Anthropogenic Groundwater Contamination
in Texas Aquifers
Volume I

By
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**LBG
GUYTON**

Prepared for the

Texas Water Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231
August 2011

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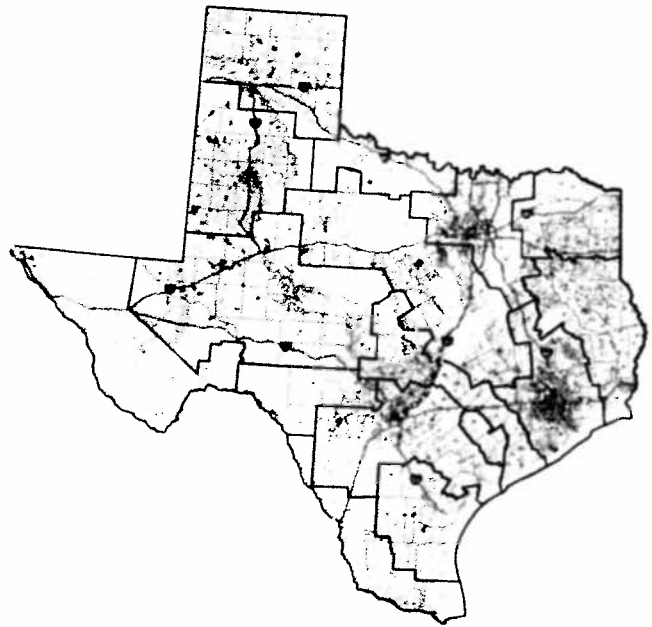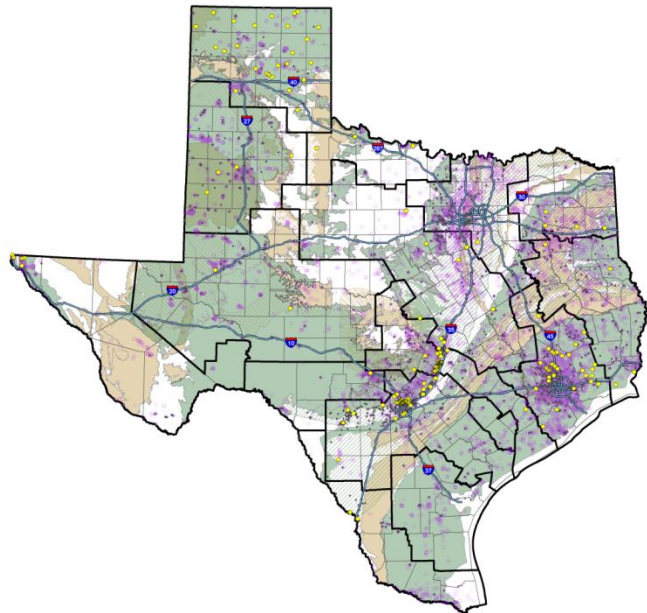P.O. Box 13231, Capitol Station
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1 Executive Summary

Anthropogenic contamination of groundwater refers to the subsurface introduction of chemical contaminants through the results of human activities. To the extent that potential or existing contaminated groundwater may impact future water supplies or water management strategies, a statewide survey of both potential sources and documented incidences of groundwater contamination in the State was undertaken to be used as a reference for future activities by the Texas Water Development Board (TWDB), Regional Water Planning Groups (RWPGs), and other affected stakeholders.

Potential sources of contamination (PSOCs) from business, industry, waste disposal, and agricultural activities were identified from databases obtained from the Texas Commission on Environmental Quality (TCEQ), the Railroad Commission of Texas (RCT), and other agencies. Over one million PSOC locations are documented in the TCEQ database which includes RCT contamination cases. The majority of these PSOCs were sites associated with mineral extraction, primarily active or abandoned oil well sites. Individual sites for all the PSOCs were located from geographic data, and a series of maps were produced that present the locations of these sites with respect to the 16 Regional Water Planning Areas, and the 9 major aquifers and 21 minor aquifers in Texas. The maps displaying proximity of PSOCs to areas of potential future groundwater development may be useful to RWPGs when considering future groundwater development as a water management strategy.

To evaluate groundwater conditions in Texas, only data describing raw groundwater, prior to any treatment or mixing, were evaluated. Documented sources of groundwater contamination were analyzed by evaluating databases with groundwater chemistry data from numerous sources, including TCEQ, the United States Geological Survey (USGS), TWDB, and others. These data were evaluated for geographic locations and any reported concentrations of the analyzed anthropogenic contaminants. A Protective Concentration Level (PCL) was determined for each chemical, based on regulatory maximum contaminant levels (MCLs) or reported Health-based Screening Levels (HBSLs). A series of maps were produced that display the locations of any

reported detections of each contaminant, and any detections greater than the PCL. Statistical summaries of the data base analyses are presented.

Contaminants with greater than 10% of samples reporting positive detections were herbicides atrazine and its metabolites, simazine, and prometon, and chlorinated compounds tetrachlorothylene (PCE), a dry-cleaning product, and chloroform, a common public water supply disinfection by-product (DBP). Atrazine was the most commonly detected compound reported in the groundwater databases, with 36% of wells and 56% of samples reporting a positive detection. However, the vast majority of all reported analytical detections are below the PCLs. Of the 32 anthropogenic chemical compounds reported in this project, 20 had no reported detections above the PCL, 10 had fewer than 1% of analyses with concentrations greater than the PCL, and only two, PCE and atrazine, had greater than 1% of detections above the PCL (2.1% and 1.1% of analyses, respectively). Maps displaying the proximity of documented contamination locations to areas of potential future groundwater development may be useful to RWPGs when considering future groundwater development as a water management strategy.

The groundwater contaminant data reviewed for this project do not indicate that groundwater contamination is widespread to the point that it threatens a significant portion of available groundwater supplies in the state of Texas. This finding is consistent with similar surveys performed by the USGS and the Edwards Aquifer Authority. Using the data available for this project, a conservative estimate of the volume of groundwater impacted by anthropogenic contamination is calculated. Cost data is provided for treatment options for contamination, to be referenced by RWPGs if development of impacted water should be selected as a water management strategy in the future.

2 Introduction

2.1 Purpose of report

Anthropogenic sources of contamination in groundwater are those chemical constituents detected in groundwater supplies that are the result of human activity and for the purposes of this report, have no natural source of occurrence. There are numerous sources for this type of impact on groundwater. The purpose of this report is to provide the Texas Water Development Board (TWDB) and Regional Water Planning Groups (RWPGs) with a centralized source of information that will be useful in the development of the Regional Water Plans and the State Water Plan. The objectives of this report are:

1. To perform a state-wide evaluation of potential sources of contamination with respect to the major and minor aquifers of the state

2. To analyze existing chemical data to determine the occurrence or prevalence of these chemicals in groundwater-sourced drinking water supplies in major and minor aquifers as indicated from existing databases

3. To estimate affected volumes of contaminated groundwater-sourced drinking water and to provide cost estimates of the treatment required to address any widespread contamination of drinking water

2.2 Organization of report

Section 1.0 of this report provides introductory information regarding the purpose and scope of the study, and background information on conditions that led to the commission of this study. A distinction is made in the presentation of report graphics between Figures and Plates. Graphics that are illustrative in nature, and are not intended to convey detailed geographic data, are folded into the text and are referred to as "Figures". Graphics that display detailed geographic data regarding business locations, water chemistry data, etc., are referred to as "Plates". Plates are presented as a separate volume of 11 x 17 color graphics.

Section 2.0 of the report provides details on the objectives, data sources, methodology, and limitations of this study.

Section 3.0 presents discussion on the various identified potential sources of contamination (PSOCs) identified through the review of the databases researched for this project, and presents mapping of selected PSOCs that could potentially impact major and minor aquifers within each Regional Water Planning Area (RWPA). Maps are provided for various groupings of PSOCs.

Section 4.0 presents the results of analysis of existing chemical databases with respect to water chemistry and the presence and extent of anthropogenic contaminants in source water. Plates are provided displaying the distribution of the most commonly detected contaminants in groundwater.

Section 5.0 provides a presentation of the methodology and results of the calculation of volumes of impacted water, and cost information for the expected treatment of the impacted water.

Section 6.0 presents a summary and discussion of the results of this study, and recommendations for further study.

2.3   State water planning

2.3.1   Regional water planning groups

Beginning in the late 1990s, the State of Texas commenced efforts at water planning to secure water supply for the state through the development of regional plans as outlined in the original Senate Bill 1. In this approach the state was divided into 16 RWPAs, each of which develops its own regional plan with local input, and these regional plans are combined to develop the State Plan. The initial plan under this structure was prepared in 2001, and has been updated every five years, most recently in 2011. The 16 RWPAs are presented in Plate 1.

2.3.2   Groundwater conservation districts

Groundwater Conservation Districts (GCDs) are districts that are created by the Texas Legislature or by the Texas Commission on Environmental Quality (TCEQ) through a local petition process. Districts have a range of required duties and are the preferred method for regulating groundwater in the state.   As of 2011, there are 98 GCDs in Texas (Plate 2), and 2

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subsidence districts. Many GCDs are defined along single county boundaries while others are multi-county districts. In some areas of the state, GCDs overlying common aquifers have teamed together not only to share staff and other resources, but also to undertake aquifer management on a regional basis. A statewide alliance has also been formed and is known as the Texas Alliance of Groundwater Districts (TAGD). The alliance provides a means of communication and exchange of information between individual districts regarding the day-to-day operation of local groundwater management. Rules governing the administration, financing, and regulatory authority of the districts vary from one to another.

2.4   Major and minor aquifer systems

2.4.1   Aquifer systems

Texas has 9 designated major aquifers, and 21 designated minor aquifers throughout the state. Several previously published documents have provided details describing the major and minor aquifers of Texas. Due to the plethora of published, publically available sources that provide details of the hydrogeology of these aquifers, minimal effort will be spent in this report repeating this data.

The 9 designated major aquifers of Texas are shown in Plate 3 and include:
- Ogallala aquifer
- Seymour aquifer
- Pecos Valley Alluvium aquifer
- Hueco-Mesilla Bolsons aquifer
- Edwards Trinity Plateau aquifer
- Trinity aquifer
- Edwards aquifer
- Carrizo-Wilcox aquifer
- Gulf Coast aquifer

The 21 designated minor aquifers of Texas are displayed in Plate 4. They are (listed approximately from west to east):
- Bone Spring-Victorio Peak

- West Texas Bolsons

- Capitan Reef Complex

- Igneous

- Rustler

- Marathon

- Dockum

- Edwards-Trinity (High Plains)

- Rita Blanca

- Lipan

- Blaine

- Ellenburger-San Saba

- Hickory

- Marble Falls

- Yegua-Jackson

- Queen City

- Sparta

- Brazos River Alluvium

- Woodbine

- Nacatoch

- Blossom

Two basic characteristics of the aquifers are important to understand when discussing groundwater contamination. The first important characteristic is the physical nature of the aquifer. Whether the aquifer is comprised of porous media (i.e., sand or sandstone) or fractured carbonate strata (karst structure) may have a significant impact on the aquifer's ability to transmit contaminants through the aquifer. In some hydrogeologic settings, karst features may provide large fractures that act as conduits for rapid transport of groundwater and any associated contaminants. The Edwards aquifer is the most productive karst type of aquifer in the state. The second important characteristic is whether or not the aquifer is exposed at the surface (unconfined, or outcrop conditions) or is buried beneath non-water-bearing strata (confined

conditions). This is significant to the aquifers' susceptibility to contamination, as will be discussed in subsequent sections. Unconfined aquifers, where there is no confining layer to impede downward percolation of contaminants introduced at the surface, are likely at greater risk for contamination from surface sources than confined aquifers. The Ogallala aquifer is the largest and most productive unconfined aquifer in the state. The major aquifers in the southern and eastern parts of the state (Trinity, Edwards, Carrizo, and Gulf Coast) have both unconfined outcrop areas along with large dipping confined segments.

Anthropogenic contamination of groundwater refers to any introduction of chemical constituents to the natural groundwater from human activity. As such, the incidence of some contamination may be correlated to the location of population within the state. Plate 5 displays the population density of Texas based on the 2010 census.

3   Objectives, methods, and limitations of study

This section of the report presents the objectives, methodology, and limitations of this study.

3.1   Objectives of study

During the preparation and development of regional and state water plans, RWPG members may require information on potential new water supply strategies, potential new groundwater sources, or the feasibility and impact of expanding existing well fields for expanded supply. Under these circumstances, RWPG members may wish to consider the potential implications of a new or expanded source being proximate to existing potential sources of contamination. One objective of this study is to present regional results of this type of mapping and analysis for easy reference for future RWPG activities.

Another objective of this study is to evaluate existing data to determine the extent and significance of any occurrence of anthropogenic contamination documented in existing databases that were reviewed for this study. To the extent that multiple sampling events are documented, any temporal trends are evaluated. Any laboratory-reported detection of a contaminant is evaluated, not just those in which established regulatory criteria are exceeded. The potential implications of siting future water projects in an area where contamination has been documented in the past may be of use to RWPG members.

After the evaluation of documented contamination, a third objective of the study is to estimate volumes of impacted groundwater using the available data that was collected for this study. Also using available data from existing studies, cost data on treatment options will be provided for use in planning, should it be desired to treat impacted groundwater to drinking water quality as a water management strategy.

3.2   Assumptions and limitations of study

3.2.1   Scale of study

It is important to note that the efforts of this study are regional, not local, in nature. The mapping that is presented covers large geographic areas, encompassing multiple counties and RWPAs. Although some of the same data is being used, this study is not intended to supersede or replace efforts such as the Source Water Assessment and Protection (SWAP) Program, in which specific individual groundwater source wells are evaluated at a local level to identify any PSOCs or documented groundwater contamination within the potential radius of influence of each of the wells.

3.2.2   Availability of data

Availability of existing data may define limitations on the extent of the study. Under the scope of this study, LBG-Guyton has collected data from numerous regulatory and governmental agencies, with the implicit assumption that these agencies have maintained the databases with the most current information. The date of transmittal for all databases is included in the analysis. LBG-Guyton can make no guarantees regarding any new data that may have been recorded after the documented data transmittal. Many of these databases are actively updated regularly by their source agencies. However, this study reflects the state of the data at the time of transmittal from the subject agencies.

Also, the scope of this project is intended to apply to potential sources of public drinking water in the State of Texas. To this end, only raw groundwater data are considered. These data are collected primarily from data for Public Water Supply (PWS) wells and untreated irrigation wells. To the extent that the TWDB database contains data for private domestic wells, these data were also included in the analysis, though no effort was made to collect additional private domestic well data.   If sampling occurred in the system after chlorination, treatment, or mixing at the entry point to the distribution system, these data are not considered.

It should be noted that many, if not most of the documented cases of impacted groundwater since the promulgation of environmental regulations in the 1980s have been on groundwater that is not used as a water supply. Site-specific groundwater contamination characterization studies

generally utilize monitoring wells clustered around a documented source of contamination. Because these monitoring wells are not used for groundwater supply and are so closely spaced as to skew data to the local level, monitor well data for groundwater contamination cases that do not impact drinking water supplies are not considered for this project.

For some of the contaminants that are not exclusively anthropogenic, such as chlorides, metals, or Total Dissolved Solids (TDS), the natural component of in-situ groundwater chemistry may be a complicating factor that could limit the clear delineation of anthropogenic contamination. Due to the ambiguity of evaluating data for contaminants that are not clearly anthropogenic in nature, these constituents are not considered in this report. The Bureau of Economic Geology (BEG) is conducting a parallel study of natural contamination of groundwater in Texas which considers naturally-occurring constituents, and these compounds are evaluated in that study.

3.2.3 Data quality

The quality of data may also be a limitation. For example, in some of the databases used for this study, there are numerous cases/points/wells etc. that have no location data recorded in their attributes. LBG-Guyton did not, under the scope of this study, attempt to gather geographic information on locations that were not clearly identified in the existing database.

Another data quality issue that may be reflected in the study results is inconsistent reported laboratory detection limits. The water quality data gathered for this project span a period of record of several decades. Over this period of time, laboratory methods have evolved and become more sophisticated, resulting in gradually decreasing detection limits for many analytical methods, resulting in the potential for detections in more recent sampling efforts that may have been reported as non-detected in previous years. Also, different data gathering efforts may generate different detection limits. For example, the recent sampling program by the United States Geological Survey (USGS) under the National Water Quality Assessment (NAWQA) program is designed to detect concentrations of contaminants well below any regulatory thresholds. To this end, they have instituted analytical methods for their project that have lower detection limits than standard environmental laboratory analytical methods. Therefore, a well sampled under the NAWQA program may result in positive detections of contaminants even if the same well had never had positive detections under previous sampling programs.

3.2.4   Natural variability of water quality and laboratory data

Data gathered in groundwater sampling programs in which wells are sampled in multiple efforts over a period of time invariably display stochastic variation in the analytical results. This is due in part to the natural variability of groundwater quality. Groundwater is continually moving through and reacting with the aquifer matrix, and this leads to the potential for variation in sampling data results. Additionally, laboratory analytical procedures reveal stochastic variation resulting from laboratory procedures themselves. Duplicate samples of groundwater collected from the same source at the same time rarely result in exactly the same concentrations of contaminants or other water quality parameters.

3.2.5   Mapping limitations

Many of the maps that are presented with this report display data on a statewide scale. This introduces a limitation of the density of data presentation and the physical scale of the maps. For example, on a state map in which the scale is 1-inch equals 100 miles, a circular data point on the map with a diameter of $1/16^{th}$ -inch covers a circular area on the map with a 3.12-mile radius, or an area of 30.7 square miles. Clearly, this area is larger than most well locations, or PSOC sites. At this scale, any sample locations within this 30.6-square mile area will have overlapping symbols. At first glance, this may give a misleading impression of a density of contaminant sites. Figure 1 displays an example of this issue. It presents the same data at three different scales. As the map scale is reduced, the true distance between the data points becomes more apparent.

In addition to scale issues, there may be issues with displaying multiple stacked significant features on a single map. For example, cities are shown in gray, but this color may be modified by the colored aquifer layer on top, and often by more features such as roads and well locations symbols, on top of the aquifer.
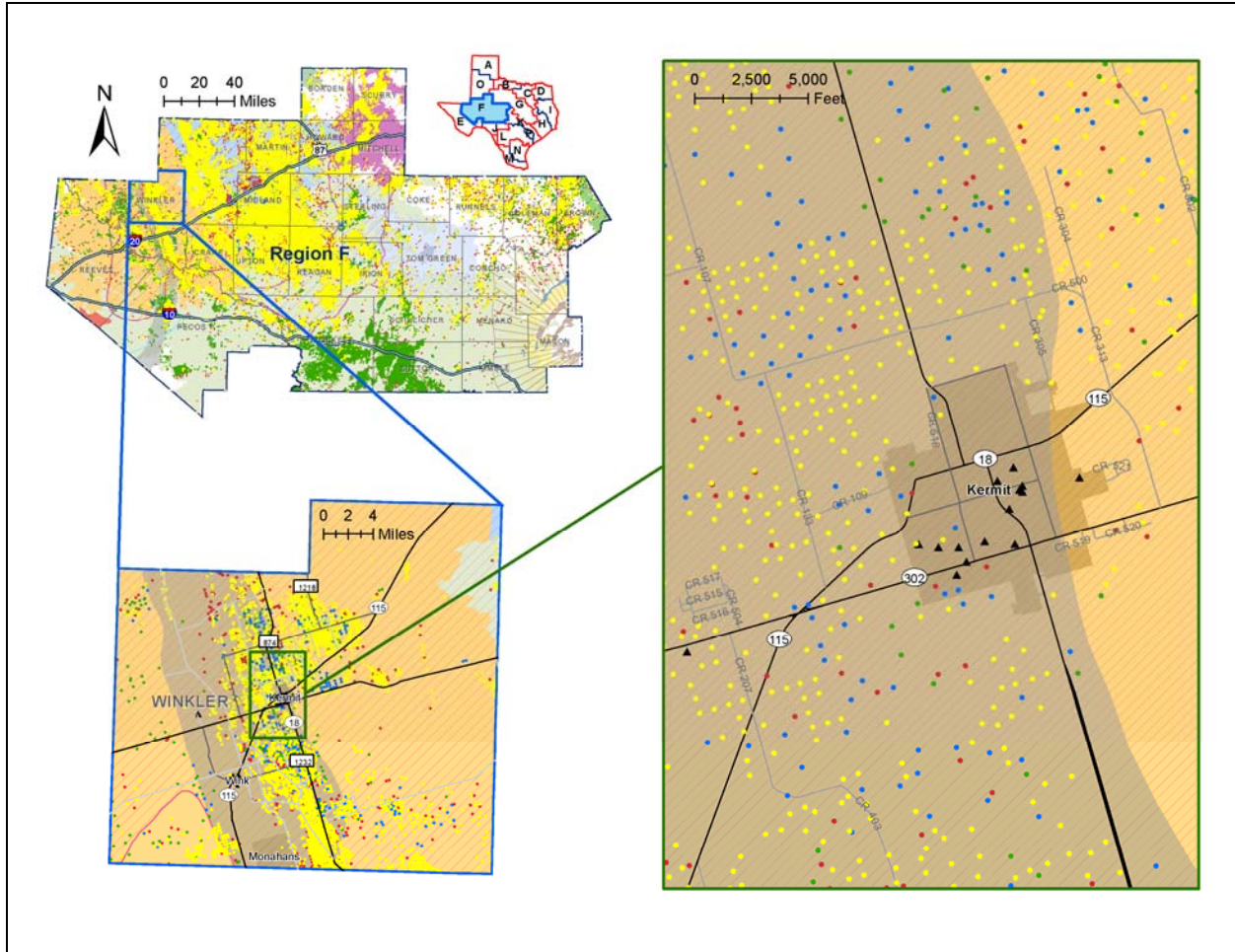
Figure 1: Map scale limitation example

3.3   Sources of data and information

This section of the report discusses the various sources of information that were referenced for this study.

3.3.1   Texas Commission on Environmental Quality

The TCEQ is the primary agency in Texas with responsibility for promulgating environmental laws and regulations. TCEQ provided the project with the SWAP database, which lists records of all registered PSOCs in the state. TCEQ also publishes an annual report titled "Joint Groundwater Contamination Report" under the direction of the Texas Groundwater Protection Committee (TGPC), which documents active and historical cases of groundwater contamination in the state.

3.3.2 Texas Water Development Board

The Texas Water Development Board (TWDB) maintains databases of well locations and physical construction details of registered wells in the state. The TWDB and its predecessor agencies have historically published hundreds of reports documenting aquifer conditions and water resource investigations in the state. Most recently, the TWDB has been the sponsoring agency in development of the Groundwater Availability Model (GAM) program in Texas, a program whose goal is to develop numerical groundwater models for all major and minor aquifers in Texas. All major aquifers have GAMs completed, and the remaining minor aquifers are scheduled for completion in the coming years. The TWDB also maintains a database of groundwater chemistry for aquifers throughout the state, although the focus of these sampling efforts is naturally-occurring, cation-anion chemistry, and not contaminant characterization. These databases are publicly maintained online and were downloaded for use in this project.

3.3.3 Railroad Commission of Texas

The Railroad Commission of Texas (RCT) has historically overseen the regulation of mineral and natural resources extraction industries in Texas, including oil and gas production, mining projects, and some pipelines. The RCT maintains a large database of oil and gas well locations, for both active production wells and inactive sites (abandoned, plugged, and dry holes). These data are updated regularly, and the most recent update at the time of this project (February 2011) was transmitted to the TCEQ for inclusion in the database of PSOC locations.

3.3.4 Bureau of Economic Geology

The Bureau of Economic Geology (BEG) is a research entity associated with the University of Texas at Austin. The BEG conducts applied research both with university funds and from competitively selected projects, including research on groundwater availability, groundwater quality, and environmental assessments. The BEG maintains a large library of research publications, updated annually. BEG data on mined lands was transmitted for use in this project. The BEG is performing a sister project to this project in which naturally-occurring groundwater contaminants such as metal, chlorides, and other compounds are evaluated.

