. Extent that the volume of contaminants is reduced.
Irreversibility of treatment	Extent that the effects of the treatment are irreversible.
Type and quantity of treatment residual	Residuals that will remain. Quantities and characteristics of the residuals. Risk posed by the treatment residuals.
Statutory preference for treatment as a principal element	Extent to which the scope of the action covers the principal threats. Extent to which the scope of the action reduces the inherent hazards posed by the principal threats at the site.

#### Criterion 4 - Implementability

This criterion evaluates the technical feasibility and administrative feasibility (i.e., the ease or difficulty) of implementing each technology and the availability of required services and materials during its implementation. The considerations evaluated during the analysis of each technology for implementability are presented in Table C-4.

TABLE C-4

Criterion 4—Implementability  
*BEG In situ Technology Evaluation*

<b>Analysis Factors</b>	<b>Considerations</b>
<b>Technical Feasibility</b>	
Ability to construct and operate the technology	Difficulties associated with the construction. Uncertainties associated with the construction.
Reliability of the technology	Likelihood that technical problems will lead to schedule delays.
Ease of undertaking additional remedial action	Likely future remedial actions that may be anticipated. Difficulty implementing additional remedial actions.
Monitoring considerations	Challenges to monitoring success of the technology Risks should the monitoring be insufficient to detect Likelihood of success or failure.
<b>Administrative Feasibility</b>	
Coordination with other agencies	Steps required to coordinate with regulatory agencies. Steps required to establish long-term or future coordination among agencies. Ease of obtaining permits for offsite activities, if required.
<b>Availability of Services and Materials</b>	
Availability of treatment, storage capacity,	Availability of adequate treatment, storage capacity, and disposal

TABLE C-4  
 Criterion 4—Implementability  
*BEG In situ Technology Evaluation*

Analysis Factors	Considerations
and disposal services	services. Additional capacity that is necessary. Whether lack of capacity prevents implementation. Additional provisions required to ensure that additional capacity is available.
Availability of necessary equipment and specialists	Availability of adequate equipment and specialists.  Additional equipment or specialists that are required. Whether there is a lack of equipment or specialists. Additional provisions required to ensure that equipment and specialists are available.
Availability of prospective technologies	Whether technologies under consideration are generally available and sufficiently demonstrated. Further field applications needed to demonstrate that the technologies may be used full-scale to treat the waste at the site. When technology should be available for full-scale use. Whether more than one vendor will be available to provide a competitive bid.

### Criterion 5 - Cost

This criterion evaluates the cost of implementing each technology. The cost of a technology encompasses all engineering, construction, and O&M costs incurred over the life of the project. According to CERCLA guidance, cost estimates for remedial alternatives were developed with an expected accuracy range of -30 to +50 percent.

The costs of the remedial alternatives are compared using the estimated net present value, capital, and annual costs. The net present value (NPV) allows costs for remedial alternatives to be compared by discounting all costs to the year that the alternative is implemented. For this study, the NPV was calculated using discount rate of 3.5 percent for a 10 year return period. Indirect costs including bid and scope contingency, project management, remedial design, and construction management/field activity oversight were added to capital costs as percentages of the total cost. Percentages were determined based on the uncertainty, total cost, and/or complexity of the project.

**Appendix D**  
**Cost Estimates and Assumptions**

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# Cost Estimates and Assumptions

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## Introduction

Cost estimates for the technologies were developed with an expected accuracy range of – 30 to +50 percent. Detailed cost estimates for the all retained technologies (Section 4.2) are presented in Tables D-1 through D-5.

The following section presents the assumptions used to develop cost estimates for each technology. These assumptions are not intended to be used for design or to provide specific recommendations for remedial technologies. In the remedial design phase, changes may be made to the approach used to implement the components of the technologies.

The summary of assumptions is broken into the following sections: present value analysis, component-specific assumptions that apply to several technologies (for example, cost assumptions associated with routine common elements for all technologies; eg. groundwater monitoring), and alternative-specific assumptions.

