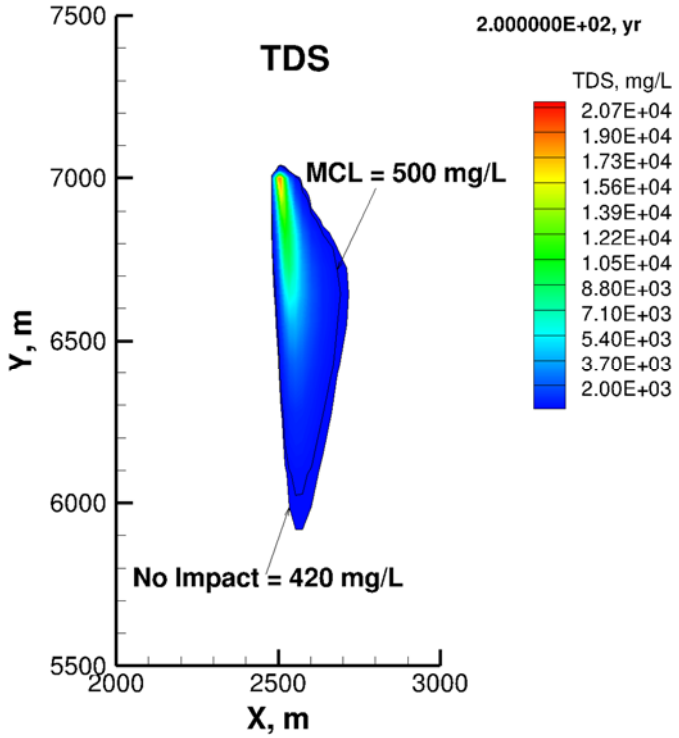

No-Impact Threshold Values for Groundwater Reduced-Order Models

28 January 2016

Office of Fossil Energy

NRAP-TRS-III-002-2016

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Cover Illustration: No-impact thresholds have been identified for groundwater quality in potential carbon storage systems.

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No-Impact Threshold Values for Groundwater Reduced-Order Models

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Acronyms, Abbreviations, and Symbols

Term	Description
ANOVA	Analysis of variance
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
GWPS	Groundwater protection standard
KGS	Kansas Geological Survey
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
MCL	Maximum contaminant level
NAWQA	National Water Quality Assessment
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
NWIS	National Water Information System
PNNL	Pacific Northwest National Laboratory
RCRA	*Resource Conservation and Recovery Act of 1976*
ROM	Reduced-order model
ROS	Regression on order statistics
TDS	Total dissolved solids
USDW	Underground sources of drinking water
USGS	U.S. Geological Survey
WIMAS	Water Information Management System

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EXECUTIVE SUMMARY

The purpose of this study was to examine methodologies for establishing baseline data sets and statistical protocols for determining statistically significant changes between background concentrations and predicted concentrations that would be used to represent a contamination plume from geologic storage of carbon dioxide (CO_2) in the second-generation hydrologic models being developed by the National Risk Assessment Partnership's (NRAP) Groundwater Protection Working Group. This could then be used to help quantitatively evaluate the impact of leaking fluids on a groundwater system.

The initial effort examined selected portions of two aquifer systems: the urban shallow-unconfined aquifer system of the Edwards-Trinity Aquifer System (being used to develop the reduced-order model for carbonate-rock aquifers), and a portion of the High Plains Aquifer (an unconsolidated and semi-consolidated sand and gravel aquifer being used to develop the reduced-order model for sandstone aquifers). No-impact threshold values were determined for cadmium, lead, arsenic, pH, and total dissolved solids that could be used to identify potential areas of contamination in overlying aquifers predicted by numerical models of carbon dioxide storage reservoirs. No-impact threshold values were later determined for chromium specifically to support the reduced-order model being developed by Lawrence Livermore National Laboratory (LLNL) for the High Plains Aquifer. These threshold values are based on an interwell approach for determining background groundwater concentrations as recommended in the U.S. Environmental Protection Agency's *Unified Guidance for Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities* (EPA, 2009).

The resulting no-impact threshold values can be used to inform a "no change" scenario with respect to groundwater impacts, rather than use a maximum concentration limit or secondary drinking water standard that in some cases could be significantly higher than existing concentrations in the aquifer. These no-impact threshold values are intended for use in helping to predict areas of potential impact. They are not intended for use as alternate regulatory limits.

Development of "generic" no-impact threshold values that could be used for a number of locations appears unlikely. Instead the threshold values must be based on site-specific groundwater quality data. However, the scarcity of existing data, proximity of the data to the target model domain, potential spatial heterogeneity, and temporal trends make development of "clean" statistically robust data sets and use of valid statistical assumptions challenging. In some cases the calculated no-impact threshold values may exceed regulatory standards. Other approaches such as the hybrid intrawell-interwell approach also examined in this study may provide other mechanisms for calculating no-impact threshold limits.

1. INTRODUCTION AND BACKGROUND

The U.S. Department of Energy's (DOE) Office of Fossil Energy has established the National Risk Assessment Partnership (NRAP) project, a multi-year project that harnesses the breadth of capabilities across the DOE national laboratory system to develop a defensible, science-based quantitative methodology for determining risk profiles at carbon dioxide (CO_2) geologic storage sites. As part of this effort, scientists from Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), and the National Energy Technology Laboratory (NETL) are developing models to evaluate the potential for aquifer impacts should CO_2 or brine leak from deep subsurface storage reservoirs.

Modeling activities have been split across three successive years, with each year culminating with the generation of a more comprehensive model. Year 1, or first-generation, models focused on changes in pH and total dissolved solids (TDS) as a result of CO_2 and brine intrusion into the aquifers via a single leakage point (leaking wellbore or fault leakage) (Dai et al., 2011; Bacon et al., 2012; Mansoor et al., 2012). Plume maps were drawn for each aquifer simulated based on the U.S. Environmental Protection Agency (EPA) National Secondary Drinking Water Regulation Limits for pH and TDS (EPA, 2012). The modeling teams identified aquifer impacts based on a pH decrease below 6.5 or an increase in TDS above 500 ppm. Feedback received from the NRAP Stakeholder Group indicated that an alternative approach to using either maximum contaminant level (MCL) or secondary drinking water standards as the threshold values to define impact was needed—one that reflects a change from current background levels (e.g., low levels) of key constituents in the aquifers.

The purpose of this study was to examine methodologies for establishing baseline data sets and statistical protocols for determining statistically significant changes between background concentrations and predicted concentrations that would be used to quantify a contamination plume in the second-generation models being developed by NRAP's Groundwater Protection Working Group. The primary objective was to evaluate the statistical variability of background groundwater concentrations of cadmium, lead, arsenic, pH, and TDS in two selected underground sources of drinking water (USDW), and to determine "no-impact threshold values" that could be used to represent contamination due to predicted impacts from CO_2 storage reservoirs. Chromium was later added for determination of no-impact threshold values for the High Plains Aquifer, specifically to support the reduced-order model (ROM) being developed by LLNL. Results from this effort will be used to inform a "no change" or "no impact" scenario with respect to groundwater impacts in those aquifers.

2. TECHNICAL SCOPE AND APPROACH

The scope of the initial effort was to examine selected principal aquifers, as defined in the *Ground-Water Atlas of the United States* (USGS, 2012), applicable to the sandstone and carbonate-rock ROMs currently under development. Portions of two aquifer systems were selected for the initial investigation: the urban shallow-unconfined aquifer system of the Edwards-Trinity Aquifer System being used to develop the ROMs for carbonate-rock aquifers; and the central portion of the High Plains Aquifer (an unconsolidated and semi-consolidated sand and gravel aquifer) being used to develop the ROMs for sandstone aquifers.

Other principal sandstone or carbonate-rock aquifers identified for future investigation include the following:

- Colorado Plateau aquifers (sandstone aquifers)
- Pennsylvanian aquifers (sandstone aquifers in the central and eastern United States)
- Lower Tertiary aquifers (sandstone aquifers in the northern Great Plains)
- Ozark Plateau aquifer system (carbonate-rock aquifers in Missouri)
- Silurian-Devonian aquifers (carbonate-rock aquifers in the northern Midwest)
- Central Valley aquifer system (unconsolidated and semi-consolidated sand and gravel aquifers in California)

To expedite the development of no-impact threshold values needed to support completion of the second-generation ROMs, the team decided to start with the groundwater quality data sets used by Bacon (2012). Bacon (2012) used data for the San Antonio Segment of the Edwards Aquifer, taken from appendices developed by Musgrove et al. (2010), using U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) data collected in 1996–2006. The appendices of Musgrove et al. (2010) are available online at http://pubs.usgs.gov/sir/2010/5129/.

The NAWQA data warehouse web interface provides access to chemical concentration data for water, bed sediment, and aquatic organism tissues for about 2,600 chemical constituents from 4,700 surface water sites and 9,500 wells. Most of these data came from the National Water Information System (NWIS) Water-Quality Data. The primary shortcoming from the data warehouse web interface is that the data are primarily limited to the NAWQA study areas and the data are not queriable online relative to their respective principal/national aquifer designation. Direct query of the underlying NAWQA database by USGS staff was necessary to bin and screen the data by Principal (National) Aquifer designation and National Aquifer Code (from GW Atlas), Aquifer Class (from the GW Atlas), Primary Aquifer (i.e., formation), and Aquifer type (i.e., shallow-unconfined, confined).

3. NO-IMPACT THRESHOLD VALUES

The objective of this study was to develop protocols for defining statistically valid no-impact threshold values indicative of a significant change in groundwater chemistry due to CO_2 or brine leakage. The intent is to use these threshold values as an alternative to MCLs or secondary drinking water standards to quantify impacts predicted from the ROMs. Summaries of the data sets and statistical protocols used to calculate no-impact threshold values for the Edwards-Trinity and High Plains Aquifers are presented below.

3.1 NO-IMPACT THRESHOLD VALUES FOR THE EDWARDS-TRINITY AQUIFER

The existing data set used by Bacon (2012) for the shallow/urban unconfined Edwards Aquifer, was used for no-impact threshold analysis. This data set was extracted from NAWQA data available as appendices to the Musgrove et al. (2010) report. Figure 1 illustrates the distribution of wells for the shallow, urban unconfined aquifer and approximates the domain used in the ROMs. Note that all data used in the analyses are within about 28 km (17 mi) of each other.

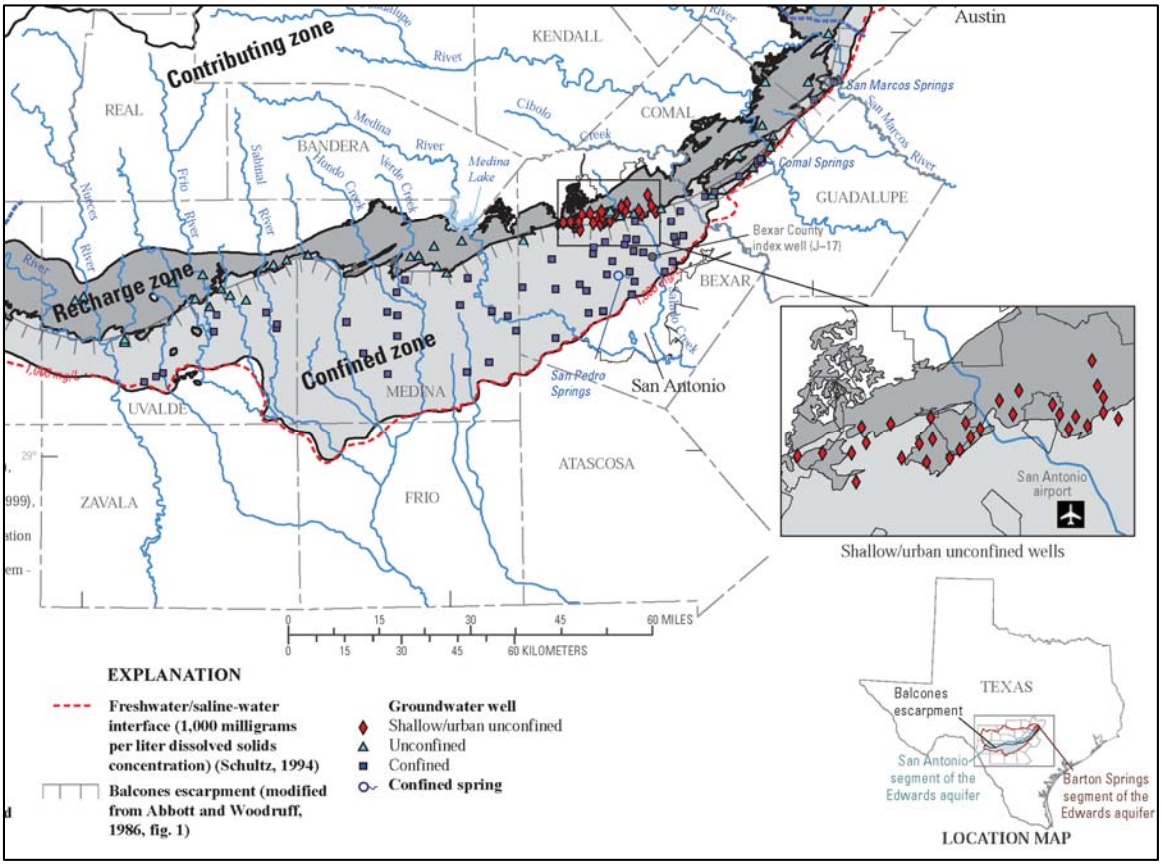

Figure 1: Location of shallow/urban unconfined wells for the Edwards Aquifer (taken from Musgrove et al. 2010).

This data set was screened and filtered to produce a data set for arsenic, cadmium, lead, pH, and TDS. A brief analysis of the proportion of nondetects revealed that arsenic, cadmium, and lead were all below detection for almost all samples collected prior to 2001 (due in part to higher detection limits). Therefore, only the 49 data that were collected after the year 2000 were used for analysis of metals concentrations (Appendix A). Arsenic data for the post-2000 period were all above detection, about half were above detection for lead, and all data were below detection for cadmium. Statistics for pH and TDS were calculated on the full 90-sample data set for the shallow urban-unconfined aquifer (Appendix B), as all samples contained detectable values; there was no statistically significant difference between data found before and after the year 2000.

The initial goal of the no-impact threshold analysis was the identification of concentration limits that can be used to identify model grid cells that exhibit contamination during reactive transport groundwater modeling runs. Based on guidance from NRAP's Stakeholder Group, it was determined that an alternative to using the MCLs for this comparison was needed, one based on a statistically significant increase or decrease (for pH) relative to background. Recommendations found in the EPA's *Unified Guidance for Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities* (EPA, 2009) were used to identify useful statistics for that purpose. Section 7.5 of that document suggests that a reasonable statistic for single-sample testing against a fixed groundwater protection standard (GWPS) based on background would be a background upper tolerance limit with 95% confidence and 95% coverage. The GWPS determined using this approach can be interpreted as an approximation to the upper 95th percentile of the background distribution. It is designed to be a reasonable maximum on the likely range of background concentrations. If the data have a normal or lognormal distribution and have a small proportion of nondetects, then a parametric tolerance limit is suggested (EPA, 2009). For larger fractions of nondetects, a nonparametric tolerance limit is recommended in the EPA Guidance (EPA, 2009). For pH, it was assumed that a background lower tolerance limit with 95% confidence and 95% coverage would be the proper statistic because the concern is with decreases in pH that would denote a change in aquifer chemistry by infiltrating CO_2.

The open-source statistical software system "R," version 2.14.1 (R Development Core Team, 2012), was used for statistical analysis. In addition to the base R installation, the R package, "tolerance" (Young, 2010), was used to calculate the parametric and nonparametric tolerance intervals. The R package "NADA" (Lee, 2012) was used to calculate statistics that account for the presence of nondetects in the data, following the methodology published by Helsel (2012).

The resulting tolerance limits (i.e., no-impact threshold values) for the relevant variables are contained in Table 1, along with assumptions that were made in developing those tolerance limits. The arsenic data exhibited a slight positive skewness (Figure 2), so a lognormal distribution was assumed and a parametric upper tolerance limit was calculated. The assumption of a lognormal distribution for contaminant concentration data is very common (Davis, 2002). Given the high proportion of nondetects for the lead data (~50%), a nonparametric upper tolerance limit was calculated. Because no data above the detection limit were available for cadmium, the upper tolerance limit was set equal to the detection limit reported for the data. Thus, a cadmium concentration value above the detection limit would indicate the presence of contamination during a groundwater-modeling run. The pH and TDS data were relatively symmetrical (Figure 3 and 4), so a normal distribution was assumed for each variable (Table 1).

Table 1: Tolerance limits for concentrations in the urban portion of the unconfined Edwards Aquifer

Analyte	Percent Nondetects	Interval Type	Assumed Distribution	Upper/Lower	Value[(a)]	Units
Arsenic	0	Parametric	Lognormal	Upper	0.55	µg/L
Cadmium	100	NA	NA	Upper	0.04	µg/L
Lead	51	Nonparametric	NA	Upper	0.15	µg/L
pH	0	Parametric	Normal	Lower	6.6	-log{H^+}
TDS	0	Parametric	Normal	Upper	420	mg/L

(a) Rounded to two significant digits.

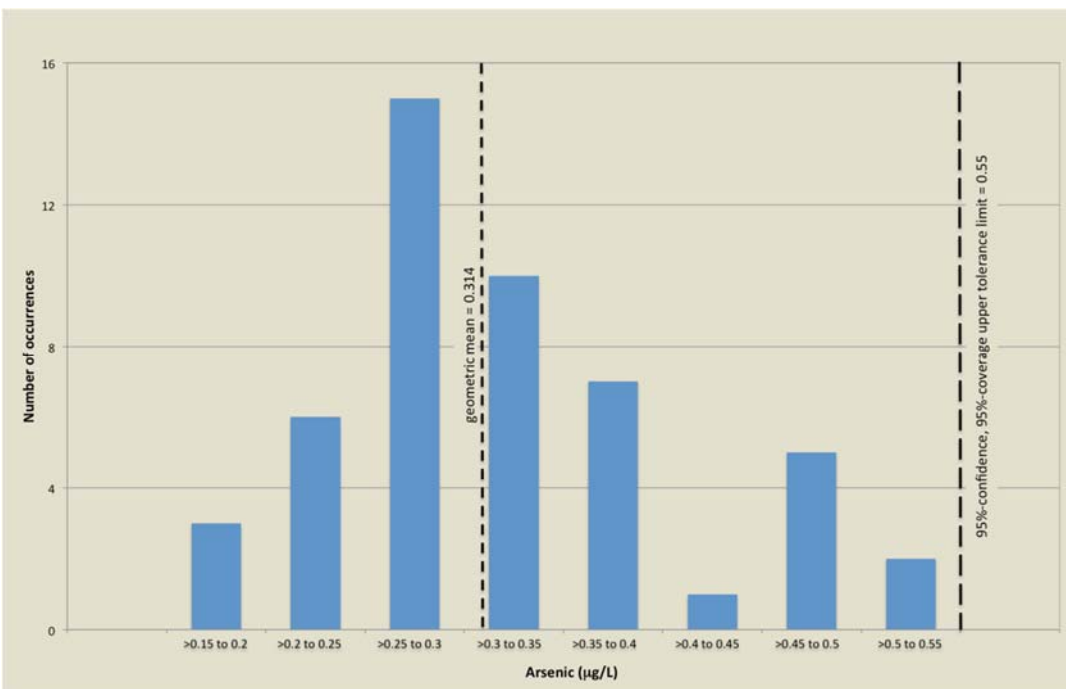

Figure 2: Histogram of arsenic concentrations for post-2000 samples from shallow/urban unconfined Edwards Aquifer.

