WISCONSIN CLOSURE PROTOCOL STUDY

A Retrospective Study of LUST Site Closures between 1999 and 2000

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List of Abbreviations

BTEX – benzene, toluene, ethylbenzene, xylenes; BTEX usually refers to the sum of the results for the individual compounds
COMM – Wisconsin Department of Commerce
CV – coefficient of variation
DL – detection limit
DNR – Wisconsin Department of Natural Resources
EDB – ethylene dibromide, a.k.a. 1,2-dibromoethane
ES – Enforcement Standard, generally equivalent to federal MCLs
FP – free product or free- phase product, synonymous with LNAPL
GIS Registry – DNR's Geographic Information System Registry of Closed Remediation Sites
i – hydraulic gradient
K – hydraulic conductivity
K_{fw} – fuel:water partition coefficient
LNAPL – light non-aqueous phase liquid
LUST – leaking underground storage tank
MCL – Maximum Contaminant Level
M-K – Mann-Kendall nonparametric statistical test
MTBE – methyl-tert-butyl ether
MW – Monitoring Well
N - Naphthalene
PAH – polycyclic aromatic hydrocarbon
PDF – portable document format created by Adobe Systems
PECFA – Petroleum Environmental Cleanup Fund Award
P/T – pump and treat
PZ – Piezometer (a monitoring well with a short screen that is fully submerged below the water table)
R^2 – Square of the correlation coefficient, synonymous with r^2.
RR – DNR's Bureau for Remediation and Redevelopment
SI – site investigation
S_W – Solubility in Water
TMB – trimethylbenzene
U.S. EPA – United States Environmental Protection Agency
USCS – Unified Soil Classification System
VOC – volatile organic chemical

Wisconsin Closure Protocol Study
April 2009

1. EXECUTIVE SUMMARY

This is a retrospective study of the regulatory management of environmental contamination at leaking underground storage tank (LUST) sites in the State of Wisconsin between the years 1999 and 2000. The regulation and management of LUST sites has evolved, particularly as regulatory agencies have come to rely on natural attenuation processes to control and remove contaminant mass from the environment. This study evaluates the information used by Wisconsin regulatory agencies to make closure decisions at LUST cases where natural attenuation processes were relied upon to meet regulatory standards. The study is not an evaluation of the effectiveness of natural attenuation processes at LUST sites, but an evaluation of information gathered to assess natural attenuation processes and how the regulatory agencies used that information to make regulatory decisions.

Natural attenuation describes any or all natural processes – physical, chemical and biological – which contribute to the overall decay and slowed movement of contaminants in the environment. The state of Wisconsin, through rule revisions in 1996 and 2001 allows closure of properties with petroleum contaminants exceeding regulatory standards if natural attenuation processes will eventually result in contaminated groundwater achieving compliance with regulatory standards (also referred to as "natural attenuation closures"). Regulatory closure in Wisconsin requires no post-closure monitoring of soil or groundwater. Public access to information on sites that have not met either soil or groundwater standards at closure is available through a web-accessible GIS Registry of Closed Remediation Sites.

In 2004, the two state agencies charged with the cleanup of LUST sites in Wisconsin – the Departments of Natural Resources (DNR) and of Commerce (COMM) in partnership with the University of Wisconsin undertook a retrospective study of LUST closure decisions. This Wisconsin Closure Protocol Study is a follow up to the regulatory and administrative revisions allowing natural attenuation closures. We examined the State's LUST closure procedure through evaluation of a select number of sites that closed under the protocol early in the process. The intent was to review the site closures made by the two agencies and determine whether the closure decisions are protective of human health and the environment and meet the statutory and regulatory requirements of the State of Wisconsin.

During 1999 and 2000, 1,376 petroleum sites were closed with contamination remaining above regulatory standards in the groundwater. These sites represent one-third of all sites closed through December 2008 with groundwater contamination above standards. Using a stratified random sampling, 123 sites from this early set of closures were selected for detailed review. Ten sites where post closure monitoring wells were installed were added to this list. The information from these 133 sites formed the core of this study.

Database study. Information from the review of 133 case files was compiled in a database. The information (over 125 entries for each site) included items such as the number of borings and wells installed, soil type encountered at the water table, volume of soil excavation, hydraulic gradient, groundwater sampling dates and monitoring results. Queries of this database provided a general picture of site investigations (SI) and remedial actions at closed LUST sites in Wisconsin.

A few statistics from the database sites are included below.

- The median number of groundwater monitoring wells per site is seven and the median depth to groundwater is 6.5 feet.
- Thirty-four (34) sites (or just 26% of the 133 database sites) have one or more monitoring wells screened below the water table (termed piezometers) for determining vertical groundwater flow and contaminant concentrations at depth.
- Active remediation efforts (defined as any remedial action besides removal of underground storage tanks and appurtenances) occurred at 95 sites (71%). No active remediation occurred at a disproportionate number of the clay sites (22 out of 53 clay sites).
- Historical maximum benzene concentrations in groundwater ranged over 6 orders of magnitude (less than 0.5 μg/l to 210,000 μg/l); then at closure, the maximum benzene levels in groundwater still spanned more than 5 orders of magnitude (less than 0.5 μg/l to 20,000 μg/l).
- The median length of time from when the historical maximum benzene concentration in the groundwater was observed to the latest benzene data before site closure was less than 3 years. For sites where active remediation occurred, this median monitoring period is 3.5 years, but for sites not actively remediated, the median monitoring period is 1.1 years.
- Groundwater flow direction was determined more than once at 111 sites (83%) and at more than half of those, the direction was estimated to vary by 33º or more.
- Data regarding seasonal water table fluctuation was available for 104 sites, and for these sites, the median fluctuation is 2 ft.

The wide range in contaminant concentrations, the short monitoring time frame, fluctuation of the water table, and the relatively large variation in groundwater flow direction limit the usefulness of nonparametric statistical tests. Six (6) or more rounds of benzene monitoring were available at only 97 sites, with 79 of them having a benzene level greater than regulatory standard (5 ug/l) at closure. To assess the utility of nonparametric tests when 6 to 8 benzene rounds are available, the tests were systematically applied to benzene data observed at a near-source well for these 79 sites. The results from the nonparametric Mann-Kendall tests showed that 49% of the 79 sites had inconclusive results, 16% showed an increasing trend and 35% showed a decreasing trend.

Field Sites. Post-closure field investigations, including the installation of 9 or more groundwater monitoring wells, were conducted at ten (10) closed LUST sites. No underground tanks are now present at any of the field sites; however, 3 sites currently have serviceable above ground petroleum tanks. Post-closure wells were placed at locations where the previous groundwater investigations had detected benzene, and, with one exception, at more distal locations. Groundwater quality at depth was determined through the installation of piezometers (8 sites) and depth-profiling wells (5 sites).

At 8 of the 10 sites, post-closure groundwater samples collected from water table monitoring wells were observed to have total BTEX concentrations greater than their respective closure concentrations observed 5 to 8 years before. At 5 sites, the post-closure BTEX plume lengths were estimated to be longer than pre-closure plume lengths. However, the post-closure results (with one exception) indicated that benzene may no longer be at the leading edge of the currently observable plume. Spatially, benzene was detected less frequently in post-closure wells. Reduced spatial benzene detection frequency was true even at the sites where higher (than closure) benzene concentrations were observed.

To assess whether the placement of post-closure monitoring wells may have missed the benzene plume, the naphthalene results were further examined. Prior to closure, naphthalene was spatially detected less frequently than benzene, and it was usually detected in monitoring wells where benzene was detected. Post-closure, however, naphthalene at 8 sites was observed at more monitoring wells than was benzene, and at 4 sites, naphthalene was observed at concentrations greater than even their previous respective historical naphthalene maximums. More importantly, post-closure naphthalene was detected in wells further downgradient and more often detected in piezometers than was benzene. These observations are consistent with the general conclusion that benzene is not at the leading edge of the observable VOC plumes at these closed sites.

Major recommendations of this study include:

- reassess the use of a natural attenuation-only remedy at LUST sites in Wisconsin and place greater emphasis on early source control actions;
- refine the assessment of natural attenuation at LUST sites so that monitoring time frames are determined by site-specific factors;
- recognize the limitations of single well analysis of contaminant trends to determine plume stability;
- revise the administrative code criteria currently applied to the Mann-Kendall non-parametric statistical test;
- better define plumes in 3-dimensions through discrete vertical profiling and installation of piezometers at sites with hydraulic conductivities greater than 10^{-4} cm/sec or where contaminants are located in bedrock; and
- monitor naphthalene more frequently at LUST sites, and where indicated, monitor PAHs more routinely.

2. INTRODUCTION

Wisconsin's statutory Groundwater Protection Standards[1] became effective in 1984. This law established standards for all groundwater in the State, regardless of location, accessibility or usability of the resource. Wisconsin's groundwater Enforcement Standards (ES) are generally equivalent to federal drinking water Maximum Contaminant Levels (MCL). The groundwater standards are the criteria for all State regulatory programs. However, the statute does not specify the time frame in which the groundwater standards must be achieved.

In the mid-1980s, federal and state governments began a concerted effort to cleanup leaking underground petroleum storage tank (LUST) sites. There are over 100,000 sites with historical underground petroleum storage tank systems in Wisconsin. Of these, over 21,300 have leaked petroleum into the underlying soil and groundwater. In 1987 the State of Wisconsin established the Petroleum Environmental Cleanup Fund Award (PECFA). PECFA, funded through a State tax on gasoline sales, reimburses the majority of expenses for cleanup of soil and groundwater after the original leaking underground tank system (including tanks, pipes, etc.) has been removed and/or replaced.

Between the mid-1990s and early 2000s, when costs significantly exceeded income to the PECFA program, a number of regulatory changes were undertaken in an effort to balance the challenges of revenue outlay and environmental risk. To reconcile the strict requirement of the Groundwater Protection Standards with the cost and time limitations available for cleanup, the Wisconsin Department of Natural Resources (DNR) implemented "flexible closure." Flexible closure allows State agencies to close sites with groundwater contamination if groundwater standards will be met at some time in the future. DNR regulations require that groundwater standards be met "within a reasonable period of time."

The acceptance by the scientific and regulatory community of natural attenuation processes as a valid remedy for subsurface petroleum contamination provided the basis for flexible closure. The DNR published guidance for assessing natural attenuation and established criteria for closing LUST sites using natural attenuation[2]. The statutory requirement that groundwater be restored to environmental standards was deemed to be met if concentrations were declining over time and the contaminant plume was "stable or decreasing" in size. The agency's rationale for this approach was that natural attenuation processes would continue to reduce contaminant concentrations after closure and that eventually groundwater standards would be achieved throughout the source area and plume at some point in the future. No post-closure groundwater monitoring is required to corroborate the assumption that standards will eventually be achieved.

This study was undertaken to evaluate the effectiveness of the agency's closure protocol (or criteria) and examine whether reliance upon natural attenuation processes is likely to meet applicable groundwater standards.

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[1] 1983 Act 410, Wisconsin Statutes Chapter 160, "Groundwater Protection Standards"
[2] WDNR Publication RR-614, 1998 (updated 2003)

The objectives of this study are:

1. Evaluate whether the information that is currently submitted for closure of petroleum discharge sites in Wisconsin sufficiently demonstrates that the distribution of a plume both spatially and temporally has been constrained so that the effectiveness of natural attenuation as a remedy can be evaluated;
2. Determine, for a limited number of sites selected from a larger database, if the forecasts made at the time of closure (e.g., the plume margin is stable or receding, and will continue to remain stable or recede further) have proven to be correct;
3. Assess the effectiveness of the closure decision process in the application of natural attenuation closure protocol to petroleum sites by repopulating monitoring wells at selected closed sites;
4. Identify the site characteristics that may indicate the need for a modified closure protocol and/or post-closure monitoring.

3. Background

As of December 2008, over 19,000 LUST sites have been cleaned up in accordance with Wisconsin laws and rules and are considered "closed" cases. Many of these LUST sites have been closed with residual soil and groundwater contamination above applicable standards. In 2004, the Wisconsin Departments of Natural Resources (DNR) and Commerce (COMM) and the University of Wisconsin (UW) undertook a study of closed Wisconsin LUST sites to determine if the agency presumption of the effectiveness of natural attenuation processes to control plume movement and reduce groundwater contamination proved to be true 5 to 8 years after site closure. This study was originally envisioned to be a one-time snapshot of groundwater conditions at ten closed LUST sites. It soon became clear that it would be difficult to assess agency closure decisions based on such a small field study. About that time the State of Arizona completed a study on LUST impacts to groundwater resources in that state. Arizona's use of a database to compile information from LUST files as an analytical tool strongly influenced the design of our study.

The study design called for a two-pronged effort. The first part involved reviewing the on-line Wisconsin GIS Registry of Closed Remediation Sites which now is a theme under the RR Sites Map website (http://dnr.wi.gov/org/aw/rr/gis/index.htm). All contaminated properties closed by the State of Wisconsin with soil or groundwater contamination above standards are placed on the GIS Registry. As discussed more fully below, we focused on the 1,376 sites closed (either conditional or final closure) between January 1999 and December 2000 that became part of the GIS Registry. Through stratified random sampling, 123 closed LUST site files were selected from this population. Ten (10) non-randomly selected field sites (2 of which did not fall within the 1999-2000 window) were added to create a database containing information from 133 case file reviews. The database effort was undertaken to methodically assess the temporal and spatial information available at the time of closure for the contaminated soil and groundwater sites. In addition, the database was used to evaluate whether the criteria for closure outlined in agency guidance were adequate to allow regulatory reviewers to determine the effectiveness of natural attenuation processes.

The second part of the study consisted of reestablishing groundwater monitoring wells at ten closed LUST sites. This was necessary because in Wisconsin all monitoring wells are required to be removed as a condition of closure. The field sites were hand picked based upon willingness of the owner to participate in the study. The field study used direct-push drilling methods to collect soil cores and soil samples for chemical analysis. Short screened probes were used to perform depth profiling of groundwater quality at a limited number of locations and temporary 1" diameter groundwater wells were installed to mimic the original groundwater monitoring system. The goals of the field effort were to determine if the predictions of contaminant decline and plume behavior made at the time of closure continue to be true 5 to 8 years after closure and to determine if the application of agency specified natural attenuation protocols result in effective closure decisions.

3.1 State of Arizona Study

The State of Arizona completed a study titled, *Impacts to Groundwater Resources in Arizona from Leaking Underground Storage Tanks (LUSTS)*[3]. The stated purpose of the Arizona study was to help guide the State legislature in "future cost-effective and protective management of LUST sites." The AZ study focused on assessing data at open and closed LUST sites through a file review of 417 LUST sites. A database was assembled and relevant data was compiled to assess empirical relationships that could be used as a predictor of groundwater contamination. In addition six LUST sites were chosen for follow-up field investigation. The AZ study found that that the magnitude of groundwater impacts was not predictably related to geology, depth to groundwater, soil concentration data, nor free-product thickness. Furthermore, the analysis of the database indicated that only about 70% of the sites with groundwater monitoring had sufficient hydraulic data to confidently determine a dominant groundwater flow direction. For the sites at which a dominant flow direction could be determined, 30% had no monitoring wells that were downgradient from the source area. This is likely associated with the relatively deep (median: 50 ft) depth to water table.

3.2 Wisconsin's Closure Protocol for Petroleum Contaminated Sites, 1996 - 2000

In November 1996, "flexible closure" was established by administrative rule in Wisconsin. After that date, sites with contaminated groundwater could be closed with contamination above Wisconsin's groundwater standards[4] if it was demonstrated that natural attenuation would bring the groundwater into compliance with applicable standards "within a reasonable period of time."[5] A "stable or receding" groundwater plume margin was taken as evidence of the effectiveness of natural attenuation. A "stable or receding" plume margin was understood to mean that the margin of the plume would not advance beyond the limits defined at the time of closure or would retreat toward the original source of contamination.

The following summarizes the closure protocol[6] process used by the Department of Natural Resources and Department of Commerce when closing out petroleum tank sites *between November 1996 and December 2000*.

- Closure request was made by the owner or his/her consultant in writing after it had been demonstrated that closing the site would not cause a threat to public health, safety, welfare, or the environment both at the time of closure and in the future.

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[3] Dahlen, P., E. Henry, M. Matsumura, P.C. Johnson (2003) Impacts to Groundwater Resources in Arizona from Leaking Underground Storage Tanks (LUSTS), February 28, 2003, 70 p. plus appendices.

[4] Numerical groundwater standards, authorized by WI Stat. Chap. 160, are promulgated in WI Administrative Code Chapter 140, Groundwater Quality. These standards are comprised of Enforcement Standards (ES) and Preventive Action Limits (PAL).

[5] The term "reasonable period of time" has not been defined in any rule in Wisconsin as a specific length of time. Most closure requests do not contain enough information to make a reliable estimate of an actual number of years to reach cleanup levels.

[6] NR 726, WI Administrative Code, contains case closure requirements. http://www.legis.state.wi.us/rsb/code/nr/nr726.pdf

- Adequate source control had been taken, including:
  - Removal or permanent closure of all underground storage tanks
  - All existing tanks, pipes, barrels, or containers that may discharge a hazardous substance have been removed/contained/controlled to prevent new releases.
  - Free product (light non-aqueous phase liquid or LNAPL) must have been removed to the extent practicable. (Few sites were closed with the known presence of free product prior to January 1, 2001.)
  - Concentration and mass of contaminants have been reduced due to naturally occurring processes to adequately protect public health and the environment and to prevent further migration of groundwater contaminants.
- An adequate site characterization was completed. Where contaminants were found at levels above groundwater standards, a full site investigation including defining the degree and extent of soil and groundwater contamination and evaluating risk to potential receptors was required.
- Soil contaminant levels were compared to statewide soil cleanup levels. Before "flexible closure," sites were cleaned up to either generic or site specific residual contaminant levels. Under "flexible closure" rules, in the majority of cases, natural attenuation of groundwater contaminants served as a presumed soil performance standard remedy (that is, soil contaminants left in-place above calculated cleanup levels were allowed to degrade and leach, and upon leaching into the groundwater, natural attenuation was the selected remedy leading to site closure).
- If an active remedy was applied to the soil (such as a soil venting system) or groundwater (such as an air sparging or pump and treat system), post-remedial soil and/or groundwater samples were collected to verify the effectiveness of the remedial system.
- The groundwater plume margin was stable or receding and further migration of groundwater contaminants would not occur. The rule at the time did not specify the statistical tests or other methods to define a stable or receding plume margin.
- Natural attenuation would bring the groundwater into compliance with State groundwater quality standards within a reasonable period of time after considering technically and economically feasible remedial action options[7] for the site.
- Groundwater monitoring wells were required to be properly removed and the borings sealed as a condition of closure to prevent them from becoming conduits of contamination.
- Institutional controls or other mechanisms were used if State groundwater or soil standards were not met at the time of closure. Those controls consisted of the following:
  - If groundwater contamination remained at levels above State groundwater standards at the time of closure, the recording of a "groundwater use restriction" (a deed restriction) on the property deed for each property with standard exceedances was required as a condition of closure. (Groundwater use conditions were eliminated after November 2001 and replaced with an on-line database system called the GIS Registry of Closed Remediation Sites.)

[7] NR 722.07, WI Adm Code, sets out the evaluation of remedial action options.

- If soil contamination remained above generic residual contaminant levels or above calculated site-specific levels either deed affidavits were placed on properties or a special closure letter was issued to the property owner. (Deed affidavits for soil contamination were largely eliminated after August 2002 and replaced with listing on the GIS Registry.)
- Deed restrictions were placed on properties that needed to maintain an engineered cover to protect from direct contact with the soil or to acknowledge the presence of inaccessible soil contamination and to require action if that soil becomes accessible in the future.

3.3 Statutory Changes Affecting Wisconsin's Closure Protocol, post-2000

Since 2000, several statutory and rule changes occurred that altered the earlier closure protocol. Three of those statutory changes affected this study.

1. <u>Shared administrative authority for LUST sites with groundwater contamination began December 1999</u>. Through legislative initiative, regulatory oversight of approximately 2,000 LUST sites was transferred from the Department of Natural Resources to the Department of Commerce on December 1, 1999. Because every LUST site in the State underwent agency review in 1999, the largest number of closures occurred between January 1999 and December 2000. The closures extended over two years because property owners needed to meet certain conditions before being granted final closure.
2. <u>Promulgation of Comm 46/NR 746 – January 2001</u>. The Department of Commerce and Department of Natural Resources jointly developed rules to streamline the assessment and closure of certain LUST sites. One of the closure criteria included in this rule is the use of statistical tests (a Wisconsin-modified version of the Mann-Kendall or Mann-Whitney tests) to establish that contaminant concentrations are decreasing at the plume boundary and along the centerline of the plume. While use of these statistical tests is only required for a limited number of sites, these statistical tests are now routinely submitted as part of most LUST closure reports. We evaluate the efficacy of these statistical approaches in this study.
3. <u>Establishment of the DNR GIS Registry of Closed Remediation Sites -- November 1, 2001</u>. The GIS Registry was used to select sites included in this study. The GIS registry is a web-based repository of information on contaminated sites closed with environmental contamination above applicable State standards. All the sites closed with a groundwater use restriction between November 1996 and November 2001 were placed on the GIS Registry.

4. METHODOLOGY

The Wisconsin Closure Protocol Study was undertaken in the following manner:

- The DNR's Bureau for Remediation and Redevelopment Tracking System (BRRTS) was used to identify the initial list of 1,376 LUST sites which were in the RR GIS Registry and were closed between January 1999 and December 2000.
- The database for this study was compiled from file reviews of 133 sites, composed of 123 selected (via stratified random sampling) from the initial list of LUST sites plus 10 field sites.
- The 10 field sites were selected by contacting the respective property owners and securing their approval for DNR, COMM and UW to conduct a year-long field study that included re-establishing a groundwater monitoring network at their properties. Eight of the field sites were among the initial list that closed between 1999 and 2000. Two field sites closed slightly outside of the 2-year window originally set for this study: one closed in mid-1998, and the other in early 2001.
- Groundwater depth and quality data were collected 2 to 3 times at each field site over the period of the field study.

Two University of Wisconsin graduate students worked sequentially to review and extract data from the 133 site files and undertook the field investigations. The first student, Nathaniel Keller, performed 82 file reviews and field work at two former gasoline station sites beginning in January 2004. Subsequently, Rachel Greve completed 53 file reviews, beginning in January 2005 and undertook the field work for the remaining 8 field sites. Keller's and Greve's file reviews overlapped on 2 sites, with each of them submitting separate reviews for the 2 sites. This overlap was used in performing part of the QA/QC of the database entries.

Keller's Master of Science thesis, completed in August 2005, can be found in **Appendix C**. Greve's thesis, completed in April 2007, can be found in **Appendix D**.

Additional support was provided to other UW students – one graduate student who extracted groundwater quality data from report tables for input to the database, and an undergraduate student who collected groundwater samples from the field sites up until November 2006.

The following summarizes the methodology used in the study.

4.1 Wisconsin Closure Protocol Database Site Selection and File Review

The graduate students used primarily paper case file information to obtain site data for entry on pre-set forms. These entries were then compiled into an Access database. Together with the paper information, several web-accessible resources, separately maintained by DNR and COMM, were also used in this study.

4.1.1 On-line Web Databases

Management of LUST sites in Wisconsin is the responsibility of the Department of Natural Resources (DNR) and the Department of Commerce (COMM). As each agency has different roles in the process, each agency keeps separate databases that are pertinent to their respective programs. Cross-agency protocols exist to synchronize the separate databases. The following on-line databases contain pertinent information regarding LUST sites in Wisconsin and in particular to the 133 sites assessed in this study. **Table 1** contains links to these on-line resources for each site included in the database.

The Department of Commerce's "Tracker" website, which provides information on claims and reimbursement awards for LUST cleanups, can be accessed at: http://commerce.wi.gov/php/ERS_Tracker_on_web/ers_tracker_on_web.php. COMM also maintains information on over 160,000 underground storage petroleum tanks in Wisconsin, and that information is available at http://commerce.wi.gov/ER/ER-EN-tanks-info.html.

The DNR's Bureau for Remediation and Redevelopment Tracking System ("BRRTS") contains site information and a record of agency actions at all contaminated sites in the State. The web-based version is available at: http://dnr.wi.gov/org/aw/rr/brrts/index.htm. The DNR also provides map location and downloadable site-specific files (like scanned report pages with map and groundwater monitoring data tables) through its "RR Sites Map" website. The GIS Registry, which now is a separate theme on RR Sites Map website, is available at: http://dnrmaps.wisconsin.gov/imf/imf.jsp?site=brrts2.gisregistry.

4.1.2 Database Site Selection and General Site Data Categorizations

In anticipation of the shared regulatory oversight of LUST sites, DNR reviewed over 4,500 site files in 1999. This review and subsequent transfer to COMM resulted in the DNR closing 965 sites during a 2-year period (1999 to 2000) and COMM closing 411 sites during a 1-year period (2000). Site-specific information (typically select pages from consultant reports) for each of the 1,376 sites was scanned and converted to pdf files, and those files became available online as part of the GIS Registry in November 2001. The sites that closed in this 2-year period comprise approximately one-third of all sites that are in the GIS Registry as of December 2008.

In the early process of populating the database for this study, an unintended bias was introduced, which resulted in the disproportional entries of DNR-closed sites, especially from counties beginning with letters A and B. After recognizing the bias and to correct it, a stratified random sampling strategy was implemented using as strata the 72 Wisconsin counties, to better reflect the proportion of closed sites per county, and to preserve the ratio of sites closed by the DNR to sites closed by COMM. The adjusted strategy resulted in 123 sites being selected for inclusion in the database.

In addition, information from the files of the 10 field sites where post-closure monitoring wells were installed was included in the database. In the final tally, 133 case files (94 DNR closed sites and 39 COMM closed sites) were reviewed and compiled in the database.

The 133 database sites represent slightly less than 10% of the initial GIS Registry sites that closed between 1999 and 2000. **Figure 1** shows the number of GIS Registry sites in each county and the number of subset sites selected for inclusion in the database. Except for Marquette County, each county with at least 10 sites is represented in the database. Out of Wisconsin's 72 counties, 27 counties are not represented in the database.

Cleanup costs were used as an independent verification of how representative this stratified random sampling methodology was of LUST sites closed between 1999 and 2000. Of the 1,378 sites in the initial pool of closed sites, 1,267 have cleanup cost data available on COMM's Tracker website. The average reimbursement cost for these 1,267 sites was $200,000. The average reimbursement for the 129 sites with cost data available (of 133 sites included in the database) was $178,000, which was fairly close to the overall average of the entire population sampled.

The geographic distribution of the 133 database sites is shown in **Figure 2**. Each of the 133 sites is identified by a SiteMap_ID number. **Table 1** lists all the sites by SiteMap_ID and provides links to web-available site information. The web-links include the on-line databases (GIS Registry, BRRTS and Tracker) mentioned in section 4.1.1, as well as links to the DNR orthophoto available via the RR Sites Map. Appendix K includes web-links for COMM tanks database information. **Table 1** also indicates the agency that was responsible for regulatory decisions (i.e., site jurisdiction) for each site. Although listed in the Table 1, site jurisdiction was not a consideration in the data analysis in this study.

As shown in **Figure 2**, each site was categorized according to whether it was actively remediated (95 "Remediated-Yes" sites) or not (38 "Remediated-No" sites). A site is considered to have been actively remediated if any remedy, besides removal of tank systems (which occurred at all sites) and groundwater monitoring, was employed. Active remedies included soil excavation, soil venting, air sparging, pump and treat and free-product removal systems.

Each site was also classified according to geology. **Figure 2** and **Table 1** identify the sites as bedrock (20 sites), clay (53) and non-clay (60). These categories are based on the description from soil borings of the material collected from the water table during the installation of monitoring wells at the site. A site where a boring or a monitoring well encountered bedrock was classified as a bedrock site. Clay sites were distinguished by soil descriptions of clayey silt or clayey sand or saturated organic soils. Non-clay sites included everything else, most commonly described as having silty and sandy soils in site reports. **Figure 3** shows the locations of the 133 database sites superimposed on a map of clay soils[8] in Wisconsin. A number of the sites falling in the soil map's "clay" areas

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[8] The Clay Soils Map was generated from US GSM data (SSURGO) available from the USDA NRCS website *http://soildatamart.nrcs.usda.gov/Survey.aspx?State=WI*

were categorized as non-clay sites either because the sites are underlain by non-clay fill or the water table is located in a sandy or gravelly layer beneath surficial clay soil.

4.1.3 File Review and QA/QC of the Database

Using fillable pdf forms, file reviewers extracted 125 separate pieces of information for each of the 133 sites. **Table 2** summarizes the information from 125 data fields and shows where and how much information is available in each field of the database table. The groundwater quality data is composed mainly of depths to water and analytical results for benzene, toluene, ethylbenzene, xylene, MTBE and naphthalene. Most of these groundwater analytical results are available through the scanned pdf pages in the GIS Registry links for the sites in **Table 1**. Secondary reviewers performed QA/QC checks on water quality, monitoring well, and soil quality information in the database.

4.2 Field Sites and Post-Closure Data Collection

The second major component of this closure protocol study involved the collection of post-closure samples to assess changes in groundwater quality. Unlike the stratified random sampling of the sites included in the database part of this study, the 10 sites where post-closure monitoring was conducted were not randomly selected. The main criterion used in selecting a field site was the willingness of the site owner to allow access to install temporary wells and collect soil and groundwater samples.

Other criteria included

- field sites needed to be fairly well characterized during the original site investigation so that reasonable comparisons could be made between information available at closure and the information from this field study.
- a variety of sites representing different soil types, including sand, clay and glacial till.
- ability to access the original source zone in order to collect samples
- no underground tanks could exist at the selected sites to avoid the possibility of a petroleum release since the original closure.

Access agreements were secured for all 10 sites. The locations of the field sites are shown in **Figure 2**, and denoted on **Table 1**. Two of the 10 are privately-owned sites[9] and the rest are municipal or state-owned properties[10]. The information pertinent to location of historical monitoring wells was mapped so the temporary wells installed for this study could be located at the source zone, near the original plume margin, and beyond the original plume margin. Access agreements could be obtained from the neighboring properties at only two sites[11] so at the remaining 8 sites monitoring wells

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[9] SiteMap_ID 63 (Charles Packard Property) and 104 (WI Lions Camp) are field study sites owned by private individuals or organizations.
[10] SiteMap_ID 9, 33, 34, 36, 55, 103, 108 and 126 are field study sites owned by a public entity.
[11] Off – property access agreements were obtained at sites SiteMap_ID 63 (Packard) and 108 (City of Racine).

were installed within the site property and/or at right-of-way locations. Access agreements stipulated that the temporary monitoring wells could remain in place for one year. Fieldwork was conducted at two sites[12] in 2004 and the results are presented in Keller's M.Sc. thesis [2005, **Appendix C**]. Fieldwork for the remaining 8 sites was conducted in 2005 and the results are presented in Greve's M.Sc. thesis [2007, **Appendix D**].

4.2.1 Field Methodology

From August 2004 to October 2005, a total of 117 temporary monitoring wells were installed at the 10 sites. In addition, depth-profiling of soil and groundwater contamination was performed during the fieldwork. Depth profiling of soils involved using a Geoprobe® rig to drill to a specified depth and remove a soil sample then drive the probe deeper and remove another sample. Depth profiling of groundwater involved setting 1"-diameter PVC pipe with a 6" to 24" screened interval at a specified depth and pumping a groundwater sample to the surface using either a peristaltic pump or a ½" rigid tubing with a foot valve. Once a groundwater sample was collected, the probe was advanced deeper into the ground and the process of sample collection was repeated.

At the two field sites[13] where work was performed late in 2005, only two rounds of groundwater samples were collected. At the other 8 study sites three rounds of samples were collected for volatile organic compound (VOC) analyses. Groundwater samples were collected for ethylene dibromide (EDB) analysis at 8 of the sites and two of those[14] were sampled twice for EDB.

Soil samples were collected at all 10 sites for VOC analyses; however, soil analytical results were reported for only 7 of the sites. Three sites[15] have no soil results because the methanol-and-water preservative in the samples leaked during shipping.

All the soil and groundwater VOC samples from the field sites were analyzed by U.S. EPA's R.S. Kerr Laboratory in Ada, OK and the results were reported via spreadsheet attachments in e-mails from EPA. Summary tables of the analytical results, together with site maps, soil boring logs, well construction, documentation of well removal, and site photos are available in Appendices A, B, E, F, G, H and I.

4.2.2 Soil Investigation Methodology

Drilling in 2004 at the first two field sites (SiteMap_IDs 33 and 36) was mainly accomplished using a solid stem auger rig. The cuttings from the solid stem augers were logged and classified according to the Unified Soil Classification System (USCS) as they

[12] Summer 2004 field work was conducted at SiteMap_ID 33 (Martin Oil) and 36 (Woods Garage).
[13] The sites where field work was performed last are SiteMap_ID 104 (WI Lions Camp) and 108 (City of Racine).
[14] Sites with two rounds of EDB analysis are SiteMap_ID 34 (Town of Rutland) and 63 (Packard).
[15] Sites with no soil analytical data are SiteMap_ID 9 (Brown County), 55 (Grandma's) and 63 (Packard).

reached the surface. Only 2 wells out of 24 installed in 2004 were by advanced using direct push (Geoprobe®). The 2 Geoprobe® wells were installed at Wood's Garage site.

In 2005, a larger Geoprobe® rig was available, and all the borings were advanced using this direct-push technique. Continuous soil cores were collected by placing a 3- or 4-ft long plastic liner inside the geoprobe probe rod before advancing the rod by the length of the liner. Continuous core samples were collected at 3 or more borings at each site drilled in 2005. The liners were brought to the surface, cut open, the soil logged and USCS-classified. Appendix F contains the completed soil boring log information forms and the photos of the soil cores.

One soil boring was placed near the location where the previous site investigation showed high levels of groundwater contamination. Once soils were removed from the borehole, samples were collected at 2-foot intervals along the length of the soil core. These samples were sub-sampled. A portion of the sub-samples were placed into a 4-oz glass jar and covered with heavy duty aluminum foil. The covered jars were then placed under the sun and allowed to warm to about 70^{o} Fahrenheit. A pre-calibrated Photovac Model 2020 photo ionization detector (PID) was used to screen each sample for the presence of VOCs. The aluminum foil was pierced with the tip of the PID probe and the maximum reading from it was recorded.

A second sub-sample, from the core cuttings with the highest PID screening levels were placed in a pre-weighed four ounce glass jar containing 15 mL of methanol and 15 mL of water. However, some of the samples collected using this procedure leaked in transit. The procedure was modified by placing a 10-g soil sample in one (1) 40-ml vial with 5 ml methanol (no water), and a second 10-g soil sample in an empty 40-ml vial. [See p. 21 of **Appendix D** – Greve's thesis]. The non-methanol preserved soil samples were used to determine dry weight of the sample.

These samples were placed on ice and shipped to the EPA Environmental Research Lab in Ada, Oklahoma for analysis. Samples were analyzed for the following parameters: benzene, ethylbenzene, toluene, o-,m- and p-xylene, MTBE, tert-amyl methyl ether (TAME), diisopropyl ether (DIPE), ethyl tert-butyl ether (ETBE), tert-butyl alcohol (TBA), ethanol, isopropanol, n-propanol, n-butanol, 1,2,3,-, 1,2,4-, and 1,3,5-trimethylbenzene and naphthalene. However, because field methanol blanks were not submitted to the laboratory, the blank corrections to determine the soil-VOC concentrations were based on laboratory methanol blanks, some of which had amounts of VOCs that exceeded the levels extracted from the soil samples. This resulted in soil sample results with negative corrected VOC concentrations. **Appendix A** contains the best estimates for soil VOC concentration results. Due to the quantitation problem, the soil lab results are given less emphasis in this report.

4.2.3 Groundwater Investigation Methodology

Temporary 1-inch diameter PVC monitoring wells were installed in selected boreholes. In general, water table wells were constructed to mimic the depth and screen lengths of the original site investigation wells. Ten-foot PVC screens were used for all water table wells, except for two wells at 1 site where 15 foot screens were used to mimic the previous investigation.

The piezometers were constructed with screen lengths that varied between 1 ft (at 1 site) and 10 ft (1 site), but most had 5 foot screens. Only 5 of the 10 field sites had piezometers installed during their previous investigations, and at one of these sites, a piezometer was not installed for this study because tight clay soils were encountered at the depth where the piezometer would have been screened. With the exception of the WI Lions Camp, the screens of the post-closure piezometers were placed at depths different from (and so are not comparable to) the previous site investigations. Placement of piezometer screens for this study was based on the results of depth profiling samples to increase the likelihood of intercepting contamination at depth.

Appendix G contains the well construction forms for the 117 monitoring wells installed at the 10 field sites. Unfortunately, due to on-going activities at 2 sites, 5 of the post-closure monitoring wells were destroyed prior to removal.

Following well installation, depth to groundwater was measured using an electric water level indicator. Wells were then developed by purging approximately 1 gallon of water (equivalent to10 well volumes) and monitoring for dissolved oxygen and conductivity while purging. After collecting geochemical parameters, the wells were sampled for VOCs. If wells purged dry, sampling commenced after approximately 4 well volumes were removed. Where shallow water levels allowed it, purging and sampling was accomplished using a peristaltic pump operating at low flow rates. Otherwise, wells were sampled using a Waterra low flow foot valve inertial pump.

Groundwater was sampled in the field for the following parameters: pH, conductivity, temperature, dissolved oxygen (DO), nitrate, total dissolved iron, and alkalinity. The natural attenuation parameters including DO, nitrate, and dissolved iron were sampled using CHEMetrics® colorimetric tests in the field. Temperature and conductivity were measured using a YSI Model 30 temperature and conductivity meter, and pH was measured using a calibrated electrode. Following measurement of the previous parameters a 60 mL polyethylene bottle was filled with groundwater for laboratory[16] sulfate analysis. Groundwater samples for petroleum contaminants were collected last. Water was collected directly into two 40 mL vials which contained 0.4g +/- 0.05 g of tri-sodium phosphate as a preservative. One 40 ml vial with 0.5 ml hydrochloric acid preservative was collected for each EDB sample. The vials were labeled and shipped to the EPA's Environmental Research Lab located in Ada, Oklahoma. Samples were analyzed for the parameters listed in section 4.2.2.

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[16] Sulfate was analyzed at the Wisconsin State Laboratory of Hygiene in 2004. The University of Wisconsin Soil and Plant Analysis Laboratory performed sulfate analysis in 2005 and 2006.

Appendices C and D contains more detailed soil and groundwater methodology. **Appendix H** contains the completed well removal forms for 122 wells. This includes 5 wells that remained at two sites from their previous site investigations.

5. RESULTS OF DATABASE ANALYSIS

This section reports the results of queries to the database. However, this analysis may not be representative of the universe of LUST sites in Wisconsin for the following reasons:

1. Geology or soil type perspective. A substantial portion of the database sites are in Wisconsin's largest metropolitan cities where clay happens to be the predominant soil type. Milwaukee and Green Bay – two cities that account for 17% of the database sites – are located within the clay-rich Green Bay lobe of the Wisconsin Age glacial deposits. Several corollary aspects, like shallow depth to the water table, low hydraulic conductivity and fewer water supply wells, are associated with "clay soils" rather than a deliberate over- or under-sampling in the study.
2. Historical program perspective. The database only reflects site closure decisions made in the 2-year time window between 1999 and 2000. The closure process for LUST sites has changed over time. For example, the application of non-parametric statistical tests to groundwater benzene data from the database sites was analyzed in order to assess the usefulness of these tools. However, these tools were not required by rule when the closure decisions were originally made. Because the database does not reflect closure decisions made post-2000 the assessment may not be reflective of current LUST closures in Wisconsin.
3. Contaminant perspective. The database analysis primarily focuses on contaminants originating from gasoline, including BTEX, benzene, and naphthalene. However, nearly 60% of the database sites include diesel fuel as part of the release. Polycyclic aromatic hydrocarbon (PAH) data other than naphthalene was not explicitly extracted from the files. PAH data available on the GIS Registry for individual sites was reviewed.

5.1 Hydrogeologic Characterization of Closed LUST Sites

Wisconsin bedrock geology can be generally divided into a limestone/dolomite region in the southern and eastern area of the state; a central region of sandstone; and a crystalline rock region comprising much of the northern area of the state [e.g., Hole, 1976]. The soil overlying the bedrock is primarily of glacial origin, with the exception of the "driftless" or unglaciated southwestern portion of the state. Glacial deposits throughout Wisconsin are associated with the Wisconsin stage of Pleistocene glaciation. Soils in the east and north, near the Lake Michigan and Lake Superior shorelines, are generally clayey and silty in texture. Mixed silt, sand, and gravel dominate much of the southern and northern portions of the state with sand plains comprising the central portion. Silty, loess soils overlie the unglaciated southwestern area of the state. **Figure 3** has the locations of the 133 database sites superimposed on a map that identifies clay soils.

