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TEXAS NATURAL RESOURCE CONSERVATION COMMISSION AND
U.S. ENVIRONMENTAL PROTECTION AGENCY

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Abstract

Of the more than 19,000 documented leaking petroleum storage tank (LPST) sites in Texas, more than 6,000 have impacted ground water and resulted in fuel hydrocarbon (FHC) plumes. The sheer number of regulated facilities and their wide geographical distribution throughout the state, however, have made gaining a regional perspective on hydrocarbon plumes difficult. A better overall understanding of the extent, mass, and duration of hydrocarbon plumes may make it possible to exercise more scientifically based decisions regarding the level of remediation needed for the thousands of LPST sites still in the corrective action program. This study is the first attempt to quantify the general site, soil, hydrogeologic, and plume characteristics throughout Texas and in different regions of the state.

This study consisted of compiling and summarizing LPST site information and quantifying the size, mass, and duration of dissolved FHC (benzene) plumes in Texas in order to determine dimensions of benzene plumes, predictability of plume concentrations and lengths, rates at which plumes self-remediate, and classification of plume behavior to assist in exposure assessments.

This study focuses on ground-water impacts from underground leaks of fuel hydrocarbon. We do not address the impact of hydrocarbon vapors in buildings or utility lines, seepage into or through utilities, and discharge of fuel hydrocarbons into springs and streams owing to leaks from underground storage tanks, all of which are important avenues of hydrocarbon migration that might directly impact human health and safety.

We compiled site, soil, hydrogeologic, and chemical analytical information from files at the Texas Natural Resource Conservation Commission (TNRCC) on 605 LPST sites and entered the information into a data base. The resulting data base contains more than half a million entries including chemical and water-level data on more than 4,000 monitoring wells. Using well location, water-level, and chemical data, we determined hydraulic gradients, ground-water flow directions, average plume benzene concentrations, and benzene plume dimensions over time for different hydrogeologic and climatic regions of Texas. We summarized site descriptive data using nonparametric statistics, histograms, and pie charts.

Most benzene plumes (75 percent) caused by leaking underground fuel tanks are less than 250 ft long and impact an area of less than 49,000 ft^2 as defined by the 10-ppb contour of benzene. Mass and size of benzene plumes follow three to four predictable stages. Even without remediation, plume mass increases, stabilizes, and rapidly declines over time. Plume length similarly increases and stabilizes but then at first slowly declines and later rapidly declines. Declines in plume mass and length result from natural attenuation processes (for example, volatilization, sorption, and biodegradation) or remediation activities or both. Most plumes we analyzed have stabilized or are decreasing in length and concentration. Only 14 percent of plumes are increasing in concentration, and only 3 percent are increasing in length.

The length of a benzene plume cannot be predicted on the basis of either hydrogeology or previous remediation activities. There is no statistical difference in benzene plume length between plumes in different hydrogeologic settings throughout Texas. However, karst aquifers such as the Edwards aquifer are probable exceptions. Limited data suggest that plume length in the Edwards aquifer can be significantly greater (more than 7,600 ft) than in other hydrogeologic settings. Likewise, we could not statistically sort benzene plume length between sites on the basis of pump-and-treat or other previous remediation activities. Source abatement and plume remediation, however, logically should shorten the time required to decrease plume length and concentration. Other factors, such as the amount of spilled and leaked fuel and natural attenuation processes, probably account for more differences in plume length than hydrogeology or previous remediation activities. Data on the timing, duration, and magnitude of the leak and biodegradation and other attenuation rates, unfortunately, are generally unknown or not measured for LPST sites in Texas. Because these data are unknown, we cannot predict the timing at which the different stages might occur for benzene plumes in the corrective action process.

Risks associated with dissolved hydrocarbon plumes include threats to water wells; direct human contact with hydrocarbon, hydrocarbon vapors, or impacted soils; and explosive risks of hydrocarbon vapors. Almost 40 percent of sites have benzene plumes that reportedly extend offsite and impact either high-quality ground water or water that has a demonstrated beneficial use. Almost 60 percent of sites have at least one public or domestic water-supply well within 0.5 mi of the leak. Because of these exposure risks, characterization of LPST sites is required to determine the lateral extent and stage of the plume and to identify potential nearby receptors such as water wells. However, because plumes appear to attenuate naturally, active remediation such as pump and treat might be required only in special cases to prevent a plume from impacting nearby receptors or to reduce a plume that has already impacted a receptor. These findings apply to clastic (sand, clay, sandstone, shale) formations. Active remediation might be required more regularly for benzene plumes in karst aquifers such as the Edwards aquifer, where plumes have the potential to become longer and thereby pose greater risk.

Keywords: benzene, BTEX, hydrocarbon, intrinsic bioremediation, leaking underground storage tanks

Introduction

More than 19,000 cases of leaking petroleum storage tanks (LPST) were documented in Texas as of August 1996. More than 6,000 of these LPST sites have impacted ground water and resulted in plumes of dissolved and sometimes liquid-phase fuel hydrocarbons (FHC). The migration of these dissolved hydrocarbon plumes away from LPST sites is often naturally attenuated by dispersion, sorption, volatilization, and biodegradation. Natural biodegradation of hydrocarbon in the ground, often referred to as intrinsic or passive bioremediation, is recognized as the most important of these natural attenuation processes and can result in a rapid decrease in the total mass and size of the plume without the use of active remediation techniques such as pump and treat (for example, Buscheck and others, 1993; McAllister and Chiang, 1994; Rice and others, 1995; and Kuehne and Buscheck, 1996). The recognition of natural attenuation can be used to enhance the Texas Natural Resource Conservation Commission's (TNRCC) current risk-based corrective action (RBCA) program, which focuses on sites of more immediate threat to the public health and avoids expensive remediation at low-risk sites.

This study represents the first attempt to develop an overall description of the extent, mass, and duration of dissolved hydrocarbon plumes throughout Texas and in different regions of the state. TNRCC staff, who oversee the monitoring and remediation of LPST sites in Texas, have noticed that some sites have plumes that appear to have abated quickly and naturally after tank removal, whereas other sites have plumes that have persisted since the 1950's and still contain high hydrocarbon concentrations. A regional perspective into LPST plume behavior may make possible better risk-management decisions concerning the level of site assessment and active site cleanup needed for thousands of LPST sites still in the corrective action process. If plumes are shown to be naturally attenuated and the sources verified and abated during site assessments, low-risk sites may be more easily directed to a more timely site closure with less corrective action, reserving resources for high-risk sites. Documentation of the range of characteristics of LPST plumes is needed to scientifically support and improve the existing RBCA program and serve as a basis for approaching corrective action in a more scientifically sound and reasonable manner.

The objective of this study was to develop and provide data to support the TNRCC's RBCA decisions by compiling and summarizing LPST site information and quantifying the size, mass, and duration of dissolved hydrocarbon plumes from LPST sites in Texas. Benzene was the focus of this study of hydrocarbon plumes at LPST sites in Texas because it is the most mobile and carcinogenic of the benzene, toluene, ethyl-benzene, and xylene (BTEX) constituents. The major questions we addressed in this report are

- What are the dimensions of benzene plumes?
- Are benzene plume dimensions predictable, either statewide or regionally?
- Do plume concentrations and lengths change over time?
- Can the duration and status of a benzene plume be predicted?
- How rapidly do plumes self-remediate after the source is removed?
- Can the behavior and characteristics of benzene plumes be classified in a way that will assist exposure assessment?

Texas is an ideal laboratory for this study owing to the wide range in hydrogeologic and climatic conditions throughout the state. Ground water occurs in a variety of aquifers in the state having different lithologies such as alluvium, sandstone, fractured limestone, and karst aquifers. Results of this study will most likely be applicable to states bordering Texas as well as other areas having similar hydrogeology.

Background

Anatomy of a Fuel Leak

Underground storage tanks are popular for storing fuel hydrocarbons, especially for neighborhood gas stations. These systems generally consist of tanks and piping that are pressurized for delivery of the gasoline to the pump. Unfortunately, these systems can fail because of corrosion of unprotected pipes and steel tanks and poor installation, accidents, and natural events. Though tanks are usually blamed for the leaks, releases from LPST piping occur twice as often as tank failures (Testa and Winegardner, 1991).

Because LPST systems are underground, soil, soil gas, and ground water may be exposed to liquid, vapor, and dissolved-phase hydrocarbon when the systems leak. Details of the fate and transport of hydrocarbons in the

subsurface are described in Testa and Winegardner (1991) and Rice and others (1995), among others. The following summarizes the movement of a fuel hydrocarbon from the source to a point of accumulation in the subsurface, the processes that attenuate or affect the size of dissolved hydrocarbon plumes, and the characteristic stages in plume development. This brief summary introduces the concepts used in this study to organize site data and interpret results.

When liquid-phase hydrocarbon leaks from an LPST system, it percolates downward through the unsaturated zone under the force of gravity. The liquid-phase hydrocarbon may also move laterally in the unsaturated zone if it encounters low-permeability layers. Exposed to the soil atmosphere, volatile components of the liquid-phase hydrocarbon volatilize and migrate through the vapor phase. In addition, soluble components of the liquid hydrocarbon dissolve into the aqueous phase and move downward toward the water table, carried by recharging waters. Once dissolved, organic components may sorb or adhere onto the solid phase (soil particles), especially where organic matter is present. In passing through the unsaturated zone, liquid hydrocarbon becomes trapped in pore throats as pendular rings and thin films between the aqueous phase (soil water) and the vapor phase (soil air).

If there is enough liquid-phase hydrocarbon, it migrates to and pools on the capillary fringe of the water table. If a pool of liquid-phase hydrocarbon forms on the water table and the water table fluctuates, liquid hydrocarbon is smeared in the aquifer and exposed to ground water. Once in contact with the ground water, liquid hydrocarbon slowly solubilizes into the aqueous phase and moves in the direction of ambient ground-water flow, forming a plume of dissolved hydrocarbon (fig. 1). In addition, dissolved hydrocarbon sorbs onto soil and aquifer material. Dissolved hydrocarbon may also volatilize where in contact with soil vapor above the water table. Sorption slows the progress of the plume by one-third to two-thirds relative to the average ground-water velocity, depending on the amount of organic carbon in the water-bearing zone (McAllister and Chang, 1994). Dispersion

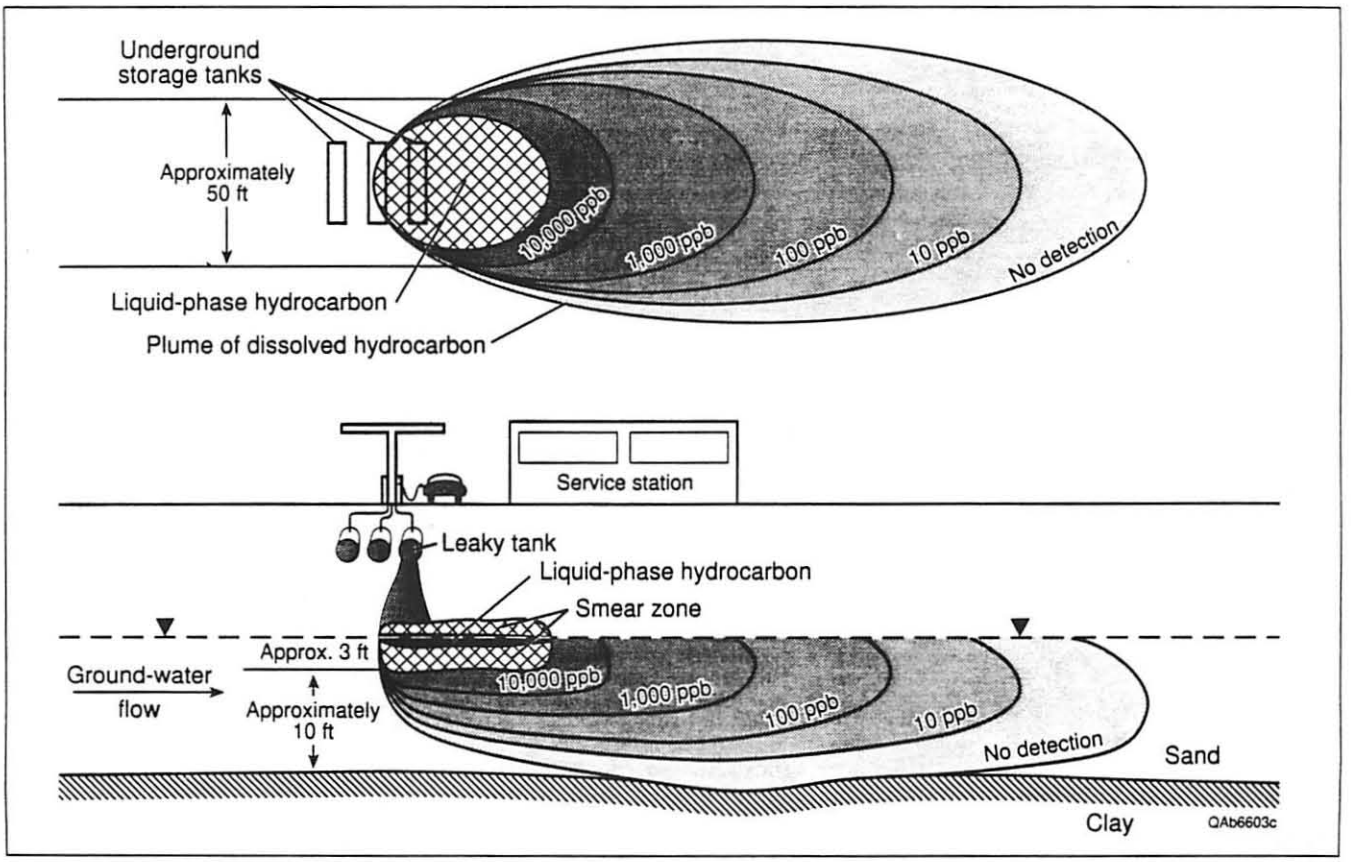


Figure 1. Map view and cross section of a hypothetical hydrocarbon leak and resulting plume from an underground storage tank (after Mobil Business Resources Corporation, 1995).

serves to mix dissolved hydrocarbon constituents with unaffected water along the plume edge, though its effects may be minimal for small plumes.

Once the hydrocarbon is in the aqueous phase and conditions in the aquifer are suitable, indigenous bacteria use the organic molecules as a fuel source and ultimately degrade the hydrocarbon to carbon dioxide and water. Anaerobic conditions may develop at the center of the plume, whereas aerobic biodegradation proceeds on the oxygenated periphery of the plume. With a continuing source of hydrocarbon, dissolved hydrocarbon mass and plume length will become stable when the amount of hydrocarbon mass entering the water-bearing zone equals the amount leaving the zone. When biodegradation occurs, the mass of dissolved hydrocarbon and the size of the plume will be much smaller than that predicted by considering only dissolution, dispersion, sorption, and volatilization (Buscheck and others, 1993; McAllister and Chang, 1994).

Rice and others (1995) presented a conceptual model for the different phases of plume length and mean concentration (fig. 2). Plume length initially increases (phase I), stabilizes (phase II), slowly decreases (phase III), and finally rapidly decreases (phase IV) (fig. 2a). Hydrocarbon mass in the plume initially increases (phase I), stabilizes (phase II), rapidly decreases at an exponential rate (phase III), and then slowly approaches zero (phase IV) (fig. 2b). The source is active (liquid hydrocarbon in the saturated or unsaturated zone or desorbing hydrocarbon in the unsaturated zone) during phases I and II (fig. 2). Plume length decreases slowly during phase III, whereas plume mass decreases rapidly. As mass is removed from the plume, sorbed hydrocarbon slowly desorbs back into the ground water, which preserves the length of the plume and slows its decline (Bear and others, 1994). In the final phase, concentrations are low, plume lengths are small, and the plume is considered "exhausted."

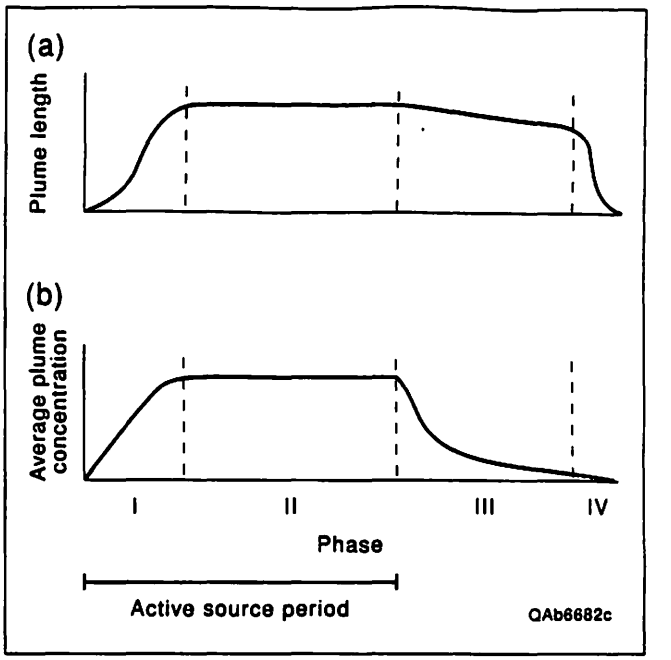


Figure 2. Hypothetical phases of (a) plume length and (b) average plume concentration for dissolved hydrocarbon in ground water (from Rice and others, 1995).

Methods

To quantify the size, mass, and duration of dissolved hydrocarbon plumes from LPST sites in Texas, we (1) compiled data on LPST sites from across the state, (2) estimated hydraulic gradient and ground-water flow directions, (3) estimated average plume concentrations and dimensions, and (4) statistically analyzed general site characteristics and relationships between plume dimensions and hydrogeologic properties. We used Rice and others (1995) as a guide for the analysis of chemical data.

Data Compilation

We compiled site, soil, hydrogeologic, and chemical data from LPST site files in Texas where ground water has or had been impacted by leaking gasoline. The initial subset of data consisted of the best quality LPST files from across the state as determined by the number of monitoring events and responsible parties using high-quality corrective action activities. We selected additional files from Lubbock, El Paso, the Edwards aquifer, and sandstone aquifers in East Texas to characterize areas inadequately covered by the initial subset.

The data base includes information from the Limited Site Assessment Report Form (Texas Water Commission, 1993), the Plan B Risk Assessment Checklist (Texas Natural Resource Conservation Commission, 1995), and water-level and water-chemistry data sheets included in quarterly, semiannual, and annual ground-water monitoring reports. In this manner, we streamlined data entry and reviewed as many LPST sites as possible during the project. Our data bases included information on site location and setting, soil properties, hydrogeologic

properties, measurements of water levels, chemical analytical results, and abatement and remediation actions (table 1) and were linked to each other by the LPST ID number. For the analytical data, we entered measured values, noted measurements with no detection of the organic contaminant (with the detection limits, if available), and noted cases where hydrocarbon concentration was not measured owing to the presence of liquid-phase hydrocarbon in the well. Where appropriate, we entered water-level elevations corrected for the free product thickness in the well. These corrections involved multiplying the product thickness in the well by the specific gravity of gasoline. No attempt was made to correct for the thickness of the liquid-phase hydrocarbon in the well, which is usually greater in the well than in the formation (see, for example, Testa and Winegardner, 1991, p. 91–107). We used spreadsheets and data-base software to organize the data bases.

After entering 100 LPST files from Harris County, we realized that including all chemical and water-level data would limit the number of files compiled during the study. Therefore, we focused on benzene and stopped entering analytical data for other BTEX constituents (toluene, ethylbenzene, xylene) or reported values of total BTEX or total hydrocarbon. Benzene is usually the most mobile and most persistent of the four organic molecules and is recognized as a carcinogen. Clean-up levels are guided by benzene concentrations, and it is the most commonly measured hydrocarbon constituent. We also continued to enter methyl tertiary butyl ether (MTBE) concentrations because MTBE is commonly observed to be more mobile than benzene. For water-level data, we entered the six most recent measurements, except at the monitoring well closest to the source of the leak, where we entered all water-level data to better define historical water-level fluctuations. This abridged scope allowed us to compile a more comprehensive data base and yet still determine hydraulic gradients, smear zones, and plume dimensions on the basis of benzene concentration. The 100 Harris County files we compiled served as a comprehensive data base to investigate the relation between benzene concentrations and concentrations of toluene, ethylbenzene, and total xylenes.

Typical LPST site files consist of correspondence between the TNRCC and the responsible party and reports including limited site assessment reports, release investigation reports, field activity reports, monthly product recovery reports, monitoring event summary and status reports, site closure requests, and final site closure reports. Our approach for inspecting these files involved first identifying standardized TNRCC data summary forms, which included

- Limited Site Assessment Report Forms,
- Existing LPST Case Questionnaires,
- Plan B Risk Assessment Checklists,
- Risk Assessment Checklists, and
- Assessment Report Forms.

If any of these forms were available, we entered the reported information into the data base. We then retrieved historical water-level and chemical analytical data from the most recent monitoring report and verified with older reports that the tables included all historical measurements. We used the most recent chronology of events, generally included in the reports, to obtain information on the plume discovery, leak and source abatement, and remediation activities. We inspected limited site assessment reports to obtain more detailed information on the hydrogeology of each site. We also looked at any tank removal reports and remediation plans and reports to discover details about abatement and remediation. We inspected aquifer test reports to cull data on hydraulic conductivity, transmissivity, and storativity. Finally, we noted any special reports on remediation or biofeasibility studies included in the files.

Well coordinates were determined by digitally scanning site maps, identifying well locations in map coordinates, and converting map coordinates to real coordinates using conversion factors based on map scales.

Estimation of Hydraulic Gradient and Ground-Water Flow Direction

Once we compiled water-level data from the LPST files and determined well coordinates, we estimated hydraulic gradient and ground-water flow direction by determining the magnitude and direction of the maximum slope of a plane fit to the measured water-level elevations. First, we used matrix-based multiple regression (Davis, 1973, p. 144) to find the best-fit plane through the measured water-level elevations. We then used the slope coefficients of the plane and vector analysis to determine the maximum slope of the plane. The maximum slope is the hydraulic gradient, and the direction of the maximum slope equals the ground-water flow direction, assuming aquifer isotropy. We analyzed different monitoring events to investigate changes in the magnitude and direction of hydraulic gradient at a site. After all the sites were analyzed, we compared the magnitude of hydraulic gradient and the variability of the flow direction for different sites.

Because a plane is a first-order approximation to a surface, it may not accurately represent gradients for a nonplanar potentiometric surface. For example, if an LPST site is on a hilltop, the potentiometric surface might look like the top of a sphere, or, if pump-and-treat remediation is active, there may be cones of depression in the potentiometric surface. To avoid these problems, we applied the planar model only to water-level measurements unaffected by pumping and used the coefficient of deter-

Table 1. Data bases* created and data fields filled during the project.

ID & Setting

LPST-ID
Responsible party
Facility name
Facility address
Facility city
Facility county
Hydrocarbon type
Percent impervious cover
Number of monitoring wells
Number of wells within 0.5 mi

Aquifer Data

LPST-ID
Geologic formation
Formation texture
Aquifer name
Hydraulic conductivity
Notes on conductivity measurement
Transmissivity
Storativity
Depth to affected water-bearing strata
Base of affected water-bearing strata
Thickness of affected water-bearing strata
Area of affected water-bearing strata
Minimum TDS of ground water from nonaffected well
Potential beneficial use category
Direction of ground-water flow
Does flow direction vary?
Hydraulic gradient
Ground-water flow rate

Remediation and Plume Data

Date of release, discovery, or report
Have remedial actions occurred?
If yes, start date
Is remediation still in operation?
What are/were remedial actions?
Has the source been abated?
Date of abatement
Free product on the water table?
Date of most recent PSH recovery
If pump and treat, describe actions
If not, date of shutdown
Number of monitoring events after shutdown
Does plume extend offsite?
If yes, distance beyond property line
If no, distance from property line

Soil Data

LPST-ID
Soil type
Organic carbon
Moisture content
Soil bulk density
Porosity
Intrinsic permeability
Notes on permeability measurement
Depth to affected soil
Base of affected soil
Thickness of affected soil
Areal extent of affected soil
Distance of affected soil to property boundary

Water-Level Data

LPST-ID
Well ID
Date of measurement
Casing height
Depth to water
PSH thickness
Corrected ground-water elevation

Chemical Data

LPST-ID
Well ID
Date sampled
Benzene
Toluene
Ethyl-benzene
Total xylenes
Total BTEX
Total hydrocarbons
MTBE
TDS
Temperature
Specific conductance
pH
Dissolved oxygen

Notes and Comments

LPST-ID
Notes on ID and setting
Notes on soil data
Notes on water data
Notes on plume data
Notes on remedial actions
General comments

*Data-base title is in boldface type.

mination and the mean average absolute error to remove poorly fitting planes from consideration.