## Conceptual Design Assumptions

To facilitate cost estimation that provides for a comparison across most if not all technologies, the configuration and physical size of the treatment zone and set-back from the supply well was standardized. Other variables such as depth to water table, depth to confining layer and general shape of the technology configuration were assumed to be the same for all technologies. The following standards were used for cost estimation purposes:

- Depth to water table: 60 ft bgs
- Depth to confining layer: 110 ft bgs
- Minimum set-back (radius) from supply well: 80 ft
- Assumed radius of influence for injected chemical and biological reagent: 30 ft
- Number of borings or wells to injection chemical or biological reagents: 7 (with 25 ft spacing provides treatment for approximately two thirds of the extracted water)
- Assumed percentage of extracted water to be treated to meet MCLs: 67%
- Number of new monitoring wells used to monitor performance: 4
- Number of Ferox injection borings: 13 (10 ft spacing)

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## Present Value Analysis

Some of the technologies require long-term operation and maintenance activities, including system maintenance, and groundwater monitoring. Each cost estimate includes a net present value (NPV) cost, based on a 10-year operating period and a discounting factor of 3.5 percent. The annual operating, maintenance, and monitoring costs are input for each alternative. Therefore, the total NPV cost for each technology is for a 10 year period discounted each year by 3.5 percent.

### Annual Groundwater Monitoring Costs

Annual groundwater monitoring costs were assumed to be the same for all technologies. This provided for cost comparisons between technologies related more to implementation costs. In some cases small differences in performance monitoring costs were noted due to more or less monitoring required due to the technology.

### Above Ground Treatment

CH2M HILL understands that additional ex situ treatment is likely needed and will be dependant on extracted water quality. Costs for the end of pipe treatment were not included in the costs estimates.

### Other Cost Assumptions

CH2M HILL prepared these cost estimates based on technology vendor information, based on either from a quote from the vendor or based on vendor quotes on similar work or technology applications. Refinement to costs estimates (not part of this study) can be made with site-specific vendor quotes based on a site-specific bid process.

### Works Cited

U.S. Environmental Protection Agency (EPA). 2000. *A Guide to Developing and Documenting Cost Estimates During the Feasibility Study*.

Table D-1a: Cost Estimate for Zero Valent Iron Permeable Reactive Barrier

Item	No. of Components	Unit Cost	Value
<b>Annual Costs</b>			
<b>Land/Groundwater Use Restrictions</b>			
Site Inspections	1 year	\$ 621 \$/yr	\$ 621
Reporting	1 year	\$ 3,105 \$/yr	\$ 3,105
Coordination with Property Owners and State and Local Agencies	1 year	\$ 2,588 \$/yr	\$ 2,588
<b>Groundwater Monitoring</b>			
Project Management	1 year	\$ 8,843 \$/yr	\$ 8,843
Sampling	1 year	\$ 24,219 \$/yr	\$ 24,219
Analyze Samples	1 year	\$ 8,644 \$/yr	\$ 8,644
Sample Management	1 year	\$ 2,881 \$/yr	\$ 2,881
Data Validation	1 year	\$ 2,803 \$/yr	\$ 2,803
Reports	1 year	\$ 26,393 \$/yr	\$ 26,393
Bid and Scope Contingency	20% of total annual cost		\$ 16,019
<b>Total Annual Costs</b>			<b>\$ 80,097</b>
<b>Expected Years of O&amp;M</b>			<b>10</b>
<b>Discount Rate</b>			<b>3.5%</b>
<b>NET PRESENT VALUE OF ANNUAL COSTS</b>			<b>\$ 666,132</b>
<b>Capital Costs</b>			
<b>Direct</b>			
<b>Permeable Reactive Barrier</b>			
Project Management (PRB Contractor)	1 1000 foot PRB	\$ 6,728 \$/320 foot PRB	\$ 2,153
Project engineer and staff	1 1000 foot PRB	\$ 15,732 \$/320 foot PRB	\$ 5,034
GIS/Drafting/ Word processing	1 1000 foot PRB	\$ 311 \$/320 foot PRB	\$ 99
Mobilization/Demobilization	1 lump sum	\$ 26,910 lump sum	\$ 26,910
PRB construction materials	1 1000 foot PRB	\$ 1,250,073 \$/320 foot PRB	\$ 400,023
Iron QA and Reactivity Test and Hydraulic pulse testing	1 1000 foot PRB	\$ 42,435 \$/320 foot PRB	\$ 13,579
Mixing Blending materials	1 1000 foot PRB	\$ 2,969,156 \$/320 foot PRB	\$ 950,130
PRB construction	1 1000 foot PRB	\$ 2,231,719 \$/320 foot PRB	\$ 714,150