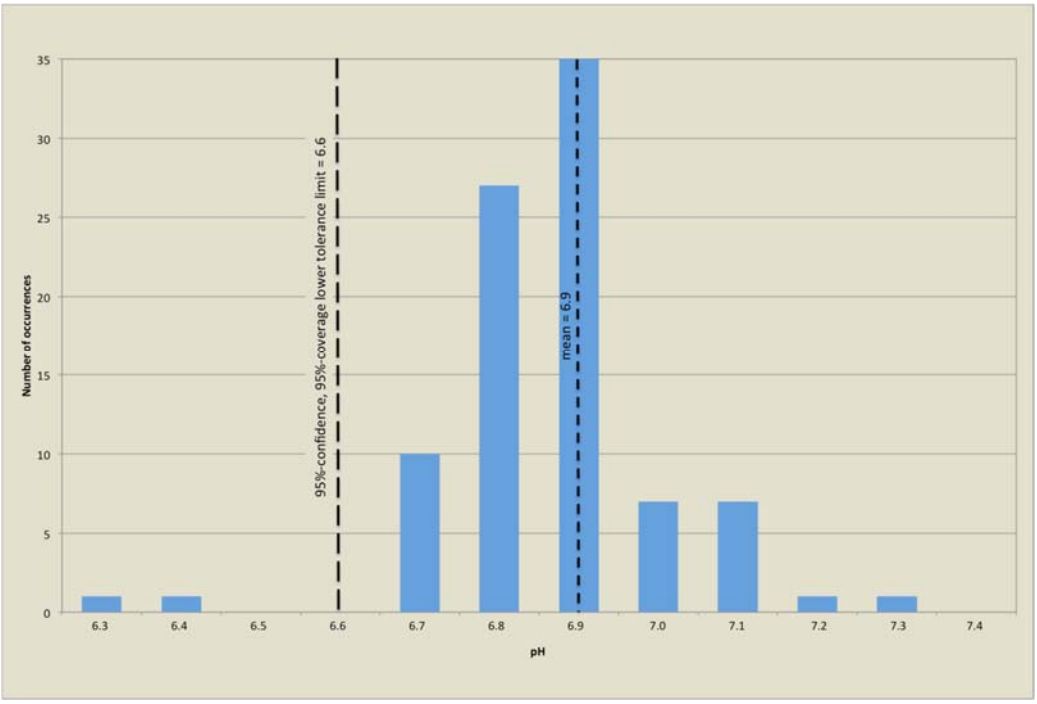

Figure 3: Histogram of pH values for all samples from shallow/urban unconfined Edwards Aquifer.

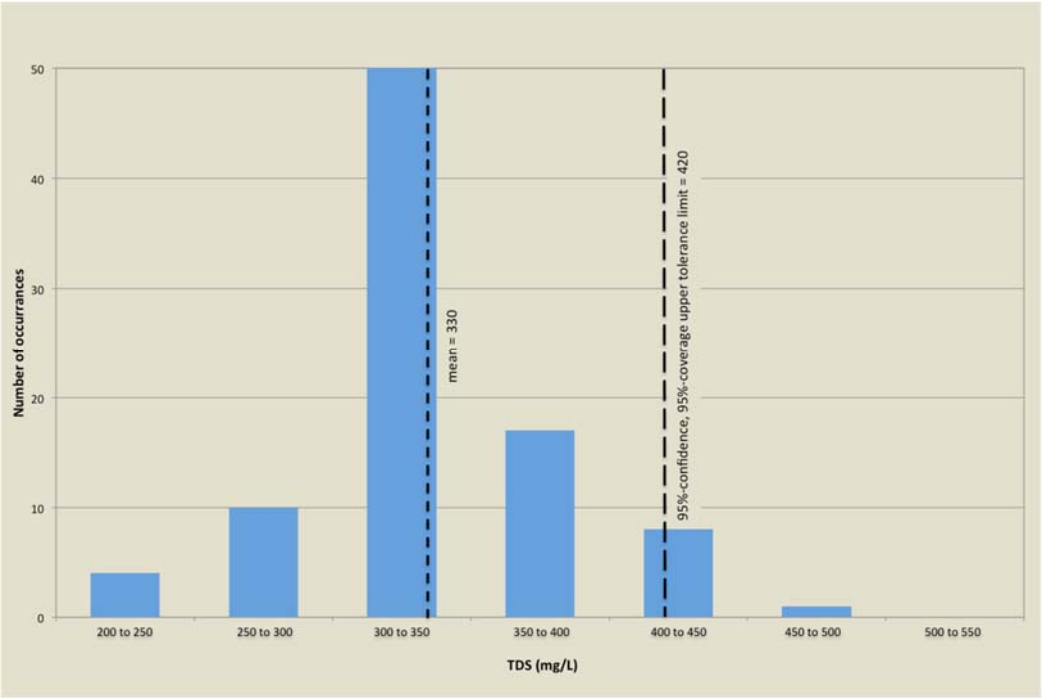

Figure 4: Histogram of TDS concentrations for all samples from shallow/urban unconfined Edwards Aquifer.

Initial concentration values for each variable were also needed for initialization of the second-generation modeling runs. These initial values were calculated using the same data sets that form the basis for Table 1, and were assumed to be uniform over the entire modeling domain. Given the assumption of a lognormal distribution for arsenic, the geometric mean of the data of 0.314 µg/L was recommended as an initial value (Table 2). No data above the detection limit were available for cadmium, so a value of zero was assumed as a reasonable initial condition. The lead data were highly skewed and had a large percentage of nondetects, so the "NADA" package was used to estimate a median value for the lead data using the regression on order statistics (ROS) method (Table 2). Given the symmetric distributions for pH and TDS, the mean values were used as initial values for the modeling runs. The tolerance limits and regulatory standards are provided for comparison to the initial values in Table 2. The regulatory standards for the metals are the EPA's MCLs; the standards for pH and TDS are from the list of National Secondary Drinking Water Regulations. The MCLs and secondary standards were taken from the EPA's Drinking Water Contaminants website (http://water.epa.gov/drink/contaminants/index.cfm). The tolerance limits for identification of contaminated drinking water in the urban unconfined Edwards Aquifer are all significantly less than the MCLs or secondary standards (Table 2). The tolerance limits for the metals based on background data are all at least an order of magnitude less than the corresponding MCLs. Thus, they should address the concerns of stakeholders by generating target levels that provide a level of protection based on existing background data, and thus are more in line with a fluctuation from initial conditions, rather than a formal standard, such as those set in regulatory limits.

Table 2: Initial values, tolerance limits, and regulatory standards for each variable

Analyte	Initial Value[(a)]	Tolerance Limits[(a)]	Regulatory Standard	Units
Arsenic	0.31	0.55	10	µg/L
Cadmium	0	0.04	5	µg/L
Lead	0.064	0.15	15	µg/L
pH	6.9	6.6	6.5	$-\log\{H^+\}$
TDS	330	420	500	mg/L

(a) Rounded to two significant digits.

An issue that was not addressed in the determination of the initial values and tolerance limits is that of spatial stationarity of the data. The EPA Unified Guidance suggests that analysis of variance (ANOVA) be used to examine data from proposed background wells to determine if the data exhibit spatial variability, such that the mean and variance of the concentrations varies between background wells (EPA, 2009). If the data exhibit spatial variability of the mean or variance, then the use of intrawell comparisons would be recommended for identification of significant increases in concentrations due to the monitored facility (EPA, 2009) in a standard *Resource Conservation and Recovery Act of 1976* (RCRA) analysis. However, the use of background data in the NRAP groundwater modeling study is very different from the use in RCRA in that the goal was to use existing well data in the model area to initialize the groundwater models, and then quantify the number of model cells (if any) that exceed a no-

impact threshold or tolerance limit to identify the size of the "plumes" caused by CO_2 or brine migration into the aquifer. The initial values for the groundwater model runs are assumed to be homogeneous over the model area. The comparison of modeled concentrations with the tolerance limits are made at all cells in the modeling grid, so the tolerance limits should reflect the variability in background concentration data found over the entire study area. Thus, the comparison approach to identification of contamination is different from the upgradient/downgradient comparisons that are typically made for a RCRA facility, and the assumption of a uniform threshold based on background data to identify significant changes to aquifer chemistry appears to be reasonable.

The approach taken for this study was to identify an upper (or lower) tolerance limit for each variable that reflects the variability in the existing data set and can be interpreted as an approximation to the upper (or lower) 95th percentile of the existing distribution. It is designed to be a reasonable maximum on the likely range of background concentrations, as an alternative to the use of an MCL as an upper limit. Thus, the spatial stationarity of the background data does not appear to be relevant to the current use of the background data. This is especially true given the limited spatial extent of the Edwards Aquifer data (Figure 1), which is much less than the spatial extent of the sample set used to derive threshold values for the High Plains Aquifer, as discussed in the following section.

3.2 NO-IMPACT THRESHOLD VALUES FOR THE HIGH PLAINS AQUIFER SYSTEM

The High Plains Aquifer extends from South Dakota to Texas, as shown in Figure 5. The hydrology and groundwater quality of the aquifer was studied during the NAWQA program. Studies were based on statistical segmentation of the aquifer. The first segmentation was into northern, central, and southern major subregions based on climatological data. The second segmentation was based on hydrogeologic units (McMahon et al., 2007).

NRAP is numerically simulating CO_2 and brine leakage into the High Plains Aquifer at the location shown on Figure 5 (Carroll et al., 2014). The groundwater models for this area simulate the resulting change in groundwater chemistry. The models are for the Ogallala Formation in the central High Plains Aquifer.

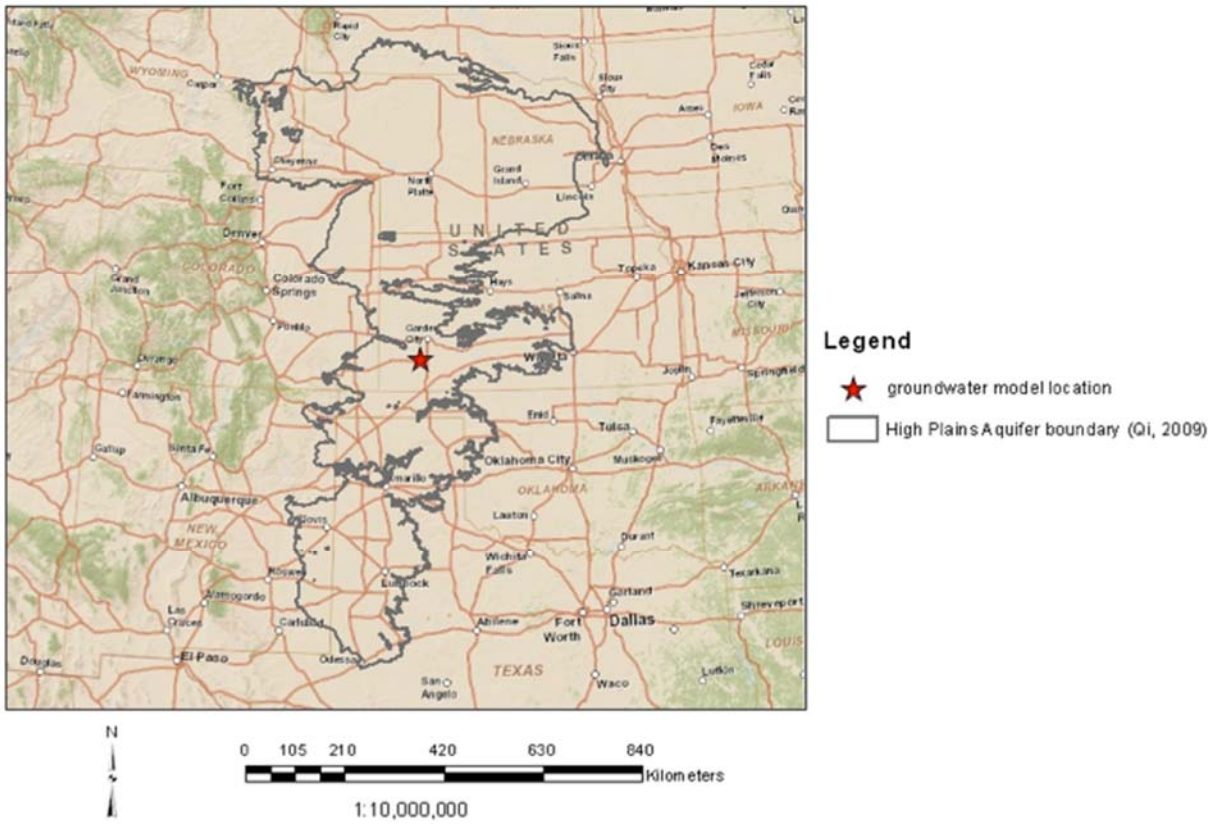

Figure 5: High Plains Aquifer and groundwater model location.

3.2.1 Data Sources

Numerous potential sources of groundwater data were investigated. The EPA operates a water quality database called STORET (http://www.epa.gov/storet/). It contained no groundwater quality data in the vicinity of the model location as of December 7, 2012.

The Kansas Geological Survey (KGS) maintains several databases that contain various information on groundwater characteristics and usage in the area. The Water Information Management and Analysis System (WIMAS; http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm) contains water rights data, including the location of water wells. Figure 6 shows the water well locations contained in WIMAS as of December 7, 2012 within the model area and vicinity.

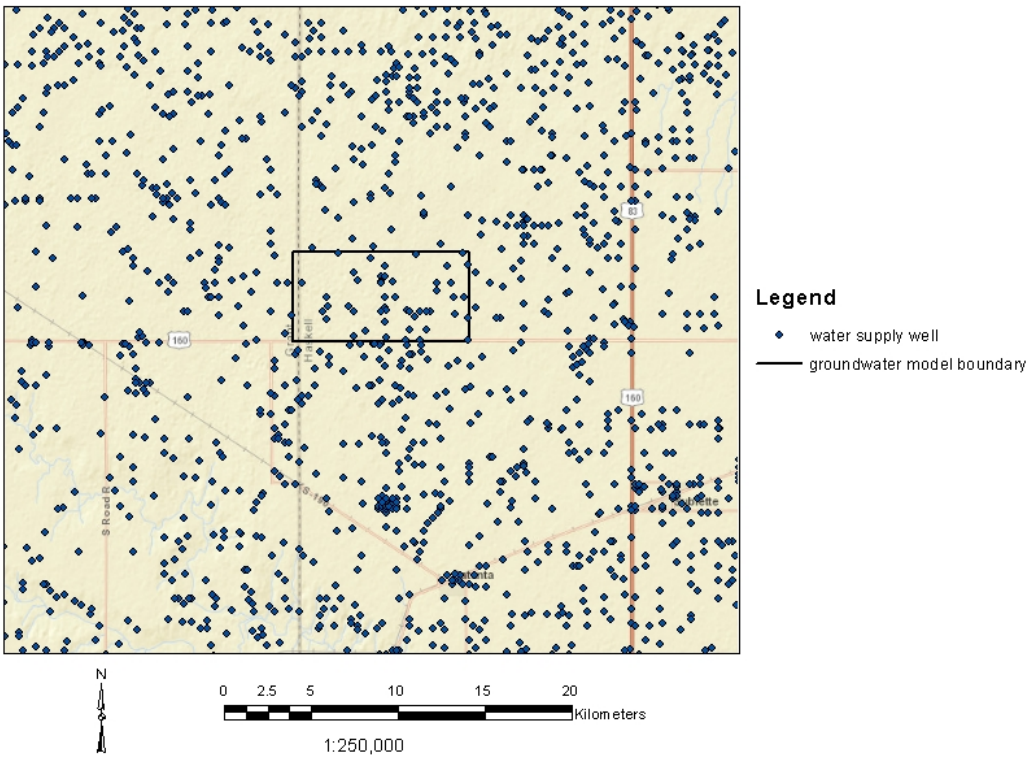

Figure 6: Groundwater model location and water supply wells.

However, none of the KGS databases or reports appears to have data on the parameters of interest at the model site or across the aquifer around the model site. One report does include TDS data, but only for counties south of those containing the model site (Whittemore et al., 2005). These data were from samples collected during a 60-year period, and compiled from a variety of sources. These factors suggest these data should not be applied to the model site if there are alternatives.

The entire High Plains Aquifer was studied as part of the NAWQA conducted by the USGS. The study actually consisted of several "nested" studies. The goal of this nesting was to efficiently characterize groundwater conditions and processes affecting those conditions. The nesting consisted of four study types, each using different types of wells. Unsaturated zone studies collected data relevant to the fate and transport of constituents in waters recharging from the land surface from sampling points screened above the water table. Land use studies collected data relevant to understanding the impact of water recharging from the land surface on groundwater quality from wells screened at the water table. Transect studies collected data relevant to understanding vertical groundwater flow and characterizing groundwater quality with depth in the aquifer from groups of wells screened at different levels in the aquifer located on a transect parallel to gradient. Major aquifer studies collected data relevant to characterizing groundwater conditions across the aquifer from randomly selected private supply wells, which are generally screened below the water table (McMahon et al., 2007).

These studies found groundwater quality was more variable at the water table than deeper in the High Plains Aquifer, presumably due to recharge of anthropogenically-altered water from the land surface (Gurdak et al., 2009). The four types of nested studies were conducted specifically for the Ogallala unit of the Central High Plains Aquifer. As with the High Plains Aquifer as a

whole, the transect study of the Ogallala in the Central High Plains Aquifer, which was located along the border between Kansas and Oklahoma, generally found greater variation in groundwater quality at the water table than deeper in the aquifer (McMahon, 2001).

The High Plains regional groundwater study website indicates the 74 wells used in the major aquifer study were sampled in 1999 and a subset of 30 wells were resampled in 2010 (http://co.water.usgs.gov/nawqa/hpgw/datarep/cos/COS.html, accessed December 7, 2012). Richard Bell at the USGS queried the NAQWA database for inorganic constituent, pH, and TDS data for High Plains Aquifer groundwater. These data were loaded into a relational database, along with tables of the well identification numbers for each of the studies in the Ogallala unit of the Central High Plains Aquifer. This allowed querying the data provided for the list of wells used in each study, as well as facilitating construction of tables for each constituent for spatial and statistical analysis. These queries resulted in identification of a third sampling event for the major aquifer study wells that took place in 2012. However, only five major aquifer study wells were resampled in this event, so these data were not considered further.