Because water levels are usually measured for several monitoring events, we investigated how hydraulic gradient and flow direction varied over time. We also investigated water-level fluctuations at each site to determine the magnitude of the sweep zone.

We assumed that the formations were isotropic and that the ground-water flow direction was in the same direction as the hydraulic gradient. However, fractured and karstic rocks may be strongly anisotropic. In these hydrogeologic settings, the ground-water flow direction and the hydraulic gradient direction may not coincide.

Estimation of Average Concentrations

We determined the average concentration of benzene at the sites for different sampling dates using a planar triangular interpolation method (Isaaks and Srivastava, 1989, p. 254–257) also used by Rice and others (1995). This method involves (1) using Delaunay triangulation to divide the area of the well field into optimal equilateral triangles with vertices defined by the wells, (2) calculating the average concentration for each triangular subarea as the mean of the concentrations measured at the vertices, and (3) calculating the average site concentration by summing the weighted averages of each triangle. We adapted a FORTRAN program that generates Voronoi diagrams (Tipper, 1991) to synthesize the vertices of Delaunay triangles and calculate average site concentrations. All calculations were made using the logarithm of benzene concentrations. Concentration measurements that resulted in no detection of benzene were assigned concentrations half their detection limit. For wells with liquid hydrocarbon in the well where benzene concentrations could not be determined, we assigned a concentration equal to the highest recorded concentration in that well. If no measurements existed in the well, we assigned a concentration equal to the highest recorded concentration at the site.

A disadvantage of using planar triangular interpolation is that average site concentration is defined by the area bounded by the monitoring wells, which may not encompass the entire plume. However, our purpose was to determine how contaminant levels change at a site with time. As long as the down-gradient extent of the plume is defined by the monitoring wells (to verify that the plume is not merely moving out of the monitoring well array), the planar triangular interpolation method is appropriate for our purpose. Average values may also be influenced by the number of wells at a site, which may change over time. To avoid this problem, we analyzed only those sites that had at least six monitoring wells, and we closely inspected average concentrations to ensure that changes in monitoring well array did not affect results. In most cases, the monitoring well array was in place soon after the leak and hydrocarbon plume were discovered.

The approach of using average site concentrations is appropriate for investigating changes in concentration at individual sites. Because it is strongly dependent on the distribution of monitoring wells, it is inappropriate for comparing average site concentration between sites or as a proxy for comparing the magnitude of concentrations between plumes.

Estimation of Plume Dimensions

We used an exponential (linear) plume model to fit a mathematical description of a plume to observed concentration data. This analytical model may overpredict the size of the plume when attempting to fit the model to concentration values that are at a great distance from the plume source (Rice and others, 1995). However, this overprediction may be desirable as a conservative estimate of plume dimensions. Rice and others (1995) found that the model required concentration data from at least six wells for dependable results.

Before we fit the model to the observed data, we assigned concentrations to wells having measurements below the detection limit or wells having liquid hydrocarbon in the monitoring well. For wells having measurements below the detection limit, we assigned a concentration equal to half the detection limit. For wells having liquid hydrocarbon in the well where samples could not be collected, we assigned a concentration equal to the highest recorded concentration in that well. If no measurements existed in that well, we assigned a concentration equal to the highest recorded concentration at the site.

Rice and others (1995) based the exponential (linear) plume model on an analytical solution by Baetsle (1969, as cited in Freeze and Cherry, 1979, p. 395), and the model has the form

$$C(x,y) = C_o \exp\left[-D_x x^2 - D_{xy} xy - D_y{}^2\right] \qquad (1)$$

where $C(x,y)$ is the concentration in the plume as a function of x and y coordinates, C_o is the maximum concentration of the plume, D_x describes dispersion in the x-direction, D_{xy} describes dispersion in the xy-direction, D_y describes dispersion in the y-direction, and x and y are Cartesian coordinates measured relative to the center of mass of the plume.

We solved equation 1 for D_x, D_{xy}, and D_y using multiple linear regression after linearizing the equation using logarithms. Plume length, l, and width, w, are estimated from

$$l = \max\left\{\sqrt{\frac{\log(C_o) - \log(C^*)}{\sigma_x}}, \sqrt{\frac{\log(C_o) - \log(C^*)}{\sigma_y}}\right\} \tag{2}$$

$$w = \min\left\{\sqrt{\frac{\log(C_o) - \log(C^*)}{\sigma_x}}, \sqrt{\frac{\log(C_o) - \log(C^*)}{\sigma_y}}\right\} \tag{3}$$

where length and width are determined for a threshold concentration of C^* and where

$$\sigma_x = \frac{2D_x\left[D_{xy}^2 + (D_y - D_x)^2\right] + \left[2D_x(D_y - D_x) - D_{xy}^2\right]\sqrt{(D_y - D_x)^2 + D_{xy}^2}}{\left[(D_y - D_x) + \sqrt{(D_y - D_x)^2 + D_{xy}^2}\right]^2 + D_{xy}^2} \tag{4}$$

$$\sigma_y = \frac{2D_y\left[D_{xy}^2 + (D_y - D_x)^2\right] + \left[2D_y(D_y - D_x) + D_{xy}^2\right]\sqrt{(D_y - D_x)^2 + D_{xy}^2}}{\left[(D_y - D_x) + \sqrt{(D_y - D_x)^2 + D_{xy}^2}\right]^2 + D_{xy}^2} \tag{5}$$

We determined plume length for a threshold concentration (C^*) of 10 ppb. In other words, we determined the maximum length of the 10-ppb plume contour.

The exponential plume model assumes that the origin of the well coordinate system (x, y) is centered on the source. Therefore, before we fit the analytical model to the concentrations measured at the wells, we used mass moments (for example, Thomas and Finney, 1984, p. 354) to shift the well coordinate system to the center of mass of the plume. We checked model results to observed data for several sites to verify that the model was making reasonable estimates of plume length.

Statistical Analysis

Owing to the non-normal distribution of many of the investigated parameters, we summarized site, soil, aquifer, and plume characteristics using quartiles and percentiles. Quartiles consist of the 25th percentile (lower quartile), the 50th percentile (median), and the 75th percentile (upper quartile) and break the distribution into four sets of equal number (Mendenhall, 1987, p. 56–58). A number at the lower quartile indicates that 75 percent of measured values are greater than that value and 25 percent are lower. The median, which is also the 50th percentile, breaks the data into halves where half the data are greater than the median and half are less. The interquartile range is defined as the difference between the lower quartile and the upper quartile and expresses the spread in the data. We tested similarities between distributions using analysis of variance and Student's t tests.

Results

The following sections describe results of the compilation and analysis and include (1) notes about the data compilation, (2) a summary of site attributes, (3) a summary of soil attributes, (4) a summary of water-bearing-zone attributes, and (5) a summary of contamination attributes. Cumulative distribution functions for selected site parameters are included in the appendices for detailed inspection. The appendices also include tables and figures that offer more detail into the hydrologic, geologic, and geographic makeup of the distributions. Using the data base, we summarized the site, soil, aquifer, and contamination characteristics of LPST sites in Texas. Units in our analysis are consistent with the units used by the TNRCC in its questionnaires.

Data Compilation

We compiled site, hydrogeologic, and chemical analytical information at 605 LPST sites in Texas where ground water is contaminated (fig. 3). The resulting data bases contain more than half a million entries including 39,662 lines of water-level data and 29,703 lines of chemical analytical data for 4,185 wells.

The 605 sites constitute about 10 percent of the 6,311 files held by the TNRCC for LPST sites having contaminated ground water. Many of the files we reviewed are from metropolitan areas such as Houston in Harris County, Dallas in Dallas County, Fort Worth in Tarrant County, San Antonio in Bexar County, Lubbock in Lubbock County, Austin in Travis County, and El Paso in El Paso County. The proportion of files for Harris, Dallas, Tarrant, El Paso, and Lubbock Counties in our data base is a little greater than in the complete data base (table 2). Travis and Bexar Counties are slightly underrepresented in our data base. The data base includes sites from all the geographic regions (fig. 3) as well as most of the hydrogeologic regions of the state.

The information available at each site varied in quality and quantity. To document the quantity of data, our plots include the number of sites that reported that particular parameter. Data quality also varied from site to site. For example, we commonly found obviously unreasonable values for hydraulic gradients, soil properties, and other parameters. Where possible, we tried to verify or censor reported values that were obviously unreasonable by checking units, unit conversions, and original analyses.

The TNRCC maintains a data base of LPST sites containing selected site data such as total dissolved solids, aquifer setting, and reported minimum depth to water; we refer to this data base as the "TNRCC data base." We included statistical summaries of these data in our discussion, tables, and figures for comparison with our data base. Some site characteristics such as minimum depth to water are also reported on TNRCC questionnaires. For comparison, we include statistical summaries of these data and refer to them as "reported" values.

General Site Attributes

The description of the sites includes the assigned case priority, amount of impervious cover, number of domestic wells near the site, and number of monitoring wells installed at the site (fig. 4).

The TNRCC developed a site priority system to qualitatively assess threats to human health and the environment (Texas Natural Resource Conservation Commission, 1994). LPST sites are prioritized on the basis of submitted data as (1) critical, (2), high risk, (3) moderate risk, and (4) low risk. Priority 1 sites represent an actual or probable impact to public health and safety and include, for example, sites where a contaminated well is used for drinking water. Priority 2 sites threaten public health and safety and include sites where the contaminant plume is moving toward a well used for drinking water. Priority 3 sites are a minimal threat to public health and safety and might have a ground-water impact. Priority 4 sites pose no threat to the public health and do not impact or threaten major or minor aquifers. Priority 4 also includes sites for which data are insufficient; these sites may be given a higher priority when additional data are collected. About 40 percent of LPST sites are not yet prioritized, so the percentages may not be fully representative.

Almost half of the sites we reviewed are priority 4 sites (fig. 4a). Most of the rest of the sites are priority 2 or 3, and fewer than 5 percent have a priority of 1 (fig. 4a). These proportions closely reflect the proportions of priorities assigned statewide in the entire TNRCC data base, which shows 5 percent priority 1 sites, 19 percent priority 2 sites, 20 percent priority 3 sites, and 56 percent priority 4 sites.

LPST questionnaires prompt site investigators to estimate the amount of impervious cover at LPST sites. A large amount of impervious cover provides a barrier to human exposure and also prevents rainfall from percolating into the ground, dissolving organics, and migrating to the water table. Most of the sites (72 percent) have between 75 and 100 percent impervious cover (fig. 4b). This high percentage is not surprising considering that most sites are gasoline service stations that are

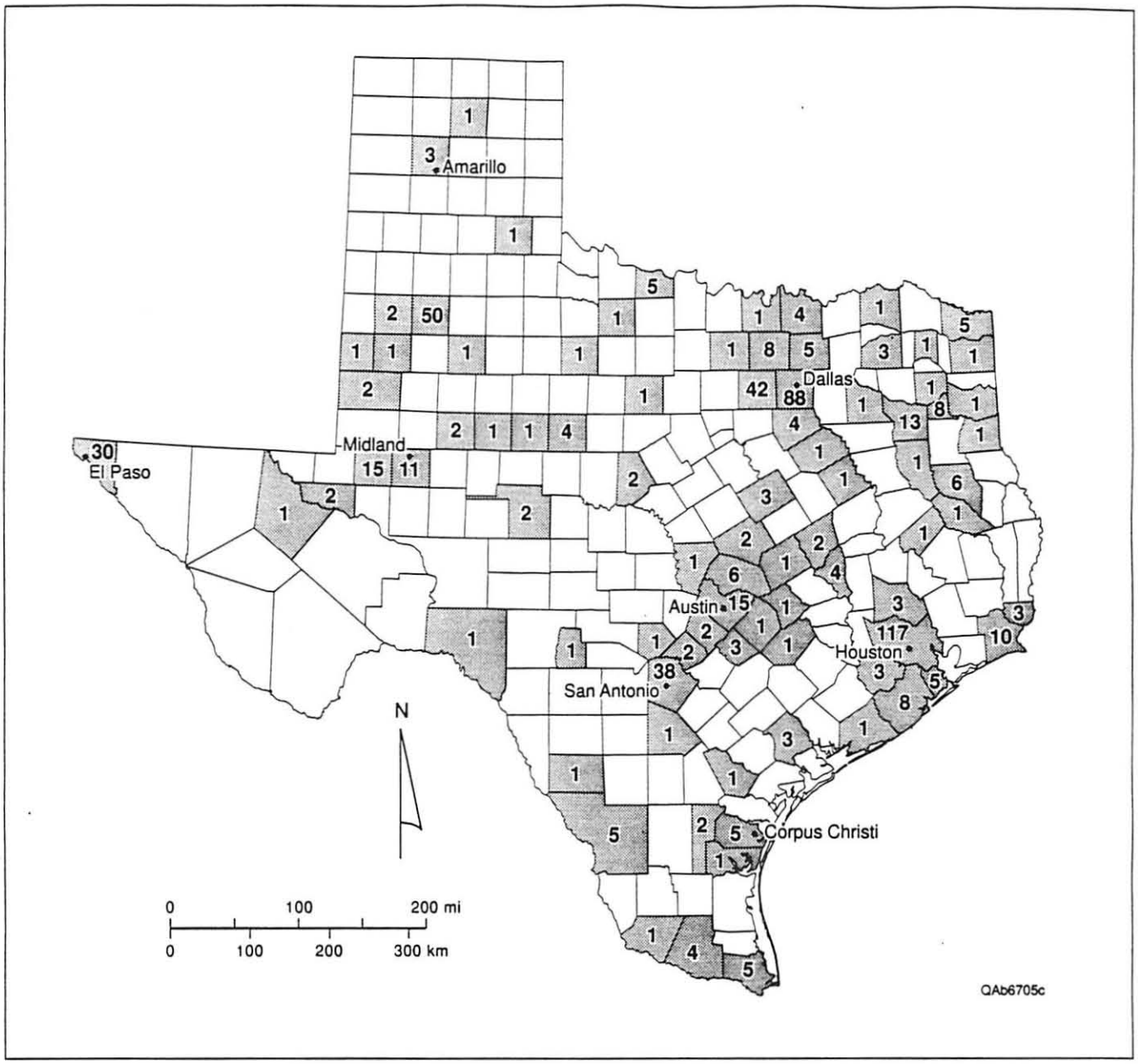


Figure 3. Map of the distribution of sites reviewed during the study showing the number of files inspected for each county. A total of 605 files were reviewed.

predominantly paved. Fewer than 4 percent of the sites have less than 25 percent impervious cover (fig. 4b). Reported impervious cover applies to the site itself and may not be applicable to neighboring properties.

The location of water wells near the sites is important for assessing the risk of a hydrocarbon spill to a drinking water supply. Site investigators generally rely on well records at the Texas Water Development Board (TWDB) and Texas Natural Resources Information System (TNRIS) to identify nearby wells. Most of the sites (58 percent) have at least one public or domestic water well within 0.5 mi, and almost 7 percent of the sites have more than 10 wells within 0.5 mi (fig. 4c). This number is considered a minimum because not all water wells are registered with the State. For example, in a thorough well survey done in Ellis County, only 12 percent of the more than 1,000 wells inventoried were registered with the State (Mace and Dutton, 1994).

Table 2. Relative percentage of LPST sites having contaminated ground water in our data base compared with those in the entire TNRCC data base.

County	Data base compiled during this study (percentage of total)*	TNRCC's complete data base (percentage of total)†
Harris	18.0	14.4
Dallas	14.8	11.5
Lubbock	8.4	3.6
Tarrant	7.1	6.8
Bexar	6.4	6.5
El Paso	5.0	2.1
Travis	2.5	3.2

*605 sites
†6,311 sites

The number of monitoring wells at the sites is in part related to the magnitude of the leak and plume and the effectiveness of initial drilling to characterize site contamination. The median number of monitoring wells at a site is 6 (table 3), most sites having between 3 and 15 monitoring wells (fig. 4d). Three hundred thirty-seven sites had six or more monitoring wells. These sites were the only ones where we could estimate plume dimensions using the analytical plume model.

Soil Attributes

The general description of soil attributes includes measures of soil physical parameters and the geometry of the contaminated soil at the site. The TNRCC requires the responsible party to report the fraction of organic carbon, soil bulk density, volumetric moisture content, effective porosity, and intrinsic permeability of the soils for use in conducting risk assessments for the site. About half of the sites have reported organic carbon fractions less than 1 percent (fig. 5a, table 3). In general, the literature reports that most soils have organic carbon (humus) contents between 1 and 3 percent, the lower values occurring in desert soils and higher values in black soils, peat, and muck (Hillel, 1980, p. 77). The median reported wet bulk density at the compiled sites is 1.86 g cm^{-3}, the reported values ranging between 1.00 and 2.75 g cm^{-3} (fig. 5b, table 3). Reported volumetric moisture content has a median of 25 percent (fig. 5c, table 3). Values of moisture content greater than 60 percent may be suspect because porosity in most soils is less than 60 percent (Hillel, 1980, p. 11). Reported porosity ranges from 4.4 to 55.2 percent and has a median of 33 percent (fig 5d, table 3).

About 12 percent of the reported intrinsic permeabilities measured and estimated by site consultants were greater than 10^{-8} cm^2, and the remaining were sites split almost evenly between values ranging from 10^{-8} to 10^{-10}, 10^{-10} to 10^{-12}, and less than 10^{-12} cm^2 (fig. 6a). The median for 137 actual measurements of intrinsic permeability is 6.4×10^{-12} cm^2 (fig. 6b, table 3). Reported estimates of intrinsic permeability for a site appear to err on the side of higher values because there are more measured (44 percent) than estimated (34 percent) permeability values less than 10^{-12} cm^2 (fig. 6b).

Attributes of the Water-Bearing Zones

This section describes physical and chemical attributes of the affected water-bearing formations including (1) the affected major and minor aquifers, (2) texture of the water-bearing zones, (3) hydraulic properties, (4) depth to water, sweep-zone thickness, and water-level fluctuations, (5) hydraulic gradients and flow directions, (6) total dissolved solids (TDS) concentration, and (7) potential beneficial use.

Affected Water-Bearing Zones

LPST sites compiled during this study are located in the outcrops of all of the major aquifers and most of the minor aquifers in Texas (table 4). Muller and Price (1979) described the geology of these aquifers as follows:

- Alluvium: generally consists of unconsolidated, alternating and discontinuous beds of silt, clay, sand, gravel, and boulders. Alluvium is common near most rivers and stream beds.
- Carrizo-Wilcox: consists of hydrologically connected ferruginous, crossbedded sand with clay, sandstone, silt, lignite, and gravel. The Carrizo-Wilcox extends from the Rio Grande northeastward into Arkansas and Louisiana.
- Edwards: consists of massive to thin-bedded, nodular, cherty, gypsiferous, argillaceous white to gray limestone and dolomite and is characterized by extensive honeycombed, cavernous strata. The Edwards aquifer underlies San Antonio and extends north of Austin.
- Edwards-Trinity: consists of the cherty, gypsiferous, argillaceous, cavernous limestones and dolomites of the Comanche Peak and Edwards Limestones and the Georgetown Formation and the sands, sandstone, gravel, and conglomerate of the Trinity Group. The Edwards-Trinity underlies the Edwards Plateau east of the Pecos River and Stockton Plateau west of the Pecos River.

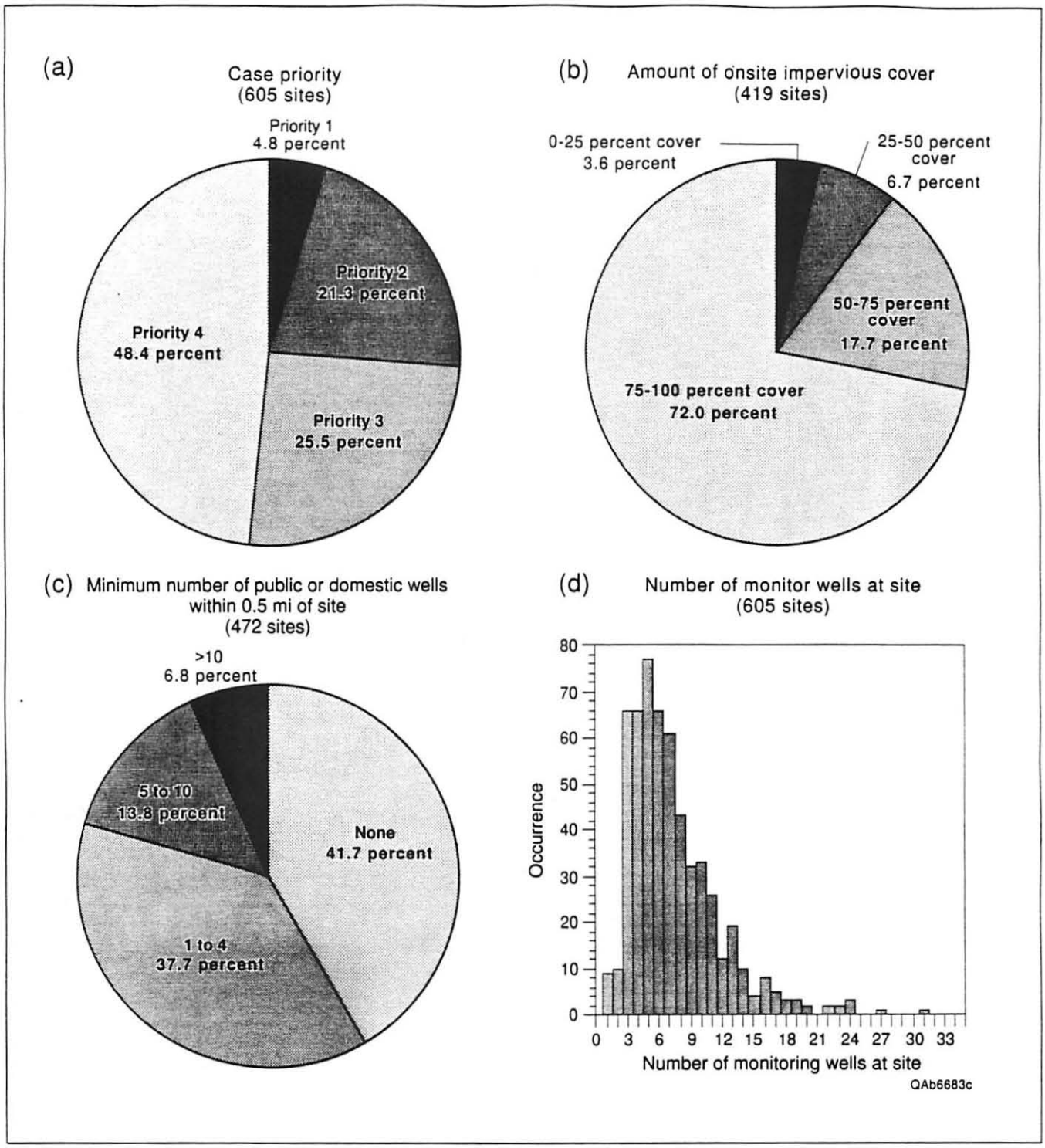


Figure 4. General characteristics of the LPST sites compiled during this study including (a) case priority (1 is critical, 2 is high risk, 3 is moderate risk, and 4 is low risk or unassigned), (b) percentage of impervious cover, (c) number of public and domestic water wells within 0.5 mi of the site, and (d) number of monitoring wells at the site. Ranges shown in (b) and (c) are used in TNRCC questionnaires. Some sites may have more monitoring wells installed in the future.

Table 3. Summary of soil and aquifer characteristics.