Wisconsin has significant surface water resources, including more than 15,000 lakes, 7,000 streams and five million acres of wetland[17]. The glacial topography and extensive surface water results in shallow groundwater levels through most of the State except in the unglaciated area, where well defined river and tributary systems drain upland areas. Low permeability soils, particularly in the east and far north, contribute to shallow and perched groundwater conditions.

Because of geological conditions, contamination from LUST sites tends to be limited to shallow soil and surficial groundwater. It is relatively rare in Wisconsin that public water supply systems are contaminated by petroleum products. Benzene has been detected in approximately 6.4% of the routinely monitored public water supply systems[18] in the state. MTBE has been detected in less than 2% of these systems.

5.1.1 Average Depth to Groundwater

Depths to groundwater were available for 123 of the 133 sites in the database. Of these 123 sites, 99 (or 80% of sites with depth data) had minimum depth to water of 12 ft or less. Because of shallow depth to groundwater, there were generally enough monitoring wells (median of 7 wells) to provide good hydrogeologic information at the sites. **Figure 4** is a histogram of minimum depth to groundwater according to geologic setting. In general, the shallow depth to water indicates that unconfined water table aquifers are the primary focus of monitoring efforts at Wisconsin LUST sites.

The mean of the minimum depths to the groundwater has implications for monitoring well installation. In Wisconsin, water table wells are installed with 10 foot well screens and must intersect the water table. Clay sites, with an average depth to water of 6 feet require setting shallower screens compared to bedrock sites or non-clay sites (average depth to water 10 and 12 feet respectively). The data shows that installing a 10 foot monitoring well screen between 5 and 15 feet below the ground surface will intercept the water table (with at least 3 feet of standing water in the well) at 47% of sites.

5.1.2 Sites with Piezometers

A piezometer in Wisconsin is usually constructed with a shorter 5-foot screen. Data collected from piezometers are used to assess vertical hydraulic gradients and vertical contaminant migration. Given the shallow depth to water, one might expect piezometers to be commonplace in site investigations; however, the reviewed sites in this study showed that piezometers were not typically installed at sites.

Only 34 of the 133 sites had at least 1 piezometer (**Table 2**). Sites with piezometers are shown in **Figure 5**. Nine out of the 34 sites (26%) with piezometers are located in a single county (Dane). Moreover, while the 46 sites in Brown, Milwaukee, Outagamie

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[17] Kassulke, Natasha and Laura Chern, "Groundwater: Wisconsin's Buried Resource", in Wisconsin Natural Resource Magazine, April 2006. http://www.wnrmag.com/supps/2006/apr06/using.htm

[18] Benzene statistics based on Safe Drinking Water Act sampling results from 1984 to present. MTBE sampling results are from 1990 to present.

and Winnebago counties constituted over a third of the database sites, only 3 sites in these counties had piezometers. Five (5) of the sites with at least 1 piezometer[19] were among our 10 field sites, and post-closure information is available for them in the latter part of this report. Because the field sites were not part of the random-selection site process, the actual frequency of Wisconsin LUST sites with piezometers may be less than the 26% stated here.

Several associations were apparent from the database sites with piezometers:

- Because piezometers were installed at only 1 in 4 sites, closure decisions did not generally rely on a 3-dimensional understanding of groundwater flow or contamination because the information in the vertical dimension was typically limited.
- Installation of a piezometer appeared to be influenced by geology. A piezometer was installed at just three (or 6%) of the 53 clay sites in the database. In contrast, the 9 bedrock and 22 non-clay sites with at least one piezometer constituted 45% and 37%, respectively of the bedrock and non-clay sites in the database. It is more likely that a piezometer will be constructed at a site where competent bedrock is encountered during soil borings.
- A correlation appears to exist between the installation of a piezometer and subsequent remediation of a site. Among the 34 sites with piezometers, 31 sites (91%) had some active remediation, including 10 with pump and treat systems. While clay sites tended not to be actively remediated, all three clay sites where piezometers were installed were actively remediated. Many of the variables leading to a decision to install piezometers at a LUST site (such as geology, nearby receptors, contaminant concentrations, experience of the site investigators, etc.) also factor into the decision to undertake active remediation. It appears that a better 3-dimensional understanding of the plume is associated with active site remediation.

5.1.3 Hydraulic Conductivity (K), Horizontal Gradient (i) and Specific Discharge (q)

Hydraulic conductivity (K) was available for 98 of the 133 database sites. Horizontal hydraulic gradient (i) was available for 126 sites. The minimum and maximum K and i values were tabulated from site investigation reports. The geometric means of K and i were generated for each site, and the site's "Darcy" velocity or horizontal specific discharge (q = Ki) was estimated from the product of the geometric means.

Figure 6 contains histograms of the geometric means for K and i, and the estimated specific discharge. The hydraulic conductivity values range over 5 orders of magnitude for both clay and non-clay sites, and 3 orders of magnitude for the bedrock sites.
The hydraulic gradient values span about 2 orders of magnitude with clay sites, as a group, having a larger gradient compared to either bedrock or non-clay sites.

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[19] Sites with piezometers that were also included in the field study portion of this investigation: SiteMap_IDs 33, 34, 36, 55 and 104

Compared to the "K" histogram (**Figure 6**) which shows a relatively flatter distribution over 4 orders of magnitude (from $1x10^{-6}$ to $1x10^{-2}$ cm/s), the specific discharge ("Ki") histogram has a semblance of a bell curve which is expected of a lognormal distribution. This information may be useful in constraining future probabilistic groundwater modeling where the distribution of model parameters may be important.

5.1.4 Variation in Groundwater Flow Direction

Groundwater flow direction was estimated more than once at 111 sites (42 clay, 15 bedrock and 54 non-clay sites). Azimuthal directions from two different dates that bracket the observed range in variations in the horizontal direction of groundwater flow were identified and noted in the database. **Figure 7** (bottom) contains the rose diagrams for the observations from the clay, bedrock and non-clay sites. The rose diagrams are compass-like histograms with each wedge representing a relative count of sites falling inside a 10º range. Instead of a compass direction, however, the data in the rose diagrams in **Figure 7** represent a change of the observed swings in the horizontal groundwater flow direction. If a site's groundwater flow direction changed by 15º, it was counted and plotted in the 10º to 20º wedge. If there was a 180º change (reversal in the flow direction), it was included in the 170º to 180º wedge.

For the clay site subset, the rose diagram's wedge from the center to the circumference represents 5 sites. As indicated in the summary table in **Figure 7,** the clay sites as a group exhibited a larger variability in flow direction, with a median azimuthal change in flow direction of 74º. Consistent closed groundwater-elevation contours[20] (with radial flow away from source) were plotted in the 350º to 360º wedge. For a few of the clay sites, the flow variations were plotted between 180º and 350º to highlight the reviewers' observations from consultant reports that the flow azimuths (at different times) for each of those site were in 3 to 4 different quadrants of the compass, complicating the simple analysis where typically the flow directions were in either 1 or 2 quadrants only.

The bedrock sites comprise the fewest sites in this study, so the rose diagram's wedge from the center out to the circle represents 4 sites with a median azimuth change of 60º for this subset. At non-clay sites, the wedge from the center to the circumference represents 11 sites. The median azimuth change for the non-clay sites is 35º, or the least of the 3 geological subsets. For 1 non-clay site, groundwater pumping affected the horizontal flow such that the flow directions were in 3 compass quadrants.

Figure 7 (top) also includes a table showing the range and median of hydraulic conductivity (K) values noted in the database for the different geological subsets. This table of hydraulic conductivity together with the summary table for the azimuth change seems to suggest a correlation between the hydraulic conductivity and the observed swings in the groundwater flow direction. The increasing median hydraulic conductivities for clay, bedrock and non-clay sites may be associated with their decreasing median azimuthal flow changes. To examine the correlation, the median values from sites where both values were available were plotted. **Figure 8** contains a plot

[20] Clay sites with closed contours are SiteMap_ID #17, 73, 81 and 130.

of the actual hydraulic conductivity and a plot of specific discharge for each site. These plots show a very large scatter, such that it is difficult to draw any conclusion regarding the correlation of these parameters.

We can conclude from this analysis that swings of more than 33º in the groundwater flow direction is to be expected over the monitoring time period at more than half of the database sites, regardless of site geology. This has important implications when the monitoring history at particular wells is projected on to conclusions about overall groundwater flow and contaminant behavior at a site. Monitoring wells designated as "downgradient" during one time period may be side gradient during another time period. Flow variation complicates the placement of sentry wells for plume behavior assessment. Together with the expected lag in the travel time (due to retardation) of a contaminant to a well, the change in the flow direction can lead to a bias in interpreting the contaminant monitoring history at these wells.

5.1.5 Water Elevation Fluctuation and Implications to Assessment of Contaminant Concentrations

The simple assessments of natural attenuation performed on data from most LUST sites consider contaminant decay with time or space only. Hydraulic factors at contaminated sites can have a significant effect on contaminant trends and these factors may or may not be associated with natural degradation processes that lead to reduction of contaminant mass. Groundwater sampling is (or should be) accompanied by measurement of the depth (or elevation) to the water table. A simple x-y plot showing contaminant concentration data and depth to water at a near-source well [e.g. Pelayo and Evangelista, 2003] may reveal a better correlation between concentration and depth to water than a plot of concentration with time.

Depth to the water table reflects several physical factors that affect interpretation of observed contaminant concentrations. For example, the amount of water purged from a well prior to sample collection is based on the depth to water (and subsequent calculation of water volume in the well). Either excessive or too-little purging before sampling may factor into changes in contaminant concentrations, especially when a large elevation fluctuation occurs between sampling rounds. Depth to water is the raw data from which the hydraulic gradient and groundwater flow direction are determined. When a shift in the direction of groundwater flow is observed, previously downgradient wells may become side gradient wells, rendering event-to-event comparison of concentration data from these wells suspect in degradation evaluations.

The groundwater elevation can affect changes in nearby light non-aqueous phase liquid (LNAPL) [e.g. Steffy et al., 1998]. When the water table falls, a substantial LNAPL can suddenly appear [e.g. Marinelli and Durnford, 1996] and concentration data from the sample can be biased by the presence of entrained nondissolved petroleum [e.g., Zemo, 2006]. The groundwater elevation can also denote an increase or decrease in recharge and infiltration [e.g. Eganhouse et al., 1996; Lee et al., 2001]. The shallower the water table becomes, the more it promotes volatilization to the atmosphere and dissolution of oxygen into the groundwater [e.g. Braddock and McCarthy, 1996; Landmeyer et al., 1996]. Hence, observations of a series of contaminant concentrations in a monitoring well are influenced by several confounding factors – particularly by water table fluctuations - that lend uncertainty to analysis of time-concentration data. Projection of decay rates, particularly using small data sets, can be misleading.[21] At minimum, water level fluctuation must be considered when assessing contaminant decay with time, especially when monitoring wells are located near LNAPL.

While recognizing the importance of depth to water measurements, our analysis of the depth dataset is limited. Correlation of water elevation variation to contaminant concentrations were not specifically assessed in the database study, however this correlation is examined in the benzene data from the near-source monitoring wells at the 10 field sites in this study.

5.2 Soil Benzene versus Groundwater Benzene Concentrations

The highest soil benzene concentrations observed from each site were plotted against their corresponding maximum historical groundwater benzene concentrations (**Figure 9)**. A linear relationship between soil and groundwater observations at a homogeneous site is predicted by a simple equilibrium-partitioning equation (i.e. the K_d concept, e.g., Jury et al. [1983]), The obvious scatter in the data shown in **Figure 9** makes it difficult to compare the data between sites, pointing to the fact that properties, such as soil f_{oc} (and hence Kd) and porosity are different for each site. The absence of a clear trend between soil and groundwater benzene was also found in the Arizona study where observations were more complicated because the 50-foot median depth to groundwater was significantly deeper than Wisconsin's.

Separate regression analyses for the bedrock and non-clay subset of sites did not produce any clear correlation between soil benzene and groundwater concentrations either. However, a correlation between soil and groundwater benzene seemed apparent at clay sites, perhaps an indication that clay site properties may not be as markedly different compared to the other soil subtypes. Clay sites in Wisconsin usually have a very shallow water table. Equilibrium may develop at clay sites due to a longer time period for direct contact of contaminated, low-permeability soils with groundwater. **Figure 10** shows the regression of soil and groundwater benzene concentrations for clay sites with a hydraulic conductivity $K \leq 1\text{x}10^{-5}$ cm/sec. The dashed line in **Figure 10** is the generalized least-squares fit that assumed a zero-intercept. The equation at the top of **Figure 10** emphasizes the theoretical equilibrium-partitioning result. While the square of the Pearson coefficient of correlation ($R^2 = 0.35$) for the line is small, it is significant at an α=0.05 test, meaning that there is a nonzero correlation at a 95% confidence level. However, the correlation may be fortuitous. A further caveat in the correlation is the fact that only 7 of the 17 soil-groundwater clay site pairs in **Figure 10** were co-located.

[21] Wilson, et. al, 2005.

With no simple correlation between them, both soil and groundwater data are needed to reach a sound decision at each site regarding the fate and movement of contaminants.

5.3 Qualitative Assessment of the Source Zone at Closed LUST Sites

Administrative rules in Wisconsin require that floating free-phase product (FP) – synonymous with light non-aqueous phase liquid (LNAPL) for petroleum – be reported to the state agency and be removed to the "maximum extent practicable." One method for determining if free product is present is when a site has repeated measurements of 0.01 feet or more of free product in a monitoring well. This criterion is also used to determine risk priority for the state agencies. The presence of FP is used to delineate the primary contaminant source area. We discuss the identification of source zones when the residual NAPL is made up of weathered petroleum product and the several problems associated with of the rule-specified FP definition in identifying source areas.

In 1999, a DNR review of 2,230 then-open LUST sites revealed that 464 of them (21%) had FP at some point in time. Between 1999 and 2000, not many FP sites were closed, and because the sites in this study are a subset of these early closures, FP sites were under-represented in this study. Specifically, only 15% (20) of the database sites reported either a FP zone or measureable FP in a monitoring well at any time in the site history. The locations of these 20 "measurable" FP sites are shown on **Figure 11**. Only 1 of the 20 sites was a clay site, so insights regarding FP in this study may not apply to clay sites in general. The VOC concentration data from the 20 FP sites were further queried to gain insight to possible correlations between contaminant levels and occurrence of FP at sites.

Determining the previous or on-going presence of FP based on soil and groundwater concentrations is not straightforward [Marinelli and Durnford].[22] Here, we looked at both the soil and groundwater contaminant concentrations to determine if these concentrations correlated with the reported presence of free product. If a correlation exists, then soil and groundwater concentrations may be useful indicators during a site investigation in determining the presence of residual or floating FP.

For a select number of compounds, Wisconsin regulations[23] provide theoretical soil concentration thresholds that indicate the presence of residual free product. Soil benzene, toluene, ethylbenzene and xylene concentration data from the database sites were compared to a look-up table in Wisconsin rules. Using the look-up table, the reviewers noted 64 sites (**Table 2**) with at least 1 compound exceeding the soil regulatory criteria.

[22] Marinelli and Dunford [1996] enumerated several general observations from their review of numerous FP sites that help to illustrate the difficulty. They observed that a monitoring well may contain no observable FP, even though soil samples above or below the water table are indicative of significant FP. When the water table drops, substantial thickness of FP can suddenly appear in a monitoring well, but if the water table drops even lower than below its normal range, once-measurable FP at a well can dramatically disappear.

[23] Indicators of Residual Petroleum Product in Soil Pores can be found in Table 1, NR 746.06, Wisconsin Administrative Code.

However, when cross-referenced with the 20 "measurable" FP sites, FP was observed at only 10 of the 64 sites that exceeded the soil FP indicator concentrations. This may be because the regulatory table thresholds were derived assuming a fresh gasoline release, and so are not appropriate when the release is diesel or fuel oil, or when a weathered NAPL is present. At the other 10 sites with FP, but with soil levels below the soil regulatory FP criteria, diesel or fuel oil tanks were present at 8 of them.

Unlike soil, Wisconsin has no regulatory groundwater FP threshold concentrations. However, determining the FP thresholds applicable to groundwater quality are theoretically possible [e.g. Cline et al., 1991] provided that constituent mole fractions in the spilled fuel are reasonably known.[24] In this study, the historical maximum groundwater concentrations observed for each site were plotted (**Figure 12**). By assuming an LNAPL composition to be that of fresh gasoline[25], the observed concentration maximums were compared to the respective theoretical effective solubilities noted in the figure. The presence of FP may be indicated if the groundwater quality reaches or exceeds any effective solubility at a monitoring well.

In **Figure 12**, the VOCs are arranged from the least water-soluble naphthalene to the most soluble MTBE. It is apparent from **Figure 12** that there is a systematic decrease in number of sites exceeding effective solubility with increasing solubility of the VOC. This is consistent with other studies [e.g. Zemo, 2006] that found the more-soluble petroleum constituents were less likely to indicate the occurrence of FP in groundwater. Indication of FP should increase considerably when data from the less-soluble constituents (ethylbenzene, xylenes and naphthalene) are compared to their respective effective solubilities.

However, upon relating the concentration data to the FP sites in **Figure 11**, it becomes apparent that the actual presence of FP does not always correspond to those situations where effective solubility limits are exceeded. Of the 8 sites[26] where benzene concentrations exceeded 18,000 µg/l, a sheen or measurable free product (parameters listed in **Table 2**) was noted in consultants' reports at only 2 sites[27]. Among the 29 sites where naphthalene was equal to or greater than 310 µg/l, only 4 sites had sheen or measurable FP reported in consultants' reports.

Based in this information, there does not appear to be a correlation between measurable FP and the observed groundwater benzene or naphthalene concentrations. This is not

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[24] *Feenstra et al.* [1991], using Raoult's law, defined an "effective solubility" level for a dissolved compound that is in equilibrium with a NAPL mixture. *Dupont et al.* [1998] termed this level as the "equilibrium concentration." The effective solubility or equilibrium concentration level is simply estimated by the compound's pure-phase aqueous solubility multiplied by the mole fraction of the compound in the NAPL mixture.

[25] Fresh gasoline composition: 10% (mole percent) MTBE [e.g. Zemo, 2006], 1% benzene, 2% ethylbenzene, 8.5% xylenes and 1% naphthalene [*e.g.* Johnson *et al.*, 1990]. LUST sites closed in 1999/2000 likely experienced petroleum release(s) prior to 1995.

[26] Sites with maximum benzene greater than 18,000 ppb: SiteMap_IDs 29, 60, 62, 76, 84, 92, 104 and 131.

[27] Sites with sheen and/or measurable free product and benzene > 18,000 µg/l: SiteMap_ID 60 and 131.

surprising given the relatively high solublity of benzene.[28] However, the observation from the sites with measurable FP (**Figure 11**) that their naphthalene data did not exceed naphthalene's effective solubility was surprising. A better correlation was expected for naphthalene because its lab-determined effective solubility closely matched its theoretical solubility [Zemo, 2006]. The seemingly poor correlation for the naphthalene concentrations is partly due to the lack of naphthalene data for the database sites – only 12 of the 20 sites where measurable FP was observed (**Figure 11**) had naphthalene data.

Unlike the naphthalene data, the groundwater concentrations for both ethylbenzene and xylene were available for all 20 sites with measureable FP.[29] Fewer sites exceeded either ethylbenzene's (E's) or xylenes' (Xs') effective solubility compared to naphthalene's (**Figure 12**). Yet out of the 20 FP sites in **Figure 11**, 10 sites exceeded either ethylbenzene's or xylenes' effective solubility, thus underscoring the fact that these compounds may have a more relevant role (compared to benzene or MTBE) when assessing whether FP is or was present at a site.

Of the other 10 sites that did not trigger either E's or Xs' effective solubilities, the reviewers noted that 8 sites had a diesel or fuel oil release, so the assumption of fresh gasoline would not apply. At the non-gasoline sites, either much-lowered effective solubilities (as the mole fraction for either E or Xs in diesel is 20x lower compared to gasoline) or PAH groundwater concentrations might have been better FP indicators. Unfortunately, naphthalene was the only PAH compound captured for the database. Because naphthalene was monitored at considerably fewer sites than BTEX, it is unlikely that other groundwater PAHs were typically included in site investigations.

A more general insight from **Figure 12** regards weathering of petroleum product in the source zone. Weathering preferentially strips the more soluble volatile components from the LNAPL, so that less-soluble VOCs, like naphthalene, xylenes and ethylbenzene, may be more indicative of the NAPL than either B or MTBE. When a NAPL is present, invoking a fuel:water partitioning coefficient[30] [i.e., K_{fw} in Cline et al., 1991] may better explain the observed VOC concentrations. Cline et al. [1991] tabulated the average K_{fw} values for MTBE (15.5) and benzene (350). Assuming a NAPL with Cline et al.'s [1991] fresh gasoline composition, these K_{fw}-estimated values predict groundwater concentrations of 3,000 mg/l MTBE and 57 mg/l benzene[31] – concentrations that are very high compared to the observed values in **Figure 12**. The much lower observed concentrations likely point to preferential weathering of the highly soluble fuel components – that is, the presence of FP can not be determined using the concentrations

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[28] Zemo [2006] found that the laboratory-equilibrated effective solubility was determined to be considerably less than theoretical effective solubilities (for both benzene and MTBE). Difference from theoretical solubility may be even greater in the natural environment.
[29] Effective solubility for ethylbenzene and xylene from fresh gasoline is 3,400 µg/l and 13,600 µg/l, respectively.
[30] The coefficient K_{fw} for a fuel component is defined as the ratio between the component's concentration in the fuel (C_f) and its concentration in water (C_w).
[31] Cline et.al. [1991] assumed a fresh gasoline composition of 5% and 2% (by volume) of MTBE and benzene, respectively.

of the highly soluble fractions because the underlying assumption of NAPL composition has changed significantly over time.

At the other end of the spectrum is the less soluble naphthalene. Using the K_{fw} approach[32], a groundwater concentration for naphthalene of 245 ug/l may be indicative of a NAPL. Naphthalene concentrations at 36 database sites exceed this level – a number that is likely an underestimate considering that 42 (out of 133) sites have no naphthalene data. This highlights the fact that naphthalene composition in weathered, residual NAPL may approximate that of relatively fresh product. Therefore, while the use of K_{fw} is dependent on knowing the NAPL composition, using "fresh" gasoline composition as an estimate for the NAPL is less problematic when applied to the relatively low-solubility petroleum components.

Of the approaches described here for delineating petroleum source zones, the least reliable method is the measurement of floating FP. By including in the assessments the low solubility components using a NAPL:water partitioning coefficient (K_{fw}), we may increase the reliability of identifying zones of residual NAPL. Because almost all petroleum releases at LUST sites have undergone some degree of weathering, analysis of low-solubility fractions, particularly naphthalene and other PAHs may more likely reflect the presence of residual NAPL and be more useful in identifying source zones.

5.4 Remediation at LUST Sites that Closed Between 1999 and 2000

Remedial actions (e.g., any remedy besides tank system removal and groundwater monitoring) were applied to 95 sites (or 71% of the 133 database sites). **Table 2** shows that that a number of remedial strategies were employed at these sites. The most common remedy, soil excavation, was performed at 85 sites. Pump and treat of contaminated groundwater occurred at 33 sites. A few of the sites (17) in the database have information on the amount of contaminant mass removed exclusive of soil excavation. This study does not assess the effectiveness of the various remedial actions.

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[32] The Kfw values for MTBE, benzene, ethylbenzene and xylenes are: 12, 310, 4500 and 7100, respectively. Cline et al. [1991] did not tabulate a K_{fw} for naphthalene, but showed an inverse relationship between a components's K_{fw} and its aqueous molar solubility. The aqueous solubility for solid naphthalene is 31 mg/l. Cline et al. [1991], however, suggested not using the solid solubility, but that of the super-cooled liquid. The super-cooled liquid solubility is the solid solubility divided by a correction factor that is dependent on the chemical's melting point. For naphthalene, this correction factor is 0.28 [Cohen et al., 1993, p. 9-46], so the aqueous solubility for naphthalene (corrected for its melting point) is 110.7 mg/l, which can easily be converted to a molar solubility by dividing by naphthalene's molecular weight. The molar aqueous solubility for naphthalene and ethylbenzene are 8.6e-4 mole/liter and 1.6e-3 mole/liter, respectively, and the ratio of the solubilities is 0.5375. This is also the ratio of the K_{fw} for ethylbenzene and naphthalene. The average K_{fw} for ethylbenzene is 4,500 [Cline et al., 1991, Table III], therefore we can calculate a K_{fw} for naphthalene of 8,370 (i.e., 4,500/0.5375). Further using Cline et al.'s 0.2% (by volume) naphthalene in fresh gasoline and naphthalene's density of 1.025 g/ml [CRC, 87th Edition], we calculate a C_f of 2,050 mg/l. Therefore, the predicted C_w for naphthalene is 245 ug/l (2,050 mg/l divided by 8,370).

No remedial action (besides tank pull) occurred at 38 sites (or 29% of 133). **Table 3** classifies these 38 database sites by their geologic setting. While the database of 133 sites included less than 40% clay sites, the non- remediated subset included 58% clay sites. Extrapolating this information suggests that, prior to 2001, remedies were not applied to approximately 4 out of 10 clay sites while only about 2 out of 10 non-clay and bedrock sites were not likely to be actively remediated. These statistics most likely reflect the shifting nature of the regulatory climate as contaminated LUST sites were discovered. As a test of this changing-regulatory-climate hypothesis, we looked at the "start dates" for the database sites. (The "start date" is the date a petroleum release was first reported to the DNR.)

Figure 13 shows time lines of the start date for the 133 database sites. The time lines were organized by the site geology categories (clay, non-clay, bedrock) and whether a remedy was implemented (Remed-Yes) or not (Remed-No). The effective date of the 1996 "flexible closure" rule is indicated in the figure. Overall, the proportion of sites not actively remediated increased after this date, consistent with the changing-regulatory-climate hypothesis. While clay sites were more likely to have no remediation (i.e., natural attenuation only) even before the implementation of the 1996 flexible closure rule, the likelihood for accepting a no-remediation approach at a clay site became more pronounced after the implementation date. It is likely that no remedy was applied to clay sites due to the limited groundwater flow and low perceived risk associated with these sites. Even though this study only looks at sites that closed between 1999 and 2000, there was an evident shift in emphasis from active remediation to natural attenuation-only remedy soon after flexible closure was allowed. Whether the shift became more pronounced or not after 2001 when additional administrative rule changes became effective is beyond this study's time frame.

5.5 Groundwater Contaminant Concentrations - Historical-Maximums and Closure-Maximums

Benzene is the primary contaminant driving most LUST investigations and cleanups. (However, there are database sites where benzene concentrations were very low and other contaminants drove cleanup decisions.) Benzene was the contaminant most frequently measured and monitored (132 out of 133 sites had results for benzene in groundwater). Slightly fewer sites assessed MTBE concentrations (124 sites), and considerably fewer sites (96) assessed naphthalene. The database includes groundwater concentration history from each monitoring well at the 132 sites with groundwater information. The histograms of the sites' historical maximum benzene, naphthalene and MTBE concentrations in the groundwater are shown in the upper bar graphs in **Figure 14**. The intervals in the histograms are base-10 factors of the respective groundwater enforcement standard (ES) of 5 ppb (benzene), 100 ppb (naphthalene) and 60 ppb (MTBE). The histogram shows that historical maximum benzene concentrations range over 7 orders of magnitude while maximum naphthalene and MTBE concentrations span more than 6 orders of magnitude. The historical maximum benzene, naphthalene and MTBE data from the sites had medians of 1,200 µg/l, 170 µg/l and 60 µg/l, respectively, which are multiples of 240, 1.7 and 1 compared to their corresponding ES.

The database was queried for each site's most-recent monitoring concentrations (i.e., latest concentrations before closure), and the maximum for each site was tallied. The term "closure maximum" is used to denote the highest concentration of a contaminant detected in the latest round of monitoring prior to closure. In almost all instances, the closure maximum was observed at the same monitoring well where the historical maximum concentration was observed or, if not, at another well very near it. In contrast to the historical-maximum concentration, the closure-maximum concentration is the level specifically noted in the deed restrictions for many of the closed sites.

A plot of the closure-maximum histograms is shown below the historical-maximum histograms in **Figure 14**. The range for the closure maximum concentrations has narrowed by an order of magnitude when compared to the range for the historical maximum histograms. From the closure maximum histograms, the median statistics for the closure maximum data is 11 times benzene's ES, and less than 1 for the ES of either naphthalene or MTBE.

5.6 Monitoring for Natural Attenuation

Wisconsin's guidance on natural attenuation[33] defines the criteria for reduction in contaminant mass and concentration as well as plume margin behavior. The guidance states that groundwater monitoring should be performed over a period of time to establish that the contaminant plume is either:

- Receding spatially and that the concentration of contaminants is either declining or stable in the source zone and plume.

Or

- Stable spatially and that contaminant concentrations are declining in either the source zone or the body of the plume (as evidence that contaminant mass is decreasing). If contaminant concentrations are stable throughout the source zone and body of the plume then source zone actions should be undertaken to the extent technically and economically feasible, in an effort to reduce the contaminant mass.

To comply with the administrative rule requirement that natural attenuation processes be documented prior to closure, groundwater contaminant concentrations, particularly of benzene, have been observed over time. **Table 2**, shows that the period of groundwater monitoring at the database sites ranges from 1 year (at 14 sites) to more than 10 years (at 2 sites), with a median total monitoring period of 4 years. However data on groundwater

[33] Wisconsin Department of Natural Resources, Guidance on Natural Attenuation for Petroleum Releases, PUB-RR-614, March 2003. http://dnr.wi.gov/org/aw/rr/archives/pubs/RR614.pdf

quality is considerably less than a 4 year monitoring time period may suggest because significant breaks in monitoring occurred at 64 sites (or 48% of the sites).

5.6.1 Comparison of the Groundwater Historical-Maximum and Closure-Maximum Benzene Concentrations

This section provides further analysis of the groundwater benzene data. This assessment is simplified by looking only at the historical-maximum and closure-maximum benzene concentrations. The 2 histograms on the left side on **Figure 15** show the same historical-maximum and closure-maximum benzene histograms included in **Figure 14**, delineates the remediated (94 sites) from the non-remediated (38 sites) sites. A table with the associated categorical statistics is shown in **Figure 15**. Considering their median and arithmetic means, the remediated sites (Remed-Yes) typically started out with much higher historical-maximum benzene levels than the natural attenuation-only (Remed-No) sites. Yet at closure, the mean for the remediated sites is lower. The indication from this categorical comparison is that improvement in the groundwater quality is more notable for a typical remediated site as compared to a typical natural attenuation-only site.

The historical-maximum and closure-maximum benzene concentrations, although separated by time, were usually observed from the same monitoring well or from wells that are in close proximity to each other. The sampling dates corresponding to these concentrations are in the database, so it is straightforward to determine a contaminant decay rate from their ratios. In doing so, the apparent decay rate determined by their ratio will typically not underestimate the decay rate from a least-square regression of all available data, but may provide an overestimate, particularly if monitoring was conducted over a short period of time. Additional analysis is provided here regarding the ratios, but the analysis is not in the context of estimating decay rates.

5.6.2 Length of Monitoring After Historical-Maximum Benzene was Observed

The 3rd histogram in **Figure 15** (right side) is a plot of the count of sites versus the length of the monitoring period (in 0.5-year increments) defined by the time interval between observation of the historical maximum the closure maximum.[34] The median for all sites was 2.6 years. The **Figure 15** histogram is further categorized by the implementation of a remedy. A considerably shorter monitoring period occurred after the historical-maximum benzene was observed at non-remediated sites. The statistics show that half of the non-remediated sites in the database were monitored for slightly over 1 year, with only one (1) non-remediated site monitored longer than 5 years after its historical-maximum benzene was observed. (This latter site is one of the field sites in this study, so post-closure data are available.) In comparison, half the remediated sites were monitored for 3.5 or more years, with one site monitored for just over 10 years after its historical-maximum benzene was observed. The relatively longer monitoring period after observation of the historical maximum benzene at remediated sites is due in part to an

[34] The date of historical maximum is the date the highest concentration of benzene was found at any well on the property before the final sampling round. The date of closure maximum is the date of the most-recent sampling before closure was approved by a State agency.

administrative code that requires a site to monitor for groundwater quality improvement after ending a remedy. For the remediated sites, the median period from when a remedy (typically soil excavation or groundwater pump and treat) was ended to the most-recent groundwater sampling was 1.9 years.

The length of time benzene was monitored after observation of the historical maximum spans from 0 to more than 10 years. Whether the benzene concentration factored into the length of the benzene monitoring period was assessed by a regression analysis, the results of which are shown in **Figure 16**. The upper plot in **Figure 16** includes all available data, and the lower plot categorizes the data from the 93 remediated sites and the 38 non-remediated sites. The squares of the correlation coefficient (R^2 shown in the figure) from the different regressions were small, yet because of the number of points in the analysis, all the R^2 results are significant at an α=0.05 t-test[35]. We can conclude that there is a relationship between the historical maximum benzene concentration and length of benzene monitoring, but the correlation is poor. The slope from the semi-log regression results indicated that there is approximately 1 year of additional monitoring for every 10-fold increase in benzene concentration. From the regression equation in **Figure 16**, one (1) year of monitoring can be expected for a site with a maximum benzene concentration of 10 µg/l, and only 3 years when the maximum benzene is 1000 µg/l. An even shorter 0.4 yr of additional monitoring for every 10-fold increase in benzene concentration is indicated in the regression analysis for the non-remediated subset. The results indicate that the historical benzene maximum level is not much of a factor in the length of monitoring at a site. Moreover, when no remedy is performed, site closure occurs much sooner, even for sites where the benzene level was greater than 10,000 µg/l.

5.6.3 Contaminant Reduction Achieved over the Monitoring Period

The benzene data were further assessed in this study by looking at the ratio of the closure maximum relative to the historical maximum. With the exception of 7 sites (e.g., SiteMap_ID 48 and112) where the historical-maximum benzene concentrations were the latest-observed concentrations before closure, the historical-maximum and closure-maximum concentrations are temporally separated. As mentioned previously, a decay rate can be estimated from the ratio of the historic and closure maximum, however relatively fast decay rates may be an artifact of short monitoring periods. This is particularly likely for the non-remediated (natural attenuation-only) sites. Therefore, a simpler comparison of the ratios was performed.

The observed historical-maximum and closure-maximum concentrations at a site were generally not separated spatially. Both maxima are typically from the same near-source monitoring well, so their ratio can be thought of as an inverse measure of the improvement in the groundwater quality at or near the source. A ratio of 1 indicates little to no improvement; the smaller the ratio, the greater the water quality improvement. For example, if the ratio is 0.1, then a 90% reduction in the benzene concentration relative to its historical maximum was observed. For sites where the closure-maximum benzene did not exceed 5 µg/l (or benzene's ES), benzene was not a factor in the agency's closure

[35] See Triola's [1998] table with critical R values

decision. There were 26 such sites (6 of which were non-remediated sites) in the database. These 26 sites were not included in the ratio analysis. For the 106 sites that closed above the enforcement standard of 5 μg/l benzene, the geometric mean for their ratios is 0.1, so as a whole there was an average of 90% reduction in the benzene concentrations. The geometric mean for the ratios was used as a simplification because the ratios range over 2 orders of magnitude.

To visualize the ratios, the data from the 106 sites that closed with above-ES benzene levels are shown in **Figure 17.** **Figure 17** is a log-log plot of the data, with the closure-maximum concentrations plotted on the y-axis (Y), and, the historical-maximum concentrations plotted on the x-axis (X). The dashed lines represent different slopes in the plot. When the Y/X ratio is near 1, then the ratio plots near the dashed "Slope = 1" line, and when the ratio is less than 0.01 (meaning more than 99% improvement), then the ratio plots below the dashed "Slope = 0.01" line. The symbols on the plot are used to categorize the sites by geology and by whether a remedy was implemented.

The lowest ratios (and largest improvement in water quality) are associated with sites where remediation occurred, regardless of geologic setting. There are several apparent incongruities in the plot of the data. At the low end of **Figure 17**, two[36] conspicuous non-remediated sites had ratios less than 0.01. The time interval between the historical and closure maximums for both these sites is less than 1 year, so if true, the benzene decay rate at these sites would be impressively fast - much faster than published literature values. However, upon closer scrutiny, the ratios at these 2 sites appear to be artifacts. One site had a groundwater flow azimuth change of 170^{o}, and at the other site, the historical-maximum benzene result came from a one-time grab sample at a geoprobe boring that is 60 ft upgradient from the monitoring well where the closure maximum was observed. When these factors are considered, it is likely that the closure/historical maximum ratio for these 2 non-remediated sites do not adequately represent groundwater-quality improvement.

Another incongruity is at the high end of the plot. While a high ratio (1 or nearly 1) may be expected at sites with no remediation, out of the 10 sites with the largest ratios, six (6) were remediated sites.[37] With their varied geology (3 clay, 2 non-clay and 1 bedrock), it is more difficult to explain this high-end incongruity in the ratio data. One non-clay site's ratio may be an artifact due to the exclusion of an early no-detect result because of a high lab detection limit (1,000 μg/l). The site with the highest closure benzene (5,790 μg/l) in this group (SiteMap_ID 112) was an active retail petroleum station throughout its cleanup and after closure. This site had a pump and treat system, and the increasing benzene may be a rebound effect after the P/T shutdown or an indication of another release.

[36] The 2 non-remediated sites with closure/historical maximum ratios of less than 0.01 are with SiteMap_IDs 42 (a clay site) and 64 (a non-clay site).
[37] The 6 above-ES remediated sites with seemingly no benzene improvement are SiteMap_IDs 32, 48, 101, 107, 112, and 118.

Notwithstanding the incongruities, the comparison of the ratios from the categories of remediated and non-remediated sites seems to indicate a difference between them. The geometric means of the closure/historical maximum ratios are tabulated in the summary table included in **Figure 17**. We are not able to determine whether the difference between the geometric ratios of the remediated and non-remediated sites in the summary table is statistically significant. There are more than twice as many remediated sites as non-remediated sites, and this simple assessment ignores the time factor associated with each ratio. Taken at face value, however, the comparison of geometric means shows that the clay sites as a group had higher closure/historical maximum ratios, with the non-remediated clay sites ratio (0.30 or 70% reduction in contamination) indicating less improvement in contaminant concentration than any other category. Coupled with the generally shorter monitoring time frames at non-remediated sites, projecting any future reduction in contaminant concentrations at these sites would be spurious. Only one (1) non-remediated clay site (SiteMap_ID 95) was monitored for more than 2 years after its historical-maximum was observed, apparently due to the fact that contamination had migrated off-property into the adjacent right-of-way and street.

One to two years of monitoring applied to LUST sites is generally not long enough to establish contaminant degradation trends and determine effectiveness of natural attenuation processes [e.g. NRC, 2001, p. 19], especially given the high levels of initial benzene concentrations found at many of the database sites. This analysis of the benzene historical and closure maxima, their ratios and the time interval between them appear to indicate that upon receipt of a closure request, there may be a greater willingness on the part of the agencies to close sites than is justified by observations of benzene degradation actually taking place at many of these sites.

5.7 Statistical Tests Applied to the Groundwater Benzene Data

Plume maps delineating contaminant location and concentration over time would be helpful in assessing plume stability, however, such maps were typically absent from site investigation reports. Moreover, site investigation reports typically did not contain results from trend analysis for the data collected from monitoring wells. Out of 133 sites, 48 sites (see **Table 2**) reported a degradation rate in the site investigation reports, but only 8 sites had any statistical trend test on the groundwater quality data. The clear indication is that while it was routine to compare groundwater quality data to groundwater standards in site investigation reports, data trend analysis and assessment were not routine. This may be due to the fact that, although state and federal guidance existed, statistical procedures were not mandated in the regulations at the time of closure review for these sites.

Here we assess the statistical tests[38] Wisconsin added to administrative rules in January 2001. While these tests were not considered in the closure decisions of the 133 database

[38] Wisconsin NR 746 and COMM 46 Administrative Codes are identical. The codes are titled, "Risk Screening and Closure Criteria for Petroleum Product Contaminated Sites, and Agency Roles and Responsibilities"

sites, the systematic application of the nonparametric tests was undertaken to gain insight into the usefulness of these statistical tools in assessing groundwater quality trends and hence their utility to future closure decisions. The statistical tests were applied only to sites that closed with benzene concentrations greater than ES (5 μg/l).

The code includes procedures for 2 nonparametric statistical tests – the Mann-Kendall test and the Mann-Whitney U test – in assessing trends in the data observed from each monitoring well at a petroleum site. In this study, these nonparametric statistical tests were applied to the benzene data from a single well – a near-source monitoring well where the closure-maximum benzene was observed – at each of the database sites. This near-source well was generally, but not necessarily, the same well where the historical-maximum benzene was observed. A simplified summary of the results is shown in **Table 4**. (Individual site analysis can be found in **Appendix L**.)