3.3.5 United States Geological Survey

The United States Geological Survey (USGS) is a federal agency that performs primary applied research in the fields of geology, geologic hazards, and natural resources, including groundwater quality and availability. The National Water Quality Assessment (NAWQA) was started in 1991 to develop long-term data on streams, rivers, ground water, and aquatic systems in support of information needs related to decisions affecting water-quality management and policy. A major focus of the NAWQA Program in its second decade (2002-2013) is on regional- and national-scale assessments of groundwater-quality status and trends in principal aquifers (Toccalino and others, 2010). The USGS Office of Groundwater has identified 62 principal aquifers nationwide. About 1/3 of the nation's principal aquifers are the focus of water-quality assessments at the regional scale by NAWQA, including several of Texas's major aquifers; Ogallala, Edwards-Trinity System (which includes the Edwards Aquifer, Trinity Aquifer, and Edwards-Trinity Plateau Aquifer), and the Texas Coastal Uplands and Lowlands System (which includes the Carrizo-Wilcox and Gulf Coast aquifers).

3.3.6 Other – GCDs

Most GCDs participate in the activities of the TAGD to communicate on issues significant to the districts. GCDs in Texas perform some data collection within their jurisdictions with respect to groundwater quality data. However, LBG-Guyton contacted several GCD managers and found that most of the data collected is usually physical parameters that can be measured in the field, such as pH, specific conductivity, and temperature. These data were generally not applicable to the objectives of this project.

One exception to this is the data collection efforts carried out by the Edwards Aquifer Authority (EAA). The EAA was created by legislation in 1993 and commenced operations in 1996 as a special groundwater district with the purpose to manage and regulate the San Antonio segment of the Balcones Fault Zone Edwards Aquifer. In support of this mission, the EAA performs applied research and generates primary groundwater quality data. A database developed during the recent completion of a groundwater quality trends study was obtained from their website and utilized for this project.

3.3.7   Texas Groundwater Protection Committee

The Texas Groundwater Protection Committee (TGPC) is an interagency steering committee created through legislation in 1989 to improve coordination among various agencies involved in groundwater activities. Participating agencies include the TCEQ, TWDB, RCT, BEG, TAGD, Department of State Health Services (DSHS), Texas Department of Agriculture (TDA), Texas State Soil and Water Conservation Board (TSSWCB), Texas AgriLife Research (TAR), and the Texas Department of Licensing and Regulation (TDLR). The TGPC publishes an annual report on groundwater monitoring activities and cases of documented groundwater contamination associated with activities regulated by state agencies, the "Joint Groundwater Monitoring and Contamination Report" for each calendar year. The most recent database associated with this report at the time of the completion of this project (year 2009) was obtained from the TGPC and utilized for this project.

3.4   Methods of assessment

3.4.1   Data collection

Data collection represents the initial task required for completion of this study. Data was collected in two separate and distinct categories: 1) location of registered PSOCs and 2) locations of documented groundwater chemical analytical data. Data was collected from the various sources previously described in the format of published reports, web-based information, electronic databases, and other regulatory records. Data sources are discussed in Section 2.3. Mapping and data analysis were completed after the data collection task. Figure 2 displays a graphical presentation of the various databases that were utilized in the implementation of this project
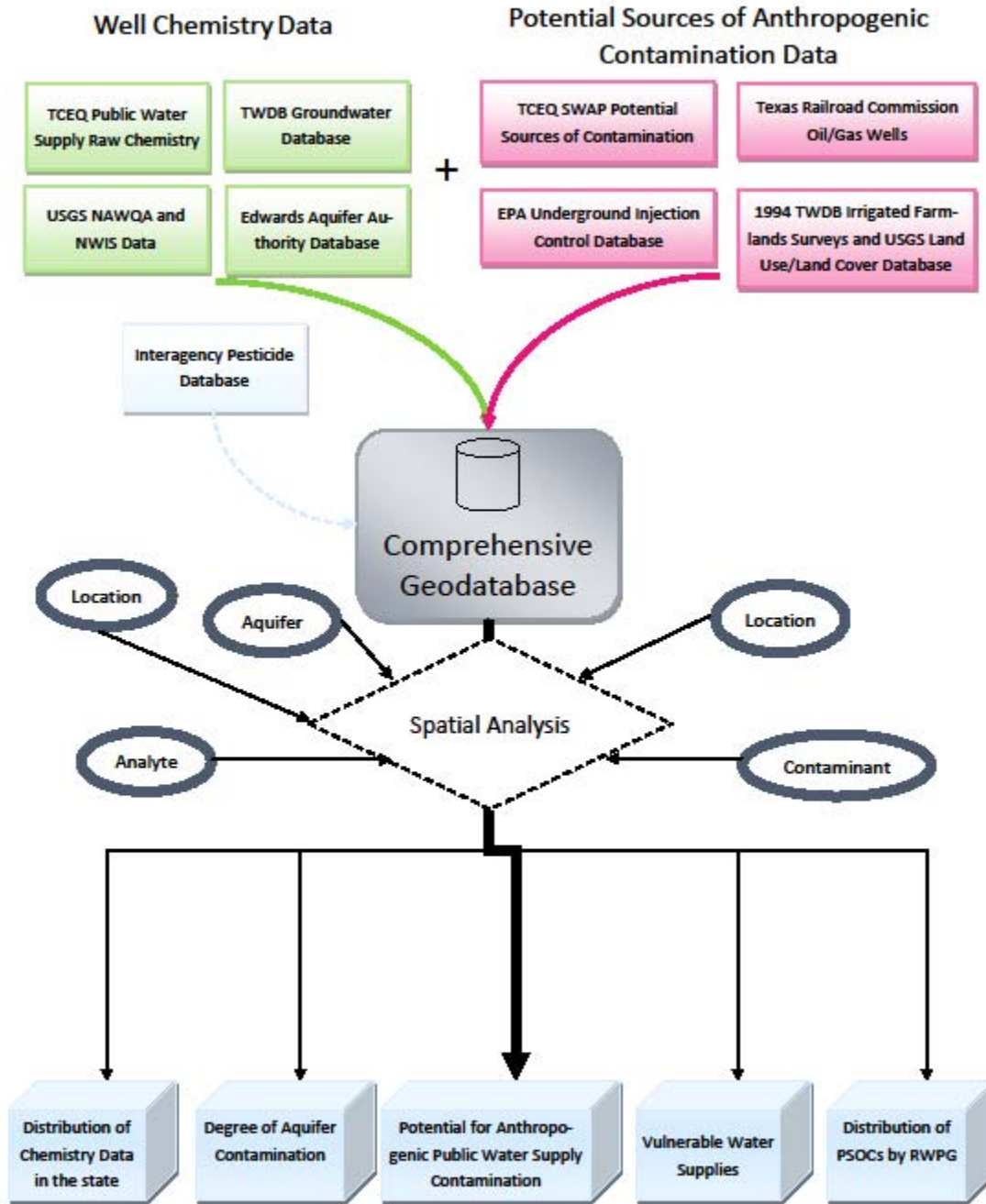
Figure 2: Database flow chart

3.4.2 *Mapping*

PSOCs were mapped by location and type. Discussion of PSOCs and details of the mapping effort are presented in Section 3.0.   As stated previously, this mapping is intended to provide an overview of the relative proximity of various PSOCs to registered PWS wells in major and minor Texas aquifers on a regional scale. This is not intended to provide a substitute for a local evaluation of source water assessment protection, in which individual wells are evaluated at a local scale for proximity to nearby PSOCs judged to potentially be within their area of influence. The SWAP Program is being administered through TCEQ; it is an ongoing program to protect drinking water sources throughout Texas, both surface water and groundwater. However, this regional display of various PSOCs may provide information to the public that could provide a starting point for a more extensive local evaluation of existing data, or help to prioritize areas that should be evaluated earlier than other areas.

In an effort to restrict the total number of maps to a manageable number, the 16 RWPAs were combined into seven groups within similar geographic regions for mapping purposes. The regions that are displayed together for mapping are:

- Regions A and O (Panhandle)
- Regions B and C (North Texas)
- Region G (Brazos River Region)
- Regions D, I, and H (East Texas)
- Regions K, L, and P (South Central Texas)
- Regions M and N (Southern Texas)
- Regions E, F, J (West Texas and Hill Country)

3.4.3 *Analysis of groundwater chemical contaminant data*

Analysis and mapping of known source groundwater contamination was completed. In this effort, chemical databases collected in the initial data collection efforts were reviewed, and the data queried for occurrences of positive detections above the associated laboratory detection limit. Maps are presented that display locations of water quality that are above ambient conditions for various chemical constituents and that are above associated regulatory threshold

concentrations for these chemicals. These mapping results are discussed and presented in Section 4.0.

3.4.4   Volume and treatment cost calculations

After evaluation of the occurrence and distribution of detectable quantities of anthropogenic contaminants documented in the various databases, a methodology was devised to estimate the volume of groundwater affected by contamination in each aquifer in the state, as well as to provide cost information for treatment options if development of impacted groundwater is pursued as a water management strategy. Details, assumptions, and limitations of this effort are discussed in Section 6.0.

4   Potential anthropogenic contamination of groundwater in Texas

This section of the report discusses PSOCs and contaminants of concern (COCs) for business, industry, waste disposal, and agriculture in the State of Texas.

Groundwater is used as a water supply source for approximately 36% of the state municipal water needs (TWDB, 2007). TCEQ documents over 22,000 public water supply (PWS) wells in the state. These wells are displayed on Plates 6 through 12. Wells with groundwater quality data are presented in Plates 13 through 19. Table 1 presents the distribution of PWS wells and groundwater data locations by RWPA.

Contamination of groundwater is commonly categorized as being either from a point source or non-point source (NPS). A point source is a single clearly identifiable source of contamination, such as a documented leak or spill at the surface. NPS contamination refers to cumulative impacts from multiple sources that are not easily delineated, such as fertilizer and pesticide application in both urban and agricultural areas.

There are two primary mechanisms for contamination of an aquifer from anthropogenic activity. In the first, a contaminant may be introduced at or near the ground surface through spills, leaks, surface application, poor storage practices, or other means. This could occur from a point source or a NPS. The chemicals introduced at the surface may then migrate through the unsaturated zone until they reach the water table. Under this mechanism, unconfined aquifers are at a greater risk for potential contamination than confined aquifers, because the confining layer by definition is comprised primarily of fine-grained materials that inhibit the transmission of water or other fluids. Some examples of this mechanism of contamination from point sources are impacts due to leaking underground storage tanks, leaky sewage lines, chemical or petroleum pipeline ruptures, percolation from municipal landfills, leaks during chemical storage and manufacturing, etc. Examples of contamination from NPSs include the application of pesticides and fertilizers to agricultural lands and urban landscaping and improperly functioning or poorly constructed septic systems over widespread areas.

Table 1: Public water supply well data

RWPA	Region Name	Operational PWS Wells	PWS Systems	Groundwater Data Locations
A	Panhandle	477	134	52
B	Region B	243	42	23
C	Region C	1,404	560	178
D	North East Texas	653	241	70
E	Far West Texas	224	81	30
F	Region F	673	181	89
G	Brazos G	1,306	551	120
H	Region H	3,491	2259	316
I	East Texas	974	437	89
J	Plateau	295	205	9
K	Lower Colorado	710	399	72
L	South Central Texas	1,023	485	108
M	Rio Grande	143	70	12
N	Coastal Bend	162	87	7
O	Llano Estacado	793	191	108
P	Lavaca	65	38	3
Unknown	*	*	*	6
Total		12,636	5,961	1,292

The second primary mechanism for introduction of anthropogenic contamination to an aquifer is through an artificial penetration (usually a well) that penetrates from the surface to deeper, confined formations. This could take the form of direct injection into a well from the surface, as in the case of oilfield brine disposal wells and industrial waste injection wells, or it could occur through the improper sealing or deterioration over time of steel well casing that isolates upper fresher aquifers from deeper aquifers of lesser quality. This situation allows vertical flow from the deeper formation to the shallower one. In this case, the conditions at ground surface are not significant, and confined formations are not necessarily buffered from the effects of contamination as they are when the source is introduced at the surface. Graphical depictions of examples of this groundwater contamination mechanism are presented on Figure 3.

It should be noted that with respect to point source contamination from past practices of industry and manufacturing, the situation has improved markedly since the creation of the United States Environmental Protection Agency (US EPA) in 1970 and promulgation of environmental regulation in the subsequent decades. Site characterization and remediation has effectively cleaned up many past contamination sites. Continuing regulation, education, and the implementation of best management practices (BMPs) now regularly mitigate further ongoing contamination that was common due to past practices.

There are numerous PSOCs due to anthropogenic activity. Table 2 presents the major PSOC Types as categorized in the TCEQ database and the distribution of these PSOC Types through the 16 RWPAs.

Table 2: PSOC distribution by RWPA

TCEQ PSOC* type	Regional water planning area																
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Total
Business	3,109	1,531	25,138	4,123	2,805	4,779	8,666	23,822	5,735	558	5,490	10,085	4,155	3,073	3,919	351	107,339
Cemetery	97	134	815	741	82	298	1,427	720	1,139	64	630	733	209	198	100	103	7,490
Chemical Pipeline	51	0	0	4	1	7	5	1	13	0	6	14	0	4	6	0	112
Chemical Storage	161	40	300	33	61	65	286	356	42	18	113	728	3	14	256	0	2,476
Class I Injection Well	47	0	5	16	0	25	7	119	66	0	30	32	5	74	3	0	429
Class II Injection Well	1,144	3,421	1,437	593	46	15,815	3,180	756	796	15	175	1,042	459	558	9,868	147	39,452
Class III Injection Well	0	0	0	0	0	0	0	0	0	0	1	7	19	107	0	0	134
Class V Injection Well	35	13	208	47	26	65	48	245	29	11	39	72	18	42	68	3	969
Gun Range	2	0	3	1	1	2	13	3	1	0	1	3	14	0	0	0	44
Natural Resource Production	52,890	111,967	58,132	41,397	3,200	207,692	163,448	48,231	57,461	2,722	20,180	76,405	43,061	61,867	41,404	11,749	1,001,806
Wastewater	324	617	8,928	1,172	1,079	384	2,979	2,993	1,842	537	3,373	4,346	209	245	706	35	29,769
Transportation	95	56	661	292	110	191	479	574	321	224	335	354	139	187	98	51	4,167
Waste	704	557	9,076	1,089	1,093	1,742	2,399	9,573	1,674	124	1,723	3,076	877	1,085	918	78	35,788
Class IV Injection Wells	3	0	4	0	0	1	0	0	0	0	0	0	0	1	0	0	9
Animal Feeding Operation	447	83	48	576	16	53	451	59	1,046	2	54	696	13	9	378	34	3,965
Total	59,109	118,419	104,755	50,084	8,520	231,119	183,388	87,452	70,165	4,275	32,150	97,593	49,181	67,464	57,724	12,551	1,233,949

*PSOC explantion of acronym

However, this report is not organized along these PSOC categories. For the purpose of discussion and presentation in this report, PSOCs are organized into four primary categories:

- Business
- Industry and manufacturing
- Waste disposal
- Agriculture
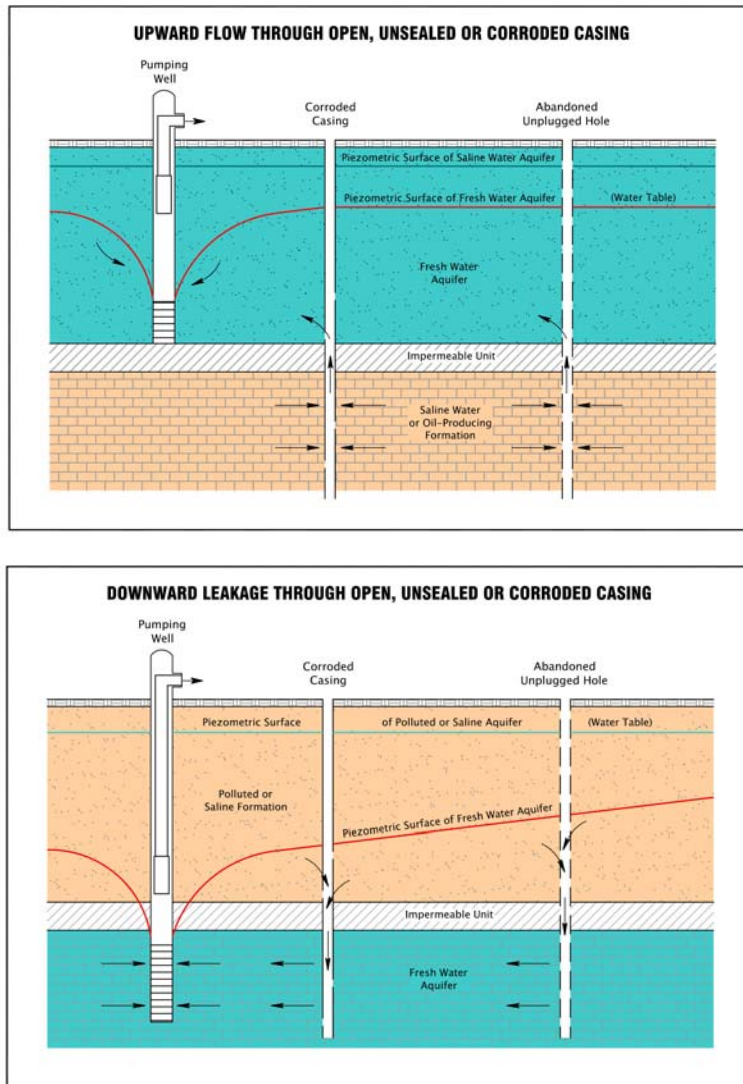
Figure 3: Subsurface source contamination mechanism

Business

Under the organization of this report, the Business category of PSOCs is defined as a for-profit venture that utilizes a dedicated retail or service location, and handles, uses, or distributes chemicals or other materials that are known to be a PSOC as defined by the TCEQ. This category does not include locations where the primary manufacturing or development of these materials is performed. Examples of PSOCs in the Business category include gas stations, dry cleaners, paint stores, automotive sales and repair, etc.

Industry and manufacturing

Under the organization of this report, the Industry and Manufacturing category of PSOCs includes entities that perform primary manufacturing and development of chemicals, petroleum products, or other compounds defined as a PSOC by the TCEQ. This category also includes the natural resource extraction industries, such as mining and oil exploration. Examples of PSOCs in the Industry and Manufacturing category include chemical manufacturing plants, petroleum refineries, oil and gas wells, chemical conveyance pipelines, etc.

Waste disposal

Under the organization of this report, the Waste Disposal classification of PSOCs includes any entity that effects the disposal of waste products created as a result of daily activities, manufacturing processes, or natural resource production. These may include both hazardous and non-hazardous materials. Examples of Waste Disposal PSOCs include municipal landfills, hazardous material storage and disposal, waste water treatment plants, some classes of injection wells, etc.

Agriculture

Irrigated agriculture is the most prevalent economic industry in the Texas Panhandle, with irrigation water supplied from the Ogallala Aquifer, although it occurs with lesser intensity in other areas and aquifers throughout the state. Agricultural activities are a contributor to anthropogenic contamination, primarily through the introduction of chemicals associated with fertilizers and pesticide application in conjunction with the application of irrigation water. The practice of irrigation induces downward migration of chemicals from the surface through the unsaturated zone, ultimately to the unconfined aquifer or water table first encountered. Unlike

the previous PSOC types discussed above, contamination from agricultural activities cannot be traced to an easily identifiable single source, or point source. Because agriculture is practiced over large areas of land, the contamination resulting from these practices may be spread out over large areas of an aquifer. Further complicating the assessment of the impact of agricultural activities on groundwater contamination is the fact that nitrate, which is a primary component of many fertilizer products, is also a naturally occurring constituent in many groundwater chemistries, resulting from the chemical reactions between natural groundwater and the soil and aquifer matrix.

However, these chemicals are not limited to rural agricultural areas. It is important to note that these chemicals are used in urban areas as lawn and garden care products and that runoff and percolation from urban areas may result in their detection in aquifers underlying major cities and high-population areas.

Silviculture, or the growth and processing of wood products, occurs most frequently in the wetter parts of the state in East Texas. Because of the natural rainfall in these areas, irrigation is not commonly applied to commercial forests, and a limited amount of fertilizer is used.

A comprehensive summary of PSOC categories as organized for the purposes of this report and distributed by RWPA is presented in Table 3.