Parameter	Units	Number of sites	25th percentile	50th percentile (median)	75th percentile
Soil attributes					
Soil moisture content	%	166	16.0	25.0	37.8
Intrinsic permeability	cm^2	143	7.9×10^{-14}	6.4×10^{-12}	8.0×10^{-9}
Soil bulk density	$g\ cm^{-3}$	115	1.67	1.86	2.02
Porosity	%	125	25	33	38
Organic carbon	%	179	0.20	0.79	3.4
Aquifer attributes					
Hydraulic conductivity	$m\ yr^{-1}$	137	0.0089	1.1	55
Transmissivity	$ft^2\ d^{-1}$	62	4.1	19	310
Storativity	-	31	0.0008	0.008	0.04
Total dissolved solids from files we compiled	ppm	447	555	770	1,520
* Total dissolved solids from the TNRCC data base	ppm	1,852	540	883	1,748
* Reported minimum depth to water	ft	2,168	7	11	19
† Minimum depth to water	ft	246	2.3	4.6	10.5
† Maximum depth to water	ft	246	11.8	16.2	24.8
† Average depth to water	ft	246	6.6	9.4	16.6
† Standard deviation of depth to water	ft	234	0.8	1.3	1.8
† Thickness of sweep zone	ft	246	6.1	9.1	14.4
Reported gradient	-	265	0.0033	0.0086	0.025
† Calculated gradient	-	467	0.0051	0.013	0.028
† Change in gradient	%	282	33	62	110
† Maximum gradient direction change	°	132	60	105	161
† Standard deviation of gradient direction	°	132	21.6	35.9	61.3
Reported flow rate	$m\ yr^{-1}$	33	0.072	6.02	30.5
Contaminant attributes					
Depth to affected soil	ft	167	2.5	4.4	9.0
Base of affected soil	ft	429	12.5	17.5	24.0
Thickness of affected soil	ft	161	7.5	11	16
Area of affected soil	ft^2	145	2,546	6,750	15,000
Distance of affected soil from property boundary	ft	137	0.6	10	20
† Plume length	ft	217	136	181	250
† Calculated plume area	ft^2	217	15,000	26,000	49,000
† Maximum product thickness	ft	102	0.5	1.5	4.6
† Number of monitoring wells	-	565	4	6	9
Depth to affected water	ft	312	6.0	12	18
‡ Base of affected water	ft	146	17	22	30
‡ Thickness of affected water	ft	157	8.0	11	15
Area of affected water	ft^2	138	4,000	11,000	28,000

*Evaluated at all sites having impacted ground water in the TNRCC data base.
†Calculated for this study. All others are reported values.
‡Probably represents a minimum thickness.

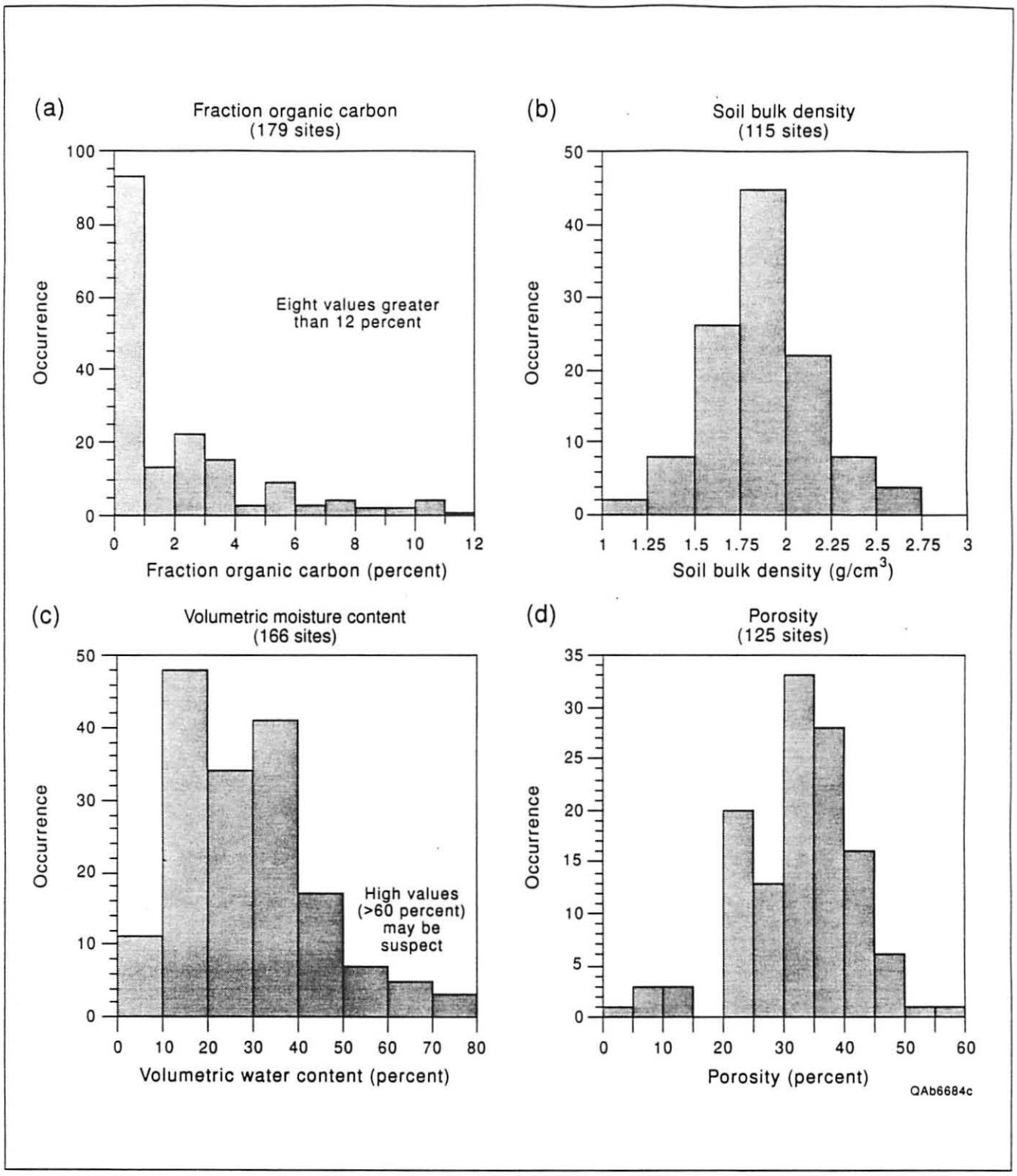


Figure 5. Ranges of reported soil parameter values for (a) fraction organic carbon, (b) soil bulk density, (c) volumetric water content, and (d) porosity.

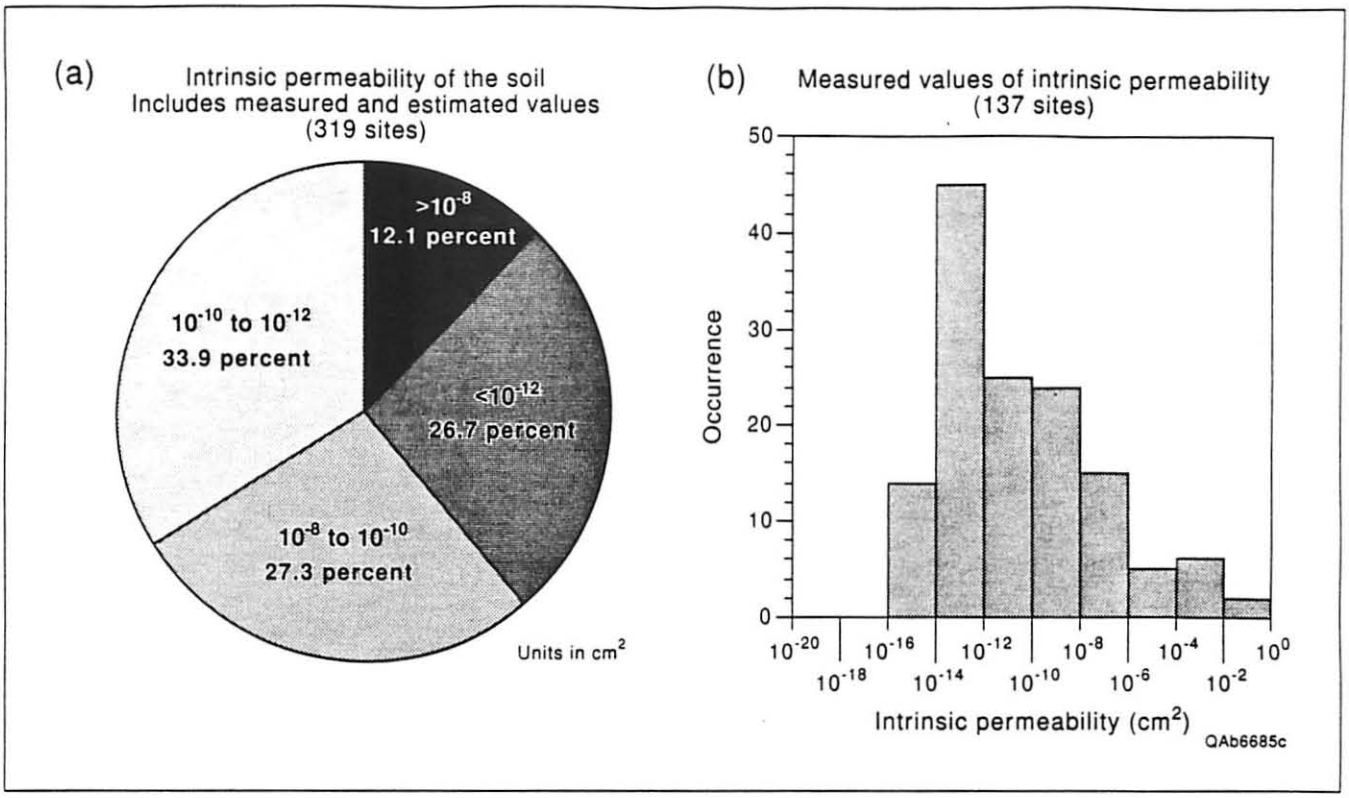


Figure 6. Estimated and measured values of intrinsic permeability for the soil zone. The pie chart includes measured and estimated values. The histogram includes only measured values. Ranges shown in (a) are used in TNRCC questionnaires.

- Gulf Coast: consists of alternating beds of clay, silt, sand, and gravel. The Gulf Coast aquifer underlies Houston and Corpus Christi.
- Hueco-Mesilla Bolson: consists of unconsolidated, alternating, and discontinuous beds of silt, clay, sand, gravel, and boulders. Bolson deposits underlie El Paso.
- Nacatoch Sand: consists of unconsolidated to indurated, massive, glauconitic, calcareous sand and marl. The narrow outcrop of the Nacatoch Sand is in northeast Texas.
- Ogallala: consists of unconsolidated, fine- to coarse-grained sand, clay, and silt. The Ogallala is the major aquifer on the High Plains of northwest Texas and underlies Lubbock and Amarillo.
- Queen City: consists of sand, loosely cemented sandstone, and interbedded clays. The Queen City is exposed in northeast Texas.
- Sparta: consists of sands and interbedded clays. The Sparta is thinly exposed from south to northeast Texas.
- Trinity Group: consists primarily of sands with interbedded clays, limestone, dolomite, gravel, and conglomerates. The Trinity Group crops out west of Fort Worth and Austin.
- Woodbine: consists of sand and sandstone beds and underlies the western part of Dallas and the eastern part of Fort Worth.

Most of the sites we compiled are located on the recharge zones of the Gulf Coast and Ogallala aquifers. Many LPST sites are also located on alluvial deposits. Twenty-three percent of the sites were not on a major or minor aquifer or alluvial deposits. These sites usually consisted of clay, sand, and fractured limestone.

Texture of Water-Bearing Zones

We determined primary aquifer composition by inventorying noun descriptors of reported aquifer texture. More than 61 percent of the 383 sites with descriptions of aquifer texture have clay present, 51 percent have sand present, and 19 percent have limestone present (table 5). About 21 percent of the sites have both sand and clay, and 11 percent of the sites have clay and limestone (table 5). Thirty percent of the sites have only clay reported, 29 percent have only sand reported, and 8 percent have only limestone reported (table 5).

Table 4. Aquifers represented in the study.

Aquifer system	Type	Number of sites
Gulf Coast	major	153
Ogallala	major	75
alluvium	-	72
Hueco-Mesilla Bolson	major	30
Carrizo-Wilcox	major	24
Woodbine	minor	19
Trinity Group	major	13
Queen City	minor	11
Edwards	major	9
Sparta	minor	8
Seymour	minor	7
Edwards-Trinity	major	4
Nacatoch Sand	minor	1
none	-	123
Austin Group	-	57
Eagle Ford Group	-	16
Pecan Gap Chalk	-	14
Permian	-	4
misc. sand, limestone, and shales	-	29
not specified	-	56

Table 5. Formation textures at the sites.

Texture	Number of sites*	Percentage
sand	196	51
clay	235	61
limestone	74	19
sand and clay	82	21
clay and limestone	42	11
sand and limestone	2	1
sand, clay, and limestone	4	1
only limestone	30	8
only clay	115	30
only sand	112	29

*Based on aquifer texture descriptions at 383 sites.

Hydraulic Properties

About 77 percent of the sites have measured and estimated hydraulic conductivities between 0.01 and 100 m yr^{-1} (fig. 7a). The median of measured values of hydraulic conductivity is 1.1 m yr^{-1} with 75 percent of the sites having values less than 55 m yr^{-1} (fig. 7b, table 3). The median transmissivity and storativity of the sites with measured values were 19 ft^2 d^{-1} and 0.008, respectively (table 3).

Hydraulic conductivity varies between aquifers (fig. 8). Hydraulic conductivity appears to be greater in the Ogallala, Carrizo-Wilcox, and Hueco-Mesilla Bolson aquifers (fig. 8e, f, g, respectively) than in the Trinity Group, Queen City, and Gulf Coast aquifers (fig. 8a, b, d, respectively). Alluvial aquifers show a wide range in hydraulic conductivity values (fig. 8c). Aquifers not shown did not have enough hydraulic conductivity measurements for analysis.

Depth to Water, Sweep Zone Thickness, and Water-Level Fluctuations

The minimum measured depth to water and the minimum reported depth to water have median values of 4.6 and 11 ft, respectively (table 3). The median of the maximum depth to water is 16 ft (table 3), and most of the values are less than 30 ft (fig. 9b). Median reported depth to water for 2,168 sites included in the TNRCC data base is 11 ft (table 3). Median average depth to water is 9.4 ft (fig. 9c). Most maximum site product thicknesses are less than 3 ft and have a median of 1.5 ft (fig. 9d).

The median reported depth to the base of the affected water-bearing zone is 22 ft (table 3), and the reported thickness of the water-bearing zone ranges from 1 to 200 ft and has a median of 11 ft (fig. 10a, table 3). These depths and thicknesses are probably biased toward smaller values because they usually represent only the depth to the bottom of the well or the completion interval of the well, which may not entirely penetrate the contaminated or water-bearing zone. Because water quality sampling is not done at vertically discrete intervals at these sites, it is very difficult to know the actual thickness of affected ground water, though it is expected to be shallow. Average depth to water varies between some aquifers (fig. 11a). The Ogallala and Hueco-Mesilla Bolson aquifers have median average depths to water of 30 and 20 ft, respectively, compared with a median average depth to water of about 10 ft for other aquifers (fig. 11a). This difference is due in part to the dryer climate in West Texas and the Panhandle compared with that of Central and East Texas. Aquifers not shown did not have enough measurements for analysis.

Sweep zones define the area in the formation where the water table fluctuates, potentially spreading product in the formation and exposing trapped product directly to ground water. We estimated the thickness of sweep zones using two methods: (1) difference between the maximum and minimum recorded water levels at a well and (2) the standard deviation of the water-level elevation.

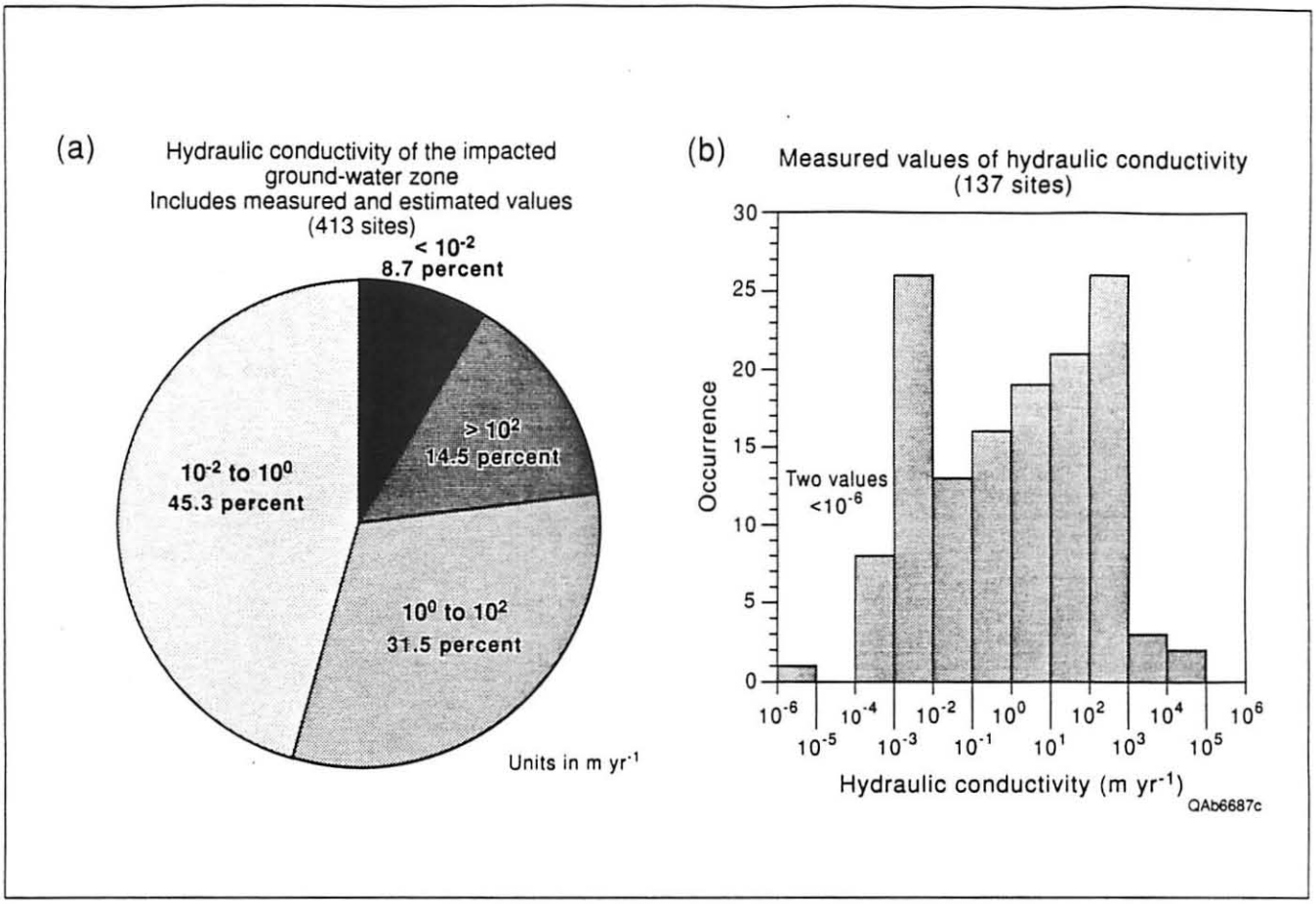


Figure 7. Estimated and measured values of hydraulic conductivity for the impacted water-bearing zone. The pie chart includes measured and estimated values. The histogram includes only measured values. Ranges shown in (a) are used in TNRCC questionnaires.

A value for the site was determined by weighting sweep-zone thickness by the period of the water-level record at each well. The median value for the difference between the maximum and minimum recorded water levels is about 9 ft, and most values are less than 20 ft (fig. 12a, table 3). The standard deviation of the water-level elevation describes 68 percent of the water-level variability for normally distributed variations and, therefore, describes the zone where the water table most commonly resides. The median of the standard deviation of the water-level elevation is 1.3 ft, most values being less than 3.5 ft (fig. 12b, table 3).

Maximum thickness of the sweep zone varies between aquifers (fig. 11b). The Edwards aquifer has a median sweep zone thickness of about 18 ft; the alluvial, Carrizo-Wilcox, and Gulf Coast aquifers have median sweep-zone thicknesses of about 10 ft; and the Hueco-Mesilla Bolson, Ogallala, Trinity, and Woodbine aquifers have median sweep-zone thicknesses of about 5 ft (fig. 11b). Aquifers not shown did not have enough measurements for analysis.

Hydraulic Gradients and Flow Directions

Most hydraulic gradients are between 0.001 and 0.1 (fig. 13a) with a median of 0.009 (table 3). The variation in hydraulic gradient, or how much the gradient changes over time, for most sites is less than a factor of 2 (fig. 13b). In other words, if the hydraulic gradient is *i*, then hydraulic gradient ranges from *i*/2 to 2**i*. If we assume that the formations are laterally isotropic, the direction of the hydraulic gradient is the same as the direction of the ground-water flow. Therefore, ground-water flow directions may vary at a maximum between 0 and 120 degrees with most variations less than 90 degrees (fig. 14, table 3). The standard deviation of ground-water flow direction is about a third of the maximum ground-water flow direction change and has a median of about 36 degrees (table 3).

Hydraulic gradient varies slightly between some aquifers (fig. 11c). For example, median hydraulic gradients

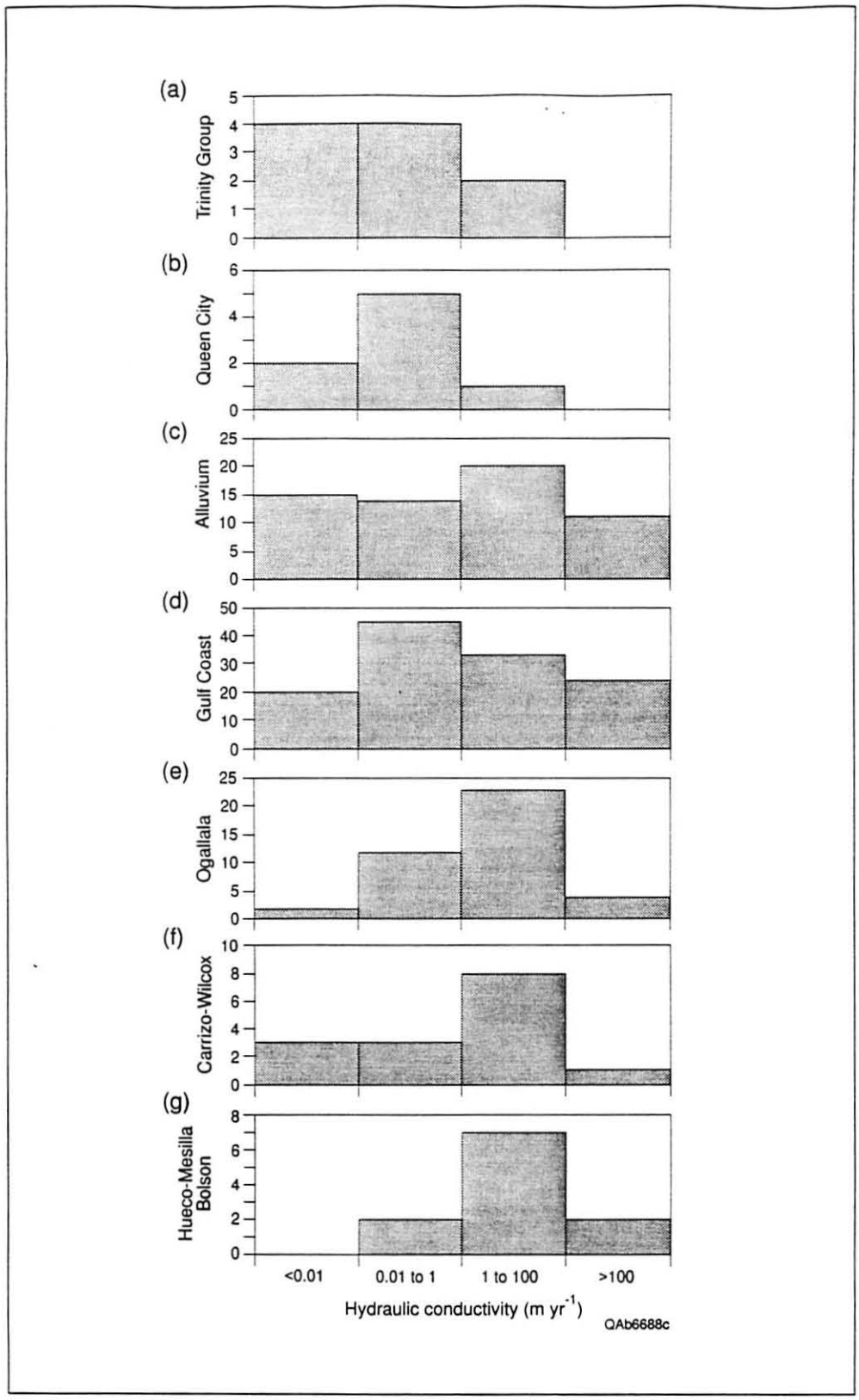


Figure 8. Distribution of measured and estimated hydraulic conductivity for LPST sites for the (a) Trinity Group, (b) Queen City, (c) alluvium, (d) Gulf Coast, (e) Ogallala, (f) Carrizo-Wilcox, and (g) Hueco-Mesilla Bolson aquifers. The *y*-axis is the number of occurrences.