From left to right, the columns in **Table 4** list the SiteMap_ID, indicate whether the site was remediated, the historical-maximum benzene concentration, the most-recent (i.e., closure-maximum) benzene concentration, the specific monitoring well where the most-recent benzene levels were observed, and the results of the statistical tests using up to 8 benzene data points. Because not all sites have 8 data points, the number of data points used in the statistical procedures for each site is indicated in the 8th column of **Table 4**. The rightmost 3 columns are the results of the (parametric) time-regression analysis of the benzene data set used. The regression results are expressed in terms of a benzene "half-life" ($t_{1/2}$, yr) that was estimated from the slope of a least-square line fit to the logarithm of the benzene concentrations. A negative $t_{1/2}$ indicates an increasing trend. A nominal α=0.1 was applied to the statistical *t*-test for significance on the square of the correlation coefficient (r^2) associated with the line fit. To pass the *t*-test for significance, r^2 must be greater than 0.8 when only 4 data points are available, and greater than 0.4 when 8 data points are used. A "yes" in the last column of **Table 4** means that the r^2 was statistically significant, indicating a good correlation between benzene concentration and time. Of the 133 sites, 112 sites had 4 or more testing rounds where the most-recent round was above benzene's groundwater standard (5 μg/l). Only 37 sites (or 33% of 112) had a significant r^2. Therefore there was not a good correlation between benzene concentration and time for two-thirds of the sites in this study. This is partly because of insufficient data (e.g., only 4 sites – or less that 4% of 112 – that had 5 or fewer data points available were found to have significant r^2), and partly to the large fluctuation typically observed in benzene concentrations at near-source wells.

For the two nonparametric statistical tests, the current code-specified approach in Wisconsin is as follows:

- Use an α = 0.1 (90% confidence level) Mann-Whitney U test on 8 observations at set intervals (quarterly or semi-annual).

- Use an α = 0.2 (80% confidence level) Mann-Kendall (M-K) test on a minimum of 4 observations with no defined time interval. An extension to this test, the coefficient of variation (CV), is applied to contaminant data when the M-K returns a “no trend” result. A “no trend” M-K with a CV < 1 is interpreted to mean the contaminant plume is “stable.” The CV extension was implemented following Wiedemeier et al. [1999].

5.7.1 Nonparametric Mann-Whitney U Test

Between the 2 nonparametric tests, the Mann-Whitney U test turned out to be more restrictive in its application simply because it requires 8 rounds of data. Of the 133 database sites, only 70 had 8 or more rounds of benzene data at a near-source well. Of these 70 sites, only 55 (or 41% of 133) had benzene concentrations greater than 5 ppb at closure. Applying the Mann-Whitney U test to data from these 55 sites, a trend in the benzene concentration could be distinguish for only 16 sites (or 29% of 55), and not be distinguish at 39 sites (or 70%) of these sites. Of the 16 sites where a trend was detected, 9 sites had indications of a decreasing benzene trend from their respective near-source wells, and 7 sites had an increasing benzene trend. The 7 sites with increasing benzene trends are marked with a red “No” in the 9th column of **Table 4** for the Mann-Whitney result to distinguish these results from the “No” result where the test was unable to discern any trend.

Because 55 sites might not be a large enough sample to render a conclusion on the usefulness of the Mann-Whitney U test in discerning contaminant trends, we loosened the constraint by including sites with less than 8 rounds of data. Theoretical consideration shows that the test will still be able to meet the code-specified $\alpha = 0.1$ significance level at sites with as few as 6 sample rounds. With the relaxed constraint of a minimum 6 rounds, 79 sites (or 59% of the database sites) that closed above 5 ppb benzene were included in the assessment of the Mann-Whitney U test. With this modification, the Mann-Whitney U statistic was computed using the earliest set of 4 observations which were then compared to a later set of between 2 to 4 observations. The additional analyses helped provide a perspective on the power of the Mann-Whitney U test and allowed conclusions from this test to be compared to the Mann-Kendall test.

A “Yes” in the Mann-Whitney column (9^{th} column) of **Table 4** indicates that a decreasing trend is discernible. A red “No” indicates an increasing Mann-Whitney U trend result, which is highlighted only for the 7 sites with 8 data rounds. The rest of the “No” results mean the Mann-Whitney U test was inconclusive either because there was truly a flat trend or there were too few data to discern any trend.

Based on the Mann-Whitney U test results from 79 sites, only 15 sites showed decreasing trends. Including the 7 sites with increasing trends, the Mann-Whitney U test detected benzene data trends at 22 sites, or less than 30% of the 79 sites with at least 6 data rounds. This analysis detected a trend at about the same proportion as the smaller subset of 55 sites with 8 data points. An implication of this analysis is that a blanket application of the Mann-Whitney U test at all LUST sites may likely lead to inconclusive results for as many as 70% of sites even when 8 rounds of data are available. **Figure 18** contains histograms summarizing the results of the Mann-Whitney U and Mann-Kendall (discussed below) trend analyses.

5.7.2 Nonparametric Mann-Kendall Test

Wisconsin rules also allow the use of the Mann-Kendall test in determining a trend in monitoring data even at a site with as few as 4 rounds of data because theoretically an $\alpha = 0.2$ test level is achievable with this minimum data set for this nonparametric test. For the evaluation here, the Mann-Kendall test was systematically used twice to qualitatively test the hypothesis that the outcome from the nonparametric test can change depending on the number of rounds included in the analysis. The first application (**Table 4**, column titled "Mann-Kendall [1st instance]") included the same 6 to 8 rounds of data that were used in the Mann-Whitney U test. The second Mann-Kendall application ([2nd instance] column, **Table 4**), included only the 4 most-recent data rounds.

The 1st instance and 2nd instance Mann-Kendall tests were applied to the 79 sites included in the Mann-Whitney U test assessment. A simple comparison of these trend analyses results (excluding the inconclusive trends) is presented in **Figure 18**. The histograms show the count of the sites where a trend was determined by each test – either decreasing (left histogram) or increasing (right histogram). One general observation is how "short" the histogram heights were relative to the possible total of 79 sites. The height difference between the Mann-Whitney U (left rectangle in either histograms) and the 1st instance Mann-Kendall (middle rectangle) is expected because their α-levels were different. The Mann-Kendall test with its higher α is expected to detect a trend at more sites. It is important to note that the sites where a trend was detected by the Mann-Whitney U test are a subset of the sites where a trend was detected by the 1st instance Mann-Kendall test. In other words, when the Mann-Whitney U test showed either a decreasing or increasing trend, the result was mimicked by the Mann-Kendall test, using the same data set. However the results from the 2 tests may differ for a site where the Mann-Whitney U test does not detect a trend. The Mann-Kendall test, with the higher-level α, may detect a trend for the same site.

The comparison between the 1st and 2nd instances of the Mann-Kendall tests is not straightforward, even though both procedures were tied to the same α=0.2 level. The comparison points to the problem of allowing as few as 4 data points for determining whether a trend exists. **Figure 18** highlights the different conclusions of the Mann-Kendall test depending upon the number of data used. When only the 4 most recent rounds of benzene data are used instead of 6 to 8 rounds, the Mann-Kendall test not only discerned a trend in fewer sites (34 sites or only 43% of 79 sites), but those sites were not necessarily the same sites where either the Mann-Whitney U or the Mann-Kendall (6-8 round) test detected a trend. The Mann-Whitney U test detected a decreasing trend at 15 sites. The 1st instance Mann-Kendall test also concluded that all 15 sites had decreasing trends. However, the 2nd instance Mann-Kendall test discerned a decreasing trend at only 7 of those 15 sites. (Compare the "Yes" results in the Mann-Whitney column with the Mann-Kendall [2nd instance] results.) At 2 sites[39] where the 2nd instance Mann-

[39] SiiteMap_ID 7 and 81 had increasing Mann-Kendall trends when 8 rounds of data were used in the test.

Kendall test concluded a decreasing trend based on the 4 most recent data rounds, increasing trends were detected when 8 rounds of data were considered. A standardized approach is needed in order to reduce these types of inconsistent results.

Among the 3 nonparametric test procedures (Mann-Whitney U, Mann-Kendall 1st instance and Mann-Kendall 2nd instance) systematically used to evaluate the benzene data from a near-source monitoring well at 79 sites, the Mann-Kendall 1st instance procedure was able to conclude a trend existed for the most number of sites. When 6 to 8 data points at a site are used, the $\alpha = 0.2$ Mann-Kendall test was able to discern (either a decreasing or an increasing) trend at 41 sites (or 51% of 79 sites), compared to 22 (<30%) where the Mann-Whitney U test discerned a trend). This implies the Mann-Kendall test with $\alpha=0.2$ may be useful in determining a trend at 1 of every 2 sites when sufficient data (minimum 6 rounds) have been collected.

Despite this apparent utility, a problem arises for approximately 50% of sites where the Mann-Kendall test fails to discern a trend. Currently, rather than attributing an inconclusive trend result to a lack of data or to the lack of power in the nonparametric test, an inconclusive result may be erroneously interpreted as “stable” due to a procedural consequence of state administrative rules. Administrative rules require that the coefficient of variation (CV) of the data be calculated when the results of the Mann-Kendall test are inconclusive.

5.7.3 Bias in the Coefficient of Variation Extension to the Mann-Kendall Test

When the Mann-Kendall test fails to indicate either a decreasing or an increasing trend (i.e., a “no-trend” result), Wisconsin rules added the calculation of the coefficient of variation[40] (CV) of the observed concentrations at monitoring wells as a test for stability. A “stable” trend is one where the CV for the concentrations observed at each monitoring well at the site is less than 1. The CV is a measure of variance of the data relative to the average of the data. A set of stable observations is expected to have CV < 1; however, having CV < 1 is not an assurance of a stable plume margin. While a set of stable observations may be expected to have a low variance, a plume that is expanding may have a high average concentration. The bias in using the coefficient of variation to determine stability is that a data set with a high average concentration may more likely pass the CV “stability” test compared to a site with a low average concentration.

The bias against sites with low concentrations can be easily shown by comparing the benzene data and CVs from two sites whose 8 rounds of data are enumerated below:

1.) Site Map_ID #62: 2,700; 15,000; 18,000; 2,300; 12,300; 10,000; 6,600; 6,900;

and

2.) Site Map_ID #54: 39; 4; 110; 3; 36; 16; 22; 17.

[40] Coefficient of Variation (CV) is equal to the standard deviation divided by the arithmetic mean. Note that when the arithmetic mean is large, the CV is small.

The Mann-Kendall tests from both these sites were inconclusive regarding a trend ("no trend" result), so their CVs were calculated in accordance with Wisconsin rules. Site SiteMap_ID 62 has an average benzene concentration of over 9,200 µg/l and a CV = 0.6, and thus passes the “stability” test. On the other hand, SiteMap_ID 54, with an average of only 31 µg/l, but a CV = 1.1, fails the “stability” test.

Because the CV test is conducted only after the Mann-Kendall test fails to detect a trend, it might be misconstrued as part of the nonparametric test when in fact, it is not. Statistics can only be used to show that data are different from the null hypothesis. Statistical analysis can not be used to show that data are the same. A statistical test can only conclude that the concentrations are increasing, decreasing, or unable to detect a trend. Not detecting a trend is not the same as a stable trend.

The current use and interpretation of the CV test may actually impede further monitoring or remedial action at a site because there is no incentive to collect enough data to provide definitive statistical support for declining concentrations over time. Additional data collection is likely needed where the minimum four sample rounds is collected for the Mann-Kendall test and at sites with relatively high contaminant concentrations. Hence, the current statistical protocol needs to be changed to eliminate the CV test (and with its elimination, the bias it introduces) and use the nonparametric test alone to determine whether the data suggest a trend. If, after collecting enough rounds (up to 8 quarterly rounds), the nonparametric test still indicates no trend, then the concentration level, along with hydrogeologic and plume information, should be the crucial information used to determine future action for the site.

6. RESULTS OF FIELD STUDY

The following discussion explains and assesses the data collected for the 10 field sites included in this study.

6.1 Background Information and Time Lines for Field Sites

The field portion of this study, including installation of soil borings and temporary groundwater monitoring wells, was undertaken in the summers of 2004 and 2005. Groundwater samples were collected through May 2006. **Figure 19** shows the locations of the field sites. **Appendix A** contains the site map for each field site. The map is followed by a figure with a time plot of the benzene levels and depths to the water table observed at the most contaminated well (closest to the source zone) for each site. (The time plots and depth to water plots are compiled in **Figure 23**.) This gives a perspective on the historical and more-recent water quality observations. This plot is followed by a compilation of post-closure detected groundwater VOC results (benzene, total xylenes, total BTEX, MTBE, total TMBs and naphthalene) from at least 2 post-closure rounds of groundwater samples.

Additional groundwater samples were collected during this study for the analysis of the gasoline additive 1,2-dibromoethane (ethylene dibromide or EDB) at 8 of the 10 field sites as part of U.S. EPA's nationwide EDB study[41] [Wilson and Adair, 2007] which began sample collection during the 2005 field season. The available EDB results are in **Appendix A** following the BTEX results.

Soil sample results for GRO, benzene, total BTEX, MTBE, TMBs and naphthalene for this study can be found in **Appendix A** following the EDB results. Soil samples results are not available for 3 of the 10 sites due to breakage of samples in transit.

Table 5 lists the 10 field sites and the timeline for each from the original site investigation (upper part of table) to the post-closure investigation (lower). In **Table 5** and subsequent tables, each site is categorized by whether it is a former petroleum retail station (4 sites) or non-commercial petroleum station (6 sites). The conditional closure date listed for the previous site investigation typically represents the date the agency decided the site qualified for closure and is the date used by this study to select sites closed in the time period between 1999 and 2000. Final closure was issued after administrative requirements, such as filing deed restrictions and removal of monitoring wells, were met.

The retail/non-retail nature of the original properties provides a natural classification for the field sites. The most observable difference between the retail/non-retail sites is their current land use. The four former retail stations have all been razed such that previous

[41] Leaded gasoline up to the late 1980s - when lead was phased out - may have as high as 190 mg/l EDB [e.g., Cline et al., 1991].

site investigation map features are now unrecognizable[42]. In contrast, many site investigation map structures at the six non-commercial sites are still present, easily recognizable and provided easy reference points for the post-closure investigation.

Table 6 contains additional historical timelines related to site remediation and short comments on some relevant site information. Two non-commercial sites[43] were of particular interest because consultants had projected a time frame of less than 5 years for attainment of groundwater quality standards near the former UST locations. The projections could be tested for accuracy by the post-closure field investigations which were conducted more than 5 years after the sites closed.

The M. Sc. theses by Keller [2005] and Greve [2007] describe the 10 field sites in detail. Rather than repeat their discussions and fieldwork details in this report, the theses are attached as **Appendices C and D** (Keller [2005] and Greve [2007], respectively). **Table 7** contains additional timelines related to the post-closure study, and lists the specific thesis page citations for each site. Each citation notes the particular page containing the geologic cross-section based on at least 3 soil boring logs from the site[44]. **Table 7** also contains information on when the post-closure VOC sample results became available. This is important to note because the most-recent post-closure data were not available when the theses were written. **Table 7** also contains a comment column regarding post-closure site features, information available for the site on the GIS Registry website, and the field investigations.

Appendix B contains site maps from the original site investigations to emphasize how the network of post-closure wells departed from the older network. For this study, post-closure temporary monitoring wells were labeled “TW” to distinguish them from the “MW” of the previous site investigations. The “TW” wells were generally installed at locations where the previous investigations had detected benzene in groundwater. At 9 of the 10 sites, “TW” water table wells were placed as far as or farther downgradient than wells installed for the previous site investigations. For this study, piezometers were installed at 8 of the 10 sites to define the contamination below the water table zone. At 5 sites, short-term (typically 1 or 2 days) depth-profiling wells where installed to collect groundwater samples below the water table using shorter (typically 6 inch to 2-ft) well screens. At one site where clay was encountered below the water table, the profiling wells were installed with 5-ft screens.

[42] Of the 4 retail stations, Woods Garage and Charles Packard Property are now highway rights-of-way. Former Grandma’s Restaurant is open land adjacent to the highway and became a county salt storage area after the post-closure well installation. Martin Oil is a city park comprised of open land.

[43] Consultants provided estimated time to meet numerical groundwater standards at SiteMap_ID 103 and 108.

[44] The cross-section page is about halfway through the detailed discussion of each site. Open the pdf version of the thesis and type the page number in the search function of the reader to quickly get to the pertinent site discussion.

6.2 Metrics for the Field Study

Determining a suitable set of metrics whereby data collected post closure could be compared to data previously collected during a site investigation (SI) was a challenge. We recognized early on that because the field sites were each located in different settings, with different SI consultants, site-to-site data comparison would be a problem. In addition, the post-closure investigation was very time-constrained such that our data may not be the most optimal. We dealt with the inherent difficulty by using several simple metrics for comparison.

The metrics used here primarily rely on groundwater quality data. In keeping with the database-study approach of using historical-maximum and closure-maximum levels, the post-closure maximum levels were used for comparisons. However, in addition to benzene, the assessment is expanded to include total BTEX, MTBE and naphthalene. Benzene (B) is of particular importance because post-closure monitoring wells were generally placed where B was previously detected during the SI. Total BTEX data is assessed because both the M.Sc. theses emphasized this metric. The fate of oxygenates post-closure are of particular interest to the regulatory community, so MTBE data is emphasized. Naphthalene (N) was not historically monitored as extensively as B at the field sites; however the naphthalene data allows assessment of a compound that is more retarded compared to BTEX.

The maximum (historical, closure and post-closure) levels assessed here were temporally separated by as much as 15 years for the benzene data. Spatially, however, much like the results from the database study, the later post-closure maximum levels were found in monitoring wells proximal to where the historical maximum level was observed. The farthest horizontal separation between wells where post-closure and historical maximum levels were observed was 50 feet at one site (Racine) where property use and traffic patterns made it impossible to install a well closer to the historic location where the pre-closure maximum was detected.

The plume footprint for total BTEX at the field sites were delineated in the 2 M.Sc. theses for two different times (closure and post-closure) and these results are used here as a metric for comparison. The pre-closure extent of the BTEX plume for the study sites was based on consultant interpretations from the previous SI report. In comparing pre- and post-closure plume dimensions, Keller [2005] used 10 ppb total BTEX concentration to delineate the plume extent while Greve [2007] used 1 ppb to delineate plume extent. Detail on methods of plume delineation can be found in each thesis.

We also assess whether the spatial detection frequency of contaminants at water table wells can be a useful surrogate for determining whether the plume has lengthened or not. The spatial detection frequency at a given time is the count of wells where a particular compound was detected divided by the total number of wells installed at the time. Three of the 5 field sites where BTEX plumes lengthened post-closure compared to closure also experienced an increase in their spatial BTEX detection frequencies post-closure as compared to the previous site investigations. This indicates that comparison of spatial frequencies at two different time frames is a useful metric to identify a site whose plume has lengthened over time. Similarly, spatial detection frequencies were determined for benzene, MTBE and naphthalene and their change from the previous investigation to post-closure investigation is another metric for comparison. The effect of water table fluctuation on benzene concentration is assessed to determine whether it is possible to project future contaminant trends.

Several sets of data, collected in the post-closure study, receive no or limited analysis here.

- Soil analytical data are not included because of quantitation problems.
- Ethylene dibromide (EDB) was measured but pre- and post-closure results were not compared. This is partly because EDB was not routinely analyzed in previous investigations – 5 of the 10 field sites have no pre-closure EDB data. Post-closure, EDB was analyzed at 8 sites and detected (detection limit, DL, of 0.02 ug/l) at 3 sites. At 2 of these sites, EDB was previously reported as not detected, but at much higher DL (0.4 ug/l or greater). At only 1 site (Rutland) did a post-closure sample confirm the presence of EDB pre-closure. At the Cambridge site, EDB was reported pre-closure once, but not detected post-closure.
- Only limited analysis of pre- and post-closure analytical data collected from piezometers are compared here because the screen lengths and depths of piezometers installed during the previous SI were not comparable to those of the post-closure piezometers.

Data tables provided in this report are a basis for comparing the various metrics discussed above. The tables highlight information that may affect interpretation of the data comparisons. For instance, the monitoring well where the highest BTEX was observed at a given site might be expected to be the same well where the highest B or N was observed. However, at 4 out of the 10 sites, the highest BTEX levels were observed at a different well than the well with the highest B or N -- this is highlighted in the tables. We attempt to provide alternative methods for assessing the information available, however, none of the approaches defined in this study are definitive by themselves but together they help put the post-closure data into context.

6.3 Comparison of Total BTEX Levels

The theses by Keller [2005] and Greve [2007] emphasized the total BTEX results from groundwater samples at the 10 field sites. Both contoured past and recent results so as to compare the historical BTEX plume footprint to the recent footprint from the post-closure results. Greve [2007] used all the post-closure concentration data available from water table wells and depth-profiling wells in determining map isoconcentration contours. In her contouring, she averaged the data from the depth-profiling wells, so that an average result - comparable to what would be expected if a single 10-ft screen was used rather than several shorter-screen wells – was used in her isoconcentration maps.

The information compiled in **Tables 8**, **9 and 10** is used in the following discussion of the closure/post-closure maximum BTEX levels and plume length. **Table 8** is a summary of the maximum historical, closure and post-closure BTEX concentrations for each field site. Because of the inherent biases in **Table 8** (discussed below), **Table 9** (comparison of plume lengths) and **Table 10** (maximum BTEX concentrations from water table wells only) help put the historical, closure, and post-closure BTEX data into context.

6.3.1 Maximum Closure BTEX and Highest Post-Closure BTEX Levels

The upper part of **Table 8** contains previous site investigation information on total BTEX data from samples collected from water table monitoring wells at the sites. The table includes the percent improvement at closure relative to the site's historical maximum BTEX level. An implicit assumption at closure was that the groundwater quality at the site would continue to improve and that the plume would shrink without any additional action. The intent of the post-closure data was to show whether improvement continued or not.

The lower part of **Table 8** is a tabulation of the highest post-closure total BTEX results found at the sites, regardless of the sample collection method. A "p" means the result was from a depth-profiling well sample; otherwise, the sample result came from a temporary water table well at the site. At all 10 sites, samples were collected that contained higher BTEX concentrations than the maximum BTEX concentration known to exist at the time of closure. In addition, post-closure BTEX concentrations from 2 sites exceeded the maximum historical concentrations recorded for those sites. However, this simple comparison is biased because at 3 sites, the respective highest post-closure BTEX levels were detected in samples from depth-profiling wells. The explicit intention of the short-screen profiling wells was to identify contaminated zones at depth in the groundwater. Therefore the quantitative percentages in **Table 8** showing negative improvement with regard to BTEX closure concentrations are not a good metric for comparison.

The influence of the one-time high levels found in depth-profiling wells can be seen in the post-closure isoconcentration plume maps generated by Keller [2005] and Greve [2007]. The plume "core" is better defined in the map from the 1st round of sampling when the one-time depth-profiling samples were collected. Later plume maps, relying solely on results from water table wells, show a more diffuse plume core.

6.3.2 Comparison of Closure and Post-Closure BTEX Plume Lengths

Keller [2005] and Greve [2007] contoured the total BTEX data, producing isoconcentration maps from both historical data and more-recent post-closure data for a "then and now" comparison. **Table 9** is a summary of closure and post-closure BTEX plume lengths; longer post-closure plume lengths are highlighted in red. **Table 9** lists the specific pages in the theses where the plume maps can be found and **Figure 20** is a compilation of the sites' plume maps from the theses.

The effect of the geological setting on plume length can also be discerned from **Table 9** and **Figure 20**. The longest plume (400') occurred at a bedrock site (Wood's Garage). Unlike the rest of the sites, the post-closure plume for Wood's Garage included concentration data observed from piezometers screened in the bedrock. While the non-clay Brown County site has the shortest post-closure plume length, the three clay sites[45] all had BTEX plume lengths of under 100'. It also appears that the lengths of the plumes in the clay sites were the least changed between closure and post-closure. The absolute difference between the closure and post-closure plume lengths for the clay sites is only about 25 ft. Greve [2007] determined that only one of the three clay field sites (Town of Rutland Garage) had a longer plume post-closure.

Both Keller [2005] and Greve [2007] recognized that the simple "then and now" map comparison must be qualified, and they include lengthy discussions on the qualifications. We can add a few more. Keller [2005], in particular, did not have the results available to him from the 2005 sampling rounds when a much-higher BTEX level was observed at 1 of his 2 former retail field sites. At this former retail station (Martin Oil), the highest BTEX concentration from a water table well available to Keller [2005] was 190 μg/l (December 2004 sample), which was not too different from the BTEX closure-maximum of 139 μg/l, but much lower compared to over 3,600 μg/l from the 2005 round.

To put the comparison of closure and post-closure BTEX plume lengths in context, **Table 10** compares total BTEX concentrations from water table well samples only. The upper part of **Table 10** displays the closure-maximum BTEX (same as in **Table 8**), and the lower part displays the post-closure maximum BTEX observed exclusively from water table monitoring wells (which excludes the "p" results of **Table 8**). **Table 10** shows 8 sites with maximum post-closure BTEX levels higher than the respective closure-maximum levels. The 2 sites exhibiting lower post-closure BTEX levels, as compared with their closure maximums, are also sites that did not have longer plumes (see **Table 9**), post-closure.

Table 10 contains other pertinent information: well-screen depth-range; depth-to-water when the maximum contaminant levels were observed; and range of the water table elevation fluctuation for the well. The inclusion of depth-to-water information helps qualify the post-closure BTEX maximum data. For example, did the post-closure well sample the same vertical horizon in the water column as the closure well at each site? **Table 10** shows that the water table was at approximately the same elevation when the closure and post-closure maximums were detected with the exception of the 3 clay sites (data highlighted in blue). The greatest difference in horizontal distances between the post-closure and closure wells (over 20 feet) also occurs at these 3 clay sites.

Of the 3 clay sites, Greve [2007] found only 1 (Rutland Town Garage) with a longer plume post-closure than at closure. For this site, the closure monitoring well (MW-3) sampled a different horizon than the post-closure monitoring well (TW-11). The Rutland Town Garage site exhibited a complex vertical heterogeneity with silty clay overlying more permeable gravelly sand. The deeper sand unit was the more contaminated zone

[45] The clay sites included in the field study are SiteMap_ID 34 (Rutland), 108 (Racine) and 126 (Oshkosh).

(>20 ft depth). Post-closure, three water table wells were installed with the screen bottoms located at depths of 21, 24 and 28 feet below ground surface. Post-closure well TW-11 was the deepest well (set at 28') with the longest screen and exhibited much higher BTEX concentrations than the 2 shallower wells. Of the 5 field sites where plumes were observed to lengthen post-closure (**Table 9**), Rutland Town Garage was the only site where the plume lengthened in both the downgradient and upgradient directions. This indicates that the previous SI for this site, with its lower BTEX concentrations, missed the highly contaminated zone identified in the post-closure study.

Tables 9 and **10** may also show that, given 2 sites with similar geology, a parallel relationship exists between BTEX plume length and depth to the water table. One non-clay site (Brown County Reforestation Camp) has the shortest post-closure plume length, and it also has shallowest water table (4') among the field sites. Another non-clay site (WI Lions Camp) has one of the longest plumes and the second deepest water table (>30'). While both sites had shorter post-closure plumes (compared to their respective closure plumes), the plume at the site with the shallower water table appears to have greater plume shrinkage.

Yet another factor for the difference in plume length between these two non-clay sites may be timing and extent of source removal. Both sites implemented a remedial pump and treat (P/T) system. Brown County undertook a major soil excavation during tank removal and soon after that implemented their P/T system. WI Lions did not implement P/T until many years after removal of the tank system. By the time the P/T system was implemented at WI Lions, BTEX was detected over 250 feet downgradient of the UST at the site's most distal well. At over 220 ft. the WI Lions plume is still an especially long plume for a non-commercial site.

Lastly, it appears that the BTEX plume at all 4 retail stations have enlarged post-closure. It is not immediately clear why this is so, although total contaminant mass remaining in the subsurface post-closure along with other factors mentioned above (geology, depth to water table and lack of or inadequate remediation) may explain these findings.

6.4 Assessment of Individual VOCs: Detection Frequency of BTEX, Benzene, MTBE and Naphthalene in Water Table Wells

While total BTEX provides one picture of the groundwater plume, does this picture change if individual VOCs are examined? The picture of the groundwater plume that emerges at these sites is dependent on which contaminants are examined. A case in point is the WI Lions Camp site where the post-closure water table well with the maximum BTEX was the well located nearest to the former UST. However, even though the total-BTEX (2,995 µg/l in the first sampling round) was high, benzene was not detected in 2 rounds of samples collected from this well. This is notable because 8 years before closure or 14 years before post-closure sampling, a groundwater sample from a similarly located monitoring well near the former UST had 210,000 µg/l benzene – which may be the highest groundwater benzene concentration ever found in Wisconsin. The monitoring well at the WI Lions Camp site with the highest benzene at closure and similarly in our post-closure investigation was located 70 ft downgradient of the former UST.

One way to quickly evaluate the plume extent and the different pictures that emerge with individual VOCs, without contouring individual results on a map, is to assess the spatial detection frequencies in the monitoring network. A compound's spatial detection frequency at a given time is the count of wells where a particular compound was detected divided by the total number of wells installed at the time. With a fixed monitoring network, an increase in the spatial detection frequency from one time to another time indicates that the compound is migrating, and, hence, that the plume is expanding.

Because the monitoring well network from the previous site investigations was the basis for placement of the post-closure monitoring wells, the previous SI network and post-closure networks are comparable. In determining the detection frequency, every well with a detection was included in the calculation, even if the detection occurred only once for the contaminant in the well. The resulting detection frequency is a time-integrated value. Water table wells and piezometers were separated in calculating contaminant detection frequency. In addition, post-closure depth profiling wells were not included in the frequency calculations

Table 11 contains the count of wells with detections (and percent spatial detection frequency) in the water table monitoring wells at each of the field sites. **Table 11** tabulates the detection frequencies of BTEX, B (benzene), MTBE (methyl tert-butyl ether) and N (naphthalene) in water table monitoring wells from the previous site investigation (upper part of **Table 11**) and from the post-closure study (lower part, **Table 11**). For a given site, the detection frequencies vary for each VOC compound. Red highlighting is used in the post-closure portion of the table to identify detection frequencies that were greater than those observed during the SI.

The BTEX detection frequency combines any detection of benzene, toluene, ethylbenzene and xylenes, so the BTEX detection frequency will be greater than the frequencies for each individual compound. Three sites showed a post-closure spatial BTEX detection frequency greater than that observed during the previous site investigation. All three sites are a subset of the 5 sites that Keller [2005] and Greve [2007] found to have longer post-closure BTEX plumes. This association helps support the assumption that pre- and post-closure detection frequencies are a conservative measure of the change in plume length over time

Spatial detection frequency calculations for benzene revealed that while benzene was detected at all 10 field sites, it was detected at relatively few (about 2 out of 10) of the post-closure temporary wells installed at each site. At all but one of the field sites, benzene was detected at no more than 33% of the post-closure water table wells; this is true even for the three former retail stations that exhibited a greater post-closure BTEX detection frequency. None of the field sites showed an increased post-closure benzene detection frequency. Detection frequencies of MTBE, like benzene, were also reduced post-closure.

We generally adopted a post-closure strategy of installing wells at or near locations where the previous SI had detected benzene, so finding substantially fewer wells with detections of benzene is a result worth noting. This result argues against a larger post-closure benzene plume. A lower frequency of detections also raises the question of whether the placement of the temporary wells missed the plume.

The spatial detection frequency of naphthalene showed increased post-closure detection frequencies at 8 (highlighted in red) of the 10 sites. The co-location of naphthalene in wells where benzene was detected was assessed in order to address the question of the adequacy of post-closure monitoring well placement. These results are tabulated in the 7th and 8th columns of **Table 11**. One column (7th column) has the count (and percent spatial frequency) of wells with detections of naphthalene. The 8th column shows the percentage of the "naphthalene wells" (wells where naphthalene was detected) which also had benzene detections. A value of 100% in the 8th column means that all naphthalene detections were at wells where benzene was also detected; and a value of 0 means that no naphthalene was co-located with benzene. During the site investigation, the percentage of naphthalene wells where benzene was also detected was quite high, 75% or more, with 6 sites at 100%. However, post-closure, the percentage of naphthalene wells with benzene detection was much reduced at 67% or less.

The fact that naphthalene was co-located with benzene during the site investigation may explain why naphthalene monitoring was rarely or intermittently monitored (as found during the database portion of this study). Naphthalene may have been considered a "tag-along" contaminant. On-going monitoring of naphthalene may have been considered redundant in the monitoring program that already tracked benzene.

However, far from being redundant, the increased post-closure naphthalene detection frequency indicates the importance of naphthalene in assessing the groundwater VOC plume as it changes over time. Unlike previous site investigations where benzene was detected more often than naphthalene, this post-closure study found a role reversal where naphthalene was detected in more wells than benzene. A higher spatial detection frequency for naphthalene than for benzene was found at 9 out of 10 field sites, suggesting that the naphthalene plumes are larger than the current benzene plumes at these 9 sites.

The 4 rightmost columns of **Table 11** record the highest closure / post-closure levels of benzene and naphthalene for each site. Information on the screened interval of the water table well is included to add context to the comparison. While all the field sites had reduced benzene detection frequencies as compared to the site investigation, concentration-wise, 5 of the 10 sites had higher post-closure benzene levels than at closure (**Figure 21**). Being more soluble, benzene would weather faster, and so is expected to be preferentially depleted in the source area as well as in the plume. The higher post-closure benzene levels at source zones may be indicative of the persistence and behavior of the residual NAPL at these sites. The dissolution of the residual NAPL is not well understood, but when NAPL is still present, it could account for the near-source benzene observations after closure. Therefore, one possible explanation for the higher levels of benzene observed post-closure is the persistence of residual NAPL, whose dissolution rate can lead to large variability in groundwater concentrations. All 3 clay field sites are among the 5 sites with maximum post-closure benzene levels greater than their respective closure-maximum levels. The other 2 sites with higher post-closure benzene are the 2 former retail stations where some remediation (excavation at both, and pump and treat at 1 site) took place and may have redistributed contaminant mass.

The naphthalene concentrations at 4 sites were higher post-closure than at closure (**Figure 22**). All 4 sites with maximum post-closure naphthalene concentrations greater than their respective maximum closure naphthalene levels also had increased spatial naphthalene detection frequency (**Table 11**). Of the 4 sites, 2 were former retail stations; one is a non-clay (sandy) site[46] that Greve [2007] estimated as having the shortest BTEX plume among the field sites; and the fourth is a clay site. The 2 sites with largest absolute post-closure naphthalene levels were the 2 former retail stations that were not remediated.

A simple picture does not emerge from the comparisons of the closure / post-closure spatial frequencies determined from the water table monitoring well samples. While total BTEX, benzene, and naphthalene concentrations suggest little apparent decay near the source, their spatial detection frequencies tend to provide different (and conflicting) views on whether the groundwater plumes are stable, shrinking (benzene and MTBE), or advancing (naphthalene and BTEX). Some of these trends reinforce the conceptual model of a weathering source where the most soluble contaminants (B and MTBE) have degraded or migrated beyond the current plume boundaries and are replaced by less soluble degradable contaminants (TEX and N). However, this doesn't explain higher benzene concentrations remaining in the source zone.

6.5 Water Quality Results and Detection Frequencies in Post-Closure Piezometers

Post-closure, piezometers were installed at 8 of the 10 field sites. Piezometers were not installed at 2 of the 3 clay sites because the piezometer screens would have been located in much less permeable material than that of the water table wells. Piezometers were installed both pre-closure and post-closure at 4 field sites. At only one of these 4 sites (WI Lions Camp) were the piezometer screen depths comparable pre-closure and post-closure. Except for this site, a straightforward comparison of pre- and post-closure data from the piezometers is not possible, either because of the differences between screen lengths and screen depths (being either deeper or shallower) or because there was no piezometer data for the site.

As with the water table well data, spatial detection frequency for BTEX, B, MTBE and N was calculated for the piezometer data. Recognizing that the analysis may be biased due to the fact that more data was available post-closure, we emphasize the post-closure results here. **Table 12** is a compilation of the data from post-closure piezometers

[46] The Brown County Reforestation site had a shorter plume post-closure but higher naphthalene concentrations post-closure.

installed at the field sites. The table is helpful in identifying sites where no piezometers were installed (5 sites in the previous SI tabulation, and 2 sites in the post-closure tabulation). The maximum benzene and naphthalene levels found in the piezometers and their respective screen depths are also included in **Table 12** to help put the data in context. Significant differences in between pre- and post-closure piezometer screen depths are highlighted in orange in **Table 12**. Depth of the piezometer screen is an important consideration because contaminants may be absent at one depth and present at another.

Piezometers were installed pre-closure at 3 of the 4 former retail stations. At one of these, Wood's Garage, (a bedrock site) 6 piezometers had been installed previously. An important post-closure finding at Wood's Garage was the detection of benzene (at 27 µg/l) in a bedrock piezometer, 400 ft away from the site's former UST location. Pre-closure, benzene was not detected at a similarly located downgradient piezometer; however the former piezometer was screened at a shallower depth. The post-closure piezometer data at Wood's Garage defined the longest post-closure BTEX plume of the 10 field sites (**Figure 20**).

Table 12 shows that, post-closure, naphthalene was detected in piezometers at 6 of the 8 sites – essentially at the same spatial detection frequency as the BTEX detections, and more often than the benzene detections for each site. These observations are consistent with the post-closure naphthalene plume being larger than at closure, especially at all 4 former retail sites. At two of the former retail sites, the maximum post-closure naphthalene detected in piezometers was at levels above naphthalene's groundwater standard (100 µg/l). It is important to note that the post-closure piezometers at both sites were constructed with 1-foot screens and at different depths as compared to pre-closure piezometers constructed at the respective sites.

6.6 Projection Analysis from Pre-Closure to Post-Closure Benzene Data

The previous analyses have focused on direct comparison of historical, closure and post-closure-maximum contaminant levels at near source groundwater monitoring wells. As discussed in the database portion of this study, contaminant levels and trends are significantly affected by water elevation levels. Here we examine the correlation between benzene concentration and depth to groundwater over time for a set of paired near source pre-closure and post-closure monitoring wells for each field site in order to determine whether temporal benzene trends can be discerned. The pairs of wells used in this analysis are the same as those used in **Table 11**.

Figure 23 is a time-plot of the benzene concentration series, showing in $\log_{10}$-scale the historical benzene concentrations and the post-closure benzene concentrations for a matched pair of pre- and post-closure wells. **Figure 23** also includes a time-plot of the depth to the water table (observed from ground surface), and notes the time frame of remedial actions that may influence the time-trend observations. Appendix A contains enlarged plots for each site as well as the data used in the plots.

The benzene concentration data associated with the historical (H), closure (C), and post-closure (P) maximums as well as the distance between the pre-closure and post-closure monitoring wells are also noted on **Figure 23**. The historical and closure-maximums were observed at the same pre-closure well at only 4 of the 10 field sites. This may be due to the dynamic nature of the benzene plume as well as the influence of the various remedial actions taken at the sites.

6.6.1 Contaminant Concentrations and Variation in Groundwater Level

Understanding the correlation of groundwater contaminant concentrations to water table elevation is critical when assessing concentration time-trends. General rising or falling groundwater elevation over time may correspond to a declining trend in contaminant concentrations which reverses when the groundwater elevation trend reverses. A strong correlation between contaminant concentration trends and groundwater elevation complicates the assessment of natural attenuation processes and contaminant degradation. This problem is exacerbated by short time frames for monitoring sites before closure and inconsistent intervals between monitoring rounds.

Depth to water data in **Figure 23** reflects the depth from the ground surface to the water table. The depth to water data is reported in site investigation reports and was determined after correcting for the height of the monitoring well stickup. This allowed for a similar (if not exact) ground elevation reference to be used between the pre- and post-closure monitoring wells. The expected range in depth to water was similar pre- and post-closure for 7 of the 10 field sites (see **Table 9**).

Among the former retail stations, Martin Oil (Map ID 33), which had an active groundwater remediation system that operated for 4 years, appears to have no correlation between the historical benzene and depth to water, although post-closure benzene data may suggest a correlation with the benzene increasing as the water table drops.

The other 3 commercial sites, however appear to show a benzene and water table depth correlation. At Woods Garage (SiteMap_ID 36), as the water table drops, the benzene concentrations increase. This same correlation was found post-closure for this site. There was slightly more than a one-foot drop in the water table between the 1st and 2nd rounds of post-closure samples, and that drop corresponded to a nearly 3-fold increase in the benzene concentrations. At Grandmas (SiteMap_ID 55), decreasing benzene concentrations are associated with a falling water table. At the Packard site (SiteMap_ID 63), declining historical benzene concentrations corresponded to a rising water table.