Item	No. of Components	Unit Cost	Value
Waste Handling	1 PRB 1000 foot PRB	\$ 102,206 \$/320 foot PRB	\$ 32,706
Contractor expenses (computer, travel, vehicle rental, per diem, sub contractor, lab work)	1 PRB 1000 foot PRB	\$ 1,445,266 \$/320 foot PRB	\$ 462,485
<b>Additional Monitoring Well Installation</b>			
2" PVC 130' well, 60' screen (drilling, installation, clean-up)	4 wells	\$ 10,166 \$/well	\$ 40,665
Field Geologist	400 hours	\$ 78 \$/hr	\$ 31,050
<b>TOTAL DIRECT COSTS</b>			<b>\$ 2,647,935</b>
<b>Indirect</b>			
<b>General</b>			
Bid and Scope Contingency	20%	of direct capital cost	\$ 529,587
Project Management	6%	of direct capital cost	\$ 158,876
Remedial Design	10%	of direct capital cost	\$ 264,794
Construction Management / Field Activity Oversight	15%	of direct capital cost	\$ 397,190
Reporting	4%	of direct capital cost	\$ 105,917
<b>TOTAL INDIRECT COSTS</b>	<b>55%</b>	<b>of direct capital cost</b>	<b>\$ 1,456,364</b>
<b>TOTAL CAPITAL COSTS</b>			<b>\$ 4,104,299</b>
<b>TOTAL PRESENT VALUE COST ESTIMATE</b>			<b>\$ 4,770,000</b>

Table D-1b: Cost Estimate for Slurry Wall System- ZVI Permeable Reactive Barrier

Item	No. of Components	Unit Cost	Value
<b>Annual Costs</b>			
<b>Land/Groundwater Use Restrictions</b>			
Site Inspections	1 year	\$ 621 \$/yr	\$ 621
Reporting	1 year	\$ 3,105 \$/yr	\$ 3,105
Coordination with Property Owners and State and Local Agencies	1 year	\$ 2,588 \$/yr	\$ 2,588
<b>Groundwater Monitoring</b>			

Item	No. of Components	Unit Cost	Value
Project Management	1 year	\$ 8,843 \$/yr	\$ 8,843
Sampling	1 year	\$ 38,750 \$/yr	\$ 38,750
Analyze Samples	1 year	\$ 8,644 \$/yr	\$ 8,644
Sample Management	1 year	\$ 17,289 \$/yr	\$ 17,289
Data Validation	1 year	\$ 5,597 \$/yr	\$ 5,597
Reports	1 year	\$ 33,638 \$/yr	\$ 33,638
Bid and Scope Contingency	20% of total annual cost		\$ 23,815
<b>Total Annual Costs</b>			<b>\$ 119,075</b>
<b>Expected Years of O&amp;M</b>			<b>10</b>
<b>Discount Rate</b>			<b>3.5%</b>
<b>NET PRESENT VALUE OF ANNUAL COSTS</b>			<b>\$ 990,297</b>