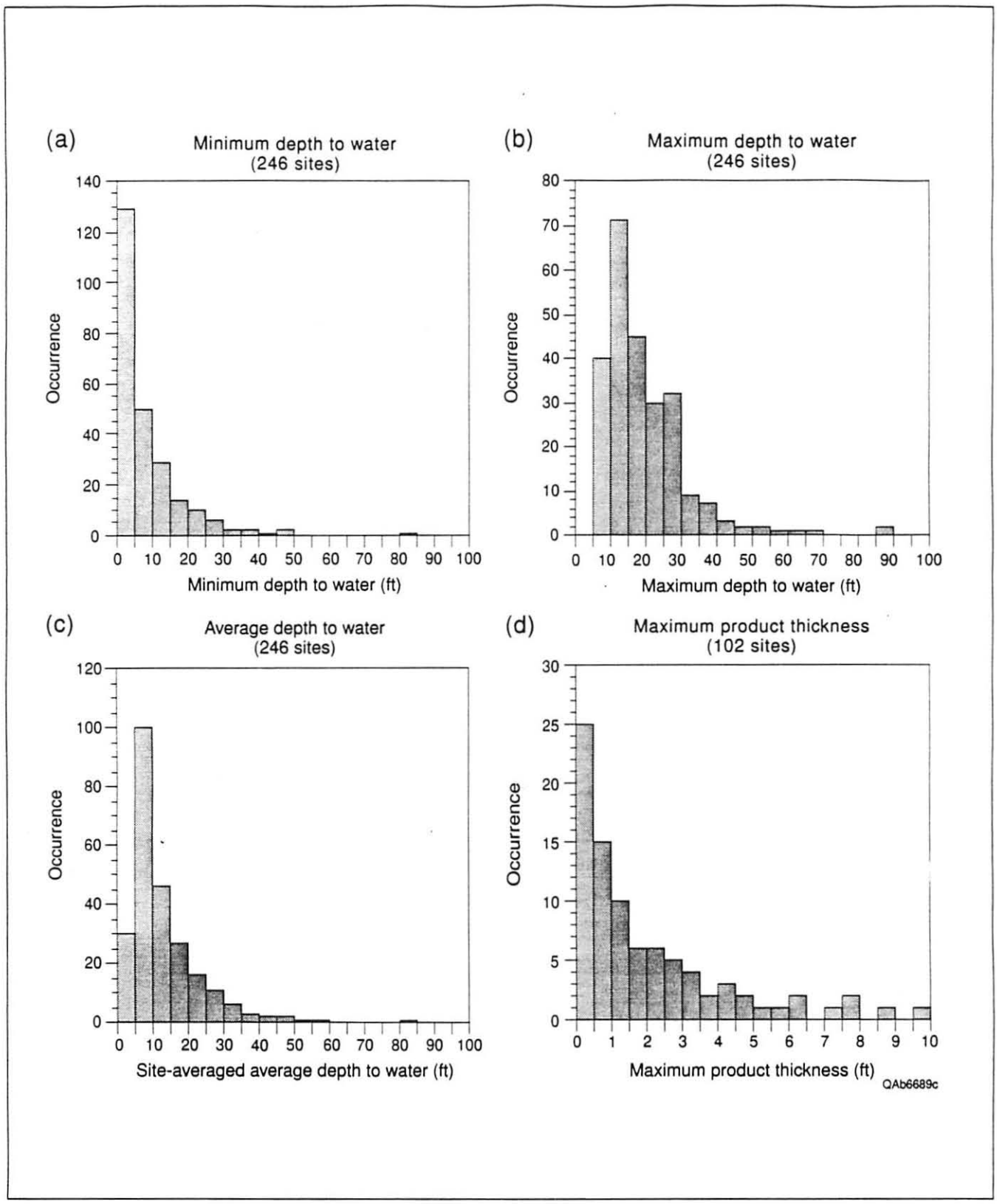


Figure 9. Results of the water-level and product analysis including (a) site minimum depth to water, (b) site maximum depth to water, (c) site-averaged average depth to water, and (d) maximum product thickness at the site. Sites shown had at least 10 water-level monitoring events in at least 1 monitoring well.

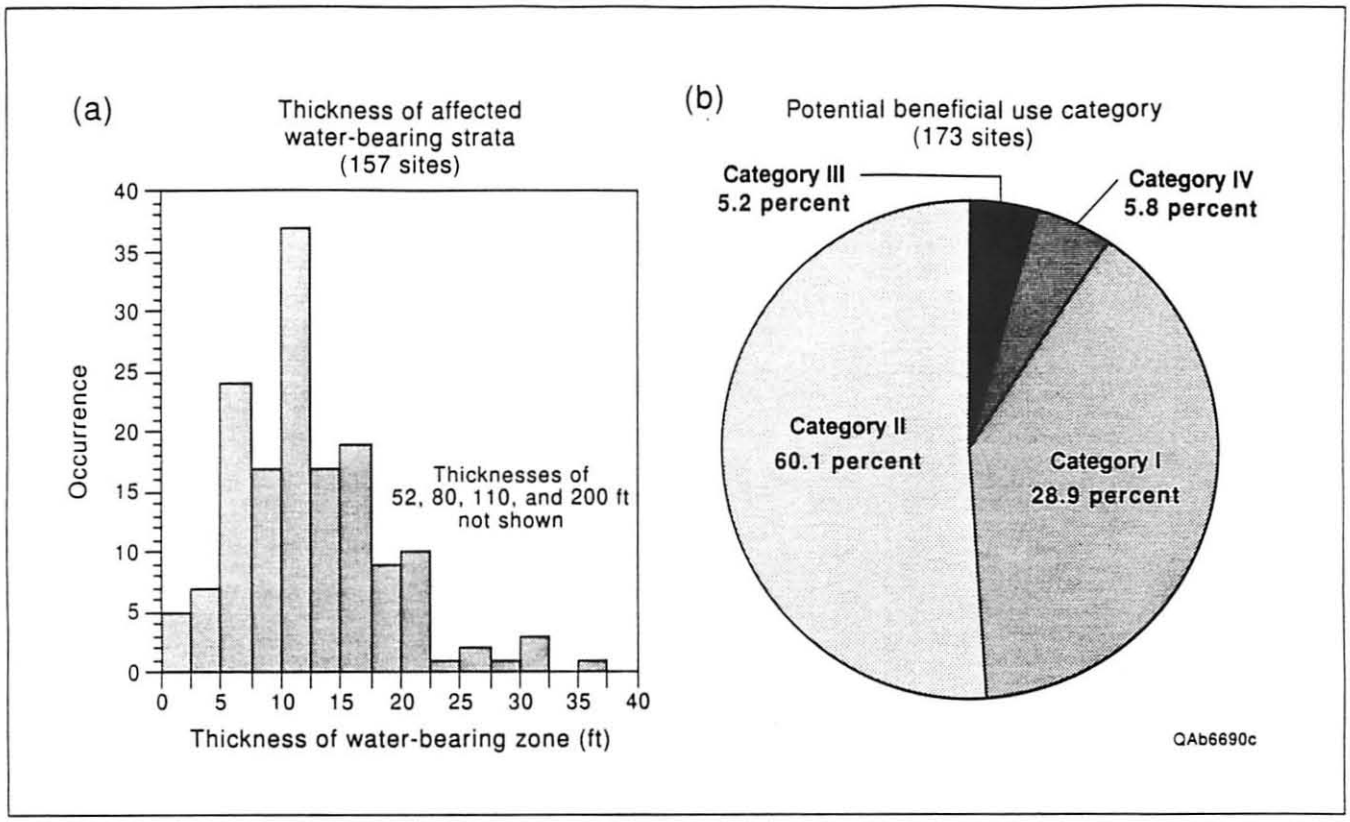


Figure 10. Reported (a) thickness of the aquifer zone and (b) beneficial use category (see text for description).

in the Hueco-Mesilla Bolson are lower than those in the Ogallala, Trinity, and Woodbine aquifers (fig. 11c). The Gulf Coast aquifer has a large interquartile range of hydraulic gradient (fig. 11c). Aquifers not shown did not have enough measurements for analysis.

Total Dissolved Solids (TDS) Concentration

Most of the sites we reviewed (92 percent) have a measured or estimated TDS concentration of less than 3,000 ppm (fig. 15a). Fresh water is defined as having a TDS concentration less than 1,000 ppm (for example, Freeze and Cherry, 1979, p. 84). A little more than 60 percent of the sites have water that is considered fresh. The median of measured TDS values is 770 ppm; 75 percent of samples are less than 1,520 ppm (fig. 15b, table 3). We also summarized information on TDS from the TNRCC data base. The TNRCC data base includes more sites that have poorer water quality (TDS greater than 3,000) (fig. 15c). However, quartiles for the TNRCC data base and for the data compiled during this study are approximately the same (table 3).

Potential Beneficial Use

Potential beneficial use of ground water is used by the TNRCC to establish cleanup objectives. The TNRCC (1994) defines beneficial use categories as

- Category I: Where water-supply wells are impacted or threatened or the TDS concentration is less than 3,000 ppm and a water well or water-supply spring is located within 0.5 mi of the site.
- Category II: Where the TDS concentration is less than 3,000 ppm and no beneficial use is documented within 0.5 mi of the site or the concentration of TDS is between 3,000 and 10,000 ppm and beneficial use is documented within 0.5 mi of the site.
- Category III: Where the TDS concentration is between 3,000 and 10,000 ppm and no beneficial use of the impacted ground water is documented within 0.5 mi of the site.
- Category IV: Where no beneficial use of the impacted ground water is documented and the TDS concentration is greater than 10,000 ppm and/or the yield of the formation is less than 150 gallons per day.

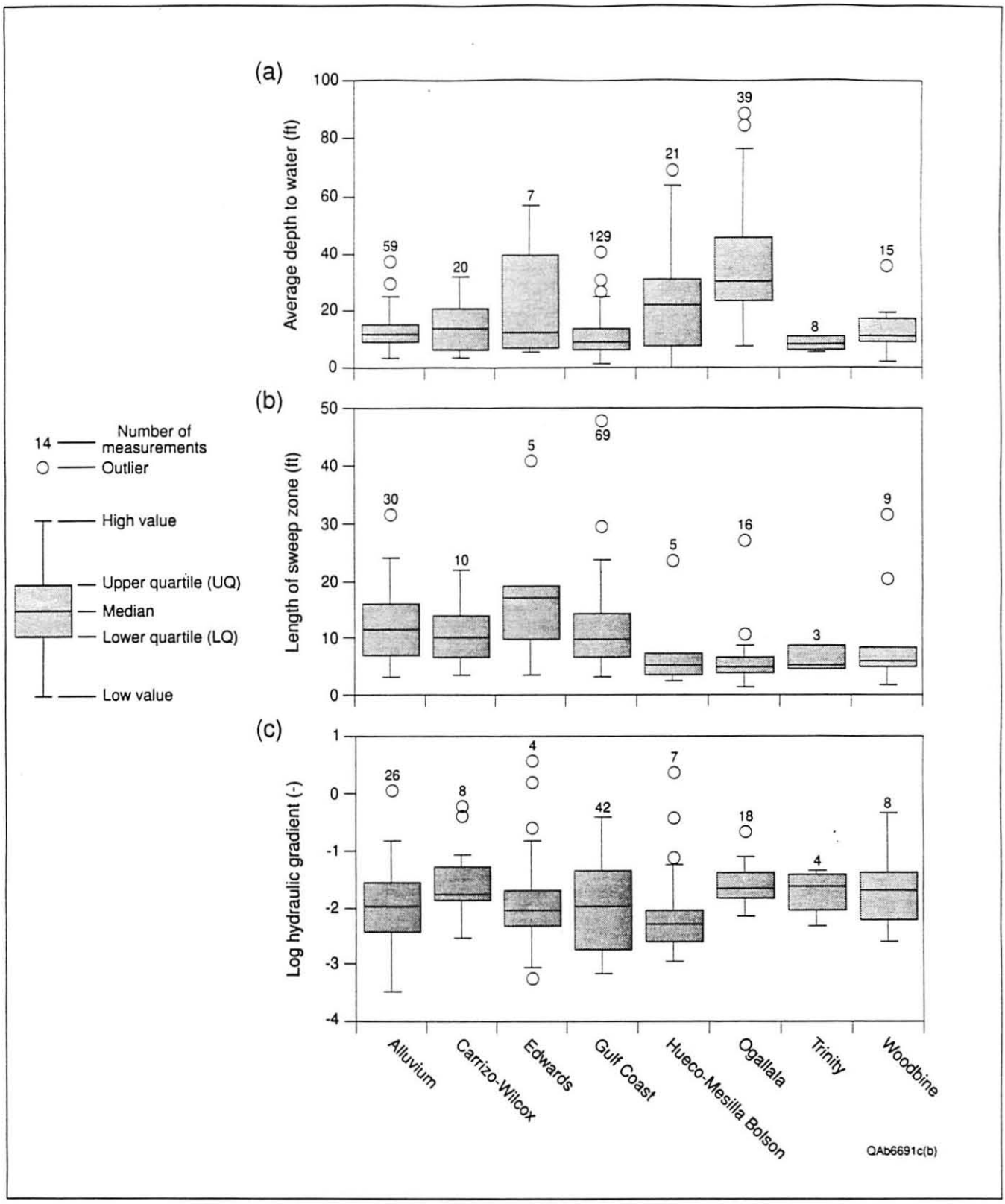


Figure 11. Variation of (a) depth to water, (b) thickness of the water-level sweep zone, and (c) logarithm of hydraulic gradient. Diagram on left explains the box plots shown on the right. The interquartile distance (IQD) is defined as the difference between the upper quartile (UQ) and the lower quartile (LQ) (that is, IQD = UQ – LQ). Outliers are defined as values greater than UQ + 1.5*IQD and less than LQ – 1.5*IQD. Low and high values are determined for data between UQ + 1.5*IQD and LQ – 1.5*IQD (that is, without the outliers).

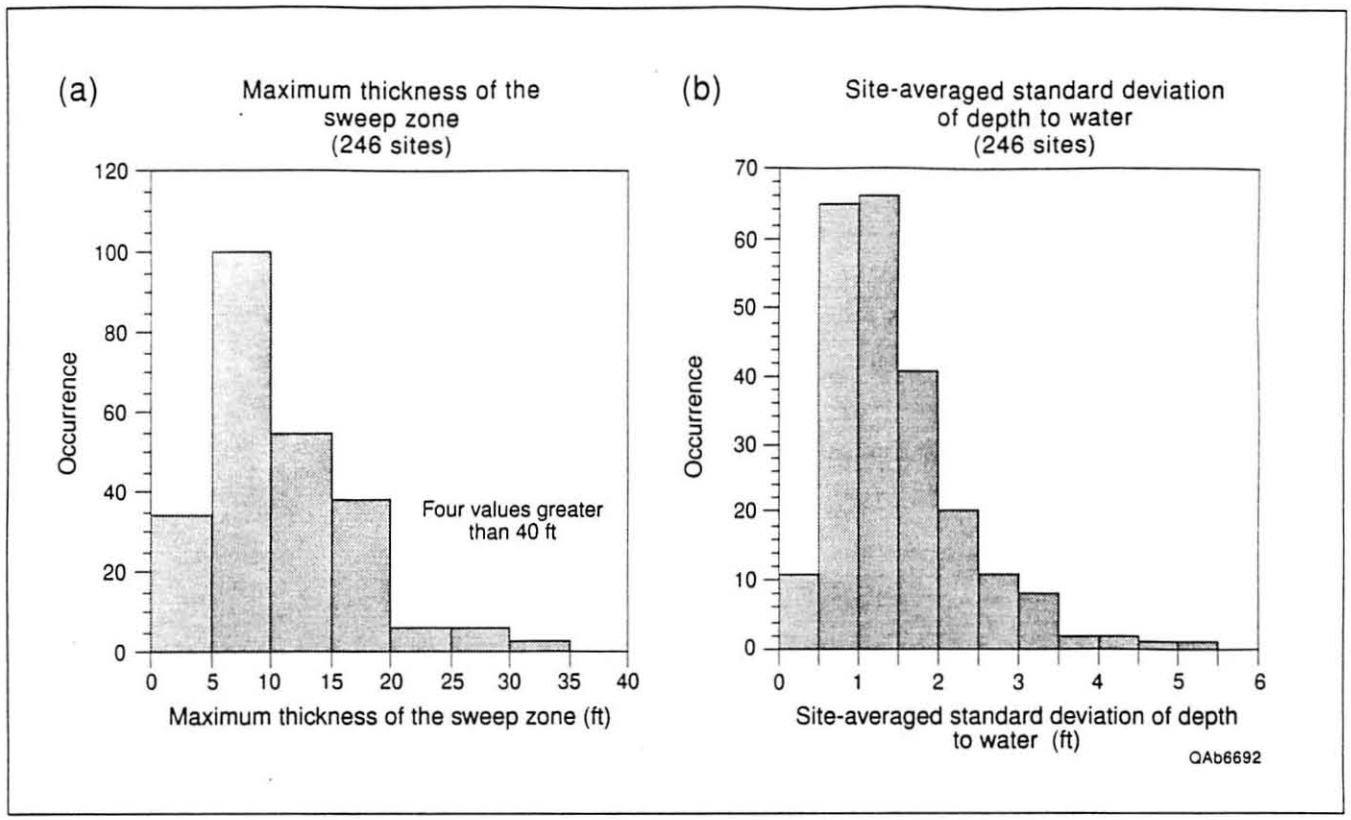


Figure 12. Variation in water levels including (a) maximum site thickness of the sweep zone and (b) site-averaged standard deviation of depth to water. The sweep zone is defined as the difference between the maximum and minimum depths to water.

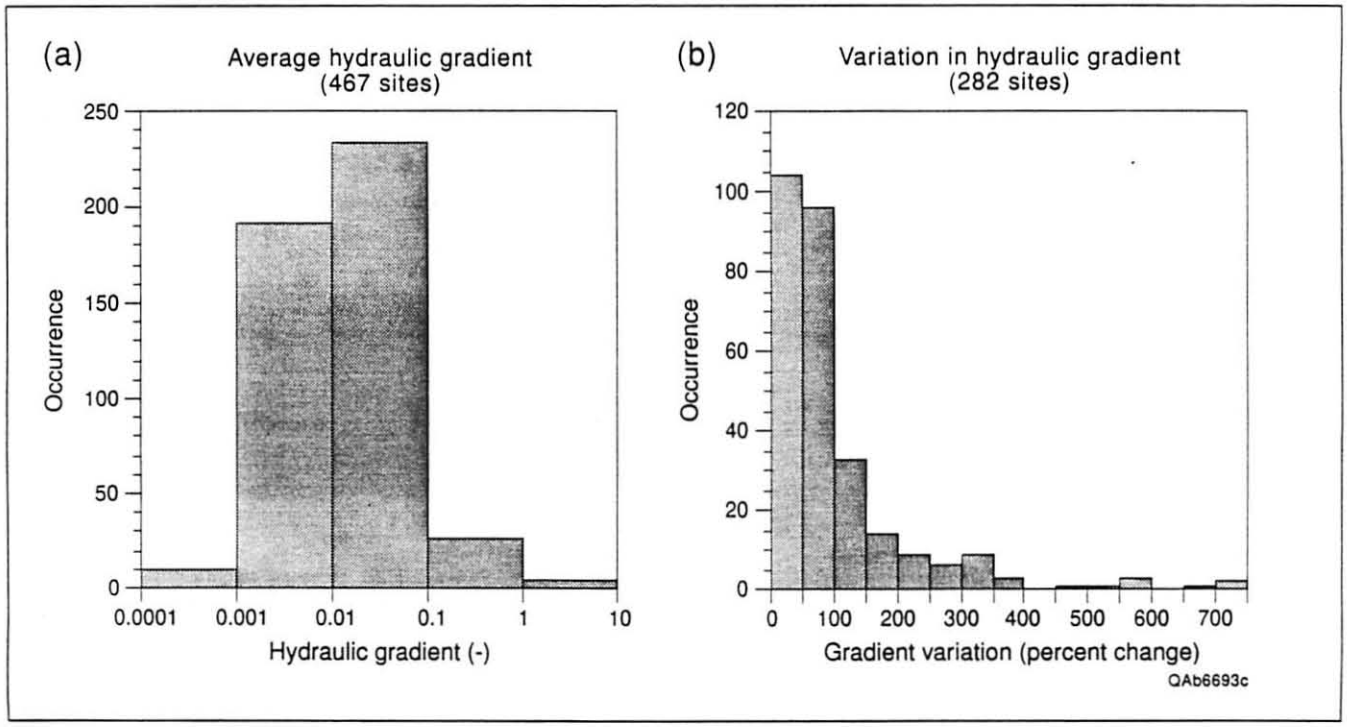


Figure 13. (a) Average hydraulic gradients and (b) variation in hydraulic gradients at the sites. The variation in hydraulic gradient was determined from the standard deviations of the logarithms of hydraulic gradient at sites having at least 10 water-level monitoring episodes.

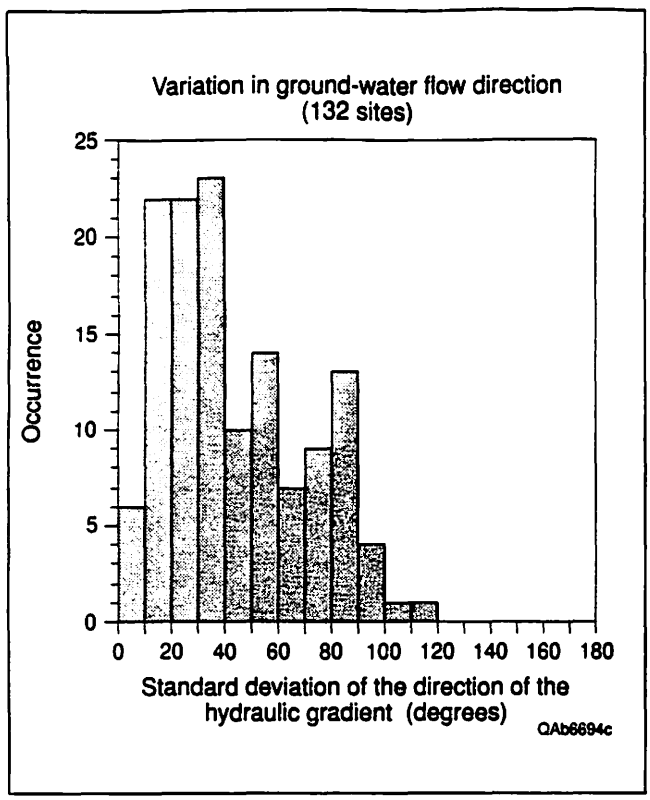


Figure 14. Standard deviations of directions of the hydraulic gradient for sites having at least 10 water-level monitoring events. If the formation is isotropic, hydraulic gradient coincides with the ground-water flow direction.

Category I ground water warrants a high degree of remediation, whereas category IV ground water typically needs only to be managed such that no other hazard results. The potential beneficial use of most (89 percent) of LPST sites we compiled is either category I or II, the remaining 11 percent consisting of category III and IV waters (fig. 10b). Therefore, LPST sites generally impact either high-quality ground water or ground water that has a demonstrated beneficial use in the area as defined by the TNRCC.

Contamination Attributes

The following sections describe the geometry of the contaminated soil, relationships between chemical concentrations, length and mass of benzene plumes, and remediation performed at the sites.

Geometry of Contaminated Soil

The geometry of the contaminated soil is defined by the depth to top, depth to base, thickness, and area of the contaminated soil and also the distance of the contaminated soil from the property boundary. Most reported values of the depth to top of contaminated soils lie between 0 to 23 ft (fig. 16a). The median reported depth to the top of contaminated soil for all the sites is 4.4 ft (table 3). Reported depth to the base of contaminated soils ranges from 2 to 140 ft (fig. 16b) with a median value of 17.5 ft (table 3). For sites where liquid-phase hydrocarbon has seeped to the water table, the depth to the base of contaminated soil is the same as the depth to water. Reported thickness of the contaminated soil ranged from 1 to 80 ft (fig. 16c) with a median of 11 ft (table 3). Reported areal extent of contaminated soil ranged from 30 to 112,000 ft^2 with a median of 6,750 ft^2 (table 3). Areal extent of the contaminated soil refers to soil that holds liquid-phase and sorbed hydrocarbon. Most sites have contaminated soil less than 30 ft from the property boundary (fig. 16d). Twenty-five percent of the sites have contaminated soil that reportedly extends beyond the property line.