Table 3: PSOC analysis summary by RWPA

Row Labels	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Unk	Grand Total
Animal Feeding Operation	447	83	48	576	16	53	451	59	1,046	2	54	696	13	9	378	34	25	3,990
Other CAFO	141	10	39	426	2	9	167	52	239	2	34	561	5	4	76	17	8	1,792
Beef	181	66	8	150	14	42	281		804		12	124	8	5	297	17	14	2,023
Chicken		2	1				2				6	11						22
Swine	125	5				2	1	7	3		2				5		3	153
Business	3,092	1,516	25,018	4,089	2,790	4,740	8,614	23,724	5,694	552	5,443	10,024	4,135	3,055	3,892	348	5	106,731
Other Businesses	43	12	258	27	35	28	58	234	45	2	61	88	22	15	45			973
Battery Mfg., Sales	8	2	62	3	8	7	14	38	8		6	15	6	9	9			195
Composting Facility											2							2
Fireworks Business	8	5	34	8	12	5	8	49	18		13	7	5	3	11			186
Golf Course	19	2	21	7	3	8	19	44	7	2	13	26	2	2	14			189
Machine Shop-Metal Working								2										2
Metal Plating Business			29	3	3	1	4	29	5		1	10			1			86
Military Armory	1					1		1			1							4
Photo Process Business	7	3	112	6	9	6	13	71	6		25	30	9	1	9			307
Sugar Refining								1							1			2
Auto Business	775	378	7,599	1,019	962	1,102	2,268	6,965	1,394	161	1,495	2,868	1,420	711	804	66		29,987
Auto Parts Business	43	22	386	87	72	62	156	335	59	11	56	156	66	40	48	6		1,605
Auto Repair, Sales, Salvage, Towing	629	315	6,121	749	709	864	1,788	5,675	1,104	128	1,240	2,216	1,083	543	627	54		23,845
New Or Used Oil Site	52	19	483	83	77	88	166	331	124	8	110	217	89	50	69	5		1,971
Tire Sales, Repair Business	51	22	609	100	104	88	158	624	107	14	89	279	182	78	60	1		2,566
Cotton Gin		2	5		1	37	18	4			4	1	1	9	213			295
Dry Cleaner	39	16	622	58	30	66	118	460	72	5	90	135	50	22	32	5		1,820
Fertilizer/Petsticide Mfg	269	95	3,178	265	190	240	889	2,601	454	61	738	1,140	309	254	302	21		11,006
Fertilizer Mfg, Sale, Application	3	3	14	2			2	9	3		7	7	1	1	1	1		54
Pesticide Mfg, Sale, Application	56	17	512	55	92	65	168	486	85	14	105	224	68	57	52	3		2,059
Pesticide, Fertilizer Mfg, Sale, Application	210	75	2,652	208	98	175	719	2,106	366	47	626	909	240	196	249	17		8,893
Grain Elevator	238	8	26	7		17	65	21	1		13	12	8		184	2	3	605
Chemical Mfg	174	22	110	46	9	65	41	444	90	3	34	79	7	45	52	2		1,223
Inorganic Chemical Industry	2	2	34	4	2	5	2	54	4		1	7	2	4	3			126
Oil And Gas Production Tanks	146	19	7	32	2	40	27	288	57		29	60	3	18	42			770
Organic Chemical Industry	3		19	1	1	3	2	27	5	1	2	3	1	2	1			71
Petroleum Chemical Industry	23	1	50	9	4	17	10	75	24	2	2	9	1	21	6	2		256
Nuclear Power Plant							2					2						4
Paint Shop	85	26	790	108	64	113	268	592	125	16	140	283	105	67	67	9		2,858
Petroleum Storage Tank	1,423	926	11,876	2,476	1,425	2,948	4,719	11,666	3,369	297	2,748	5,179	2,129	1,839	2,150	237	2	55,409
Plastic Mfg, Sale	3	2	214	13	24	17	37	201	15	1	23	45	13	7	3	2		620
Silviculture			18	4	3	2	1	11	6		1	3	1					50
Pulp Or Paper Mill			14	3				8	3			2	1					31
Wood Preserving			4	1	3	2	1	3	3		1	1						19
Radiochemical Site	43	29	322	66	47	105	130	525	123	6	94	191	70	86	40	4		1,881
Cemetery	97	134	815	741	82	298	1,427	720	1,139	64	630	733	209	198	100	103	17	7,507
Chemical Pipeline (Miles)	16,094	3,339	11,916	6,801	2,406	33,863	26,947	20,232	15,734	643	6,586	10,368	7,436	14,331	7,637	2,689		187,022
Chemical Storage	161	40	300	33	61	65	286	356	42	18	113	728	3	14	256		2	2,478
Other Chemical Storage	11		73	3	2	5	86	71	7	1	22	193		3	53			527
Chemical Mixing Site							28								4			32
Drum, Small Containers, Bags	10		72	2	2	3	56	62	7	1	22	188			19			444
Transformer	1		1	1		2	2	9				5			30			51
Chemical Storage	150	40	227	30	59	60	200	285	35	17	91	535	3	14	203		2	1,951
Class I Injection Well	47		5	16		25	7	119	66		30	32	5	74	3			429
Class II Injection Well	1,144	3,421	1,437	593	46	15,815	3,180	756	796	15	175	1,042	459	558	9,868	147		39,452
Class III Injection Well												1	7	19	107			134
Class IV Injection Well	3		4			1									1			9
Class V Injection Well	35	13	208	47	26	65	48	245	29	11	39	72	18	42	68	3		969

Table 3: PSOC analysis summary by RWPA

Category	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total
Agricultural Drainage					11					1				98				110
Auto Repair Floor Drain	31	2	3	2	1	5	8	4	2	1	1	4	4	5	45			118
Cesspool										1			4					5
Class V Injection Well	3	13	173	32	84	12	73	125	46	1	98	17	5	8	80	2		772
Septic Drainfield				1	1	1	3	2			2			1				11
Septic Undifferentiated	1	1	18	11	2	14	71	1	23	5	9	9	1	7	1			174
Storm Drainage									1		2		2					5
Untreated Sewage	2										2			1				5
Natural Resources Production	57,435	131,203	65,531	43,549	3,077	233,189	181,294	50,064	61,485	3,197	21,041	86,352	45,829	65,691	44,135	12,381	1	1,105,454
Mined Land: Active or Abandoned	501	230	1,168	285	588	2,384	1,827	760	378	121	916	1,516	304	388	598	34	1	11,999
Oil/Gas Well: Active/Permitted	34,068	53,041	30,305	16,939	1,239	123,118	61,227	15,513	26,104	1,445	5,837	35,057	20,103	20,534	25,621	3,667		473,818
Oil/Gas Well: Inactive	22,866	77,932	34,058	26,325	1,250	107,687	118,240	33,791	35,003	1,631	14,288	49,779	25,422	44,769	17,916	8,680		619,637
Transporation	95	56	661	292	110	191	479	574	321	224	335	354	139	187	98	51	84	4,251
Airport	77	37	243	79	101	136	260	190	85	203	159	249	107	87	81	25	2	2,121
Airport	60	29	224	72	36	69	205	143	64	59	106	144	62	47	65	22		1,407
Landing Strip	17	7	18	6	64	66	50	46	21	142	52	95	45	35	15	3	2	684
Military Air Base		1	1	1	1	1	5	1		2	1	10		5	1			30
Heliport	1	2	97	16	7	3	36	159	32	2	24	32	9	14	6	1		441
Watercraft	17	17	321	197	2	52	183	225	204	19	152	73	23	86	11	25	82	1,689
Boat Ramp	15	17	246	130	1	39	129	96	148	15	80	64	8	66	9	24	61	1,148
Marina	2		75	67	1	13	54	129	56	4	72	9	15	20	2	1	21	541
Waste	704	557	9,058	1,080	1,093	1,737	2,396	9,570	1,671	122	1,720	3,073	877	1,085	910	78	6	35,737
Other Waste	6	10	69	2		1	2	78	10		3	1	1	3	1			187
Coal Combustion Product Disposal								1										1
Municipal Setting Designation			68	1				3	7					1	1			81
Oil Field Sludge Disposal	6	10	1	1		1	2	52	3				1		2			79
Salt Water Disposal Pit								22							1			
Recycling Facility												3						3
Contamination Sites	536	412	8,348	799	1,020	1,459	1,869	8,785	1,332	78	1,436	2,444	717	821	689	52	6	30,803
Groundwater Contamination Site						1									1			2
Innocent Operator Program		1	166	2	1	4	35	94	19	1	10	11	5	3	3		1	356
Perchlorate Site	1			2			1											4
Site Discovery-TCEQ	65	34	211	59	23	65	124	286	91	1	30	86	73	34	175	5	1	1,363
TCEQ Voluntary Cleanup	8	13	518	41	8	21	89	442	38		87	74	32	18	19	4		1,412
TCEQ Waste Registration	399	345	6,940	571	923	1,203	1,468	7,304	1,006	69	1,193	2,028	536	656	422	41	1	25,105
TCEQ Brownfields Sites			14	3	2	1	4	9	3		6	7	1		1		2	53
TCEQ Corrective Action Sites	60	19	483	105	61	152	143	609	152	7	108	225	66	104	66	2	1	2,363
Superfund Site	3		16	16	2	12	5	41	23		2	13	4	6	2			145
Industrial Hazardous Waste TSD	11	3	40	19	9	18	20	149	39	2	12	16	4	20	3			365
MSW-Abandoned	70	55	386	126	20	125	233	317	149	22	179	463	75	181	114	5		2,520
MSW-Active	81	77	215	134	44	134	272	241	141	20	90	149	80	60	103	21		1,862
Wastewater	256	570	8,541	837	1,018	287	2,496	1,877	1,562	519	3,209	3,963	83	126	599	13	2	25,958
Cesspool	1														82			83
Agricultural Wastewater Outfall	3			1		1	6				1	1			4			17
Private Wastewater Outfall	6	2	68	50	7	8	63	347	60	5	54	30	18	9	4	2		733
Industrial Wastewater Outfall	54	13	138	155	14	44	152	677	290	1	64	173	56	92	28	3		1,954
Land Application Sludge		4	49	19	1	3	58	53	29		22	15	4	4	3	1		265
Liftstation			2	148		1	3	4	22	3		4		5	1	1	11	205
Septic System	188	548	8,116	602	995	223	2,186	704	1,157	512	3,040	3,710	2	17	456	4	2	22,462
Treatment Plant	4	1	22	10		5	27	74	23	1	24	29	2	3	11	3		239
Grand Total	63,516	137,593	111,626	51,853	8,319	256,466	200,678	88,064	73,851	4,724	32,790	107,076	51,789	71,147	60,307	13,158	142	1,333,099

4.1   Business

4.1.1   Petroleum storage tanks

The single most numerous type of business sites that has historically caused groundwater contamination is associated with petroleum storage tanks (TGPC, 2010). These businesses are primarily gas stations, although other businesses may operate onsite petroleum storage tanks. The general mechanism for this contamination is the leaking of petroleum products from underground tanks into the subsurface. If the groundwater surface is relatively shallow, the released gasoline (or other petroleum product) may reach the water table and cause contamination to the aquifer. Although the leak may not pose any immediate threat to drinking water sources, cleanup is still mandated by state and federal regulation. The regulatory programs implemented to address these cases are discussed in more detail in Section 4.

The primary contaminants of concern (COCs) for petroleum storage tanks are fuels such as gasoline and diesel and fuel components. The fuel components most frequently referenced and detected are benzene, toluene, ethylbenzene, and xylenes (BTEX), which are contained in both diesel and gasoline. Another commonly detected COC associated with petroleum storage tanks is methyl-tert butyl ether (MTBE).

Plates 20 through 26 display the locations of registered petroleum storage tanks as documented in the TCEQ PSOC database. Table 3 includes the number of petroleum storage tanks per RWPA documented in the PSOC database.

4.1.2   Automotive business sites

The second most numerous type of business in the PSOC business category is automotive businesses, including sales, repair, salvage, and tire facilities. The primary COCs at automotive business sites are gasoline, diesel, BTEX/MTBE, and other fuel components. Salvage and repair facilities may also handle chlorinated solvents associated with engine parts cleaning, including degreasing agents such as perchloroethene (PCE), also known as tetrachloroethylene, and trichloroethene (TCE) and their breakdown products, and used automotive oil, which commonly includes concentrations of metals such as lead and chromium which may be classified as

contaminants if they reach the groundwater. Traditional industry solvents such as TCE and 1,1,1 trichloroethane (TCA) have the advantage of rapidly dissolving oils and greases on parts, and of rapidly evaporating thereby minimizing drying time.

Plates 27 through 33 display the locations of automotive businesses as documented in the TCEQ PSOC database. Table 3 includes the number of automotive business sites per RWPA documented in the PSOC database.

4.1.3 Other businesses with PSOC's

Dry cleaning operations in the past have used industrial solvents such as PCE and TCE to perform their operations and have managed these chemicals with onsite storage. Other common COCs associated with dry cleaning operations include degradation products of PCE, including 1,1,1-TCA, cis-1,2-dichloroethylene (cis-1,2-DCE), carbon tetrachloride, and vinyl chloride. Leaking underground storage tanks containing these chemicals have the potential to contaminate groundwater. Past cases of groundwater contamination from dry cleaners have been numerous enough to warrant the development of a special program by the TCEQ to assist with funding and remediation of former dry cleaner sites (TGPC, 2010).

Paint shops are also among the more numerous of business types with PSOCs in the database. COCs associated with paint shops include chlorinated solvents used as paint thinners, and metals that are used as color tints.

Metal plating shops use a number of chemicals in their operations including solvents, acids, bases, as well as cyanide and metal compounds. The primary function of solvents in the metal plating industry is for the cleaning of parts. Traditional industry solvents such as TCE and 1,1,1-TCA are used as degreasers. Acids and bases are used in oxidizing, plating, and stripping baths and in the waste treatment process. Cyanide compounds are used in plating baths. Finally, metals (e.g. cadmium, chromium, nickel, etc.) are coated onto parts in metal plating shops to increase wear resistance, corrosion resistance, or for enhanced appearance.

Plates 34 through 40 display the locations of these and other miscellaneous businesses as documented in the TCEQ PSOC database. Table 3 includes the number of selected other business with PSOCs per RWPA documented in the PSOC database.

4.1.4 *Transportation-related activities*

To the extent chemicals that may be considered potential groundwater contaminants are transported by truck or rail, the location of arterial transportation corridors as they overlie or coincide with aquifer outcrops may be significant to potential incidence of groundwater contamination. The TCEQ is responsible for oversight of cleanup of surface spills from truck or rail accidents and compiles annual data on such occurrences. Table 4 presents recent data on surface spills obtained from TCEQ that have required an onsite investigation. There are several hundred such incidents each year, ranging from a low of 438 spills in 2009 to a high of 731 in 2007.

Table 4: TCEQ surface spill incidents requiring onsite investigation

Year	2005	2006	2007	2008	2009	2010
Number of Cases	549	666	731	491	438	462

Plates 41 through 47 display transportation elements that may be relevant to potential cases of groundwater contamination in major and minor aquifers, including highways, railroad lines, airports, marinas, and military air bases.

4.2 Industry

As discussed previously, under the organization of this report Industry and Manufacturing PSOCs include entities that perform primary manufacturing and development of chemicals, petroleum products, or other compounds defined as a PSOC by the TCEQ. This category also includes the natural resource extraction industries such as mining and oil exploration.

4.2.1 Chemical industry sites

The term "chemical industry" is applied to those industries engaged in the production of chemical compounds most of which are used directly in industry or by further conversion. The production of chemicals in Texas makes up the largest manufacturing industry in the state. Chemical industry sites include organic chemical manufacturing, inorganic industrial chemical manufacturing, petroleum chemical industry locations, and finished chemical products such as detergents, soaps, paints, and pharmaceuticals.

Chemical manufacturing takes place throughout Texas, but historically the greatest growth and highest concentration of chemical industry sites has been along the Gulf Coast, primarily between Houston/Galveston Bay and the Louisiana state line, where plants may take advantage of the cheap water transportation available in the Houston Ship Channel, the Sabine-Neches Waterway, and the Sabine Pass Ship Channel. This area has come to be referred to as the "spaghetti bowl" for its intricate network of channels and pipelines for the conveyance of chemical products throughout the region. Most of the chemical industry in this location has developed in support of the petroleum and refining industries sited here since oil was first discovered in Texas. Inland areas such as Dallas, Borger, Longview, and Midland are also noted industrial areas. (The agricultural chemical industry is discussed in section 3.3.2.)

Industrial inorganic chemicals include those produced from raw materials such as salt, sulfur, sea water, oyster shells, and other material. These materials and the resulting industry locations are also located primarily along the Gulf Coast.

Plates 48 through 54 display Chemical Industry site locations in the database, including organic, inorganic, and petrochemical manufacturing sites, as well as oil and gas production tanks. Table 3 includes the number of chemical industry sites per RWPA documented in the PSOC database.

4.2.2 Fertilizer and pesticide industry sites

Fertilizer and pesticide production is a part of the greater chemical industry in the state, but is discussed separately because it is somewhat distinct in purpose and locale from the petroleum-dominated chemical manufacturing industry. In West Texas and on the High Plains, demand has been strong for agricultural chemicals. Texas has been the leading state in the production of

ammonia-based fixed nitrogen fertilizers, important for the economic support of the farming industry in the state.

Plates 55 through 61 display the locations of documented fertilizer and pesticide industry sites documented in the TCEQ PSOC database. Table 3 includes the number of fertilizer and pesticide industry sites per RWPA documented in the PSOC database.

4.2.3   Oil and gas wells

Since the first commercial oil well was completed in Texas in 1866, oil and gas production has been an important part of the state's economy. Oil production peaked in the first half of the twentieth century, followed by a period of declining well yields. Currently there is a new wave of exploration for natural gas, primarily in the Barnett Shale in north central Texas, the Haynesville Shale in east Texas, and the Eagle Ford Shale in south central Texas. Enhanced production from formations previously developed has been made possible in recent years by hydraulically fracturing (or "fracking") shales and other tight formations that had previously produced all that could be economically recovered via traditional methods. Those interested in detailed information on the geology of oil and gas reservoirs in Texas are directed to the BEG publications "Atlas of Major Texas Oil Reservoirs" (Galloway et al, 1983) and "Atlas of Major Texas Gas Reservoirs" (Kosters et al, 1989).

Oil and gas production is usually accompanied by large volumes of produced brine, or saline water, characterized by a high concentration of Total Dissolved Solids (TDS). Wells generally produce increasing amounts of brine with age. Produced brine is a major contaminant in the state's aquifers. In the early period of the state's oil and gas development, brine disposal was not regulated and was often discharged into unlined pits which had the potential to leak brine to the underlying groundwater and/or overflow into surrounding surface water. This practice was halted by the Railroad Commission of Texas in a statewide no-pit order effective January 1, 1969 (Texas Water Commission, 1989). Table 5 presents ranges of constituents found in a typical oil field brine.

Table 5: Range of constituents found in a typical oil field brine

Element	Range (ppm)
Sodium	12,000 to 150,000
Potassium	30 to 4,000
Lithium	1 to 50
Rubidium	0.1 to 7
Cesium	0.01 to 3
Calcium	1,000 to 120,000
Magnesium	500 to 25,000
Strontium	5 to 5,000
Barium	0 to 1,000
Chloride	20,000 to 250,000
Bromine	50 to 5,000
Iodine	1 to 300
Source: Miller and others, 1977	

After this, the most prevalent method of brine disposal became injection wells constructed for disposal, or re-injection of the brine into the producing zones to augment further recovery. An injection well used for either brine disposal or re-injection of brine for augmented oil and gas production is classified as a Class II injection well. When injecting brine into deep formations, it is essential that there be no hydraulic connection between the injection zone and any fresh water zone, or underground source of drinking water (USDW), because high injection pressures may cause upward migration of brines into overlying strata. Additionally, injection pressures must be monitored to prevent unintentional fracturing of the injection zone, potentially creating vertical pathways for migration of brine.

In addition to the possibility of upward migration through the geologic formations, another and possibly more prevalent mechanism for migration of brine into fresh water formations is leaking through improperly abandoned wells and deteriorated well casings. Brine is highly corrosive. If well casings are not coated with plastic or other inert material, the steel casing may deteriorate over time. Corroded or unsealed casings may provide a preferential pathway for the migration of brines. Deeper saline zones with a higher pressure than shallower freshwater zones may impact

the fresh water zones through upward interaquifer flow via the conduits provided by deteriorated casings.

In addition to brines, a variety of other chemicals are used in oil and gas exploration and development, including drilling fluids (which may contain various chemical additives), acids and other chemicals used to treat wells, corrosion inhibitors (which may include arsenic compounds), fuels, and various other substances. These may also be transported through the conduits provided by the casings.

Plates 62 through 68 display active oil and gas wells listed in the PSOC database within the established RWPA groups. Plates 69 through 75 display inactive wells documented as abandoned, plugged, or dry holes. Table 3 includes the number of oil and gas wells per RWPA documented in the PSOC database.

4.2.4 Pipelines

Pipelines are used to convey chemical products between industrial plants, from industrial plants to shipping ports, and from the site of extraction to shipping centers. Pipelines cross over nearly every aquifer in the state, but are especially dense in areas of oil production and industrial chemical manufacturing.

The RCT maintains a database containing the locations of industrial transport pipelines in the state. The locations of pipelines conveying crude, refined petroleum, natural gas, or chemical materials are presented in Plates 76 through 82.

4.2.5 Mining

Mining activities in Texas refer to operations that extract and process geologic materials, ores, and minerals. In this context, a "mined land" might refer to anything from a massive strip mine for coal and lignite to a small caliche pit or gravel pit to collect aggregate for local cement production. The small scale caliche and gravel operations are usually registered business, but in general these operations do not generate a significant potential for groundwater contamination.

The three most prevalent types of large-scale mining in Texas are mining of coal and lignite, uranium, and aggregate quarries (limestone, sand, and gravel). Mining may be performed via surface methods (quarrying, open pit mines), underground methods (construction of shafts to reach deeper ore), or solution mining, in which heated water or chemicals is injected into a subsurface strata via wells to dissolve the ore, and the mixed solution is pumped to the surface for processing. Mining activities have the potential to impact groundwater through mine drainage, surface stockpiling of mined material, dewatering activities, or runoff from chemical processing activities, among other mechanisms.

4.2.5.1 Coal and Lignite Mining

Coal mining has taken place in Texas since the 1800's. Most of the deposits worked through the 1940's were mined using underground methods, with shafts and adits used to access the seams. Since the 1950's, surface mining methods have predominated, employing dragline sidecasting or scrapers to access the deposits.

Prior to 1977 coal mining in Texas was essentially unregulated. In August 1977 the Surface Mining Control and Reclamation Act (SMCRA) was enacted, and all coal mining since is performed under this regulation. Mining companies that had operated and abandoned any mine sites prior to the passing of SMCRA were not required to be reclaimed. Plate 83 displays the locations of these sites.

Texas lignite occurs primarily in three geologic units: the Wilcox Group, the Jackson Group, and the Yegua Formation. Of these, lignite from the Wilcox is the best grade, the Yegua is intermediate, and the Jackson group is the poorest grade lignite in Texas. As of January 2011, 21 coal mining locations were permitted by the Railroad Commission of Texas in the state (Plate 83).

Surface mining may be accomplished without permanent damage to the local environment if proper practices are followed and a responsible reclamation program is implemented post-mining. If proper materials handling and disposal practices are not adhered to, surface mining has the potential to result in conditions and waste that could affect the quality of groundwater in

the vicinity. The primary mechanisms for groundwater contamination near a surface mine are acid mine drainage. Rain water or groundwater may pass through sulfide minerals in tailings, spoils piles, or the mine. Chemical reactions between the sulfide minerals and the water may result in the generation of sulfuric acid, which could then run off into surrounding surface water or percolate into the groundwater below. Acid-bearing water is the most prevalent cause of groundwater pollution near mines. In response to documented conditions from past practices nationwide, all permitted mining operations are now required to implement a post-closure reclamation plan to reduce or prevent the off-site migration of acid mine drainage.

Although coal mining has occurred in Texas since the 1800's, little evidence of groundwater contamination has been documented, beyond immediate and local effects. LBG-Guyton performed a file review of groundwater monitoring data for permitted coal and lignite mines in the state, and found no significant or widespread documentation of contamination to the surrounding groundwater. However, any future production wells planned in the vicinity of lignite mines should undertake local investigation and characterization of water chemistry prior to implementation. This site characterization is part of the permitting process with the RCT.

4.2.5.2 In-Situ Mining

In-situ mining uses injection well techniques to dissolve the mined mineral in the subsurface prior to pumping the solution back to the surface for processing. The fluid injected may be water, heated water, or a chemical solution designed to achieve maximum dissolution of the mined mineral. Minerals that are mined using this technique include brine, sodium sulfate, and sulfur. However, the primary mineral mined using in-situ methods in Texas is uranium. These are regulated under the Class III injection well program. Plate 84 displays the location of uranium mining operations in Texas.

4.2. 5.3 Sand and Gravel Mining

By far the most prevalent mining activity in the state in terms of the number of locations is the near-surface extraction of sand, gravel, clay, caliche, quarried rock, and other common earth materials used for construction and industrial applications such as sand blasting, cement and

concrete ready mix, masonry, etc. Sand is also used in fracking operations for oil and natural gas recovery. The mining process is generally simple and performed using excavators, backhoes, and other earth-moving equipment.

There are over 12,000 locations of mined lands present in the PSOC database. These locations and the river or stream bodies they are often near are presented on Plates 85 through 91. Table 3 includes the number of mining sites per RWPA documented in the PSOC database.

4.3 Waste Disposal

This section of the report deals with known and potential sources of groundwater contamination associated with the disposal of waste products from human activities. These activities include various classes of land-based disposal, various classifications of injection well disposal, and various aspects of wastewater treatment and transmission.

4.3.1 Land-based disposal

Most waste products generated by individuals, businesses, municipalities, and industry are disposed of on the land surface. Sites of land-based disposal may become a source of groundwater contamination. As water percolates through the waste materials, it can dissolve constituents of the solid waste into a liquid waste known as leachate. Leachate is a highly mineralized fluid which may be characterized by a variety of organic chemicals, metals, chloride, nitrate, and sodium. The type of waste disposed of at a site determines the characteristics of the leachate generated. Both the leachate and the contaminated water may migrate downward through the unsaturated zone, and ultimately to the water table. Table 6 presents typical characteristics of leachate from municipal landfills.