It is more difficult to assess this correlation for the non-commercial sites because 4 of the 6 sites have a history of active groundwater remediation and the other 2 sites have only a few rounds of monitoring. However, the Rutland site (SiteMap_ID 34) has the most rounds of monitoring and also the largest fluctuation (over 11 ft) in the depth to the water table. At Rutland, the observed declines in the historical benzene concentrations consistently correspond to a rising water table or times when the full 15-ft well screen for was submerged.

When benzene and depth to water are better correlated than contaminant time-trend analysis then it is likely that cyclic release of contaminants from the source zone are masking changes in contaminant concentrations due to natural degradation. This makes standard approaches to natural attenuation assessment, such as time trend analysis for predicting degradation rates or time to cleanup, unreliable in the source zone. While there seems to be a stronger correlation between benzene concentration and water table elevation for some field sites than others, significant benzene trends pre-closure to post-closure are not discernable at any of the 10 field sites.

6.6.2 Assessment of Projected Time Frames for Restoration of Groundwater Quality at Two Field Sites

Few attempts to calculate a time frame for restoration of groundwater standards have been made for LUST sites in Wisconsin. This is likely due to the limited amount of data available upon which to base such calculations, the inability to predict future land use changes or time frames, and the fact that, to our knowledge, no one has actually demonstrated restoration of groundwater standards at a LUST site in Wisconsin using natural attenuation processes alone.

Closure requests for two of the 10 field sites did include an estimate of the time frame for restoration of groundwater to environmental standards. Those sites and their maximum closure benzene levels were Village of Grafton, 389 µg/l, and City of Racine, 122 µg/l. Historically, these two non-commercial sites had the lowest benzene concentrations of the 10 study sites. At closure, groundwater standards were predicted to be met at the Village of Grafton within 4 years and at the City of Racine site within 1 year. This post-closure study took place 8 years after closure at Village of Grafton and 5 years after closure at City of Racine, well beyond the predicted cleanup time frames. The consultants at both sites used linear regression of groundwater concentrations from the source zone monitoring well to make their predictions. The data from one site was log-transformed prior to the regression analysis.

While degradation rates calculated for these sites will affect the length of the groundwater plume, weathering of contaminants from the source area controls the life time of the source mass and ultimately of the contaminant plume. As can be seen from **Tables 9 and 10**, concentrations are basically unchanged since closure (215 µg/l at Grafton and 191 µg/l at Racine) and the plume length has remained the same (90 feet) at Grafton and decreased somewhat at Racine (from 100 feet to 75 feet), leading to the conclusion that source mass continues to dissolve into the groundwater at a fairly constant rate. However, there is no indication of how much mass remains in the source area.

Experience with these 2 sites demonstrates the problems with trying to predict future contaminant concentrations. Contaminant mass remaining in the subsurface and source zone weathering rate are unknown at all of the field sites. Additional information is needed to quantify both the source area mass term and dissolution into groundwater before predictions can be made for cleanup time frames.

Because this information is not available from either the original site investigation or this study, we can only report the observation that at two field sites with fairly low benzene concentrations in near-surface groundwater, very little change in benzene concentration or plume length has occurred since the time of site closure.

7. SUMMARY AND CONCLUSIONS

In November 1996, Wisconsin instituted "flexible closure," which allowed regulatory agencies to close contaminated LUST sites where groundwater contamination exceeded State standards. The 133 sites in this study represent about 10% of all LUST flexible closures that were granted by the State of Wisconsin between the years 1999 and 2000.

This retrospective study assesses the pre-closure information available from these 133 LUST sites and information collected post-closure for 10 of those sites. The criteria for closure of contaminated sites were delineated in State administrative rules, and State and Federal guidance documents provided information on assessment of natural attenuation processes. Over 125 separate pieces of information were extracted and compiled in a database from the case file reviewed for each of the database sites. Groundwater quality data, chiefly BTEX, naphthalene and MTBE concentrations, and depth-to-water information from monitoring wells were likewise collected and included in the database. Our assessment targets data believed to have the greatest effect on the evaluation of natural attenuation processes, including hydrogeologic characterization, contaminant levels and trends, presence of free phase product, remediation history, and groundwater monitoring history. The data assessment from the 10 field sites focuses on comparison of information available at site closure and information collected post-closure, again emphasizing data critical to determining the effectiveness of natural attenuation, including the effect of the rise and fall of the water table on benzene concentrations, total BTEX and naphthalene concentrations, plume footprints, and spatial detection frequency of the individual contaminants.

An adequate hydrogeologic characterization is critical to understanding the effectiveness of natural attenuation at a given site. Site investigations at petroleum contaminated sites in Wisconsin, where the depth to the groundwater is typically shallow (less than 10 feet below ground surface), generally provide good information to characterize the sites hydrogeologically in two dimensions. Vertical hydraulic groundwater gradients and the extent of contaminants deeper in the groundwater flow system are poorly defined because the majority of sites are not instrumented with piezometers. Assessment of vertical contaminant movement may be less important at sites with extensive, low permeability clay soil. However, the vertical gradients and the depth to which contamination extends at sites with heterogeneous clay soils, non-clay and bedrock sites are critical to understanding plume extent, site risk, and effectiveness of natural attenuation processes.

Beyond issues of site characterization and well placement, the dynamic nature of the groundwater flow system presents a problem when assessing the adequacy of a natural attenuation remedy. This study found a median swing in the horizontal groundwater flow direction of more than 33º for all geologic settings represented in the database, with considerably larger swings at bedrock and clay sites. As a result, the designation of downgradient wells needs to be evaluated each sampling round or else the reduction in concentrations may be inappropriately interpreted as contaminant degradation.

Benzene is typically the contaminant that drives agency management decisions at LUST sites. This study assessed benzene monitoring at the 133 database sites. The historical-maximum benzene groundwater concentrations in the source zones at the database sites ranged over 6 orders of magnitude (from 0.1 µg/L to more than 100,000 µg/L). By the time of closure, about half of the 133 sites showed a decrease in benzene concentrations to less than 10% of the respective historical maximum level, or a ratio of 0.1 between closure-maximum and historical-maximum levels. Discernible difference in this ratio exists between sites that were remediated actively versus sites that were not (natural attenuation-only remedy). Clay sites with a natural attenuation-only remedy exhibited the least improvement in groundwater quality, which is in concert with the slow weathering expected in these soil types.

Active remedies (including soil excavation) were applied at over 70% of the LUST sites in the database. The decision to apply an active remedy versus no remedy besides natural attenuation alone at a site appears to have been influenced by the adoption of flexible closure in 1996 and by the soil type at the LUST site. The LUST sites discovered after the 1996 onset of flexible closure were more likely to implement a natural attenuation-only remedy than the sites discovered before the onset date. The effect of flexible closure on clay sites is even more pronounced, with the proportion of non-remediated clay sites exceeding remediated clay sites after 1996.

While higher contaminant levels in soil may presumably account for higher contaminant levels in the groundwater, a correlation of contaminant concentrations for soil and groundwater samples isn't necessarily expected and was not observed in this study, except for a very specific subset of clay sites. The data on maximum soil-benzene correlated with the maximum groundwater-benzene levels observed from clay soil sites with hydraulic conductivities less than 10^{-5} cm/sec. The correlation may be fortuitous, but plausible because an equilibrium condition is more likely to occur at these sites with slow groundwater movement. No correlation is demonstrable for soil and groundwater benzene concentrations in the remaining (perhaps more hydrogeologically dynamic) subsets in this study.

Analysis of groundwater data to identify residual NAPL suggests that a high concentration of either total xylenes (>13,600 µg/l) or ethylbenzene (>3,400 µg/l) – levels exceeding their respective effective solubilities - is a better determinant of the presence of residual NAPL than high benzene or MTBE concentrations. Naphthalene may be indicative of the presence of NAPL, too, but over 25% of the database sites lack naphthalene data. Measurable free-phase product (FP), observed historically at 20 database sites, did not correlate well with observed groundwater concentrations. This assessment of the typical occurrence of free-phase product (FP) at LUST sites is limited by the fact that relatively few sites with FP were closed prior to 2001. In particular, clay sites with FP are underrepresented in this study.

Evaluation of contaminant degradation depends on contaminant monitoring history. While swings in the horizontal flow direction can bias the evaluations, the problem in degradation evaluations is exacerbated by the short time frames devoted to groundwater monitoring. One static measure of the monitoring period used here is the time frame between detection of the historically highest contaminant level and the date of the most-recent sampling before closure. By this measure, the median time frame for groundwater benzene monitoring at Wisconsin LUST sites is about 1 year for natural attenuation-only sites and about 3.5 years for sites that underwent some type of active remediation (including soil excavation). Another measure is the nominal number of monitoring data that can be used in degradation evaluations using statistical tests for contaminant trends. This study found only 70 sites (or just 53% of the database sites) that had 8 or more rounds of benzene monitoring - with many of these rounds not collected on a quarterly basis.

This study found that data trend analysis and assessment of contaminant degradation rates were not routinely performed on groundwater data collected at LUST sites prior to 2001. This may be partly due to lack of data – any statistical test will more than likely yield inconclusive results in the face of insufficient data – which limits the utility of trend tests.

The nonparametric Mann-Kendall and Mann-Whitney statistical tests were added to Wisconsin's regulations in January 2001, after the closure time frame for sites in this study. However, we were able to assess the usefulness of these tests using the database. Several factors appear to argue against the routine use of these tests at LUST sites. Trend analysis at a downgradient well is dependent on a fairly constant flow system. Natural swings in groundwater flow direction can cause a once-downgradient monitoring well to become a side- (or even an up-) gradient well. Because the coefficient of variation (CV) is determined after an inconclusive Mann-Kendall test result, the ensuing CV-based stability test can be biased and often results in inconclusive trends being found at low concentration sites (tens of ppb) while stable trends are more likely to be found at high concentration sites (thousands of ppb). Lastly, with the use of very few rounds of contaminant data, the tests are more likely to produce inconclusive results. For example, of the 70 sites with 8 or more rounds of sampling data, the nonparametric Mann-Kendall test concluded that 12 sites had an increasing benzene trend at closure. At 6 of the 12, trends were either inconclusive (4) or decreasing (2) when only the 4 most recent sampling rounds were used in the Mann-Kendall test.

As a regulatory decision-making tool, the utility of the nonparametric tests, especially that of the Mann-Kendall test, can be increased by: 1) increasing to 8 the minimum required quarterly sampling rounds needed prior to applying the test; and 2) dropping the use of the coefficient of variation test after an inconclusive result. Inconclusive results that involve high VOC concentrations should prompt assessment of additional action before closure rather than merely relying on natural attenuation.

The 10 field sites in this study were either former retail petroleum stations (4 sites) or non-commercial (6 sites). At these sites, post-closure temporary wells were installed near former site-investigation monitoring wells that had detected benzene. At 5 sites (all 4 former retail station sites and 1 non-commercial site), post-closure monitoring showed that the total BTEX plumes had lengthened post-closure. The 1 non-commercial site with a longer post-closure plume is unique because its plume has lengthened upgradient – due to the fact that the most-contaminated post-closure well was installed upgradient of the location where the closure-maximum levels had been observed.

Another metric used for comparison was the post-closure-maximum and the closure-maximum VOC levels observed from water table monitoring wells at each of the 10 sites. This study found total BTEX concentrations were higher post-closure at 8 sites, including all 4 former retail stations. However, post-closure maximum benzene levels were greater than the respective closure-maximum benzene at only 5 of the 8 sites. Post-closure naphthalene levels were greater than the respective closure-maximum naphthalene at 4 of the 8 sites.

Spatial detection frequency of individual VOCs was used to gain insight into plume changes since the time of closure that may be attributable to natural attenuation processes. During the previous site investigations, the spatial detection frequencies for BTEX and for benzene individually were high – meaning that these contaminants were detected at most SI water table monitoring wells. What is striking in the post-closure investigation is that although the spatial detection frequency for BTEX may still be high, the frequency of benzene detections in post-closure monitoring wells had decreased at all 10 sites. Except for the one former retail station situated on bedrock where above-standard (>5 µg/l) benzene was observed 400 ft from the former UST location, the post-closure data is generally consistent with a picture of a VOC plume where benzene remains in the plume core, but is absent along its fringes. This picture of a VOC plume is not as simple as it seems, however. While the spatial detection frequency for benzene has decreased, the frequency of naphthalene detection has increased at 8 of the 10 sites. During the previous site investigations, naphthalene was detected less frequently, and was generally detected in the same wells where benzene was also detected. In contrast, post-closure data show that naphthalene is detected as frequently as BTEX, and in wells where benzene may not have been detected. In a weathered source, residual phase product becomes enriched in less soluble components, such as naphthalene, over time and these components increase in the downgradient plume. Because naphthalene is less degradable than benzene, it will likely remain in the groundwater for a longer period of time than benzene, therefore the inclusion of naphthalene in a routine monitoring program is important.

Another metric assessed in this study is the benzene time-trends at the field sites. However, the rising and falling of the water table, a seasonal phenomenon in Wisconsin, further complicates assessment of the trends apparent in the contaminant histories. Among the field sites, several (all 4 former retail service stations and at least 1 non-commercial site) appear to show some correlation between benzene concentration and depth to the water table, but to varying degrees. The post-closure benzene data at 1 site (Martin Oil) increased some 20-fold associated with a 2-ft rise in the water table, but another site (Woods Garage) exhibited just a 3-fold increase with a 1-ft drop in the water table.

From the post-closure data, it appears that natural attenuation processes may be largely controlling the lateral extent of groundwater benzene plumes at closed LUST sites in

Wisconsin, especially when only benzene levels above the groundwater standard are considered. However, the BTEX and naphthalene *detections* indicate plume expansion at most of the field sites. Based on detections at post-closure wells, the BTEX plume boundaries lengthened at 5 field sites, and 1 of those had a significantly longer plume in the bedrock. Naphthalene was detected more frequently and in more downgradient water table wells and piezometers, indicating it is in the leading fringes of the VOC plume, but at levels below its groundwater standard of 100 µg/l, except at near-source wells. Much like the post-closure benzene data, the naphthalene concentrations exceed its groundwater standard in post-closure monitoring wells in the source zones near the former UST locations at 7 of out 10 field sites.

The petroleum contaminant concentrations are not decreasing in the source zones and the improvement in groundwater quality expected at the time flexible closure was instituted in 1996 is not demonstrable 5 to 8 years post-closure for all the field sites. With enough information, it may be possible to estimate a time frame to cleanup to groundwater standards. However, the information needed (e.g., estimates of residual petroleum remaining in soil pore space, weathering rates, estimates of contaminant mass in groundwater) was not available for sites included in this study and are generally not available from routine investigations conducted at LUST sites in Wisconsin.

The lack of a reliable estimate for depletion of the source zone and subsequent groundwater cleanup is particularly relevant as land use changes occur and former LUST sites are redeveloped. Regulators, land use planners, redevelopers and others should assume that whatever contaminants existed at the time of closure will remain at the LUST site into the foreseeable future. The greatest likelihood of contact with contaminants at former LUST sites is through excavation of contaminated soil or through vapor intrusion into buildings placed near source zones. Vapor migration from LUST sites was not considered in closure decisions for sites included in this study. As former gas stations are redeveloped to other uses, this pathway may be a concern depending upon the type of development and placement of new building foundations. At this time (2009), Wisconsin has not developed target soil or groundwater levels for screening for potential vapor intrusion at petroleum contaminated properties.

Ultimately cost and property transactions are the major drivers for investigation and remediation of LUST sites. It is unlikely that the limited groundwater monitoring (both time frame and sampling rounds) currently performed at LUST sites in Wisconsin will change significantly in the future. With only a limited period of time available to evaluate and cleanup LUST sites, it appears that the key to reducing long-term contaminant concentrations is the removal of contaminant mass at the source zone. Natural attenuation may be able to control the extent of petroleum plumes in unconsolidated materials at plume margins where concentrations are near state standards. However, it does not appear from the data at hand that natural attenuation processes alone, within the higher concentration source zones, will result in actual cleanup of groundwater or achieve state standards within the time frame investigated within this retrospective study.

8. RECOMMENDATIONS

1. The use of a natural attenuation-only remedy at LUST sites in Wisconsin needs further examination. Implementation of source control actions early in the site cleanup process should be considered. A better balance between active source control remedies and environmental monitoring is needed in order to cost effectively reduce contaminant mass and concentration at source zones prior to case closure.

2. An abbreviated groundwater monitoring time frame applied when natural attenuation is the sole remedy (typically 1 year) is too short to evaluate the long-term effect of natural attenuation on site contamination. This evaluation is essential to agency closure decisions. Enough groundwater sampling should take place such that LUST sites can be evaluated for fluctuations and ranges in site-specific factors, particularly contaminant concentrations and extent, water table fluctuation and changes in the groundwater flow direction. In general, this would require at least 8 quarterly rounds of sampling.

3. Revise the state administrative code to require data from a minimum of 8 quarterly sampling rounds for use in non-parametric statistical tests and eliminate the coefficient of variation (CV) test after an inconclusive Mann-Kendall test result. This study found that even with 8 rounds of sampling, half of the LUST sites have inconclusive trend-test results. If declining contaminant trends can not be established after a period of monitoring, site-specific factors, particularly contaminant concentrations and extent, geology, complications in the monitoring history brought about by water table fluctuation and changes in the groundwater flow direction, proximity to receptors and whether source control has been implemented, should be considered to determine whether monitoring data adequately supports a site closure decision.

4. Given concerns regarding single-well analysis (affected by shifting flow direction and fluctuating water table) to estimate a contaminant reduction rate, consideration should be given to more robust analytical approaches. One approach is the spatial integration of observed concentrations over the groundwater sampling network to estimate total dissolved plume mass at various points in time, Changes in mass with time may help determine NAPL dissolution rate and be used to estimate a timeframe for the plume's persistence.

5. Contaminant plumes need to be better defined vertically. When possible, discrete vertical profiling should be used to better define the three dimensional aspects of the plume. Once the plume is defined in three dimensions, piezometers should be installed to monitor plume behavior at depth. Piezometers should be installed at sites with hydraulic conductivities greater than or equal to 10^{-4} cm/sec or where contaminants may have entered bedrock.

6. Additional attention is needed for those petroleum sites where the water table is deeper than 20 feet below the ground surface. The field study showed that the longer VOC plumes were present at sites with greater depth to the water table.

7. Naphthalene monitoring should be included as a routine parameter in LUST site investigations. Polycyclic aromatic hydrocarbons (PAH) should be monitored routinely at sites where a release of diesel or fuel oil has occurred and at sites with free-phase product.

8. Analytical result tables in reports should indicate the minimum detection level of the analytical method rather than no detect (ND), especially for soil results where NDs can span several orders of magnitude due to lab dilution or high levels of contamination.

9. Consider developing an electronic form that would be submitted at closure, to easily capture groundwater depth and quality data so that any future follow-up evaluations can be done in a more expeditious manner.

Future Field Studies

Several questions raised by peer reviewers of this report could not be successfully addressed without completing additional field work. Specifically, additional data gathering would be needed to evaluate:

- Methods for determining the presence of NAPL and how source weathering may affect groundwater contamination.
- How the horizontal and vertical components of hydraulic conductivity affects the distribution of hydrocarbon contamination.
- The importance of determining mass flux when evaluating LUST sites.
- How the accuracy of field measurements affects the ability to estimate the timeframe for meeting environmental standards.

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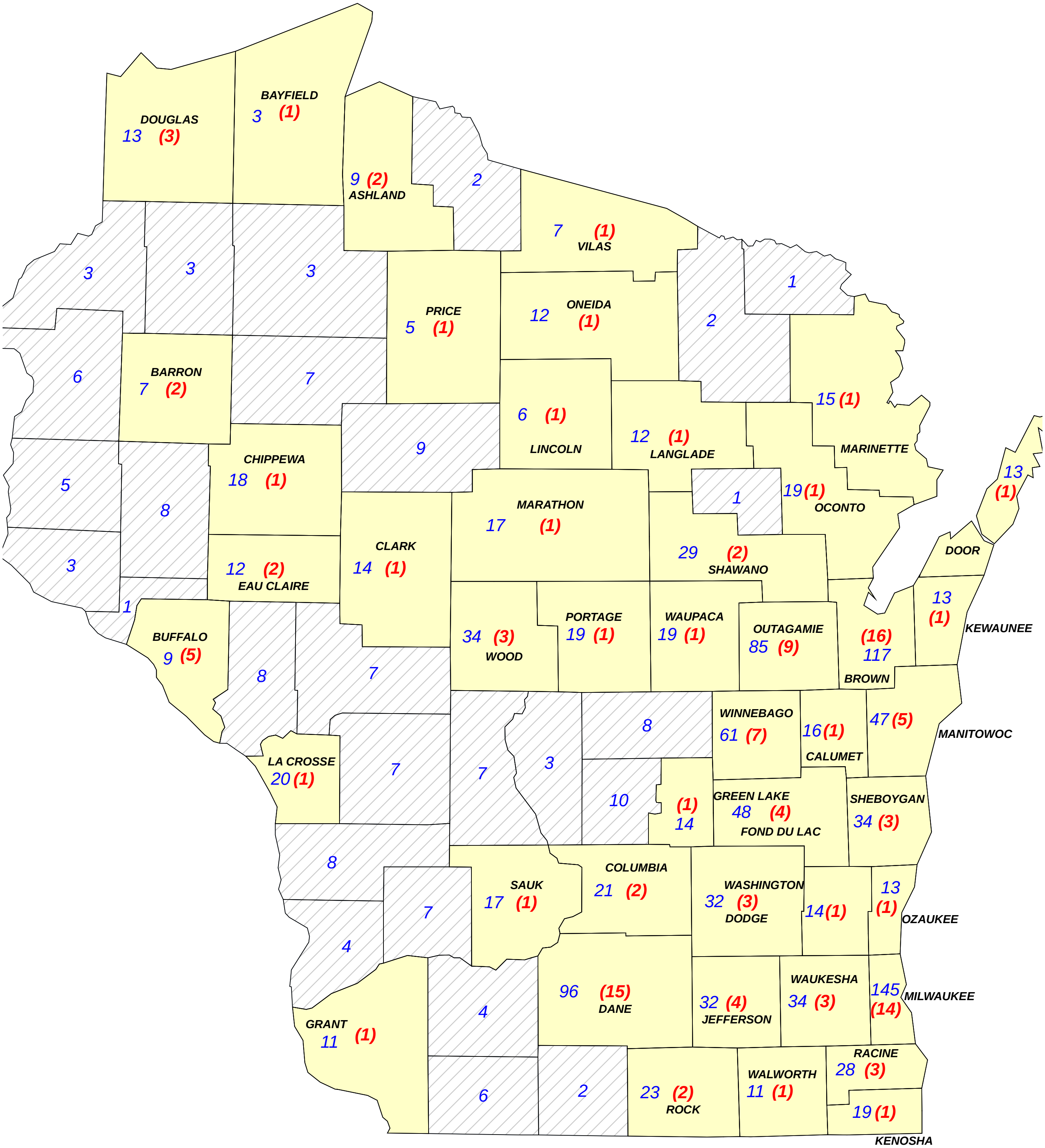
County Distribution of the ***1,378*** GIS-Registry Sites from where a Subset of Sites ***(133)*** was Selected and Reviewed

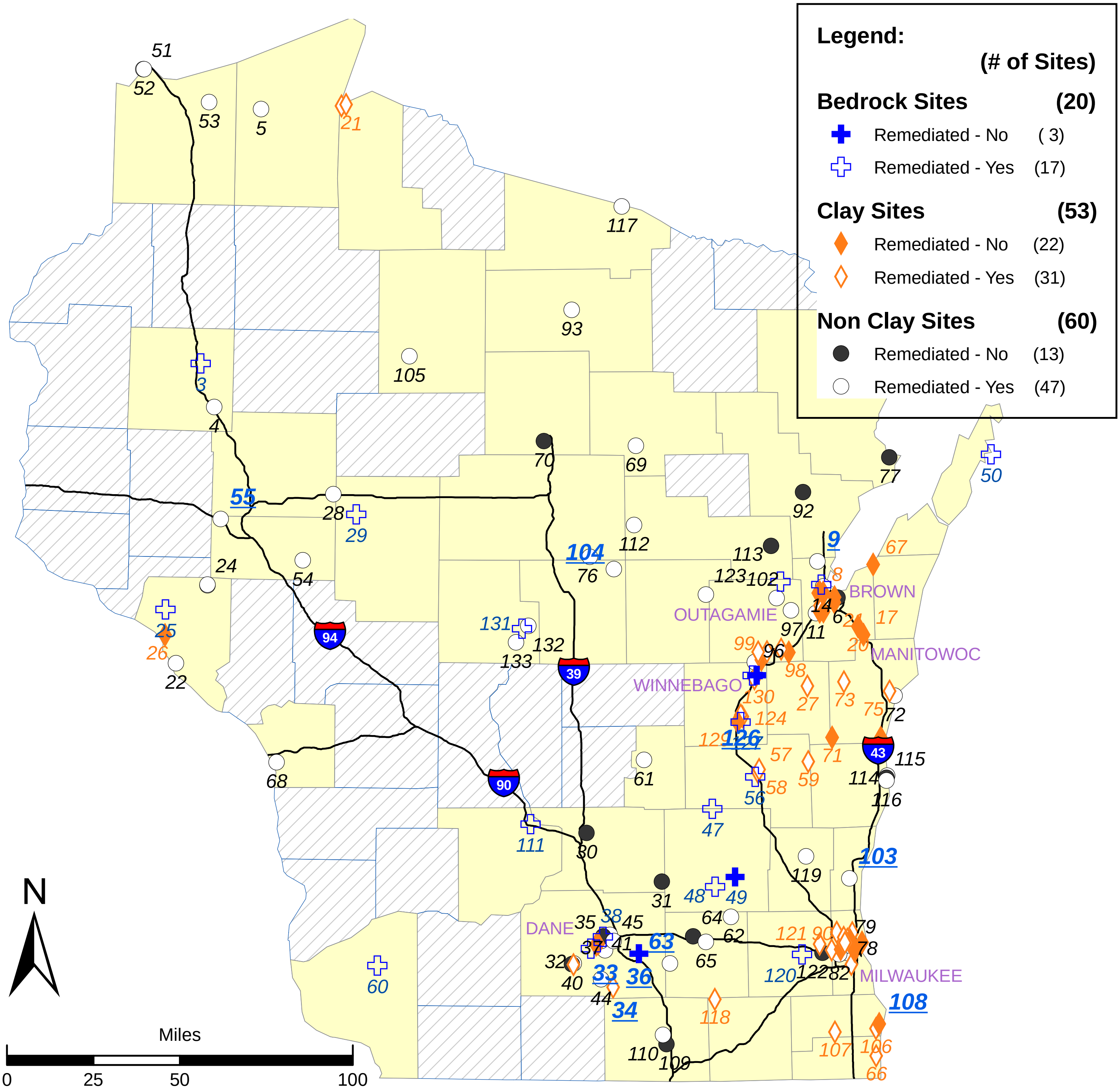


A blue number shows how many GIS Registry sites in the county were in the initial pool of 1,378 sites.

A red number in parenthesis shows how many of the 133 reviewed sites are in the county. Information from the site reviews are compiled in the current database.

Figure 1

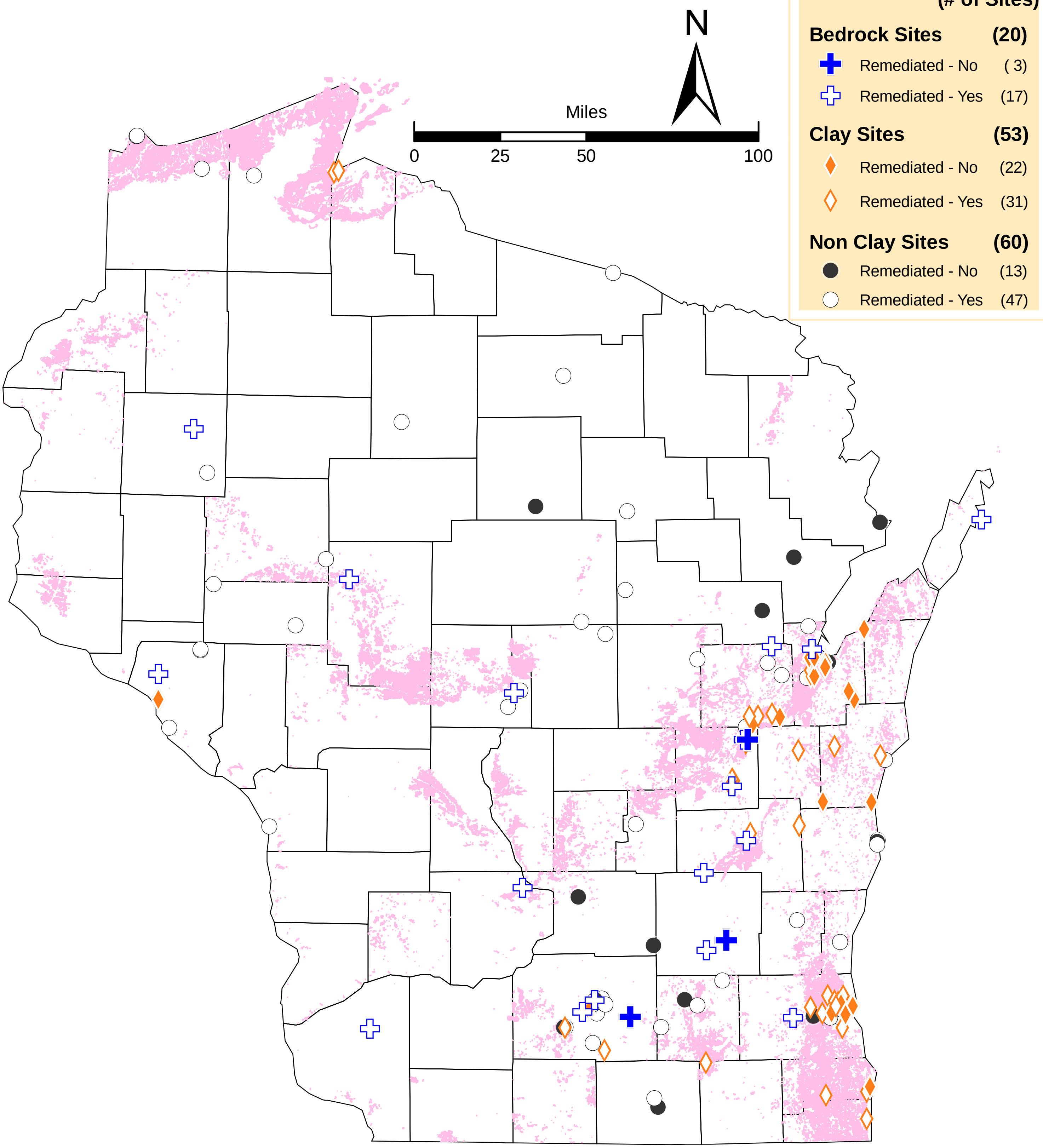
Sites in the Wisconsin Closure Protocol Study Database



The information from the review of case files from 133 closed sites in 45 counties were compiled in a database. No site was reviewed in the 27 counties shown hachured in the map. About half of the reviewed sites are in the 6 labeled counties. The italized numbers are SiteMap_IDs that are listed in Table 1. To reduce clutter, not all SiteMap_IDs are shown. Underlined blue labels indicate the 10 field sites where we installed post-closure groundwater monitoring wells. Blue crosses indicate "bedrock" sites (20 sites) where borings encountered bedrock; orange diamonds indicate "clay" sites (53); black circles show "non clay" sites (60) which are neither clay nor bedrock sites. Filled symbols indicate sites where no remediation occurred; unfilled symbols show sites where some remediation took place.

Figure 2

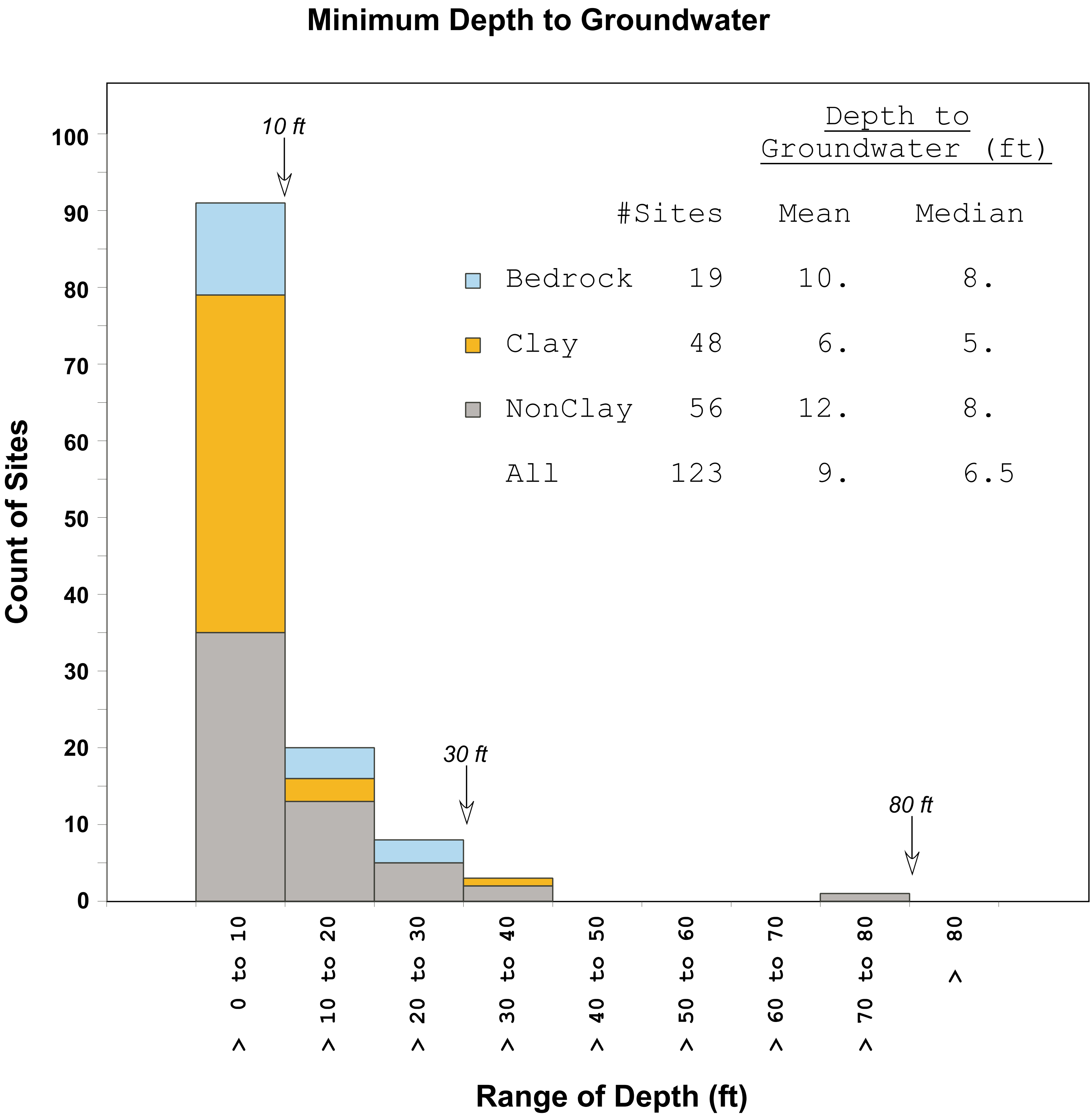
Clay Soils in Wisconsin



The locations of the database sites are superimposed on a generalized clay soils map of Wisconsin. The colored portion of the map highlights where soils with a clay fraction of 35% or more (clays, silty clays, silty clay loams, clay loams or sandy clays) may be expected. The source of the digital soil map is NRCS' Soil Survey Geographic (SSURGO) Database available at: *http://soildatamart.nrcs.usda.gov/Survey.aspx?State=WI*

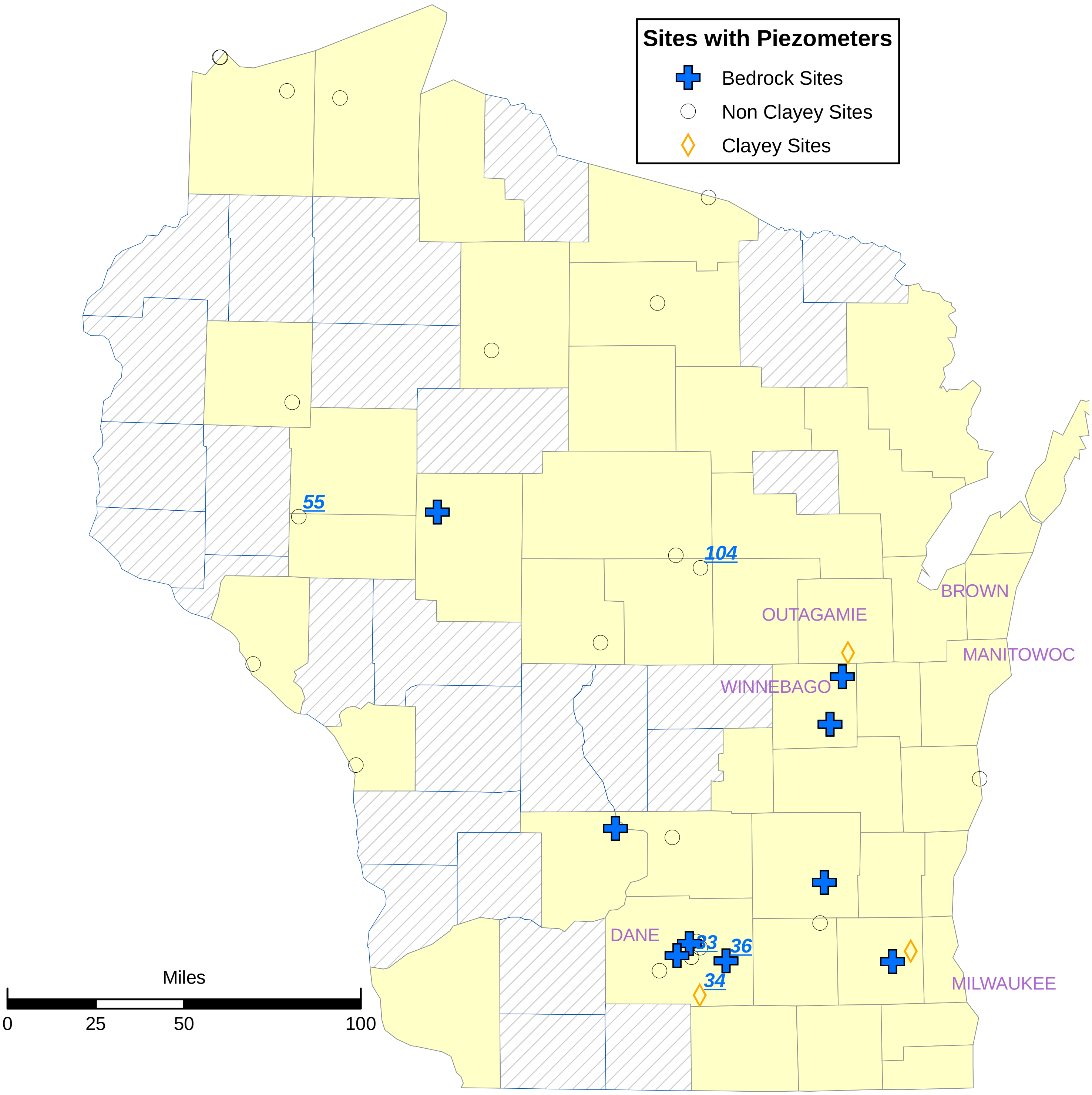
Additional information on WI soils and the underlying bedrock geology is available at:
http://digicoll.library.wisc.edu/cgi-bin/EcoNatRes/EcoNatRes-idx?id=EcoNatRes.Hole01

Figure 3



The groundwater depths were available for 123 of the 133 sites reviewed. Of these, 99 sites (or 80% of 123 sites with depth data) had minimum depth to water at 12 ft or less. For the above histogram, the individual site data on minimum depth to the groundwater were binned in 10-ft increments, and color-coded to reflect the geology at the water table. The mean for the minimum depths to water for clay sites (6' depth) is shallower by 4 ft compared to the mean for bedrock sites (10'), which in turn is shallower by 2 ft than non-clayey sites (12'). The shallow depth to the groundwater is one general reason that sites have enough monitoring wells (median of 7 wells) from which relatively good hydrogeologic information had been collected.