#### Capital Costs

##### Direct

##### Permeable Reactive Barrier

Project Management (PRB Contractor)	1	1000 foot PRB	\$ 6,728	\$/160 foot PRB	\$ 1,076
Project engineer and staff	1	1000 foot PRB	\$ 15,732	\$/160 foot PRB	\$ 2,517
GIS/Drafting/ Word processing	1	1000 foot PRB	\$ 311	\$/160 foot PRB	\$ 50
Mobilization/Demobilization	1	lump sum	\$ 26,910	\$/160 foot PRB	\$ 26,910
PRB construction materials	1	1000 foot PRB	\$ 1,250,073	\$/160 foot PRB	\$ 200,012
Slurry Wall construction materials	1	1000 foot	\$ 262,500	\$/240 foot	\$ 63,000
Iron QA and Reactivity Test and Hydraulic pulse testing	1	1000 foot PRB	\$ 42,435	\$/160 foot PRB	\$ 6,790
Mixing Blending materials	1	1000 foot PRB	\$ 2,969,156	\$/160 foot PRB	\$ 475,065
PRB construction	1	1000 foot PRB	\$ 2,231,719	\$/160 foot PRB	\$ 357,075
Waste Handling	1	1000 foot PRB	\$ 102,206	\$/160 foot PRB	\$ 16,353
Contractor expenses (computer, travel, vehicle rental, per diem, sub contractor, lab work)	1	1000 foot PRB	\$ 1,445,266	\$/160 foot PRB	\$ 231,243

##### Additional Monitoring Well Installation

2" PVC 130' well, 60' screen (drilling, installation, clean-up)	4	wells	\$ 10,166	\$/well	\$ 40,665
Field Geologist	400	hours	\$ 78	\$/hr	\$ 31,050

Item	No. of Components	Unit Cost	Value
<b>TOTAL DIRECT COSTS</b>			<b>\$ 1,420,755</b>
<b>Indirect</b>			
<b>General</b>			
Bid and Scope Contingency	20% of direct capital cost		\$ 284,151
Project Management	6% of direct capital cost		\$ 85,245
Remedial Design	10% of direct capital cost		\$ 142,076
Construction Management / Field Activity Oversight	15% of direct capital cost		\$ 213,113
Reporting	4% of direct capital cost		\$ 56,830
<b>TOTAL INDIRECT COSTS</b>	<b>55% of direct capital cost</b>		<b>\$ 781,415</b>
<b>TOTAL CAPITAL COSTS</b>			<b>\$ 2,202,170</b>
<b>TOTAL PRESENT VALUE COST ESTIMATE</b>			<b>\$ 3,192,000</b>

Table D2: Cost Estimate for Ferox ZVI Injection

Item	No. of Components	Unit Cost	Value
<b>Annual Costs</b>			
<b>Land/Groundwater Use Restrictions</b>			
Site Inspections	1 year	\$ 621 \$/yr	\$ 621
Reporting	1 year	\$ 3,105 \$/yr	\$ 3,105
Coordination with Property Owners and State and Local Agencies	1 year	\$ 2,588 \$/yr	\$ 2,588
<b>Groundwater Monitoring</b>			
Project Management	1 year	\$ 8,843 \$/yr	\$ 8,843
Sampling	1 year	\$ 38,750 \$/yr	\$ 38,750
Analyze Samples	1 year	\$ 17,289 \$/yr	\$ 17,289
Sample Management	1 year	\$ 5,597 \$/yr	\$ 5,597

Item	No. of Components	Unit Cost	Value
Data Validation	1 year	\$ 5,597 \$/yr	\$ 5,597
Reports	1 year	\$ 33,638 \$/yr	\$ 33,638
Bid and Scope Contingency	20% of total annual cost		\$ 23,206
<b>Total Annual Costs</b>			<b>\$ 116,028</b>
<b>Expected Years of O&amp;M</b>			<b>10</b>
<b>Discount Rate</b>			<b>3.5%</b>
<b>NET PRESENT VALUE OF ANNUAL COSTS</b>			<b>\$ 964,956</b>