Further querying concluded the only data for the Central High Plains Ogallala unit outside of the well groups used in the four types of studies was from a group of public supply wells. These were the subject of another study comparing water quality from these wells with that from paired, nearby private supply wells. Given the typically different construction (longer screens) and pump rate (higher) for the public supply wells compared to the major aquifer study wells, data from the public supply wells was not utilized in this study.

The generally greater variation in water quality at the water table rather than deeper in the aquifer is illustrated by comparing the pH results from the major aquifer and irrigated agricultural land use study wells shown on Figure 7 and Figure 8. The 2010 results from the subset of major aquifer study wells that were resampled are shown in Figure 7. They are generally spatially correlated and indicate a trend in pH across the site from higher values in the west to lower in the east. Figure 8 shows the 2000 results from irrigated agriculture land use, which cover a smaller area, and are not as spatially correlated. This is particularly so where the sampling density is highest northeast of the model area, further suggesting a lack of spatial correlation.

To the extent monitoring for groundwater quality changes due to leakage might occur, monitoring points would likely be located deeper in the aquifer to provide for earlier detection. Such monitoring might use newly installed wells, appropriately located existing private supply wells, or a mixture of the two. Given the existence of numerous private supply wells in the area, it is also likely groundwater quality changes might be detected first at such a well that may not be part of a regular leakage detection monitoring program.

For reasons of aquifer position, well type, greater uniformity of spatial data density and data values, and geographic coverage around the study site, 1999 and 2010 data from the major aquifer study wells were selected as the basis for groundwater impact threshold development. These data are included in Appendix C. The 2010 data from the major aquifer study wells were selected to be representative of recent conditions should there have been a temporal trend in any of the parameter values. The 1999 and 2010 results from the 30 major aquifer wells sampled at both times are compared in a discussion section below. All future references to these data will not include the phrase “major aquifer study.”

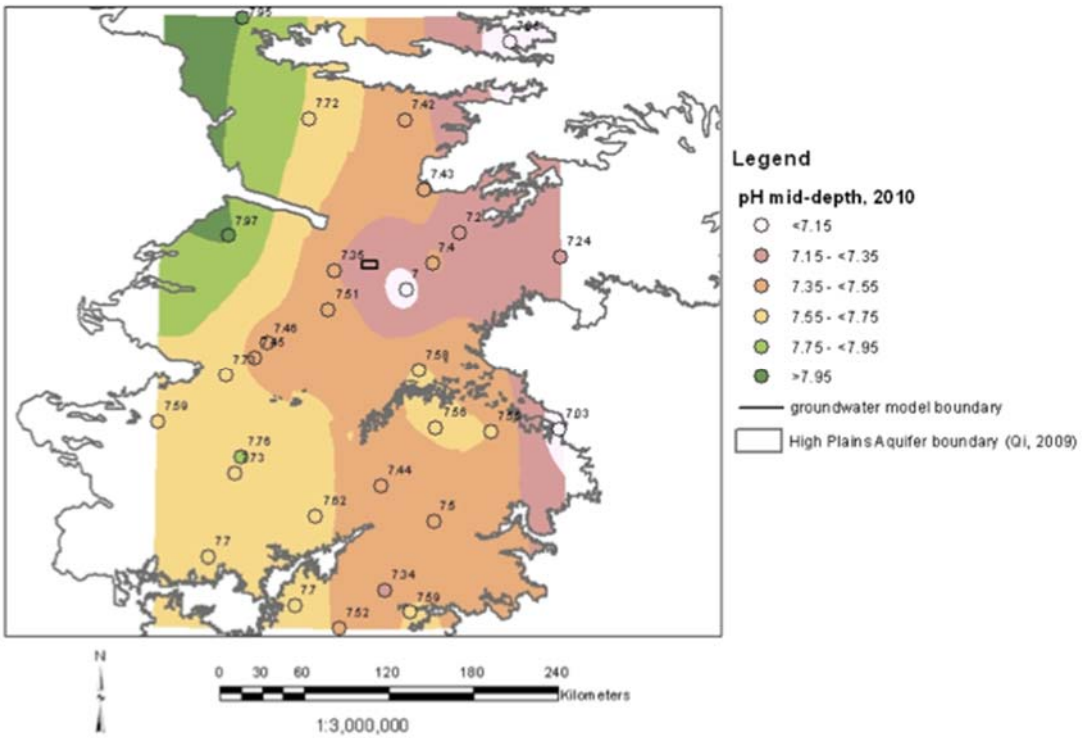

Figure 7: Resampled major aquifer study well pH in 2010 superimposed on contours resulting from kriging with a spherical variogram.

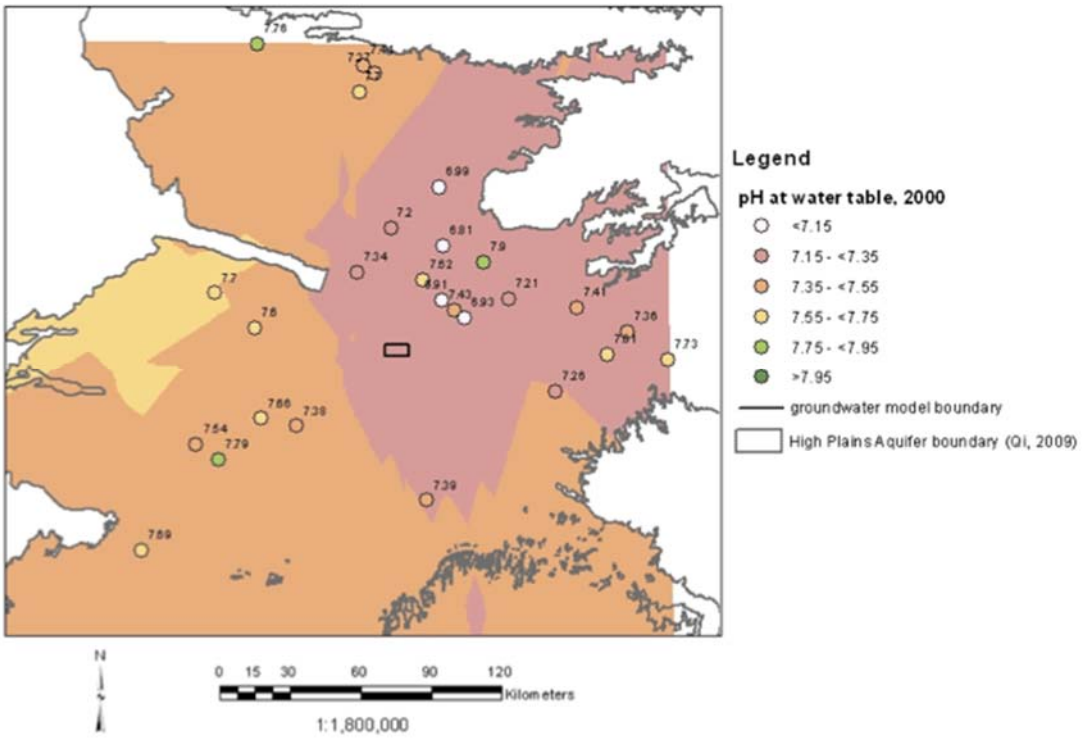

Figure 8: Irrigated agriculture study well pH in 2000 superimposed on contours resulting from kriging with a spherical variogram.

3.2.2 No-Impact Threshold Summary

The no-impact threshold values for the central portion of the High Plains Aquifer to be used for mapping significant changes in the groundwater quality parameters considered by NRAP in the second-generation integrated risk assessment are given in Table 3. These are the 95%-confidence, 95%-coverage tolerance limits similar to those developed for the Edwards Aquifer (Section 3.1). The threshold values were based on the data sets selected, as described below, excluding outliers. Note that all the selected data are located some distance (tens of kilometers) from the model domain.

Table 3: No-impact thresholds for the High Plains Aquifer models based on sample data

Analyte	Initial Value Used in Second-Generation ROMs[a]	Mean of Selected and Adjusted 2010 Data[b]	Threshold Concentration[c]	Regulatory Standard
pH	7.4	7.5[d]	7.0[d]	6.5
Total Dissolved Solids	430 mg/l[d]	440 mg/l[d]	1300 mg/l[d,e]	500 mg/l[e]
Arsenic	2.9 µg/l[d]	1.5 µg/l[d]	9.3 µg/l[d]	10 µg/l
Cadmium	0.078 µg/l[d]	0.059 µg/l	0.25 µg/l	5 µg/l
Chromium (total)	0.0[f] and 1.0[a] µg/l	1.0 µg/l	3.9 µg/l	100 µg/l
Lead	0.32 µg/l[d]	0.086 µg/l	0.63 µg/l	15 µg/l

(a) Liange Zheng, personal communication via email dated December 13, 2012 and January 28, 2013.

(b) Geometric mean except for pH, which is already a log value.

(c) 95%-confidence, 95%-coverage tolerance limit based on log values except for pH, which is already a log value. See text for explanation of whether threshold value is based on upper or lower limit.

(d) Rounded to two significant digits.

(e) Threshold value exceeds regulatory standard, however using the regulatory standard may result in widespread false positives under field conditions (see Section 3.2.4).

(f) Susan Carroll, personal communication via email dated January 28, 2012.

A concern during subsurface sequestration is that brine and CO_2 leakage from the target reservoir into shallower USDWs will cause an increase in all parameters of interest except pH, for which the concern is a decrease. Consequently, the no-impact threshold is the upper tolerance limit for all parameters except pH. For pH, the threshold is the lower limit. All the data sets were log normal (noting pH is a log concentration), so parametric tolerance limits provided the thresholds. The tolerance limits for the High Plains data were computed using a spreadsheet (http://statpages.org/tolintvl.xls) that implemented the National Institute of Standards/SEMATECH (2012) description of tolerance limits for a normal distribution. The software implementations of tolerance limits used for the Edwards and High Plains data are equivalent, and comparison of upper tolerance limits computed using tolintvl.xls and R's normtol.int function showed very close agreement.

The mean values from each selected data set are also included for use in initialization of future second-generation modeling runs. Outliers were excluded from both calculations. Outliers were

defined as values greater than the 75th percentile plus 1.5 times the interquartile range or less than the 25th percentile minus 1.5 times the interquartile range. Given the parameters in the groundwater in some locations are likely due to anthropogenic perturbations superimposed on natural processes discussed above, outliers are expected.

3.2.3 pH

Figure 9 shows the 2010 pH data selected for calculating the threshold. The selected data are within 95 km of the model site. This set was selected because the spatial correlation and trend were weaker in this area than in the data set overall. Figure 10 shows the distribution of the selected data. Given the small sample size, this distribution is consistent with a normal distribution. The mean and lower tolerance were calculated for the selected set.

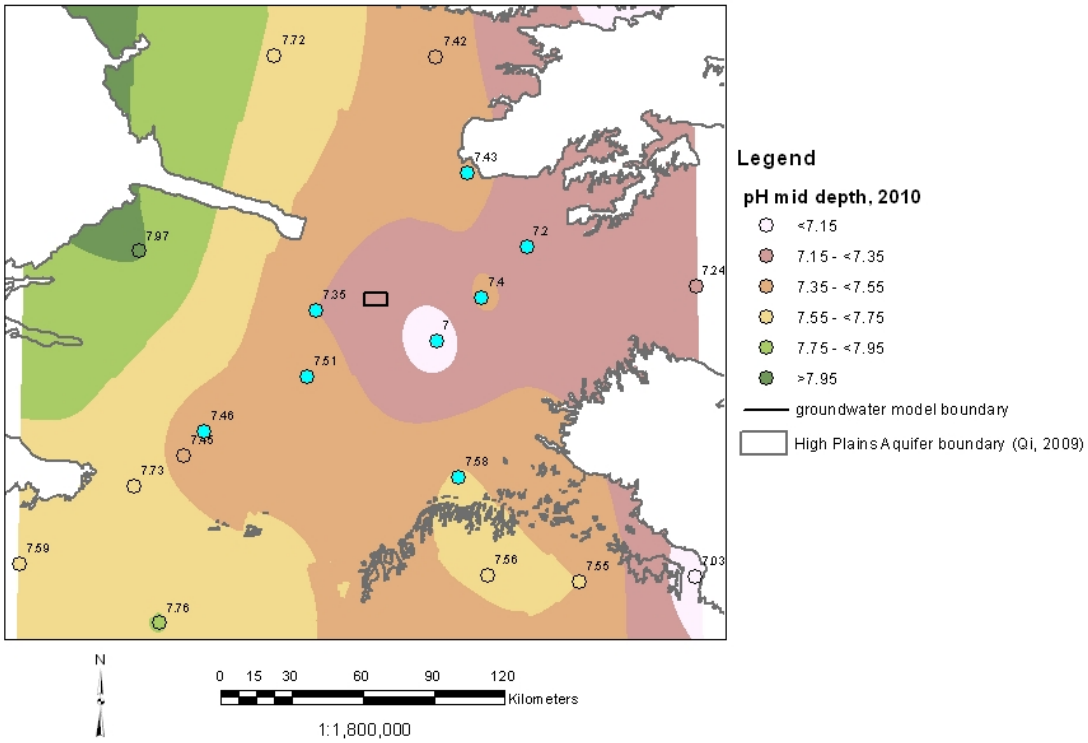

Figure 9: Results for pH in 2010 from resampled major aquifer study wells with data selected for threshold calculation indicated in blue.

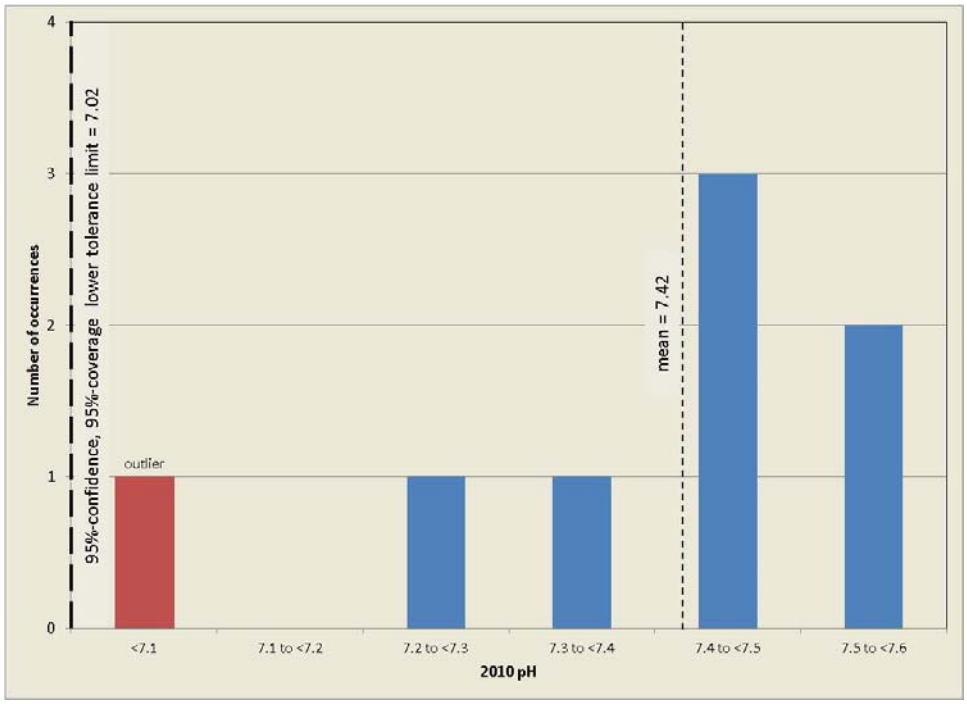

Figure 10: Histogram of selected pH in 2010 from major aquifer study wells.

3.2.4 Total Dissolved Solids

The 2010 TDS data are mapped on Figure 11. There is a general trend from higher TDS in the north to lower in the south. Values to the south of the model area are more spatially correlated and more correlated to this trend than are values around the model and to the north. The values in the northern area indicated in Figure 11 were used in threshold development. Note that 7 of the 15 samples selected for calculating the threshold exceeded the 500 mg/l secondary drinking water standard for TDS, with the maximum concentration estimated at 955 mg/l.

Figure 12 shows the distribution of the log of the selected data. Given the small sample size, this distribution is consistent with normal distribution. Consequently, the geometric mean and upper tolerance limit were calculated from the log of the data.

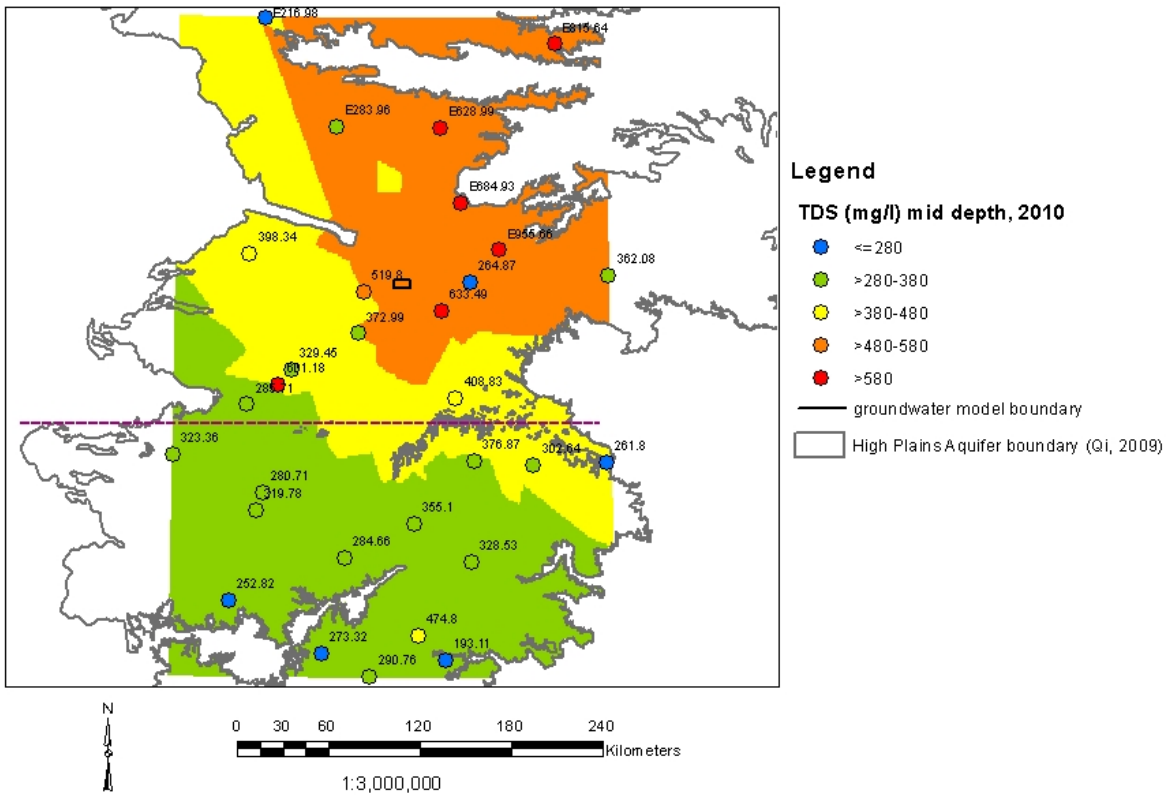

Figure 11: Results for TDS in 2010 from resampled major aquifer study wells superimposed on contours resulting from kriging with a spherical variogram. Values north of the purple dashed line were used for calculating the threshold.