Table 6: Leachate characteristics from municipal solid waste

Components	Median Value (mg/L)	Range (mg/L)
Alkalinity	3050	0 – 20,850
Biochemical Oxygen Demand	5700	81 – 33,360
Calcium	438	60 – 7,200
Chemical Oxygen Demand	8100	40 – 89,520
Copper	0.5	0 – 9.9
Chloride	700	4.7 – 2,500
Hardness	2750	0 – 22,800
Iron	94	0 – 2,820
Lead	0.75	<0.1 – 2.0
Magnesium	230	17 – 15,600
Manganese	0.22	0.06 – 125
Nitrogen (NH_4)	218	0 – 1,106
Potassium	371	28 – 3,770
Sodium	767	0 – 7,700
Sulfate	47	1 – 1,558
Total Dissolved Solids	8955	584 – 44,900
Total Suspended Solids	220	10 – 26,500
Total Phosphate	10.1	0 – 130
Zinc	3.5	0 – 370
pH	5.8	3.7 – 8.5
Source: Novotny and Chesters		

Municipal Landfills

Landfills are the most common method of disposal of general municipal waste in Texas. Municipal landfills receive solid waste from private residences, small businesses, and other commercial activities. Municipal Solid Waste (MSW) is defined as "solid waste, resulting from or incidental to municipal, community, commercial, institutional, and recreational activities, including garbage, rubbish, ashes, street cleanings, dead animals, abandoned automobiles, and all other solid waste other than industrial solid waste" (30 TAC Chapter 330, Subchapter A). In the past, landfills were sited with little consideration of groundwater or hydrologic conditions in the vicinity. As a result of past practices, there were many cases of poorly designed landfills

contributing to local groundwater contamination. There have been more than 700 MSW landfill closures in Texas since 1986, largely due to the more stringent regulatory requirements of the Federal Resource Recovery and Conservation Act (RCRA) Subtitle D. However, since the late 1990s, this trend has leveled out with approximately 217 MSW facilities reporting. Even with the reduced number of landfills, available capacity has grown in the past ten years, indicating a continued trend away from smaller community landfills to larger regional operations, as well as reflecting improved technology that has nearly doubled the waste compaction rates over the past twenty years. Figure 4 presents the number of permitted Texas landfills and their estimated combined remaining capacity since 1987. Figure 5 displays historical cumulative and per capita waste disposal amounts for Texas. Table 7 presents summary historical data for MSW landfills in Texas (TCEQ, 2011).

Plates 92 through 98 display active and abandoned MSW landfills in the RWPAs, as well as waste transfer stations and recycling facilities. Annual summary reports of MSW in Texas are produced by the TCEQ and are available on the TCEQ website (TCEQ, 2011). Table 3 includes the number of non-hazardous solid waste sites per RWPA documented in the PSOC database.

Table 7: Texas MSW landfill data

Year	Waste disposal (tons)	State population	Per capita disposal	Number of landfills accepting waste	Number of landfills not accepting waste	Remaining capacity		
						Cubic yards	Tons	Years
1988	18.1	16,668,639	5.95	750	84	1,162,374,628	377,771,754	20.9
1989	18.5	16,806,521	6.04	616	83	1,111,902,033	361,368,161	19.5
1990	20.0	16,986,510	6.44	493	142	1,124,524,795	393,583,678	19.7
1991	20.0	17,349,000	6.31	405	135	1,183,699,041	414,294,664	20.7
1992	21.7	17,655,650	6.73	345	77	1,193,233,770	440,730,048	20.3
1993	21.5	18,031,484	6.54	289	62	1,205,635,627	456,161,796	21.2
1994	21.8	18,378,185	6.5	199	58	1,269,565,453	483,752,986	22.2
1995	21.6	18,723,991	6.33	191	39	1,071,520,039	523,633,365	24.2
1996	21.7	19,128,261	6.23	186	35	1,023,799,597	554,095,949	25.5
1997	22.1	19,439,337	6.23	181	37	1,169,628,669	659,694,441	29.9
1998	23.3	19,759,614	6.45	184	29	1,300,609,247	716,302,147	30.8
1999	25.8	20,044,141	7.05	179	34	1,557,349,331	862,778,821	33.4
2000	28.0	20,851,820	7.37	183	44	1,633,321,824	904,891,939	32.3
2001	27.9	21,235,018	7.18	186	42	1,710,713,869	939,383,633	33.6
2002	29.1	21,779,893	7.31	190	40	1,691,970,227	971,314,962	33.4
2003	29.1	22,118,509	7.2	184	39	1,506,807,849	963,972,887	33.1
2004	29.6	22,490,022	7.21	189	34	1,826,587,075	1,134,462,509	37.4
2005	29.7	22,859,968	7.11	186	32	1,870,868,394	1,217,845,562	41
2006	30.5	23,507,783	7.1	187	28	2,110,807,960	1,366,311,822	45
2007	33.2	23,904,380	7.61	188	28	2,158,501,232	1,403,592,411	42.2
2008	33.1	24,326,974	7.45	191	35	2,167,272,920	1,439,621,096	44.3
2009	32.3	24,782,302	7.13	190	20	2,351,154,567	1,567,806,257	48.6
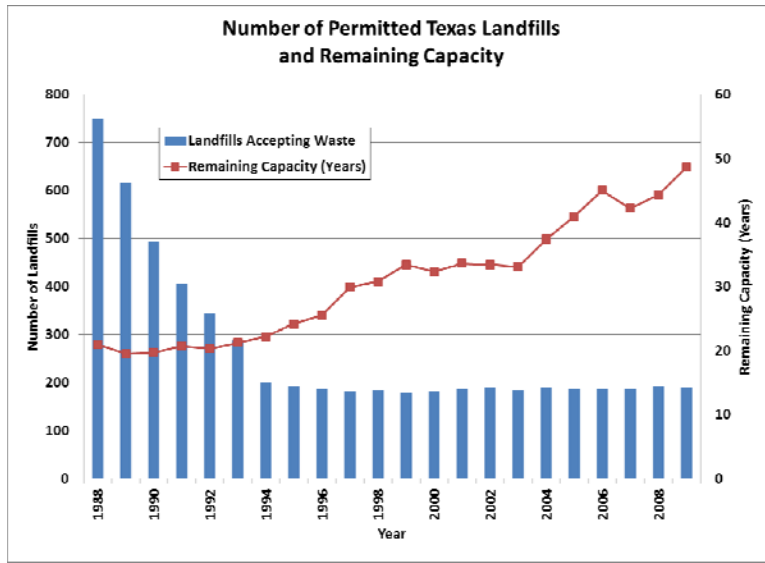
Figure 4: Historical and projected landfill capacity
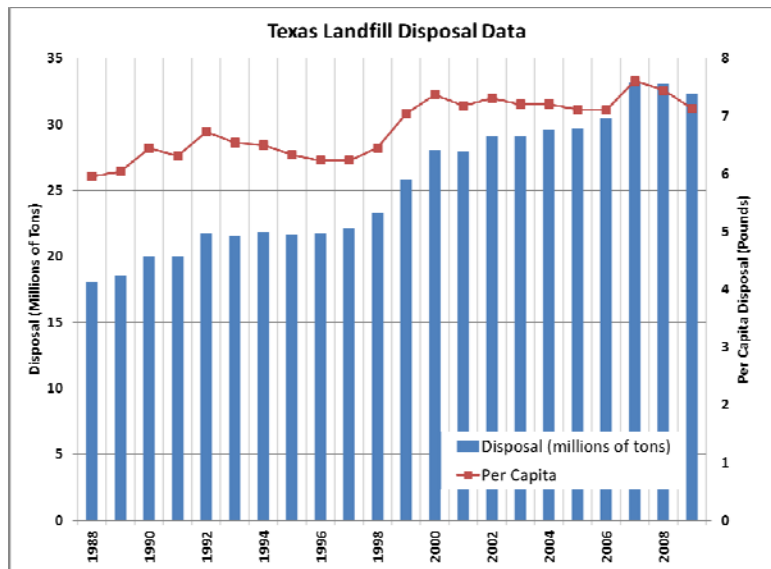
Figure 5: Texas landfill disposal data

Industrial and Hazardous Waste

The US EPA and the state of Texas define MSW in terms of hazardous or non-hazardous. Texas also defines industrial solid waste as separate and distinct from municipal waste, and also as

hazardous and non-hazardous, with the non-hazardous waste further defined by classes. Class I industrial non-hazardous includes waste that, based on its constituents and properties, may pose a substantial danger to human health or the environment if not properly managed. Texas uses the same definition of hazardous as is promulgated by the US EPA in 40 CFR, Part 261. Wastes are defined as hazardous if exhibiting one or more of the following characteristics:

- Ignitability – Having the potential to create fires or explode under certain conditions.
- Toxicity – Are harmful or deadly when swallowed or absorbed by the skin.
- Reactivity – May have violent chemical reactions when in contact with water or air.
- Corrosivity – Are acidic and can eat away or corrode metal.

Class I wastes have special handling requirements. Class 2 wastes cannot be described as hazardous, Class I, or Class 3. Class 3 wastes are inert, insoluble materials not readily decomposable, such as construction or demolition debris.

In 2009, the last year that data was available at the time of this report, 13,461,911 tons of RCRA Hazardous Waste was generated in Texas. Of this amount, 85.6% (11,597,324 tons) was disposed of via deep well or underground injection. Injection wells are discussed in Section 3.4.2 of this report.

Industrial Hazardous Waste Treatment Storage and Disposal sites are presented on Plates 92 through 98. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

Septic Systems

Many rural areas of Texas are not served by municipal or regional waste water systems and rely on on-site wastewater treatment systems to dispose of their wastewater. In a traditional residential septic system, solids are collected in a septic tank and fluids are diverted to a leach field where they are allowed to percolate downward through the unsaturated zone. In a properly designed septic system, there is adequate distance between the leach field and the groundwater for natural microbial activity during soil absorption processes to break down any waste

contaminants prior to reaching the water table. Table 8 presents Typical Septic Tank Effluent Characteristics.

Table 8: Typical septic tank effluent chemical characteristics

Characteristic	Mean Value	Range
pH	6.90	6.53 – 7.45
Total Suspended Solids	176	68 – 624
Biochemical Oxygen Demand	280	140 – 666
Chemical Oxygen Demand	568	240 – 2026
Soluble Organic Carbon	73	24 – 190
Total Phosphates	11.6	30 – 625
Ammonia Nitrogen	97	77 – 111
Nitrate-Nitrogen	0.026	0 – 0.10
Total Soluble Iron	2.63	0 – 20
Chlorides	53	37 - 101
Source: EPA, after Bouma		

Presently there are several design alternatives to traditional septic tank systems. Not all systems use the traditional model of subsurface percolation. Some on-site systems are on soil that is too thin for traditional septic application. Many systems now contain an aerobic component to enhance the breakdown of waste, either through aeration in the tank, or through disposal via drip or spray irrigation rather than subsurface percolation.

The TCEQ maintains a database of reported septic systems within its greater database of PSOCs. There are over 22,000 septic systems documented in the PSOC database. However, it should be noted that TCEQ is not responsible for regulating and registering septic systems in the state. That is a responsibility of each county or its designated agency. It is not within the scope of this project to check with every single county and obtain registration for the tanks. The septic system data in the PSOC database is likely not complete. Some counties may not forward this information to the state. However, the septic system locations in the PSOC database are displayed to provide a general indication of distribution and density of these systems.

Septic System sites are displayed in Plates 99 through 105. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.3.2 Injection Wells

Underground injection is the placement of fluids into the subsurface through a well bore. Many of the wells used for injection are "high tech" in their construction. However, some are very simple, including dug wells and other shallow subsurface fluid distribution systems. In the late 1960s, the realization that subsurface injection could contaminate groundwater if wells were not properly located and operated prompted many states to develop programs and methods to protect underground sources of usable water. A federal Underground Injection Control (UIC) Program was also established under the authority and standards of the federal Safe Drinking Water Act of 1974. The TCEQ has regulatory primacy over Texas' UIC Program.

Injection wells are divided into five different classes. The classes are generally based on the kind of fluid injected and the depth of the fluid injection compared with the depth of the lowermost USDW.

4.3.2.1 Class I – Waste Disposal

Class I wells are used to inject industrial or municipal waste to a depth beneath the lowermost USDW. Class I wells typically inject from 1,700 to over 10,000 feet below the surface and may inject hazardous, non-hazardous, and municipal waste water. Site selection for a Class I disposal well is dependent upon geologic and hydrogeologic conditions, and only certain areas and horizons are suitable. Many of these wells are located along the Gulf Coast where a large number of waste generators such as refineries and chemical plants, as well as deep geologic formations that are ideal for the injection of wastes, are located.

Texas has the largest number of hazardous waste Class I wells in the nation, with 175 wells. These well locations are displayed on Plate 106. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.3.2.2 Class II – Oil and Gas Operations

Class II injection wells are used specifically for oil field and related activities, and have been in use since the 1930's. Nationwide, there are approximately 170,000 Class II injection wells in 31 states. Because the oil industry has historically been important in the economic development of the State of Texas, there are a significant number of Class II injection wells in the state.

Class II wells may be classified according to one of three primary functions: salt water (brine) disposal wells, enhanced oil recovery wells, and hydrocarbon storage wells. The production of oil is normally accompanied by a large amount of produced water, which is generally saline (greater than 10,000 mg/L chlorides). Brine disposal wells are designed to dispose of this produced water by re-injecting it into an appropriate formation below any USDW. Enhanced Oil Recovery (EOR) Wells are wells designed for re-injection of brine into producing horizons in order to create pressure gradients to induce secondary flow of oil to producing wells to augment primary recovery of oil from the well. Up to 60% of the brine produced from oil and gas wells on shore in the U.S. is ultimately re-injected into EOR wells. Hydrocarbon storage wells are designed for the underground storage of crude oil and liquid hydrocarbons. The wells are designed for both injection and removal of the stored hydrocarbons. Storage is often in either salt domes or bedded salt deposits.

There are nearly 40,000 Class II injection wells recorded in the RCT database. Plates 107 through 113 display the locations of these wells in Texas. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.3.2.3 Class III – Mining

Class III UIC wells are specifically related to mineral extraction. The techniques used for mineral extraction by these wells are either solution mining of salts and sulfur, or in-situ leaching for minerals such as copper, gold, or uranium.

There are 153 Class III injection wells recorded in the TCEQ database. Many of these are clustered in relatively close proximity to one another. The locations of these wells in Texas are

displayed on Plate 114. Table 3 includes the number of these sites per RWPA group documented in the PSOC database.

4.3.2.4 Class IV – Injection Into or Above USDWs

Class IV wells are defined as those in which dangerous wastes are injected into or above potential USDWs. These wells have been banned for many years as a significant threat to human health as well as the environment. Occasionally Class IV wells are still discovered, and when this occurs they are prioritized for abandonment and remediation.

A new category of Class IV wells that are not considered environmental threats have been defined in recent years. These are wells that exist at sites that are being actively remediated under the Resource Conservation and Recovery Act (RCRA) or the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) programs. Some approved remediation technologies involve pumping contaminated water to the surface, treating it for removal of select contaminants, then pumping it back into the aquifer, in essence creating a treatment loop for the contaminated groundwater. Under this approach, the injected water may still have residual contamination, but because the intent is to ultimately re-extract and treat again, this is permitted. However, because contaminated water is injected above a USDW, this is technically a Class IV well.

There are 9 Class IV wells documented in the database. They are included on Plate 106 with the Class I injection well locations. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.3.2.5 Class V – Other

Class V wells are defined as any injection well that does not fit into one of the previously described four categories. These may range from a simple cesspool, which may receive untreated waste from a household, to deep geothermal wells with complex designs used for heat exchange. Generally the number of simple shallow Class V injection wells is far greater than the deep ones. They may exist anywhere but are more likely to exist in areas not serviced by central sewage collection. Some of the various types of Class V wells are:

- Agricultural Drainage Wells

- Storm Water Drainage Wells

- Large capacity septic systems

- Mine Backfill Wells

- Aquifer Remediation Wells

- Heat pump/air conditioning return flow wells

- Aquifer storage and recovery wells

- Saltwater intrusion barrier wells

- Subsidence control wells

- Industrial disposal wells

Nationwide, there are over 1,500,000 Class V wells. Approximately 83% of these fall into two categories: drainage wells (57%) and sewage-related wells (26%).

Two categories of special concern are large capacity cesspools and automotive waste disposal wells. Large capacity cesspools dispose of untreated sewage into or above a USDW, potentially introducing significant concentrations of bacteria into a USDW. Automotive waste disposal wells may introduce significant concentrations of oil, chemicals, solvents, metals, and other contaminants into a drinking water source. These two types of wells are subject to additional regulation because of the risk they posed to USDWs. New large capacity cesspools and automotive waste disposal wells have been banned, and procedures for closing existing facilities have been promulgated.

There are 969 Class V injection wells documented in the TCEQ database. The locations of these wells are displayed on Plates 115 through 121. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.3.3   Wastewater Facilities

Properly managed wastewater disposal systems and associated collection lines play an important role in protecting community health and local water quality. However, many of the wastewater collection and treatment systems were developed in the early part of the 20th century.

Maintenance, retrofits, and rehabilitations since have resulted in patchwork systems consisting of technologies from different eras. The dated systems have the potential to release various contaminants to groundwater and surface water bodies. The primary COCs for sewage-related contamination include nitrates, nitrites, metals, hydrocarbons, and chlorinated compounds. Wastewater sewage also has the potential to introduce microbial contaminants including Escherichia Coli, Cryptosporidium, Giardia Lamblia, coliform, and fecal viruses. Survival rates of microorganisms in groundwater depend on the type of soil, the type of microorganisms present, ground temperature, and the amount of rainfall in the area. With respect to microbial contamination from sewage, the presence of these contaminants in groundwater would indicate a connection with a nearby source, such as seepage from a waste lagoon or a septic tank.

Plates 122 through 128 display the locations of documented wastewater facilities in the RWPAs documented in the TCEQ PSOC database. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.3.4   Cemeteries

Cemeteries have the potential to degrade water quality through the decomposition of bodies and introduction of chemicals used in the embalming process, such as formaldehyde and chloroform. Seepage may result in bacteria, viruses, and organic and inorganic chemical decomposition products. Typical microorganisms known to be present in seepage include *micrococcaceae, streptococci, bacillus*, and *enterobacteria*. Survival rates of microorganisms in burial sites depend on the type of soil, the type of microorganisms present, ground temperature, and the amount of rainfall in the area. If the cemetery is located in a porous soil type, such as sand or gravel, movement of seepage may be rapid and could mix with the groundwater beneath the site. There has never been any documented case of water supply contamination from cemeteries in Texas. However, studies in Europe have documented water quality impacts in shallow unconfined aquifers within 18 feet down gradient of a cemetery.

Plate 129 displays all cemeteries in the state as documented in the SOC database. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.4 Agricultural Activities

Agriculture is a major industry in Texas, providing the economic engine for large parts of the state. This occurs despite semi-arid conditions in much of the state. Irrigation of agricultural lands is common to maintain the desired level of production. When surface water or groundwater is applied to cultivated land, consumptive use of the water by the crop is not total. Some portion of the applied water ultimately returns to the water table through the mechanism of deep percolation. This has consequences for the in situ groundwater chemistry of the aquifer. As crops consume water, whether the source is natural rainfall or applied irrigation water, the crops take up the water and leave behind cations and anions present in the source water, resulting in a buildup of salts in the soil. In arid parts of the state, natural rainfall is generally not sufficient to leach accumulated salts from the soil. Therefore, when excess irrigation water is applied, the water that percolates to the water table may have higher salinity content than natural percolation. Additionally, chemicals applied for fertilizers and pesticides can be dissolved into excess irrigation water and transported to the water table through percolation resulting in contamination of the water table aquifer. Occurrence and detection of specific pesticides, herbicides, and fertilizer nutrients in groundwater is discussed in detail in Section 5.25 of this report. Plates 130 through 136 display irrigated agricultural land above unconfined aquifers in Texas.

4.4.1 CAFOs

Over the past 50 years, agricultural animal production has progressively shifted from small family or community-run farms to large scale animal processing facilities commonly referred to as Concentrated Animal Feeding Operations (CAFO). An animal feeding operation (AFO) is defined by TCEQ as "a lot or facility, other than an aquatic animal production facility, where animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period, and in which the animal confinement areas do not sustain crops, vegetation, forage growth, or post-harvest residues in the normal growing season over any portion of the lot or facility." CAFOs are designated as large or medium based on the classifications listed below in Table 9. In addition to facilities of these sizes, any AFO may be designated a small CAFO by the TCEQ if it is a significant contributor of pollutants into or adjacent to waters of the state.

Table 9: CAFO categorization data

Animal Type	Large (# head)	Medium (#head)
Veal calves and non-mature dairy cattle	1,000	300 – 999
Mature Dairy Cattle	700	200 – 699
Swine > 55 pounds	2,500	750 – 2,499
Swine < 55 pounds	10,000	3,000 – 9,999
Ducks (liquid manure handling system)	5,000	1,500 – 4,999
Ducks (non-liquid manure handling system)	30,000	10,000 – 29,999
Horses	500	150 – 499
Sheep or lambs	10,000	3,000 – 9,999
Turkeys	55,000	16,500 – 54,999
Laying hens or broilers (non-LMHS)	82,000	25,000 – 81,999
Laying hens or broilers (LMHS)	30,000	9,000 – 29,999
Chickens (non-LMHS)	125,000	37,500 – 124,999

The concentrated raising of livestock leads to the production of very large quantities of manure in relatively small areas and may lead to problems with the management and disposal of this animal waste, and the associated contaminants, such as *E. coli* bacteria, nitrates, and phosphates. Texas is the largest manure-producing state in the nation. Frequently the manure is diverted to lagoons, and sometimes incorporated with water into a land-application system wherein the liquid manure is sprayed on fields of grass or some other crop or plant in order to consume the waste products through biologic activity. In general, CAFO operations may pose a greater risk to surface waters, as the lagoons may overflow into local creeks and streams during large rainfall events. However, shallow unconfined groundwater in the vicinity of a CAFO is subject to potential contamination by percolation into the water table beneath the ponds.

There are nearly 4,000 animal feeding operations registered in the TCEQ database throughout the state. Plates 137 through 143 display the locations of these facilities in the RWPAs. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

4.4.2   Silviculture

Silviculture is the growth, treatment, and processing of wood products. In Texas this industry is most prevalent in the eastern part of the state, where rainfall is heaviest. The processing of lumber may include the use of numerous chemicals that could potentially affect underlying groundwater. Silviculture industry sites, including pulp or paper mills, and wood preserving locations, are included in Plates 34 through 40. Most of these sites are located in Regions D and I, where the silviculture industry is predominantly located in the state. Table 3 includes the number of these sites per RWPA documented in the PSOC database.

5 Anthropogenic Groundwater Contamination in Regional Water Planning

This section of the report discusses instances of anthropogenic groundwater contamination as documented in the collected databases, and regulatory programs in place to monitor and remediate documented cases.

5.1 Impacted Groundwater

5.1.1 Groundwater Monitoring and Regulatory Programs

TCEQ

The TCEQ is the primary agency in Texas responsible for regulation and oversight of groundwater contamination. Chapter 26 of the Texas Water Code authorizes the TCEQ to establish the level of water quality to be maintained and to control sources of pollutants that may affect the quality of water in the state, including groundwater. As such, TCEQ is the lead regulatory agency for most groundwater contamination cases pursued in the state. In particular instances, regulatory primacy may lie with the US EPA.

US EPA

The US EPA is the federal regulatory agency responsible for oversight of surface and groundwater quality. In most cases, US EPA cedes primacy of regulatory authority to the TCEQ for groundwater contamination cases. The EPA also may provide funding mechanisms and grant opportunities for state agencies like the TCEQ to coordinate groundwater protection strategies.

Interagency Pesticide Database (IPD)

The Interagency Pesticide Database (IPD) is a database maintained by the TCEQ that incorporates water chemistry data from various sources including the USGS, TCEQ, TWDB, BEG, and USDA. This data collection effort was initiated through a grant from the US EPA, and its objective is the monitoring of pesticides, herbicides, and other chemicals associated with

agriculture that are generally considered to be non-point source pollutants due to the dispersed nature of their application.

USGS NAWQA

The USGS conducts regular monitoring of groundwater and surface water nationwide. In the past 20 years, the USGS has implemented the NAWQA program. Under this program, groundwater wells have been sampled nationwide under a unified data collection program, and the results have been documented in a series of published reports.

Edwards Aquifer Authority

The Edwards Aquifer Authority (EAA) was created by the Texas legislature in 1993 to manage the San Antonio segment of the Edwards-Balcones Fault Zone Aquifer. The EAA has no regulatory authority regarding water quality, but maintains a monitoring program of the groundwater, surface water, and springs within the aquifer to assess the presence or level of contamination of the water under their jurisdiction. The results of their program have been published in public reports and a publicly available database. The groundwater chemistry data published under this program was included in the data queried for this project.