### Capital Costs

#### Direct

#### Injection Well Installation

Ferox Injection	13 boreholes	\$ 130,000 \$/well	\$ 1,690,000
Ferox Injection Contingency	5% of Ferox Injection Costs		\$ 84,500
Injection Field Crew Subcontract	500 hr	\$ 83 \$/hr	\$ 41,577

#### ZVI Cost and Shipping

Freight for ZVI	14 loads	\$ 776 \$/load	\$ 10,868
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#### Electrical/ Communications

Electrician	2 system	\$ 5,175 \$/system	\$ 10,350
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#### Groundwater Use Restrictions

Incorporate Restrictions in Base General Plan	1	\$ 6,210 \$/ea	\$ 6,210
Update/Create Layers in GIS Database	1	\$ 9,315 \$/ea	\$ 9,315
Communicate Restrictions to Other Offices	1	\$ 7,763 \$/ea	\$ 7,763
Develop Processes for Permit Review and Training	1	\$ 4,658 \$/ea	\$ 4,658
Coordination with Property Owners and State and Local Agencies	1	\$ 5,175 \$/ea	\$ 5,175

#### TOTAL DIRECT COSTS

**\$ 1,870,414**

#### Indirect

Item	No. of Components	Unit Cost	Value
<b>General</b>			
Bid and Scope Contingency	20%	of direct capital cost	\$ 374,083
Project Management	6%	of direct capital cost	\$ 112,225
Remedial Design	10%	of direct capital cost	\$ 187,041
Construction Management	15%	of direct capital cost	\$ 280,562
Reporting	4%	of direct capital cost	\$ 74,817
<b>TOTAL INDIRECT COSTS</b>			<b>\$ 1,028,728</b>
<b>TOTAL CAPITAL COSTS</b>			<b>\$ 2,899,142</b>
<b>TOTAL PRESENT VALUE COST ESTIMATE</b>			<b>\$3,864,000</b>

Table D-3: Cost Estimate for In Situ Chemical (Dithionite) Treatment

Item	No. of Components	Unit Cost	Value
<b>Annual Costs</b>			
<b>Land/Groundwater Use Restrictions</b>			
Site Inspections	1 year	\$ 621 \$/yr	\$ 621
Reporting	1 year	\$ 3,105 \$/yr	\$ 3,105
Coordination with Property Owners and State and Local Agencies	1 year	\$ 2,588 \$/yr	\$ 2,588
<b>Groundwater Monitoring</b>			
Project Management	1 year	\$ 8,843 \$/yr	\$ 8,843
Sampling	1 year	\$ 24,219 \$/yr	\$ 24,219
Analyze Samples	1 year	\$ 8,644 \$/yr	\$ 8,644
Sample Management	1 year	\$ 2,881 \$/yr	\$ 2,881
Data Validation	1 year	\$ 2,803 \$/yr	\$ 2,803
Reports	1 year	\$ 26,393 \$/yr	\$ 26,393
<b>Operation and Maintenance</b>			
Dithionite	100,000 pounds	\$ 1 \$/lbs	\$ 100,000
Freight for Dithionite	2 loads	\$ 776 \$/load	\$ 1,553
Maintenance of System	7 Wells	\$ 4,140 \$/year per well	\$ 28,980
<b>General Operation and Maintenance Costs</b>			
Project Plans	1 year	\$ 393 \$/yr	\$ 393
Project Management	1 year	\$ 10,350 \$/yr	\$ 10,350
Data Validation	1 year	\$ 1,553 \$/yr	\$ 1,553
Quarterly Reporting	1 year	\$ 15,525 \$/yr	\$ 15,525
Database Management	1 year	\$ 590 \$/yr	\$ 590
Regulatory Interaction	1 year	\$ 507 \$/yr	\$ 507
<b>Bid and Scope Contingency</b>	15% of total annual cost		\$ 35,932
<b>Total Annual Costs</b>			<b>\$ 275,479</b>
<b>Expected Years of O&amp;M</b>			<b>10</b>
<b>Discount Rate</b>			<b>3.5%</b>
<b>NET PRESENT VALUE OF ANNUAL COSTS</b>			<b>\$ 2,291,050</b>
<b>Capital Costs</b>			
<b>Direct</b>			
<b>Passive Injection Well Installation</b>			
2" PVC 130' well, 60' screen (drilling, installation, clean-up)	4 wells	\$ 10,166 \$/well	\$ 40,665
6" PVC 120' well, 60' screen (drilling, installation, clean-up)	13 wells	\$ 55,700 \$/well	\$ 724,100