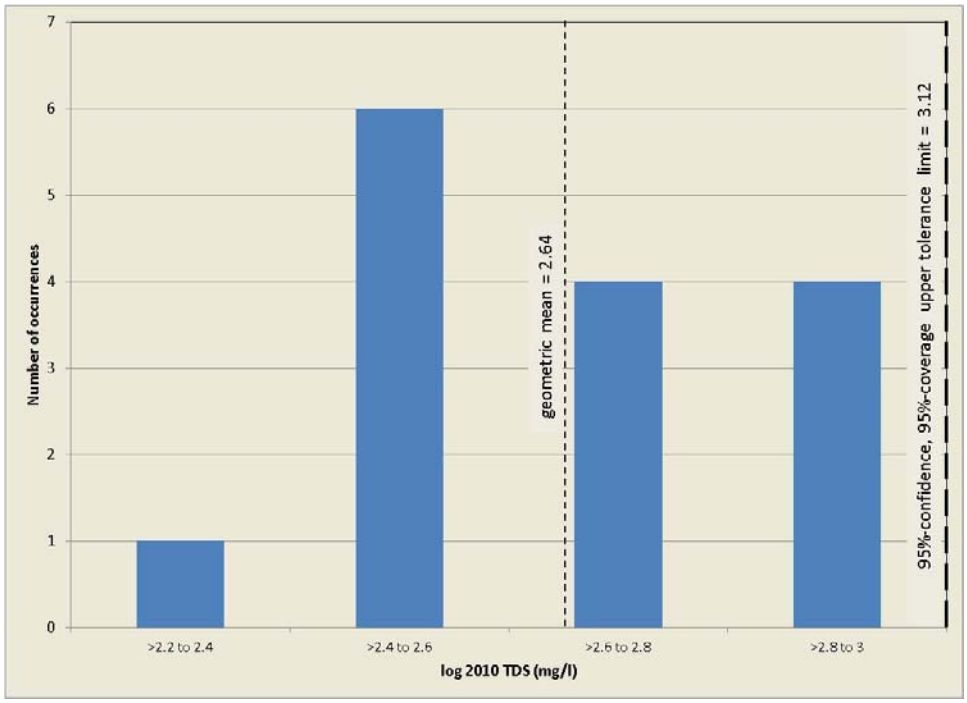

Figure 12: Histogram of select 2010 log TDS from major aquifer study wells.

3.2.5 Arsenic

The 1999 arsenic concentrations are mapped on Figure 13. The values are generally spatially correlated, predominantly in an east-west direction. The 2010 concentrations are plotted on the 1999 contours in Figure 14. While there have been changes in the concentration, most of the values still match the contours or are within one interval. Most of the 1999 values in the vicinity of the model area were nondetect, which was not the case in 2010 due to a lower detection limit. Consequently, a subset of the 2010 data that are not spatially correlated among themselves, as shown in Figure 14, were selected for threshold analysis.

Figure 15 shows the distribution of the log of the selected data. This distribution is consistent with a normal distribution. Consequently, the geometric mean and upper tolerance limit were calculated from the log of the data.

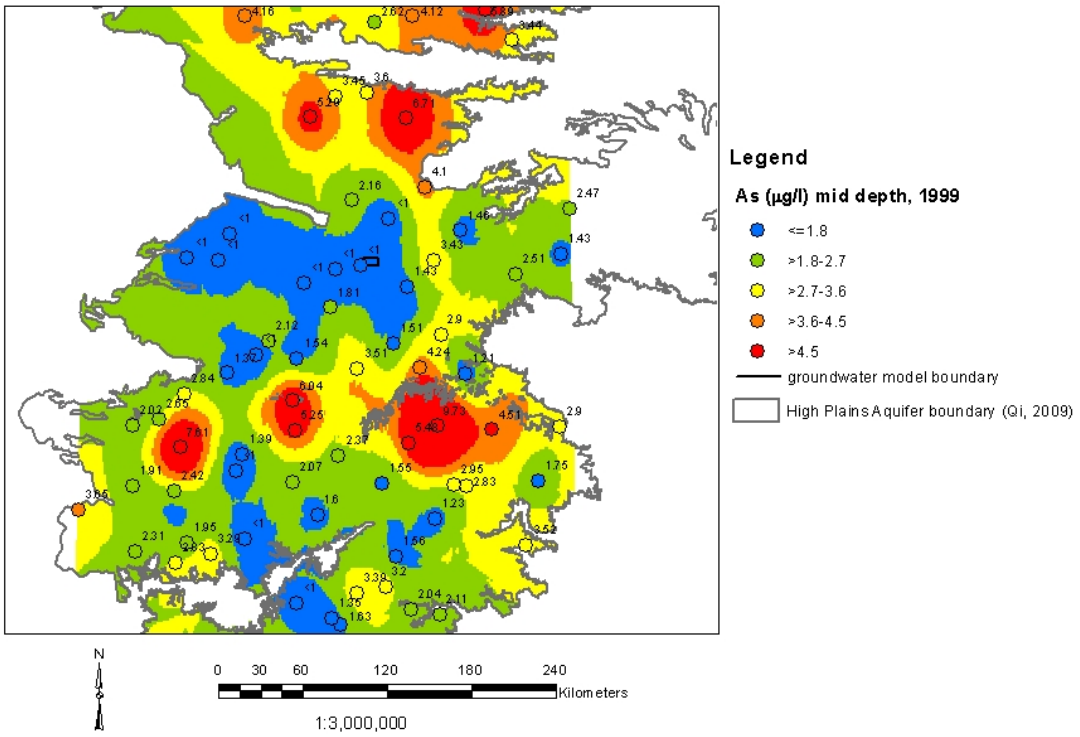

Figure 13: Results for arsenic in 1999 from major aquifer study wells superimposed on contours resulting from kriging with a spherical variogram.

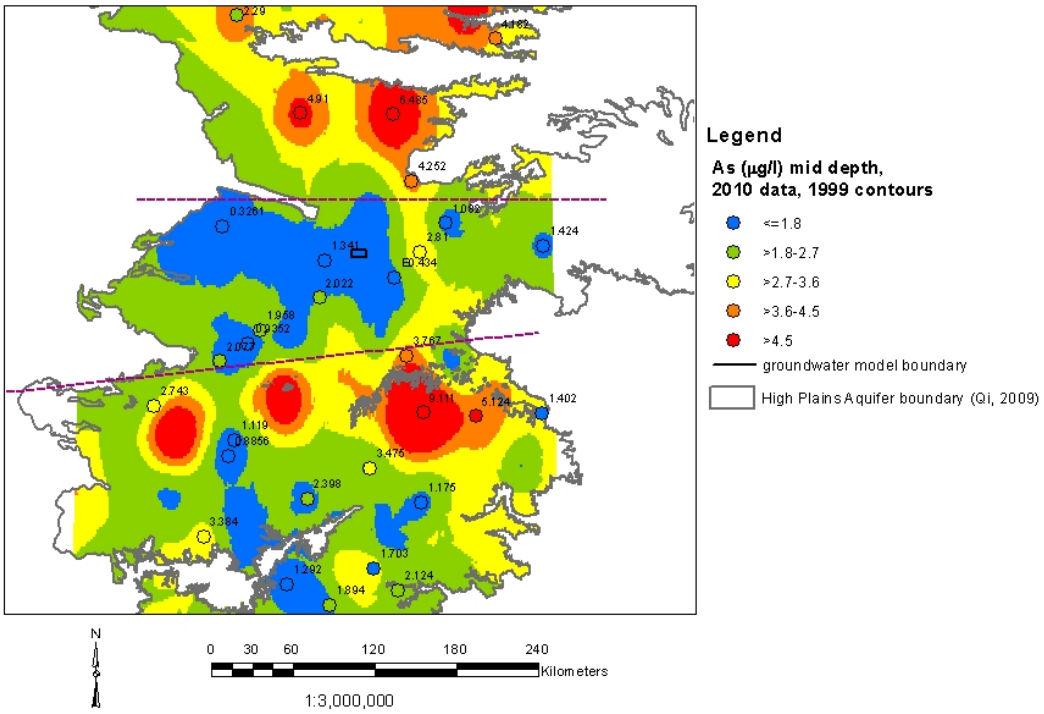

Figure 14: Results for arsenic in 2010 from resampled major aquifer study wells superimposed on contours resulting from kriging 1999 concentrations with a spherical variogram. Values between the purple dashed lines were selected for calculating the threshold.

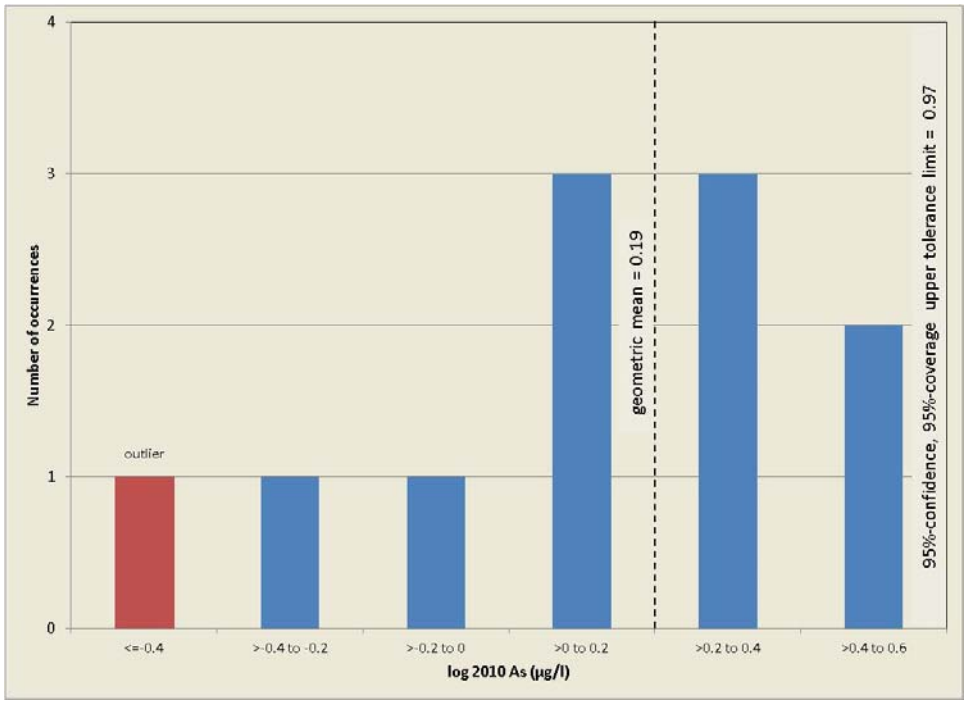

Figure 15: Histogram of select 2010 log arsenic concentrations from major aquifer study wells.

3.2.6 Cadmium

The 2010 cadmium concentrations are mapped on Figure 16. Like TDS, there is a general trend from higher concentrations in the north to lower in the south. Also like TDS, concentrations to the south of the model area are more spatially correlated and more correlated to this trend than are values around the model and to the north. The values in the northern area indicated on Figure 16 were used in threshold development.

One of these results was below the 0.02 µg/l detection limit. Because the approximate quantification limit appears to be less than 0.0114 µg/l, this result was assigned a value of 0.005 µg/l. Figure 17 shows the distribution of the log of the selected data. The distribution is consistent with a normal distribution. Consequently, the geometric mean and upper tolerance limit were calculated from the log of the data.

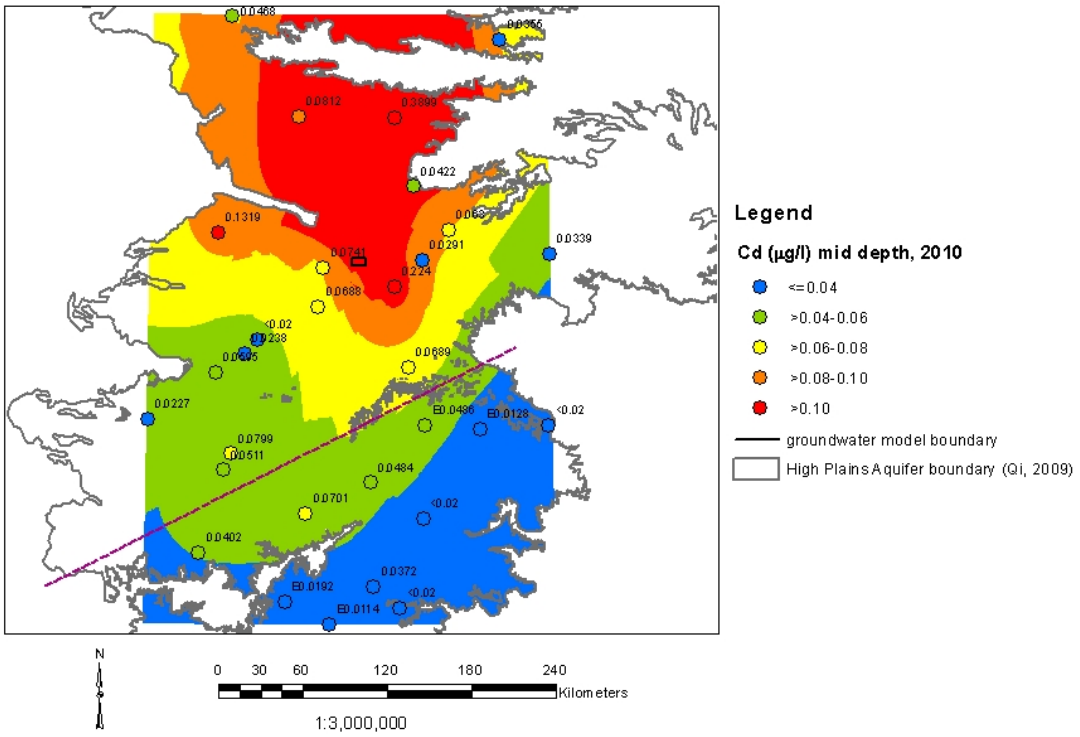

Figure 16: Results for cadmium in 2010 from resampled major aquifer study wells superimposed on contours resulting from kriging with a spherical variogram. Values north of the purple dashed line were used for calculating the threshold.

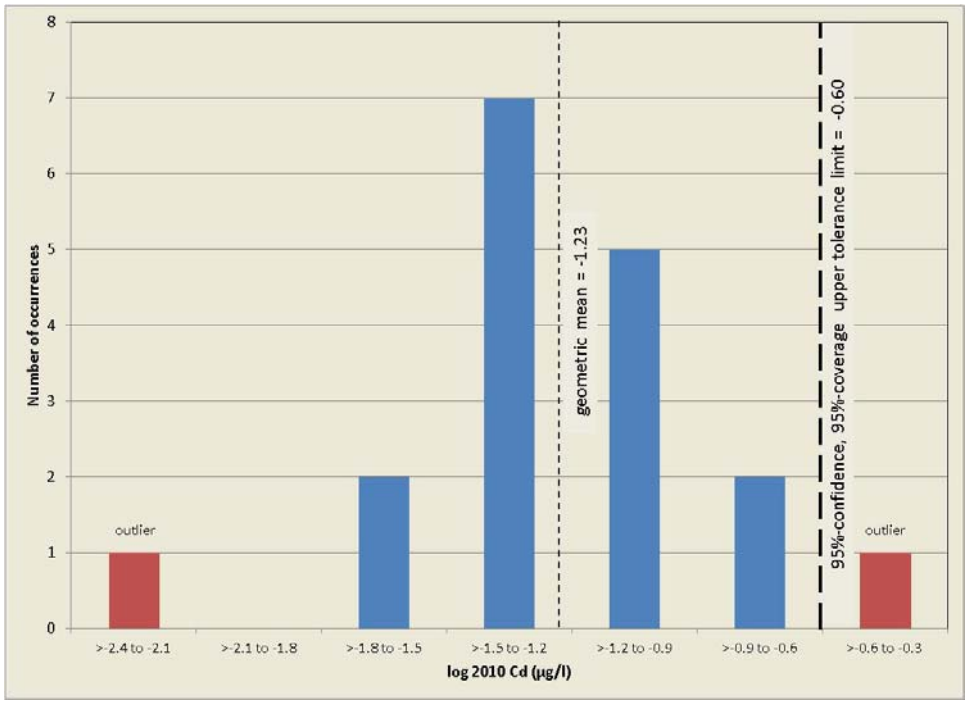

Figure 17: Histogram of select log cadmium concentrations in 2010 from major aquifer study wells.

3.2.7 Chromium (total)

The 2010 total chromium concentrations are mapped on Figure 18. Of the 30 results in 2010, 2 were below the detection limit. The detection limit for one was 0.12 µg/l. There was one approximately quantified result of 0.985 µg/l. Taking this as the approximate quantification limit, the aforementioned nondetect result was assigned a value of about half this limit, 0.05 µg/l.

The detection limit for the other nondetect was 1.2 µg/l. This same sample had high concentrations of some other inorganic constituents. For instance, the iron and manganese concentrations (567.2 and 924.8 µg/l, respectively) were more than an order of magnitude higher than the next highest concentrations. This suggests the higher detection limit for chromium in this sample was due to analytical interference due to the high concentrations of other analytes. In any event, a value of half the detection limit, 0.6 µg/l, was assigned to this result.

Figure 18 shows the distribution of concentrations varies spatially. South of the southern purple dashed line, the distribution is bimodal. There is not a single value in the central category in this area. In the north, there is a suggested trend of decreasing concentrations to the north. In particular, the two northernmost results are the second and fourth lowest in the data set given the nondetect assignments. The values between the purple dashed lines on Figure 18 have a more uniform and consistent distribution extending from the model area. Consequently, those values were selected for threshold analysis.