Active Case Statistics

The Texas Groundwater Protection Committee (TGPC) is an interagency organization created in 1989 to bridge gaps between existing state groundwater programs and develop policy recommendations for protecting state groundwater resources. The TGPC has representatives of the TWDB, TCEQ, RCT, Texas Department of Agriculture (TDA), Department of State Health Services, and others. The coordination of groundwater activities of the various state programs has been funded and guided through EPA grants administered under the Clean Water Act. The TGPC has produced an annual publication entitled "Joint Groundwater Monitoring and Contamination Report" for each year since 1990 for the purpose of describing the current status of groundwater programs for each participating agency. This report does not focus exclusively on drinking water sources, but also reports on cases of groundwater cleanup and remediation in

the state. Most of the cases reported do not affect drinking water supplies, but are associated with cleanup of landfills, leaking underground storage tanks, etc.

In 2009, the last year for which data was available, the TGPC reported 4,503 groundwater contamination cases under enforcement during the 2009 calendar year. Of these, approximately 91% are under the jurisdiction of the TCEQ. Most of the remaining 9% fall under the jurisdiction of the RCT. A single case fell under the jurisdiction of a groundwater conservation district under the umbrella organization of TAGD. Forty-nine percent (49%) of the documented contamination case sites are in the petroleum storage tank program.

Figure 6 is a graph displaying the history of documented cases since 1992. A few general observations may be made based on this graph. The difference between the number of new and completed cases and the number of total cases reflects the number of cases that are in some interim degree of project completion. The highest number of new cases was in 1998-1999, coincident with a regulatory deadline to file to qualify for reimbursement through a state program. The jump in new cases after 1995 coincides with the initiation of the Voluntary Cleanup Program. Since 1999, the number of total cases has decreased steadily as the number of closed cases (action completed) has remained higher than the number of new cases. For all of the agencies reporting between 1992 and 2009, there have been a total of 13,185 groundwater contamination cases reported as "action complete."

Plates 144 through 150 display reported cases of groundwater contamination as documented in the "Joint Groundwater Contamination Report – 2009" prepared by the Texas Groundwater Protection Committee.
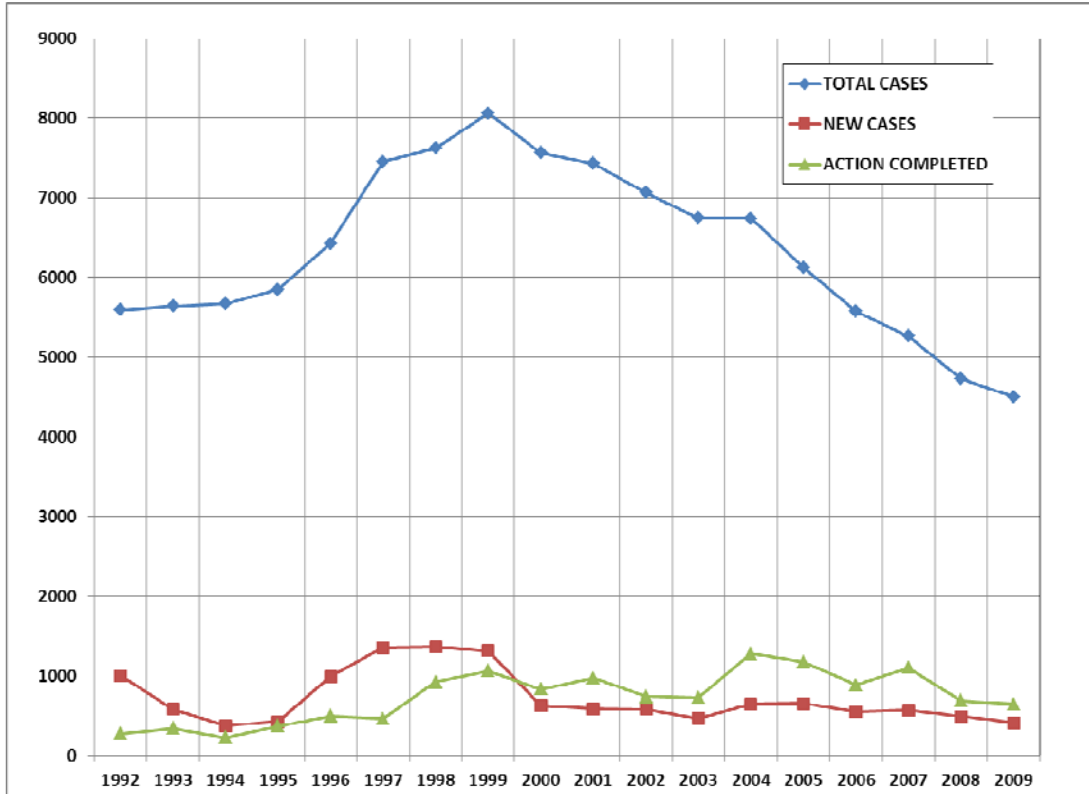
Figure 6: Case history of groundwater contamination- total, new and completed cases

Notification to Private Well owners

A law enacted by the state legislature in 2003 (House Bill 3030) and incorporated into the state water code (TWC Chapter 26, Section 408) requires that when the TCEQ documents a case of groundwater contamination, they must provide notice via first class mail to any owner of a private drinking water well that may be affected by a contamination case. Table 10 presents the number of contamination cases subject to this law and the associated number of public notices for these cases for the years 2006-2009.

Table 10: Contamination cases requiring public notification of private well owners since 2003

Year	Number of Sites Requiring Notifications	Number of Notifications
2004	24	9,695
2005	10	183
2006	31	423
2007	38	843
2008	42	610
2009	39	419
2010	23	476
Source: TGPC, 2009. 2010 (Draft)		

5.2   Raw Water Chemistry Data Survey

To present a statewide survey of groundwater source water quality data throughout the state of Texas, all of the databases referenced in Sections 2.3 and 4.1 were queried for published groundwater chemistry data. Several of the databases were combined for the purpose of eliminating potential double-counting of sample results that may be reported in multiple databases. Details of specific contaminants are discussed in the following sections. A summary of results for all significant contaminant is presented in Table 11.

Table 11: Groundwater chemistry data summary

	Protective Concentration Level (ug/L)	Maximum Concentration Detected (ug/L)	Total Number of Wells	# Wells with Positive Detection	# Wells with Detection > PCL	% Wells with Positive Detection	% of Wells with Detection > PCL	Total # of Analyses	# Analyses with Positive Detection	# Analyses > PCL	% Analyses with Positive Detection	% of Analyses with Detection > PCL
Hydrocarbons												
Benzene	5	43	1,398	15	4	1.07%	0.29%	1,403	18	4	1.28%	0.29%
Toluene	1,000	122	3,353	157	0	4.68%	0.00%	3,361	186	0	5.53%	0.00%
Ethylbenzene	700	23	3,345	20	0	0.60%	0.00%	3,353	20	0	0.60%	0.00%
Xylenes	10,000	250	1,744	14	0	0.80%	0.00%	1,747	17	0	0.97%	0.00%
MTBE	13	108.4	2,408	39	4	1.62%	0.17%	2,414	45	6	1.86%	0.25%
Chlorinated Compounds												
PCE	5	6000	2,335	158	23	2.31%	0.99%	2,376	445	51	18.73%	2.15%
TCE	5	230	1,963	58	6	2.95%	0.31%	1,988	90	7	4.53%	0.35%
Vinyl Chloride	2	32	3,170	5	1	0.16%	0.03%	3,178	9	2	0.28%	0.06%
cis-1,2 DCE	70	82	2,460	11	2	0.45%	0.08%	2,470	15	3	0.61%	0.12%
1,1,1-TCA	200	5.8	3,181	37	0	1.16%	0%	3,190	59	0	1.85%	0%
Chloroform	80	282.8	3,190	295	1	9.25%	0.03%	3,208	582	1	18.14%	0.03%
Carbon Tetrachloride	5	4	2,947	6	0	0.20%	0%	2,954	6	0	0.20%	0%
Pesticide/Herbicides												
Atrazine	3	183.1	2,666	954	20	35.78%	0.75%	2,684	1493	31	55.63%	1.15%
Deethylatrazine	NE	1.73	1,229	224	N/A	18.23%	N/A	1,243	494	N/A	39.74%	N/A
Deisopropylatrazine	NE	0.09	280	29	N/A	10.36%	N/A	290	43	N/A	14.83%	N/A
Simazine	4	0.2	1,559	110	0	7.06%	0%	1,587	274	0	17.27%	0%
Prometon	400	262	1,346	108	0	4.01%	0%	1,391	185	0	13.30%	0%
Diazinon	1	1.2	1,782	53	1	2.97%	0.06%	1,821	66	1	3.62%	0.05%
2,4-D	70	250	1,262	31	1	2.46%	0.08%	1,280	33	1	2.58%	0.08%
Metolachlor	700	63.5	1,437	24	0	3.76%	0%	1,465	25	0	1.71%	0%
Tebuthiuron	1000	0.121	1,204	14	0	1.16%	0%	1,210	18	0	1.49%	0%
Carbaryl	2	0.116	1,252	12	0	0.96%	0%	1,292	20	0	1.55%	0%
Alachlor	2	0.68	1,502	9	0	0.60%	0%	1,512	9	0	0.60%	0%
Diuron	2	60	644	8	2	1.24%	0.31%	654	8	2	1.22%	0.31%
Dieldrin	0.002	0.22	1,979	4	0	0.20%	0.00%	1,991	1	0	0.05%	0.00%
Chloropyrifos	2	0.025	1,494	4	0	0.27%	0%	1,525	4	0	0.26%	0%
Cyanizine	10	10	1,168	3	0	0.26%	0%	1,181	3	0	0.25%	0%
Lindane	0.2	1.1	1,380	2	1	0.14%	0.07%	1,391	2	1	0.14%	0.07%
Acetochlor	1	N/A	1,087	0	0	0%	0%	1,091	0	0	0%	0%
Aldicarb	3	N/A	679	0	0	0%	0%	688	0	0	0%	0%
Chlorothalonil	5	N/A	601	0	0	0%	0%	603	0	0	0%	0%
Dinoseb	7	N/A	836	0	0	0%	0%	846	0	0	0%	0%
Nutrients												
Nitrate as N (mg/L)	10	335.15	3,990	3497	341	0.88	8.55%	4,005	3750	360	93.63%	8.99%

Notes:
1) All results reported in ug/L except for Nitrates, reported in mg/L.
2) NE = Not Established
3) NA = Not Applicable

5.2.1   Laboratory Detection Limits

Through the years laboratory methods have grown more sophisticated, and the practical detection limit for contaminant analysis has decreased. Because this study is evaluating data from various agencies, time periods, sampling programs, and with different objectives, not all data will necessarily maintain identical methods of quality control. For example, the recent groundwater sampling associated with the NAWQA program specifically used laboratory methods capable of very low detection limits to assess levels of contamination well below the published MCLs for various compounds. Older data will likely not reflect similar detection limits.

5.2.2   Protective Concentration Levels (PCLs)

There are various different thresholds or regulatory criteria considered in this analysis, as follows. An EPA MCL (Maximum Contaminant Level) is the maximum allowed concentration of a contaminant in groundwater allowed by law and promulgated by federal law. This is the most far-reaching and most regularly enforced of the various sample detection thresholds that will be discussed. In general, TCEQ adopts the MCLs set by the EPA and uses those to enforce cleanup at documented contamination sites. In some instances, however, the EPA or TCEQ may not have adopted an MCL for a particular contaminant, but the regulatory authorities in another state or country may have done so. For example, California has adopted an enforceable MCL for MTBE, which is not presently on EPA's list. In some instances, there is no MCL set by any governmental agency. In many of these cases, the USGS has adopted Health-Based Screening Levels (HBSLs) based on internal analysis. HBSLs and Health Advisory Levels (HALs) are published for informational purposes. These values do not carry the weight of legislated regulatory criteria. In some instances, sources outside the United States such as Canada or the World Health Organization may have published criteria on some chemicals not regulated in the United States.

For the purpose of discussion in this report and for presentation on the Plates, all of these various regulatory thresholds will be collectively referred to as Protective Concentration Levels (PCLs).

For the purpose of display in the Plates displaying chemistry data, if no TCEQ/EPA criteria exist, and if an alternative published threshold criteria was found, then values higher than this threshold were called out on the Plates. LBG-Guyton understands that these are not regulatory criteria recognized or enforced in the state of Texas, but it is useful to have some threshold in order to identify areas of relatively elevated concentrations within the spatial distribution of positive detections. In Sections 5.2.3 through 5.2.7, where the analytical results for each chemical contaminant are discussed, the basis for the PCL employed for that particular chemical will be explained.

The number of chemical contaminants of concern reported in the TCEQ PSOC documentation is vast, with far too many total anthropogenic chemicals to evaluate and map under the scope of this project. In order to reduce the quantity of chemicals to a manageable number for this project, LBG-Guyton selected those chemicals that were reported as being detected most frequently in the USGS NAWQA reports and some additional volatiles, herbicides, and pesticides identified by the TWDB as being of particular interest because of their prevalence of use. The following report sections provide a brief description of each contaminant mapped, discussion of use, likely route of introduction into the subsurface, and statistical summaries of the sample detection results.

In the Plates that are discussed in the following section, some well sample locations had only a single sample collected, while some had multiple samples collected over time. The Plates displaying results for each analyte reflect a positive detection if any of multiple sampling events resulted in a positive detection. Similarly, the Plates display a symbol indicating a chemical value greater than the PCL if any of multiple historical sampling events ever resulted in a detection above the PCL.

5.2.3   *Hydrocarbons and Fuel Constituents*

As mentioned in Section 5.1.1, nearly half of the active groundwater contaminant cases regulated by the TCEQ are from leaking petroleum storage tanks (LPSTs). However, due to the chemical properties of gasoline and the geochemical reactions governing the fate and transport of these chemicals in the subsurface, the vast majority of these cases never reach the status of impacting public water supplies in Texas. Gasoline and diesel, as well as the primary components of

benzene, toluene, ethylbenzene, and xylenes (BTEX) are lighter than water, so they tend to float on the first encountered water table surface rather than sink into deeper strata. Contaminants displaying this physical characteristic are referred to as Light Non-Aqueous Phase Liquids (LNAPLs) when encountered in groundwater. In addition, volatile fuel components commonly are metabolized by naturally occurring bacteria in the soil into carbon dioxide and water. As a result of this, petroleum contaminant plumes tend to reach a maximum length and stabilize, at which time the plume contaminant concentrations will decrease due to microbial degradation. Figure 7 presents a conceptual model of the hypothetical phases of plume length and concentration for dissolved hydrocarbons in groundwater (Rice and others, 1995).

Hypothetical phases of (a) plume length and (b) average plume concentration for dissolved hydrocarbon in groundwater.
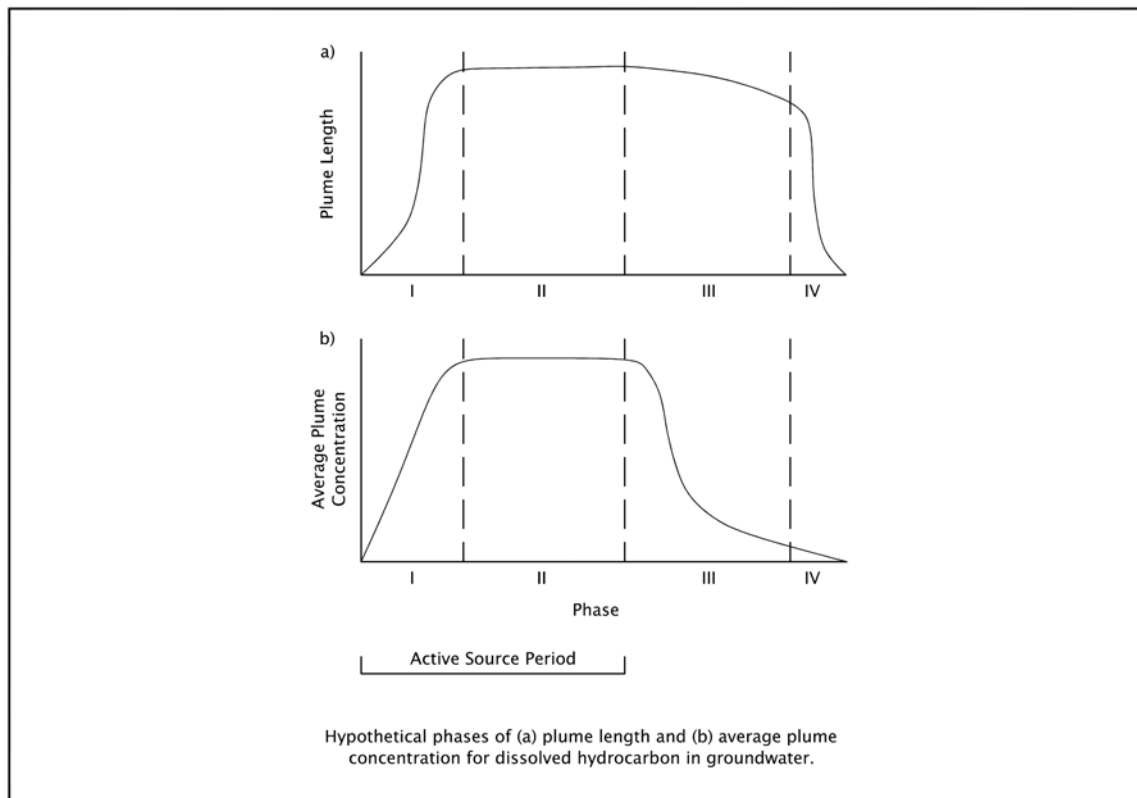
Figure 7: Conceptual model of phases of hydrocarbon plume development

5.2.3.1 Benzene

Benzene is a basic component of refined petroleum products, including gasoline and diesel. The US Department of Health and Human Services (DHHS) classifies benzene as a human carcinogen. Because of the prevalence of petroleum-contaminated groundwater, benzene

exposure is an ongoing concern. The US EPA has set the MCL for benzene in drinking water at 5 micrograms per liter (µg/L), and this threshold is referenced as the PCL for this report.

Benzene was detected at a concentration greater than the detection limit in 1.1% of wells (15 out of 1,398) and 1.3% of samples (18 out of 1,403) in the databases queried. It was detected at concentrations greater than the PCL in 0.3% of wells (4 out of 1,374) and 0.3% of samples (4 out of 1,398). These relatively low detection frequencies reflect the geochemical constraints on the spread of groundwater plumes discussed previously.

Plate 151 displays the summary of reported data of benzene in groundwater in Texas.

5.2.3.2 Toluene

The TCEQ MCL for toluene in drinking water is 1,000 µg/L. This threshold is referenced as the PCL for this report.

Toluene was detected at a concentration greater than the detection limit in 4.7% of wells (157 out of 3,353) and 5.5% of samples (186 out of 3,361) in the databases queried. Toluene was not detected at concentrations greater than the PCL in any samples.

Plate 152 displays the summary of reported data of toluene in source groundwater in Texas. Toluene is the most commonly detected hydrocarbon component. Most of the detections are clustered along the Edwards Aquifer and in the greater Houston area, with lesser amounts scattered throughout the Ogallala and the Carrizo-Wilcox in East Texas.

5.2.3.3 Ethylbenzene

The TCEQ MCL for ethylbenzene in drinking water is 700 µg/L, and this threshold is referenced as the PCL for this report.

Ethylbenzene was detected at a concentration greater than the detection limit in 0.6% of wells (30 out of 2,270) and 0.6% of analyses (20 out of 3,353) in the databases queried. Ethylbenzene was not detected at concentrations greater than the PCL in any samples.

Plate 153 displays the summary of reported data of ethylbenzene in source groundwater in Texas. Most detections are located in the Edwards Aquifer. This indicates that the karst structure of the Edwards may result in greater susceptibility to this contaminant.

5.2.3.4 Xylenes

The TCEQ MCL for total xylenes in drinking water is 10,000 µg/L, and this threshold is referenced as the PCL for this report.

Xylenes were detected at a concentration greater than the detection limit in 0.8% of wells (14 out of 1,744) and 1.0% of samples (17 out of 1,747) in the databases queried. Xylenes were not detected at concentrations greater than the PCL in any samples.

Plate 154 displays the summary of reported data of xylenes in source groundwater in Texas. Most detections are located in the urban areas of San Antonio, Houston, Dallas, and Abilene.

5.2.3.5 MTBE

MTBE is a volatile, flammable, colorless liquid used almost exclusively as a fuel component for gasoline. It is an oxygenate that has been used in gasoline since 1979 to replace tetra ethyl lead, to increase octane rating, and to help prevent engine knocking. Since 1999, due to widespread contamination from leaking petroleum fuel tanks, various agencies have banned the use of MTBE. Consequently, production and associated new contamination cases have declined in America. The US EPA has not yet established a national MCL for MTBE. However, the California EPA has set the state MCL at 13 µg/L, and this threshold is referenced as the PCL for this report.

MTBE was detected at a concentration greater than the detection limit in 1.6% of wells (39 out of 2,408) and 1.9% of analyses (45 out of 2,414) in the databases queried. It was detected at concentrations greater than the PCL in 0.2% of wells (4 out of 2,408) and 0.25% of samples (6 out of 2,414).

Plate 155 displays the summary of reported data of MTBE in groundwater in Texas.

5.2.4 Chlorinated Compounds

Chlorinated compounds are a class of chemicals distinguished by the presence of chlorine molecules in the molecular structure. They include both solvents and chemicals historically used in industrial applications as well as disinfection by-products (DBPs) generated during drinking water treatment. These chemicals are volatile organic compounds, and are common groundwater contaminants as a result of their many historical uses in a variety of industrial applications. Chlorinated solvents have a specific gravity greater than one, so have greater potential to sink once they reach a water table aquifer, and a greater potential to reach deeper aquifers than petroleum fuel contaminants. Large accumulations of groundwater contaminants that are heavier than water are referred to as Dense Non-Aqueous Phase Liquids, or DNAPLs.

A DBP is the term used to describe a chemical formed in the water as a result of treatment disinfection process (i.e., chlorination). A chlorine residual in treated water distribution systems is required by law, with the intent of preventing the growth of any bacteria or microbes in the distribution system after the water has left the treatment plant. These chemicals are regulated under the Clean Water Act.

Hydrocarbons, chlorinated solvents, and DBPs may all be collectively referred to as Volatile Organic Compounds (VOCs).

5.2.4.1 PCE

PCE (another name for perchloroethylene or tetrachloroethylene) is a common chemical used extensively in the dry cleaning industry. It has also historically been used as a solvent or metal degreaser and in the manufacture of refrigerants. The TCEQ MCL for PCE is 5 µg/L. This is the PCL referenced in the data analysis.

PCE was reported with a positive detection in 6.8% of the wells (158 out of 2,335 wells) and 18.7% of analyses (445 out of 2,376) in the databases queried. It was detected at concentrations greater than the PCL in 1.0% of wells (23 of 2,335 wells) and 2.2% of analyses (51 out of 2,376).

Plate 156 displays the distribution of tested well locations and analytical result summaries for PCE in Texas aquifers in the queried database. Most of the PCE detections occurred along the Edwards Aquifer, again indicating the greater susceptibility of karst aquifers to anthropogenic contamination. PCE was the VOC with the highest percentage incidence of both number of wells and number of analyses with results greater than the PCL. This reflects the fact that chlorinated hydrocarbon plumes are more persistent in the groundwater environment than petroleum hydrocarbon plumes, and that PCE in particular does not quickly degrade in the subsurface.

5.2.4.2 TCE

Trichloroethylene (TCE) is a chemical similar in molecular structure to PCE, but with three rather than four chlorine molecules. It has historically been used for similar applications, including dry cleaning, as a metal degreaser, and in refrigerant manufacturing. The TCEQ MCL for TCE is 5 µg/L. This is the PCL referenced in the data analysis.