Chemical Relationships

Benzene concentration is approximately correlated with toluene, ethyl-benzene, and total xylenes but not with MTBE (figs. 17 and 18). Because concentrations are log-normally distributed, the cross plots are shown with log axes. Plots of benzene against toluene, ethyl-benzene, and total xylenes are for LPST sites in Harris County, and plots of benzene against MTBE are for LPST sites all over Texas. Toluene concentrations tend to be lower than benzene concentrations (fig. 17a, where the solid line represents where the concentration of toluene equals that of benzene). Only 36 percent of the toluene concentrations are greater than the benzene concentrations (fig. 17b). Ethyl-benzene concentrations also tend to be lower than benzene concentrations. About 17 percent of ethyl-benzene concentrations are greater than benzene concentrations. Total xylenes concentration exceeds benzene concentration in 45 percent of the samples (fig. 18a). About 61 percent of measured MTBE concentrations are greater than their companion benzene concentrations, although there are still many cases where the concentration of MTBE is much lower than that of benzene (fig. 18b). Benzene and MTBE concentrations do not appear to be related. The position of the points on these plots is partly a function of original fuel composition, solubility, degradation rates, sorption, volatilization, and spatial and temporal position in the plume.

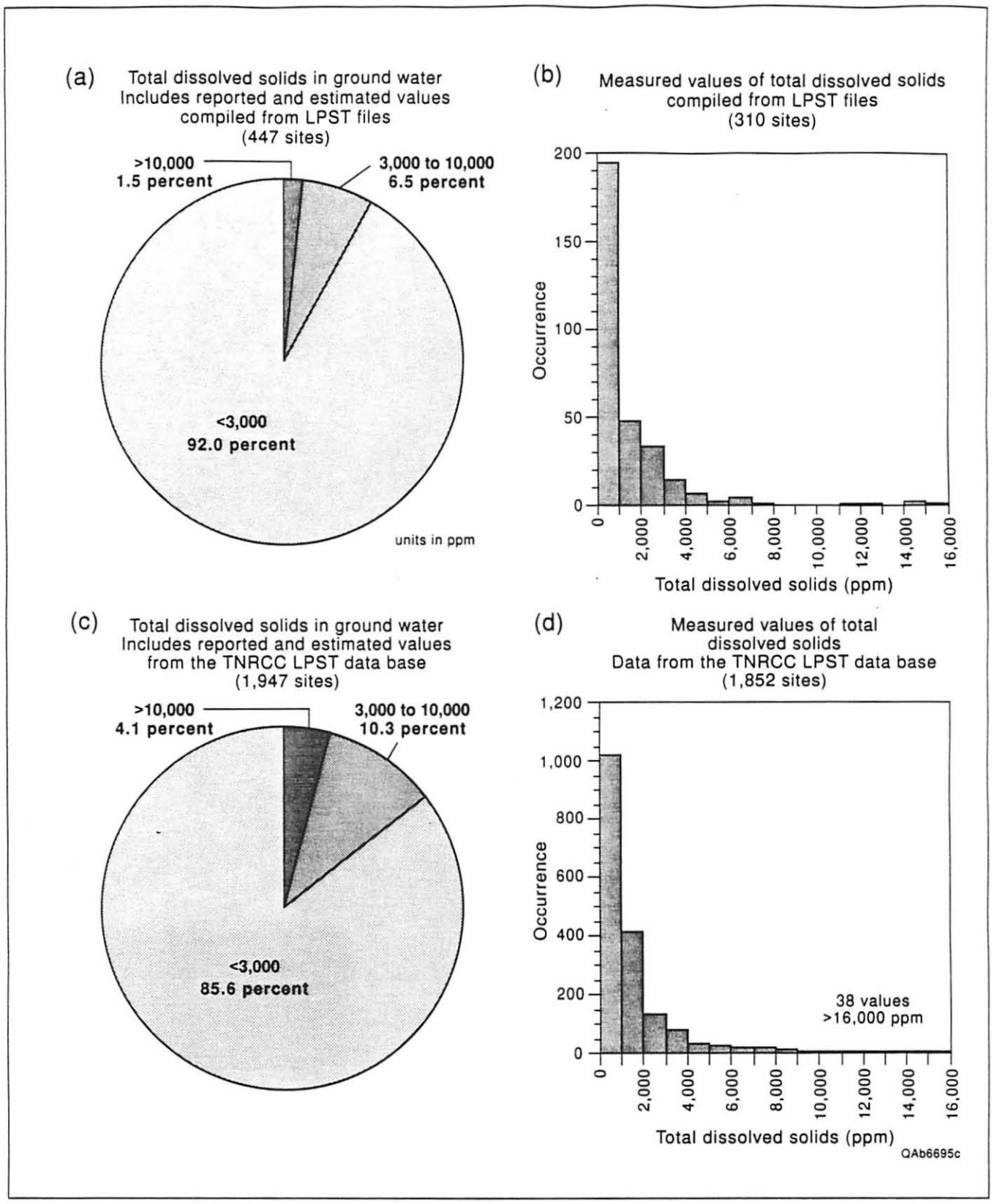


Figure 15. Total dissolved solids in the least affected monitoring well for LPST files compiled during this study (a, b) and in the TNRCC LPST data base (c, d). Pie charts include measured and estimated values. Measured values are measured in a laboratory, and estimated values are estimated by site investigators. Histograms include only measured values. Ranges shown in (a) and (c) are used in TNRCC questionnaires.

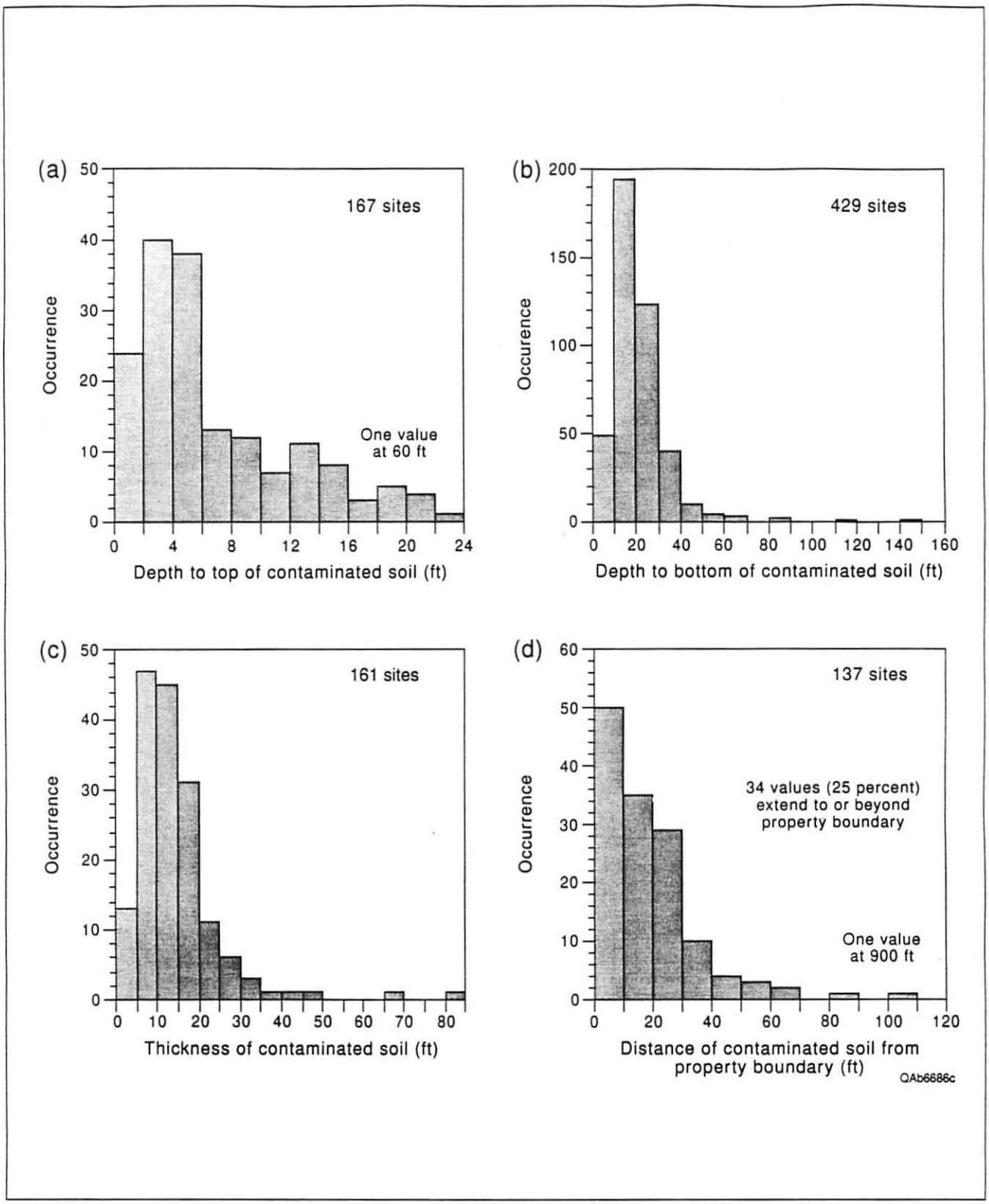


Figure 16. Reported dimensions of the contaminated soil including (a) depth to top of contaminated soil, (b) depth to bottom of contaminated soil, (c) thickness of contaminated soil, and (d) distance of contaminated soil from the boundary of the property. Depth to the base of contaminated soil typically coincides with the top of the water table.

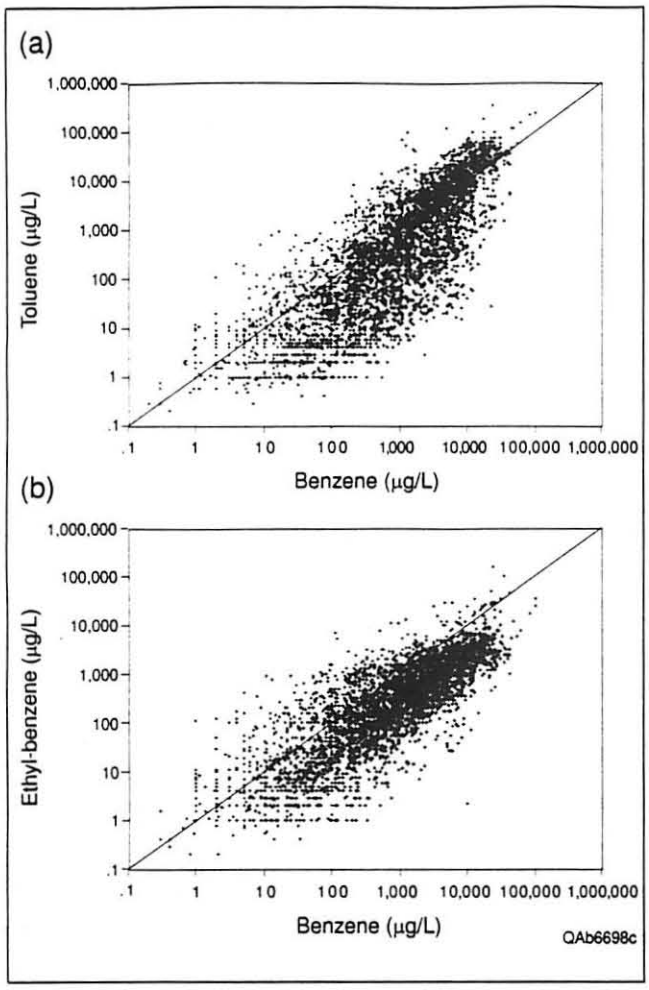


Figure 17. Relationship between concentrations of benzene and (a) toluene and (b) ethyl-benzene at LPST sites in Harris County. For (a) there were 542 monitoring events where benzene was detected but toluene was not, and there were 185 events where toluene was detected and benzene was not. For (b) there were 993 events where benzene was detected but ethyl-benzene was not, and there were 79 events where ethyl-benzene was detected but benzene was not. The straight lines show where benzene concentration equals that of (a) toluene or (b) ethyl-benzene.

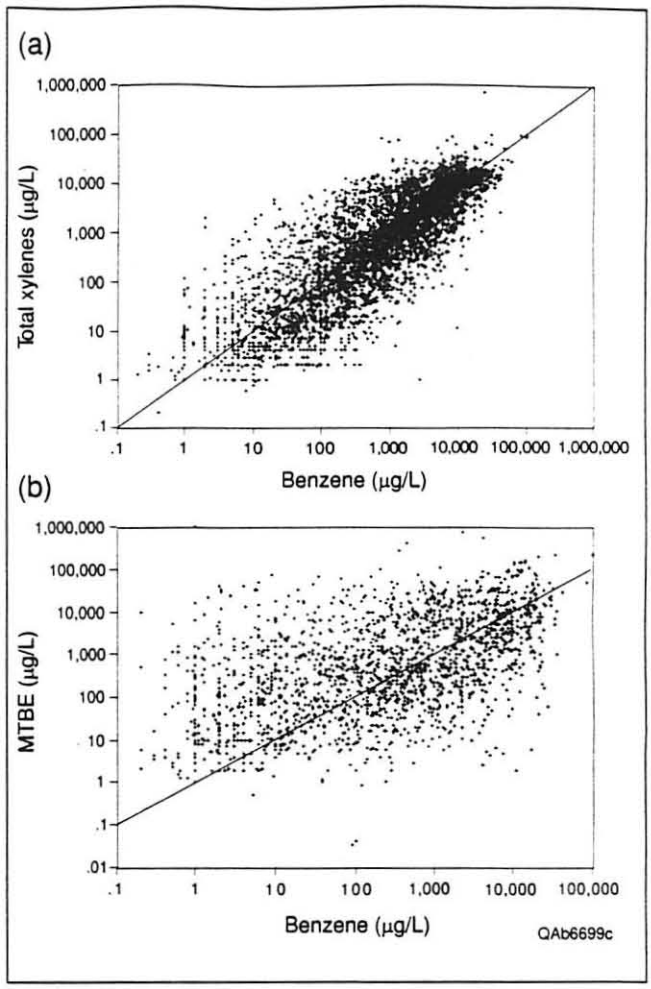


Figure 18. Relationship between concentrations of benzene and (a) total xylenes at LPST sites in Harris County and (b) MTBE at sites in Texas. For (a) there were 200 monitoring events where benzene was detected but xylene was not, and there were 331 events where xylene was detected and benzene was not. For (b) there were 890 events where MTBE was detected but benzene was not, and there were 331 events where benzene was detected but MTBE was not. The straight lines show where benzene concentration equals that of (a) total xylenes or (b) MTBE.

Plume Length and Mass

We determined plume length, as defined by the 10-ppb contour, at 217 of the 605 LPST sites we reviewed. The number analyzed was limited by the presence of six or more monitoring wells having benzene concentration data. Most plumes were less than 300 ft long (fig. 19a) and have a median length of about 180 ft (table 3), as determined using the exponential plume model. Ninety percent of the plumes have lengths of less than about 380 ft, and 99 percent have lengths of less than about 1,200 ft. These lengths are probably biased toward larger values because our analysis required at least six wells and therefore excluded sites with fewer than six wells.

Area of the affected water-bearing zone refers to the area of the dissolved-phase hydrocarbon plume at the site. Most of the sites had plume areas between 10,000 and 100,000 ft^2 (fig. 19b). The median plume area was about 26,000 ft^2, which was more than twice the median of 11,000 ft^2 reported by site investigators in LPST

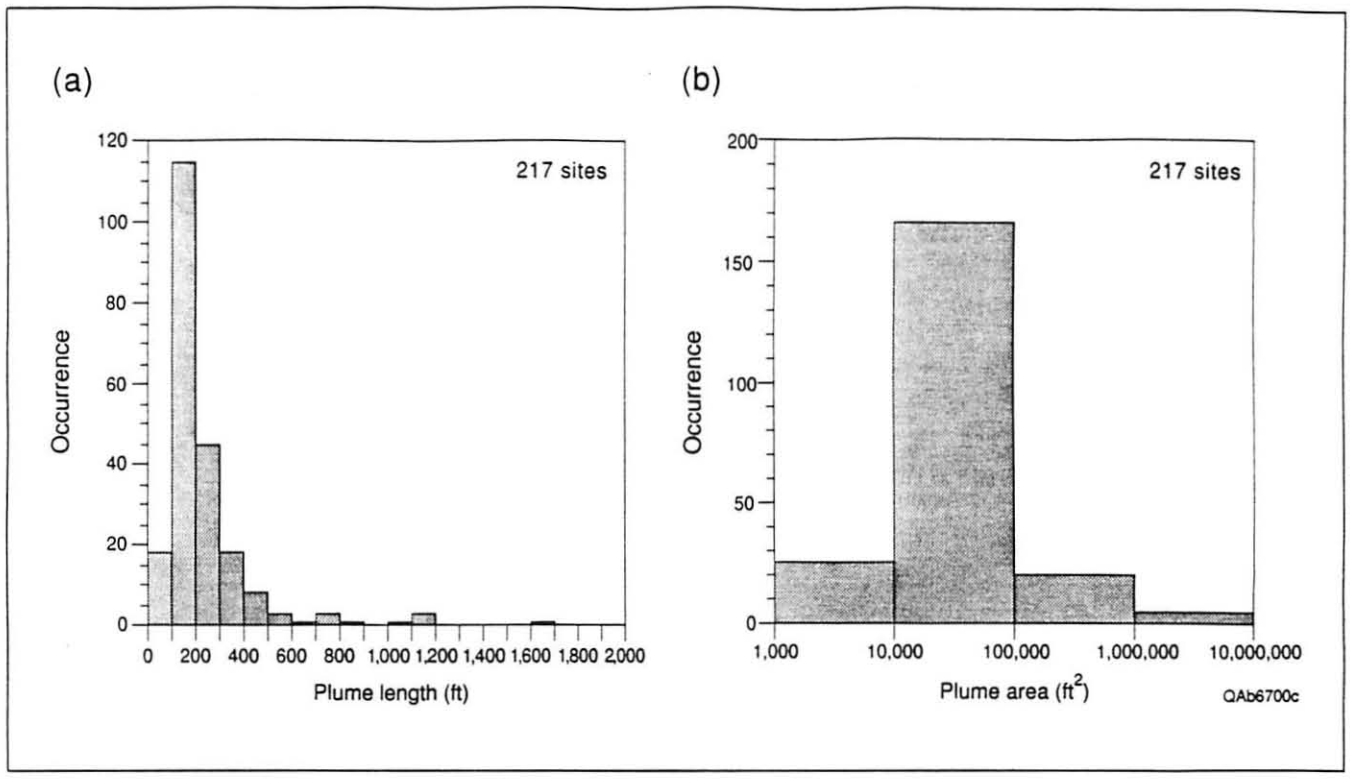


Figure 19. (a) Plume length and (b) area defined by the 10-ppb contour for the most recent monitoring episode at the sites. Plume lengths defined using exponential model.

questionnaires (table 3). Ninety percent of the plumes have areas of less than about 120,000 ft^2, and 99 percent have areas of less than about 1.1 million ft^2.

Many of the LPST sites with multiple sampling episodes show temporal variations in mean benzene concentration and plume length (fig. 20). Some LPST sites show a rise, equilibration, and decline in average site benzene concentration (fig. 20c, d). Others show a period of stable concentrations followed by a rapid decrease in concentrations (fig. 20a, b, e) or only the decline period (fig. 20f). For these sites, the plume may have already been established before monitoring wells were installed, or there were not enough monitoring wells early in the development of the plume to document increasing concentrations. In addition to showing general trends, some plumes have episodic variations in concentrations (fig. 20b, c, d, e, f). These variations may be due to (1) fluctuations in water levels that smear liquid-phase hydrocarbon in the saturated zone and thus increase this dissolution of liquid-phase hydrocarbon, (2) an influx of recharging waters carrying dissolved hydrocarbon from the unsaturated zone, or (3) an artifact of sampling techniques. Some sites possibly show evidence of another leak or an additional source where concentrations have stabilized and then later increase and stabilize at a much higher level.

Plume lengths tend to be more stable than concentrations (fig. 20b, c, d, e). However, there are more plumes showing a gradual decrease in length (fig. 20b, c, d, e, f) than there are plumes showing a large decrease in length at later times (fig. 20a, f). Plume lengths tend to approach a value greater than zero after a rapid decline. For example, plume lengths at LPST site 91071 appear to approach a plume length of 300 ft (fig. 20a), and plume lengths in LPST site 96497 appear to stabilize at 100 ft (fig. 20f) after decreasing rapidly. These postdecline stabilization levels range from 60 to 300 ft with a mean of 140 ft; the larger sizes are generally associated with larger maximum plume lengths. Similar to plume mass, we do not commonly see plumes increasing in length probably because of inadequate monitoring soon after the leak and FHC plume were detected.

We calculated the rates at which average benzene concentration decreased in plumes (fig. 21). As in actuarial analysis the rates are determined on the logarithm of the data value. The median decline rate is 0.002 day^{-1} with an interquartile range that spans 0.0015 to 0.003 day^{-1}

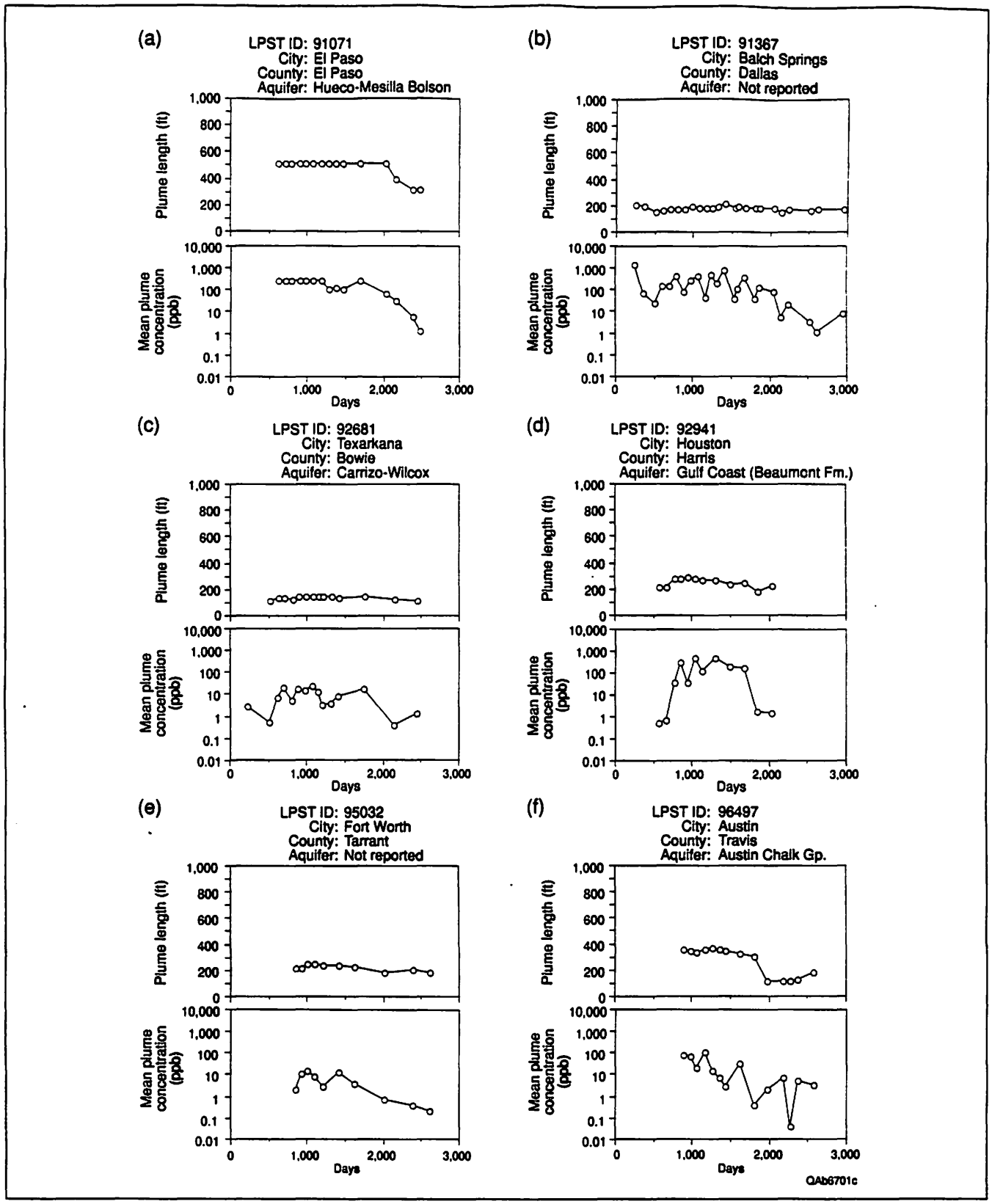


Figure 20. Examples of changes in mean plume length and concentration for benzene plumes at LPST sites (a) 91071, (b) 91367, (c) 92681, and (d) 92941, (e) 95032, and (f) 96497. Several of the plumes show a decrease in mean plume concentration with time (a, b, d, e, and f). A couple of the plumes show plume length decreasing with time (a and f). Plume lengths are determined from the exponential model. Both vertical and horizontal scales for the plots are for the same ranges. The *x*-axes (days) are also the same interval but not concurrent times.