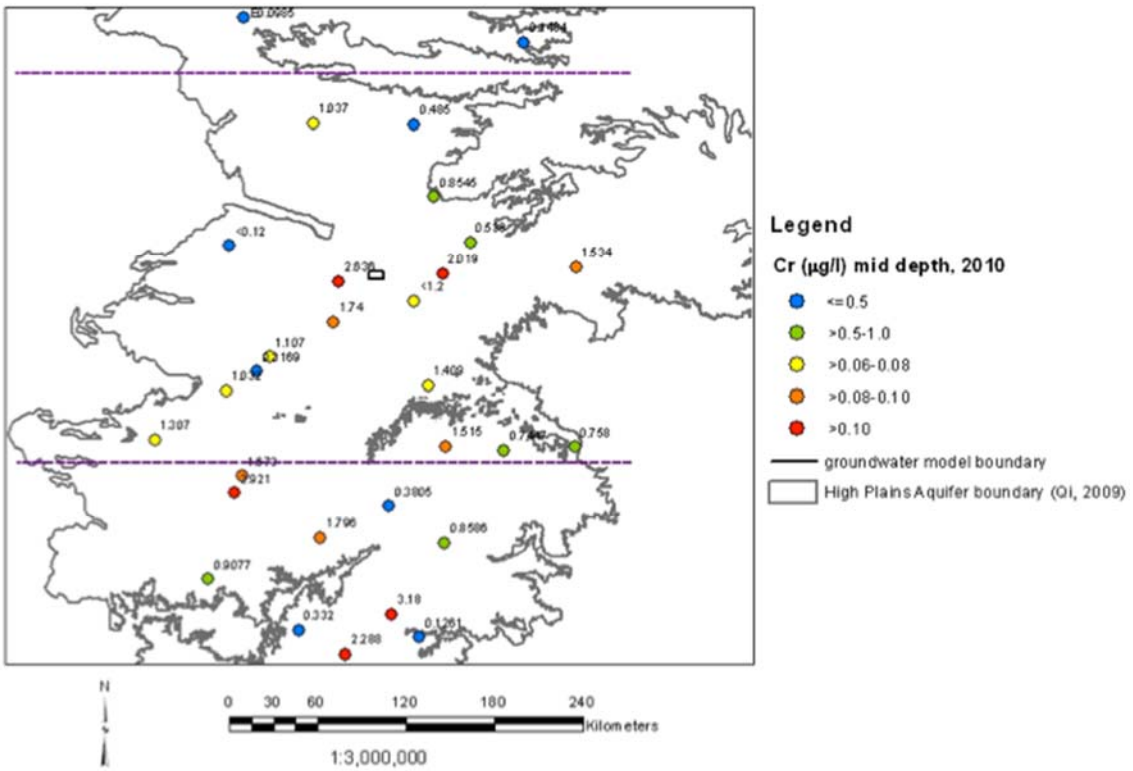

Figure 18: Results for chromium in 2010 from resampled major aquifer study wells. Values between the purple dashed lines were used for calculating the threshold.

Figure 19 shows the distribution of the log of the selected data. The distribution is consistent with a normal distribution. Consequently, the geometric mean and upper tolerance limit were calculated from the log of the data.

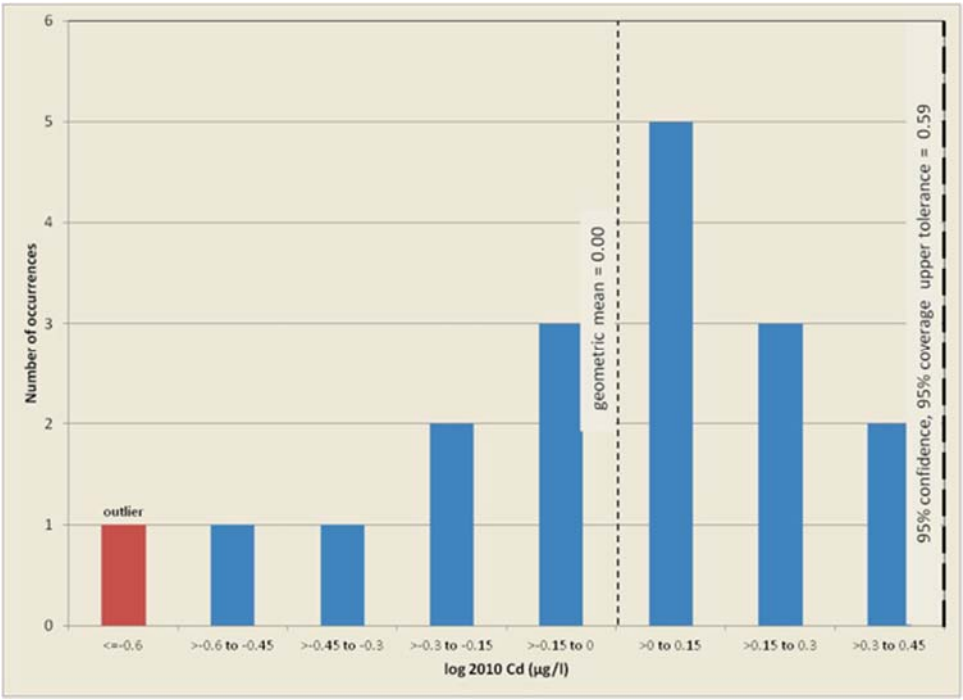

Figure 19: Histogram of log chromium concentrations in 2010 from resampled major aquifer study wells.

3.2.8 Lead

The 2010 lead concentrations are mapped on Figure 20. The values do not appear to be spatially correlated. Of the 30 results in 2010, 3 were below the detection limit of 0.03 µg/l. These were assigned values half the limit.

Figure 21 shows the distribution of the log of the selected data. The distribution is consistent with a normal distribution. Consequently, the geometric mean and upper tolerance limit were calculated from the log of the data.

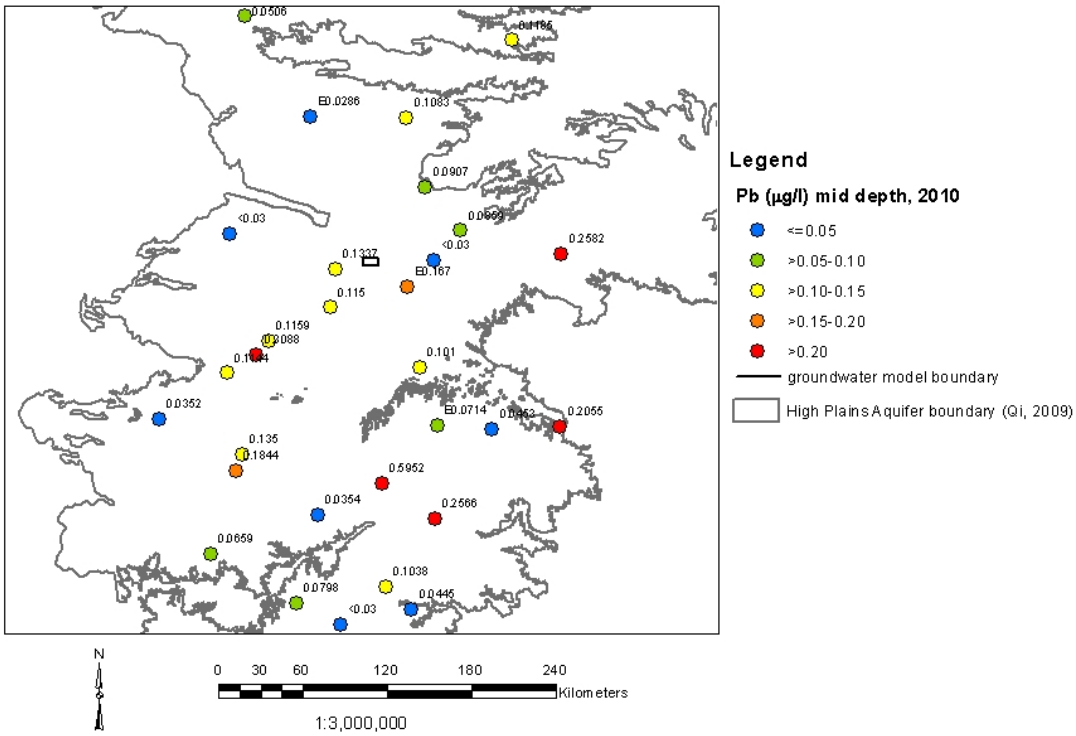

Figure 20: Results for lead in 2010 from resampled major aquifer study wells.

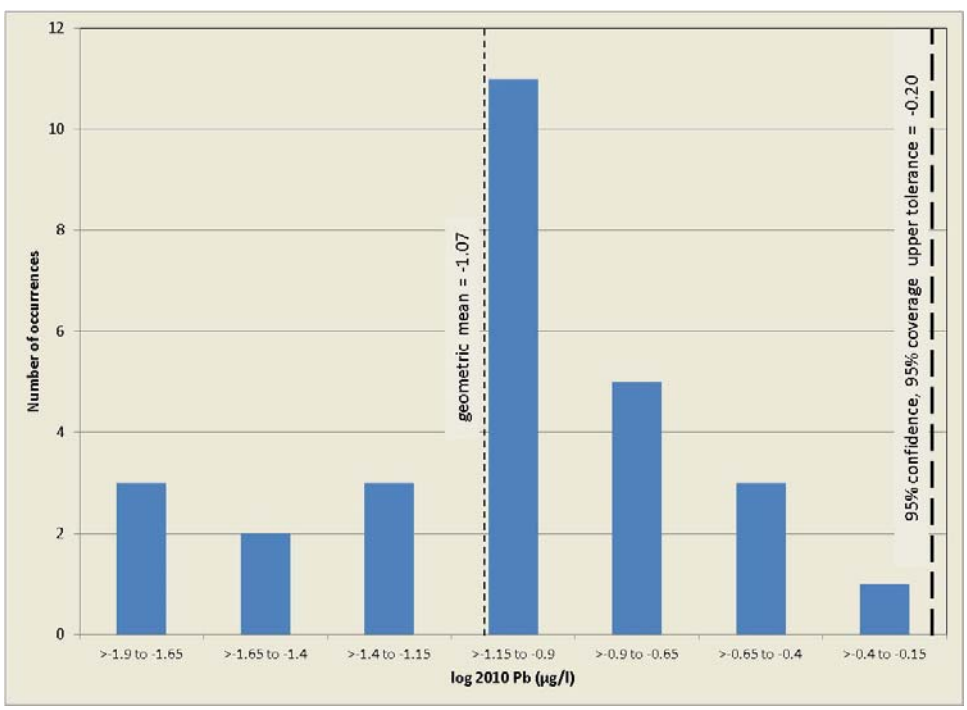

Figure 21: Histogram of log lead concentrations in 2010 from resampled major aquifer study wells.

3.3 DISCUSSION

The analyses in this report generally follow the "interwell" approach recommended for determining background groundwater concentrations at sites regulated under the *Resource Conservation and Recovery Act of 1976* (EPA, 2009). This approach provides a no-impact threshold value for an area of interest based on background groundwater constituent concentrations from wells in a nearby area. This approach requires the mean and variance of the groundwater constituent concentrations in wells across the nearby area to be constant (i.e., stationary) and the same as in the area of interest.

However, the results for several variables in the High Plains Aquifer (e.g., Figure 7, Figure 9, Figure 11, and Figure 16) show significant non-stationarity of the data, with large trends present across the map that indicate the presence of spatial correlation in the data. This is compounded by the relatively small data set from the large regional extent of the Central High Plains region used for this study (e.g., Figure 20). The regional extent of the data covers hundreds of kilometers, more than an order of magnitude larger than the spatial extent of the data set used for the Edwards Aquifer. The presence of this non-stationarity led to an investigation of methods to account for it.

One approach that was investigated was analysis of the change in concentrations between the 1999 and 2010 data sets. Figure 22 shows the distribution of the 2010 arsenic concentration minus the 1999 arsenic concentration. The mean is almost 0, suggesting no change in overall concentration distribution with time. Mapping the difference indicates little spatial correlation, suggesting the change data might more closely meet the assumption of stationarity of the data.

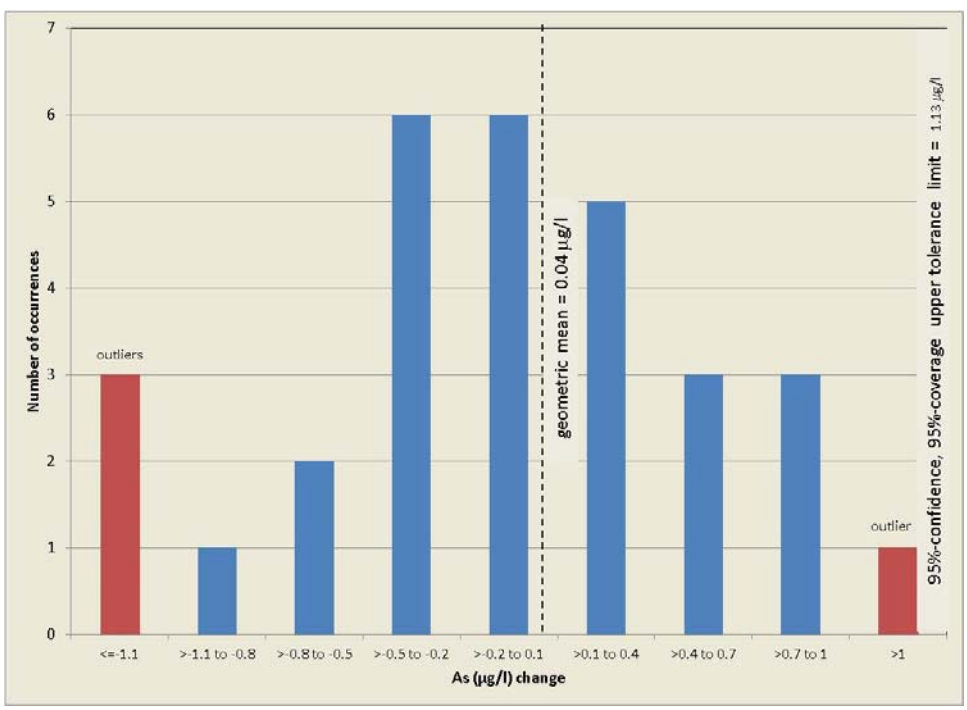

Figure 22: The distribution of 2010 minus 1999 arsenic concentrations at the major aquifer study wells.

Figure 23 and Figure 24 plot the 2010 arsenic data against the 1999 data from the major aquifer study wells. These data do not plot randomly across the range box, but are rather concentrated along the "no change line," which is the locus of unchanging concentrations through time. This indicates arsenic concentrations in the High Plains Aquifer are not temporally independent at an 11-year time interval. Consequently, these data do not comply with the constant mean assumption for the "interwell" approach on the decade time scale. The groundwater at wells with lower concentrations would require more perturbation before triggering the threshold than at wells with higher concentrations.

This suggests an approach that is a hybrid of the interwell and "intrawell" approaches. The intrawell approach sets thresholds based on the sequence of concentrations measured at a specific well through time (EPA, 2009). The suggested hybrid approach sets thresholds based on aggregating changes with time from numerous wells. This would allow development of statistics on the temporal distribution of concentration change from a smaller number of sampling events than would be possible with the interwell approach.

The lack of uniformity of the difference in concentration between the upper tolerance limit based on the log 2010 data and the mean concentration at each well is apparent in Figure 24. At the geometric mean, this upper tolerance limit is far in excess of upper tolerance limit at the 11-year time step implied by the upper tolerance limit of the concentration difference.

The difference between the 1999 and 2010 values for TDS and pH are also normally distributed and show little spatial correlation. Figure 25 and Figure 26 show similar plots for TDS and pH. Figure 25 shows a large difference between the thresholds at the geometric mean resulting from the two approaches for TDS. Figure 26 shows the difference for pH is relatively small at the geometric mean. This difference is in part because the mean difference in pH from 1999 to 2010 is –0.11, indicating an overall decline in pH with time.

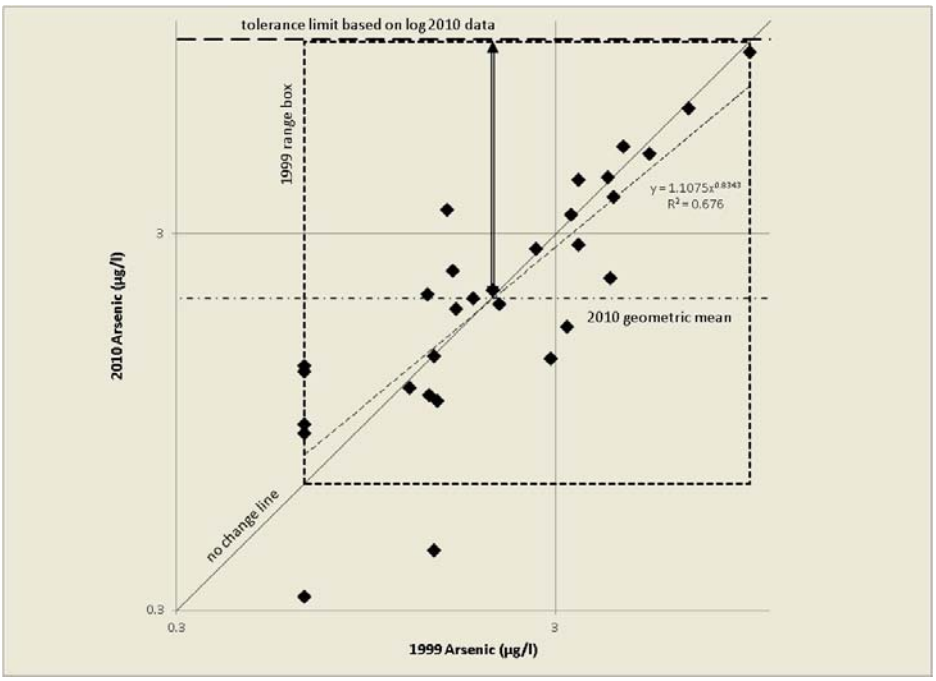

Figure 23: Log-log plot of the 2010 against 1999 arsenic concentrations at the major aquifer study wells.

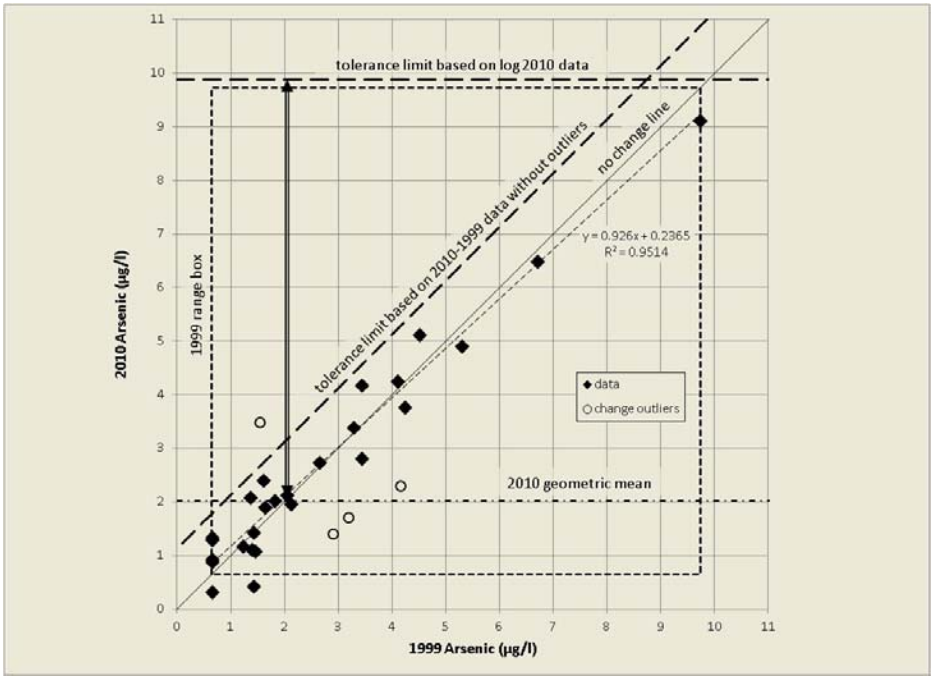

Figure 24: Linear plot of the 2010 against 1999 arsenic concentrations at the major aquifer study wells.