Figure 4

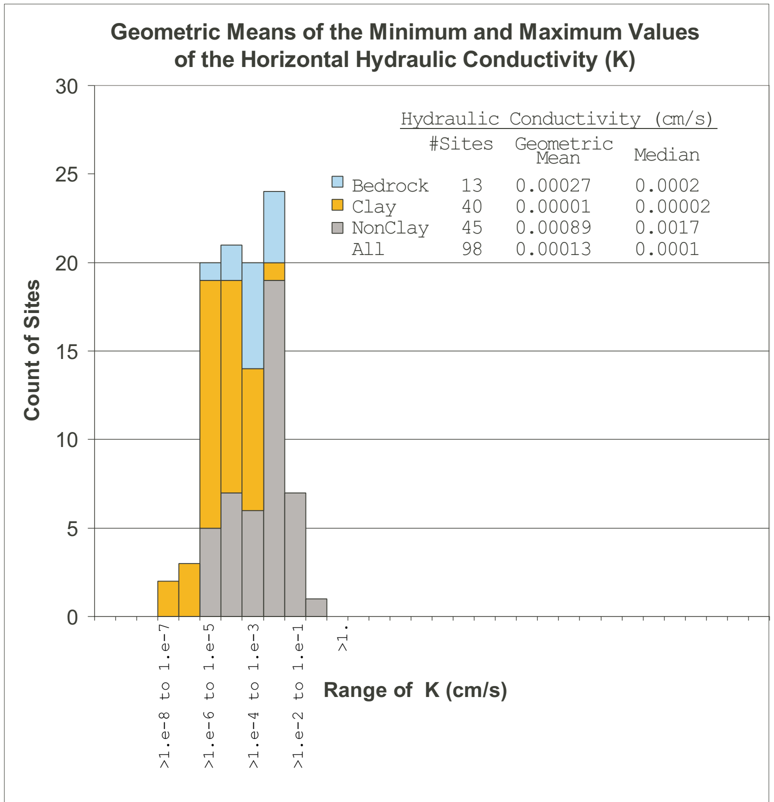


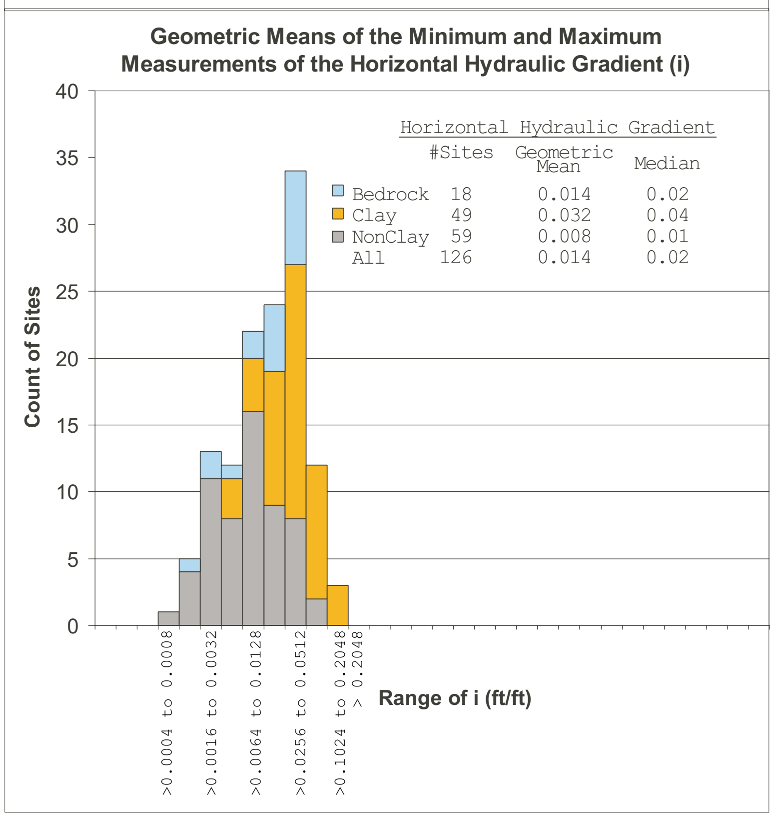
Sites with Piezometers.

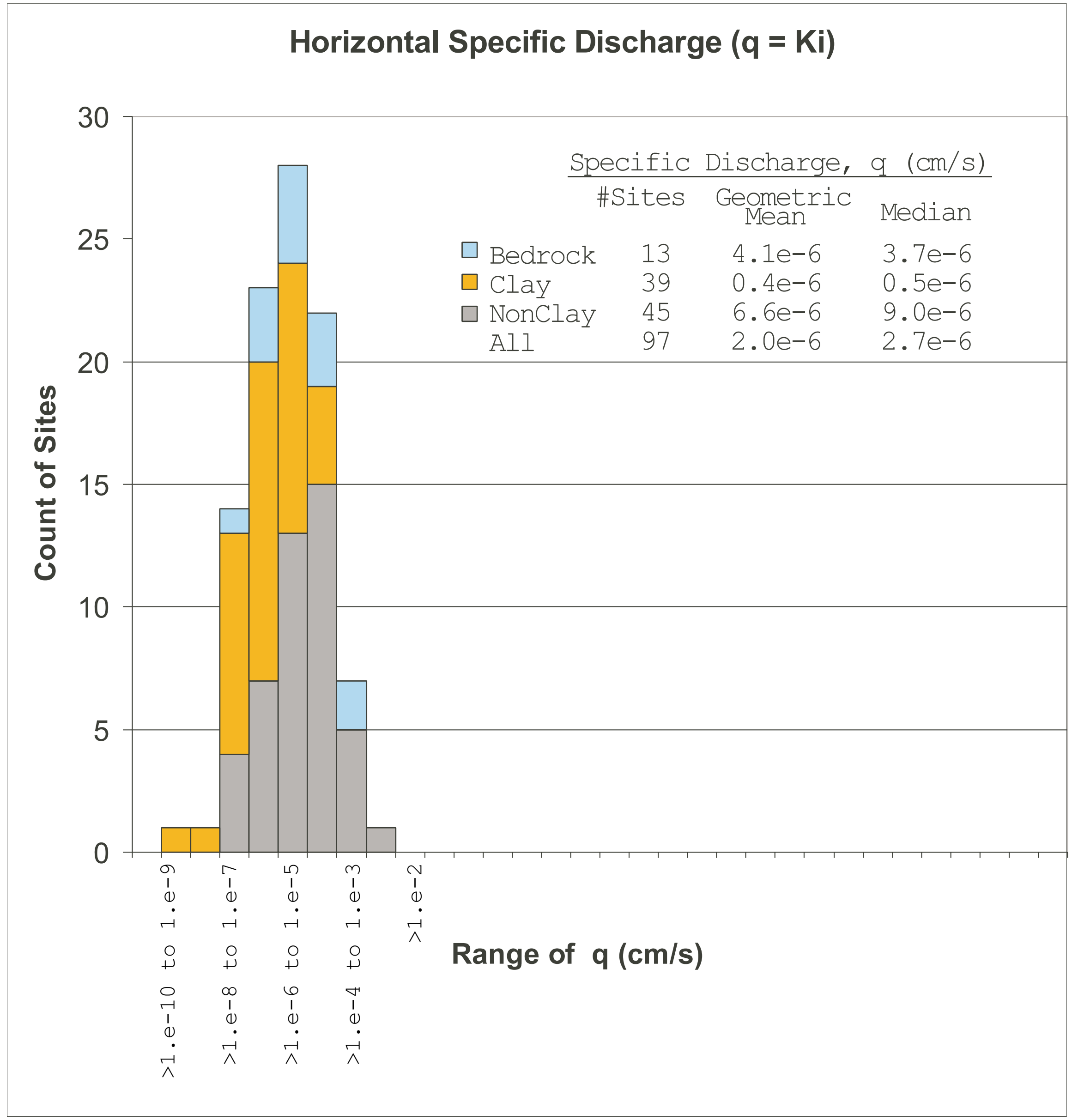
Out of 133 DB sites, 34 sites had at least 1 piezometer (PZ). Of these, 9 PZ sites are in Dane County. Two (2) of the Dane sites have multiple piezometers: 6 PZs at SiteMap_ID 36, and 3 PZs at SiteMap_ID 33. Both sites, and another Dane PZ site (34) are field sites in this study. The 5 PZ sites that are also field sites in this study are labeled.

The breakdown of the PZ sites is as follows: 3 clay, 22 non-clay, and 9 bedrock PZ sites - or 6%, 37% and 45%, respectively, of the total clay, non-clay and bedrock sites in this study's database.

Figure 5







The histograms for the hydraulic conductivity (K), horizontal gradient (i) and specific discharge (q) data. Clay sites, as a group, tended to have a larger gradient. The distribution of the estimated specific discharges from the sites assumed more of a lognormal distribution than either conductivity or gradient alone.

Figure 6

Change in the Groundwater Flow Direction

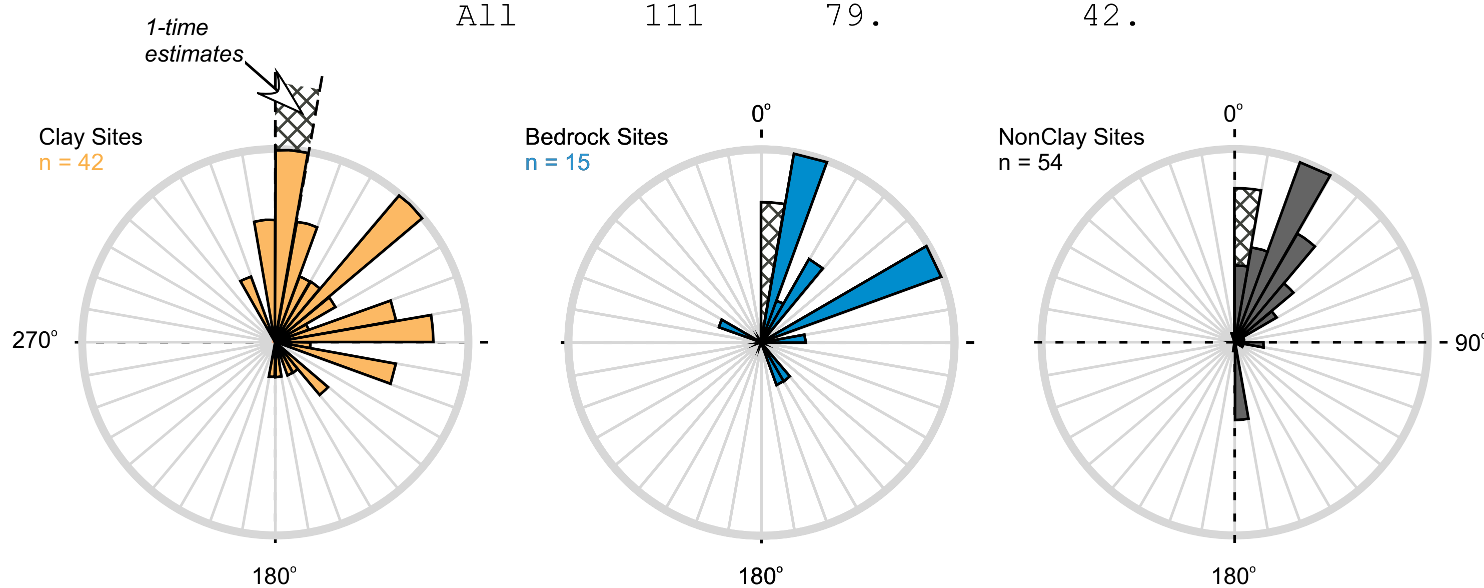
Hydraulic Conductivity (K)
(98 sites with data)

	#Sites	K (cm/s) Minimum	Median*	Maximum
Clay	40	1.E-08	2.E-05	1.E-03
Bedrock	13	1.E-05	2.E-04	9.E-03
Non-Clay	45	1.E-06	2.E-03	2.E-01

**Median of geometric means*

Change in the Groundwater Flow Direction
(111 sites with estimates from 2 or more dates)

	#Sites	Azimuth Change Mean	Median
Clay	42	107.	74.
Bedrock	15	72.	60.
Non-Clay	54	58.	33.
All	111	79.	42.



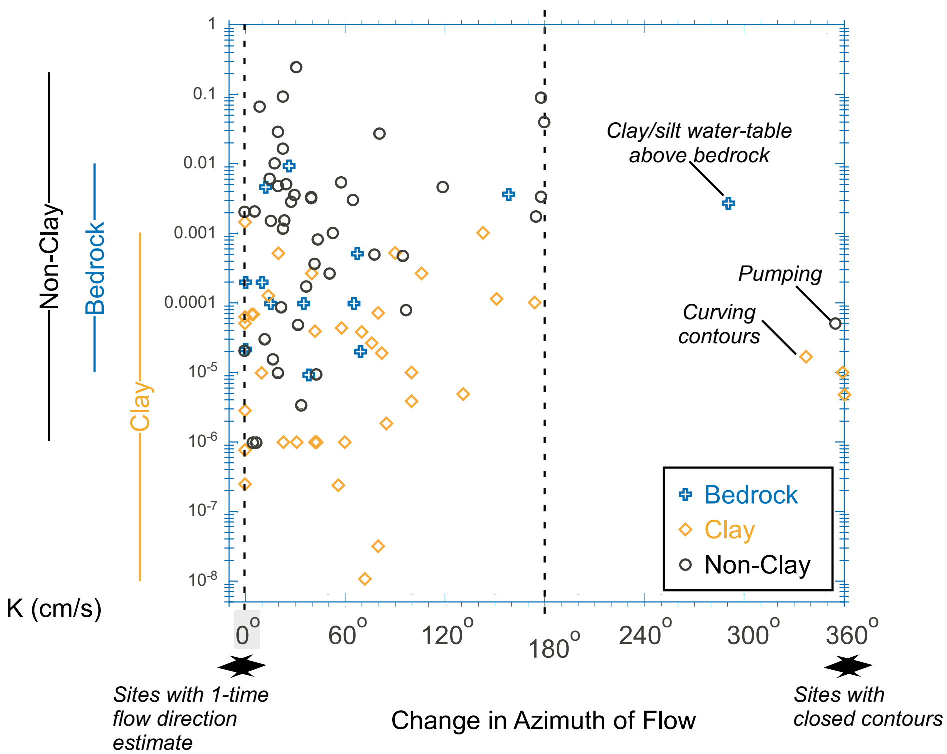
The upper table shows the statistics on the hydraulic conductivity (K) values for the geology-grouped sites. The clay sites as a group had an order of magnitude lower K compared to the bedrock and non-clay sites. The lower table shows the statistics on the observed variation in the groundwater flow direction. The variations in the groundwater flow direction are shown in the rose diagrams below the tables.

To plot the rose diagram, the estimated flow directions at each site were first tabulated, and when 2 estimates were present at a site, the angular difference between the estimates was noted. This difference was binned and plotted in the rose diagrams. Each wedge in the rose diagram represents an angular range of 10°. A flow-direction reversal (opposite direction from a previous estimate) was included in the 170° to 180° wedge. Several clay sites had closed or near-closed contours (even without pumping at the sites), and these sites we plotted in the 350° to 360° slice. A few sites shown with over 180° variation had some pumping history when the flow direction was estimated, or a very complicated horizontal flow direction was shown in reports (*e.g.*, SiteMap_ID 111). A projection from the data is that at over 50% of sites, the flow direction is expected to vary by 33° or more.

Figure 7

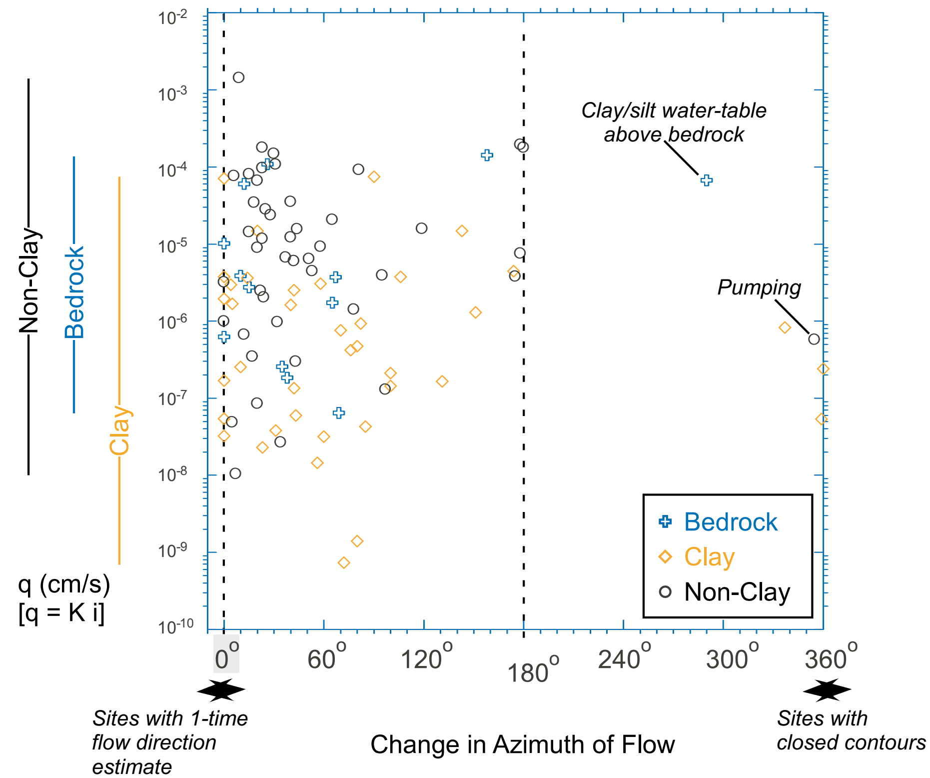
Hydraulic Conductivity, Specific Discharge, and Change in the Groundwater Flow Direction

Hydraulic Conductivity and Groundwater Flow Direction Change



From the tables in Figure 7, the comparison between the: 1.) median azimuthal change in flow direction, and 2.) median of the geometric means of the hydraulic conductivity (K) seems to indicate that sites with higher K are less prone to large swings in the groundwater flow direction. However, the data when plotted as shown above do not support any correlation. From the data, swings of 33° or more were evident for over half the sites regardless of their respective hydraulic conductivities.

Specific Discharge and Groundwater Flow Direction Change

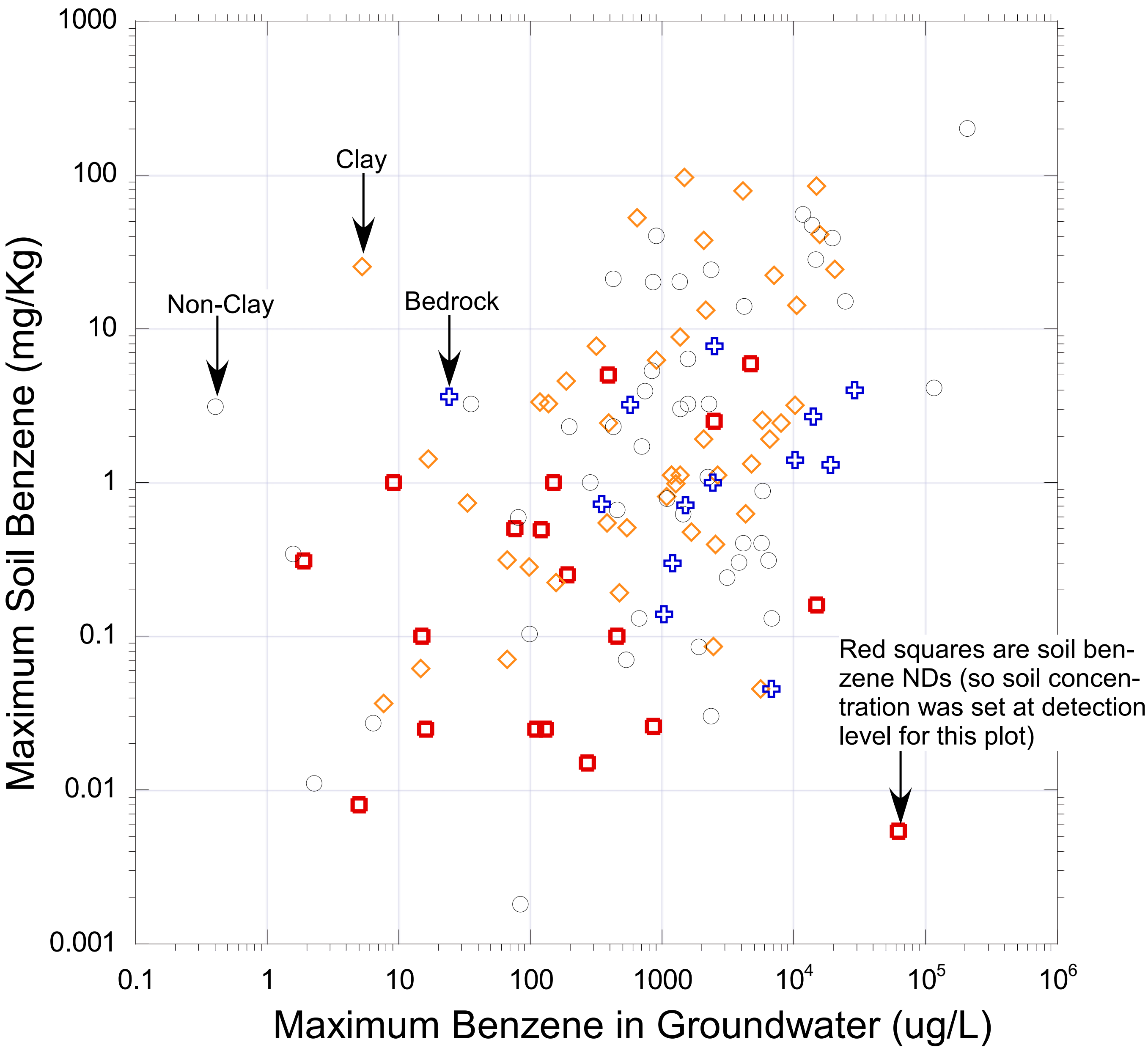


Because the horizontal hydraulic gradient (i) at clay sites is typically larger, we included i as a factor to see if sites with "faster" Darcy velocities tend to have a smaller variation in flow direction. The resulting plot shown above, however, does not support this explanation, especially for the clay sites. For instance, a swing of over 60° was observed for a clay site with fast Darcy velocity of 1e-4 cm/s as well as sites with a slow Darcy velocity of 1e-09 cm/s.

Although the median statistics on hydraulic conductivity and change in groundwater flow direction seemed to indicate a correlation, the plots for either hydraulic conductivity (left) or specific discharge (right) *versus* observed change in groundwater flow direction showed too much scattering to determine any significant correlation.

Figure 8

Soil-Benzene Data Versus Groundwater-Benzene Data

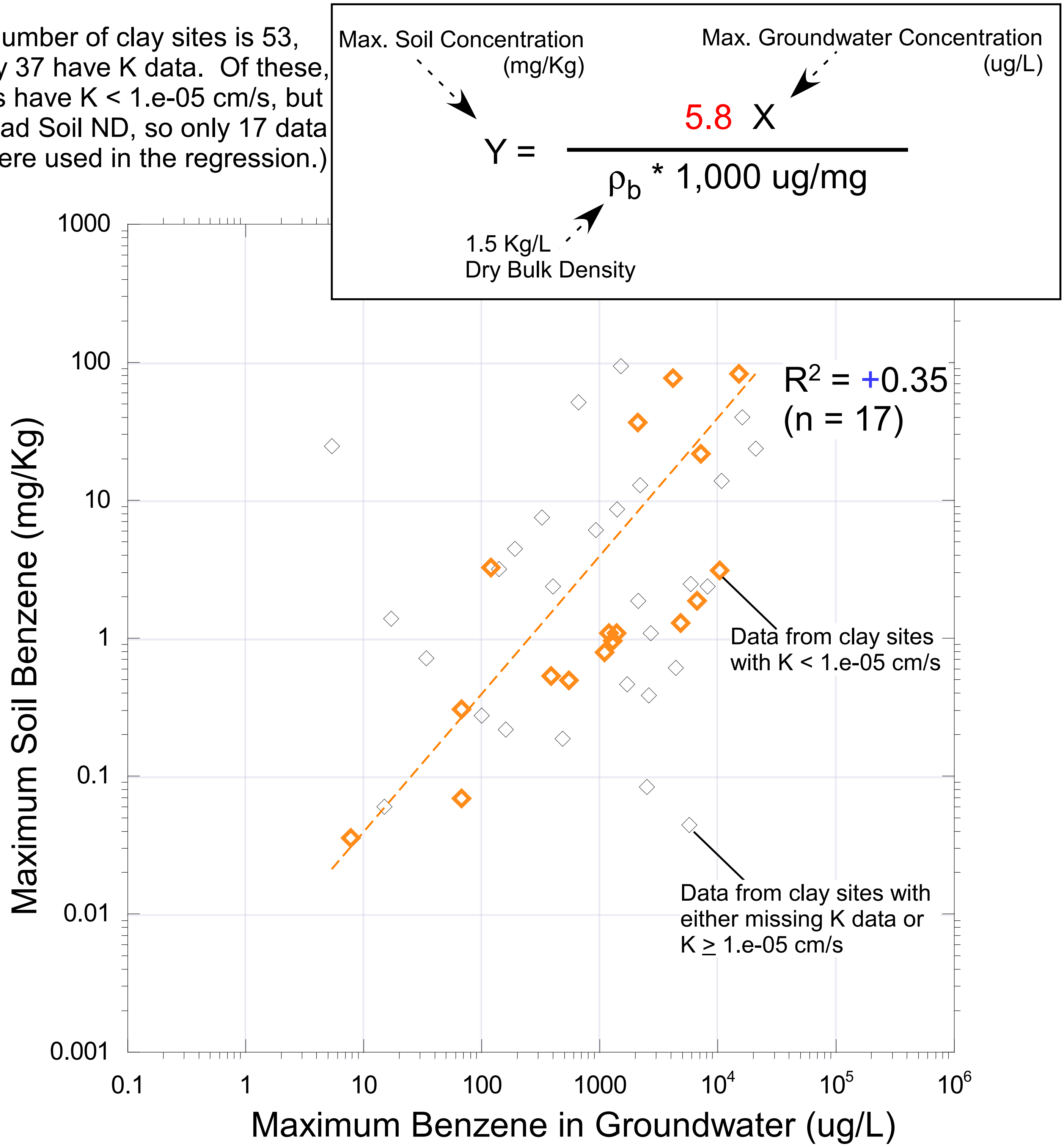


For each site, the maximum soil benzene (mg/Kg) was plotted as a function of the maximum benzene found in groundwater (ug/L). Soil NDs present a complication as soil detection levels span about 3 orders of magnitude. However even after excluding soil NDs, no meaningful regression result was found between the soil and groundwater concentrations. Separate regressions for the bedrock, clay and non-clay subsets only highlighted the non-correlation in the data, with the clay subset seemingly having the least non-correlation.

Figure 9

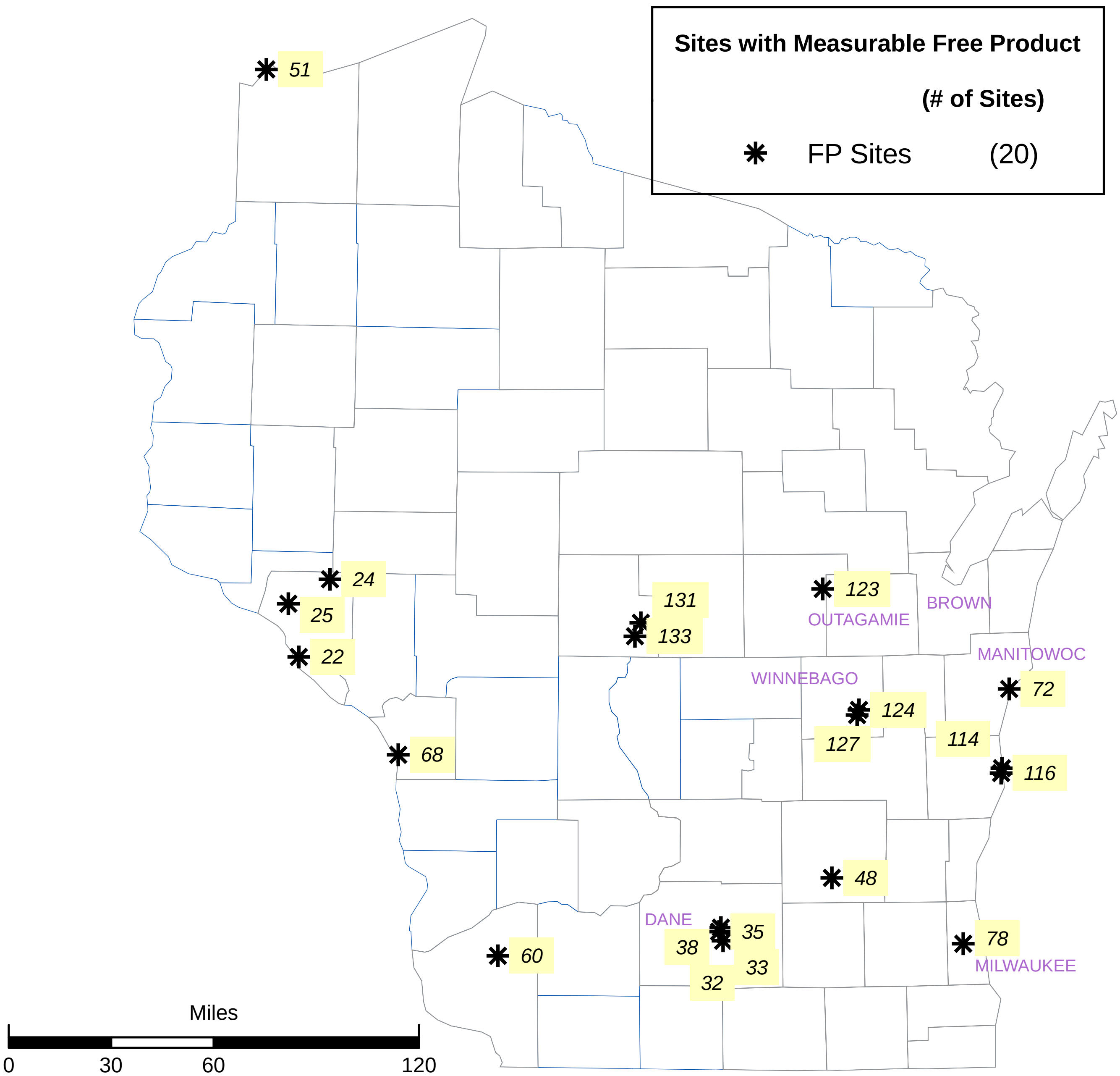
Clay Sites Data

(Total number of clay sites is 53, but only 37 have K data. Of these, 18 sites have K < 1.e-05 cm/s, but 1 site had Soil ND, so only 17 data pairs were used in the regression.)



Clay sites with hydraulic conductivity (K) of less than 1.e-05 cm/s showed a relatively more robust correlation between the maximum benzene levels in groundwater and soil. The dashed line is the generalized least-squares fit assuming a line with a zero-intercept. The least-squares line equation is shown above the plot. The square of the Pearson coefficient of correlation ($R^2 = 0.35$) associated with the line may be small, but it is significant at an α=0.05 test. Or in other words, we are certain at a 95% confidence level that we have a nonzero correlation. The equation shows that at benzene's groundwater standard of 5 ug/l, the maximum soil level for clay sites with K < 1.e-05 cm/s would be 0.02 mg/kg (or 20 ug/Kg), which is larger than the 5.5 ug/Kg benzene set for the protection of groundwater quality in NR 720.

Figure 10



Database Sites Where Measurable Free Product was Found

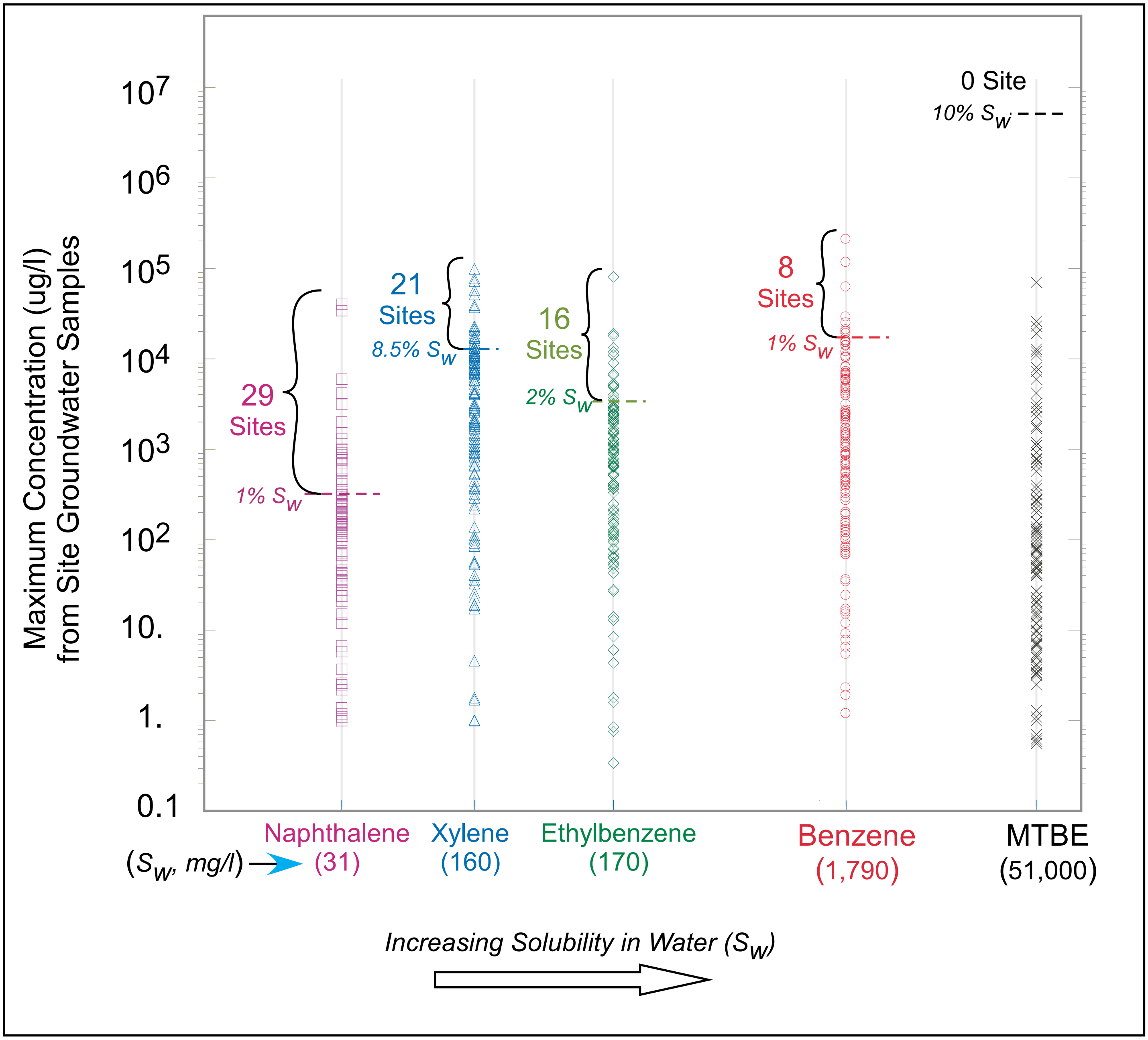
The 20 sites where measurable free product (FP) was found represented 15% of the database sites.

Soil FP indicator levels: Only 10 of the above 20 FP sites had soil levels that exceeded a free-product indicator level in NR 746, Wis. Adm. Code.

Groundwater FP indicator levels: Only 6 of the 20 FP sites had groundwater contaminant levels that had benzene > 18,000 ug/l or naphthalene > 310 ug/l.

Figure 11

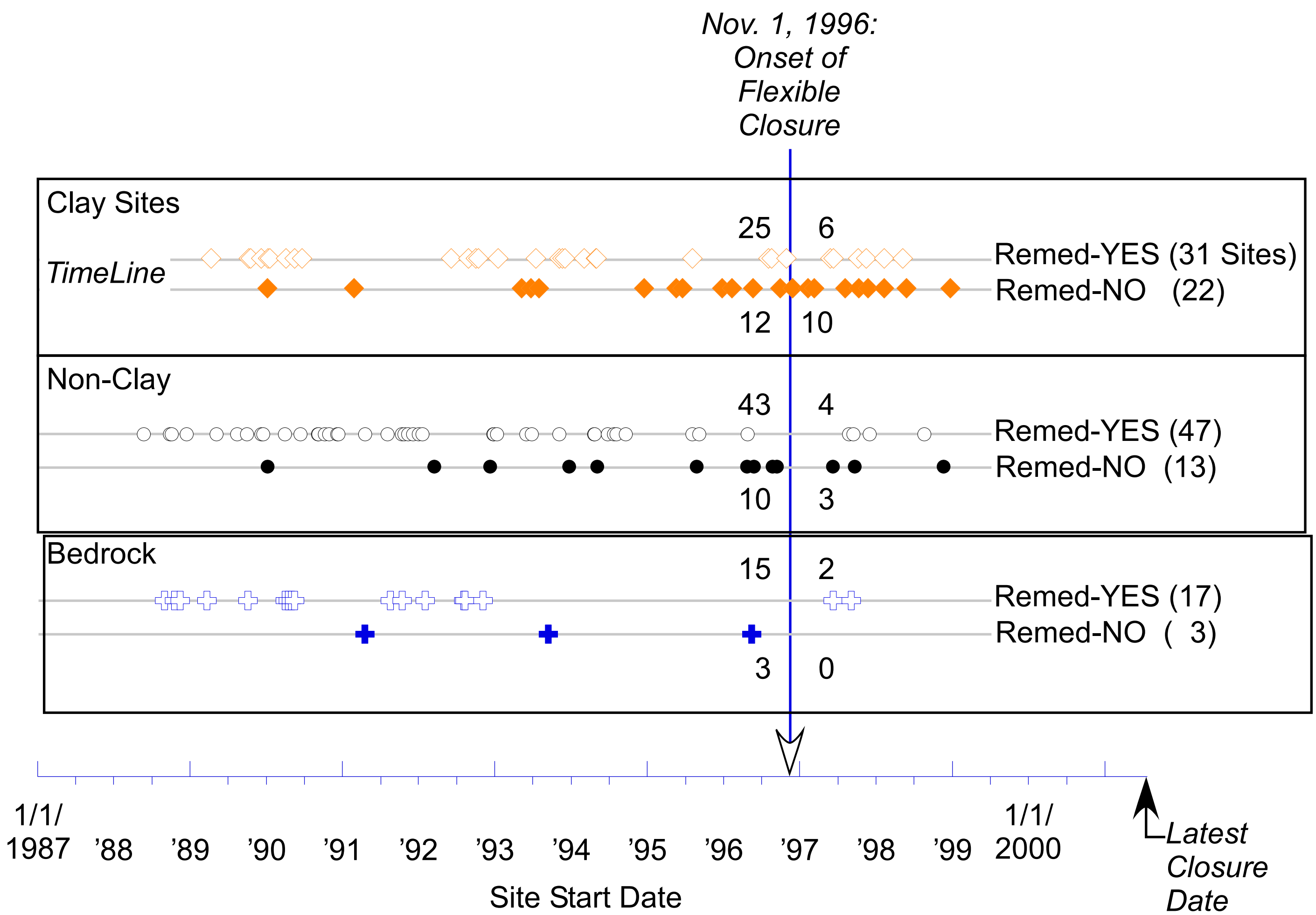
Range of the Maximum Concentrations Observed from Groundwater Samples at the Database Sites



Effective solubility - estimated by a compound's solubility in water multiplied by its mole fraction in gasoline or diesel - is typically used as a "rule of thumb" free product (FP) indicator concentration. The effective solubilities determined for naphthalene (1% mole percent in gasoline or diesel), xylene (8.5% in gasoline), ethylbenzene (2% in gasoline), benzene (1% in gasoline) and MTBE (10% in gasoline) are indicated by short horizontal dashed lines in the plot. The count of sites that had concentrations at or exceeding the respective FP indicator concentrations are shown for each compound. The naphthalene data indicate considerably more potential FP sites than do the benzene data, with the MTBE data suggesting no FP site at all.