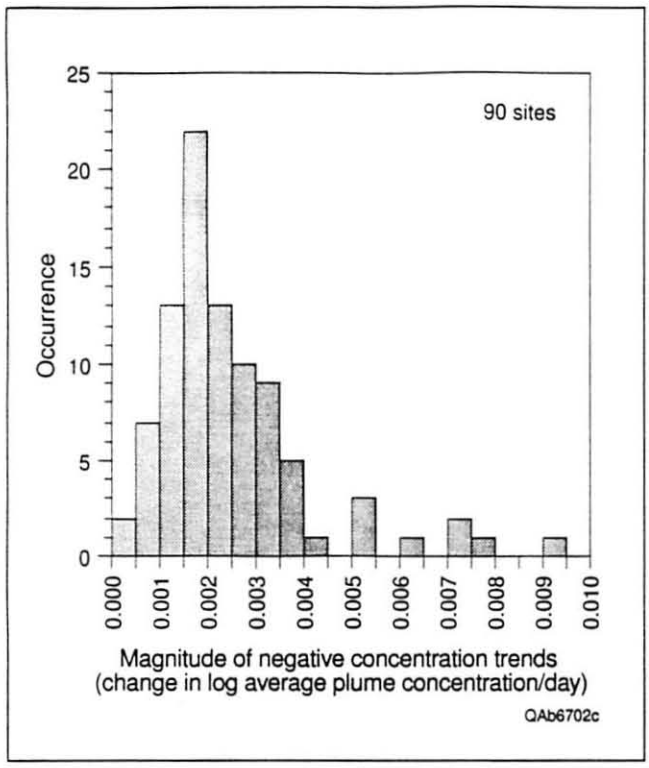


Figure 21. Magnitude of negative concentration trends in LPST benzene plumes. Inverse of this rate is the time required to lower concentration an order of magnitude, or 10 times.

(table 3). The inverse of these rates indicates the amount of time required to lower average site concentrations an order of magnitude (tenfold). Therefore, the median time required to lower average site concentrations tenfold is 500 days with an interquartile range that spans about 350 to 700 days.

On the basis of the conceptual plume model developed by Rice and others (1995) and shown in figure 2, most of the plumes we analyzed are in phases II and III, where plume lengths are stable or slowly declining (fig. 22a). Only 3 percent of the plumes we analyzed were in the growing phase (I), and 9 percent were in the final phase of rapidly decreasing plume lengths (IV) (fig. 22a). Many releases at these sites are historical: they occurred years before they were discovered and therefore are more likely to have stabilized over time.

The conceptual model developed by Rice and others (1995) shows that plume length decreases to zero in the last phase (fig. 2a). However, as discussed earlier, we found that plumes in the last phase approached a value greater than zero. We adjusted the Rice and others (1995) conceptual model of plume length to reflect this behavior (compare figs. 2 and 22a).

On the basis of the conceptual model for plume concentration developed by Rice and others (1995), almost half of the plumes we investigated were in phase III with rapid decreases in plume mass (fig. 22b). About a third of the plumes had stable concentrations (phase II), and 14 percent were in phase I with increasing mass with time (fig. 22b). The relative percentage of sites in each phase for plume length and concentration does not agree (compare figs. 22a and 22b). This discrepancy may be due to sites at which additional mass was added to the plume before plume lengths decreased (for example, another leak at the same site), ambiguity of interpreting trends in plume length and concentration, or phenomena not considered by the conceptual model.

Remediation

Remediation attempts to remove the contaminant source and remove and clean the impacted ground water. There are two types of sources at LPST sites: primary and secondary. A primary source relates to leaking tanks and lines, overfills, and accidental spills. A secondary source refers to the sorbed and liquid-phase hydrocarbon that has leaked into the ground and supplies dissolved hydrocarbon to the ground water. Primary sources are generally easy to abate either by stopping the activity that caused the spill or by taking leaking underground storage tanks out of use. Secondary sources have a long-term effect on ground water and are much more difficult to abate and remediate.

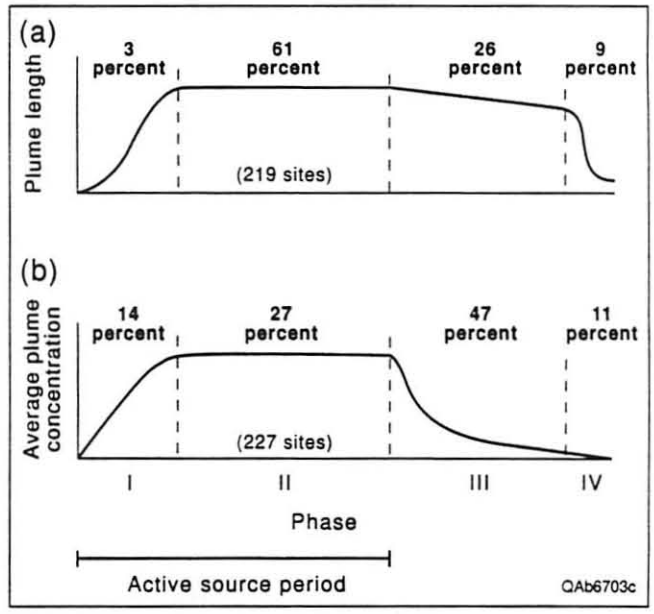
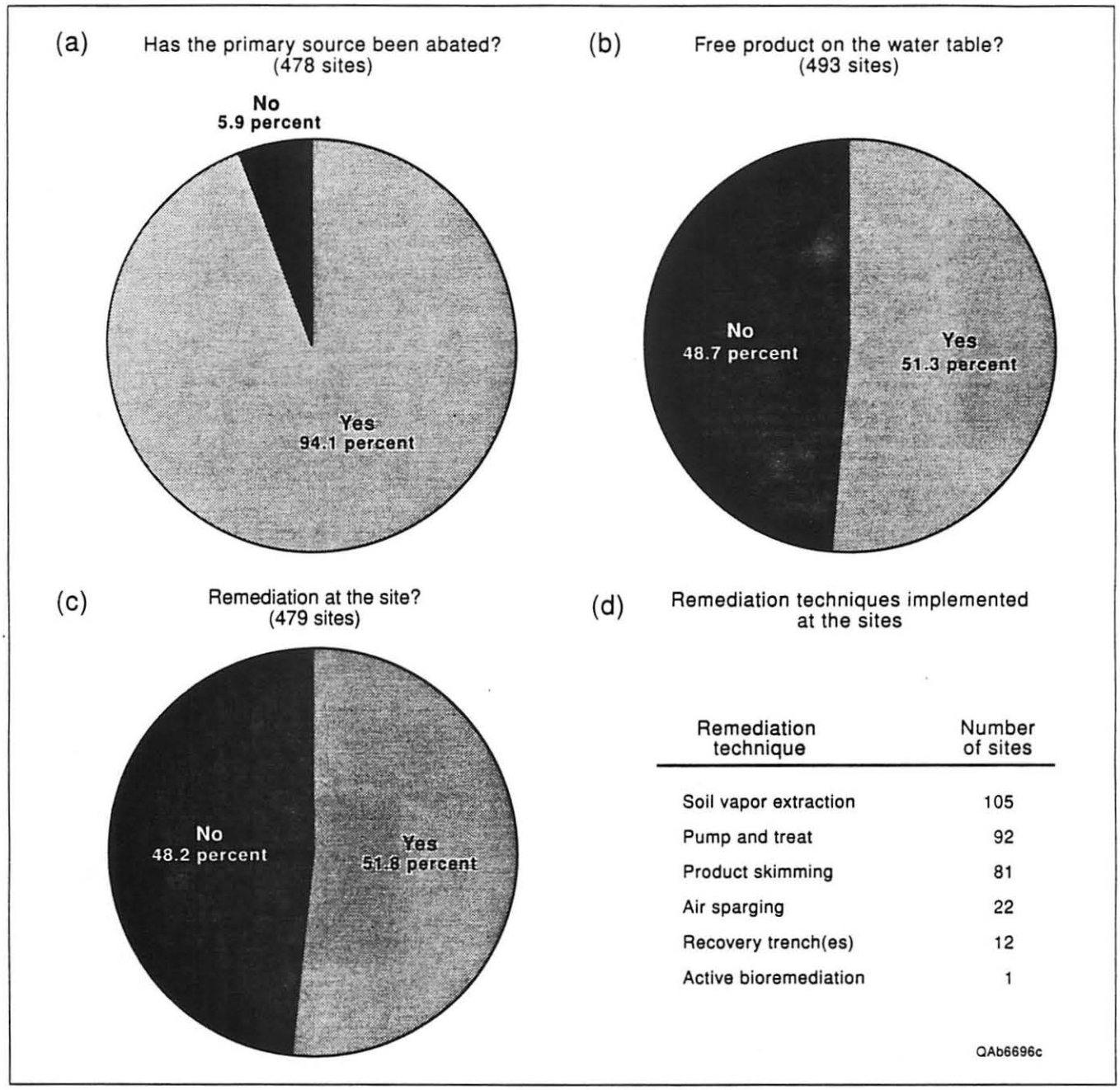


Figure 22. The percentage of well-characterized sites in Texas that fall into the different hypothetical phases of (a) plume length and (b) average plume mass. We were unable to determine the status at 1 percent of the sites.

The primary source was abated at most LPST sites (94 percent) we compiled (fig. 23a). Primary source abatement usually consisted of repairing leaks to the system or removing the underground storage tank system. A little more than half of the sites reportedly had free product floating on the water table at some point in their history (fig. 23b). About 52 percent of the sites have had some sort of remedial activity to address secondary sources (fig. 23c) either to volatilize product trapped in the vadose zone, to remove free product (liquid-phase hydrocarbon) floating on the water table, or to remove or intercept impacted ground water. The most common remediation techniques reportedly applied at sites have been soil vapor extraction, pump and treat, or



Remediation technique	Number of sites
Soil vapor extraction	105
Pump and treat	92
Product skimming	81
Air sparging	22
Recovery trench(es)	12
Active bioremediation	1

Figure 23. Response to leaking petroleum storage tanks including (a) whether the primary source was abated (leak fixed, tank removed, and so forth), (b) whether there is or was free product on the water table, (c) whether remediation has occurred at the site, and (d) what type of remediation techniques are or were used at the sites. Details about the techniques are in the text. Note that many sites had multiple remedial activities (for example, pump and treat, soil vapor extraction, and product skimming). The primary source refers to the origin of the release such as a leaking tank or line.

product skimming (fig. 23d). In our analysis, we treated product skimming as including both active (skimmer pumps) and passive (bailing, resin canisters, absorbent socks) product removal. Fewer sites had air sparging, recovery trenches, or active bioremediation implemented (fig. 23d).

Almost 40 percent of the sites have dissolved hydrocarbon plumes that reportedly extend offsite (fig. 24a). Of the plumes that have not moved offsite, most are within 50 ft of the property boundary (fig. 24b). Of the plumes that have moved offsite, most reportedly extend less than 150 ft from the property boundary (fig. 24c).

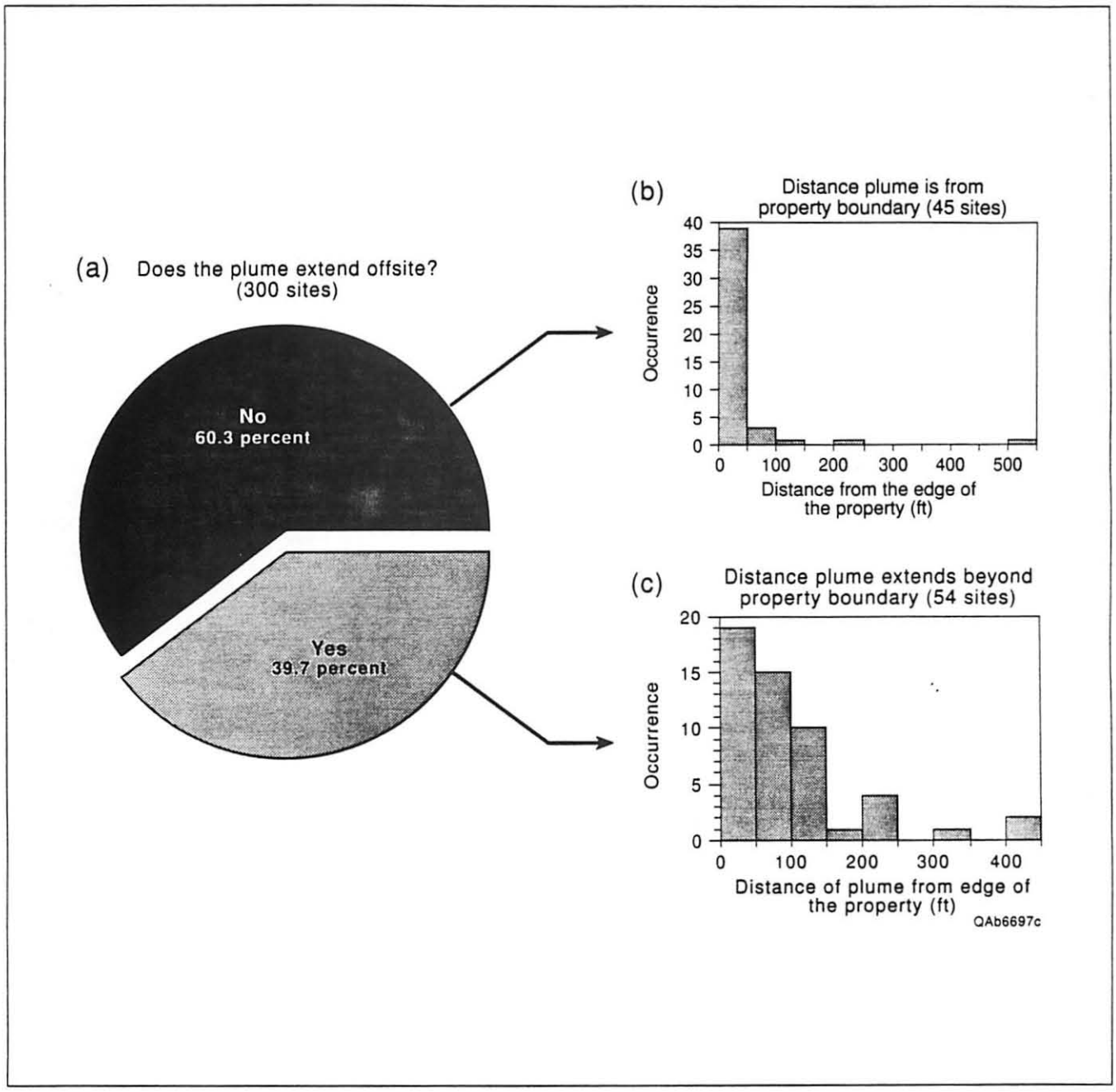


Figure 24. Reported position of the plume with respect to the property boundary of the site including (a) whether the plume extends offsite, (b) how far the plume is from the property boundary if it does not extend offsite, and (c) how far past the property boundary the plume extends. There are fewer sites in the histograms than in the pie chart because not all site reports defined the distance from or beyond the property line.

Influence of Site Conditions and Site Activities

When looking at the population of all the plumes, hydrogeologic site characteristics and site activities considered in this study do not explain the variation in average plume length or plume mass and concentration. Aquifer system, aquifer texture, hydraulic conductivity, and the presence of free product appear to have less influence than other variables on the median of maximum plume length, which was close to 200 ft for all cases (table 6). One exception is a large LPST plume in the Edwards aquifer, a karst limestone, at Georgetown, Texas. This plume had a length of 7,600 ft, possibly reflecting the potential for plumes in fractured and karstic limestones to be much longer than plumes in clastic (sand, clay, sandstone, shale) formations.

Plume length cannot be predicted by the depth to water, thickness of the sweep zone, hydraulic gradient, and percentage of organic carbon in the water-bearing zone. Other variables, such as the amount and areal extent of spilled hydrocarbon, which were beyond the scope of this study to consider, might be the critical factors for predicting plume length. For most sites, however, details on the timing and volume of the leak are sparse at best.

Table 6. Influence of site conditions on maximum plume length.

Parameter	Number of sites	25th quartile	50th quartile (median)	75th quartile	Maximum
Aquifer system					
alluvium	30	180	200	330	820
Edwards	3	-	-	-	7,600
Gulf Coast	70	150	190	290	1,300
Hueco-Mesilla Bolson	10	190	260	380	530
Ogallala	12	170	200	260	650
Aquifer texture					
with sand	63	180	220	340	1,700
with clay	95	190	200	300	970
with limestone	26	170	200	300	7,600
only sand	26	180	240	350	1,700
only clay	40	170	200	300	820
only limestone	7	170	220	400	7,600
Hydraulic conductivity					
<0.01 m d^{-1}	23	200	230	330	1,700
0.01 to 1 m d^{-1}	57	160	200	310	1,300
1 to 100 m d^{-1}	57	160	200	260	860
>100 m d^{-1}	33	150	190	300	1,200
Free product?					
Yes	115	170	210	330	7,600
No	78	160	200	290	1,700

The proportion of phase II plumes having stable concentrations is very similar between sites being cleaned up with pump and treat (61 percent) and other sites without pump and treat (52 percent) (table 7); the latter includes sites with no action and sites with other treatments. Both "pump and treat" sites and "other" sites have similar percentages of plumes having stable concentrations. The similarity of size between plumes with and without pump and treat is probably due to two factors: (1) pump and treat probably starts after plumes have stabilized, and (2) though mass is removed from the plume, desorption from soil and aquifer surfaces maintains concentrations and plume lengths. Pump and treat should theoretically decrease the time required to reach target concentrations. Unfortunately, we cannot gauge this effect owing to the lack of information on the size and timing of the fuel leak. We found no difference in plume length between different remediation techniques and sites with no remedial action.

There are more plumes with decreasing concentrations with pump and treat than without, but there are also more exhausted plumes when there is no pump and treat. When phases III and IV are taken together, the percentages between sites with pump and treat and without pump and treat are very similar (table 7).

Table 7. Influence of remediation on plume phase described by average benzene concentrations.

	Sites with pump and treat*	Sites without pump and treat†
Phase II stable concentrations	35	38
Phase III decreasing concentrations	61	52
Phase IV exhausted concentrations	4	10

*67 sites
†117 sites

Discussion

General Characteristics of LPST Sites in Texas

In general, benzene plumes in Texas are less than 250 ft in lateral extent and normally affect only shallow ground water. However, many benzene plumes extend offsite, and many sites have at least one water well within half a mile. The size and contaminant concentrations in benzene plumes appear to be stable or decreasing at 85 percent of the sites. Our data compilation and analysis show the following general characteristics of LPST sites in Texas:

- About 25 percent of LPST sites impact or are a potential high-risk threat to public health and safety.
- Almost 70 percent of sites have greater than 75 percent impervious cover.
- About 58 percent of sites have at least one public or domestic well within 0.5 mi of the site.
- Most sites have organic carbon content less than 1 percent, a soil bulk density of 1.86 g cm^{-3}, a volumetric moisture content of 25 percent, a porosity of 33 percent, and an intrinsic permeability of 6.4×10^{-12} cm^2.
- Median depth to top, depth to bottom, and the thickness of the contaminated soil are 4.4, 17.5, and 11 ft, respectively.
- Twenty-five percent of sites have contaminated soil that extends beyond the property boundary.
- More than 90 percent of site water-bearing zones have a TDS concentration less than 3,000 ppm.
- About 45 percent of sites have hydraulic conductivities greater than 1 m yr^{-1}.
- A little more than half of the sites have had free product floating on the water table.
- About half of the sites have had some sort of remediation implemented.
- Almost 40 percent of the ground-water benzene plumes extend beyond the property boundary.
- The median minimum, maximum, and average depth to water are 4.6, 16.2, and 9.4 ft, respectively.
- Median sweep-zone thickness is about 9 ft.

- Gradients are around 0.013, vary less than a factor of 2, and have a median direction change of about 36 degrees.
- Seventy-five percent of the plumes have lengths as defined by the 10-ppb contour of benzene of less than 250 ft and plume areas of less than 49,000 ft^2.
- Fourteen percent of plumes we studied have increasing average concentrations, and three percent have increasing length. The remaining plumes either are stabilized, are decreasing in mass and length, or are nearly exhausted.

What Are the Dimensions of Benzene Plumes in Texas?

The current median plume length for dissolved hydrocarbon plumes in Texas as defined by the 10-ppb contour of benzene is 180 ft, 75 percent of plumes having lengths of less than 250 ft and 90 percent of plumes having lengths less than 380 ft. The current median area of LPST plumes is 26,000 ft^2, 75 percent of plumes having areas less than 49,000 ft^2 and 90 percent of plumes having areas less than 120,000 ft^2. Median depth of the plumes beneath land surface (median depth to water) is 9.4 ft, 75 percent having depths less than 16.6 ft.

Do Plume Dimensions Vary Either Statewide or Regionally?

LPST sites in Texas occur under a variety of soil and aquifer conditions. However, plume size does not appear to be predicted by hydrogeologic properties, aquifer system, or rock type. The greatest plume length (7,600 ft), however, is in the Edwards aquifer, known for its high transmissivity and abundant subsurface conduits. The nine sites we reviewed in the Edwards aquifer, three of which had enough data to estimate plume lengths, do not allow us to conclude that median plume lengths in the Edwards aquifer are larger than in other aquifers. However, it suggests that plumes may be much larger in fractured limestone and karst rocks such as the Edwards than in sands, clays, sandstones, and shales.

The fact that plume length cannot be statistically differentiated on the basis of aquifer or rock type suggests that some other variable, such as the timing, duration, and magnitude of the leak, might be important factors for predicting plume length. The variability in source from site to site might overwhelm the influence of other hydrogeologic factors that are expected to control individual plume movement and dimensions. Another possible contributing factor is the variability in biodegradation and other natural attenuation rates between different aquifers and lithology types. Information on the timing, duration, and magnitude of the hydrocarbon leak and biodegradation rate is sketchy at best and usually nonexistent for most LPST sites.

The use of active ground-water remediation has not yet resulted in a lower median plume length at LPST sites throughout the state where corrective action is under way. This does not mean that remediation does not improve ground-water conditions at individual sites, but that when all LPST sites are reviewed, plume lengths at sites with remediation do not appear different from plume lengths at sites without remediation. This probably means that significant spills occur before being detected and that most plumes are in place and in equilibrium before active remediation takes effect. Theoretically, remediation should decrease the time required to reduce the size of dissolved hydrocarbon plumes. We were unable to discern this effect, however, owing to the lack of information on the size and timing of the fuel leak.

Do Plume Concentrations and Lengths Change Predictably over Time?

Plume mass and size appear to follow a path of predictable stages, although the exact timing of these stages is difficult to predict. Plume lengths generally increase, stabilize, slowly decline, and then quickly decline at LPST sites. Currently, 3 percent are increasing, 61 percent are stabilized, 26 percent are slowly declining, and 9 percent are quickly declining. The status of 1 percent of the sites was undetermined owing to erratic fluctuations. Most plumes in the last phase do not decrease to a value of zero but instead stabilize at a mean value that ranges from 60 to 300 ft and is a function of maximum plume concentration, the larger maximum concentrations resulting in larger last-phase stabilization levels. This behavior may be due to a tailing off of the source because of either solution, volatilization, biodegradation, or sorption.