TCE was reported with a positive detection in 2.9% of wells (58 out of 1,963 wells) and 4.5% of analyses (90 out of 1,988) in the databases queried. It was reported with a concentration greater than the PCL in 0.3% of wells (6 out of 1,963 wells) and 0.35% of analyses (7 out of 1,988).

Plate 157 displays the distribution of tested well locations and analytical result summaries for TCE in Texas aquifers. Most detections occur in the Edwards Aquifer.

5.2.4.3 Vinyl Chloride

Vinyl chloride is an important industrial chemical chiefly used to produce polyvinyl chloride (PVC), used frequently in plumbing and water distribution applications. Vinyl chloride remains in common use worldwide. Approximately 31 million tons were produced in the year 2000. It is generally used as an intermediate chemical in industrial applications, and not as a final product. The TCEQ MCL of vinyl chloride is 2 µg/L, This is the PCL referenced in the data analysis.

Vinyl chloride was reported at concentrations above the method detection limit in 0.2% of wells (5 out of 3,170 wells) and 0.3% of analyses (9 out of 3,178) in the databases queried. It was detected at a concentration exceeding the PCL in 1 out 3,170 wells (0.03%) wells and 0.06% of analyses (2 out of 3,178).

Plate 158 displays the distribution of tested well locations and analytical result summaries for Vinyl chloride in Texas aquifers. The few detections for vinyl chloride are not clustered in any one aquifer or geographic region.

5.2.4.4 Cis-1,2 DCE

Cis-1,2 DCE is a common degradation product in the groundwater environment of parent chemicals such as TCE and PCE. The TCEQ MCL of cis-1,2 DCE is 70 µg/L. This is the PCL referenced in the data analysis.

Cis-1,2 DCE was reported with a positive detection in 0.4% of wells (11 out of 2,460 wells) and 0.6% of sample analyses (15 out of 2,470 sample analyses) in the databases queried. It was reported at concentrations greater than the PCL in 0.1% of wells (2 out of 2,460 wells) and 0.1% of samples (3 out of 2,470 samples).

Plate 159 displays the distribution of data from the queried databases for tested well locations and analytical result summaries for cis-1,2 DCE in Texas aquifers. The few detections are limited to the urban areas of Houston, San Antonio, and Austin.

5.2.4.5 1,1,1-TCA

1,1,1-Trichloroethane (1,1,1-TCA) is a common degradation product in the groundwater environment of parent chemicals such as TCE and PCE. The TCEQ MCL of 1,1,1-TCA is 200 µg/L. This is the PCL referenced in the data analysis.

1,1,1-TCA was reported with a positive detection in 1.2% of well locations (37 out of 3,181 wells) and 1.8% of samples (59 out of 3,190 analyses) in the databases queried. No samples from any wells were detected above the PCL.

Plate 160 displays the distribution of data from the queried databases for tested well locations and analytical result summaries for 1,1,1-TCA in Texas aquifers. Most detections are located in the Edwards Aquifer.

5.2.4.6 Chloroform

Chloroform is a common disinfection byproduct. It is also a degradation product of parent VOCs such as PCE and TCE. However, as evidenced by the relatively widespread distribution in groundwater, the primary source is likely from DBPs. Because chloroform is an artifact of the disinfection treatment process, and does not occur in groundwater naturally, the most likely mechanism for introduction of chloroform into the groundwater is through infiltration and recharge of chlorinated water to the aquifers. Potential sources of chloroform and other DBPs include chlorinated water used to irrigate lawns, golf courses, parks, gardens, etc. Other potential sources are leaking septic systems, swimming pools, and drinking water or wastewater distribution systems. The TCEQ MCL for chloroform is 80 µg/L. This is the PCL referenced in the data analysis.

Approximately 9.2% of well locations (295 out of 3,190 wells) and 18.7% of the sample analyses (582 out of 3,208 analyses) reported positive detections for chloroform. However, the vast majority of these detections were at very low concentrations. Only a single sample in the databases queried reported a concentration greater than the PCL of 80 µg/L.

Plate 161 displays the distribution of sampled wells and analytical result summaries for chloroform in Texas groundwater. Many detections are located along the Edwards Aquifer, but others are clustered in the Houston area and scattered throughout the Ogallala.

5.2.4.7 Carbon Tetrachloride

Like chloroform, carbon tetrachloride is both a disinfection byproduct as well as a degradation product of parent VOCs such as PCE and TCE. The TCEQ MCL for carbon tetrachloride is 5 µg/L. This is the PCL referenced in the data analysis.

This contaminant was reported with a positive detection in 0.2% of wells (6 out of 2,947) and 0.2% of samples (6 out of 2,954) in the queried databases. No samples from any wells were detected above the PCL.

Plate 162 displays the distribution of data for tested well locations and analytical result summaries for Carbon Tetrachloride in Texas aquifers. The relatively few detections are not clustered in any one region or aquifer.

5.2.5   *Herbicide and Pesticide Compounds*

This section of the report discusses documented records of groundwater impacted by agricultural and commercial pesticide and herbicide compounds.

5.2.5.1 Atrazine

Atrazine, one of the most widely used herbicides in the world, is used to suppress the emergence of weeds in major crops. Its largest use nationwide is application to corn crops in corn-growing states. Its use remains controversial due to widespread occurrence of contamination in groundwater and reported health effects including birth defects and menstrual problems when consumed by people at concentrations lower than government standards. Atrazine was banned in the European Union in 2004 due to persistent groundwater contamination. In the United States it is still widely used. The TCEQ MCL for atrazine is 3 µg/L. This is the PCL referenced in the data analysis.

Atrazine was reported at a positive detection in 35.8% of wells in the queried databases (954 out of 2,666 wells). This is the highest percentage of positive detections for any contaminant evaluated for this project. The percentage of samples with positive detection of atrazine is 55.6% (1,493 out of 2,684 samples). This is also the highest percentage of positive detections among analyzed samples. Atrazine was detected at concentrations exceeding the PCL is 0.8% of wells (20 out of 2,666) and 1.1% of analyzed samples (31 out of 2,684 samples).

Plate 163 displays the distribution of data for tested well locations and analytical result summaries for atrazine in Texas aquifers. Atrazine detections are clustered largely in the

Southern Ogallala aquifer, the Edwards Aquifer, and to a lesser extent in the Gulf Coast Aquifer including the Houston area. Most of the locations where concentrations exceeded the PCL are in agricultural areas. The Ogallala detection locations confirm the supposition that agricultural sources dominate the distribution of this contaminant, but the detections in the Houston area indicate a secondary urban source as well.

5.2.5.2 Atrazine Metabolites

Deethylatrazine and deisopropylatrazine are two common degradation compounds of atrazine. There is no PCL established for these compounds.

Deethylatrazine was detected in 18.2% of wells (224 out of 1,229) and 39.7% of analyses (494 out of 1,243) in the databases queried. Deisopropylatrazine was detected in 10.4% of wells (29 out of 280) and 14.8% of analyses (43 out of 290).

Plates 164 and 165 display the distribution of data for tested well locations and analytical result summaries for these two compounds in Texas aquifers. These detections are clustered in the Edwards Aquifer, the Southern Ogallala, the Gulf Coast Aquifer northwest of Houston, and in the Dallas area.

5.2.5.3 Simazine

Simazine is an herbicide used to control broad leaved weeds and annual grasses. Like atrazine, it functions by inhibiting photosynthesis. It is now banned in the European Union. The PCL of simazine is 4 µg/L, based on the TCEQ MCL.

Simazine was detected in 7.1% of wells (110 out of 1,559) and 17.3% of samples (274 out of 1,587 analyzed samples) in the databases queried. Simazine was not reported at a concentration above the PCL in any of the samples reported.

Plate 166 displays the distribution of data for tested well locations and analytical result summaries for simazine in Texas aquifers. Most detections are located in the Edwards Aquifer, with a lesser amount in the Houston area.

5.2.5.4 Prometon

Prometon is an herbicide used to control weed emergence. It is adapted to industrial use. The PCL for prometon is 400 µg/L, based on a USGS HBSL.

Prometon was reported at a concentration above the detection limit in 8.0% of wells (108 out of 1,346) and 13.3% of samples (185 out of 1,391 analyzed samples) in the databases queried. Prometon was not detected at a concentration above the PCL in any of the samples reported.

Plate 167 displays the distribution of tested well locations and analytical result summaries for Prometon in Texas aquifers. The majority of the positive detections appear to have occurred in the Edwards aquifer in the San Antonio area, indicating a probable urban source for the contamination rather than agricultural. Other locations with a positive detection occur in the Ogallala, Trinity, and Gulf Coast Aquifers.

5.2.5.5 Diazinon

Diazinon is an organophosphate insecticide heavily used in the 1970s and 1980s for general garden and pest control against cockroaches, silverfish, ants, and fleas. In 1988, the US EPA banned the use of diazinon at golf courses and sod farms due to documented bird die-offs in those areas. Residential use was banned in the U.S. in 2004, but it is still approved for agricultural applications. The PCL for diazinon is 1 µg/L, based on a USGS HBSL.

Diazinon was detected in 3.0% of wells reported in the database (53 out of 1,782 wells), and in 3.6% of samples (66 out of 1,821 analyzed samples) in the databases queried. It was only detected above the PCL in a single sample in the database.

Plate 168 displays the distribution of data for tested well locations and analytical result summaries for diazinon in Texas aquifers. Most of the positive detections occurred in samples from the Edwards aquifer, with lesser frequency of detections in the Trinity, Wilcox, and Gulf Coast aquifers.

5.2.5.6 2-4D

2,4-Dichlorophenooxyacetic acid (2,4-D) is a common herbicide used to control broadleaf weeds. It is the most widely used herbicide in the world, and the third most commonly used herbicide in North America. Some European countries are starting to impose restrictions on its use, but the US EPA approved the continued use of 2,4-D in 2005. The PCL for 2,4-D is 70 µg/L, based on the TCEQ MCL.

2,4-D was detected in 2.5% of wells (31 out of 1,262) and 2.6% of samples (33 out of 1,280) recorded in the databases queried. Only a single sample from one well reported a concentration of 2,4-D greater than the PCL.

Plate 169 displays the distribution of data for tested well locations and analytical result summaries for 2,4-D in Texas aquifers. Most of the relatively few positive detections have occurred in samples collected from the Edwards aquifer, indicating a probable urban source.

5.2.5.7 Metolachlor

Metolachlor is an organic compound used as an herbicide to suppress grass and weeds in agricultural applications. The PCL for metolachlor is 700 µg/L, based on the USGS HBSL.

Positive detections for metolachlor were reported in 1.7% of wells (24 out of 1,437 wells), and in 1.7% of samples (25 out of 1,465 analyzed samples) in the databases queried. No samples from any wells contained reported concentrations above the PCL.

Plate 170 displays the distribution of data for tested well locations and analytical result summaries for metolachlor in Texas aquifers. Detections are not limited to any one geographic area but are scattered throughout the Ogallala, Edwards, Trinity, and Gulf Coast aquifers.

5.2.5.8 Tebuthiuron

Tebuthiuron is an herbicide used to control weeds and woody and herbaceous plants. The US EPA considers tebuthiuron to have a great potential for groundwater contamination, due to high water solubility, low soil particle adsorption, and high persistence in soils. The PCL for metolachlor is 1,000 µg/L, based on the USGS HBSL.

Tebuthiuron was reported with a positive detection in 1.2% of wells (14 out of 1,204 wells) and 1.5% of samples (18 out of 1,210 analyzed samples) in the databases queried. It was not detected at a concentration greater than the PCL in any reported groundwater samples.

Plate 171 displays the distribution of data for tested well locations and analytical result summaries for tebuthiuron in Texas aquifers. The relatively few detections are not clustered in any one area, but are scattered across several aquifers throughout the state.

5.2.5.9 Carbaryl

Carbaryl is an insecticide used commonly in the United States in multiple settings, including home gardens, commercial agriculture, and forestry and rangeland protection. It is a chemical in the carbamate family; the development of carbamate pesticides has been called a breakthrough in pesticides because carbamates do not have the environmental persistence of chlorinated pesticides. It is toxic to insects, but eliminated rapidly in vertebrates, and is not concentrated in fat or secreted through milk. For these reasons it has become favored for use with food crops in the United States. The PCL for Carbaryl is 40 µg/L, based on the USGS HBSL.

Carbaryl was detected in 1.0% of wells (12 out of 1,252) and 1.5% of analyses (20 out of 1,292) in the databases queried. Carbaryl was not detected at a concentration greater than the PCL in any of the samples reported.

Plate 172 displays the summary of reported data for carbaryl in groundwater in Texas. The detections are primarily in the Edwards Aquifer and in the Houston area.

5.2.5.10 Alachlor

Alachlor is an herbicide marketed under a variety of trade names that is used to control grasses and broadleaf weeds in corn, soybeans, and peanuts. It is most commonly applied as microgranules, rather than spraying. The PCL for alachlor is 2 µg/L, based on the TCEQ MCL.

Alachlor was reported at a positive detection in 0.6% of wells (9 out 1,502) and in 0.6% of analyses (9 out of 1,512 analyzed samples) in the queried databases. It was not detected above the PCL in any sample for any well.

Plate 173 displays the distribution of data for tested well locations and analytical result summaries for alachlor in Texas aquifers. (Some of the wells with reported detections did not contain latitude and longitude data; these are not displayed.)

5.2.5.11 Diuron

Diuron is an herbicide that inhibits photosynthesis. In addition to its use as an herbicide, it is sometimes used in research applications to evaluate energy flow in photosynthesis. The PCL of Diuron is 2 µg/L, based on the USGS HBSL.

Diuron was reported at a concentration above the detection limit in 1.2% of wells (8 out of 644 wells) and 1.2% of samples (8 out of 654 analyzed samples) in the queried databases. Diuron was detected at a concentration above the PCL in 0.3% of wells (2 out of 644 wells) and 0.3% of samples (2 out of 654 analyzed samples) in the queried databases.

Plate 174 displays the distribution of data for tested well locations and analytical result summaries for Diuron in Texas aquifers. The few positive detections are not clustered in any one particular geographic area of the state, or in any particular aquifer.

5.2.5.12 Dieldrin

Dieldrin is an insecticide originally developed in the 1940's, and was widely used from the 1950s through the early 1970s as an alternative to DDT. It does not chemically degrade easily. It is a very persistent organic pollutant, and exposure to it has been linked to several serious health problems. It is now banned in most of the world. The PCL for Dieldrin is 0.002 µg/L, based on the USGS HBSL.

Dieldrin was reported at a positive detection in 0.2% of wells (4 out of 1.979 wells) and in 0.3% of samples (5 out of 1,991 analyzed samples) in the queried databases. It was not reported at a concentration greater than the PCL in any of the samples reported.

Plate 175 displays the distribution of data for tested well locations and analytical result summaries for Dieldrin in Texas aquifers. Four out of five historical Dieldrin detections have occurred in the Edwards Aquifer, and one in the Woodbine Aquifer near Dallas.

5.2.5.13 Chlorpyrifos

Chlorpyrifos was originally one of the most widely used household pesticides in the US. Since 2001, it is registered only for agricultural use in the United States, and it is still widely used in agriculture in the US. The PCL of chlorpyrifos is 2 µg/L, based on the USGS HBSL.

Chlorpyrifos was detected in only 0.3% of wells (4 out of 1,494 wells) and 0.3% of samples (4 out of 1,525 analyzed samples) in the queried databases. No samples with concentrations above the PCL were reported.

Plate 176 displays the distribution of data for tested well locations and analytical result summaries for chlorpyrifos in Texas aquifers. The few positive detections are not clustered in any one particular area or aquifer, but are scattered throughout the state.

5.2.5.14 Cyanizine

Cyanazine is an herbicide used to control grass and weed in agriculture. The US EPA classifies it as a Restricted Use Pesticide, indicating that it may only be bought and used by certified applicators. The EPA does not consider cyanazine to have significant groundwater contamination potential, but a groundwater advisory statement on cyanazine product labels is required because of reported contamination. The referenced PCL for cyanizine is 10 µg/L, based on the Canadian Maximum Acceptable Contamination level.

Cyanazine was reported at a positive detection in 0.3% of wells (3 out of 1,168) and 0.3% of samples (3 out of 1,181) recorded in the queried databases. It was not detected at a concentration greater than the PCL in any sample results reported in the database.

Plate 177 displays the distribution of data for tested well locations and analytical result summaries for cyanazine in Texas aquifers.

5.2.5.15 Lindane

Lindane has been used both as an agricultural insecticide and as a pharmaceutical treatment for lice and scabies. The US EPA began limiting use of lindane in agriculture in the 1970s, and in 2007 the last uses were cancelled. Pharmaceutical applications have also been restricted in various states over the past 10 years. The PCL for lindane is 0.2 µg/L, based on the TCEQ MCL.

Lindane was reported at positive detections in groundwater in 0.1% of wells (2 out of 1,380) and 0.1% of samples (2 out of 1,391 analyzed samples). It has historically been detected in only a single sample out of the 1,391 analyzed sample documented in the queried databases.

Plate 178 displays the distribution of data for tested well locations and analytical result summaries for lindane in Texas aquifers. Most detections have occurred in the Edwards Aquifer. The lone concentration above the PCL is located in the Seymour Aquifer.

5.2.5.16 Acetochlor

Acetochlor is an herbicide used primarily to control weeds in corn. It has been classified as a probable human carcinogen. The PCL of acetochlor is 1 µg/L, based on the USGS HBSL.

Acetochlor was not reported at any concentration above the detection limit in any of the 1,091 samples from 1,087 wells in the queried databases.

Plate 179 displays wells that were sampled for acetochlor.

5.2.5.17 Aldicarb

Aldicarb is an insecticide important in potato production in the United States. It is not approved by the US EPA for household use. In November 2009, corn treated with an aldicarb-containing commercial pesticide was placed in and around peanut fields in Eastland County, Texas, near the town of Cisco. The corn was eaten by feral hogs and deer, leading to the Texas Parks and Wildlife Department (TPWD) issuing a hunting ban in the area. The PCL of aldicarb is 9 µg/L, based on the USGS HBSL.

Aldicarb was not detected at any positive concentration above the method detection limit in any of the samples queried in the databases used for this project.

Plate 180 displays wells that were sampled for aldicarb.

5.2.5.18 Chlorothalonil

Chlorothalonil is used as a fungicide, pesticide, and wood protectant in the US, used in agricultural applications on peanuts, potatoes, and tomatoes, applied on lawns and golf courses, and used as a preservative in paint. The PCL of chlorothalonil is 5 µg/L, based on the USGS HBSL.

Chlorothalonil was not reported with a positive detection in any of the 603 samples from 601 wells in the queried databases.

Plate 181 displays wells that were sampled for chlorothalonil.

5.2.5.19 Dinoseb

Dinoseb is a pesticide. The PCL for dinoseb is 7 µg/L, based on the TCEQ MCL.

Dinoseb was not reported with a positive concentration in any of the 846 samples from 836 wells in the queried databases.

Plate 182 displays wells that were sampled for dinoseb.

5.2.6   Agricultural Nutrients

This section discusses agricultural nutrient compounds found in fertilizers, primarily nitrates. Although nitrates are not strictly anthropogenic, but are also naturally occurring in groundwater, they are included in this discussion because of the significant documented anthropogenic component in their occurrence.

5.2.6.1 Nitrates

Nitrates are the most common nutrient present in commercial and agricultural fertilizer products. Nitrate contamination of groundwater is commonly associated with the application of fertilizers

to crops grown over unconfined aquifers facilitating the percolation of nutrient-rich irrigation water past the crop root zone to the groundwater table below. However, it is not necessarily restricted to areas of commercial agriculture. The same mechanism applies to urban and suburban areas where fertilization of residential lawns is widespread.

Nitrates are also present at elevated concentrations in animal manure and sewage. Therefore, it is a contaminant that is also associated CAFOs, areas where septic systems have failed, and possibly areas where wastewater collection system piping is cracked or compromised, and has allowed leakage. Nitrates also may occur naturally in certain geologic settings, so there may be some ambiguity in groundwater quality results with respect to the origin of the nitrate in question and whether and to what extent the results represent anthropogenic or naturally occurring sources. However, because it is a common contaminant from agricultural and other practices, it will be discussed in this section of the report. The PCL for nitrate as nitrogen (NO3-N) is 10 mg/L, based on a long standing MCL promulgated by the US EPA.

In 1999, Hudak used Geographic Information System (GIS) software to evaluate groundwater data from the TWDB database. He found nine counties in north central and west central Texas in which more than 50% of the reported nitrate concentrations exceeded the MCL, and the highest nitrate concentrations in the Seymour aquifer, with a median value of 59.9 mg/L. Hudak also reported an inverse relationship between nitrate concentration and well depth, suggesting a land surface source for the contamination.

For the current project, nitrates were reported at concentrations above the detection limit in 88% of wells in the database (3,497 out of 3,990), and in 94% of samples in the database (3,750 out of 4,005). Detections were reported in nearly every aquifer in Texas. Because nitrate is naturally occurring, positive detections below the PCL are not significant.

Nitrates were detected at a concentration above the PCL in 8.6% of wells (341 out of 3,990 wells) and 9% of samples (360 out of 4,005 analyzed samples) in the queried databases.

Plate 183 displays the distribution of analytical results and tested wells for nitrate as nitrogen in Texas aquifers. The majority of PCL exceedences occur in the irrigated agricultural regions in West Texas, in the Edwards-Trinity, southern Ogallala and Seymour aquifers.

5.2.7   *Semi-volatile Organic Compounds*

Semi-volatile Organic Compounds (SVOCs) are a class of chemicals used in industry, often as plasticizers. SVOCs are less mobile in the subsurface environment than VOCs or agricultural chemicals, and therefore are less likely to be detected far from the point source. Therefore, there are less data in available databases for these chemicals than for VOCs. The most frequently detected SVOC in a published EAA study was bis (2-ethylhexyl) phthalate, which is commonly considered a contaminant from sampling equipment, well construction material such as PVC plastic, or the laboratory. Bis (2-ethylhexyl) phthalate was detected in 179 of 387 samples in the queried databases. However, because of the ambiguities introduced from the laboratory sampling and well material contamination issue, these results are not considered significant. The second most frequently detected SVOC in the EAA study was phenol. Phenol was detected in 179 of 564 samples. Other than one anomalous result, none were near the HBSL of 2,000 µg/L. No maps were generated for SVOC results.

5.3   Groundwater Contaminant Trends Over Time

Because no regulations have existed in Texas that mandate regular sampling of PWS wells for contaminants that are not commonly found, there is not a great deal of time series data for chemical concentrations in groundwater to analyze. LBG-Guyton reviewed well locations with the greatest number of records for analytical results, and presents here some of the hydrographs displaying concentrations over time for some of the most frequently detected contaminants.

5.3.1   *Atrazine*

Plate 184 displays analytical data hydrographs for wells with records of multiple sampling events in which the samples were analyzed for atrazine. There is no strong trend indicating gradually increasing concentrations of atrazine over the time period represented in these hydrographs. Sampling events with relatively elevated atrazine concentrations are routinely followed by events

with lower concentrations. Bearing in mind that the PCL for atrazine is 3 µg/L, it is apparent that very few of the reported detections approach this threshold. Only one sampling event for one well (08155395) resulted in a concentration exceeding the PCL, and most of the rest of the samples for that well had concentrations well below 0.5 µg/L. There does not appear to be any strong indication of increasing concentrations with time; rather, an attenuation of concentration appears to be occurring.

5.3.2   Simazine

Plate 185 displays analytical data hydrographs for wells with multiple sampling events in which the samples were detected for simazine. Some of the graphs appear to reflect some increase in concentrations in recent years, but the results are not general throughout the sampled wells, and the number of samples is too small to infer any larger trends. Bearing in mind that the PCL for simazine is 3 µg/L, it is apparent that very few of the reported detections approach this threshold. There does not appear to be any strong indication of increasing concentrations with time.