Figure 12

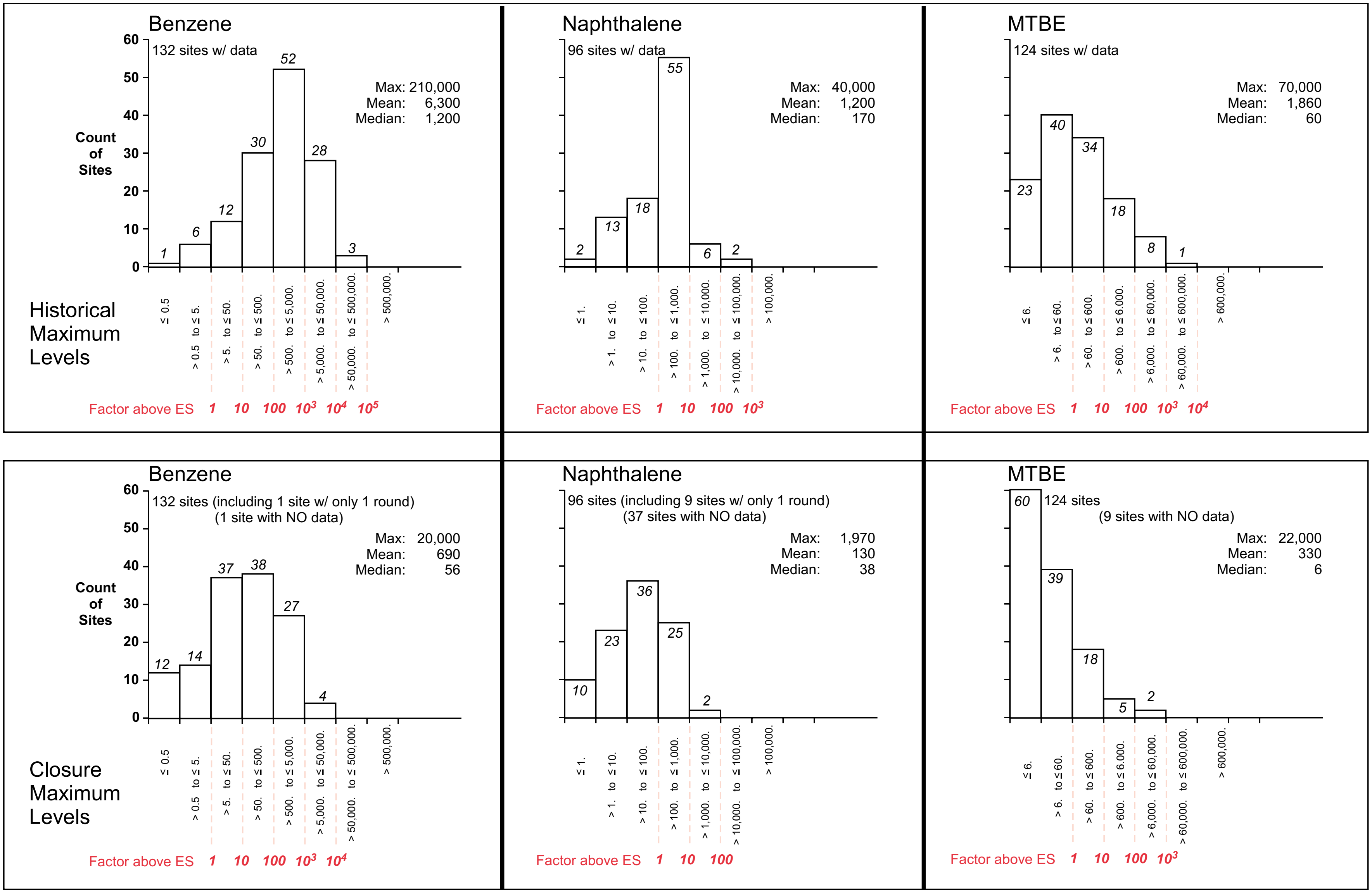
Starting Dates for the Database Sites and Remediation



The early effect of a change in the administrative rule seems apparent in the database sites when the relative proportion of sites that ultimately had some remediation is considered before and after the onset date of flexible closure. The numbers to the left of the onset date are the counts of sites that opened before the date, and the numbers to the right are the counts of sites that opened after the date. The left and right counts are broken down per water-table aquifer geology and whether some remediation occurred (number above the timeline) or not (number below the timeline). The proportion of Remed-NO sites is increasing after the onset date.

Figure 13

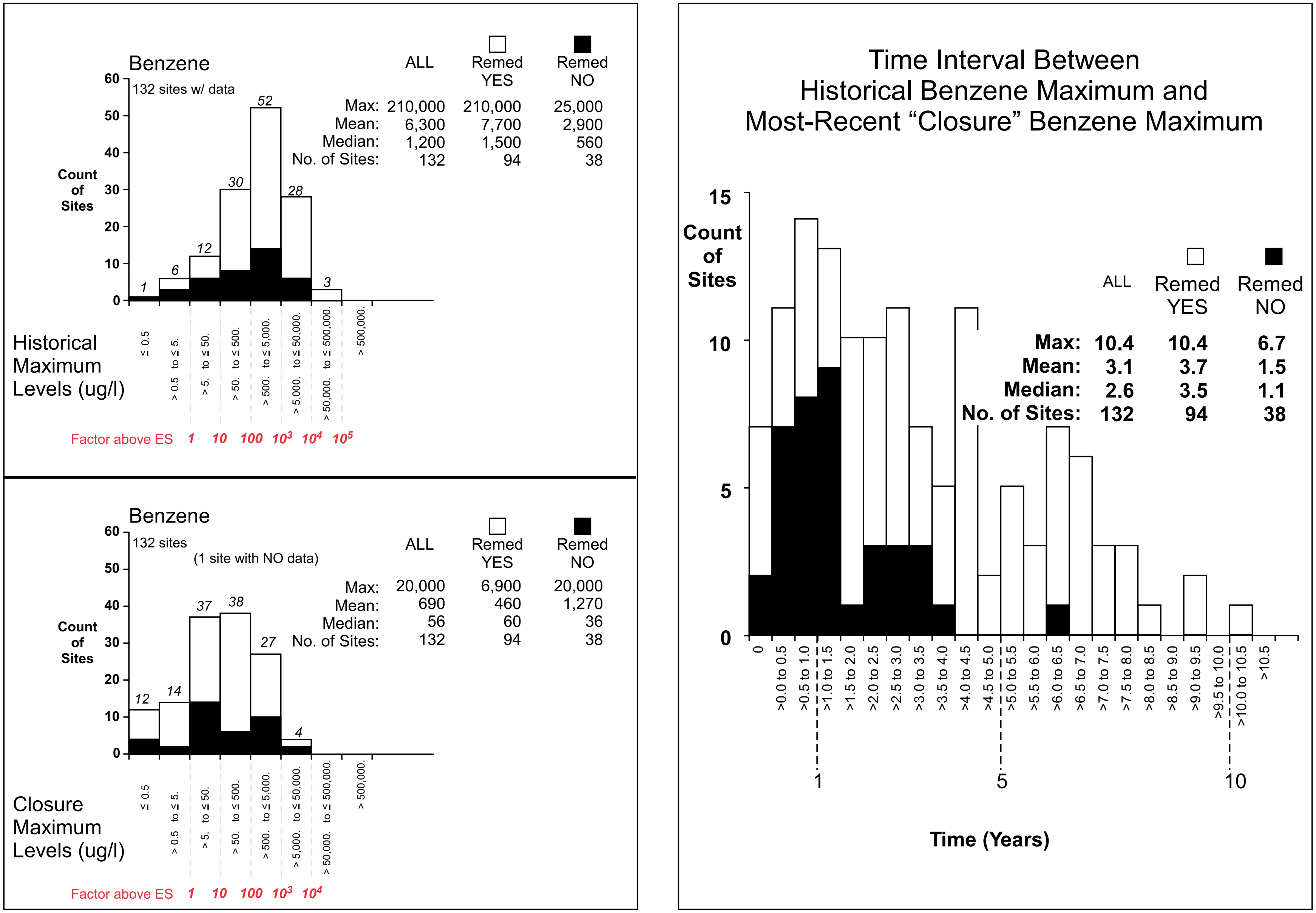
Contaminant Concentrations (ug/l) in the Groundwater



Histograms of the historical maximum (upper plots) and closure maximum (lower plots) benzene, naphthalene and MTBE concentrations in groundwater samples from the database sites. The bins in the histograms are base-10 factors of the respective NR 140 ES of 5 ug/l (benzene), 100 (naphthalene) and 60 (MTBE). The range of the historical maximum levels spanned 7 orders of magnitude for benzene and 6 orders for either naphthalene or MTBE. There is 1 less bin in the closure maximum histograms compared to the historical maximum histograms. This is because the few sites that had the largest historical concentrations had 10x less concentration at closure. The data statistics are available in each of the histograms. Compared to the number of sites with benzene data (132 sites out of 133), there are slightly fewer sites with MTBE data (124 sites), and the number of sites with naphthalene data (at 96) is considerably less.

Figure 14

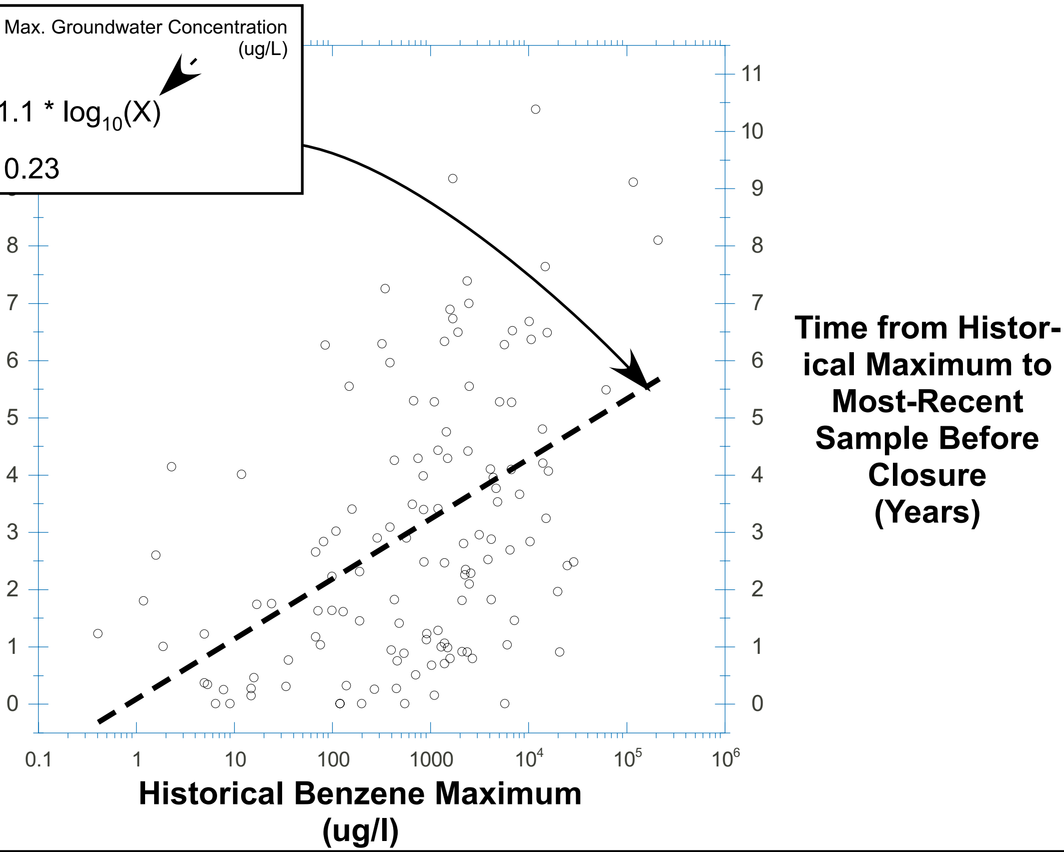
Groundwater Benzene Data and Length of Monitoring



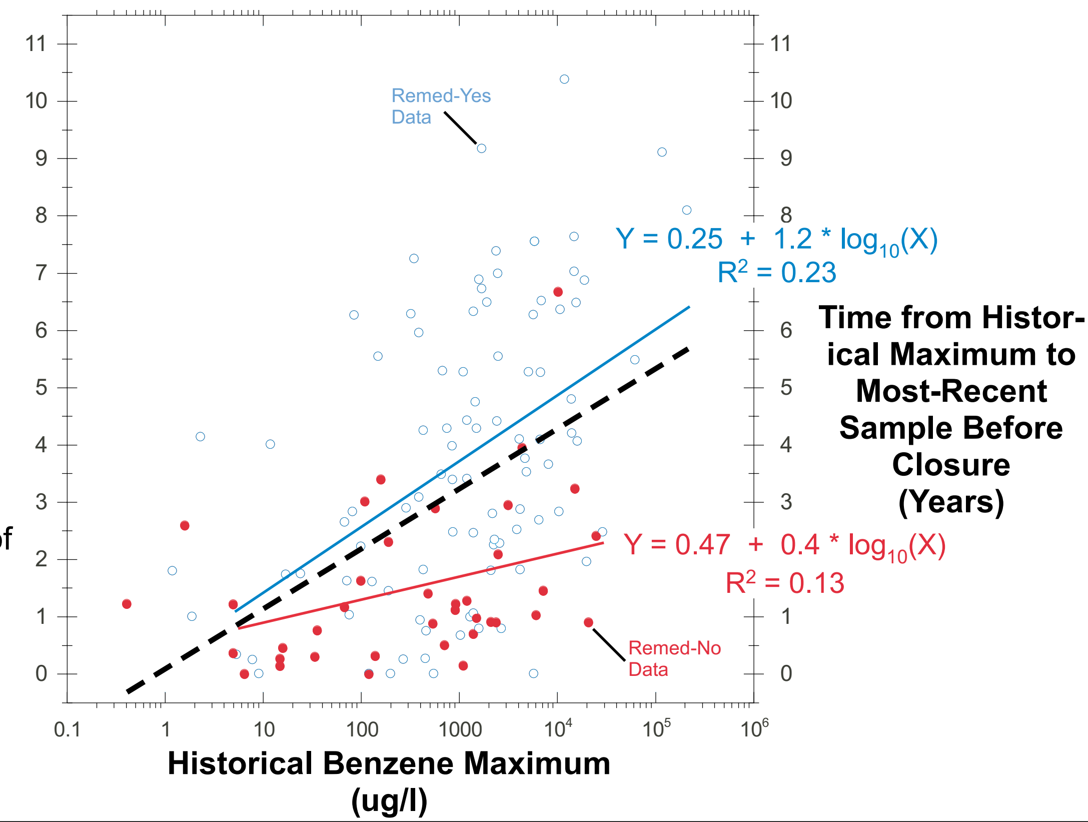
The historical-maximum (upper left plot) and closure-maximum (lower left) benzene data were categorized according to whether some remedy had been implemented (Remed-YES) or not (Remed-NO). The time interval between the 2 observations were tabulated, binned in 0.5-year increments and plotted into a histogram (right plot). The result showed a considerably shorter monitoring time is attributed to Remed-NO sites. Half the Remed-NO sites were monitored for just over 1 year, with only 1 Remed-NO site (Site ID 36) monitored over 5 years after its benzene maximum was observed. The Remed-NO site in the database with over 5 years of monitoring (SiteMap_ID 36) was one of our field sites, so post-closure data for this site is available.

Figure 15

Length of Benzene Monitoring and Maximum-Observed Benzene in the Groundwater



On average, a factor of 10 increase in the benzene concentration lengthens monitoring by only 1 year (*i.e.*, slope is 1.1 yr per unit-$\log_{10}$ increase).

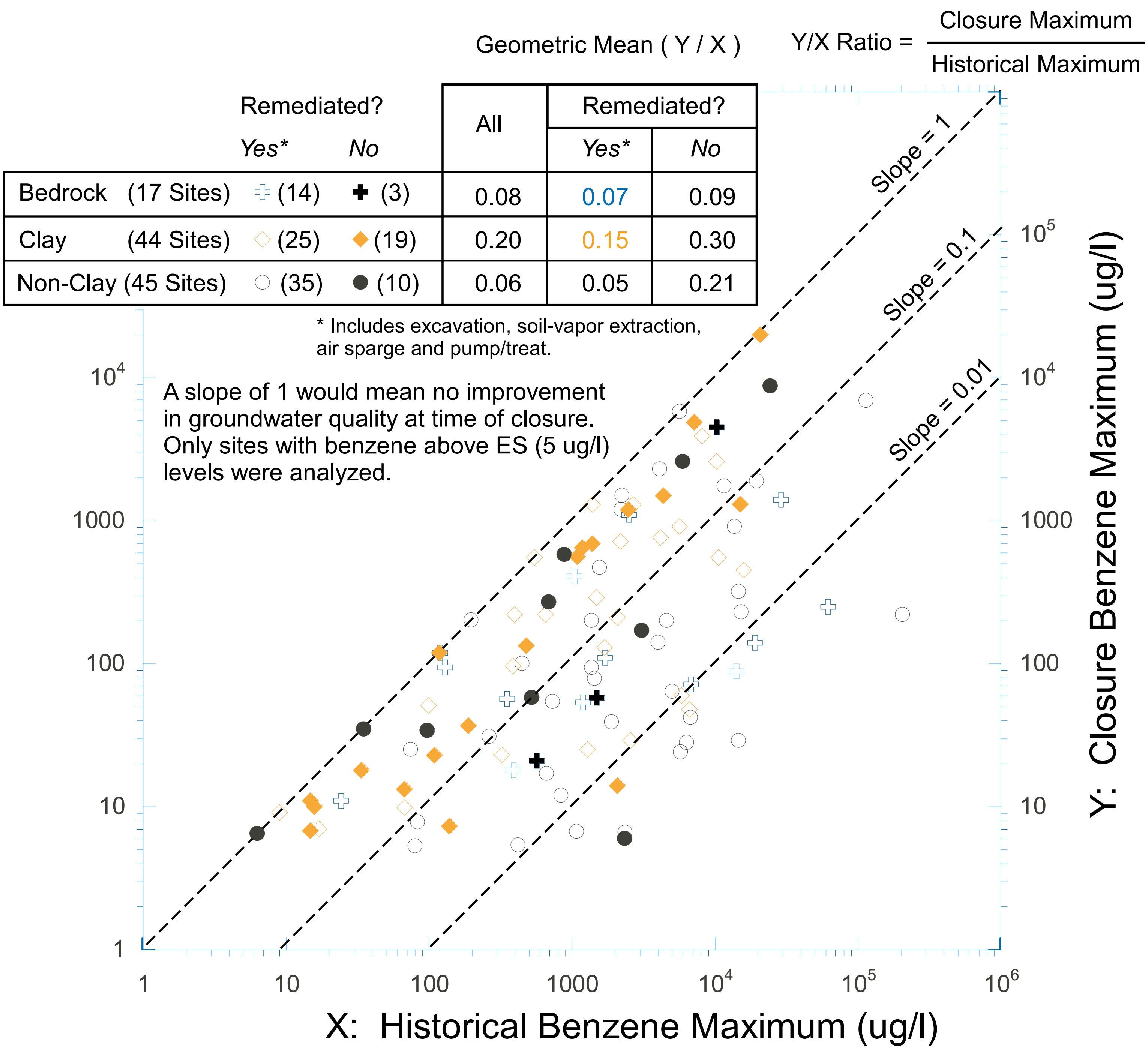


Correlation is much less for "Remed-No" sites. This (Remed-No) subset's regression result predicts less than half a year (slope: 0.4 yr per unit-$\log_{10}$) lengthening of monitoring for a 10-fold increase in benzene concentration.

A longer period of monitoring might be expected at sites where higher contaminant levels had been observed. Our regression analysis showed some correlation (albeit poor, but statistically significant at an α=0.05 t-test for the R^2). However, the result (upper plot) showed that only 1 additional year of monitoring for every 10-fold increase in benzene concentration could be expected. A separate regression involving Remed-No site data alone (lower plot) shows a flatter slope (red line) that predicts less than half a year of additional monitoring for every 10-fold increase in benzene concentration.

Figure 16

Benzene Groundwater Quality Improvement at Closure



	Remediated? Yes*	Remediated? No	All	Remediated? Yes*	Remediated? No
Bedrock (17 Sites)	✚ (14)	✚ (3)	0.08	0.07	0.09
Clay (44 Sites)	◇ (25)	◆ (19)	0.20	0.15	0.30
Non-Clay (45 Sites)	○ (35)	● (10)	0.06	0.05	0.21

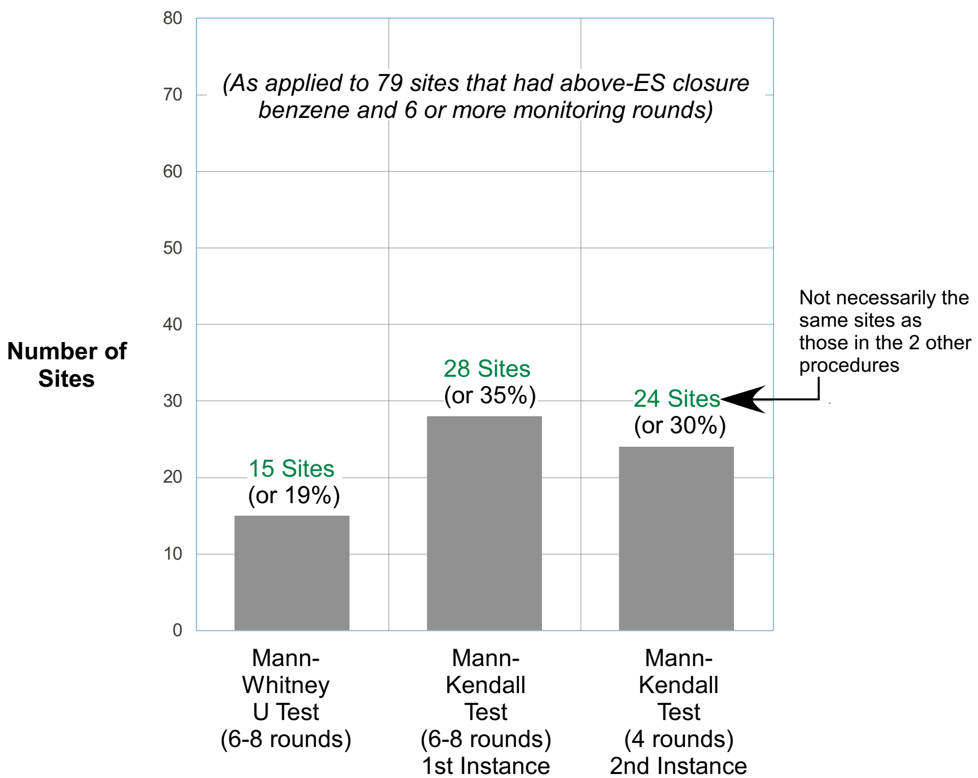
Of the 133 sites in the database, 95 had some remediation, predominantly soil excavation (85 sites). Of 38 non-remediated sites, 32 are included in the plot above; not included were 6 sites that had benzene levels below 5 ug/l. There are about twice as many non-remediated clay sites as non-remediated non-clay sites (19 and 10, respectively).

A point falling along the Slope=0.01 line shows that there was a 99% reduction in the benzene concentration observed at closure relative to the historical maximum benzene. Only 2 non-remediated sites (1 Clay and 1 Non-Clay) fall below this line. The data from clay sites shows that as a class, they have a higher Y/X ratio even when remediation is considered. This could be interpreted as either hydrogeological (*i.e.*, clay sites retain more of the original contamination), or regulatory (*i.e.*, relatively early decision to close clay sites even when only a small reduction from the maximum levels was observed).

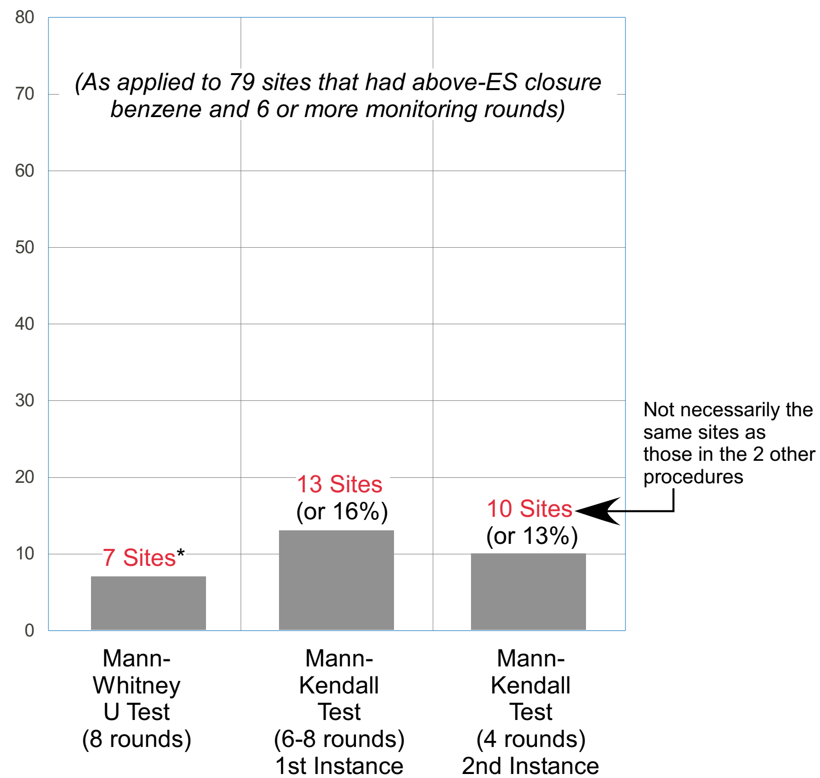
Figure 17

Histograms of Nonparametric Statistical Test Results

Did the nonparametric test indicate a decreasing trend for the benzene levels at a near-source well?



Did the nonparametric test indicate an increasing trend for the benzene levels at a near-source well?

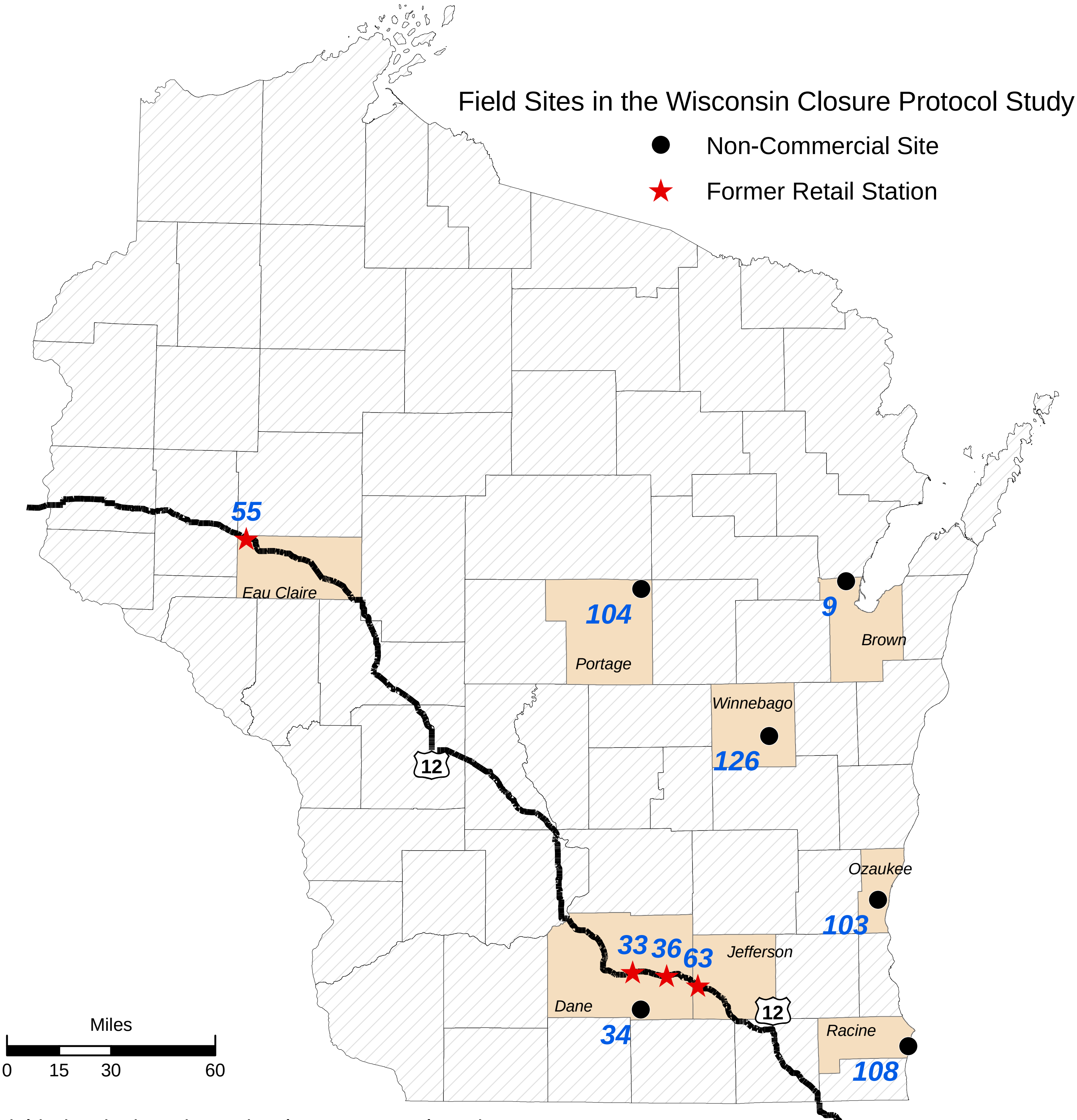


We systematically applied 3 nonparametric statistical-test procedures to the most-recent benzene levels observed at a near-source monitoring well at 79 sites with sufficient number of rounds and their most-recent benzene over ES (5 ug/l).

* As applied to fewer sites. The appendix in NR 746, Wis. Adm. Code, that describes the nonparametric statistical tests, does not instruct the use of the Mann-Whitney U procedure to test for an increasing trend; however, the WDNR-supplied spreadsheet for the Mann-Whitney U test will test for an increasing trend when provided with 8 rounds of data. The 7 sites where the Mann-Whitney U test indicated an increasing trend were from the subset of 55 sites with above-ES closure benzene that had 8 rounds of data available for the test.

The nonparametric statistical tests were designed to detect trends in a time series of very few observations. As can be seen by the low percentages in the histograms, each test procedure may be able to discern trends in the data at only 51% or less of the sites, thus limiting their utility in closure decisions.

Figure 18



Field Sites in the Wisconsin Closure Protocol Study.

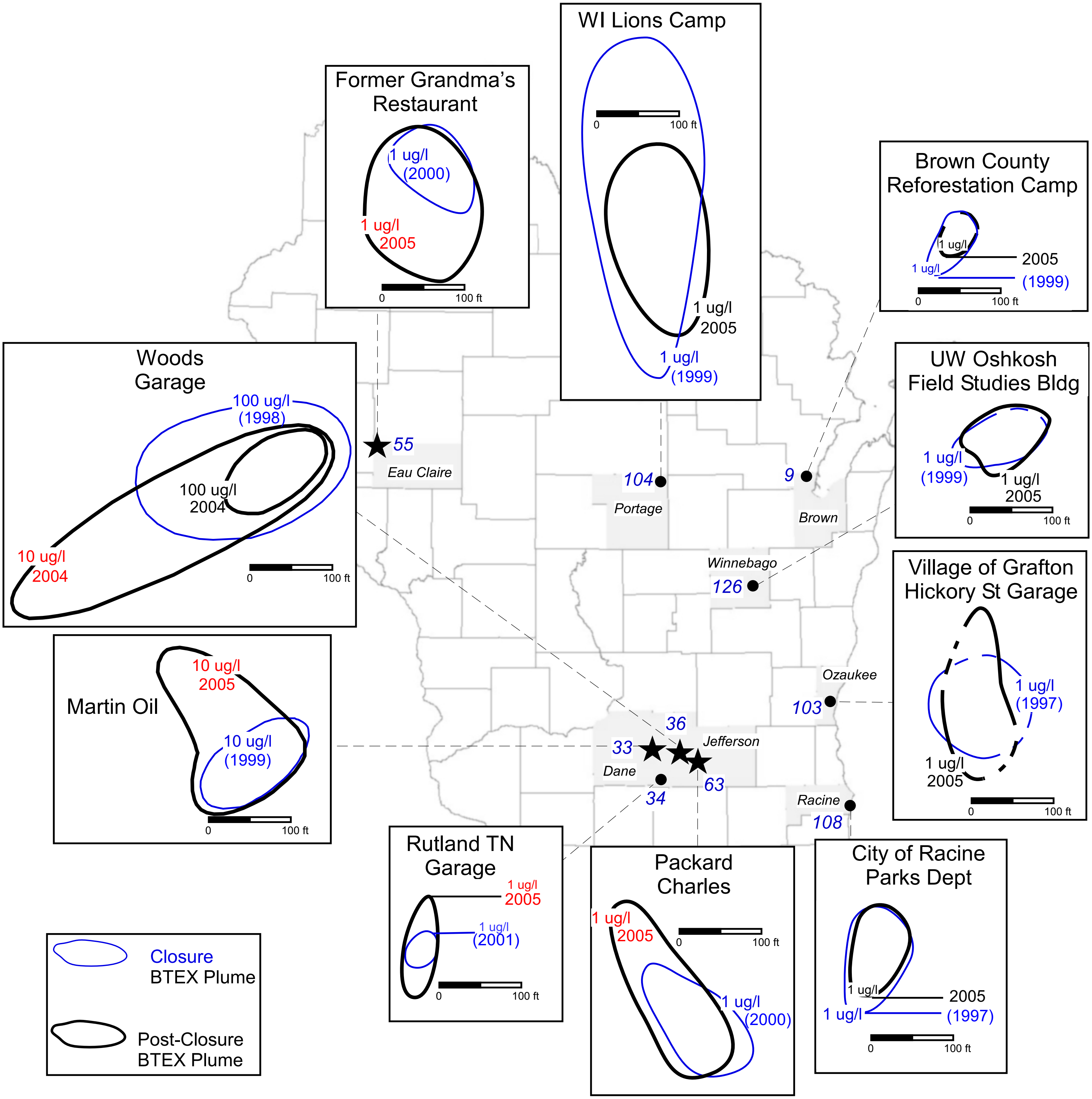
Post-closure monitoring wells were installed at 10 sites in 8 counties. The web links for the sites are in Table 1.

The red stars were 4 former retail petroleum stations along USH 12. They were subsequently purchased by the Wisconsin Department of Transportation as roadway improvement occurred. All structures related to the retail business are now gone.

The black circles are the 6 sites that are non-commercial in nature. For these, most of the structures present during the original site investigation are still intact.

Figure 19

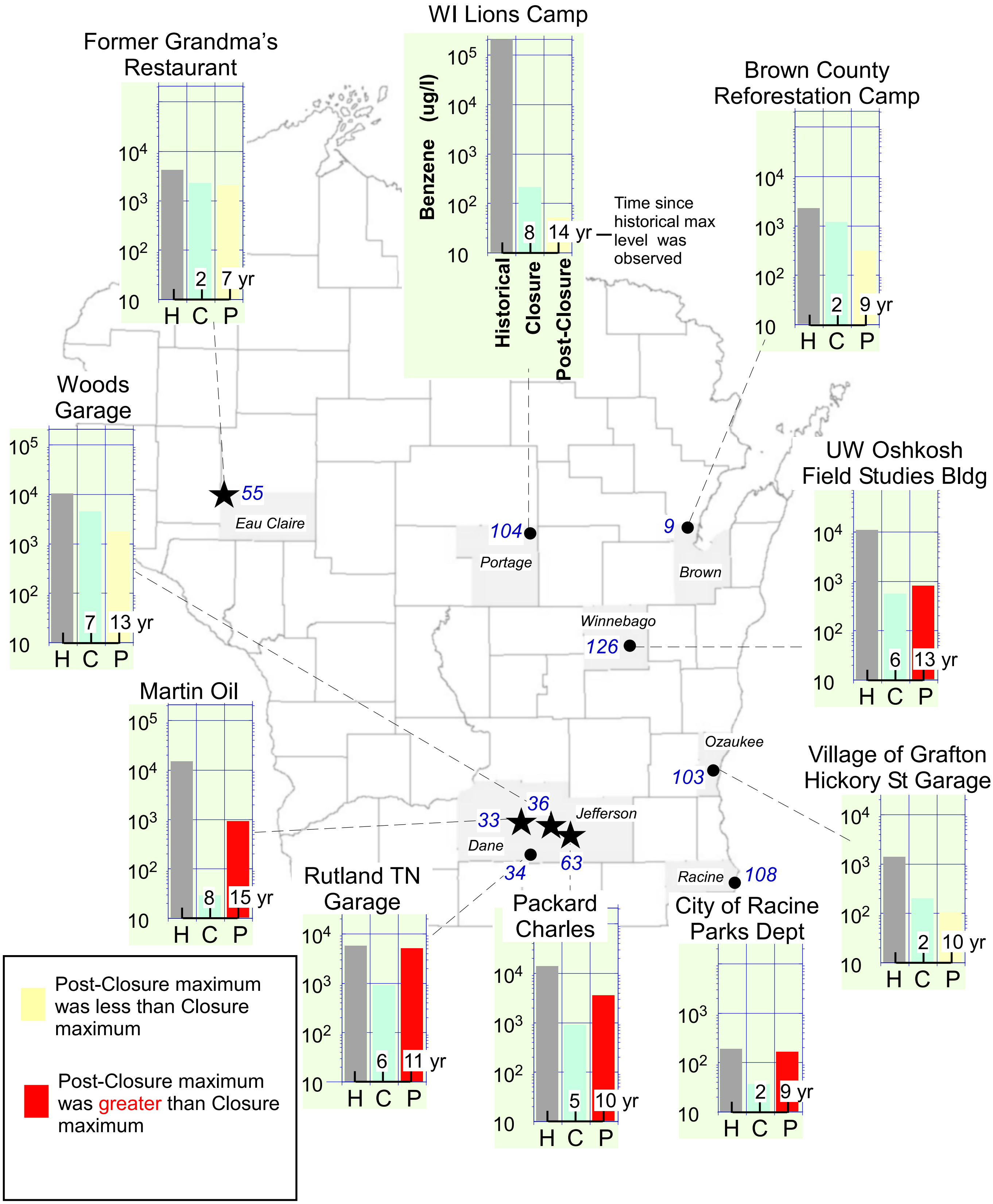
Total BTEX (Closure and Post-Closure) Plumes
Compiled from Keller [2005] and Greve [2007]



Summary plots depicting BTEX plumes at 2 different times (closure and post-closure) for the 10 field sites as delineated by Keller [2005] and Greve [2007]. The areal scale for each plot is exaggerated compared to the scale of the state map in the back drop. The scale for each plot is the same, so comparison between sites can be made. However, Keller had outlined the plume for 2 sites (SiteMap_ID 33 and 36) using the 10 ug/l contour, while Greve [2007] outlined the plume for 8 field sites using the 1 ug/l contour. Year and concentration in red highlight the sites where the plumes may have lengthened post-closure.

Figure 20

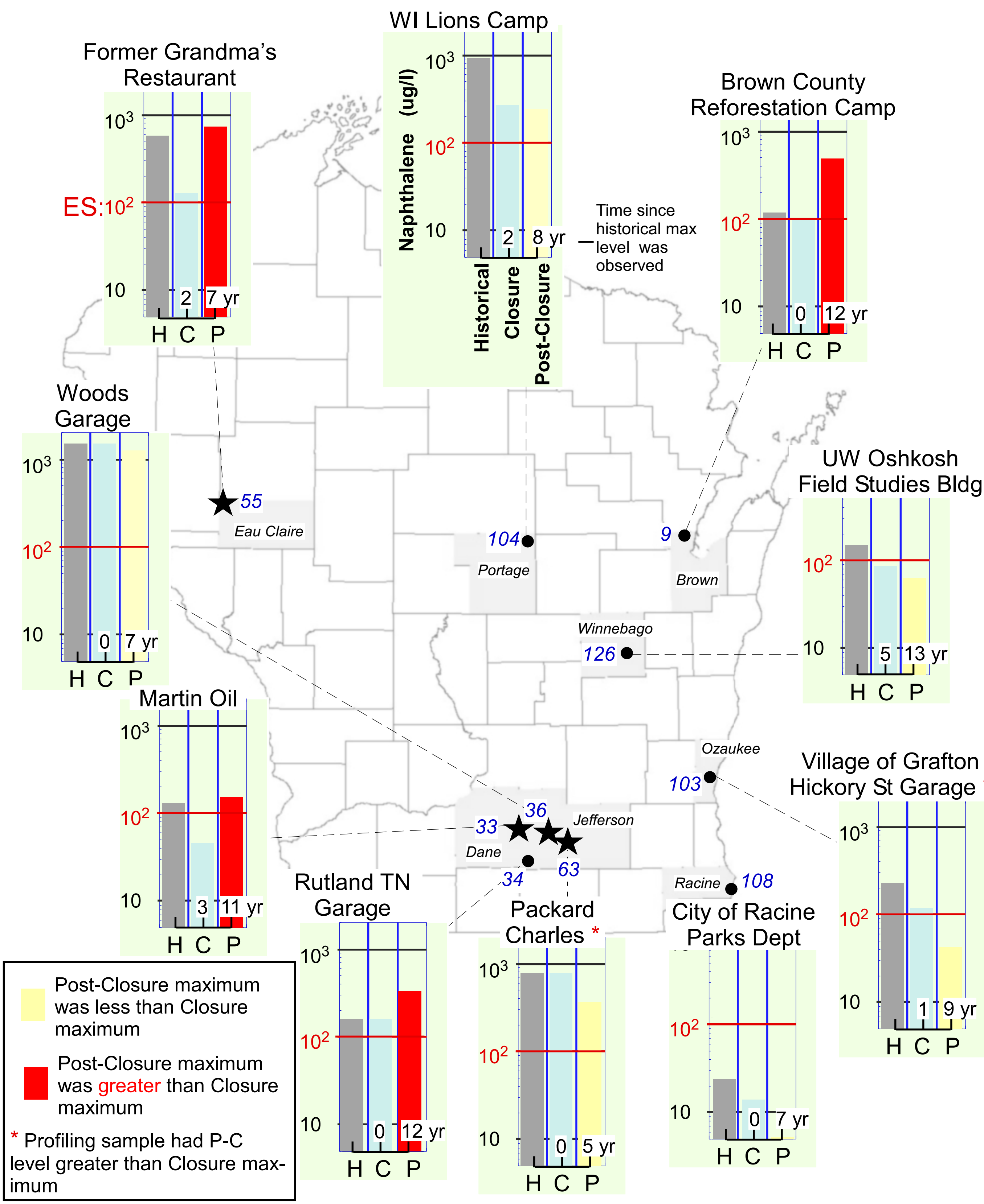
Benzene Data Maximum from Water-Table Monitoring Well Samples



Summary column plots showing the maximum levels observed at different times at each of the field sites. See the plot for the WI Lions Camp near the top of the figure for the labels on the x and y axes that were omitted or shortened on the other plots. The length of time since the historical-maximum level was observed is indicated in each plot.