Mean plume concentrations, and analogously plume mass, similarly increase, stabilize, rapidly decrease, and become exhausted. For well-sampled LPST sites in Texas, 14 percent are increasing, 27 percent have stabilized, 47 percent are rapidly decreasing, and 11 percent are exhausted, and 1 percent have an undetermined status owing to erratic fluctuations.

Can the Duration and Status of Plumes be Predicted?

Duration of benzene plumes is difficult to predict when there is little knowledge of how much liquid-phase hydrocarbon there is at the site and how much hydrocarbon is sorbed onto soil and aquifer surfaces. If this information is known, it may be possible to use analytical models (for example, Domenico, 1987) to predict plume length and duration. If liquid hydrocarbon is removed from the unsaturated zone by soil vapor extraction and from the water table with skimmer pumps, it may be possible to predict how long before the plume enters phases III and IV (figs. 2 and 22). However, although remediation techniques might be effective at individual sites, the persistence of plumes in phases II and III does not appear predictable solely on the basis of remediation.

How Rapidly Do Plumes Self-Remediate after the Source Is Removed?

The rate at which concentrations in plumes decrease once the plume is in phase III has a median value of 0.002 day^{-1} with an interquartile range of 0.0015 to 0.003 day^{-1}. The corresponding time to lower average site concentrations by a factor of 10 has a median of 500 days with an interquartile range of about 350 to 700 days.

Can the Behavior and Characteristics of Plumes Be Classified in a Way That Will Assist Exposure Assessment?

Results of this study show that characteristics of most dissolved hydrocarbon plumes are well constrained in Texas. For example, once monitoring shows that concentrations in the plume have stabilized, the exposure assessment can assume that the plume will not get larger and, at some point in the future after the primary source is removed and the secondary source is exhausted, the plume will rapidly decrease in size. If the plume is in the later phases of plume behavior where concentrations or plume lengths are decreasing rapidly, exposure assessments could consider the lessening impact of the plume on public health. Because plumes appear to attenuate naturally, active remediation such as pump and treat may be required only as a hydraulic barrier to prevent a plume from impacting nearby receptors.

Conclusions

Most benzene plumes sourced at LPST sites are less than 250 ft in lateral extent, appear to be stabilized, and can be expected to attenuate naturally with time. However, many sites have benzene plumes that extend offsite and impact either high-quality ground water or water that has a demonstrated beneficial use. Furthermore, most sites have at least one public or domestic well within half a mile of the LPST site and threaten public health and safety. Because of this exposure risk, the characterization of LPST sites is required to determine the lateral extent and stage of the plume and to identify potential nearby receptors such as water wells and subsurface municipal utilities such as sewers. Because plumes appear to attenuate naturally, active remediation such as pump and treat may be required only in special cases as a hydraulic barrier to prevent a plume from impacting nearby receptors or to help reduce a plume that has already affected a receptor. Our results hold for clayey and sandy formations: limited results from our study indicate that benzene plumes in karst aquifers such as the Edwards aquifer may be much larger.

Our four main conclusions are (1) benzene plumes are limited in lateral extent, yet many extend beyond property boundaries, (2) LPST sites are a potential threat to public health, (3) benzene plumes behave in a predictable manner, and (4) benzene plume length cannot be predicted on the basis of either hydrogeology or previous remediation activities, most likely because other factors exert greater influence.

- *Benzene plumes are limited in lateral extent*

Seventy-five percent of the plumes have lengths of less than 250 ft (defined by the 10-ppb contour) and areas of less than 49,000 ft^2. Though plume lengths are limited, almost 40 percent reportedly extend beyond the property boundary. Limited data suggest that plumes in karst

formations, such as the Edwards aquifer, may be as long as 7,600 ft. Plumes can also be long where they intersect and travel along preferential pathways created by subsurface utilities.

- *LPST sites are a potential threat to public health*

Almost 60 percent of sites have at least one public or domestic well within half a mile of the site. About half of the sites have or have had free product floating on the water table, and about half of the sites have had some form of remediation implemented at the site. According to TNRCC rankings, about 25 percent of LPST sites impact or pose a potentially high risk to public health and safety. This high risk includes threats to water wells; direct human contact with hydrocarbon, hydrocarbon vapors, or impacted soils; and/or explosive risks of hydrocarbon vapors.

- *Plumes behave in a predictable manner*

Plume mass and size appear to follow a path of predictable stages. Plume lengths increase, stabilize, slowly decline, and then rapidly decline over time. Plume mass increases, stabilizes, and rapidly declines with time. Most plumes we analyzed have stabilized or decreasing lengths and concentrations. Only 14 percent of plumes are increasing in concentrations, and only 3 percent are increasing in length. However, because the timing, duration, and amount of the fuel leak are unknown, we cannot predict the timing of these different stages.

- *Benzene plume length cannot be predicted on the basis of either hydrogeology or previous remediation activities*

There is no statistical difference in plume length between benzene plumes in different hydrogeologic settings in clastic aquifers (sand, clay, sandstone, shale formations) throughout Texas. Karst aquifers such as the Edwards aquifer are probably an exception; limited data suggest that benzene plumes in the Edwards may be significantly longer than in other formations. Likewise, we found no statistical difference on the basis of pump-and-treat or other previous remediation activities. When all the sites are taken as a whole, therefore, hydrogeologic setting and remediation activities cannot be used to predict the size of the plumes. Although this finding seems counterintuitive, it probably indicates that some other factor or factors, such as the amount of spilled fuel and natural biodegradation rates, have greater influence on plume length than hydrogeology or previous remediation activities. Data on the timing, duration, and magnitude of the fuel leak and biodegradation rates, unfortunately, are generally unavailable for LPST sites in Texas. However, even without remediation, plume concentrations and lengths decrease naturally. Therefore, consideration should be given to using natural attenuation in corrective action plans after site-specific studies show that natural attenuation is feasible given the site risks.

Acknowledgments

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List of Variables

b	aquifer thickness
$C(x,y)$	concentration in the plume as a function of x and y coordinates
C_o	maximum concentration in the plume
C^*	specified concentration for defining plume dimensions
D_x	dispersion in the x-direction
D_{xy}	dispersion in the xy-direction
D_y	dispersion in the y-direction
l	plume length
w	plume width
x	Cartesian coordinate measured relative to the center of mass of the plume
y	Cartesian coordinate measured relative to the center of mass of the plume

List of Acronyms

BTEX	Benzene, toluene, ethyl-benzene, and total xylenes
FHC	Fuel hydrocarbon
ID	Identification
IQD	Interquartile distance
LPST	Leaking petroleum storage tank
LQ	Lower quartile
MTBE	Methyl tertiary butyl ether
ppb	Parts per billion (equivalent to micrograms per liter)
ppm	Parts per million (equivalent to milligrams per liter)
PSH	Phase-separated hydrocarbon
PST	Petroleum storage tank
RBCA	Risk-based corrective action
TDS	Total dissolved solids
TNRCC	Texas Natural Resources Conservation Commission
TNRIS	Texas Natural Resources Information System
TWC	Texas Water Commission*
TWDB	Texas Water Development Board
UQ	Upper quartile

*Became the TNRCC in 1993.

Appendix A

County distribution of LPST sites

A Total number of sites in the TNRCC data base having affected ground water as of August 1996.
B Number of sites we reviewed in the county.
C Percentage of the sites we reviewed in the county.

County	A	B	C
Anderson	8	0	0.0
Andrews	9	0	0.0
Angelina	15	1	6.7
Aransas	17	0	0.0
Atascosa	6	1	16.7
Austin	4	0	0.0
Bailey	4	0	0.0
Bandera	2	0	0.0
Bastrop	7	1	14.3
Baylor	8	1	12.5
Bee	6	1	16.7
Bell	37	2	5.4
Bexar	413	38	9.2
Blanco	1	0	0.0
Borden	1	0	0.0
Bowie	64	5	7.8
Brazoria	61	8	13.1
Brazos	18	4	22.2
Briscoe	2	0	0.0
Brooks	7	0	0.0
Brown	33	2	6.1
Burnet	7	1	14.3
Caldwell	12	3	25.0
Calhoun	12	0	0.0
Callahan	10	0	0.0
Cameron	158	5	3.2
Camp	9	0	0.0
Carson	1	0	0.0
Cass	14	1	7.1
Chambers	9	0	0.0
Cherokee	17	1	5.9
Childress	3	0	0.0
Clay	4	0	0.0
Cochran	3	0	0.0
Coke	2	0	0.0
Coleman	7	0	0.0
Collin	57	5	8.8
Collingsworth	1	0	0.0
Colorado	6	0	0.0
Comal	24	2	8.3
Comanche	2	0	0.0
Concho	2	0	0.0
Cooke	11	1	9.1
Coryell	7	0	0.0
Crane	1	0	0.0
Crosby	8	0	0.0
Culberson	1	0	0.0
Dallam	1	0	0.0
Dallas	727	88	12.1
Dawson	22	0	0.0
Deaf Smith	4	0	0.0
Denton	83	8	9.6
De Witt	5	0	0.0
Dickens	4	0	0.0
Dimmit	2	1	50.0
Donley	2	0	0.0
Duval	5	0	0.0
Eastland	4	0	0.0

County	A	B	C
Ector	58	15	25.9
Ellis	26	4	15.4
El Paso	134	30	22.4
Erath	3	0	0.0
Fannin	5	0	0.0
Fayette	12	1	8.3
Fisher	1	0	0.0
Floyd	5	0	0.0
Foard	3	0	0.0
Fort Bend	28	3	10.7
Franklin	5	0	0.0
Freestone	2	1	50.0
Frio	1	0	0.0
Gaines	14	2	14.3
Galveston	66	5	7.6
Garza	6	1	16.7
Gillespie	15	0	0.0
Glasscock	1	0	0.0
Goliad	4	0	0.0
Gonzales	3	0	0.0
Gray	2	0	0.0
Grayson	28	4	14.3
Gregg	121	8	6.6
Grimes	4	0	0.0
Guadalupe	8	0	0.0
Hale	25	0	0.0
Hall	1	1	100.0
Hamilton	1	0	0.0
Hardeman	23	0	0.0
Hardin	7	0	0.0
Harris	906	107	11.8
Harrison	29	1	3.4
Haskell	9	1	11.1
Hays	27	2	7.4
Hemphill	7	0	0.0
Henderson	22	0	0.0
Hidalgo	155	4	2.6
Hill	4	0	0.0
Hockley	30	2	6.7
Hood	8	0	0.0
Hopkins	17	3	17.6
Houston	13	0	0.0
Howard	20	2	10.0
Hunt	13	0	0.0
Hutchinson	8	1	12.5
Jack	1	0	0.0
Jackson	4	0	0.0
Jasper	7	0	0.0
Jeff Davis	3	0	0.0
Jefferson	106	10	9.4
Jim Hogg	2	0	0.0
Jim Wells	19	2	10.5
Johnson	21	0	0.0
Jones	18	0	0.0
Karnes	4	0	0.0
Kaufman	11	0	0.0
Kendall	3	1	33.3
Kerr	7	0	0.0

Appendix A (cont.)

County distribution of LPST sites

A Total number of sites in the TNRCC data base having affected ground water as of August 1996.
B Number of sites we reviewed in the county.
C Percentage of the sites we reviewed in the county.

County	A	B	C
King	1	0	0.0
Kinney	1	0	0.0
Kleberg	25	1	4.0
Knox	9	0	0.0
Lamar	16	1	6.3
Lamb	3	0	0.0
Lampasas	4	0	0.0
Lavaca	6	0	0.0
Lee	3	1	33.3
Leon	4	0	0.0
Liberty	12	0	0.0
Limestone	2	0	0.0
Lipscomb	2	0	0.0
Live Oak	4	0	0.0
Llano	8	0	0.0
Lubbock	230	50	21.7
Lynn	8	0	0.0
Madison	1	0	0.0
Marion	1	0	0.0
Martin	3	0	0.0
Mason	2	0	0.0
Matagorda	15	1	6.7
Maverick	7	0	0.0
McCulloch	8	0	0.0
McLennan	47	3	6.4
Medina	4	0	0.0
Menard	1	0	0.0
Midland	34	11	32.4
Milam	3	1	33.3
Mitchell	12	1	8.3
Montague	6	0	0.0
Montgomery	31	3	9.7
Moore	3	0	0.0
Morris	4	0	0.0
Motley	2	0	0.0
Nacogdoches	30	6	20.0
Navarro	25	1	4.0
Newton	2	0	0.0
Nolan	5	1	20.0
Nueces	196	5	2.6
Orange	28	3	10.7
Palo Pinto	10	0	0.0
Panola	11	1	9.1
Parker	12	0	0.0
Parmer	1	0	0.0
Pecos	6	0	0.0
Polk	1	0	0.0
Potter	22	3	13.6
Presidio	2	0	0.0
Rains	1	0	0.0
Randall	6	0	0.0
Reagan	3	0	0.0
Real	1	1	100.0
Red River	8	0	0.0
Reeves	30	1	3.3
Refugio	9	0	0.0
Roberts	2	0	0.0
Robertson	3	2	66.7
Rockwall	4	0	0.0
Runnels	10	0	0.0
Rusk	14	0	0.0
Sabine	1	0	0.0
San Augustine	3	0	0.0
San Jacinto	2	0	0.0
San Patricio	36	0	0.0
San Saba	2	0	0.0
Schleicher	1	0	0.0
Scurry	10	0	0.0
Shackelford	6	0	0.0
Shelby	13	0	0.0
Sherman	1	0	0.0
Smith	90	13	14.4
Somervell	1	0	0.0
Starr	4	1	25.0
Stephens	4	1	25.0
Sterling	1	0	0.0
Stonewall	3	0	0.0
Sutton	1	0	0.0
Swisher	1	0	0.0
Tarrant	426	42	9.9
Taylor	105	4	3.8
Terrell	1	0	0.0
Terry	24	1	4.2
Throckmorton	2	0	0.0
Titus	8	1	12.5
Tom Green	43	2	4.7
Travis	204	15	7.4
Trinity	2	1	50.0
Tyler	2	0	0.0
Upshur	14	1	7.1
Upton	4	0	0.0
Uvalde	3	0	0.0
Val Verde	8	1	12.5
Van Zandt	9	1	11.1
Victoria	14	3	21.4
Walker	10	0	0.0
Waller	4	0	0.0
Ward	11	2	18.2
Washington	4	0	0.0
Webb	51	5	9.8
Wharton	4	0	0.0
Wheeler	3	0	0.0
Wichita	58	5	8.6
Wilbarger	12	0	0.0
Willacy	8	0	0.0
Williamson	34	6	17.6
Wilson	1	0	0.0
Winkler	1	0	0.0
Wise	7	1	14.3
Wood	21	0	0.0
Yoakum	4	1	25.0
Young	7	0	0.0
Zavala	2	0	0.0

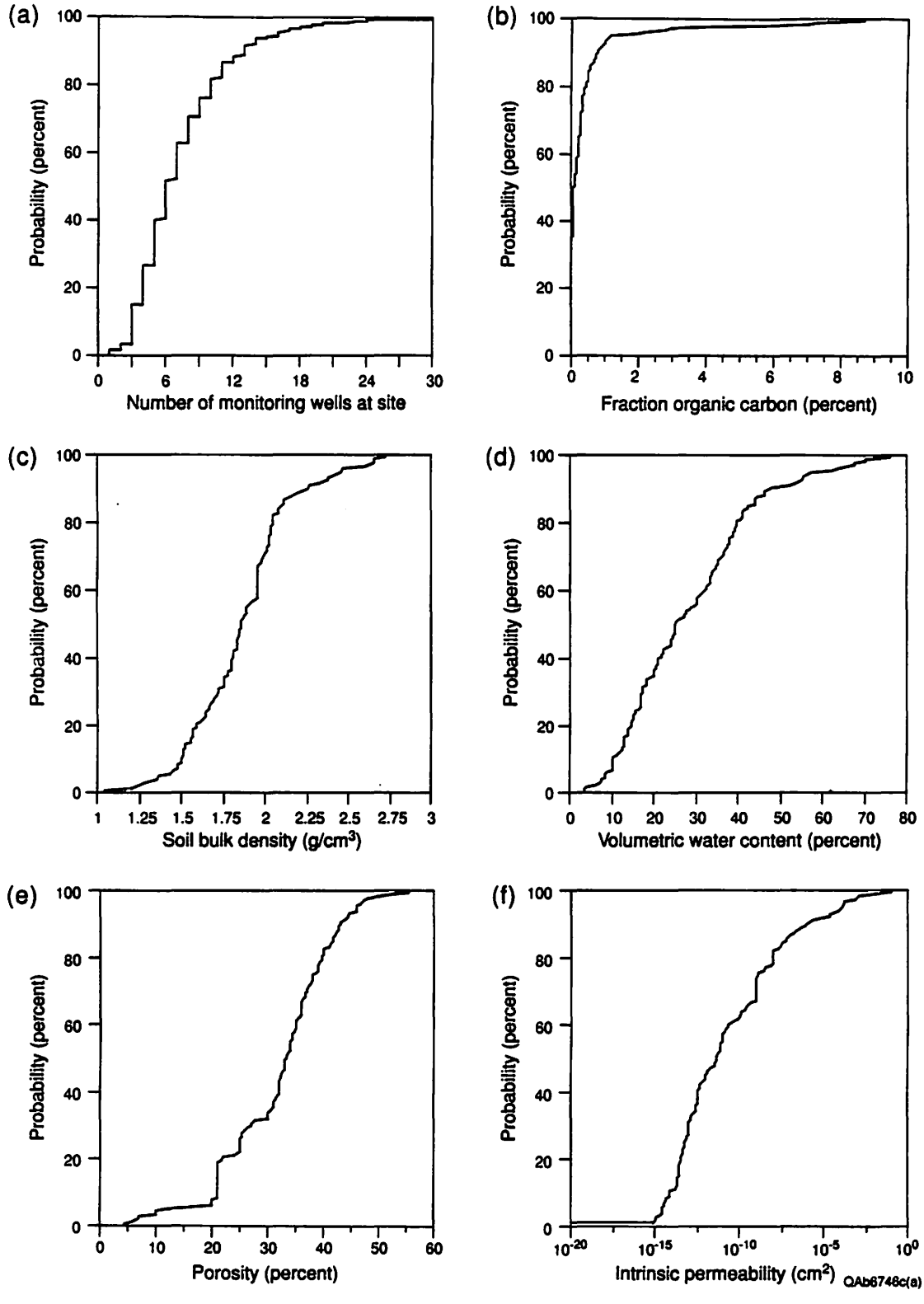
Appendix B

Cumulative distribution functions

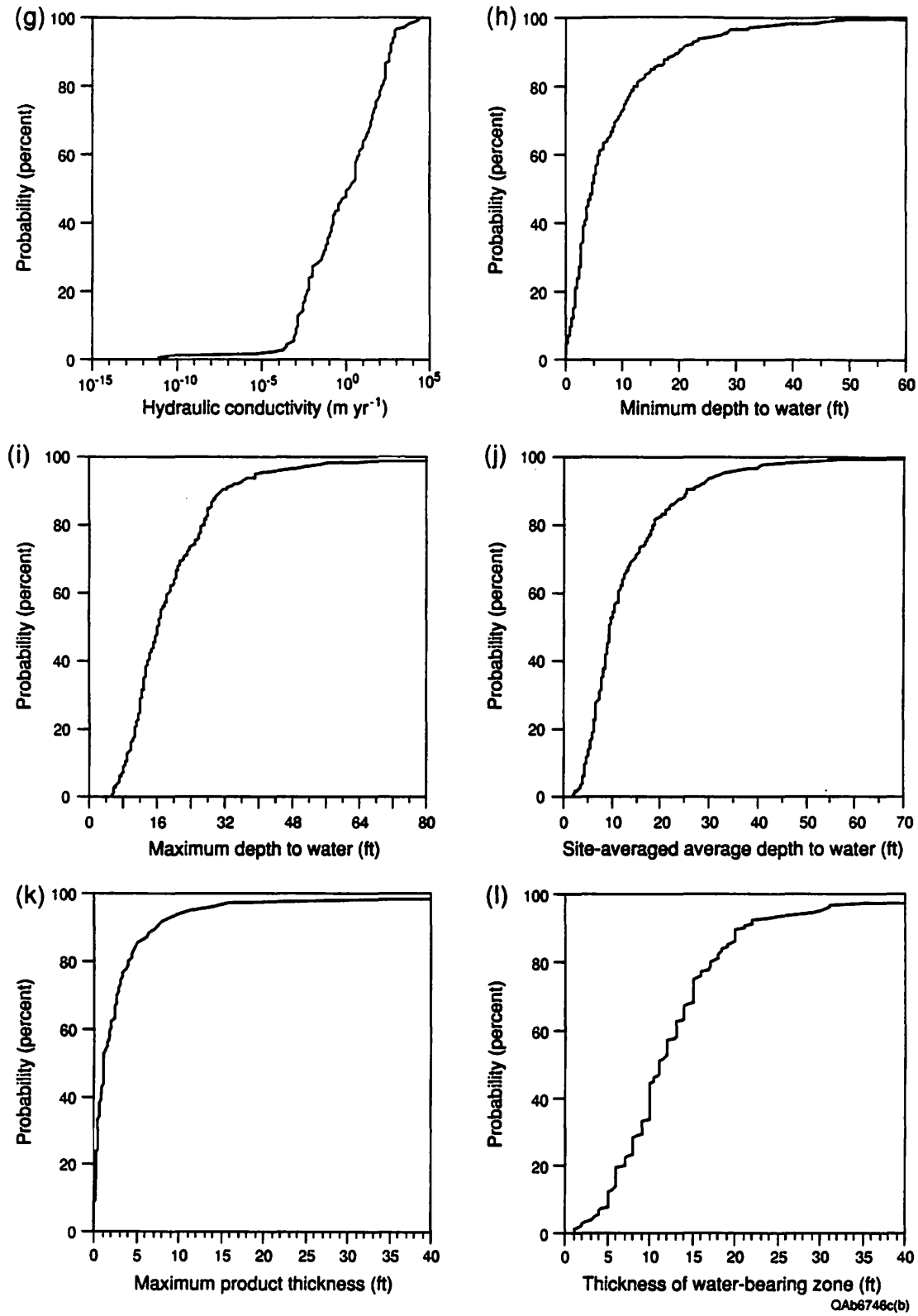
We present cumulative distribution functions for selected histograms so that specific percentiles can be determined. Cumulative distribution functions are presented for

Figure	Title	Corresponding figure in text
(a)	Number of monitoring wells at site	4d
(b)	Fraction organic carbon	5a
(c)	Soil bulk density	5b
(d)	Volumetric water content	5c
(e)	Porosity	5d
(f)	Intrinsic permeability	6b
(g)	Hydraulic conductivity	7b
(h)	Minimum depth to water	9a
(i)	Maximum depth to water	9b
(j)	Site-averaged depth to water	9c
(k)	Maximum product thickness	9d
(l)	Thickness of water-bearing zone	10a
(m)	Maximum thickness of the sweep zone	12a
(n)	Site-averaged standard deviation of depth to water	12b
(o)	Hydraulic gradient	13a
(p)	Gradient variation	13b
(q)	Standard deviation of the direction of the hydraulic gradient	14
(r)	Depth to top of contaminated soil	16a
(s)	Depth to bottom of contaminated soil	16b
(t)	Thickness of contaminated soil	16c
(u)	Distance of contaminated soil from property boundary	16d
(v)	Plume length	19a
(w)	Plume area	19b
(x)	Magnitude of negative concentration trends	21

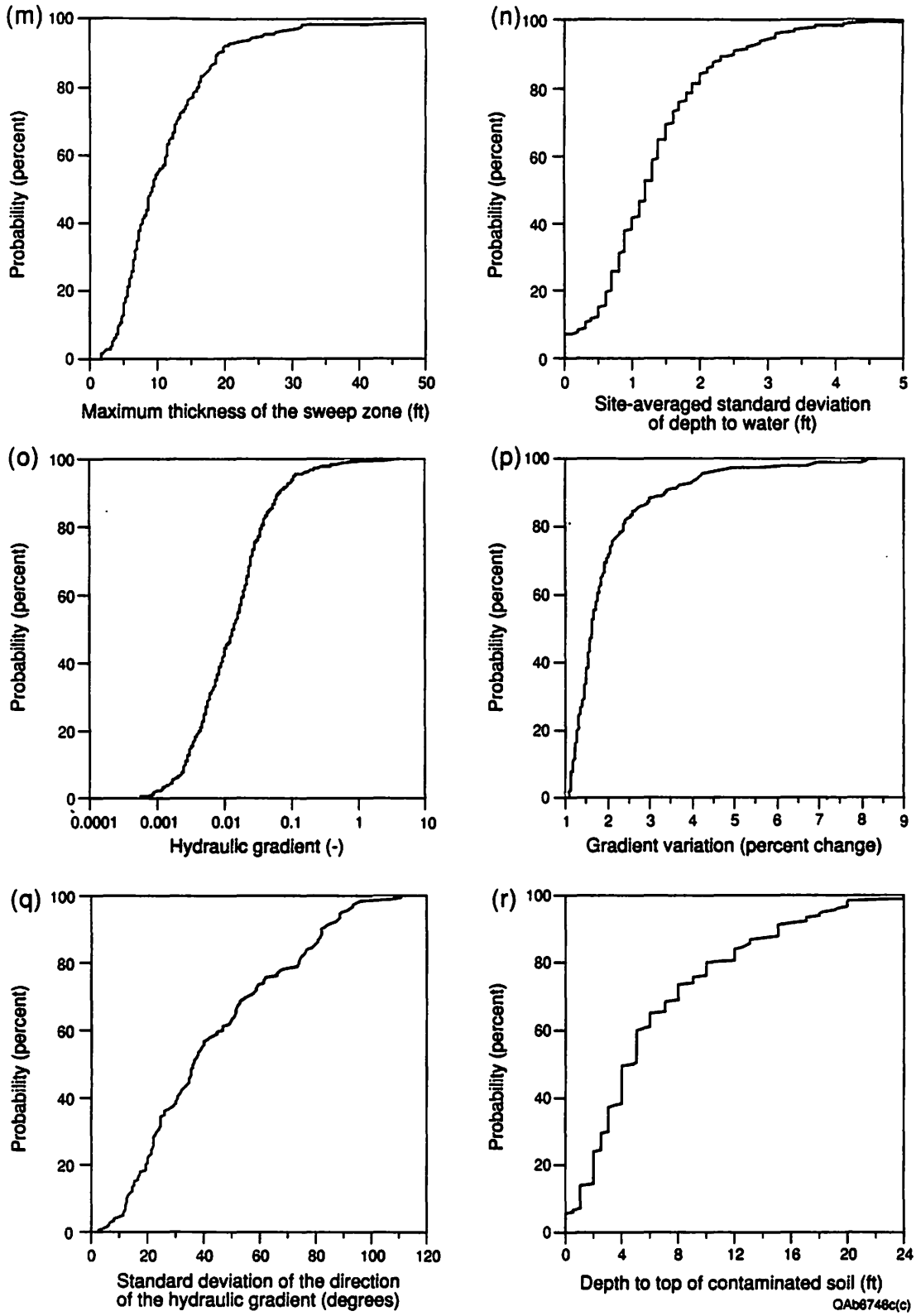
Appendix B (cont.)