5.3.3   Chlorinated Compounds

Plate 186 displays analytical data hydrographs for wells with multiple sampling events and detections for chlorinated solvents (PCE, TCE, and 1,1,1-TCA) over time. Chlorinated solvents are generally introduced to groundwater from a point source of contamination, such as a surface spill or a leaking underground storage tank. None of these graphs reveal concentrations near the respective PCLs. Most reveal decreasing concentrations with time, which is consistent with the conceptual model of natural attenuation of contaminants introduced from a point source of contamination.

5.3.4   Chloroform

Plate 187 displays analytical data hydrographs for wells with multiple detections for chloroform over time. Although about half of these graphs appear to have higher concentrations in more recent years, there is no strong trend indicating gradually increasing concentrations of chloroform over the time period represented in these hydrographs. Sampling events with relatively elevated chloroform concentrations are routinely followed by events with lower concentrations. The PCL for chloroform is 80 µg/L. None of the reported detections even approach the 1 µg/L threshold, so hazardous levels of chloroform do not appear to be an issue in Texas groundwater at present.

5.3.5 Nitrates

Plate 188 displays analytical data hydrographs for 5 wells which have records of multiple sampling events with analyses for nitrates. There does not appear to be any strong indication of increasing concentrations with time in any of these five hydrographs. The great majority of results indicate concentrations well below the PCL of 10 mg/L. Two of the wells (SAAN98 and GUM075) display time series that reflect the possibility of single sampling events yielding nitrate concentrations that are significantly higher than all other events. This stochastic variation should be considered when evaluating spatial distribution of elevated nitrate concentrations.

6   Volume Estimates and Treatment Cost Data

As part of the statewide evaluation of anthropogenic impacts of groundwater quality, a methodology was developed to estimate volumes of affected groundwater for each region and the potential costs to treat this volume of water to drinking water standards. This effort does not include any specific case study or review of individual sampling documentation. All data used to generate these estimates are available in the databases that were utilized for the mapping and water quality data review. Costs were developed based on published cost data for drinking water supply applications.

In order to calculate volumes of affected groundwater in each regional water planning area, the following assumptions were made. First, an assumption is made that only groundwater with water chemistry parameters that exceeded published maximum contaminant levels (MCLs) or Health-Based Screening Levels (HBSLs) would be considered. In other words, the assumption is made that positive detections for analytes that are below MCLs would not be considered in volume calculation methodology because there are no regulatory requirements mandating treatment for these low levels. The recent USGS NAWQA investigations use analytical laboratory methods with very low method detection limits, and so may report positive detections that are well below any regulatory threshold.

It should be noted that it was necessary to develop a methodology for calculating volumes that could be performed using the data available for this project. The data for this project utilized source groundwater chemistry data in the publicly available databases previously discussed that are statewide in scope. A more accurate estimation of affected volumes of groundwater could possibly be performed on a case-by-case basis if local data are available from site characterization investigations. Contaminant site characterization field methods generally utilize monitoring wells that are located considering in-situ contaminant data, with monitor wells located with a much greater spatial density than PWS wells or irrigation wells provide. Detailed case reviews were not performed under the scope of this project, so such locally detailed data were not available for these calculations. The spacing of public supply and irrigation wells is

likely greater than that which would be utilized if a detailed monitoring plan were in place, so the delineation of affected areas may be larger than would be defined if a higher density monitoring network data were in place. The calculated volume estimates are limited by the available data, and therefore should likely be considered overestimates of actual volumes.

Parameters required to calculate a volume of groundwater in storage are:

- lateral area of affected groundwater,
- vertical depth of affected groundwater, and
- porosity

To generate these values from the existing data, the following methodologies were developed. A different methodology was adopted to estimate the lateral areal extent of contamination for each major category of contaminant, based on the data available for that contaminant category.

6.1   Delineation of Lateral Extent of Contaminated Groundwater

6.1.1   Hydrocarbons and Fuel Constituents

For hydrocarbon contamination from a point source, area was calculated using published statistics for average hydrocarbon plume sizes in Texas. Mace and others published a statistical study of the size of hydrocarbon plumes in Texas (1997). They reported that the median size of a stabilized hydrocarbon plume in the state was approximately 26,000 ft^2. LBG-Guyton applied this value to represent hydrocarbon plume areas indicated by detections above the MCL.

6.1.2   Chlorinated Compounds and Agricultural Chemicals

In order to estimate the areal extent of impacted groundwater for chlorinated solvents, disinfection by-products, and pesticides, the following method was developed.
Water quality sampling locations with data that exceed MCLs were examined. For each location (or clustered group of locations) with a detection above the MCL, a polygon was generated that encompasses these samples. The initial estimates of the areas of these polygons were defined by using a Thiessen polygon approach. In this method, a point is defined half way between the MCL

location and the next closest non-MCL sample location (positive detection locations, non-detect locations, or PWS locations with no available data were all used as control points). When these points are connected with straight lines, an irregular polygon is generated, as displayed in Figure 8. The area of this polygon may then be calculated using GIS. However, because of the lack of control points in many areas due to large distances between PWS wells, this initial approach often led to unrealistically large areas being defined. Therefore, although the Thiessen polygon approach was used as an initial estimate, engineering judgment was necessarily applied in delineating the areas representing the plumes of impacted groundwater for each subject contaminant. In the end, an area was defined that surrounded each occurrence (or cluster of occurrences) of a detection of a subject contaminant above the MCL or other applicable screening level. This polygon is assumed to represent the areal distribution of the plume being considered for volatile compounds and agricultural pesticides. As mentioned previously, the lack of local data and the relatively wide spacing of PWS and irrigation wells will likely result in a conservative over-estimate of area using this method.
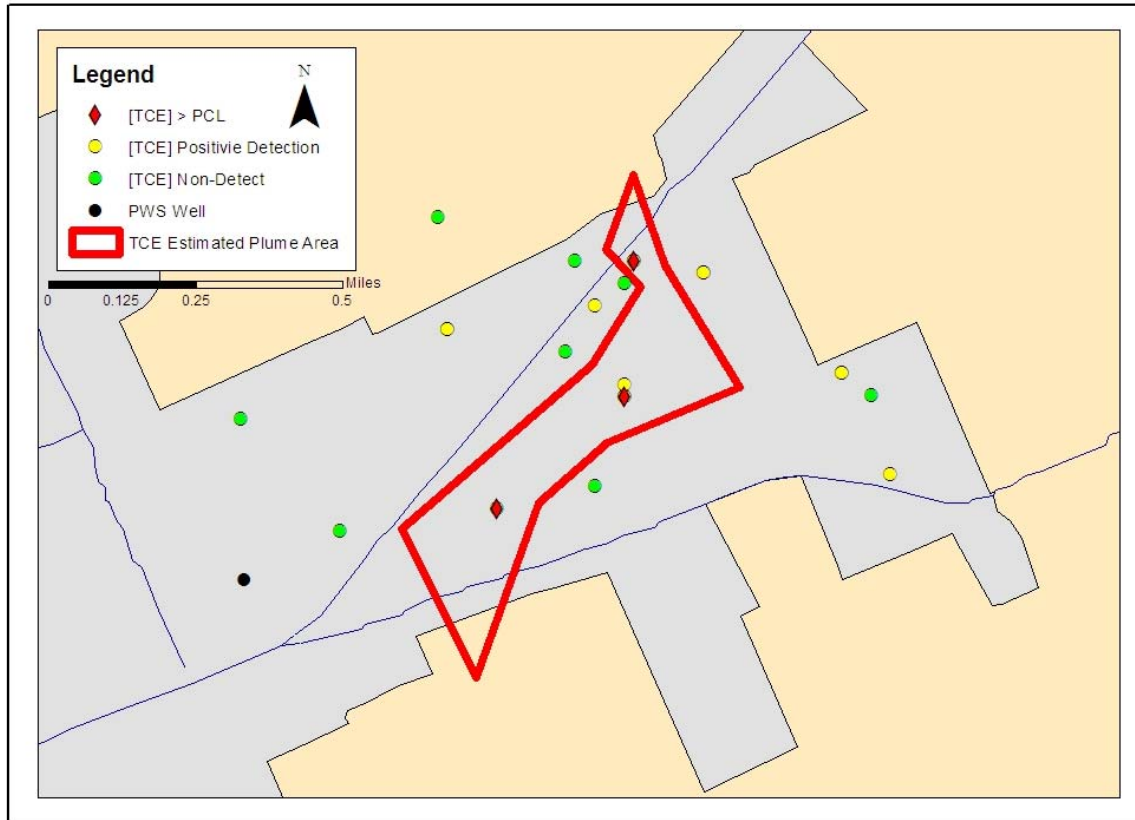
Figure 8: Example of plume area definition method

6.1.3   *Nitrates as Nitrogen Delineated Areas*

Because nitrates are a contaminant with both a naturally occurring and an anthropogenic component, they are addressed in more detail in the BEG report on naturally-occurring groundwater contamination. For this reason, volume calculations for nitrates were not addressed in this report.

6.2   **Estimation of Vertical Depth of Contamination**

Estimating the vertical depth of a groundwater contaminant plume using the data available for this project was more involved. It is generally accepted, and documented in several publications, that positive detections of contaminants do not necessarily represent conditions integrated throughout the entire vertical extent of the saturated zone of the aquifer (McMahon et al., 2004). The vertical extent of contamination is a parameter that is not often well-defined, even in intensive field investigations of contaminant plumes.   The databases that were available to use

for this project did not contain any data on vertical extent of contamination. The only data available in the databases were sample locations, water chemistry data, screened aquifer, and possibly well screen interval. External sources such as published aquifer reports and TWDB Groundwater Availability Models (GAMs) were available to estimate aquifer properties.

In order to generate an estimate of vertical depth of contamination using this data, LBG-Guyton applied the following equation used to estimate contaminant mixing zone depth, as per the illustration in Figure 9. This equation was derived during an EPA review of contaminated sites nationwide as part of the development of a soil screening tool to be used in risk assessment of contaminated sites. The equation is meant to estimate the vertical mixing zone of the contaminant in groundwater due to processes of dispersion and advection in an unconfined aquifer as a result of a source of contamination at the land surface which reaches the water table below. The original document may be consulted for details on the origin and derivation of the equation. The equation is:

$$H = (0.0112*L^2)^{0.5} + b\{1-\exp[(-L*I)/(K*i*b)]\}$$

Where

H = mixing zone depth (ft)

L = Source length parallel to flow direction (ft)

I = Infiltration rate (ft/yr)

K = Aquifer hydraulic conductivity (ft/yr)

i = Hydraulic gradient (ft/ft)

b = Aquifer thickness (ft)

Vertical Mixing Region Depth
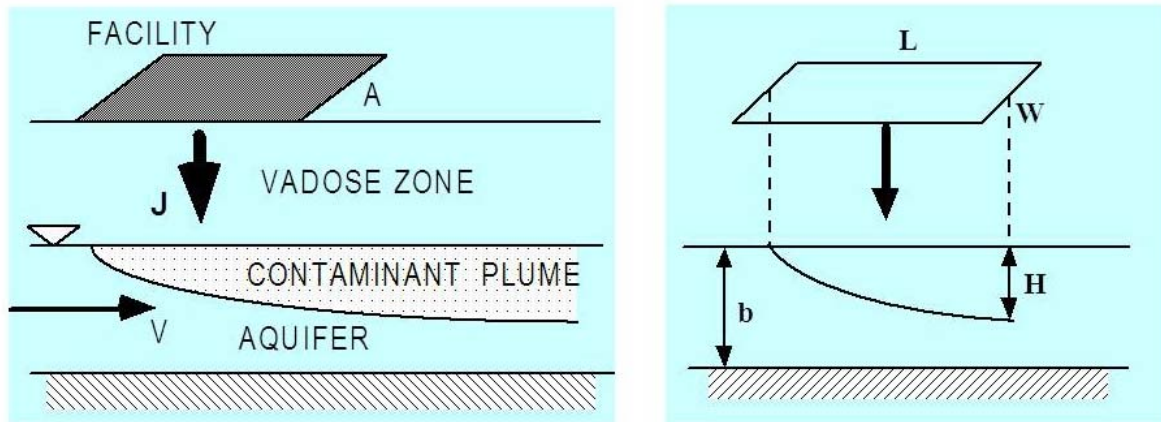
Figure 9: Vertical contaminant mixing paramenters (from Charbeneau)

The parameters of this equation were defined using the following assumptions.

As per guidance in the EPA soil screening document, long term recharge rate is used as a substitute for infiltration rate. Recharge rates were obtained from the GAMs of the aquifers corresponding to those indicated in the contaminant data. Additionally, hydraulic conductivity and aquifer thickness were obtained from the GAMs for the areas covered by the contaminant plumes.

The source length, L, was approached separately for contaminants assumed to be from a point source, such as hydrocarbons and chlorinated solvents, and contaminants assumed to be from non-point sources, such as pesticides. For the contaminants assumed to be non-point source, the estimation of a source area separate from the plume area is not assumed to be applicable. In essence, the source area is assumed to be equivalent to the plume area.

For delineated plumes that are associated with point sources, it is not appropriate to estimate a source area equivalent to the plume area. The plume area is always larger than the source area due to advection and dispersion of contaminant particles during downgradient groundwater

transport in the direction of groundwater flow. A brief study was performed of readily available published data of case study documentation for chlorinated solvent plumes at military bases across the US. For case studies in which both the source area and the plume area are documented, it was found that source areas varied from about 2% to 7% of the plume area (Parsons, 1999 and Kavanaugh et al., 1998). After evaluating this information, a large estimate of source area is assumed to be 10% of the estimated plume area. The length (L) of this source area is then calculated as the square root of the area. Using a combination of these two approaches, for each location of sample detection above the MCL, an estimate for the mixing depth H was calculated. In some instances, particularly those in which a large non-point source area was delineated, the calculated vertical mixing depth exceeded the actual aquifer thickness at the location in question. In this event, the full thickness of the aquifer was used for the calculations, and the resulting volumes may be considered a conservatively large estimate. This was in fact the case for over half of the delineated areas identified in Table 12.

Table 12: Volume calculation

Contaminant/Aquifer	County	Plume Area (acres)	Estimated Source Area [1] (acres)	Estimated Source Length [2] (ft)	Aquifer Thickness [3] (ft)	Infiltration Rate [3] (in/yr)	Hydraulic Conductivity [3] (ft/d)	Hydraulic Gradient [3] (ft/ft)	Vertical Depth of Contamination [4] (ft)	Porosity	Volume (ac-ft)
TCE Edwards	Bexar	116	12	710	550	1.57	34	0.0008	84	0.05	489
TCE Edwards	Uvalde	75	8	573	700	1.26	34	0.0008	67	0.05	251
PCE Edwards	Uvalde	95	9	643	700	1.26	34	0.0008	75	0.05	354
PCE Edwards	Uvalde	321	32	1,183	700	1.26	34	0.0008	138	0.05	2,208
PCE Edwards	Uvalde	98	10	654	700	1.26	34	0.0008	76	0.05	374
PCE Edwards	Uvalde	170	17	860	700	1.26	34	0.0008	100	0.05	851
PCE Edwards	Bexar	232	23	1,004	500	1.57	34	0.0008	119	0.05	1,382
Dieldrin Edwards	Uvalde	2,867	NA	11,175	725	1.26	34	0.0008	725	0.05	103,920
Dieldrin Edwards	Medina	3,564	NA	12,460	525	1.26	34	0.0008	525	0.05	93,553
Dieldrin Edwards	Bexar	1,177	NA	7,161	550	1.57	34	0.0008	550	0.05	32,374
Diazinon Edwards	Hays	1,046	NA	6,751	500	1.90	34	0.0008	500	0.05	26,156
Atrazine Ogallala	Deaf Smith	17,975	NA	27,982	260	0.07	28	0.007	260	0.15	701,031
Atrazine Ogallala	Parmer	151	NA	2,567	310	0.07	4.3	0.003	275	0.15	6,237
Atrazine Ogallala	Swisher	174	NA	2,755	160	0.07	28	0.0015	160	0.15	4,183
Atrazine Ogallala	Hale	24	NA	1,023	331	0.07	14	0.0009	110	0.15	395
Atrazine Ogallala	Hale	2,791	NA	11,026	284	0.07	6.5	0.002	284	0.15	118,888
Diuron Ogallala	Lubbock	3,646	NA	12,603	151	0.03	4.3	0.004	151	0.15	82,585
Benzene Ogallala	Dallam	1	0	51	284	0.07	6.5	0.002	5	0.15	0.5
Benzene Ogallala	Floyd	1	0	51	284	0.07	6.5	0.002	5	0.15	0.5
MTBE Ogallala	Dallam	1	0	51	284	0.07	6.5	0.002	5	0.15	0.5
PCE Evangeline	Harris	256	26	1,057	3,000	3.00	1.2	0.001	658	0.15	25,326
24D Burkeville	Washington	3,095	NA	11,611	300	0.50	0.02	0.001	300	0.15	139,265
Vinyl Chloride Woodbine		375	37	1,278	116	0.86	1.0	0.004	116	0.1	
TCE Woodbine	Tarrant	375	37	1,278	116	0.88	1.0	0.004	116	0.1	4,349
PCE Woodbine		375	37	1,278	116	0.88	1.0	0.004	116	0.1	
Dieldrin Woodbine	Tarrant	75	NA	1,804	192	2.85	0.3	0.004	192	0.1	1,435
Atrazine Dockum	Howard	8,511	NA	19,254	677	0.15	0.3	0.003	677	0.05	288,091
Lindane Seymour	Knox	2,168	NA	9,717	50	1.26	34	0.014	50	0.1	10,839
Atrazine Seymour	Hardemann	547	NA	4,879	86	1.26	66	0.014	86	0.1	4,700
Atrazine Seymour	Knox	1,091	NA	6,894	36	1.26	860	0.014	36	0.1	3,927
Atrazine Seymour	Haskell	141	NA	2,475	40	1.26	38	0.014	40	0.1	563
TOTAL											1,653,728

Notes:
1. Source area for point source plumes estimated to be 10% of plume area. Not applicable to non-point source plumes. See text for details.
2. Source length estimated at square root of source area. See text for details.
3. Data taken from Groundwater Availability Models
4. Calculated from Mixing Equation. See text for details.

6.3   Volume Calculations

Having estimated the area and depth of contamination for each delineated contaminant plume, the final parameter required to calculate volumes of groundwater in storage is an estimate of porosity. Porosity is the ratio of the volume of void space in a rock to the total volume of the rock or sediment, and thus represents the volume available for storage of groundwater in an unconfined aquifer. Therefore, the equation to calculate total volume of impacted groundwater in storage is

$$V = A \, (ft2) * H \, (ft) * Porosity \, (dimensionless)$$

Average porosity values for the aquifers in question were obtained from agency hydrogeologic reports and from information published in the Brackish Groundwater Manual for Texas Regional Water Planning Groups. They are displayed on Table 12. A summary of volumes calculated for each identified contaminant is presented in Table 12. Using the methodology previously described and the aquifer parameters summarized in the Table, a total estimate of anthropogenically contaminated groundwater (hydrocarbons, chlorinated compounds, pesticides, and herbicides) in storage in the state of Texas is approximately 1.7 million acre-feet (ac-ft) of groundwater.

To place this volume in context, Figure 10 presents a graph of historical pumping in Texas from the 2007 State Water Plan. Figure 10 indicates that approximately 530 million acre-feet have been pumped statewide since 1940; the calculated volume of impacted groundwater (1.7 million ac-ft) is approximately 0.3% of this volume. The 2007 State Water Plan reports total Texas groundwater availability in 2010 to be 12.7 million ac-ft. So the estimate of 1.7 million ac-ft of contaminated groundwater calculated using the methodology developed for this project is approximately 13% of total annual groundwater availability. (However, it should be noted that availability as defined in the State Water Plan is not equivalent to groundwater in storage, but rather is defined by current infrastructure limitation; if more wells were drilled, the availability number would increase.) In the past 10 years, total groundwater withdrawals in the state have been approximately 10 million acre-feet per year (Figure 10), so the estimated volume of in-situ

contaminated groundwater calculated using the methodology developed for this project is approximately 17% of the annual withdrawals. However, it is important to note that the aquifer systems in Texas are dynamic systems that receive recharge every year and allow the volume of withdrawals to be repeated with each succeeding year. By contrast, there is no evidence that the volume of anthropogenic contaminated groundwater is increasing. In fact, the volume of anthropogenic contaminated groundwater is likely decreasing due to regulation and prevention of future contamination, treatment and remediation of active cases, and natural attenuation of contaminants in the aquifers. If this assumption is made, then one could view the volume estimate of 1.7 million acre-feet of contaminated groundwater as approximately 1.7% of the roughly 100 million acre-feet that will be pumped from Texas aquifers over the next ten years.

However, as has been pointed out at each step of the volume calculation methodology, this method of volume estimation has essentially piled over-estimate upon over-estimate to make this calculation. First, the number of point locations assuming concentrations exceeding the PCL are likely over-estimated because a single analytical result that exceeds the PCL will identify that location with an MCL exceedence even if subsequent sampling events reveal reduced concentrations. Second, the lateral contaminant areas are likely over-estimated due to the relatively sparse distribution of wells used as data points in the raw groundwater quality data. Third, as an artifact of the large lateral area estimates, the vertical extent of contamination is consequently over-estimated, often estimating the full thickness of the aquifer as contaminated, which is normally not the case. All of these assumptions lead to a conservative over-estimate of in-situ volume of contaminated groundwater. A more realistic estimate of groundwater volumes may be reflected in the percentages of samples with concentrations exceeding PCLs, which indicate that approximately 1% or less of groundwater has contaminants that exceed PCLs in most areas.
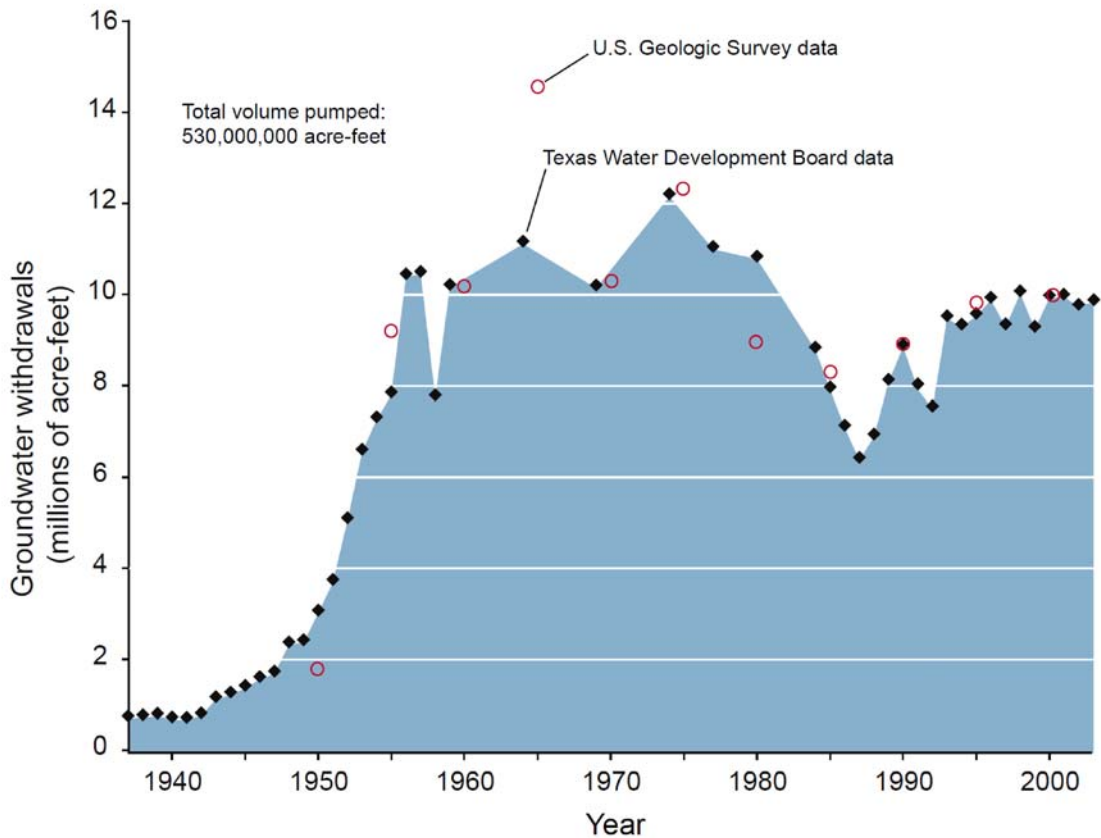
Figure 10: Historical Groundwater pumpage from Texas aquifers (State Water Plan, 2007)

6.4 Treatment Options and Cost Information

This section of the report provides discussion of treatment options to improve the quality of contaminated groundwater to concentrations below the regulatory criteria. A brief description of the various options appropriate for treatment of the contaminants previously discussed is provided, and unit cost information on appropriate treatment options is presented. Costs are reflective of well head treatment at water supply wells locations, not full scale treatment plants. Also, cost information reflects options for water supply wells with the contaminant concentrations identified in the data, for relatively large volumes at relatively low concentrations, as opposed to treatment costs for remediation of concentrated contaminant plumes that represent relatively small volumes at relatively high concentrations.