Figure 21

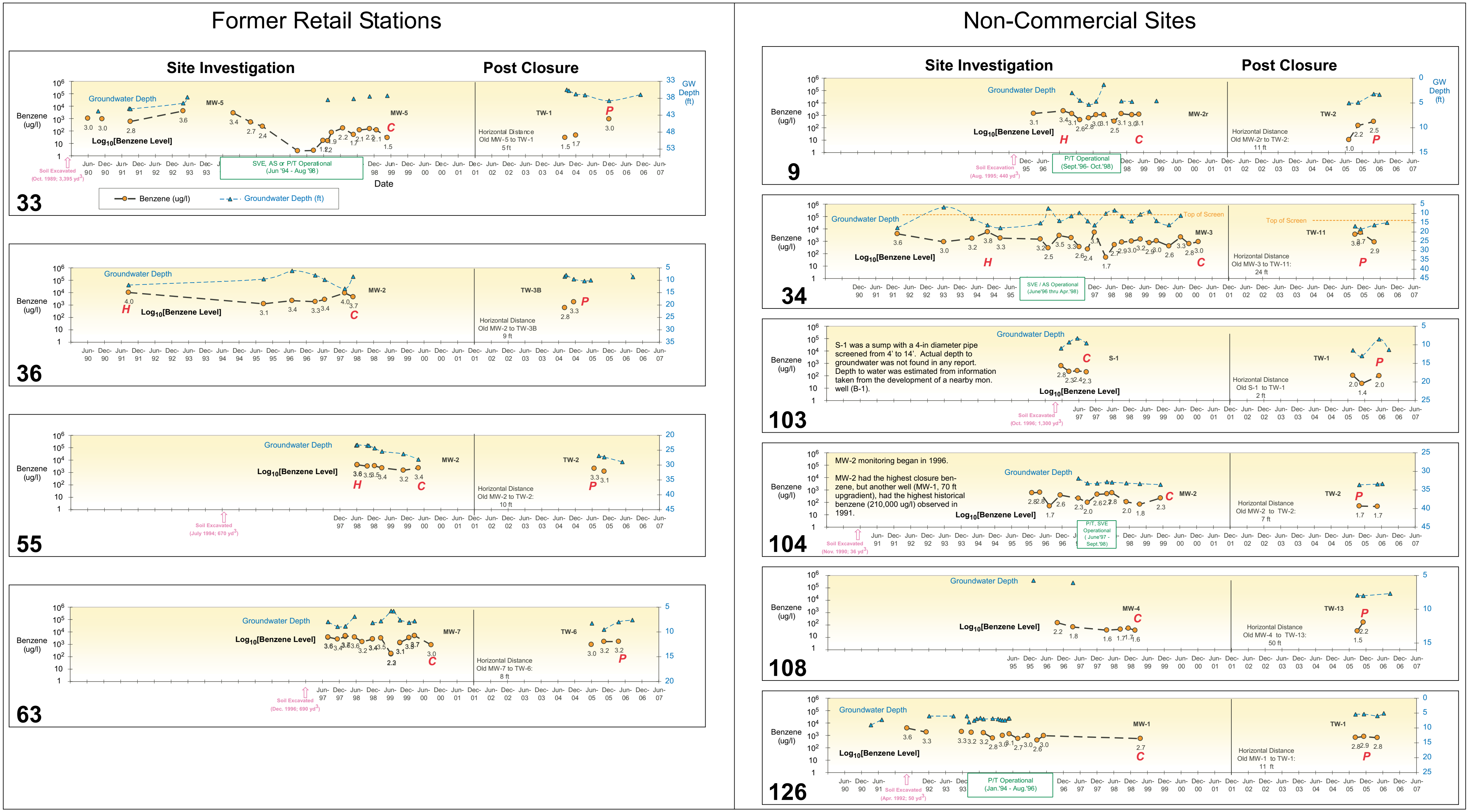
Naphthalene Data Maximum from Water-Table Monitoring Well Samples



See the plot for the WI Lions Camp near the top of the figure for the labels on the x and y axes that were omitted or shortened on the other plots. The red horizontal line across the bars indicates a concentration of 100 ug/l (naphthalene's groundwater standard). The length of time since the historical-maximum level was observed is indicated for each plot. At sites where the time between H(istorical) and C(losure) is 0 yr, naphthalene monitoring was either done only once or curtailed before 1 year.

Figure 22

Benzene History and Groundwater Depth Fluctuation at a Near-Source Well



The figure presents groundwater monitoring data available from a near-source well at the field sites. The benzene data (circles) are plotted in $\log_{10}$-scale (from 1 to 1-million ppb) as shown on the left-side y-axis. The depth data (triangles) are plotted linearly as shown on the right-side y-axis. Appendix A has the individual plots (and data) for each site.

The x-axis covers the period from December 1989 to June 2007 for each plot. A vertical line is arbitrarily drawn along December 2001 to separate the historical site investigation observations from the post-closure observations. The distance between the 2 wells from where the observations were made is indicated in each plot. A green rectangle represents the period when an active groundwater remediation system was operational at the site. A purple arrow indicates when contaminated soil excavation occurred at the site

What is interesting to note, even at the reduced scale of this figure, is that when a downward spike in the benzene concentration occurs (SiteMap_IDs 63 and 34), a corresponding "spike" in the depth to water is also observed. The apparent influence of the depth to water to the benzene concentration is likewise seen, albeit subtly, at other field sites (SiteMap_IDs 36 and 55). When the depth to water seems to affect the benzene concentration, any time-trend observed on the benzene concentration is suspect.

"H", "C" and "P" refer to historical-maximum, closure-maximum and post-closure maximum benzene levels (see Figure 22), respectively. If "H" is not shown in a site plot (6 sites above), then the site's historical-maximum benzene level was observed at a well other than where the closure-maximum level was observed.

Figure 23

Table 1
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Sites Included in the Wisconsin Closure Protocol Study

BRRTS No.	Site Name	Web Links (Mouse-Click to open)				Jurisdiction		Map ID				
		GIS Registry	BRRTS	Tracker	Orthophoto	DNR	COMM		Field Site	Bed Rk	Clay	Non Clay
0302000921	Lakeshore Sales and Service	PDF 1	RR 1	COMM 1	DOP 1	×		1			□	
0302188069	Baron's Radiator Service	PDF 2	RR 2	COMM 2	DOP 2	×		2			□	
0303000171	Mastercraft Industries	PDF 3	RR 3	COMM 3	DOP 3		×	3		□		
0303000228	Nelson Oil	PDF 4	RR 4	COMM 4	DOP 4		×	4				□
0304000155	Bayfield Co. Hwy Shop	PDF 5	RR 5	COMM 5	DOP 5		×	5				□
0305000269	Jacob C Basten Construction	PDF 6	RR 6	COMM 6	DOP 6	×		6				□
0305000945	Brown Cnty Hwy Dept.	PDF 7	RR 7	COMM 7	DOP 7		×	7		□		
0305001288	Stock Lumber	PDF 8	RR 8	COMM 8	DOP 8	×		8			□	
0305001404	Brown County Reforestation Camp	PDF 9	RR 9	COMM 9	DOP 9	×		9	o			□
0305001467	Former Red Owl	PDF 10	RR 10	COMM 10	DOP 10	×		10			□	
0305001495	Pro Care Auto Body	PDF 11	RR 11	COMM 11	DOP 11	×		11				□
0305001631	Shipyard Marine	PDF 12	RR 12	COMM 12	DOP 12		×	12			□	
0305001764	Gene's Plaza Gas & Wash	PDF 13	RR 13	COMM 13	DOP 13	×		13			□	
0305001884	PBBS Equipment Corp.	PDF 14	RR 14	COMM 14	DOP 14	×		14				□
0305109570	Jones Sign Co Inc	PDF 15	RR 15	COMM 15	DOP 15	×		15			□	
0305118555	Former Earthheart Cafe	PDF 16	RR 16	COMM 16	DOP 16	×		16			□	
0305153673	Brown County Publishing	PDF 17	RR 17	COMM 17	DOP 17		×	17			□	
0305173684	Market Square Shopping Center	PDF 18	RR 18	COMM 18	DOP 18	×		18			□	
0305176447	Green Bay East High School	PDF 19	RR 19	COMM 19	DOP 19		×	19			□	
0205181560	Hansen Oil Company	PDF 20	RR 20	COMM 20	DOP 20		×	20			□	
0305208565	Biebel's Supermarket	PDF 21	RR 21	COMM 21	DOP 21		×	21			□	
0206000072	Kochendorfer Oil	PDF 22	RR 22	COMM 22	DOP 22	×		22				□
0306000279	Buffalo Co. Hwy Shop	PDF 23	RR 23	COMM 23	DOP 23	×		23				□
0306000438	United Bank	PDF 24	RR 24	COMM 24	DOP 24	×		24				□
0306000731	Reinhart Farm	PDF 25	RR 25	COMM 25	DOP 25	×		25		□		
0306001366	Buffalo County Hwy. Dept.	PDF 26	RR 26	COMM 26	DOP 26	×		26			□	
0308000350	Kuehne Classic Truck & Auto	PDF 27	RR 27	COMM 27	DOP 27	×		27			□	
0309001480	Clay's Self Service	PDF 28	RR 28	COMM 28	DOP 28	×		28				□
0310169812	Cozy Corner Bar	PDF 29	RR 29	COMM 29	DOP 29	×		29		□		
0311002155	Crawford 66	PDF 30	RR 30	COMM 30	DOP 30		×	30				□
0311100033	Columbus Car Care	PDF 31	RR 31	COMM 31	DOP 31	×		31				□
0313000411	Suburban III Motors	PDF 32	RR 32	COMM 32	DOP 32	×		32				□
0313000420	Martin Oil	PDF 33	RR 33		DOP 33	×		33	o			□
0313000458	Town of Rutland Garage	PDF 34	RR 34	COMM 34	DOP 34	×		34	o		□	
0313000563	Munz Property	PDF 35	RR 35	COMM 35	DOP 35	×		35				□
0313000781	Woods Garage	PDF 36	RR 36	COMM 36	DOP 36	×		36	o	□		
0313001096	Jones & Wayland Transfer	PDF 37	RR 37	COMM 37	DOP 37	×		37				□
0313001661	Burrow's Park Associates	PDF 38	RR 38	COMM 38	DOP 38	×		38		□		
0313001694	Danco Prairie FS Cooperative	PDF 39	RR 39	COMM 39	DOP 39	×		39			□	
0313002698	Town & Country Ford Tractor	PDF 40	RR 40	COMM 40	DOP 40	×		40				□
0313104765	Mike's Place (Former)	PDF 41	RR 41	COMM 41	DOP 41		×	41				□
0313116686	Curran Property	PDF 42	RR 42	COMM 42	DOP 42	×		42			□	
0313152094	Parman's Service	PDF 43	RR 43	COMM 43	DOP 43		×	43		□		
0313172866	Village of Oregon Garage	PDF 44	RR 44	COMM 44	DOP 44		×	44				□
0313178379	Ron's Service Center	PDF 45	RR 45	COMM 45	DOP 45	×		45				□
0313190167	Faust Property	PDF 46	RR 46	COMM 46	DOP 46	×		46			□	
0314001176	Phillips 66 Station	PDF 47	RR 47	COMM 47	DOP 47	×		47		□		
0314001620	Aunt Nellie's Farm Kitchen	PDF 48	RR 48	COMM 48	DOP 48	×		48		□		
0314101094	River Valley Coop Mobil Station	PDF 49	RR 49	COMM 49	DOP 49	×		49		□		
0315000128	Cana Light House	PDF 50	RR 50		DOP 50	×		50		□		

Table 1
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Sites Included in the Wisconsin Closure Protocol Study

BRRTS No.	Site Name	Web Links (Mouse-Click to open)				Jurisdiction		Map ID				
		GIS Registry	BRRTS	Tracker	Orthophoto	DNR	COMM		Field Site	Bed Rk	Clay	Non Clay
0316000434	Sampsons 76	PDF 51	RR 51	COMM 51	DOP 51	×		51				□
0316000536	Indianhead Trucking Line	PDF 52	RR 52	COMM 52	DOP 52	×		52				□
0316000818	Maple Coop Store	PDF 53	RR 53	COMM 53	DOP 53	×		53				□
0318000889	Bridge Creek Town Shop	PDF 54	RR 54	COMM 54	DOP 54	×		54				□
0318001254	Grandma's Restaurant & Truck Stop	PDF 55	RR 55	COMM 55	DOP 55	×		55	o			□
0320000386	C & W Transport	PDF 56	RR 56	COMM 56	DOP 56	×		56		□		
0320001643	Amoco # 15650	PDF 57	RR 57	COMM 57	DOP 57	×		57			□	
0320001963	MR Marine	PDF 58	RR 58	COMM 58	DOP 58	×		58			□	
0220150469	EG Will Oil Co.	PDF 59	RR 59	COMM 59	DOP 59		×	59			□	
0322000450	Kwik Trip - Fennimore	PDF 60	RR 60	COMM 60	DOP 60	×		60		□		
0224209932	Condon Oil -- AST	PDF 61	RR 61	COMM 61	DOP 61	×		61				□
0328000280	Jaeger Farm	PDF 62	RR 62	COMM 62	DOP 62	×		62				□
0328000754	Charles Packard Property	PDF 63	RR 63	COMM 63	DOP 63		×	63	o			□
0328113275	Milford Motors	PDF 64	RR 64	COMM 64	DOP 64		×	64				□
0328172906	Schroeder Standard	PDF 65	RR 65	COMM 65	DOP 65	×		65				□
0330000621	Kenosha News	PDF 66	RR 66	COMM 66	DOP 66	×		66			□	
0331002230	Deprey's Kwik Stop	PDF 67	RR 67	COMM 67	DOP 67		×	67			□	
0332000116	Amoco Station # 15273	PDF 68	RR 68	COMM 68	DOP 68	×		68				□
0334001325	Hackbarth Spur Station	PDF 69	RR 69	COMM 69	DOP 69	×		69				□
0335153171	Domino's Pizza	PDF 70	RR 70	COMM 70	DOP 70		×	70				□
0336000741	Household Utilities Inc (HUI)	PDF 71	RR 71	COMM 71	DOP 71	×		71			□	
0336001049	Pietroske Body Shop	PDF 72	RR 72	COMM 72	DOP 72		×	72				□
0336001186	J & J Service	PDF 73	RR 73	COMM 73	DOP 73	×		73			□	
0236097503	Weber Oil - Cleveland Bulk Plant	PDF 74	RR 74	COMM 74	DOP 74	×		74			□	
0336168408	Manitowoc Cnty HWY Dept.	PDF 75	RR 75	COMM 75	DOP 75		×	75			□	
0337000983	Ben & Janette's Shantytown Bar	PDF 76	RR 76	COMM 76	DOP 76	×		76				□
0338171775	Corner Station/Former Meyer's Service Sta	PDF 77	RR 77	COMM 77	DOP 77	×		77				□
0341000453	Godfrey West/ Sentry Foods	PDF 78	RR 78	COMM 78	DOP 78	×		78				□
0341000541	Suds Your Duds	PDF 79	RR 79	COMM 79	DOP 79		×	79				□
0341000667	O'Connor Petroleum Oil	PDF 80	RR 80	COMM 80	DOP 80	×		80			□	
0341000674	FJA Christiansen Roofing Company	PDF 81	RR 81	COMM 81	DOP 81	×		81			□	
0341000824	Mayflower School Bus Company	PDF 82	RR 82	COMM 82	DOP 82	×		82				□
0341003021	Solvox Mfg. Co Site No. 2	PDF 83	RR 83	COMM 83	DOP 83		×	83			□	
0341003343	Mian's Oil	PDF 84	RR 84	COMM 84	DOP 84		×	84			□	
0341003474	Amoco Service Station #15168	PDF 85	RR 85	COMM 85	DOP 85		×	85			□	
0341003808	Amoco Station #15219	PDF 86	RR 86	COMM 86	DOP 86		×	86			□	
0341004174	Mashianna's Self Serve	PDF 87	RR 87	COMM 87	DOP 87		×	87			□	
0341004248	Civic Minded Inc./Hospitality Inn	PDF 88	RR 88	COMM 88	DOP 88		×	88			□	
0341104241	Knapp Railroad Service Site	PDF 89	RR 89	COMM 89	DOP 89	×		89			□	
0341108626	E. Eggert and Sons	PDF 90	RR 90	COMM 90	DOP 90	×		90			□	
0341208241	Milwaukee Scrap Metal Co	PDF 91	RR 91	COMM 91	DOP 91		×	91			□	
0343108715	Soukup's Bar	PDF 92	RR 92	COMM 92	DOP 92	×		92				□
0344000132	Dan's Mobile	PDF 93	RR 93	COMM 93	DOP 93	×		93				□
0345000048	Farm Credit Union	PDF 94	RR 94	COMM 94	DOP 94	×		94		□		
0345000785	Kwik Trip #639	PDF 95	RR 95	COMM 95	DOP 95		×	95			□	
0345000814	Enterprise Motor Cars	PDF 96	RR 96	COMM 96	DOP 96	×		96				□
0345001649	Chicago Corner Store	PDF 97	RR 97	COMM 97	DOP 97	×		97				□
0345002066	Domino's Pizza	PDF 98	RR 98	COMM 98	DOP 98	×		98			□	
0345106855	Open Pantry Food Mart Site	PDF 99	RR 99	COMM 99	DOP 99		×	99			□	
0345111229	The Moasis (Restaurant)	PDF 100	RR 100	COMM 100	DOP 100		×	100			□	

Table 1
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Sites Included in the Wisconsin Closure Protocol Study

BRRTS No.	Site Name	Web Links (Mouse-Click to open)				Jurisdiction		Map ID				
		GIS Registry	BRRTS	Tracker	Orthophoto	DNR	COMM		Field Site	Bed Rk	Clay	Non Clay
0345182451	Van Handel's Cheese Hut	PDF 101	RR 101	COMM 101	DOP 101		×	101			□	
0345202035	Outagamie Cnty Hwy Dept. - Seymour Gai	PDF 102	RR 102	COMM 102	DOP 102	×		102				□
0346004166	Grafton DPW	PDF 103	RR 103	COMM 103	DOP 103	×		103	o			□
0350000508	WI Lions Camp	PDF 104	RR 104	COMM 104	DOP 104	×		104	o			□
0351000236	Long Branch Bar	PDF 105	RR 105	COMM 105	DOP 105	×		105				□
0352000197	Pugh Oil	PDF 106	RR 106	COMM 106	DOP 106	×		106			□	
0352000913	Farmers Grain & Supply	PDF 107	RR 107	COMM 107	DOP 107		×	107			□	
0352005009	City of Racine Parks Dept	PDF 108	RR 108	COMM 108	DOP 108		×	108	o		□	
0254001556	Chicago & Northwestern RR	PDF 109	RR 109	COMM 109	DOP 109	×		109				□
0354001751	Cole Electric	PDF 110	RR 110	COMM 110	DOP 110	×		110				□
0357000416	Hitchcock's Service	PDF 111	RR 111	COMM 111	DOP 111	×		111		□		
0359000728	Wagner Shell Food Mart	PDF 112	RR 112	COMM 112	DOP 112		×	112				□
0359001372	Graf Creamery	PDF 113	RR 113	COMM 113	DOP 113	×		113				□
0360001800	Amoco Service Station 15320	PDF 114	RR 114	COMM 114	DOP 114	×		114				□
0360002235	R-Way Furniture Garage	PDF 115	RR 115	COMM 115	DOP 115	×		115				□
0360004309	Q-Mart # 209	PDF 116	RR 116	COMM 116	DOP 116	×		116				□
0364001090	Christl Motors	PDF 117	RR 117	COMM 117	DOP 117	×		117				□
0365174949	Former Kim Property	PDF 118	RR 118	COMM 118	DOP 118	×		118			□	
0367002151	O'Connor Oil	PDF 119	RR 119	COMM 119	DOP 119	×		119				□
0368000313	Dixon Oil Inc.	PDF 120	RR 120	COMM 120	DOP 120	×		120		□		
0368003755	Amoco Station #15357 (Landrys)	PDF 121	RR 121	COMM 121	DOP 121		×	121			□	
0368206024	Brookfield Hills Golf Course	PDF 122	RR 122	COMM 122	DOP 122		×	122				□
0369000214	Dennison Quality Oil	PDF 123	RR 123	COMM 123	DOP 123	×		123				□
0371000174	Mercury Marine - PLT 33	PDF 124	RR 124	COMM 124	DOP 124	×		124			□	
0371000368	Michael Nikodem/Try R Auto	PDF 125	RR 125	COMM 125	DOP 125		×	125		□		
0371000726	UW Oshkosh Field Studies Building	PDF 126	RR 126	COMM 126	DOP 126		×	126	o		□	
0371001243	Basler Flight Service - Office	PDF 127	RR 127	COMM 127	DOP 127	×		127		□		
0371001590	Celebrations Connection	PDF 128	RR 128	COMM 128	DOP 128	×		128		□		
0371114489	Amoco Food Shop - US Oil	PDF 129	RR 129	COMM 129	DOP 129		×	129			□	
0271203076	Wisc Central - Neenah Locomotive Area	PDF 130	RR 130	COMM 130	DOP 130	×		130			□	
0372000075	Consolidated Papers Inc	PDF 131	RR 131		DOP 131	×		131		□		
0372000722	Kwik Trip #331	PDF 132	RR 132	COMM 132	DOP 132	×		132				□
0372000906	Old Port Edwards Fire Station	PDF 133	RR 133		DOP 133	×		133				□

Table 2: Information Notes and Counts of Log Entries to the Database

	Description	Information Notes / Counts
General Information		
	SiteCount	133 Sites
	SiteName	132 different names (2 sites w/ same name Domino's Pizza)
	BRRTS Number	133 Sites
	Facility ID Number	83 Sites with FIDs; 50 Sites without FIDs
	Reviewers	2 reviewers (NK: 82 sites; RG: 51 sites)
	Date of File Review	Earliest 2/7/2004; latest 3/24/2006
	Consultant Co. Name	~58 different Consulting Companies
	FacilityName	131 different facility names; named Amoco Service Station (2 sites); Kwik Trip (2)
	County	45 different counties. Most sites in Brown (16 sites), Dane (15), Milwaukee (14) and Outagamie (9)
	Setting	89 Urban Sites; 23 Suburban; 21 Rural
	Number of UST sites within ¼ mi (1320 ft)	72 sites with nearby USTs; 1 Site (Map_ID 85) has 12 nearby UST sites.
	No. of GW receptors within ¼ mile of the source	70 sites with nearby GW receptor(s); 1 Site (Map_ID 55) has 7 nearby receptors
	Other receptors of concern (list)	53 sites with nearby lake, stream, wetland or utility trenches
	Site Dimensions Length (ft)	130 sites w/ info. Range: 70' to 3,900'. Median: 230'
	Site Dimensions Width (ft)	130 sites w/ info. Range: 50' to 1,600'. Median: 154'
Characteristic of Interest		
	Extensive GW analytical record?	89 Yes; 44 No
	MTBE monitoring?	127 Yes
	Piezometers on site?	34 Yes
	Number of piezometers	0 PZ (99 sites); 1 PZ (27 sites); 2 PZ (2 sites); 3 PZ (2 sites); 4 PZ (1 site); 6 PZs (2 sites)
	Possible Water Level / Concentration relationship?	53 Yes (40 Yes by NK); 34 No (28 No by NK); 46 Unknown (34 Unknown by RG)
	NA monitoring parameters?	99 Yes; 34 No
	Degradation rate data?	38 Yes
	Number of downgradient mon. wells > 250 ft away from site	15 sites w/ MWs > 250' away
Spill Description		
	Year spill reported	Earliest is 1987, but for this site, no monitoribg until 1998 (over 10 yrs after release)
	Year service station opened	48 sites w/ info. Earliest is 1910. 24 sites opened between 1960 and 1980.
	Date tanks removed / upgraded	129 stes w/ info.
	Product (check all that apply): Gasoline?	123 sites w/ gasoline; 10 sites w/ no gasoline, but w/ diesel; 1 site w/ no gasoline, but w/ fuel oil.
	Product (check all that apply): Diesel?	78 sites; 68 of these had both diesel and gasoline
	Product (check all that apply): Waste Oil?	33 sites
	Active service station at closure date?	33 Yes
	Volume (gallons) for ALL products	40 sites w/ info. Smallest volume is 34 gallons; largest is 73,560 gallons.
Point of Release		
	Number of recorded releases	24 sites either single or multiple; 109 sites unknown.
	Distance: source to downgradient property boundary (ft)	121 sites with info. Range is 10' to 3,000'. Median: 80'
	Number of tanks removed from the site	129 sites w/ info. Range: 0 to 10 tanks. Median: 3 tanks
	Release points (check all that apply): Tanks?	80 Yes
	Release points (check all that apply): Lines?	35 Yes; 50 No line release had Yes Tank Release instead
	Release points (check all that apply): Dispensers?	51 Yes; 40 No Dispenser release had Tank Release instead.
	Release points (check all that apply): Unknown?	42 Yes (unknown release unrelated to tank, line or dispenser)
Soil Borings		
	Total number	131 sites w/ info. Range: 3 to 73 soil borings. Median: 14.
	Number inside source zone	131 sites w/ info. Range: 0 to 18 soil borings. Median: 3.
	Number outside source zone	131 sites w/ info. Range: 0 to 43 soil borings. Median: 11.
	Unknown	127 sites w/ info. Range: 0 to 18 soil borings. Median: 0.

Table 2: Information Notes and Counts of Log Entries to the Database

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	Description	**Information Notes / Counts**
Source Zone		
	Length (ft) from Consultant Report	39 sites w/ info. Range: 12' to 365'
	Width (ft) from Consultant Report	39 sites w/ info. Range: 8' to 105'
	Length (ft) Reviewer Interpreted	127 sites w/ info. Range: 12' to 365'. Median: 40'
	Width (ft) Reviewer Interpreted	127 sites w/ info. Range: 10' to 100'. Median: 30'
	Criteria: Soil data (Conc. > NR 746 Table 1?)	64 Yes
	Criteria: GW data Total BTEX > 50 mg/l?	3 Yes
	Criteria: GW data Benzene > 10 mg/l?	21 sites with >10 mg/l gw Benzene was observed
	Criteria: Free product zone (including sheen)?	16 Sites
	Criteria: Soil-gas survey?	17 Yes
	Criteria: Drill cutting observation (staining, odor?)	74 Yes
	Criteria: Tank bed used to determine SZ?	95 Yes
	Criteria: Is there more than 1 source zone on site?	33 Yes
	Criteria: Does SZ extend off the property boundary?	11 Yes
	Criteria: Has sheen been observed?	18 Yes
	Criteria: Most-recent sheen observation date	Most recent date is 6/16/2000 -- a few months before closure
	Criteria: Maximum FP thickness (ft) observed	16 sites w/ measurable FP. Range: 0.01' to 6.13'; median: 1.1'
	Criteria: Date when max. thickness was observed	The 6.13' FP (fuel oil release) was observed in 1991.
	Criteria: If FP was present, most recent date observed	The 6.13' FP site still had FP in Feb. 1999. It closed in Dec. 1999.
Monitoring Wells		
	Total number of wells with groundwater data	131 sites with wells. Range: 1 well (2 sites) to 23 wells (1 site). Median: 7 wells
	Number of wells relative to SZ: Upgradient	114 sites w/ at least 1 upgradient well; 1 site had 12 upgradient wells.
	Number of wells relative to SZ: In SZ	114 sites w/ at least 1 SZ well; 1 site had 6 SZ well
	Number of wells relative to SZ: Downgradient	122 sites w/ at least 1 downgradient well
	Number of wells relative to SZ: Crossgradient	113 sites w/ at least 1 crossgradient well
	Number of wells relative to SZ: Unknown	13 sites w/ wells whose location relative to the SZ is unknown.
	Wells too few to determine groundwater flow direction?	6 Yes (i.e., 6 sites w/ 2 wells or less)
Remediation		
	Soil Excavation?	85 Yes
	Soil Volume excavated (yd^3)	83 site w/ info. Range: 5 to 8,400 yd3. Median: 486 yd3. Max. 8,400 yd3 for 1 site where cost was >$1M. The other $1M site had no soil excavation.
	Free Product Removal?	10 Yes (There are more FP sites, but not all have FP removal.)
	Volume of FP pumped (gallons)	7 sites w/ info. Range: 0.25 to 6,000 gallons
	Active Bioremediation?	1 Yes
	Vapor Extraction?	20 Yes
	Air / Bio Sparge?	12 Yes
	Pump and Treat?	33 Yes
	Total Mass of contaminant removed (kg) thru remediation	17 sites w/ info. Range: 0.058 to 9,900 Kg. Median: 700 kg
	Nat. Att. assessed after remedy(ies)?	78 Yes
	GW Natural Attenuation?	95 Yes
	NA Based on: GW trends along plume centerline?	98 Yes
	NA Based on: GW degradation rates?	48 Yes
	NA Based on: Statistical tests (e.g. Mann-Kendall)?	8 Yes
	NA Based on: Other?	50 Yes
	NA Based on: List Other technique(s) used to assess NA	48 Sites w/ info on OTHER basis (low K, SESOIL, low conc., NA Parameters, etc.)
	NA Based on: Unknown Evidence?	10 Yes
Hydrogeologic Setting		
	Hydrogeologic District	128 out of 133 sites have info; 68 sites are in Eastern Drift Carbonate Region setting
	Bedrock Encountered?	20 Yes (20 Bedrock Sites)
	Unconsolidated Sediments Saturated Zone	53 sites "Clay" (includes organic soil sites)

Table 2: Information Notes and Counts of Log Entries to the Database

	Description	Information Notes / Counts
Groundwater Flow		
	Closure report gw Azimuth MinValue Direction	126 sites have info
	Closure report gw Azimuth MaxValue Direction	111 sites with estimates from 2 or more dates
	Closure report MinValue Horizontal hydraulic gradient (H.Grad.)	105 sites w/ info. Range: 0.0003 to 0.106. Median: 0.013
	Closure report MaxValue Horizontal hydraulic gradient (H.Grad.)	105 sites w/ info; Range: 0.0007 to 0.240. Median: 0.02
	Closure report MinValue V.Grad. direction	23 sites w/ info (13 Downward; 10 Up)
	Closure report MaxValue V.Grad. direction	23 sites w/ info (14 Downward; 9 Up)
	Reviewer Interpreted MinValue H.Grad.	47 sites w/ info (21 of which was independently analyzed by reviewers)
	Reviewer Interpreted MaxValue H.Grad.	47 sites w/ info (21 of which was independently analyzed by reviewers)
	Reviewer Interpreted MinValue V.Grad. direction	9 sites w/ info (6 Down; 3 Up)
	Reviewer Interpreted MaxValue V.Grad. direction	9 sites w/ info (5 Down; 4 Up)
	Azimuth of plume axis	72 sites w/ info
	Reviewer Interpreted Est. of actual flow, Azimuth	42 sites w/ info, 4 of which the reviewer's estimate was different than above
	Reviewer Interpreted Est. of H. Gradient	44 sites w/ info
	Reviewer Interpreted Est. of V. Gradient direction	8 sites w/ info
Aquifer Characteristic		
	Min K	98 sites w/ info. Range: 7.7e-09 to 0.24 cm/s. Median: 5.8e-5 cm/s
	Max K	98 sites w/ info. Range: 1.6e-08 to 0.24 cm/s. Median: 2.1e-4 cm/s
	Method K was determined	96 sites w/ info. (58 sites slug/bailer tests; 17 literature; 10 pump tests)
	Consultant Report, Date/Page	97 has exact refrerence for K
Water Level Fluctuation		
	Ground surface elev. at tanks or dispenser (ft msl)	75 sites w/ info
	Nearest to Tank, MonitoringWell Name	127 sites w/ info
	Depth to water (ft bgs), Min	123 sites w/ info. Range: 0.9' to 75.6'. Median: 6.5'. 87 sites have depth to water < 10 ft.
	Depth to water (ft bgs), Max	119 sites w/ info. Range: 2.1' to 78.2'. Median: 9.7'. 5 site have >30 ft to GW
	Long-term rising, falling or seasonal trend?	112 Sites w/ info.
	Approx. rise (ft)	Only 1 site showed a general rise. Rise is 4'.
	Approx. drop (ft)	7 sites showed a general drop. Range: 1' to 5'.
	Approx. range (ft)	104 sites w/ fluctuation from 1' to 10'. Median: 2'
	How many years of water-level monitoring	123 sites w/ info. Range: 0 to 11 years. Median: 3 years
Contamination from Other Source(s)		
	Any upgradient well(s) contaminated with HC?	35 Yes
	Is uprgradient contamination site related?	31 Yes
	Is site within an area-wide GW casing restriction?	0 Yes (133 No)
	Are non-petroleum found or co-mingled w/ petrol. plume?	26 Yes
	If co-mingled, what type contamination?	14 chlorinateds; 11 metals/lead; 1 nitrate
Extent of GW monitoring data		
	Number of Rounds of GW sampling	133 sites w/ info, including sump samples. Range: 1 (3 sites) to 48 (1 site). Median: 9 rounds.
	Sampling conducted over how many years?	126 sites w/ info. Range: 1 yr (14 sites) to 10 yrs (2 sites). Median: 4 years
	Significant break in sampling record (i.e., missed >2 sampling rounds)?	64 Yes
	Were all MWs sampled throughout monitoring life?	77 Yes
	Were there MWs w/ concentrations < ES throughout monitoring history?	123 Yes
Reviewer Comment		
	Comment	122 sites with unique comments by reviewers

Table 3: Count of Sites Where No Remedy was Implemented

What is a typical "Remediated-No" site?

Count of Database Sites	Water-Table Aquifer	Count of "Remed-No" Sites	"Remed-No" Fraction Relative to Aquifer Type	% Relative to Total "Remed-No" Sites
133	**All**	**38**	0.29	100 %
20	**Bedrock***	**3**	0.15	8 %
53	**Clay**	**22**	0.42	58 %
60	**NonClay***	**13**	0.22	34 %

** Bedrock refers to sites where borings encountered bedrock.*
NonClay refers to sites that are neither Clay nor Bedrock.