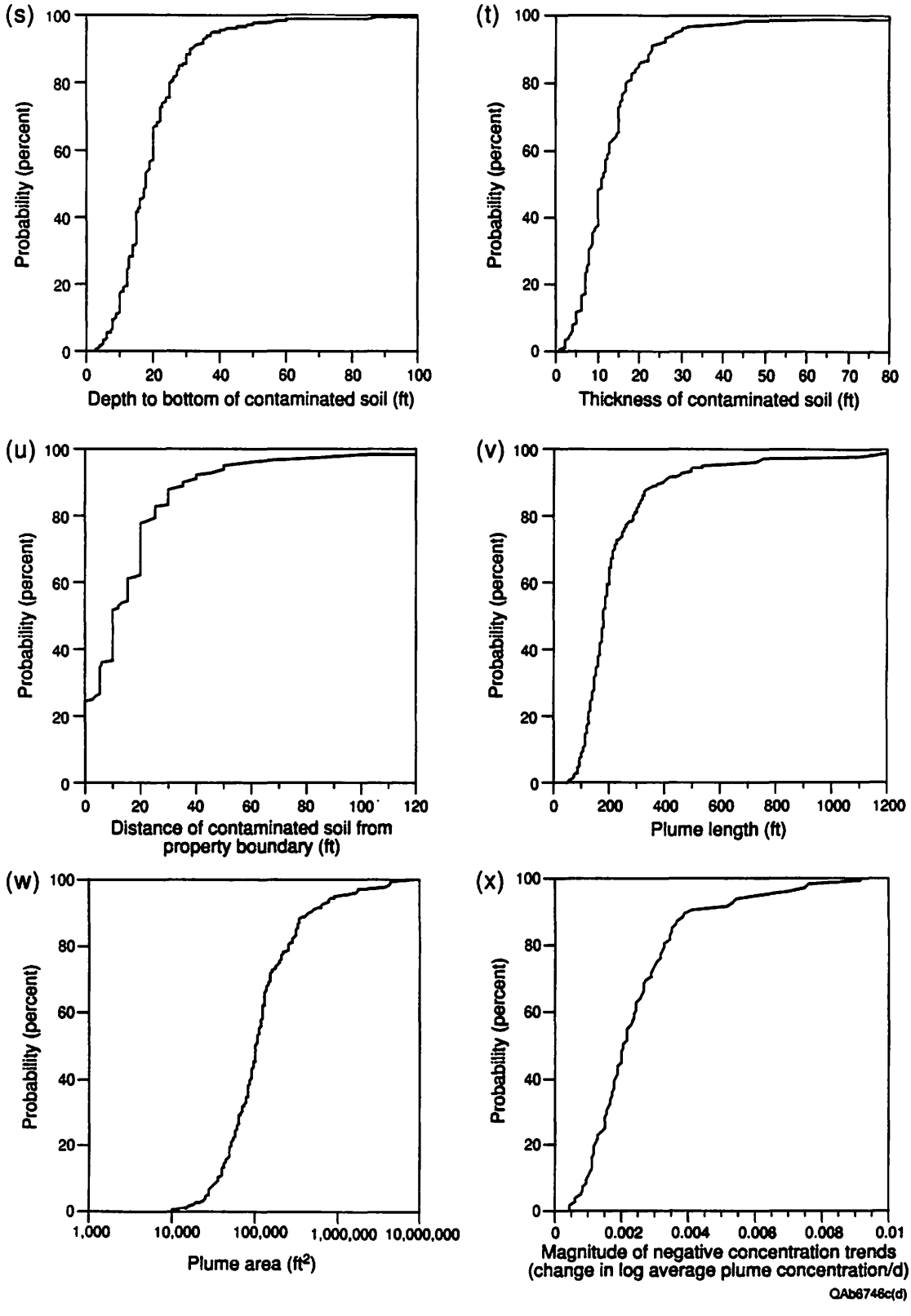
Appendix B (cont.)



Appendix B (cont.)



Appendix B (cont.)



Appendix C

Distribution of data for different aquifers, aquifer textures, and counties

This appendix shows how the compiled and analyzed data are divided between different aquifers, aquifer textures, and counties. Only those counties having at least five reviewed sites (as shown in fig. 3) are included in this table.

Appendix C (cont.)

Appendix C (cont.)

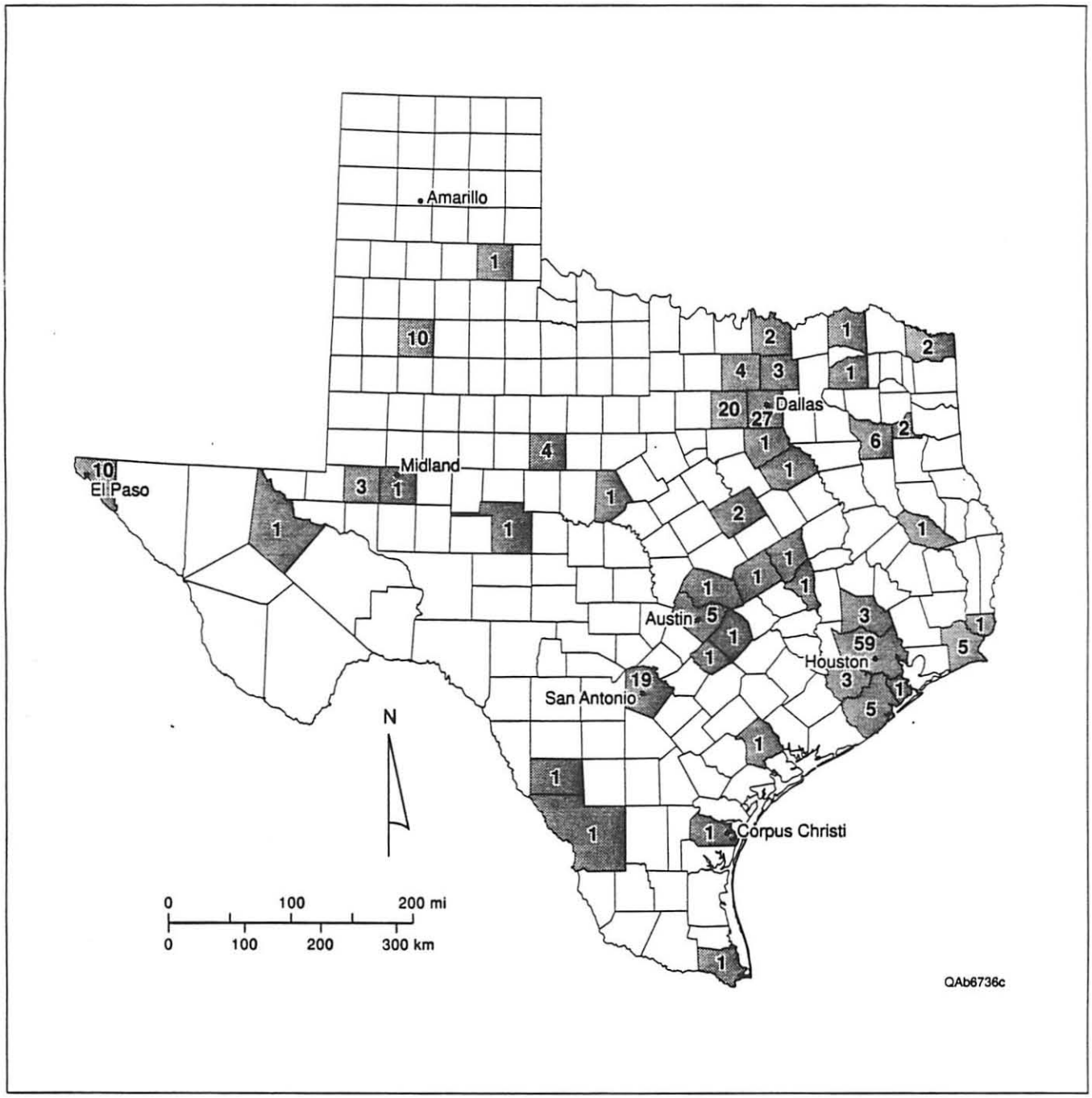
Appendix C (cont.)

PARAMETER	AQUIFER																AQUIFER TEXTURE									
	Alluvium	Blossom Sand	Carrizo-Wilcox	Edwards	Edwards-Trinity	Gulf Coast	Hueco-Mesilla Bolson	Nacatoch Sand	None	Ogallala	Queen City	Seymour	Sparta	Trinity Group	Woodbine	Unknown	Clay	Clay and limestone	Limestone	Sand	Sand and clay	Sand and limestone	Only clay	Only limestone	Only sand	Unknown
Fraction organic carbon	26	0	8	4	0	46	8	0	45	20	2	3	0	4	9	4	81	14	23	73	28	2	39	7	43	46
Soil bulk density	15	0	8	4	0	14	9	0	28	20	3	1	0	3	6	4	58	10	16	56	19	0	29	6	37	14
Volumetric water content	25	0	7	4	0	40	7	0	46	14	3	4	0	3	9	4	78	14	23	64	25	2	39	7	37	42
Porosity	16	0	9	4	0	17	10	0	26	21	3	5	0	3	7	4	61	9	15	65	22	0	30	6	43	15
Depth to top of contaminated soil	17	1	10	0	1	60	4	1	35	13	5	2	1	5	2	10	72	16	20	59	25	0	31	4	34	57
Depth to bottom of contaminated soil	62	1	15	1	3	131	14	1	109	45	5	6	2	9	18	7	185	35	54	151	66	2	84	17	83	142
Thickness of contaminated soil	18	1	11	0	1	60	5	1	36	14	4	2	1	4	2	1	74	18	21	57	22	0	34	3	35	49
Distance of contaminated soil from property boundary	14	1	12	0	1	48	2	1	31	9	4	1	1	3	2	7	65	16	18	42	19	0	30	2	23	47
Hydraulic conductivity of impacted ground-water zone	60	1	15	2	1	122	11	1	108	41	8	5	2	10	18	8	186	32	53	160	70	2	84	19	88	118
Measured values of hydraulic conductivity	23	0	6	0	0	38	2	0	34	17	2	1	0	3	8	3	63	10	16	58	24	2	29	4	32	36
Nonmeasured values of hydraulic conductivity	37	1	9	2	1	84	9	1	74	24	6	4	2	7	10	5	123	22	37	102	46	0	55	15	56	82
Minimum depth to water	30	1	10	5	0	69	5	1	59	16	3	3	0	3	9	32	107	24	32	70	34	0	49	8	36	95
Maximum depth to water	30	1	10	5	0	69	5	1	59	16	3	3	0	3	9	32	107	24	32	70	34	0	49	8	36	95
Average depth to water	30	1	10	5	0	69	5	1	59	16	3	3	0	3	9	32	107	24	32	70	34	0	49	8	36	95
Maximum product thickness	8	1	4	2	0	35	2	0	15	8	1	1	0	1	3	21	31	2	4	28	14	0	15	2	14	55
Thickness of affected water-bearing zone	16	1	11	0	1	56	3	1	37	14	4	1	1	4	2	5	75	20	22	51	22	0	33	2	29	51
Potential beneficial use category	18	1	13	2	1	55	3	1	36	20	4	1	1	4	4	9	83	16	22	61	26	0	41	6	35	49
Maximum thickness of sweep zone	30	1	10	5	0	69	5	1	59	16	3	3	0	3	9	32	107	24	32	70	34	0	49	8	36	95
Site-averaged standard deviation of depth to water	30	1	10	5	0	69	5	1	59	16	3	3	0	3	9	32	107	24	32	70	34	0	49	8	36	95
Average hydraulic gradient	62	1	18	6	1	133	19	1	103	43	7	5	5	9	14	40	187	33	54	143	58	1	96	20	84	175
Gradient variation	14	1	4	1	0	49	2	1	38	4	3	3	0	2	1	9	56	16	21	35	17	0	23	5	18	53

PARAMETER	AQUIFER																AQUIFER TEXTURE									
	Alluvium	Blossom Sand	Carrizo-Wilcox	Edwards	Edwards-Trinity	Gulf Coast	Hueco-Mesilla Bolson	Nacatoch Sand	None	Ogallala	Queen City	Seymour	Sparta	Trinity Group	Woodbine	Unknown	Clay	Clay and limestone	Limestone	Sand	Sand and clay	Sand and limestone	Only clay	Only limestone	Only sand	Unknown
Standard deviation of the direction of hydraulic gradient	14	1	4	1	0	49	2	1	38	4	3	3	0	2	1	9	56	16	21	35	17	0	23	5	18	53
TDS in ground water (reported and estimated), LPST files	62	1	18	4	2	131	15	1	103	47	8	5	4	13	15	18	192	34	53	166	70	1	88	18	95	141
Reported values of TDS, LPST files	47	1	9	2	2	96	9	1	67	35	5	5	3	6	7	15	140	26	36	121	53	1	61	9	67	93
Nonreported values of TDS, LPST files	15	0	9	2	0	35	6	0	36	12	3	0	1	7	8	3	52	8	17	45	17	0	27	9	28	48
Plume length	29	0	12	3	2	62	9	0	45	21	2	1	3	2	8	18	89	15	27	67	27	0	47	12	40	76
Plume area	29	0	12	3	2	62	9	0	45	21	2	1	3	2	8	18	89	15	27	67	27	0	47	12	40	76
Magnitude of negative concentration trends	18	1	3	1	1	24	3	0	23	4	0	0	2	1	1	8	46	9	13	33	19	0	18	4	14	26
Free product on the water table?	65	1	21	8	3	141	23	1	111	44	9	5	3	12	16	30	201	33	62	165	74	2	94	27	89	174
Has the source been abated?	63	1	21	7	3	123	20	1	99	63	9	4	4	12	17	31	199	31	58	173	74	2	94	25	97	155
Case priority	70	1	24	9	4	150	30	1	125	75	11	7	8	13	19	58	235	38	70	193	82	2	115	30	109	229
Amount of impervious cover	63	1	19	9	3	123	23	1	99	58	7	6	6	12	13	30	180	29	54	160	64	2	87	23	94	174
Intrinsic permeability of the soil (measured and estimated)	42	0	13	7	2	88	10	0	72	44	4	3	3	8	6	17	122	17	35	109	41	1	64	17	67	112
Measured values of intrinsic permeability	16	0	8	1	0	26	3	0	39	24	0	2	1	7	2	8	59	6	13	51	19	0	34	7	32	39
Nonmeasured values of intrinsic permeability	26	0	5	6	2	62	7	0	33	20	4	1	2	1	4	9	63	11	22	58	22	1	30	10	35	73
Number of monitoring wells at site	70	1	24	9	2	147	25	1	120	65	10	5	8	11	19	48	228	36	65	191	80	2	112	27	109	199
Public or domestic wells within 0.5 mi	31	0	15	6	2	71	18	0	58	38	5	4	3	9	9	336	116	12	28	112	45	2	59	14	65	408
Plume extends offsite (y)	10	0	8	1	1	42	2	0	17	15	5	1	0	4	4	9	44	9	9	45	17	0	18	0	28	47
Plume does not extend offsite (n)	27	1	5	2	0	62	9	1	40	15	2	5	1	3	6	2	78	10	16	62	24	1	44	5	37	60

PARAMETER	COUNTY																							
	Bexar	Bowie	Brazoria	Cameron	Collin	Dallas	Denton	Ector	El Paso	Galveston	Gregg	Harris	Jefferson	Lubbock	Midland	Nacogdoches	Nueces	Smith	Tarrant	Travis	Webb	Wichita	Williamson	Unknown or other
Fraction organic carbon	10	0	3	3	1	31	3	9	8	2	2	32	1	6	4	1	2	1	14	6	2	3	1	34
Soil bulk density	11	0	2	3	0	4	1	8	9	2	2	?	1	6	5	1	2	1	11	6	2	1	1	36
Volumetric water content	10	0	3	3	0	31	2	5	7	2	2	26	1	5	3	0	2	1	15	6	1	4	1	36
Porosity	11	1	2	3	0	4	2	9	10	2	2	2	1	6	5	1	2	1	11	6	2	4	1	37
Depth to top of contaminated soil	11	4	2	1	2	25	2	6	3	2	5	46	5	3	5	0	1	1	8	4	0	1	0	30
Depth to bottom of contaminated soil	29	4	7	4	3	72	8	12	12	5	7	99	9	17	10	0	3	3	34	10	5	5	0	71
Thickness of contaminated soil	9	3	2	1	3	26	2	5	5	2	5	45	5	4	4	0	1	1	7	4	0	1	0	26
Distance of contaminated soil from property boundary	7	4	2	0	1	25	2	5	2		5	36	5	2	4	0	1	1	6	2	0	1	0	26
Hydraulic conductivity of impacted ground-water zone	30	4	7	3	3	64	7	11	11	4	7	90	10	14	11	0	3	4	33	11	4	5	0	77
Measured values of hydraulic conductivity	6	2	2	1	0	29	4	7	2	1	1	28	1	2	3	0	1	1	10	3	0	1	0	32
Nonmeasured values of hydraulic conductivity	24	2	5	2	3	35	3	4	9	3	6	62	9	12	8	0	2	3	23	8	4	4	0	45
Minimum depth to water	16	4	3	0	2	47	1	5	6	1	3	59	4	6	5	0	1	3	22	7	1	3	2	45
Maximum depth to water	16	4	3	0	2	47	1	5	6	1	3	59	4	6	5	0	1	3	22	7	1	3	2	45
Average depth to water	16	4	3	0	2	47	1	5	6	1	3	59	4	6	5	0	1	3	22	7	1	3	2	45
Maximum product thickness	4	1	1	0	0	9	0	3	3	0	1	29	2	2	2	0	1	2	5	4	1	1	2	29
Thickness of affected water-bearing zone	10	4	2	0	2	30	2	7	3	2	4	43	5	5	4	0	1	3	7	3	0	1	0	19
Potential beneficial use category	12	4	2	1	3	14	2	7	3	2	4	35	5	7	7	0	2	2	11	6	1	1	2	40
Maximum thickness of sweep zone	16	4	3	0	2	47	1	5	6	1	3	59	4	6	5	0	1	3	22	7	1	3	2	45
Site-averaged standard deviation of depth to water	16	4	3	0	2	47	1	5	6	1	3	59	4	6	5	0	1	3	22	7	1	3	2	45
Average hydraulic gradient	27	3	6	5	4	77	7	12	18	4	6	106	9	23	8	1	4	9	35	11	3	4	3	82
Gradient variation	10	1	1	0	0	29	0	1	3	2	3	41	2	1	3	0	0	2	7	6	0	3	1	16

PARAMETER	COUNTY																							
	Bexar	Bowie	Brazoria	Cameron	Collin	Dallas	Denton	Ector	El Paso	Galveston	Gregg	Harris	Jefferson	Lubbock	Midland	Nacogdoches	Nueces	Smith	Tarrant	Travis	Webb	Wichita	Williamson	Unknown or other
Standard deviation of the direction of hydraulic gradient	10	1	1	0	0	29	0	1	3	2	3	41	2	1	3	0	0	2	7	6	0	3	1	16
TDS in ground water (reported and estimated), LPST files	28	5	6	4	5	73	6	14	14	4	7	100	9	19	10	1	4	6	30	10	4	4	1	83
Reported values of TDS, LPST files	20	2	3	4	5	48	3	14	9	3	4	72	7	11	9	0	4	4	16	6	2	4	1	59
Nonreported values of TDS, LPST files	8	3	3	0	0	25	3	0	5	1	3	28	2	8	1	1	0	2	14	4	2	0	0	24
Plume length	18	3	7	2	2	26	2	6	11	2	4	47	2	15	3	2	1	4	14	3	3	0	2	38
Plume area	18	3	7	2	2	26	2	6	11	2	4	47	2	15	3	2	1	4	14	3	3	0	2	38
Magnitude of negative concentration trends	11	1	1	0	3	12	1	2	4	0	1	19	4	2	1	0	1	3	7	4	0	0	0	13
Free product on the water table?	34	5	5	5	3	75	7	14	22	5	8	111	8	16	11	3	4	7	36	14	5	4	3	88
Has the source been abated?	29	4	5	4	5	68	7	15	19	5	7	89	10	32	11	4	5	9	34	11	5	2	3	95
Case priority	38	5	8	5	5	88	8	15	30	5	8	117	10	50	11	6	5	13	42	15	5	5	6	105
Amount of impervious cover	30	4	6	3	4	68	7	9	24	3	7	97	10	40	11	3	4	8	29	13	4	4	5	80
Intrinsic permeability of the soil (measured and estimated)	23	4	5	3	3	47	3	12	10	5	4	65	5	26	4	3	1	4	21	8	3	2	3	55
Measured values of intrinsic permeability	11	3	1	1	2	26	2	5	3	3	2	17	2	14	1	2	0	2	8	4	0	2	0	26
Nonmeasured values of intrinsic permeability	12	1	4	2	1	21	1	7	7	2	2	48	3	12	3	1	1	2	13	4	3	0	3	29
Number of monitoring wells at site	37	5	8	5	4	86	8	15	24	5	8	116	9	36	11	5	5	13	39	14	5	4	6	97
Public or domestic wells within 0.5 mi	18	2	7	2	1	28	6	12	18	2	4	52	5	13	7	1	2	6	15	8	1	2	2	391
Plume extends offsite (y)	4	2	2	1	3	11	0	5	2	1	5	32	4	6	2	0	1	2	7	1	1	1	1	25
Plume does not extend offsite (n)	16	0	3	1	0	21	4	3	9	4	2	38	5	7	2	0	4	1	9	4	2	4	1	41

Appendix D

Distribution of the 217 sites at which plume length was estimated