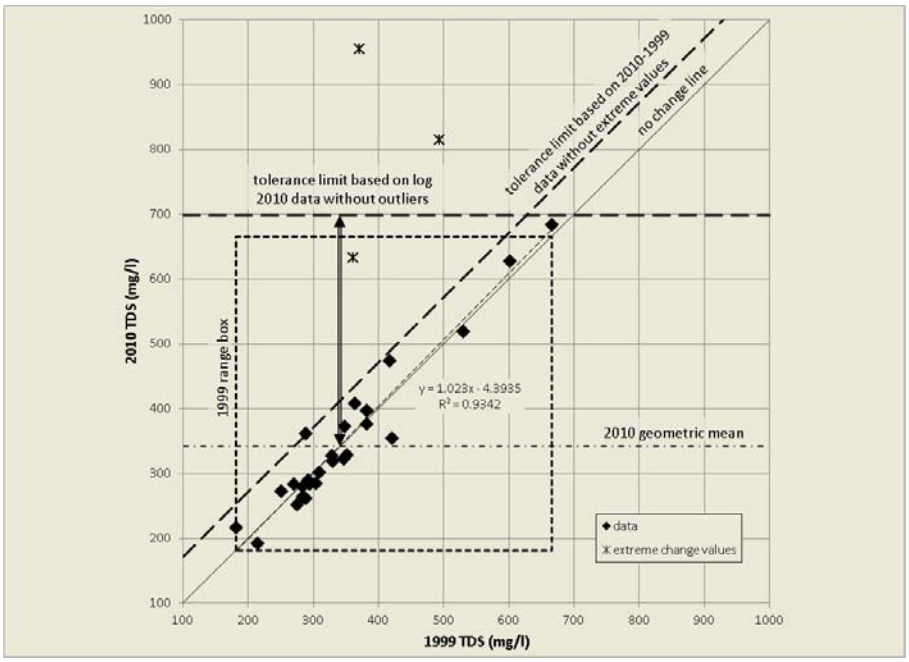

Figure 25: Linear plot of the 2010 against 1999 TDS at the major aquifer study wells.

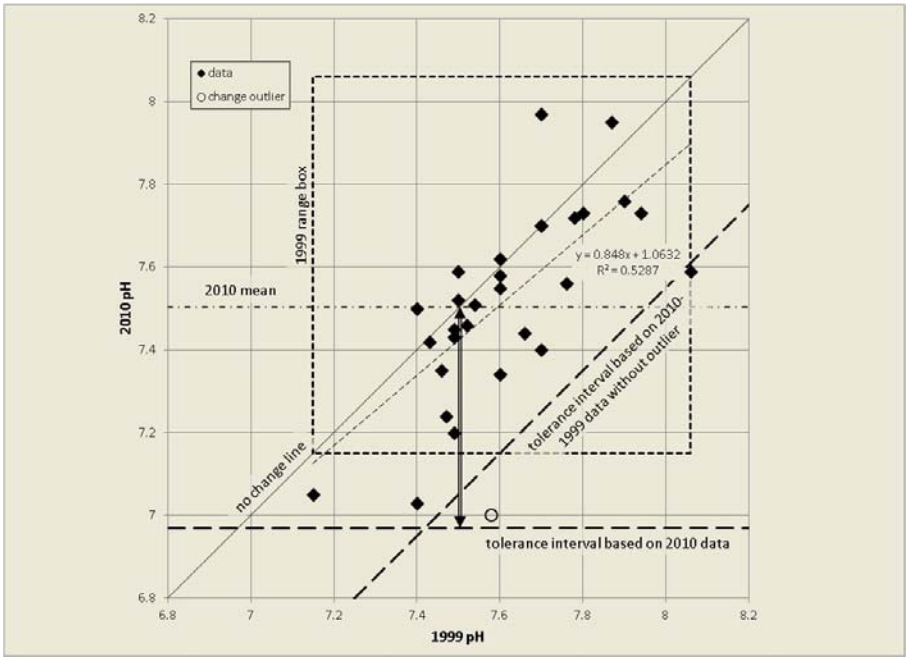

Figure 26: Linear plot of the 2010 against 1999 pH at the major aquifer study wells.

Differences between the 2010 and 1999 results for chromium could not be calculated for 12 of the 30 results because of nondetections in 1999 (2 locations, which also were nondetect in 2010). The difference between 16 of the other 18 pairs was negative. For the 10 sites with nondetects in 1999 and detects in 2010, all but 1 of the 2010 results was less than the 1999 detection limit. The

distribution of these 2010 results does not suggest a predominance of positive differences is likely if the 1999 results had been quantified.

The distribution of available chromium differences indicates the 2010 results were less on average than the 1999 results, with a mean and median decrease of 0.29 and 0.20 µg/l, respectively. Whether this was due to changes in the aquifer or analytical changes is not known.

The same analysis could not be carried out for cadmium and lead concentrations because all and almost all the concentrations were below detection in 1999, respectively. This could be a problem with a change-based approach, as pairs of data separated by a common time step would be needed, and this is often unavailable.

Given the 11-year time step, the hybrid approach will tend to give false positives and the interwell approach described in this report will tend to give false negatives. The hybrid approach also appears to be more spatially independent, but it is likely time dependent as the distribution of the difference in parameter values over time is time dependent. For example, the range of the difference in parameter values over time likely increases as the time step increases until the difference approaches time independence. Consequently, the hybrid approach described here can only be used when the time steps at the monitoring point of interest match time steps in the available background data.

The interwell approach is the available option when there is a question if a previously unmonitored point has been impacted by leakage. This is a likely scenario at storage sites and has been recommended here for assessing the model results. The hybrid approach is an option for judging if the results from monitoring points have crossed thresholds after a few to several sampling events, at which time the data may be insufficient for the intrawell approach to provide a robust result but be sufficient to judge if the assumptions of the interwell approach hold. Such monitoring points might be implemented adjacent to deep wells or along faults of concern for leakage.

More research into the hybrid approach described in this report is needed to develop a better understanding of the change in range, and perhaps type of distribution, of the parameter differences with different length time steps. A goal of this research would be modeling the range change through time with empirical equations, which would make this method more robust and useful.

An additional approach that should be investigated in the future would be use of a non-uniform starting value and the use of an alternative “intrawell” approach for identification of cells that exhibit significant changes in concentrations over time. This approach would only be suitable for study areas where spatial heterogeneity of the input data was found to be significant, e.g., through the use of ANOVA (EPA, 2009) or geostatistical methods. Then, if there were sufficient data available to map the concentration of the contaminant across the study area, a heterogeneous starting concentration could be developed. During the modeling runs, local backgrounds would be provided by the time series of concentrations at each cell prior to the time that injection of CO_2 begins. Continued monitoring of the time series of concentrations at each cell after injection begins would allow identification of cells where a significant increase occurred, possibly using an approach similar to the Shewhart-CUSUM control chart method described in the EPA Unified Guidance (EPA, 2009). This procedure would be analogous to one of the main intrawell testing procedures described in EPA (2009), and recommended when spatial heterogeneity indicates that the interwell comparison approach is not suitable.

4. CONCLUSIONS

Initial efforts to develop no-impact threshold values for the urban shallow-unconfined Edwards Aquifer and the High Plains Aquifer demonstrate potential methodologies and statistical protocols for determining statistically significant changes between background concentrations and concentrations predicted by second-generation models. Threshold values were determined based on an interwell approach for determining background groundwater concentrations as recommended in the EPA's *Unified Guidance for Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities* (EPA, 2009). These no-impact threshold values could be used instead of drinking water limits (e.g., MCLs) to inform a "no change" scenario with respect to groundwater impacts. They are intended for use in helping to predict areas of potential impact. They are not intended for use as alternate regulatory limits.

Development of "generic" threshold values that could be used for a number of model domains appears unlikely. Instead, the threshold values must be based on site-specific groundwater quality data. The scarcity of existing data, proximity of the data to the target model domain, potential spatial heterogeneity, and temporal trends make development of "clean" statistically robust data sets and use of valid statistical assumptions challenging. As seen with High Plains Aquifer TDS, calculated no-impact threshold values based on the 95%-confidence and 95%-coverage tolerance limits can in some cases exceed regulatory standards. Other approaches, such as the hybrid intrawell-interwell approach or the use of control charts to monitor the time series of concentrations at each cell, may provide other mechanisms for calculating no-impact threshold limits.

5. REFERENCES

Bacon, D. H. *Reduced-order Model for the Geochemical Impacts of Carbon Dioxide, Brine and Trace Metal Leakage into an Unconfined, Oxidizing Carbonate Aquifer, Version 2.0*; PNNL-22049 (Limited Distribution); Pacific Northwest National Laboratory: Richland, WA, 2012.

Bacon, D. H.; Dai, Z.; Keating, E.; Viswanathan, H. Development of a Reduced-Order Model of the Geochemical Impacts of CO_2 and Brine Leakage into an Unconfined Limestone Aquifer. Presented at the 11th Annual Conference on Carbon Capture Utilization & Sequestration, Pittsburgh, PA, May 2, 2012; PNNL-SA-87348.

Carroll, S.A.; Keating, E.; Mansoor, K.; Dai, Z.; Sun, Y.; Trainor-Guitton, W.; Brown, C.; Bacon, D. Key Factors for determining potential groundwater impacts due to leakage from geologic carbon sequestration reservoirs. *International Journal Greenhouse Gas Control* **2014,** *29*, 153–168. DOI: 10.1016/j.ijggc.2014.07.007

Davis, J. *Statistics and Data Analysis in Geology*, 3rd ed.; John Wiley & Sons, Inc.: New York, 2002.

Dai, Z.; Keating, E.; Viswanathan, H. *Impact of the Leaked CO_2 from Deep Reservoirs on Quality of Shallow Groundwater*; 2011 NRAP progress report; Los Alamos National Laboratory: Los Alamos, NM, 2011.

EPA. Drinking Water Contaminants. U.S. Environmental Protection Agency: Washington, DC. http://water.epa.gov/drink/contaminants/index.cfm (accessed Nov 20, 2012).

EPA. *Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities, Unified Guidance*; EPA 530/R-09-007; U.S. Environmental Protection Agency: Washington, DC, 2009.

Gurdak, J. J.; McMahon, P. B.; Dennehy, K. F.; Qi, S. L. *Water Quality in the High Plains Aquifer, Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, 1999–2004*; U.S. Geological Survey Circular 1337; 2009; pp 63.

Helsel, D. R. *Statistics for Censored Environmental Data Using Minitab and R*, 2nd ed.; John Wiley & Sons, Inc.: New York, 2012.

Lee, L. NADA: Nondetects and Data Analysis for Environmental Data. R package version 1.5–4, 2012. http://CRAN.R-project.org/package=NADA.

Mansoor, K.; Sun, Y.; Jones, E. D.; Trainor-Guitton, W. J.; Carroll, S. A. Assessing Impact of CO_2 Leakage in Groundwater Aquifers in the Presence of Data Uncertainties. XIX International Conference on Computational Methods in Water Resources, University of Illinois at Urbana-Champaign, Urbana, IL, June 17–21, 2012.

McMahon, P. B. *Vertical Gradients in Water Chemistry in the Central High Plains Aquifer, Southwestern Kansas and Oklahoma Panhandle, 1999*; USGS Water-Resources Investigations Report 01-4028; 2001; pp 47.

McMahon, P. B.; Dennehy, K. F.; Bruce, B. W.; Gurdak, J. J.; Qi, S. L. *Water-Quality Assessment of the High Plains Aquifer, 1999–2004*; U.S. Geological Survey Professional Paper 1749; 2007; pp 136.

Musgrove, M.; Fahlquist, L.; Houston, N. A.; Lindgren, R. J.; Ging, P. B. *Geochemical Evolution Processes and Water-Quality Observations Based on Results of the National Water-Quality Assessment Program in the San Antonio Segment of the Edwards Aquifer, 1996–2006*; U.S. Geological Survey Scientific Investigations Report 2010−5129; 2010; pp 93.

National Institute of Standards/SEMATECH. e-Handbook of Statistical Methods. Accessed, at http://www.itl.nist.gov/div898/handbook/ (December 2012).

R Development Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria, 2012.

Resource Conservation and Recovery Act of 1976. Public Law 94-580, as amended, 42 USC 6901 et seq. and 42 USC 6927(c) et seq., 1976.

USGS. Ground Water Atlas of the United States, 1990–2000. U.S. Geological Survey. http://pubs.usgs.gov/ha/ha730/ (December 2012).

Whittemore, D. O.; Grieve, E. R.; Young, D. P.; Wilson, B. B. *Water Quality in the High Plains Aquifer and the Cimarron River in Seward and Meade Counties, Kansas; Part of Data, Research, and Technical Support for Ogallala-High Plains Aquifer Assessment, Planning, and Management – Kansas Water Plan – FY 2005*; Kansas Geological Survey Open File Report 2005-27; 2005.

Young, D. S. Tolerance: An R Package for Estimating Tolerance Intervals. *Journal of Statistical Software* **2010,** *36*, 1–39. http://www.jstatsoft.org/v36/i05/

APPENDIX A: DATA FROM THE SHALLOW URBAN UNCONFINED EDWARDS AQUIFER USED FOR ANALYSIS OF METALS CONCENTRATIONS

Table A.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of metals concentrations

USGS_ID	USGS_ID_Cen	Sample_date (yyyymmdd)	Sample_date_Cen	Arsenic (µg/L	AsCen	Lead (µg/L)	LeadCen	Ln_Lead	Ln_LeadCen
293404098382001	False	20010604	False	0.28	False	0.08	True	−2.52573	True
293436098343001	False	20010605	False	0.34	False	0.08	True	−2.52573	True
293516098325501	False	20010605	False	0.35	False	0.08	True	−2.52573	True
293535098304101	False	20010606	False	0.24	False	0.14	False	−1.9951	False
293436098343001	False	20021119	False	0.46	False	0.08	True	−2.52573	True
293516098325501	False	20021120	False	0.47	False	0.05	False	−2.99573	False
293404098382001	False	20021203	False	0.37	False	0.08	True	−2.52573	True
293643098264001	False	20021204	False	0.34	False	0.05	False	−2.99573	False
293535098304101	False	20021205	False	0.26	False	0.08	True	−2.52573	True
293643098264001	False	20041202	False	0.3	False	0.08	True	−2.52573	True
293535098304101	False	20041203	False	0.37	False	0.08	True	−2.52573	True
293404098382001	False	20041203	False	0.4	False	0.08	True	−2.52573	True
293436098343001	False	20041209	False	0.38	False	0.08	True	−2.52573	True
293516098325501	False	20041209	False	0.52	False	0.08	True	−2.52573	True

Table A.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of metals concentrations (continued)

USGS_ID	USGS_ID_Cen	Sample_date (yyyymmdd)	Sample_date_Cen	Arsenic (µg/L	AsCen	Lead (µg/L)	LeadCen	Ln_Lead	Ln_LeadCen
293520098254101	False	20060816	False	0.29	False	0.08	True	−2.52573	True
293615098262301	False	20060817	False	0.18	False	0.08	True	−2.52573	True
293537098262401	False	20060817	False	0.29	False	0.08	True	−2.52573	True
293504098270901	False	20060818	False	0.27	False	0.08	True	−2.52573	True
293528098274301	False	20060821	False	0.24	False	0.11	False	−2.20727	False
293456098280201	False	20060821	False	0.29	False	0.15	False	−1.89712	False
293643098264001	False	20060822	False	0.22	False	0.05	False	−2.99573	False
293746098265401	False	20060822	False	0.31	False	0.05	False	−2.99573	False
293559098284801	False	20060823	False	0.19	False	0.08	True	−2.52573	True
293534098282801	False	20060823	False	0.31	False	0.08	True	−2.52573	True
293516098325501	False	20060824	False	0.46	False	0.08	True	−2.52573	True
293439098324101	False	20060824	False	0.46	False	0.08	True	−2.52573	True
293611098311901	False	20060828	False	0.27	False	0.08	True	−2.52573	True
293408098331301	False	20060829	False	0.27	False	0.05	False	−2.99573	False
293459098321401	False	20060829	False	0.28	False	0.07	False	−2.65926	False

Table A.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of metals concentrations (continued)

USGS_ID	USGS_ID_Cen	Sample_date (yyyymmdd)	Sample_date_Cen	Arsenic (µg/L	AsCen	Lead (µg/L)	LeadCen	Ln_Lead	Ln_LeadCen
293348098334101	False	20060830	False	0.28	False	0.06	False	−2.81341	False
293340098344701	False	20060830	False	0.3	False	0.05	False	−2.99573	False
293535098304101	False	20060831	False	0.17	False	0.09	False	−2.40795	False
293436098343001	False	20060831	False	0.34	False	0.06	False	−2.81341	False
293359098405401	False	20060901	False	0.27	False	0.12	False	−2.12026	False
293405098394201	False	20060905	False	0.23	False	0.12	False	−2.12026	False
293404098382001	False	20060905	False	0.31	False	0.12	False	−2.12026	False
293429098373801	False	20060906	False	0.3	False	0.09	False	−2.40795	False
293350098355801	False	20060906	False	0.37	False	0.08	False	−2.52573	False
293508098375101	False	20060907	False	0.29	False	0.06	False	−2.81341	False
293516098362801	False	20060907	False	0.33	False	0.09	False	−2.40795	False
293635098302301	False	20060908	False	0.33	False	0.08	False	−2.52573	False
293252098380801	False	20060911	False	0.4	False	0.1	False	−2.30259	False
293425098350801	False	20060911	False	0.42	False	0.08	False	−2.52573	False

Table A.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of metals concentrations (continued)

USGS_ID	USGS_ID_Cen	Sample_date (yyyymmdd)	Sample_date_Cen	Arsenic (µg/L	AsCen	Lead (µg/L)	LeadCen	Ln_Lead	Ln_LeadCen
293530098343401	False	20060912	False	0.49	False	0.11	False	−2.20727	False
293535098304101	False	20061213	False	0.21	False	0.12	True	−2.12026	True
293643098264001	False	20061213	False	0.24	False	0.12	True	−2.12026	True
293404098382001	False	20061218	False	0.31	False	0.12	True	−2.12026	True
293436098343001	False	20061219	False	0.4	False	0.12	True	−2.12026	True
293516098325501	False	20061219	False	0.52	False	0.12	True	−2.12026	True

APPENDIX B: DATA FROM THE SHALLOW URBAN UNCONFINED EDWARDS AQUIFER USED FOR ANALYSIS OF PH AND TDS CONCENTRATIONS

Table B.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of pH and TDS concentrations

State Well Number	USGS Identification Number	Sample Date (yyyymmdd)	pH	TDS (mgL)
AY-68-27-610	293252098380801	20060911	6.8	337
AY-68-27-610	293252098380801	19981210	6.9	319
AY-68-28-516	293340098344701	20060830	6.8	362
AY-68-28-516	293340098344701	19981208	6.9	344
AY-68-28-515	293348098334101	20060830	7	320
AY-68-28-515	293348098334101	19981106	6.9	312
AY-68-28-406	293350098355801	20060906	6.9	331
AY-68-28-406	293350098355801	19981106	6.9	364
AY-68-27-517	293359098405401	20060901	6.9	347
AY-68-27-517	293359098405401	19981110	6.8	361
AY-68-27-612	293404098382001	20061218	6.9	335
AY-68-27-612	293404098382001	20060905	6.8	347
AY-68-27-612	293404098382001	20041203	7	351
AY-68-27-612	293404098382001	20021203	6.8	345
AY-68-27-612	293404098382001	20010604	6.7	327
AY-68-27-612	293404098382001	20000607	6.9	331
AY-68-27-612	293404098382001	19990525	6.8	229
AY-68-27-612	293404098382001	19981210	6.9	332