Item	No. of Components	Unit Cost	Value
Sample Analysis	7 samples	\$ 118 \$/sample	\$ 825
Field Geologist	400 hr	\$ 78 \$/hr	\$ 31,050
<b>Chemical Delivery</b>			
Delivery Tank (2,500 gallons), nozzles, support skirt	5 units	\$ 4,658 \$/ea	\$ 23,288
In-line static mixer (1.25-inch diameter, 12-inch length)	2 units	\$ 155 \$/ea	\$ 311
Chemical Metering Pump, installed	2 units	\$ 5,175 \$/ea	\$ 10,350
Centrifugal Pump (0.5 horsepower), installed	2 units	\$ 2,174 \$/ea	\$ 4,347
Flowmeter with display and totalizer, installed	6 units	\$ 518 \$/ea	\$ 3,105
8" Structural Concrete Slab on Grade and Prefab Building	1 lump sum	\$ 36,225 lump sum	\$ 36,225
<b>Electrical/ Communications</b>			
Electrician	1 system	\$ 25,875 \$/system	\$ 25,875
1.5-inch PVC (conduit)	500 feet	\$ 4.07 \$/ft	\$ 2,035
SCADA, wellhead costs, installed	2 wells	\$ 12,245 \$/well	\$ 24,490
SCADA, system costs, installed	1 system	\$ 30,630 \$/system	\$ 30,630
<b>TOTAL DIRECT COSTS</b>			<b>\$ 957,295</b>
<b>Indirect</b>			
<b>General</b>			
Bid and Scope Contingency	20%	of direct capital cost	\$ 191,459
Project Management	6%	of direct capital cost	\$ 57,438
Remedial Design	8%	of direct capital cost	\$ 76,584
Construction Management	15%	of direct capital cost	\$ 143,594
Reporting	4%	of direct capital cost	\$ 38,292
Bench- and Pilot-Scale Treatability Studies	1	set of studies	\$ 310,500 \$/Both Studies
<b>TOTAL INDIRECT COSTS</b>			<b>\$ 817,866</b>
<b>TOTAL CAPITAL COSTS</b>			<b>\$ 1,775,161</b>
<b>TOTAL PRESENT VALUE COST ESTIMATE</b>			<b>\$4,066,000</b>

Table D-4: Cost Estimate for In Situ Chemical (Calcium Polysulfide) Treatment

Item	No. of Components	Unit Cost	Value
<b>Annual Costs</b>			
<b>Land/Groundwater Use Restrictions</b>			
Site Inspections	1 year	\$ 621 \$/yr	\$ 621
Reporting	1 year	\$ 3,105 \$/yr	\$ 3,105
Coordination with Property Owners and State and Local Agencies	1 year	\$ 2,588 \$/yr	\$ 2,588
<b>Groundwater Monitoring</b>			
Project Management	1 year	\$ 8,843 \$/yr	\$ 8,843
Sampling	1 year	\$ 24,219 \$/yr	\$ 24,219
Analyze Samples	1 year	\$ 8,644 \$/yr	\$ 8,644
Sample Management	1 year	\$ 2,881 \$/yr	\$ 2,881
Data Validation	1 year	\$ 2,803 \$/yr	\$ 2,803
Reports	1 year	\$ 26,393 \$/yr	\$ 26,393
<b>Operation and Maintenance</b>			
Calcium Polysulfide	50,000 pounds	\$ 1 \$/lbs	\$ 50,000
Freight for Polysulfide	2 loads	\$ 776 \$/load	\$ 1,553
Maintenance of System	14 Wells	\$ 4,140 \$/year per well	\$ 57,960
<b>General Operation and Maintenance Costs</b>			
Project Plans	1 year	\$ 393 \$/yr	\$ 393