In order to determine means and methods for the effective removal of multiple chemicals of concern from a local groundwater source, six methods of pollutant removal were analyzed. These methods are listed and described as follows:

Air Stripping: Air stripping is a routine technology used in the removing of volatile organic compounds (VOCs) from groundwater. Two main configurations for air strippers include the low profile and packed tower systems. In the low profile aeration system, contaminated water is pumped to the top of the air stripper, where it flows over an inlet weir onto a baffled aeration tray. Air is forced upward through holes in the tray bottom, causing turbulent conditions which maximize the contact of air with the water. In a packed tower air stripping system, contaminated water passes downward by gravity through a column which is filled with randomly packed or structured packing material. Air is pumped into the tower from beneath the packed bed and rises through the column against the flow of water. This method is most commonly used with Granular Activated Carbon (GAC) to filter the off-gases depending on what chemical is being removed.

Activated Carbon: Activated carbon is utilized for its high porosity and surface area to catch pollutants. One gram of GAC is estimated to have as much as 500 square meters of surface area. Powdered activated carbon (PAC) is another common form which is distinguished from granular carbon by having a particle size of less than that of the opening of a #50 sieve. It is important to note activated carbon captures contaminants and will need to be replaced once the pores have reached capacity. Disposal of used carbon will need to be added to annual O&M for any entity considering this method of treatment.

Advanced Oxidation Process (AOP): This term covers a variety or treatment options which create hydroxyl radicals to oxidize pollutants. Treatment options utilize UV light, ozone, hydrogen peroxide or a combination of the three.

Reverse Osmosis (RO): Reverse osmosis is a filtration method that removes many types of large molecules and ions from solutions by applying pressure to the solution when it is on one side of a

selective membrane. The result is that the contaminated fluid is retained on the pressurized side of the membrane and the pure water is allowed to pass to the other side.

Surfactant-modified zeolite (SMZ): SMZ is a naturally occurring aluminosilicate possessing a high surface area and a high cation exchange capacities. This capacity is exploited in water treatment processes to remove nitrogen based pollutants and heavy metals. Like GAC, SMZ's must be disposed of once their sorption capacity has been reached.

Ion Exchange Resin: A manmade polymer or resin which has a developed structure of pores on the surface facilitates trapping and releasing of ions (charged pollutants). The resins or polymers are designed to trap one or several different types of ions. The life of ion exchange resins depends on the types and volumes of ions to be removed. Like GAC and SMZ, ion exchange resins trap pollutants.

The chemicals which are being evaluated in this study are found in very small quantities and fall into a group known as micro-pollutants. The table below outlines the targeted micro-pollutants and the abilities of the six methods of removing each of the micro-pollutants.

Table 13: Summary of applicable contaminant treatment options

Chemical	Air Stripping	Activated Carbon	Advanced Oxidation	RO	SMZ	resin
MTBE	X	X	X			
BTEX	X	X	X		x	
PCE	X	X	X			
TCE	X	X	X			
1,1,1-TCA	X	X	X			
Cis1,2-DCE	X	X	X			
chloroform	X	X	X	x		
Atrazine		X	X	x		x
Alachlor		X	X			
Metolachlor		X		x		
Simazine		X	X	x		
Prometon		X				x
Deethylatrazine		X				x
Deisopropylatrazine		X				x

Research shows that across the spectrum of examined micro-pollutants, Activated Carbon was found to be the most effective within the group, with Advanced Oxidation being the next most effective means of treating micro-pollutants. For contaminants such as MTBE, BTEX, deethylatrazine, and deisopropylatrazine, standard activated carbon removal only achieves 50-60% removal based upon field studies. Cost for activated carbon removal varies based upon technology utilized.

Cost for removal is difficult to determine without key variables such as concentration, flow rates and the desired removal percentage for each micro-pollutant. An EPA study showed removal costs at $0.86/1,000 gallons at a flow rate of 500gallons per minute (gpm) (equivalent to 0.72 million gallons per day, or MGD) with an MTBE concentration of 100 ug/L. Removal was seen to be as high as 95% utilizing activated carbon. One key factor that should be noted with the utilization of activated carbon is that it works through adsorption. So the more constituents and less pure the water, the shorter the life of the carbon and more frequently it will have to be replaced, thus increasing the O&M costs of the system.

The graph presented in Figure 11 is based on multiple independent studies which document costs associated with the use of GAC to remove micro-pollutants under different flows and concentrations. Costs are presented in 2010 dollars per 1,000 gallons treated. Cost trend lines for 60-gpm and 650-gpm flows are displayed in their relation to the concentration of micro pollutant present in the influent. For a flow rate of 60 gpm, estimated treatment costs range from about $2.50 to $4.00 per 1,000 gallons. For a higher assumed flow rate of 650 gpm, the economy of scale reduces estimated treatment costs from about $0.70 to $1.00 per 1,000 gallons. Final effluent for the chart is 0.5 ug/L, which is listed as being below detectable levels. For less stringent effluent removal standards, it can be assumed that the treatment costs per 1000 gallons would be reduced uniformly throughout the graph. Costs presented in the table have been adjusted to 2010 dollars and are inclusive of capital funds, annual O&M, and include disposal if needed.
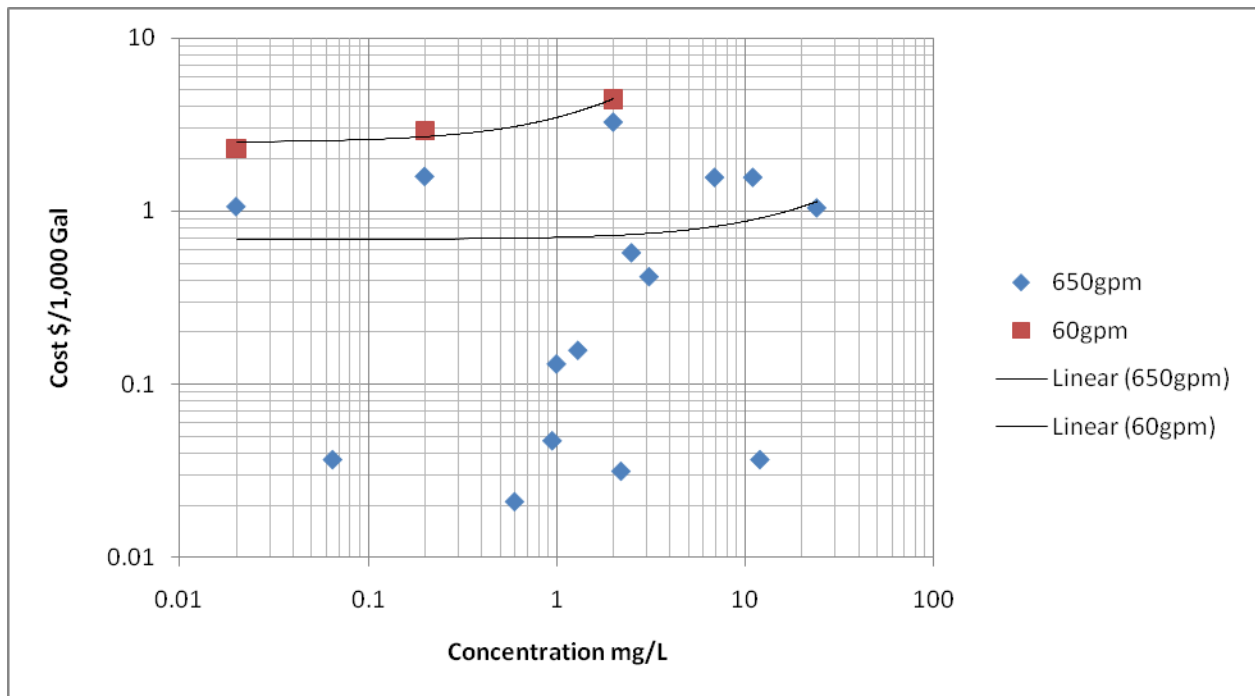

Figure 11: Treatment cost summary for VOC removal

7   Discussion and Conclusions

This section of the report presents general discussion and observations on the results of the study presented in previous sections.

7.1   Potential Sources of Contamination

The objective of this project is to perform a statewide survey of potential and documented anthropogenic groundwater contamination in Texas using available databases from various state agencies. The scale of the analysis is statewide, and necessarily precludes in-depth review of local conditions at individual source wells or from individual specific contamination investigations.

The geographical information displayed in Plates 6 through 150 presents the location and relative density of various categories of potential sources of contamination in each Regional Water Planning Area in Texas. These data were mapped for ready availability in support of early planning level considerations when evaluation of new water supply strategies are being evaluated that may include new well fields. The scale of the Plates makes them useful for regional scale evaluation of potential contaminant issues when considering new water management strategies with respect to existing or potential new PWS wells. This regional information is not intended to replace the need for a detailed source water assessment plan (SWAP), in which each PWS evaluates potential sources of contamination within a local radius that has the potential to impact a local production well. The local SWAP analysis is required by TCEQ in an ongoing program.

Over 1.3 million PSOCs are documented in this project. More than 1 million of these sites are oil/gas well locations, both active and inactive. Because of the potential for migration between formations via corroded casing or unplugged wells, this presents one of the most significant sources of potential groundwater contamination documented in this study.

7.2 Documented Records of Source Groundwater Contamination

Available databases of raw groundwater quality were assembled for this project. Raw groundwater refers to groundwater sampled prior to any mixing, treatment, or chlorination that is required prior to entry into the distribution system. The databases include both public water supply and irrigation wells sampled under various governmental programs, but specifically omit any data for contaminant remediation sites administered under RCRA, CERCLA, or other state programs such as the leaking underground petroleum storage tank program. Contaminant plume groundwater chemistry data was not included because in the great majority of cases it has no impact on drinking water supply. The focus of this study is to assess the impact of groundwater contamination on water supply.

To the extent that an individual well was subject to multiple sampling events, the Plates that present the groundwater contaminant results reflect the maximum concentration detected in any of the reported sampling events. If it was detected once, it is displayed on the Plate as a positive detection. If it exceeded the PCL once, it is displayed as having exceeded the PCL.

Nitrate as nitrogen (NO_3-N) was far and away the most commonly detected contaminant at concentrations greater than the PCL, with nearly 9% of samples exceeding this threshold. Nitrate occurs not only in agricultural areas, but in urban and suburban areas introduced through residential lawn and garden product application.

Evaluation of the distribution of data in Plates 151 through 183 reveals that for many of the anthropogenic hydrocarbons and chlorinated compounds, the greatest frequency of detections has occurred in the Edwards Aquifer. This may be explained because of the high groundwater velocities and preferential pathways afforded by the solution cavities and fractures associated with karst geology. The great majority of the detections are at concentrations well below any regulatory threshold or PCL. However, the vulnerability of the karst aquifer to contamination from anthropogenic activity, along with the high percentage of the central Texas population that depends on the Edwards for water supply, should be considered in the planning and implementation of future groundwater quality monitoring programs by the TWDB, EAA, and USGS.

7.3   Comparisons with other studies

This section discusses the comparison of the results from this study with other, similar projects that have been performed on a national scale by the USGS and at a more local scale by the EAA.

7.3.1   USGS NAWQA Study

When comparing results of the NAWQA Study with the current LBG-Guyton study, it is important to understand the different project conditions under which the respective data was collected and analyzed. The USGS NAWQA project performed its own primary data collection, collecting samples in the field under a defined protocol and quality assurance program. The USGS NAWQA study focused exclusively on source water wells, those used for community water supply. Through inclusion of the TCEQ-maintained Interagency Pesticide Database (IPD), LBG-Guyton included in its evaluation a significant number of wells that are not PWS wells, but that are irrigation wells. Therefore the LBG-Guyton study includes more agricultural irrigation wells that may be at risk from pesticide and herbicide contamination associated with modern farm practices. Additionally, the laboratory methods selected to analyze the chemical data under the NAWQA program were designed to have very low detection limits, usually lower than the standard laboratory method for a given contaminant. This resulted in a greater frequency of positive detections in the NAWQA data. In contrast, the LBG-Guyton study relied on data already collected under a variety of programs, with data collected for different purposes, and over a greater period of time than the NAWQA study. The larger time period covered by the data introduces the possibility of different detection limits being in place as time went on.

In the USGS NAWQA program, chloroform was the most commonly detected chemical in sampled source water, present in 36% of samples. In the current LBG-Guyton study, chloroform was detected in approximately 18% of samples. In the current LBG-Guyton study, atrazine was the most commonly detected chemical, detected in approximately 36% of wells and 56% of samples;. The greater detection incidence of atrazine in the LBG-Guyton study may be attributable to the fact that this study included data from many agricultural wells which were more susceptible to pesticide/herbicide contamination associated with modern farm methods.

Table 14: Comparison of contaminant detection frequencies with other studies

Parameter	Data Source		
	Current TWDB-funded Study	**EAA Study [1]**	**USGS Study [2]**
Volatile Organic Compounds			
Benzene	1.3%	0.7%	2.1%
Toluene	5.5%	3.8%	0.0%
Ethylbenzene	0.6%	1.2%	0.6%
Total Xylenes	1.0%	0.6%	1.7%
MTBE	1.9%	0.7%	12.7%
PCE	18.7%	22.2%	19.5%
TCE	4.5%	6.2%	14.0%
1,1,1-Trichloroethane	1.8%	1.2%	9.5%
cis-1,2-Dichloroethene	0.6%	0.5%	9.5%
Vinyl Chloride	0.3%	0.4%	0.9%
Carbon Tetrachloride	0.2%	0.4%	1.4%
Chloroform	18.1%	18.9%	36.1%
Pesticides and Herbicides			
Atrazine	55.6%	25.8%	29.9%
Simazine	17.3%	15.5%	16.7%
Prometon	13.3%	17.4%	11.3%
Deethylatrazine	39.7%	63.5%	34.4%
Deisopropylatrazine	14.8%	No data	13.0%
Diazinon	3.6%	2.8%	0.0%
2,4-D	2.6%	2.7%	0.5%
Carbaryl	1.5%	1.0%	0.5%
Metolachlor	1.7%	1.6%	10.9%
Tebuthiuron	1.5%	0.5%	0.9%
Diuron	1.2%	1.1%	3.3%
Dieldrin	0.1%	0.3%	0.5%
Alachlor	0.6%	0.0%	1.4%
Dinoseb	0.0%	0.0%	0.9%
Acetochlor	0.0%	0.0%	0.5%
Chlorothalonil	0.0%	0.0%	0.0%
Aldicarb	0.0%	0.0%	0.0%
Chlorpyrifos	0.3%	0.0%	0.0%
Notes:			
1) Data summarized from EAA Report No. 09-03, July 2009.			
2) Data summarized from USGS Report 2009-5200, 2009.			

The NAWQA study reported detections of five compounds at concentrations greater than the PCLs. These were:

- PCE
- TCE
- 1,2-dibromomethane
- acrylonitrile
- Dieldrin

The current study reports detections of twelve (12) compounds at concentrations greater than the PCL (Table 10). They are (presented with number of exceedences in parentheses):

- Atrazine (31)
- PCE (51)
- TCE (7)
- Benzene (4)
- MTBE (6)
- Cis-1,2 DCE (3)
- Diuron (2)
- Vinyl Chloride (2)
- Lindane (1)
- Chloroform (1)
- Diazinon (1)
- 2,4-D (1)

Three of the five chemicals detected greater than the PCL in the NAWQA study were also detected at similar levels in the current study. The Texas data revealed detections greater than the PCL of chlorinated solvent degradation products cis-1,2 DCE, and vinyl chloride that were not reported in the NAWQA study. The greater incidence of pesticide/herbicide chemicals in the current study may be a result of including more agricultural wells in the database. Four of these

chemicals were detected at these elevated concentrations in a single sample, suggesting confirmation sampling is advised before drawing any conclusions about these data.

Many of the general results for both studies were similar. Both the NAWQA study and the TWDB-funded/LBG-Guyton study reported atrazine and its metabolites - metolachlor, prometon, and simazine - as among the most commonly detected compounds. Both found that significant contamination of groundwater from distinctly anthropogenic sources is not widespread. Both studies found a very low incidence of contaminant concentrations greater than the PCL. Table 14 presents comparative detection frequencies from the two studies.

7.3.2   *EAA Study*

Like the current LBG-Guyton study, The EAA Study utilized data from multiple databases, including EAA data, USGS Data, and TWDB data. However, the EAA study only queried data for wells tapping the Edwards Aquifer, thus pulling from a smaller database than the current study. Table 16 presents a comparison of detection rates for the most common contaminants encountered in both studies. The detection frequencies are comparable for most of the analytes. The same compounds that are detected at elevated frequencies (greater than 10% positive detections) in the current TWDB-funded study (chloroform, PCE, atrazine and metabolites, prometon, and simazine) are also detected at elevated frequencies in the EAA study. The detection frequency of atrazine is greater in the current study than in the EAA study, probably reflecting the fact that the current study incorporates irrigation wells from the agricultural regions of West Texas in the analysis.

7.4   Conclusions

Inspection of the spatial distribution of anthropogenic contaminants displayed in Plates 151 through 182 indicate that the counties located along the Edwards Aquifer have the most frequent incidence of positive detections of anthropogenic contaminants in groundwater. These counties are located primarily in RWPAs Region L and Region K. The prevalence of detections in this area is attributable to the karst structure of the Edwards aquifer, which provides more accessible

conduits for the introduction and transport of contaminants in the subsurface. Volatile Organic Compounds appear to be preferentially located in the Edwards Aquifer counties compared with other aquifers and areas of the state. Herbicide and pesticide compounds such as atrazine and simazine are also concentrated in the Edwards Aquifer, though not preferentially; many detections of these chemicals are observed in the agricultural regions of the Panhandle and West Texas.

An estimate was calculated of approximately 1.7 million acre-feet of anthropogenically contaminated groundwater in place in Texas aquifers. This value represents approximately 13% of annual groundwater availability as per the most recent State Water Plan. However, this estimate was based on the data available for this project, and for reasons previously discussed, likely over-estimates actual volumes. A more realistic reflection of the percentage of groundwater supplies impacted from anthropogenic contamination may be indicated by the percentage of groundwater samples that exceed regulatory drinking water criteria; these percentages averaged less than 1%, and ranged up to 2% for some analytes.

8 References

Charbeneau, R.J., Personal Communication, 2011.

EPA Office of Emergency and Remedial Response, May 1996. Soil Screening Guidance: Technical Background Document, Second Edition, U.S., EPA/540/R95/128, 160 p.

Galloway, W.S., Ewing, T.E., Garrett, C.M., Tyler, N., Bebout, D.G., 1983. Atlas of Major Texas Oil Reservoirs; BEG Publication, 139 p.

Hackney, J., M. R. Wiesner (1996): Cost assessment of Produced Water Treatment, Working paper, Durham, NC: Duke University, 40 p.

Hopple, J.A., Delzer, G.C., and Kingsbury, J.A., 2009. Anthropogenic Organic Compounds in Source Water of Selected Community Water Systems that Use Groundwater, 2002-05; USGS Scientific Investigations Report 2009-5200, 74p.

Johnson, S., Schindel, G., and Hoyt, J., July 2009. Water Quality Trends Analysis of the San Antonio Segment, Balcones Fault Zone Edwards Aquifer, Texas; Edwards Aquifer Authority Report No. 09-03, 49 p.

Kavanaugh, M.C., Mercer, J., Leeson, A., 1998. A Technical Review of Groundwater Remedial Actions at Massachusetts Military Reservation, 45 p.

Kosters, E.C., Bebout, D.G., Seni, S.J., Garrett, C.M., Brown, L.F., Hamlin, H.S., Dutton, S.P., Ruppel, S.C., Finley, R.J., and Tylel, N., 1989. Atlas of Major Texas Gas Reservoirs; BEG Publication, 161 p.

Mace, R.E., Fisher, R.S., Welch, D.M., and Parra, S.P., 1997. Extent, Mass, and Duration of Hydrocarbon Plumes from Leaking Petroleum Storage Tank Sites in Texas; Bureau of Economic Geology Geological Circular 97-1, 52 p.

Melin, Gina, eds. Treatment Technologies for the Removal of Methyl Tertiary Butyl Ether (MTBE) from Drinking Water: Air Stripping, Advanced Oxidation Processes, Granular Activated Carbon, Synthetic Resin Sorbents, Second Edition. Center for Groundwater Restoration and Protection, National Water Research Institute NWRI-99-06, 2000, 246 p.

McMahon, P.B., Bohlke, J.K., and Lehman, T.M., 2004. Vertical Gradients in Water Chemistry and Age in the Southern High Plains Aquifer, 2002; USGS Scientific Investigations Report 2004-5053, 53 p.

Parsons Engineering Science, October 1999. Natural Attenuation of Chlorinated Solvents, Performance and Cost Results from Multiple Air Force Demonstration Sites; Air Force Center for Environmental Excellence, Technology Demonstration Technical Summary Report, 101 p.

Rice, D.W., Grose, R.D., Michaelsen, J.C., Dooher, B.P., MacQueen, D.H., Cullen, S.J., Kastenberg, W.E., Everett, L.G., and Marino, M.A., 1995. California Leaking Underground Fuel Tank (LUFT) Historical Case Analyses; Environmental Protection Department, Environmental Restoration Division, Lawrence Berkeley Laboratories, UCRL-AR-122207, 65 p.

Texas Groundwater Protection Committee, August 2010. Joint Groundwater Monitoring and Contamination Report – 2009; Report SFR-056/09, 79 p.

TCEQ, 2008. The Interagency Pesticide Database and Pesticide Occurrence in the State's Aquifers , TCEQ Publication, 33 p.

TCEQ, 2011. Municipal Solid Waste in Texas – A Year in Review, FY 2009 Data Summary and Analysis; TCEQ Publication AS-187/10, 30p.

Texas Water Commission, 1989. Ground-Water Quality of Texas - An Overview of Natural and Man-Affected Conditions, Report 89-01, 197 p.

Texas Water Development Board, 2007. Water for Texas, State Water Plan, Volume I.

Toccalino, P.L., Norman, J.E., and Hitt, K.J., 2010. Quality of Source Water from Public-Supply Wells in the United States, 1993-2007; USGS Scientific Investigations Report 2010-5024, 126 p.

U. S. Environmental Protection Agency, November 2010. National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2009 Data); US EPA Solid Waste and Emergency Response (5305P), EPA530-R-10-014A, 70 p.

Zogorski, J.S., Carter, J.M., Ivahnenko, T., Lapham, W.W., Moran, M.J., Rowe, B.L., Squillace, P.J., and Toccalino, P.L., 2006. Volatile Organic Compounds in the Nation's Ground Water and Drinking-Water Supply Wells; USGS Circular 1292, 101 p.