Table B.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of pH and TDS concentrations (continued)

State Well Number	USGS Identification Number	Sample Date (yyyymmdd)	pH	TDS (mgL)
AY-68-27-609	293405098394201	20060905	6.9	328
AY-68-27-609	293405098394201	19981110	6.9	313
AY-68-28-519	293408098331301	20060829	6.8	363
AY-68-28-519	293408098331301	19981114	6.7	374
AY-68-28-407	293425098350801	20060911	7.1	284
AY-68-28-407	293425098350801	19981113	7.3	304
AY-68-27-611	293429098373801	20060906	6.9	323
AY-68-27-611	293429098373801	19981112	6.8	324
AY-68-28-517	293436098343001	20061219	6.8	300
AY-68-28-517	293436098343001	20060831	7.1	305
AY-68-28-517	293436098343001	20041209	7.1	318
AY-68-28-517	293436098343001	20021119	7	316
AY-68-28-517	293436098343001	20010605	6.8	316
AY-68-28-517	293436098343001	20000628	6.9	298
AY-68-28-517	293436098343001	19990526	6.8	329
AY-68-28-517	293436098343001	19981208	6.8	335
AY-68-28-518	293439098324101	20060824	6.8	393
AY-68-28-518	293439098324101	19981211	7	342
AY-68-29-418	293456098280201	20060821	6.7	401
AY-68-29-418	293456098280201	19981209	6.7	407

Table B.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of pH and TDS concentrations (continued)

State Well Number	USGS Identification Number	Sample Date (yyyymmdd)	pH	TDS (mgL)
AY-68-28-609	293459098321401	20060829	6.9	345
AY-68-28-609	293459098321401	19981111	6.9	306
AY-68-29-213	293504098270901	20060818	6.8	408
AY-68-29-213	293504098270901	19981105	6.7	391
AY-68-27-307	293508098375101	20060907	6.9	345
AY-68-27-307	293508098375101	19981023	6.9	311
AY-68-28-211	293516098325501	20061219	6.8	335
AY-68-28-211	293516098325501	20060824	6.9	340
AY-68-28-211	293516098325501	20041209	7.1	313
AY-68-28-211	293516098325501	20021120	7.1	319
AY-68-28-211	293516098325501	20010605	6.8	407
AY-68-28-211	293516098325501	20000629	6.9	320
AY-68-28-211	293516098325501	19990527	6.8	315
AY-68-28-211	293516098325501	19981114	6.9	301
AY-68-28-113	293516098362801	20060907	7	299
AY-68-28-113	293516098362801	19981112	6.9	280
AY-68-29-214	293520098254101	20060816	6.9	343
AY-68-29-214	293520098254101	19981108	6.8	355
AY-68-29-114	293528098274301	20060821	6.8	423
AY-68-29-114	293528098274301	19981103	6.7	378

Table B.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of pH and TDS concentrations (continued)

State Well Number	USGS Identification Number	Sample Date (yyyymmdd)	pH	TDS (mgL)
AY-68-28-210	293530098343401	20060912	6.9	201
AY-68-28-210	293530098343401	19981026	6.9	323
AY-68-29-113	293534098282801	20060823	6.8	395
AY-68-29-113	293534098282801	19981107	6.8	364
AY-68-28-314	293535098304101	20061213	6.8	409
AY-68-28-314	293535098304101	20060831	6.7	420
AY-68-28-314	293535098304101	20041203	6.9	327
AY-68-28-314	293535098304101	20021205	6.7	375
AY-68-28-314	293535098304101	20010606	6.3	266
AY-68-28-314	293535098304101	20000608	6.8	401
AY-68-28-314	293535098304101	19990528	7	246
AY-68-28-314	293535098304101	19981207	6.7	366
AY-68-29-215	293537098262401	20060817	7.2	327
AY-68-29-215	293537098262401	19981105	6.9	315
AY-68-29-112	293559098284801	20060823	6.9	456
AY-68-29-112	293559098284801	19981209	6.8	373
AY-68-28-315	293611098311901	20060828	6.8	339
AY-68-28-315	293611098311901	19981111	6.8	354
AY-68-29-217	293615098262301	20060817	7.1	340
AY-68-29-217	293615098262301	19981109	7.1	236

Table B.1: Data from the shallow urban unconfined Edwards Aquifer used for analysis of pH and TDS concentrations (continued)

State Well Number	USGS Identification Number	Sample Date (yyyymmdd)	pH	TDS (mgL)
AY-68-28-313	293635098302301	20060908	6.7	385
AY-68-28-313	293635098302301	19981104	6.9	288
AY-68-29-216	293643098264001	20061213	6.9	314
AY-68-29-216	293643098264001	20060822	6.9	320
AY-68-29-216	293643098264001	20041202	7	295
AY-68-29-216	293643098264001	20021204	6.9	310
AY-68-29-216	293643098264001	20010606	6.4	328
AY-68-29-216	293643098264001	20000629	6.9	312
AY-68-29-216	293643098264001	19990527	6.9	313
AY-68-29-216	293643098264001	19981109	6.9	264
AY-68-21-806	293746098265401	20060822	6.9	300
AY-68-21-806	293746098265401	19981207	6.8	301

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APPENDIX C: SELECT NATIONAL WATER QUALITY ASSESSMENT CENTRAL HIGH PLAINS AQUIFER DATA

The following tables were developed from a file provided by Richard Bell resulting from a query of the National Water Quality Assessment (NAWQA) database for all the inorganic, pH, and total dissolved solids (TDS) data developed by NAWQA for the High Plains Aquifer.

The data was queried for all the data that might regard the Ogallala hydrogeologic unit in the Central High Plains area defined by NAWQA, and then further subset by the site lists for each of the nested studies available from http://co.water.usgs.gov/nawqa/hpgw/datarep/TOC.html. This left aside the Central High Plains Quaternary unit major aquifer study data as well as the urban land use study data around Wichita, Kansas

The following tables contain only records with data on arsenic, cadmium, lead, pH, or TDS.

Some sites are utilized in more than one of the studies, and so these sites, and even data from them, may appear in two of the tables.

Table C.1: Central High Plains irrigated agriculture land use study

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
360159103044401	36.0330666667	-103.0789833333	9/11/2000 3:00:00 PM									7.26	366
364846102161201	36.8129916667	-102.2700000000	9/17/2000 10:00:00 AM									7.69	542
370033100534204	37.0091861111	-100.8952583333	8/27/1999 2:00:00 PM									7.65	331
370033100534204	37.0091861111	-100.8952583333	8/27/1999 2:09:00 PM		4.55	<	1		2.6	<	1		
370033100534204	37.0091861111	-100.8952583333	9/13/2000 9:00:00 AM									7.39	328
370941101540001	37.1615305556	-101.9002388889	9/16/2000 1:00:00 PM									7.79	964
371303102003001	37.2177027778	-102.0086083333	9/14/2000 5:00:00 PM									7.54	624
371728101311401	37.2912166667	-101.5207888889	9/15/2000 11:00:00 AM									7.38	782
371909101413101	37.3193805556	-101.6921333333	9/16/2000 10:00:00 AM									7.66	720
372511100155601	37.4199638889	-100.2658138889	9/27/2000 9:00:00 AM									7.26	1090
373234099430201	37.5429194444	-99.7173055556	9/25/2000 1:00:00 PM									7.73	287
373346100005701	37.5630277778	-100.0158333333	9/27/2000 2:00:00 PM									7.61	300
373904099545701	37.6512222222	-99.9158916667	9/28/2000 1:00:00 PM									7.36	380
374005101433501	37.6681833333	-101.7265277778	8/8/2000 8:00:00 AM									7.6	400

Table C.1: Central High Plains irrigated agriculture land use study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
374220100422501	37.7055833333	-100.7069722222	2/4/1999 11:00:00 AM									7.19	642
374220100422501	37.7055833333	-100.7069722222	6/28/2000 11:00:00 AM									6.93	554
374412100453201	37.7367777778	-100.7588333333	7/10/2000 11:00:00 AM									7.43	675
374412100453201	37.7367777778	-100.7588333333	11/27/2000 6:00:00 PM										
374412100453201	37.7367777778	-100.7588333333	8/15/2001 11:00:00 AM									7.68	
374430100093801	37.7417833333	-100.1606722222	9/28/2000 9:00:00 AM									7.41	489
374625100490701	37.7735555556	-100.8186944444	6/29/2000 11:00:00 AM									6.91	680
374625100490701	37.7735555556	-100.8186944444	8/14/2001 10:00:00 AM									7.31	
374642100291701	37.7783972222	-100.4883277778	6/30/2000 12:00:00 PM									7.21	396
374750101553501	37.7973166667	-101.9266305556	8/9/2000 9:00:00 AM									7.7	493
375106100544301	37.8516750000	-100.9120027778	9/26/2000 2:00:00 PM									7.62	300
375251101135301	37.8808472222	-101.2314055556	8/11/2000 10:00:00 AM									7.34	1306
375502100363601	37.9173972222	-100.6102500000	9/26/2000 10:00:00 AM									7.9	485
375734100452301	37.9595833333	-100.7564166667	2/2/1999 11:30:00 AM									7	1058

Table C.1: Central High Plains irrigated agriculture land use study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
375855100484001	37.9820833333	-100.8110000000	2/3/1999 11:00:00 AM									6.96	4916
375855100484001	37.9820833333	-100.8110000000	6/27/2000 12:00:00 PM									6.81	4512
380256101035901	38.0489111111	-101.0664027778	8/10/2000 8:00:00 AM									7.2	782
381201100495101	38.2004388889	-100.8309555556	7/11/2000 12:00:00 PM									6.99	1036
383334101131301	38.5595277778	-101.2205444444	8/8/2000 3:00:00 PM									7.7	374
383803101084701	38.6343277778	-101.1466166667	7/13/2000 11:00:00 AM									7.37	382
383936101120801	38.6602222222	-101.2023750000	7/12/2000 3:00:00 PM									7.44	407
384422101434201	38.7395055556	-101.7285472222	7/14/2000 12:00:00 PM									7.76	277

Table C.2: Central High Plains Ogallala Unit major aquifer study

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
344800101324901	34.8002305556	-101.5469888889	7/14/1999 10:00:00 AM									7.5	325
344800101324901	34.8002305556	-101.5469888889	7/14/1999 10:09:00 AM		5.57	<	1		1.1	<	1		
345826100580501	34.9740000000	-100.9680611111	6/28/1999 11:00:00 AM									7.3	359
345826100580501	34.9740000000	-100.9680611111	6/28/1999 11:09:00 AM		3	<	1	<	1	<	1		
351656101161101	35.2822222222	-101.2699861111	5/19/1999 9:00:00 AM		1.63	<	1		2.7	<	1	7.5	291
351656101161101	35.2822222222	-101.2699861111	4/28/2010 2:30:00 PM		1.894	E	0.0114		2.288	<	0.03	7.52	290.76
351914101204401	35.3207361111	-101.3457333333	7/1/1999 8:00:00 AM									7.5	330
351914101204401	35.3207361111	-101.3457333333	7/1/1999 8:09:00 AM		1.35	<	1		5.2		1.889		
352035100293301	35.3432333333	-100.4926000000	7/13/1999 9:00:00 AM									7.3	299
352035100293301	35.3432333333	-100.4926000000	7/13/1999 9:09:00 AM		2.11	<	1	<	1	<	1		
352249100425401	35.3804833333	-100.7152222222	6/30/1999 9:00:00 AM									7.5	213
352249100425401	35.3804833333	-100.7152222222	6/30/1999 9:09:00 AM		2.04	<	1	<	1	<	1		
352249100425401	35.3804833333	-100.7152222222	4/29/2010 10:40:00 AM		2.124	<	0.02		0.1261		0.0445	7.59	193.11
352513101372101	35.4202777778	-101.6225000000	5/20/1999 8:00:00 AM	<	1	<	1	<	1	<	1	7.7	250

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
352513101372101	35.4202777778	-101.6225000000	4/28/2010 10:30:00 AM		1.292	E	0.0192		0.332		0.0798	7.7	273.32
352909101084001	35.4860305556	-101.1446416667	7/1/1999 2:00:00 PM									7.7	1028
352909101084001	35.4860305556	-101.1446416667	7/1/1999 2:09:00 PM		3.39	<	1		3.5	<	1		
353110100550401	35.5195138889	-100.9178944444	6/29/1999 10:00:00 AM									7.6	416
353110100550401	35.5195138889	-100.9178944444	6/29/1999 10:09:00 AM		3.2	<	1		3.5	<	1		
353110100550401	35.5195138889	-100.9178944444	4/29/2010 2:40:00 PM		1.703		0.0372		3.18		0.1038	7.34	474.8
353110100550401	35.5195138889	-100.9178944444	4/11/2012 11:00:00 AM		1.66		0.0374		3.366		0.1823	7.46	482.11
353941102350201	35.6614416667	-102.5841638889	7/15/1999 11:00:00 AM									7.7	285
353941102350201	35.6614416667	-102.5841638889	7/15/1999 11:09:00 AM		2.83	<	1	<	1	<	1		
354248100501501	35.7133833333	-100.8375138889	7/19/1999 8:00:00 AM									7.6	322
354248100501501	35.7133833333	-100.8375138889	7/19/1999 8:09:00 AM		1.56	<	1		1.2	<	1		
354331102183601	35.7252833333	-102.3100888889	6/23/1999 9:00:00 AM									7.7	274
354331102183601	35.7252833333	-102.3100888889	6/23/1999 9:09:00 AM		3.29	<	1	<	1	<	1		
354331102183601	35.7252833333	-102.3100888889	4/30/2010 3:00:00 PM		3.384		0.0402		0.9077		0.0659	7.7	252.82

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
354348102543601	35.7300000000	-102.9100000000	7/21/1999 11:00:00 AM									7.7	243
354348102543601	35.7300000000	-102.9100000000	7/21/1999 11:09:00 AM		2.31	<	1	<	1	<	1		
354656099480301	35.7822361111	-99.8010888889	5/17/1999 11:00:00 AM		3.52	<	1	<	1	<	1	7.32	279
354728102295901	35.7913333333	-102.4999944444	7/16/1999 12:00:00 PM									7.6	297
354728102295901	35.7913333333	-102.4999944444	7/16/1999 12:09:00 PM		1.95	<	1		2.2	<	1		
354918102020901	35.8218444444	-102.0360611111	6/23/1999 2:00:00 PM									8	324
354918102020901	35.8218444444	-102.0360611111	6/23/1999 2:09:00 PM	<	1	<	1		2.2	<	1		
355701100313001	35.9504500000	-100.5252333333	5/18/1999 10:00:00 AM									7.4	328
355701100313001	35.9504500000	-100.5252333333	5/18/1999 10:09:00 AM		1.23	<	1		1	<	1		
355701100313001	35.9504500000	-100.5252333333	4/15/2010 4:00:00 PM		1.175	<	0.02		0.8586		0.2566	7.5	328.53
355852101274101	35.9812666667	-101.4616500000	7/2/1999 12:00:00 PM									7.6	294
355852101274101	35.9812666667	-101.4616500000	7/2/1999 12:09:00 PM		1.6	<	1		2	<	1		
355852101274101	35.9812666667	-101.4616500000	4/30/2010 11:00:00 AM		2.398		0.0701		1.796		0.0354	7.62	284.66
355916103215201	35.9878666667	-103.3644888889	6/25/1999 12:00:00 PM									7.7	864

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
355916103215201	35.9878666667	-103.3644888889	6/25/1999 12:09:00 PM		3.65	<	1	<	1	<	1		
360703102361901	36.1177555556	-102.6055055556	6/22/1999 10:00:00 AM									7.7	302
360703102361901	36.1177555556	-102.6055055556	6/22/1999 10:09:00 AM		2.42	<	1	<	1	<	1		
360838102560301	36.1439888889	-102.9342472222	6/24/1999 8:00:00 AM									7.6	267
360838102560301	36.1439888889	-102.9342472222	6/24/1999 8:09:00 AM		1.91	<	1	<	1	<	1		
360944100162101	36.1622222222	-100.2725000000	4/12/1999 9:00:00 AM		2.83	<	1		3.5	<	1	7.77	314
361014100221001	36.1706500000	-100.3695611111	4/8/1999 11:00:00 AM		2.95	<	1		1.1	<	1	7.53	397
361049100564901	36.1802777778	-100.9469444444	5/21/1999 12:00:00 PM		1.55	<	1		3.2	<	1	7.66	420
361049100564901	36.1802777778	-100.9469444444	4/15/2010 11:00:00 AM		3.475		0.0484		0.3805		0.5952	7.44	355.1
361054101393601	36.1817972222	-101.6600444444	6/21/1999 11:00:00 AM									7.6	367
361054101393601	36.1817972222	-101.6600444444	6/21/1999 11:09:00 AM		2.07	<	1		1.3	<	1		
361114099420501	36.1873944444	-99.7016138889	7/22/1999 11:00:00 AM									7.3	413
361114099420501	36.1873944444	-99.7016138889	7/22/1999 11:09:00 AM		1.75	<	1	<	1	<	1		
361517102065301	36.2547222222	-102.1147222222	5/26/1999 9:00:00 AM	<	1	<	1		3.3	<	1	7.8	329

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
361517102065301	36.2547222222	-102.1147222222	4/27/2010 2:00:00 PM		0.8856		0.0511		2.921		0.1844	7.73	319.78
362115101173901	36.3543138889	-101.2943222222	5/25/1999 10:00:00 AM		2.37	<	1		1.8	<	1	7.6	416
362134102035101	36.3594722222	-102.0642722222	5/25/1999 2:00:00 PM		1.39	<	1		1.8	<	1	7.9	283
362134102035101	36.3594722222	-102.0642722222	5/1/2010 10:00:00 AM		1.119		0.0799		1.673		0.135	7.76	280.71
362615100435801	36.4376194444	-100.7329805556	5/24/1999 11:00:00 AM		5.48	<	1		3.9	<	1	7.6	382
362744102334901	36.3963833333	-102.5627305556	7/20/1999 9:00:00 AM									8.3	468
362744102334901	36.3963833333	-102.5627305556	7/20/1999 9:09:00 AM		7.61	<	1			<	1		
363057101384701	36.5160638889	-101.6466611111	5/27/1999 8:00:00 AM		5.25	<	1		1.2	<	1	7.7	268
363104100035501	36.5178333333	-100.0652805556	4/9/1999 9:30:00 AM		4.51	<	1	<	1	<	1	7.6	308
363104100035501	36.5178333333	-100.0652805556	4/14/2010 3:30:00 PM		5.124	E	0.0128		0.7447		0.0453	7.55	302.64
363154099310401	36.5316666667	-99.5180305556	7/22/1999 2:00:00 PM									7.4	288
363154099310401	36.5316666667	-99.5180305556	7/22/1999 2:09:00 PM		2.9	<	1	<	1	<	1		
363154099310401	36.5316666667	-99.5180305556	4/13/2010 11:00:00 AM		1.402	<	0.02		0.758		0.2055	7.03	261.8
363157102565601	36.5326055556	-102.9491083333	4/16/1999 10:00:00 AM		2.02	<	1		1.1		2.289	8.08	276