Item	No. of Components	Unit Cost	Value
Project Management	1 year	\$ 10,350 \$/yr	\$ 10,350
Data Validation	1 year	\$ 1,553 \$/yr	\$ 1,553
Quarterly Reporting	1 year	\$ 15,525 \$/yr	\$ 15,525
Database Management	1 year	\$ 590 \$/yr	\$ 590
Regulatory Interaction	1 year	\$ 507 \$/yr	\$ 507
<b>Bid and Scope Contingency</b>	15% of total annual cost		\$ 32,779
<b>Total Annual Costs</b>			<b>\$ 251,306</b>
<b>Expected Years of O&amp;M</b>			<b>10</b>
<b>Discount Rate</b>			<b>3.5%</b>
<b>NET PRESENT VALUE OF ANNUAL COSTS</b>			<b>\$ 2,090,013</b>

### Capital Costs

#### Direct

##### Passive Injection Well Installation

2" PVC 130' well, 60' screen (drilling, installation, clean-up)	4 wells	\$ 10,166 \$/well	\$ 40,665
6" PVC 120' well, 60' screen (drilling, installation, clean-up)	13 wells	\$ 55,700 \$/well	\$ 724,100
Sample Analysis	7 samples	\$ 118 \$/sample	\$ 825
Field Geologist	400 hr	\$ 78 \$/hr	\$ 31,050

##### Chemical Delivery

Delivery Tank (2,500 gallons), nozzles, support skirt	3 units	\$ 4,658 \$/ea	\$ 13,973
In-line static mixer (1.25-inch diameter, 12-inch length)	2 units	\$ 155 \$/ea	\$ 311
Chemical Metering Pump, installed	3 units	\$ 5,175 \$/ea	\$ 15,525
Centrifugal Pump (0.5 horsepower), installed	2 units	\$ 2,174 \$/ea	\$ 4,347
Flowmeter with display and totalizer, installed	7 units	\$ 518 \$/ea	\$ 3,623
8" Structural Concrete Slab on Grade and Prefab Building	1 lump sum	\$ 36,225 lump sum	\$ 36,225

##### Electrical/ Communications

Electrician	1 system	\$ 25,875 \$/system	\$ 25,875
1.5-inch PVC (conduit)	500 feet	\$ 4.07 \$/ft	\$ 2,035
SCADA, wellhead costs, installed	2 wells	\$ 12,245 \$/well	\$ 24,490
SCADA, system costs, installed	1 system	\$ 30,630 \$/system	\$ 30,630

#### TOTAL DIRECT COSTS

**\$ 953,672**

#### Indirect

##### General

Bid and Scope Contingency	20% of direct capital cost	\$ 190,734
Project Management	6% of direct capital cost	\$ 57,220
Remedial Design	8% of direct capital cost	\$ 76,294

Item	No. of Components	Unit Cost	Value
Construction Management Reporting	15% of direct capital cost		\$ 143,051
Bench- and Pilot-Scale Treatability Studies	4% of direct capital cost		\$ 38,147
	1 set of studies	\$ 310,500 /\$Both Studies	\$ 310,500
<b>TOTAL INDIRECT COSTS</b>			<b>\$ 815,946</b>
<b>TOTAL CAPITAL COSTS</b>			<b>\$ 1,769,618</b>
<b>TOTAL PRESENT VALUE COST ESTIMATE</b>			<b>\$ 3,860,000</b>