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
363239100301801	36.5443222222	-100.5051916667	4/6/1999 10:00:00 AM		9.73	<	1		1.8	<	1	7.76	381
363239100301801	36.5443222222	-100.5051916667	4/13/2010 3:00:00 PM		9.111	E	0.0486		1.515	E	0.0714	7.56	376.87
363427102440401	36.5743916667	-102.7346000000	4/15/1999 9:00:00 AM		2.65	<	1		1.5	<	1	8.06	346
363427102440401	36.5743916667	-102.7346000000	5/1/2010 1:00:00 PM		2.743		0.0227		1.307		0.0352	7.59	323.36
363427102440401	36.5743916667	-102.7346000000	4/10/2012 2:00:00 PM		2.655		0.0171		1.594		0.312	7.48	334.16
364219101394101	36.7054750000	-101.6616055556	6/11/1999 12:00:00 PM									7.8	312
364219101394101	36.7054750000	-101.6616055556	6/11/1999 12:09:00 PM		6.04	<	1		1.2	<	1		
364411102321201	36.7365861111	-102.5368444444	6/10/1999 8:00:00 AM									7.7	466
364411102321201	36.7365861111	-102.5368444444	6/10/1999 8:09:00 AM		2.84	<	1	<	1	<	1		
365223102113001	36.8731083333	-102.1917055556	4/14/1999 11:00:00 AM		1.37	<	1		1.1	<	1	7.94	303
365223102113001	36.8731083333	-102.1917055556	4/26/2010 11:00:00 AM		2.077		0.0595		1.032		0.1144	7.73	285.71
365422101083701	36.9062000000	-101.1436916667	6/11/1999 2:00:00 PM									7.6	328
365422101083701	36.9062000000	-101.1436916667	6/11/1999 2:09:00 PM		3.51	<	1		3.7	<	1		
365445100381901	36.9126527778	-100.6387472222	4/7/1999 11:00:00 AM		4.24	<	1		2.4	<	1	7.6	363

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
365445100381901	36.9126527778	-100.6387472222	4/14/2010 10:00:00 AM		3.767		0.0689		1.409		0.101	7.58	408.83
365821101375301	36.9727250000	-101.6313944444	5/28/1999 12:00:00 PM		1.54	<	1		1.4	<	1	7.4	545
365934101573001	36.9929388889	-101.9584083333	4/13/1999 10:00:00 AM	<	1	<	1	<	1	<	1	7.49	
365934101573001	36.9929388889	-101.9584083333	4/27/2010 10:00:00 AM		0.9352		0.0238		0.3169		0.3088	7.45	601.18
370358100510301	37.0662222222	-100.8507500000	4/15/1999 10:00:00 AM		1.51	<	1		2.2	<	1	7.56	323
370458101514401	37.0827500000	-101.8621111111	4/22/1999 10:00:00 AM		2.12	<	1		1.8	<	1	7.52	351
370458101514401	37.0827500000	-101.8621111111	4/25/2010 5:00:00 PM		1.958	<	0.02		1.107		0.1159	7.46	329.45
370458101514401	37.0827500000	-101.8621111111	4/10/2012 10:00:00 AM		2.674	<	0.016		1.589		0.3097	7.29	335.24
370724100281601	37.1234166667	-100.4709722222	4/23/1999 11:00:00 AM		2.9	<	1		1.9	<	1	7.48	517
371738101220301	37.2940000000	-101.3674444444	4/20/1999 10:00:00 AM		1.81	<	1		1.9	<	1	7.54	347
371738101220301	37.2940000000	-101.3674444444	3/17/2010 2:00:00 PM		2.022		0.0688		1.74		0.115	7.51	372.99
372534100443501	37.4261944444	-100.7429722222	4/16/1999 10:00:00 AM		1.43	<	1	<	1	<	1	7.58	360
372534100443501	37.4261944444	-100.7429722222	3/18/2010 10:30:00 AM	E	0.434		0.224	<	1.2	E	0.167	7	633.49
372649101344701	37.4468611111	-101.5799444444	4/19/1999 11:00:00 AM	<	1	<	1	<	1	<	1	7.64	296

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
372956099512201	37.4987777778	-99.8561388889	5/26/1999 3:00:00 PM		2.51	<	1	<	1	<	1	7.55	297
373229101193201	37.5415000000	-101.3254166667	4/21/1999 11:00:00 AM	<	1	<	1		2.8	<	1	7.46	529
373229101193201	37.5415000000	-101.3254166667	3/17/2010 10:00:00 AM		1.341		0.0741		2.636		0.1337	7.35	519.8
373345101070801	37.5625555556	-101.1188611111	4/6/1999 11:00:00 AM	<	1	<	1		1.3	<	1	7.58	345
373507102162001	37.5855500000	-102.2724555556	6/9/1999 9:00:00 AM									7.6	380
373507102162001	37.5855500000	-102.2724555556	6/9/1999 9:09:00 AM	<	1	<	1			<	1		
373527100312701	37.5908055556	-100.5240833333	4/9/1999 10:00:00 AM		3.43	<	1		1.2	<	1	7.7	283
373527100312701	37.5908055556	-100.5240833333	3/18/2010 1:00:00 PM		2.81		0.0291		2.019	<	0.03	7.4	264.87
373559102314901	37.5997444444	-102.5290666667	6/9/1999 2:00:00 PM									7.8	312
373559102314901	37.5997444444	-102.5290666667	6/9/1999 2:09:00 PM	<	1	<	1	<	1	<	1		
373732099291201	37.6255277778	-99.4865555556	5/19/1999 4:00:00 PM		1.43	<	1		1.4	<	1	7.47	288
373732099291201	37.6255277778	-99.4865555556	3/16/2010 11:00:00 AM		1.424		0.0339		1.534		0.2582	7.24	362.08
373732099291201	37.6255277778	-99.4865555556	4/12/2012 10:00:00 AM		1.397	<	0.016		1.511		0.2459	7.22	320.99
374535102110301	37.7597222222	-102.1841666667	6/8/1999 10:00:00 AM									7.7	381

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
374535102110301	37.7597222222	-102.1841666667	6/8/1999 10:09:00 AM	<	1	<	1	<	1	<	1		
374535102110301	37.7597222222	-102.1841666667	3/15/2010 2:00:00 PM		0.3261		0.1319	<	0.12	<	0.03	7.97	398.34
374650100181901	37.7805000000	-100.3053888889	4/14/1999 9:00:00 AM		1.46	<	1		1.1	<	1	7.49	370
374650100181901	37.7805000000	-100.3053888889	3/18/2010 5:00:00 PM		1.082		0.063		0.538		0.0859	7.2	955.66
375129100532301	37.8580555556	-100.8898055556	4/18/1999 3:00:00 PM	<	1	<	1		1.5	<	1	7.6	243
375447099245001	37.9130555556	-99.4137777778	5/19/1999 10:00:00 AM		2.47	<	1	<	1	<	1	7.32	1064
375828101111801	37.9743888889	-101.1884444444	4/7/1999 11:00:00 AM		2.16	<	1	<	1	<	1	7.45	862
380331100352801	38.0588888889	-100.5907500000	4/17/1999 9:00:00 AM		4.1	<	1		1	<	1	7.49	666
380331100352801	38.0588888889	-100.5907500000	3/19/2010 11:20:00 AM		4.252		0.0422		0.8545		0.0907	7.43	684.93
380331100352801	38.0588888889	-100.5907500000	4/12/2012 2:00:00 PM		4.174	<	0.016		0.8196		0.252	7.23	668.28
382947100443201	38.4963333333	-100.7421666667	4/8/1999 11:00:00 AM		6.71	<	1	<	1	<	1	7.43	601
382947100443201	38.4963333333	-100.7421666667	3/20/2010 2:00:00 PM		6.485		0.3899		0.485		0.1083	7.42	628.99
383008101315601	38.5022500000	-101.5321944444	4/28/1999 10:00:00 AM		5.29	<	1	<	1	<	1	7.78	269
383008101315601	38.5022500000	-101.5321944444	3/21/2010 12:00:00 PM		4.91		0.0812		1.037	E	0.0286	7.72	283.96

Table C.2: Central High Plains Ogallala Unit major aquifer study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
383758101195801	38.6326944444	-101.3327500000	5/22/1999 9:00:00 AM		3.45	<	1	<	1	<	1	7.51	453
383919101040101	38.6553333333	-101.0668333333	4/29/1999 12:00:00 PM		3.6	<	1		1	<	1	7.58	381
385210100164501	36.8697250000	-100.2799611111	6/7/1999 11:00:00 AM		1.21	<	1			<	1	7.4	311
385904099522201	38.9844444444	-99.8730277778	5/24/1999 10:00:00 AM		3.44	<	1	<	1	<	1	7.15	493
385904099522201	38.9844444444	-99.8730277778	3/21/2010 6:00:00 PM		4.182		0.0355		0.1484		0.1185	7.05	815.64
390622101003201	39.1060833333	-101.0086388889	5/23/1999 5:00:00 PM		2.62	<	1		1.2	<	1	7.65	365
390830102052001	39.1409722222	-102.0888333333	4/30/1999 12:00:00 PM		4.16	<	1	<	1	<	1	7.87	181
390830102052001	39.1409722222	-102.0888333333	3/22/2010 10:00:00 AM		2.29		0.0468	E	0.0985		0.0506	7.95	216.98
390838100411701	39.1440555556	-100.6882222222	5/21/1999 10:00:00 AM		4.12	<	1		1.1	<	1	7.47	282
391044100051001	39.1790277778	-100.0861111111	5/25/1999 10:00:00 AM		5.89	<	1	<	1	<	1	7.5	289
391921101385501	39.3225833333	-101.6486388889	5/20/1999 10:00:00 AM		2.04	<	1		1.3		1.183	7.84	276

Table C.3: Central High Plains public water supply well study

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
352030101224801	35.3417916667	-101.3800111111	7/23/1999 9:00:00 AM									7.54	320
352030101224801	35.3417916667	-101.3800111111	7/23/1999 9:09:00 AM		1.33	<	1		3.7	<	1		
353114100571301	35.5206638889	-100.9535472222	7/23/1999 2:00:00 PM									7.59	934
353114100571301	35.5206638889	-100.9535472222	7/23/1999 2:09:00 PM		1.22	<	1		2	<	1		
354714099465201	35.7871111111	-99.7810916667	7/24/1999 10:00:00 AM									7.37	312
354714099465201	35.7871111111	-99.7810916667	7/24/1999 10:09:00 AM		1.79	<	1	<	1	<	1		
360428102321101	36.0744111111	-102.5365083333	7/21/1999 11:00:00 AM									7.65	290
360428102321101	36.0744111111	-102.5365083333	7/21/1999 11:09:00 AM		2.33	<	1		1	<	1		
361956102043201	36.3322805556	-102.0756555556	7/20/1999 10:00:00 AM									7.65	377
361956102043201	36.3322805556	-102.0756555556	7/20/1999 10:09:00 AM	<	1	<	1		3.1		1.464		
362424100481401	36.4065305556	-100.8039666667	7/25/1999 9:00:00 AM									7.62	380
362424100481401	36.4065305556	-100.8039666667	7/25/1999 9:09:00 AM		4.9	<	1		2.6	<	1		
364411102292601	36.7364972222	-102.4906805556	7/19/1999 10:00:00 AM									7.44	407
364411102292601	36.7364972222	-102.4906805556	7/19/1999 10:09:00 AM		2.27	<	1			<	1		

Table C.3: Central High Plains public water supply well study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
365937101562401	36.9936777778	-101.9399416667	7/22/1999 11:00:00 AM									7.37	456
365937101562401	36.9936777778	-101.9399416667	7/22/1999 11:09:00 AM	<	1	<	1	<	1	<	1		
370308100544801	37.0521916667	-100.9133361111	7/25/1999 2:00:00 PM									7.77	336
370308100544801	37.0521916667	-100.9133361111	7/25/1999 2:09:00 PM	<	1	<	1	<	1	<	1		
373409101233501	37.5692944444	-101.3931111111	7/26/1999 11:00:00 AM									7.53	514
373409101233501	37.5692944444	-101.3931111111	7/26/1999 11:09:00 AM		2.35	<	1		7.9	<	1		
373529100284501	37.5913083333	-100.4792638889	7/27/1999 1:00:00 PM									7.42	309
373529100284501	37.5913083333	-100.4792638889	7/27/1999 1:09:00 PM		1.07	<	1		1.3	<	1		
374902100203501	37.8173611111	-100.3430805556	7/27/1999 9:00:00 AM									7.48	352
374902100203501	37.8173611111	-100.3430805556	7/27/1999 9:09:00 AM		1.2	<	1		1.4	<	1		
375417100531901	37.9046388889	-100.8886972222	7/28/1999 11:00:00 AM									7.66	248
375417100531901	37.9046388889	-100.8886972222	7/28/1999 11:09:00 AM		1.59	<	1		1.2	<	1		

Table C.4: Central High Plains reconnaissance study

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
363817101213101	36.6382500000	-101.3588333333	2/17/1999 11:00:00 AM									7.73	390
365610101484301	36.9361944444	-101.8121944444	2/5/1999 1:00:00 PM									7.69	379
374220100422501	37.7055833333	-100.7069722222	2/4/1999 11:00:00 AM									7.19	642
374220100422501	37.7055833333	-100.7069722222	6/28/2000 11:00:00 AM									6.93	554
375734100452301	37.9595833333	-100.7564166667	2/2/1999 11:30:00 AM									7	1058
375855100484001	37.9820833333	-100.8110000000	2/3/1999 11:00:00 AM									6.96	4916
375855100484001	37.9820833333	-100.8110000000	6/27/2000 12:00:00 PM									6.81	4512

Table C.5: Central High Plains transect study

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
370033100534201	37.0091861111	-100.8952583333	8/26/1999 10:00:00 AM									7.47	364
370033100534201	37.0091861111	-100.8952583333	8/26/1999 10:09:00 AM		2.61	<	1		1.8	<	1		
370033100534202	37.0091861111	-100.8952583333	8/26/1999 2:00:00 PM									7.59	309
370033100534202	37.0091861111	-100.8952583333	8/26/1999 2:09:00 PM		3.6	<	1		3.6	<	1		
370033100534203	37.0091861111	-100.8952583333	8/27/1999 10:00:00 AM									7.72	311
370033100534203	37.0091861111	-100.8952583333	8/27/1999 10:09:00 AM		1.67	<	1		3.2	<	1		
370033100534204	37.0091861111	-100.8952583333	8/27/1999 2:00:00 PM									7.65	331
370033100534204	37.0091861111	-100.8952583333	8/27/1999 2:09:00 PM		4.55	<	1		2.6	<	1		
370033100534204	37.0091861111	-100.8952583333	9/13/2000 9:00:00 AM									7.39	328
370130101180901	37.0250166667	-101.3026111111	8/28/1999 10:00:00 AM									7.64	381
370130101180901	37.0250166667	-101.3026111111	8/28/1999 10:09:00 AM		1.57	<	1		1.9	<	1		
370130101180902	37.0250166667	-101.3026111111	8/28/1999 2:00:00 PM									7.66	366
370130101180902	37.0250166667	-101.3026111111	8/28/1999 2:09:00 PM		1.73	<	1		2.4	<	1		
370130101180903	37.0250166667	-101.3026111111	8/29/1999 2:00:00 PM									7.5	397
370130101180903	37.0250166667	-101.3026111111	8/29/1999 2:09:00 PM		2.01	<	1		2.3	<	1		

Table C.5: Central High Plains transect study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
370130101180904	37.0250166667	-101.3026111111	8/29/1999 10:00:00 AM									7.65	372
370130101180904	37.0250166667	-101.3026111111	8/29/1999 10:09:00 AM		3.67	<	1		2.2	<	1		
370130101180904	37.0250166667	-101.3026111111	9/14/2000 8:00:00 AM									7.79	388
370402101394401	37.0673527778	-101.6624222222	8/30/1999 2:00:00 PM									7.47	862
370402101394401	37.0673527778	-101.6624222222	8/30/1999 2:09:00 PM		1.81	<	1		1.8	<	1		
370402101394402	37.0673527778	-101.6624222222	8/30/1999 10:00:00 AM									7.7	290
370402101394402	37.0673527778	-101.6624222222	8/30/1999 10:09:00 AM		2.27	<	1	<	1	<	1		
370434100405201	37.0761361111	-100.6811305556	8/31/1999 2:00:00 PM									7.15	15430
370434100405201	37.0761361111	-100.6811305556	8/31/1999 2:09:00 PM		12.08	<	10	<	1	<	10		
370434100405201	37.0761361111	-100.6811305556	10/18/2000 2:00:00 PM		9.41	<	0.37		8.34	<	0.8	7.3	15430
370434100405202	37.0761361111	-100.6811305556	9/1/1999 2:00:00 PM									7.13	404
370434100405202	37.0761361111	-100.6811305556	9/1/1999 2:09:00 PM	<	1	<	3	<	1	<	3		
370434100405203	37.0761361111	-100.6811305556	8/31/1999 10:00:00 AM									7.5	414
370434100405203	37.0761361111	-100.6811305556	8/31/1999 10:09:00 AM		1.03	<	1		1.9	<	1		
370434100405204	37.0761361111	-100.6811305556	9/1/1999 10:00:00 AM									7.59	370

Table C.5: Central High Plains transect study (continued)

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
370434100405204	37.0761361111	-100.6811305556	9/1/1999 10:09:00 AM	<	1	<	1		1	<	1		

Table C.6: Central High Plains unsaturated zone study

staid	Latitude1983	Longitude1983	Datetime	As rem	As (µgl)	Cd rem	Cd (µgl)	Cr rem	Cr (µgl)	Pb rem	Pb (µgl)	pH	TDS (mg/l)
370349101431001	37.0635000000	-101.7193333333	7/25/2000 12:00:00 PM									7.5	336
370349101431001	37.0635000000	-101.7193333333	11/29/2000 3:00:00 PM										
370349101431001	37.0635000000	-101.7193333333	8/16/2001 12:00:00 PM									7.7	
374412100453201	37.7367777778	-100.7588333333	7/10/2000 11:00:00 AM									7.43	675
374412100453201	37.7367777778	-100.7588333333	11/27/2000 6:00:00 PM										
374412100453201	37.7367777778	-100.7588333333	8/15/2001 11:00:00 AM									7.68	
374625100490701	37.7735555556	-100.8186944444	6/29/2000 11:00:00 AM									6.91	680
374625100490701	37.7735555556	-100.8186944444	8/14/2001 10:00:00 AM									7.31	

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NRAP is an initiative within DOE's Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO_2). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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