Table D-5: Cost Estimate for In Situ Biological Treatment

Item	No. of Components	Unit Cost	Value
<b>Annual Costs</b>			
<b>Land/Groundwater Use Restrictions</b>			
Site Inspections	1 year	\$ 621 \$/yr	\$ 621
Reporting	1 year	\$ 3,105 \$/yr	\$ 3,105
Coordination with Property Owners and State and Local Agencies	1 year	\$ 2,588 \$/yr	\$ 2,588
<b>Groundwater Monitoring</b>			
Project Management	1 year	\$ 8,843 \$/yr	\$ 8,843
Sampling	1 year	\$ 24,219 \$/yr	\$ 24,219
Analyze Samples	1 year	\$ 8,644 \$/yr	\$ 8,644
Sample Management	1 year	\$ 2,881 \$/yr	\$ 2,881
Data Validation	1 year	\$ 2,803 \$/yr	\$ 2,803
Reports	1 year	\$ 26,393 \$/yr	\$ 26,393
<b>Operation and Maintenance</b>			
Carbon (Electron) Donor	50 drums	\$ 466 \$/55-gallon drum	\$ 23,288
Freight for Electron Donor	2 loads	\$ 776 \$/load	\$ 1,553
Maintenance of Biostimulation System	7 Wells	\$ 4,140 \$/year per well	\$ 28,980
<b>General Operation and Maintenance Costs</b>			

Item	No. of Components	Unit Cost	Value
Project Plans	1 year	\$ 393 \$/yr	\$ 393
Project Management	1 year	\$ 10,350 \$/yr	\$ 10,350
Data Validation	1 year	\$ 1,553 \$/yr	\$ 1,553
Quarterly Reporting	1 year	\$ 15,525 \$/yr	\$ 15,525
Database Management	1 year	\$ 590 \$/yr	\$ 590
Regulatory Interaction	1 year	\$ 507 \$/yr	\$ 507
<b>Bid and Scope Contingency</b>	15% of total annual cost		\$ 24,425
<b>Total Annual Costs</b>			<b>\$ 187,260</b>
<b>Expected Years of O&amp;M</b>			<b>10</b>
<b>Discount Rate</b>			<b>3.5%</b>
<b>NET PRESENT VALUE OF ANNUAL COSTS</b>			<b>\$ 1,557,365</b>

#### Capital Costs

##### Direct

##### Passive Injection Well Installation

2" PVC 130' well, 60' screen (drilling, installation, clean-up)	4 wells	\$ 10,166 \$/well	\$ 40,665
6" PVC 120' well, 60' screen (drilling, installation, clean-up)	13 wells	\$ 55,700 \$/well	\$ 724,100
Sample Analysis	7 samples	\$ 118 \$/sample	\$ 825
Field Geologist	400 hr	\$ 78 \$/hr	\$ 31,050

##### Biological Reagent Delivery

Portable Delivery Trailer	1 units	\$ 56,925 \$/ea	\$ 56,925
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##### Electrical/ Communications

Electrician	1 system	\$ 25,875 \$/system	\$ 25,875
1.5-inch PVC (conduit)	500 feet	\$ 4.07 \$/ft	\$ 2,035
SCADA, wellhead costs, installed	2 wells	\$ 12,245 \$/well	\$ 24,490
SCADA, system costs, installed	1 system	\$ 30,630 \$/system	\$ 30,630

##### TOTAL DIRECT COSTS

**\$ 936,595**

##### Indirect

##### General

Bid and Scope Contingency	20%	of direct capital cost	\$ 187,319
Project Management	6%	of direct capital cost	\$ 56,196
Remedial Design	8%	of direct capital cost	\$ 74,928
Construction Management	15%	of direct capital cost	\$ 140,489
Reporting	4%	of direct capital cost	\$ 37,464
Bench- and Pilot-Scale Treatability Studies	1	set of studies	\$ 310,500 \$/Both Studies \$ 310,500

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Item	No. of Components	Unit Cost	Value
<b>TOTAL INDIRECT COSTS</b>			<b>\$ 806,895</b>
<b>TOTAL CAPITAL COSTS</b>			<b>\$ 1,743,490</b>
<b>TOTAL PRESENT VALUE COST ESTIMATE</b>			<b>\$ 3,301,000</b>

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