Table 4: Statistical Tests on the Benzene Monitoring Data

(p. 1 of 5)

Site Map_ID (Struck-through if Low-K site)	Remediated (1=Yes)	Historical Benzene Maximum (ug/l) *	Date When Historical Maximum Was Observed	Most-Recent Benzene Used in Statistical Tests (ug/l) *	Date of Most-Recent Sample Used in Statistical Tests	Monitoring Well in Statistical Tests **	Number of Rounds (n) in Statistical Tests and Regression ***	Did the Mann-Whitney (α = 0.1) Test Show a DECREASE? ****	Did the Mann-Kendall (α = 0.2) Test Show a DECREASE (n > 4)? [1st instance] ****	If M-K Result is "No," is CV<1? ****	Did the Mann-Kendall (α = 0.2) Test Show a DECREASE Using Only the 4 Most-Recent levels? [2nd instance] ****	If M-K (Recent 4) Result is "No," is CV<1? ****	$t_{1/2}$ (yr) [Half-life is negative if time trend is increasing] *****	r^2 *****	Is r^2 significant (at α = 0.1 level test)? *****
1	1	*100*	07/25/1996	51.0	10/15/1998	MW3	7	No	No	Yes	No	Yes	4.3	*0.12*	*No*
~~2~~	1	*8*	02/11/1999	0.2	05/11/1999	MW10A	3								
3	1	*390*	07/25/1996	18.0	08/25/1999	MW1	5				No	No	0.7	*0.99*	*Yes*
4	1	*430*	03/04/1992	3.2	06/04/1996	MW2	8	Yes	Yes		No	No	1.0	*0.22*	*No*
5	1	862	05/22/1996	12.0	10/12/1999	MW6	8	Yes	Yes		No	Yes	0.6	*0.58*	*Yes*
6		*912*	06/06/1996	580.0	07/21/1997	M28	4				No	Yes	2.4	*0.27*	*No*
7	1	*1040*	05/20/1998	410.0	01/21/1999	SMP	8	No	No	*Increasing Trend*	Yes		-0.4	*0.71*	*Yes*
8	1	1200	10/14/1994	0.2	03/17/1999	MW1	3								
9	1	2260	01/17/1997	1200.0	04/19/1999	MW2r	8	No	No	*Increasing Trend*	No	Yes	-1.6	*0.24*	*No*
10		*2500*	07/06/1995	1200.0	08/06/1997	MW1	6	Yes	Yes		Yes		3.6	*0.71*	*Yes*
11	1	870	07/15/1996	4.5	01/05/1999	MW9	8	Yes	Yes		No	Yes	0.6	*0.50*	*Yes*
12	1					NO Data									
13	1	2600	04/17/1996	29.0	07/28/1998	MW-1	8	No	No	*Increasing Trend*	No	*Increasing Trend*	-0.2	*0.43*	*Yes*
14	1	3900	12/01/1995	3.9	06/08/1998	MW2	8	No	No	No	No	Yes	-88.8	*0.00*	*No*
15		*483*	06/02/1997	134.0	10/29/1998	MW1	6	Yes	Yes		Yes		1.1	*0.81*	*Yes*
~~16~~		68	03/21/1997	13.3	05/22/1998	MW3	7	Yes	Yes		Yes		0.6	*0.80*	*Yes*
~~17~~		*1400*	05/27/1999	690.0	02/07/2000	MW12	6	No	No	Yes	Yes		-0.2	*0.36*	*No*
~~18~~		*120*	08/05/1998	**120.0**	08/05/1998	M5W	1								
19		930	02/11/1998	0.1	05/04/1999	MW-6	1								
20		*15*	09/01/1999	11.0	12/08/1999	MW1	3								
21		*15*	10/22/1999	6.8	12/14/1999	MW1	3								
22	1	*12*	12/27/1994	0.8	12/29/1998	B-1	8	Yes	Yes		No	Yes	1.2	*0.51*	*Yes*
23	1	85	11/06/1992	7.8	02/08/1999	MW4	8	No	No	Yes	No	Yes	-5.2	*0.07*	*No*
24	1	1100	04/05/1993	6.7	07/13/1998	MW8	8	No	No	No	Yes		-0.7	*0.10*	*No*
25	1	14100	06/05/1996	89.0	08/16/2000	MW4	6	No	Yes		No	Yes	0.9	*0.83*	*Yes*
26		*4400*	08/15/1995	1500.0	07/27/1999	MW2	7	No	Yes		No	Yes	3.0	*0.56*	*Yes*
27	1	5900	07/05/1991	60.0	01/20/1999	EW-3	8	Yes	Yes		No	Yes	0.5	*0.73*	*Yes*
28	1	6500	01/22/1997	28.0	09/28/1999	MW2	6	No	No	Yes	No	Yes	-1.4	*0.15*	*No*
29	1	29000	10/06/1997	1400.0	03/27/2000	PZ1400	5				No	Yes	-14.1	*0.08*	*No*
30		*3160*	08/14/1996	170.0	07/28/1999	MW1	4				Yes		0.8	*0.98*	*Yes*

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31		***36***	12/18/1998	35.0	09/22/1999	MW1	5				No	Yes	-2.9	*0.03*	*No*
32	1	**201**	10/15/1996	**201.0**	10/15/1996	MW4	8	Yes	Yes		No	No	0.7	*0.37*	*No*
33	1	15000	09/12/1991	29.0	04/29/1999	MW5	8	No	No	Yes	No	Yes	-2.6	*0.04*	*No*
34	1	5700	10/04/1994	911.0	01/08/2001	MW3	8	No	No	Yes	No	Yes	6.6	*0.02*	*No*
35	1	850	12/20/1995	5.0	12/10/1999	MW4	8	No	No	Yes	No	Yes	-3.5	*0.02*	*No*
36		***10300***	08/27/1991	4530.0	04/29/1998	MW2	7	No	No	Yes	No	*Increasing Trend*	7.2	*0.07*	*No*
37	1	1930	05/22/1992	39.0	11/15/1998	MW5	8	Yes	Yes		No	Yes	1.1	*0.49*	*Yes*
38	1	150	02/04/1993	1.3	08/21/1998	MW1	8	No	No	No	No	No	-13.8	*0.00*	*No*
39	1	1700	11/18/1992	130.0	08/09/1999	MW4	6	No	No	Yes	No	Yes	13.9	*0.00*	*No*
40		0	09/18/1997	0.1	12/10/1998	MW1	7	No	No	Yes	Yes		2.3	*0.13*	*No*
41		***100***	12/03/1997	34.0	07/21/1999	MW2	5				No	Yes	0.4	*0.22*	*No*
42		2100	02/14/1997	14.0	01/12/1998	MW1	4				Yes		0.1	*0.63*	*No*
43	1	190	04/03/1998	2.5	09/14/1999	MW-B-13	6	No	No	Yes	No	Yes	-1.2	*0.37*	*No*
44	1	***76***	02/18/1999	25.0	03/01/2000	MW1	5				No	Yes	0.8	*0.41*	*No*
45	1	***1600***	04/20/1998	470.0	02/03/1999	MW1	4				No	Yes	0.7	*0.23*	*No*
46		***16***	10/07/1998	10.0	03/23/1999	MW1	3								
~~47~~	1	***130***	03/28/1996	95.0	11/06/1997	MW6	8	No	No	Yes	No	Yes	2.3	*0.03*	*No*
48	1	***120***	08/05/1998	**120.0**	08/05/1998	MW5	8	No	No	*Increasing Trend*	No	*Increasing Trend*	-12.7	*0.01*	*No*
49		1500	03/02/1999	58.0	02/23/2000	MW4	4				Yes		1.4	*0.75*	*No*
50	1	***1700***	06/14/1989	110.0	08/14/1998	MW1	2								
51	1	460	10/27/1997	100.0	07/27/1998	MW-3	8	No	Yes		Yes		0.7	*0.48*	*Yes*
52	1	290	05/17/1995	0.5	04/09/1998	MW-11	8	No	No	No	No	Yes	1.0	*0.32*	*No*
53	1	***2300***	10/16/1997	1500.0	02/17/2000	MW-1A	8	No	Yes		Yes		4.4	*0.32*	*No*
54	1	680	10/05/1993	17.0	01/18/1999	MW1	8	No	No	No	No	Yes	66.6	*0.00*	*No*
55	1	***4200***	06/12/1998	2300.0	04/06/2000	MW2	6	Yes	Yes		No	Yes	1.6	*0.63*	*Yes*
56	1	***1200***	02/03/1992	54.0	06/29/1995	MW5	6	No	Yes		No	No	1.2	*0.21*	*No*
~~57~~	1	1300	06/22/1995	25.0	06/18/1996	MW9	8	No	No	*Increasing Trend*	No	*Increasing Trend*	-0.6	*0.42*	*Yes*
~~58~~	1	4200	09/28/1995	760.0	08/11/1998	MW8	8	No	No	Yes	No	Yes	-1.9	*0.09*	*No*
59	1	***2200***	12/10/1998	711.0	09/25/2001	MW1	8	No	Yes		Yes		12.2	*0.01*	*No*
60	1	19000	02/28/1992	140.0	01/11/1999	MW1	8	No	No	Yes	No	Yes	-1.3	*0.06*	*No*

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61	1	82	08/16/1996	5.3	06/15/1999	MW-11	8	No	No	Yes	Yes		6.0	0.03	No
62	1	117000	02/06/1990	6900.0	03/16/1999	MW1	8	No	No	Yes	Yes		-44.7	0.00	No
63	1	14000	11/15/1995	910.0	08/30/2000	MW7	8	No	No	Yes	No	Yes	95.0	0.00	No
64		2400	05/26/1998	6.0	04/21/1999	MW1	5				No	No	0.1	0.62	No
65	1	430	04/28/1998	5.4	02/21/2000	MW-F	5				No	Yes	0.4	0.58	No
~~66~~	1	68	08/08/1994	9.9	04/02/1997	MW2	6	No	No	No	No	No	1.2	0.18	No
~~67~~		7240	01/21/1998	4900.0	07/07/1999	MW8	8	Yes	Yes		Yes		4.8	0.45	Yes
68	1	6900	09/24/1992	42.0	03/30/1999	OW-12	8	No	No	No	No	Yes	-2.0	0.07	No
69	1	750	04/20/1995	54.4	08/02/1999	MW3	8	No	No	Yes	No	Yes	6.7	0.02	No
70		710	09/21/1999	270.0	03/23/2000	MW4	8	No	No	Increasing Trend	No	Yes	-1.2	0.28	No
71		160	09/06/1995	0.3	01/28/1999	MW22	7	No	Yes		No	Yes	0.7	0.49	Yes
72	1	15000	04/20/1992	320.0	04/27/1999	MW1	8	Yes	Yes		No	Yes	1.4	0.94	Yes
73	1	658	08/31/1995	220.0	02/22/1999	MW7	8	No	No	Yes	Yes		7.6	0.17	No
~~74~~		1100	04/28/1999	560.0	06/23/1999	MW1	4				No	Increasing Trend	-0.8	0.79	No
75	1	2700	05/14/1998	1300.0	02/26/1999	MW4	4				Yes		0.6	0.88	Yes
76	1	20000	07/02/1997	1900.0	06/17/1999	MW2	8	Yes	Yes		Yes		0.6	0.93	Yes
77		7	08/04/1998	6.5	08/04/1998	MW3	2								
78	1	1400	05/08/1992	94.0	09/02/1998	MW22	4				No	Increasing Trend	-1.5	0.38	No
79	1	5900	03/16/1990	24.0	10/01/1997	MW3	8	No	No	Yes	No	Yes	3.8	0.11	No
~~80~~	1	2100	01/15/1998	210.0	11/05/1999	MW2	7	No	No	Yes	No	No	1.4	0.32	No
81	1	17	02/03/1997	7.0	10/29/1998	MW1	8	No	No	Increasing Trend	Yes		-2.7	0.37	No
82	1	1	01/02/1997	2.5	10/20/1998	MW2	8	No	No	No	No	Increasing Trend	1.3	0.08	No
83	1	72	05/09/1997	2.1	12/21/1998	MW-1	8	Yes	Yes		No	Yes	2.8	0.80	Yes
84		21000	08/26/1999	20000.0	07/20/2000	MW-1	8	No	No	Increasing Trend	No	Yes	60.1	0.00	No
~~85~~		1200	03/05/1999	650.0	06/16/2000	MW2	8	No	No	Yes	Yes		-8.4	0.14	No
~~86~~	1	390	06/25/1994	96.0	06/07/2000	MW3	8	No	No	Increasing Trend	No	Yes	-1.8	0.30	No
~~87~~	1	6700	01/24/1995	48.0	02/25/1999	RW1	7	No	No	No	Yes		-5.3	0.01	No
88	1	1500	08/23/1994	290.0	12/04/1998	MW14	7	No	No	Yes	No	Yes	2.2	0.04	No
89		140	08/11/1998	7.3	12/04/1998	MW6	7	No	No	No	No	No	-0.3	0.26	No
90	1	400	12/08/1997	220.0	11/16/1998	MW3	7	No	No	Yes	No	Yes	-83.8	0.00	No

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~~91~~		5	09/22/1999	2.5	02/03/2000	MW3	2								
~~92~~		25000	04/10/1997	8700.0	09/08/1999	MW-1	8	No	Yes		Yes		3.6	0.43	Yes
93	1	11860	01/25/1989	1750.0	06/11/1999	B-13R	8	No	No	Increasing Trend	No	Increasing Trend	-0.7	0.21	No
94	1	2430	11/29/1995	2.4	04/25/2000	MW6	8	Yes	Yes		No	Yes	0.7	0.46	Yes
~~95~~		15200	02/25/1997	1310.0	05/23/2000	VMP-1	8	Yes	Yes		Yes		2.6	0.62	Yes
~~96~~	1	5130	07/12/1993	64.1	10/19/1998	MW3	8	No	Yes		No	Yes	2.0	0.08	No
97	1	270	03/29/1999	31.0	06/30/1999	MW-1	8	No	No	Yes	No	Yes	15.1	0.01	No
98		34	06/09/1998	18.0	09/28/1998	MW4	5				No	Yes	4.2	0.04	No
~~99~~	1	4900	03/26/1997	0.3	10/02/2000	MW2	8	Yes	Yes		No	No	0.2	0.74	Yes
~~100~~	1	10400	03/25/1997	2600.0	01/24/2000	MW3	8	No	Yes		Yes		2.9	0.51	Yes
101	1	1400	10/28/1998	1300.0	11/19/1999	MW1500	5				No	Yes	8.3	0.15	No
102	1	2	04/01/1999	0.4	04/01/2000	MW2	2								
103	1	1400	03/15/1995	200.0	08/28/1997	S-1	4				Yes		0.5	0.64	No
104	1	210000	10/09/1991	220.0	11/10/1999	MW2	8	No	No	Yes	No	Yes	3.1	0.05	No
105	1	2400	09/19/1991	6.6	02/04/1999	MW2	8	No	No	No	No	Yes	1.8	0.26	No
106	1	324	08/21/1992	23.0	12/02/1998	MW4	7	No	No	Increasing Trend	No	Yes	-1.0	0.68	Yes
~~107~~	1	550	09/30/1999	550.0	09/30/1999	MW-1	8	No	No	Increasing Trend	No	Increasing Trend	-0.5	0.24	No
108		190	10/04/1996	37.0	01/25/1999	MW4	6	No	Yes		No	Yes	1.4	0.73	Yes
109		2	05/03/1996	0.1	12/07/1998	MW-1	8	No	Yes		No	Yes	1.9	0.23	No
110	1	4100	01/04/1994	140.0	02/08/1998	SW	8	No	No	Yes	Yes		2.2	0.01	No
111	1	6800	01/27/1993	72.0	05/04/1998	MW5	8	No	No	No	No	Increasing Trend	-3.8	0.01	No
112	1	5790	02/28/2000	5790.0	02/28/2000	MW6	8	No	No	Increasing Trend	No	Increasing Trend	-0.4	0.28	No
113		6110	07/09/1998	2600.0	07/19/1999	EX-1	8	No	Yes		Yes		2.2	0.51	Yes
114	1	450	08/28/1996	0.5	12/05/1996	MW5	8	No	No	No	No	No	1.2	0.06	No
~~115~~		5	12/29/1994	2.5	03/18/1996	MW6	2								
~~116~~	1	4700	05/01/1995	200.0	02/01/1999	MW4	6	No	Yes		No	Yes	0.9	0.88	Yes
117	1	2	06/08/1995	0.1	07/28/1999	MW-1	8	No	Yes		Yes		2.0	0.16	No
118	1	9	12/17/1998	9.1	12/17/1998	GP7	1								
119	1	1600	06/10/1992	0.1	04/29/1999	MW3	8	Yes	Yes		Yes		0.4	0.51	Yes
120	1	2500	04/07/1994	1100.0	10/21/1999	SMW7	8	No	Yes		No	Yes	13.8	0.15	No

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121	1	***8200***	06/07/1996	3910.0	02/02/2000	MW11	6	Yes	Yes		Yes		3.4	*0.73*	*Yes*
122		***540***	03/23/1999	58.0	02/09/2000	W-3	4				Yes		0.3	*0.93*	*Yes*
123	1	15582	09/18/1992	230.0	03/11/1999	MW5	8	Yes	Yes		No	Yes	0.6	*0.63*	*Yes*
124	1	16000	10/17/1996	452.0	11/07/2000	33E92-1	8	No	No	Yes	No	*Increasing Trend*	7.8	*0.02*	*No*
125	1	350	12/01/1991	57.0	03/01/1999	MW6	3								
126	1	10700	11/11/1992	554.0	03/23/1999	MW-1	8	No	No	Yes	No	Yes	7.6	*0.10*	*No*
127	1	24	07/01/1996	11.0	04/01/1998	MW2	3								
128		***571***	09/13/1994	21.0	08/06/1997	MW-5C	7	Yes	Yes		No	Yes	0.5	*0.85*	*Yes*
129		***110***	09/04/1996	23.0	09/10/1999	Sump	7	No	No	No	No	*Increasing Trend*	5.2	*0.01*	*No*
130	1	***5***	09/02/1999	1.0	01/03/2000	MW9	3								
131	1	62000	03/03/1994	250.0	08/24/1999	MW-1	8	No	No	Yes	Yes		1.2	*0.08*	*No*
132	1	2480	03/04/1992	3.6	03/01/1999	MW3	8	No	No	No	Yes		2.8	*0.01*	*No*
133	1	1470	03/11/1993	78.8	12/09/1997	MW-14	8	No	No	No	No	No	-1.0	*0.05*	*No*

		Above-ES Closure Subset
No. of Sites with GW Data:	132	106
No. of Sites without GW Data:	1	
Sites with n ≥ 4:	116 (87%)	98
Sites with n ≥ 6:	**97 (73%)**	**79**
Sites with n = 8:	70 (53%)	55

~~Site_ID~~ has a strikethrough if site has low permeability, which is defined by hydraulic conductivity (K) < 1e-05 cm/s, which is typically, but not necessarily, a clay site.

* The historical benzene maximum is italized in red if it was used in the statistical tests. Typically, it is not included in the statistical tests here either because there are more-recent data available, or because the most-recent benzene high was observed at a different well.

** The data from the monitoring well that had the most-recent benzene maximum were used in the statistical tests.

*** Only the most-recent rounds (up to 8 rounds) were used in the statistical tests. Two (2) Mann-Kendall tests were performed: 1st instance, 6 to 8 rounds, when available, were used; 2nd instance, only the 4 most-recent rounds were used. The data used in the 1st instance of the use of Mann-Kendall statistics is the same set of data used in the Mann-Whitney statistics.

**** The Mann-Whitney (M-W) and Mann-Kendall (M-K) nonparametric statistical tests are described in NR 746, Wis. Adm. Code. The α = 0.2 (or 80% 2-tail confidence level) M-K test requires a minimum of 4 observations, and the α = 0.1 (90% CL) M-W test requires 8 observations. A red "No" in the M-W column indicates an increasing trend given 8 observations. As used here, we ignored the fact that the time interval between samples typically vary from round to round, or that the data variability may be seasonal. We applied the tests simultaneously when there are 6 to 8 observations, as a 90% CL M-W test can be applied to 6 observations. The M-W statistic is computed using an early set comprised of the first 4 observations, which is then compared to a late set that has the 2 to 4 subsequent observations. The M-W statistic and the 1st instance of the M-K statistic use the same set of data, so the results from the nonparametric tests (M-W and 1st M-K) can be comparable. When the M-K test fails to show a decreasing trend, we determined if trend is increasing or estimate if the coefficient of variation (CV) is less than 1. A CV < 1 is used in the NR 746 to define "stability." However, the use of CV shows a bias, as it tends to show stability when concentrations are high and show instability when the they are low.

***** The regression analysis uses the most-recent 4 to 8 available benzene data, so the trend results are more comparable to the Mann-Whitney and Mann-Kendall (1st instance) test results for sites with 6 to 8 observations. The regression trend results are comparable to the Mann-Kendall (2nd instance) only when there is exactly 4 observations. A t-test was done on the r^2; a "Yes" in the last column indicates that the t-test shows that r^2 is singnificantly different from 0.

All the data used to compute the nonparametric statistics for the tests are in Appendix L.

Table 5: Timelines for Field Sites

Previous Site Investigation

SiteMap ID	Site Name	RP Letter Sent / Notificaton	Earliest Monitoring	Most-Recent Monitoring	Conditional Closure	Final Closure	Added to the GIS Registry	
33	Martin Oil	05 / 1990	06 / 1990	04 / 1999	08 / 1999	07 / 2003	10 / 2003	Former Retail Stations
36	Woods Garage	04 / 1991	08 / 1991	04 / 1998	09 / 1999	09 / 2000	09 / 2001	
55	Former Grandma's Restaurant	07 / 1994	06 / 1998	04 / 2000	08 / 2000	08 / 2002	02 / 2005	
63	Packard Charles Property	03 / 1991	11 / 1991	08 / 2000	12 / 2000	05 / 2001	11 / 2001	
9	Brown County Reforestation Camp	02 / 1993	01 / 1994	04 / 1999	06 / 1999	01 / 2000	09 / 2001	Non-Commercial Sites
34	Rutland Town Garage	05 / 1990	01 / 1992	01 / 2001	03 / 2001	08 / 2001	01 / 2002	
103	Grafton DPW Hickory St. Garage	04 / 1994	03 / 1995	08 / 1997	04 / 1998	05 / 1998	09 / 2001	
104	WI Lions Camp	06 / 1991	10 / 1991	11 / 1999	04 / 2000	11 / 2000	04 / 2001	
108	City of Racine Parks Dept	07 / 1995	10 / 1996	03 / 1999	05 / 2000	11 / 2002	11 / 2003	
126	UW Oshkosh Field Studies Building	01 / 1991	04 / 1992	03 / 1999	01 / 2000	09 / 2002	09 / 2003	

Post-Closure Investigation (This Study)

SiteMap ID	Site Name	Well Construction	Round 1	Round 2	Round 3	Round 4	Well Abandonment	
		Start					*End*	
33	Martin Oil	08 / 2004	08 / 2004	12 / 2004	06 / 2005	*11 / 2005 ** *	11 / 2006	Former Retail Stations
36	Woods Garage	08 / 2004	08 / 2004	11 / 2004	04 / 2006		08 / 2006	
55	Former Grandma's Restaurant	06 / 2005	06 / 2005	*10 / 2005 ** *	04 / 2006		06 / 2006	
63	Packard Charles Property	06 / 2005	06 / 2005	10 / 2005 *	03 / 2006 *		09 / 2006	
9	Brown County Reforestation Camp	07 / 2005	07 / 2005	10 / 2005 *	04 / 2006		06 / 2006	Non-Commercial Sites
34	Rutland Town Garage	08 / 2005	08 / 2005	*11 / 2005 ** *	03 / 2006 *		08 / 2006	
103	Grafton DPW Hickory St. Garage	07 / 2005	07 / 2005	11 / 2005 *	05 / 2006		08 / 2006	
104	WI Lions Camp	10 / 2005	10 / 2005	04 / 2006			06 / 2006	
108	City of Racine Parks Dept	08 / 2005	08 / 2005	11 / 2005 *			11 / 2006	
126	UW Oshkosh Field Studies Building	08 / 2005	08 / 2005	11 / 2005 *	04 / 2006		06 / 2006	

* Asterisk indicates a separate EDB analysis was performed; however all Round 3 samples collected in 2006 were preserved in TSP (not in HCl as required for EDB samples) and analyzed for EDB after 9 months, so their EDB results were compromised. No EDB sample was collected at 2 sites.

*** Double asterisks* indicate EDB detections from the groundwater samples. The EDB results are in Appendix A following the BTEX results.

Table 6: Remedies Implemented Before Closure

Previous Site Investigation

SiteMap ID	Site Name		UST Removal(s)	Soil Excavation (Volume, yd^3)	Other Remediation: SVE = Soil Vapor Extraction AS = Air Sparging P/T = Pump and Treat	Site Investigation/Remediation Features
33	Martin Oil	Former Retail Stations	1985	1989 (3,395)	1994 - 1998: SVE, AS and groundwater P/T system	In 1989, excavation floor @ 29' depth, 820 ppm soil TPH-Diesel remained. In 1990 and 1991, free product was observed (1.5' thick in MW-1). Wells MW-8, -9, -10 and MW-11 had 15-ft screens. The 2 piezometers were screened from 70 to 75 ft and were the deepest wells among field sites with PZs. In-situ remediation systems removed an estimated 7,700 kg of petoleum VOCs.
36	Woods Garage	Former Retail Stations	1991	None	None	Among the Remed-No database sites, this site had the longest monitoring history, but with a 4-yr gap after initial round. Site had the most piezometers: 2-ft screens in PZ-2A, -5A, -8A, and -9A; and 5-ft screens in PZ-2B and -10A.
55	Former Grandma's Restaurant	Former Retail Stations	1986; 1994	1994 (670)	None	Only 2 years of groundwater monitoring - briefest among the field sites.
63	Packard Charles Property	Former Retail Stations	1990	1996 (690)	None	The installation of 8 monitoring wells was staggered over 6 years, with 4 of the older wells abandoned during excavation on the 6th year. Well with highest contamination levels at closure (MW-7) had a 15-ft screen; it replaced MW-6 which had a 10-ft screen.
9	Brown County Reforestation Camp	Non-Commercial Sites	1992	1995 (440)	1995 - 1998: P/T system	Soil excavation was followed by paving and the replacement of the most-contaminated monintoring well, but it was installed at a different location. The old remediation building is still at the site. In-situ remediation system removed an estimated 3 kg of petroleum VOCs
34	Rutland Town Garage	Non-Commercial Sites	1990	None	1996 - 1998: SVE and AS	Most-contaminated well, MW-3, had a 15-ft screen.
103	Grafton DPW Hickory St. Garage	Non-Commercial Sites	1970; 1994	1996 (1,300)	None	The site investigation report's groundwater flow map indicated the nearby pond nearby to be a discharge area; however, several private wells are located to the south which may affect flow direction. After soil excavation, high DRO soil (420 ppm @ 12 ft) still remained. Consultant in an October 1997 report estimated that naphthalene would drop to its PAL concentration by August 2000, and benzene to its PAL by January 2002.
104	WI Lions Camp	Non-Commercial Sites	1990	1990 (36)	1997 - 1998: P/T system	Serviceable ASTs in containment area are located 40 ft away from former USTs. Extraction well screen got clogged by silt. In-situ remediation systems removed an estimated 680 kg of petoleum VOCs.
108	City of Racine Parks Dept	Non-Commercial Sites	1995	None	None	Without any remediation, the groundwater-benzene level was projected in 1999 by consultant to drop below ES (5 ug/l) in 1 year.
126	UW Oshkosh Field Studies Building	Non-Commercial Sites	1990	1992 (50)	1994 - 1996: SVE and P/T system	Site is situated near the bank of Fox River. Old remediation pipes were installed very near sewer line. Protective casings of some of the SI wells remain. In-situ remediation systems removed an estimated 1,860 kg of petoleum VOCs.

Table 7: Post-Closure Timelines

Post-Closure Investigation (This Study)

SiteMap ID	Site Name		Availability Date of Lab Results for Round 1	Availability Date of Results for All Rounds (inc. EDB)	Post-C Fieldwork Reference (Geologic X-section page)	Post-closure Investigation Features
33	Martin Oil	Former Retail Stations	11 / 2004	02 / 2007	Keller [2005], p. 87 - 124 (102)	Now part of a City of Madison park (Thut Park). Highly heterogeneous glacial till geology. RR GIS Registry point location is closer to Monona muni well than to the former gasoline station. Naphthalene data is not in the RR GIS Registry PDF.
36	Woods Garage	Former Retail Stations	11 / 2004	09 / 2006	Keller [2005], p. 39 - 86 (57)	Now an agricultural field. Post-closure wells were placed along highway ditch or gravel shoulder, so lacking good azimuthal coverage - not optimal in determining flow direction. Groundwater flow is better defined in SI. Deep piezometers encounter competent bedrock. No profiling samples, but 4 PZs installed. Illegible gw-result tables in the RR GIS Registry PDF.
55	Former Grandma's Restaurant	Former Retail Stations	10 / 2005	09 / 2006	Greve [2007], p. 153 - 188 (164)	Now county-owned with salt storage structures. Three (3) of our TWs were destroyed with the county construction that started before Round 2 samples could be collected. No profiling samples; instead, 2 PZs were installed. Addtional water-quality data from a nearby (but separate) UST case in the RR GIS Registry PDF.
63	Packard Charles Property	Former Retail Stations	09 / 2005	02 / 2007	Greve [2007], p. 189 - 225 (198)	Now a private residence, but highest contamination at the right of way. South edge of the paved portion of improved USH-12 is moved 15 ft to the north of its former location. Original source area is overlain by gravel. Peat soil north of site is overlain by silt deposited from sand and gravel operation. Old MW-2 was found abandoned with bentonite, but with its above-ground metal casing intact. We pulled casing out to complete abandonment of this well. Much higher BTEX levels when depth-profiling samples are considered. Site map in RR GIS Registry PDF is NOT to scale: x-scale is different from the y-scale.
9	Brown County Reforestation Camp	Non-Commercial Sites	10 / 2005	09 / 2006	Greve [2007], p. 226 - 258 (232)	Remains a garage/storage for North East Wisconsin Zoo. Serviceable ASTs in concrete containment area are located 2 buildings away from former USTs. No depth-profiling samples collected, but 3 PZs installed. Sand unit (23' thick) overlies stiff clay. Installed PZs had their screen bottom placed at the top of the clay. Illegible gw-result table in the RR GIS Registry PDF.
34	Rutland Town Garage	Non-Commercial Sites	10 / 2005	02 / 2007	Greve [2007], p. 298 - 332 (305)	Remains a garage/storage for the town. Heterogeneous vertical geology. Inside a building (south garage) is a serviceable AST that sits atop former UST location. Free product encountered during installation of temporary well nearest this building. No profiling samples, but installed 3 water-table wells screened at different depths. RR GIS Registry PDF site map has onsite water supply well in wrong location, but found a map in case file with its correct location.
103	Grafton DPW Hickory St. Garage	Non-Commercial Sites	09 / 2005	09 / 2006	Greve [2007], p. 361 - 393 (369)	Remains a garage/sorage for the village. Contrary to the SI, post-closure temporary wells indicate pond to be hydraulically high, so flow more to the south. Much higher BTEX levels when depth-profiling samples are included. Forecast in 1997 on benzene and naphthalene (getting to PAL) did not materialize. RR GIS Registry PDF site map only covers a very small area and is missing important details (such as nearby pond).
104	WI Lions Camp	Non-Commercial Sites	01 / 2006	09 / 2006	Greve [2007], p. 394 - 429 (403)	Remains a Lions International camp. Large difference in depth to groundwater is related to topo relief, with a depression on the southwest portion where shallower groundwater was encountered. Much higher BTEX levels when depth-profiling samples are included. TW-1 - the highest BTEX well - had no detect of B. TW-2 was the water-table well with highest B. RR GIS Registry PDF site map is missing the south addition to the eyeglass recycling bldg, as well as a new building to its west.
108	City of Racine Parks Dept	Non-Commercial Sites	10 / 2005	09 / 2006	Greve [2007], p. 333 - 360 (340)	Remains a City Parks Department facility where tree saplings and agricultural chemicals are stored. Three (3) of the original 7 SI monitoring wells were found intact. At end of this project, we abandoned 4 of the 7 original SI wells. Decay forecast in 1999 on benzene did not occur. RR GIS Registry PDF site map has location for MW-3, -4 and -7 which most likely were not abandoned properly before closure.
126	UW Oshkosh Field Studies Building	Non-Commercial Sites	11 / 2005	09 / 2006	Greve [2007], p. 259 - 297 (268)	Remains a UW-Oshkosh property with the building being renovated to serve as a research facility. Wood chips are present as fill. TW-2 - the highest BTEX well - was not well with highest B. TW-1 had the highest B. RR GIS Registry address is Warren Road, which is no longer existent; access to the building is via Pearl Ave.

Table 8: Highest BTEX Level in Groundwater Samples at the Field Sites

Previous Site Investigation

SiteMap ID	Site Name	Closure Highest BTEX ug/l	Date Closure High	Historical Highest BTEX ug/l	Date Historical High	Improvement wrt Hist. High***	(time interval, yr)
33	Martin Oil	139	04 / 1999	28,400	11 / 1990	100%	(8)
36	Woods Garage	31,770	04 / 1998	40,340	08 / 1991	21%	(7)
55	Former Grandma's Restaurant	3,450	04 / 2000	15,500	06 / 1998	78%	(2)
63	Packard Charles Property	4,630	08 / 2000	46,500	11 / 1995	90%	(5)
9	Brown County Reforestation Camp	6,590	04 / 1999	19,070	04 / 1997	65%	(2)
34	Rutland Town Garage	1,242	01 / 2001	13,050	10 / 1994	90%	(6)
103	Grafton DPW Hickory St. Garage	389	08 / 1997	2,159	03 / 1995	82%	(2)
104	WI Lions Camp	7,550	11 / 1999	822,000	10 / 1991	99%	(8)
108	City of Racine Parks Dept	122	01 / 1999	425	10 / 1996	71%	(2)
126	UW Oshkosh Field Studies Building	1,078	03 / 1999	29,468	11 / 1992	96%	(6)

Post-Closure Investigation

SiteMap ID	Site Name	Post-Closure Highest BTEX ug/l	Date	Improvement wrt Closure High***	(time interval, yr)	Improvement wrt Historical High***	(time interval, yr)
33	Martin Oil	3,654	11 / 2005	-2533%	(7)	87%	(15)
36	Woods Garage	46,690	11 / 2004	-47%	(7)	-16%	(13)
55	Former Grandma's Restaurant	3,700	06 / 2005	-7%	(5)	76%	(7)
63	Packard Charles Property	*32,780. p*	06 / 2005	-608%	(5)	30%	(10)
9	Brown County Reforestation Camp	11,322	04 / 2006	-72%	(7)	41%	(9)
34	Rutland Town Garage	24,598	11 / 2005	-1881%	(5)	-88%	(11)
103	Grafton DPW Hickory St. Garage	*944. p*	07 / 2005	-143%	(8)	56%	(10)
104	WI Lions Camp	*9,313. p*	10 / 2005	-23%	(6)	99%	(14)
108	City of Racine Parks Dept	191	11 / 2005	-57%	(7)	55%	(9)
126	UW Oshkosh Field Studies Building	4,744	11 / 2005	-340%	(7)	84%	(13)

A *"p"* after level indicates data is from a depth-profiling well that had a short (≤ 5') screen placed below WT.

*** Negative improvement if Post-Closure level > closure or historical high.

Table 9: BTEX Groundwater Plume at the Field Sites

			BTEX Plume Map				
			Historical		Post-Closure*		
SiteMap ID	Site Name	Reference	Specific Thesis pp.	Plume Length (Closure)	Specific Thesis pp.	Plume Length (Post-Closure)	Comment
33	Martin Oil	Keller [2005]	p. 112	120 '	p. 113	150 '	Non-Clay site. Closure plume length was measured perpendicular to post-closure's.
36	Woods Garage	Keller [2005]	p. 70 - 71	240 '	p. 70 - 72	400 '	Bedrock site. TW w/ highest BTEX in 2004 was dry in 2006.
55	Former Grandma's Restaurant	Greve [2007]	p. 179 - 180	85 '	p. 181-182	145 '	Non-Clay site. Closure plume length azimuth is rotated 40o to post-closure's.
63	Packard Charles Property	Greve [2007]	p. 214 - 215	130 '	p. 216; 218	210 '	Non-Clay site.
9	Brown County Reforestation Camp	Greve [2007]	p. 248 - 249	75 '	p. 250 - 251	45 '	Non-Clay site with sandy aquifer (20' thick) over clay.
34	Rutland Town Garage	Greve [2007]	p. 321 - 322	45 '	p. 323 - 324	70 '	Clay site
103	Grafton DPW Hickory St. Garage	Greve [2007]	p. 385 - 386	90 '	p. 387; 389	90 '	Non-Clay site with fill (15' thick) over clay. GW flow more to the S, not NE as indicated in SI.
104	WI Lions Camp	Greve [2007]	p. 420 - 421	270 '	p. 422	220 '	Greve estimated the post-closure plume length to be between 220' and 270'
108	City of Racine Parks Dept	Greve [2007]	p. 354	100 '	p. 356	75 '	Clay site
126	UW Oshkosh Field Studies Building	Greve [2007]	p. 285 - 286	95 '	p. 287 - 288	80 '	Clay site

* Red indicates post-closure plume length longer than observed at closure.

Table 10: Maximum BTEX Levels Observed in Water-Table Wells

Previous Site Investigation

SiteMap ID	Site Name		MW with Maximum-BTEX at Closure (Screen depth range, ft)	Maximum BTEX (ug/l) at closure	Depth to water	Range of Depth to Water (ft) at MW with Closure-Max BTEX	Comments
33	Martin Oil	Former Retail Stations	MW-5 (37. - 47.)	139	37.25	37.3 - 41.8	
36	Woods Garage	Former Retail Stations	MW-2 (7.5 - 17.5)	31,770	8.52	6.2 - 13.4	
55	Former Grandma's Restaurant	Former Retail Stations	MW-2 (20. - 30.)	3,450	28.13	23.3 - 28.1	
63	Packard Charles Property	Former Retail Stations	MW-7 (4.7 - 19.7)	4,630	Not found for most-recent 8/30/2000 sampling	5.8 - 8.9	Depth was 7.82' when BTEX was 22,900 ug/l (3/30/2000)
9	Brown County Reforestation Camp	Non-Commercial Sites	MW-2R (2. - 12.)	6,590	Not found for most-recent 4/19/1999 sampling	1.3 - 5.3	Depth was 4.72' when BTEX was 5,960 ug/l (2/1/1999). We assumed screen placement to be the same as MW-2.
34	Rutland Town Garage	Non-Commercial Sites	MW-3 (10. - 25.)	1,242	Not found for most-recent 1/08/2001 sampling	6.7 - 17.8	Depth was 11.18' when BTEX was 4,656 ug/l (6/30/2000)
103	Grafton DPW Hickory St. Garage	Non-Commercial Sites	S-1 (4. - 14.)	389	S-1 is an extraction sump with a 4-in diameter pipe screened from 4' to 14' depth.	Actual depths to water NOT found in any report. Depth to water at nearby B-1 was 10.18' on 3/15/95 during well development	Water table at S-1 fluctuated 2.7 ft between 11/1996 and 8/1997.
104	WI Lions Camp	Non-Commercial Sites	MW-1 (28. - 38.)	7,550	33.92	32.3 - 33.9	
108	City of Racine Parks Dept	Non-Commercial Sites	MW-4 (4. - 14.)	122	Not found for most-recent 1/25/1999 sampling	5.7 - 6.1	Depth was 6.08' when BTEX was 292 ug/l (3/21/1997)
126	UW Oshkosh Field Studies Building	Non-Commercial Sites	MW-1 (3. - 13.)	1,078	Not found for most-recent 3/23/1999 sampling	6.0 - 9.0	MW-1 was used as an extraction well. Depth was 6.76' when BTEX was 3,840 ug/l (5/1/1995)

Post-Closure Investigation

SiteMap ID	Site Name		TW with Post-C Max BTEX Screen depth range, ft)	Maximum BTEX at Water-Table Wells (ug/l)	Depth to water (ft) when Maximum BTEX was observed (underlined if depth is either min or max for the well)	Range of Depth to Water (ft) Observed at TW with Post-C Max BTEX	Approximate Distance (ft)
33	Martin Oil	Former Retail Stations	TW-1 (35. - 45.)	3,654. q	38.74	35.5 - 38.7	TW-1 to MW-5 : 5.
36	Woods Garage	Former Retail Stations	TW-3B (4. - 14.)	46,690.	9.55	7.9 - Deeper than 14	TW-3B to MW-2 : 9.
55	Former Grandma's Restaurant	Former Retail Stations	TW-2 (20. - 30.)	3,700.	Initial Sampling. Soil boring WT @ 26.5'	26.9 - 28.9	TW-2 to MW-2 : 10.
63	Packard Charles Property	Former Retail Stations	TW-6 (7. - 17.)	14,930. q	8.00	8.0 - 9.5	TW-6 to MW-7 : 8.
9	Brown County Reforestation Camp	Non-Commercial Sites	TW-2 (3. - 13.)	11,322. q	3.20	3.2 - 5.0	TW-2 to MW-2R: 11.
34	Rutland Town Garage	Non-Commercial Sites	TW-11 (13. - 28.)	24,598.	18.43	16.3 - 18.4	TW-11 to MW-3 : 24.
103	Grafton DPW Hickory St. Garage	Non-Commercial Sites	TW-1 (8. - 18.)	215.	11.47	8.5 - 13.0	TW-1 to S-1 : 2.
104	WI Lions Camp	Non-Commercial Sites	TW-1 (30. - 40.)	2,995.	33.46	33.3 - 33.5	TW-1 to MW-1 : 4.
108	City of Racine Parks Dept	Non-Commercial Sites	TW-13 (6. - 16.)	191.	7.99	7.9 - 8.0	TW-13 to MW-4 : 50.
126	UW Oshkosh Field Studies Building	Non-Commercial Sites	TW-2 (3. - 13.)	4,744.	5.25	5.3 - 5.4	TW-2 to MW-1 : 22.

Red indicates level higher than closure. A "q" indicates the data is more recent than those included in Keller [2005] or Greve [2007]

Blue indicates a range in depth to the water table that is different from the SI information.

Table 11: Detection Frequency in Water-Table Wells at the Field Sites

Previous Site Investigation

SiteMap ID	Site Name	Total Number of SI WT Wells	Detections					MW Benzene		MW Naphthalene	
			MWs w/ BTEX detection	MWs w/ B detection	MWs w/ MTBE detection	MWs w/ N detection	Percent of MWs w/ N that also had B detections	Closure Maximum B ug/l	Screen Depth	Closure Maximum N ug/l	Screen Depth
33	Martin Oil	12	9 (75 %)	8 (67 %)	5 (42 %)	2 (17 %)	100 %	29	37. ' - 47. ' (MW-5)	46	32.' - 47.' (MW-9) *
36	Woods Garage	10	6 (60 %)	6 (60 %)	0 (0 %)	4 (40 %)	100 %	4530	7.5' - 17.5' (MW-2)	1500	7.5' - 17.5' (MW-2)
55	Former Grandma's Restaurant	11	6 (55 %)	4 (36 %)	4 (36 %)	4 (36 %)	75 %	2300	20. ' - 30. ' (MW-2)	130	20. ' - 30. ' (MW-2)
63	Packard Charles Property	8	4 (50 %)	4 (50 %)	3 (38 %)	4 (50 %)	75 %	910	4.7' - 19.7' (MW-7)	780	4.7' - 19.7' (MW-7)
9	Brown County Reforestation Camp	4	3 (75 %)	2 (50 %)	2 (50 %)	1 (25 %)	100 %	1200	2. ' - 12. ' (MW-2)	100	2. ' - 12. ' (MW-2)
34	Rutland Town Garage	5	5 (100 %)	3 (60 %)	3 (60 %)	2 (40 %)	100 %	911	10. ' - 25. ' (MW-3)	160	10. ' - 25. ' (MW-3)
103	Grafton DPW Hickory St. Garage	6	5 (83 %)	3 (50 %)	4 (67 %)	2 (33 %)	100 %	200	4. ' - 14. ' (S-1)	120	4. ' - 14. ' (S-1)
104	WI Lions Camp	15	12 (80 %)	9 (60 %)	3 (20 %)	12 (80 %)	75 %	220	28. ' - 38. ' (MW-2) *	270	28. ' - 38. ' (MW-1)
108	City of Racine Parks Dept	7	6 (86 %)	4 (57 %)	5 (71 %)	1 (14 %)	100 %	37	4. ' - 14. ' (MW-4)	14	4. ' - 14. ' (MW-4)
126	UW Oshkosh Field Studies Building	12	11 (92 %)	10 (83 %)	9 (75 %)	11 (92 %)	91 %	554	3. ' - 13. ' (MW-1)	88	3.' - 13.' (EX-1) *

Post-Closure Investigation

SiteMap ID	Site Name	Total Number of Post-C Water-Table Wells	Detections					TW Benzene		TW Naphthalene	
			MWs w/ BTEX detection	MWs w/ B detection	MWs w/ MTBE detection	MWs w/ N detection	Percent of MWs w/ N that also had B detections	Maximum B ug/l	Screen Depth	Maximum N ug/l	Screen Depth
33	Martin Oil	9	7 (78 %)	2 (22 %)	4 (44 %)	4 (44 %)	50 %	913	35. ' - 45. ' (TW-1)	140	35. ' - 45. ' (TW-1)
36	Woods Garage	9	6 (67 %)	3 (33 %)	0 (0 %)	5 (56 %)	60 %	1780	4. ' - 14. ' (TW-3B)	1250	4. ' - 14. ' (TW-3B)
55	Former Grandma's Restaurant	12	4 (33 %)	2 (17 %)	0 (0 %)	6 (50 %)	33 %	2120	20. ' - 30. ' (TW-2)	732.2	20. ' - 30. ' (TW-2)
63	Packard Charles Property	10	6 (60 %)	2 (20 %)	0 (0 %)	6 (60 %)	33 %	1690	7. ' - 17. ' (TW-6)	382	7. ' - 17. ' (TW-6)
9	Brown County Reforestation Camp	9	1 (11 %)	1 (11 %)	0 (0 %)	3 (33 %)	33 %	316	3. ' - 13. ' (TW-2)	492	3. ' - 13. ' (TW-2)
34	Rutland Town Garage	12	6 (50 %)	2 (17 %)	1 (8 %)	5 (42 %)	40 %	5100	13. ' - 28. ' (TW-11)	332	13. ' - 28. ' (TW-11)
103	Grafton DPW Hickory St. Garage	10	4 (40 %)	2 (20 %)	3 (30 %)	5 (50 %)	40 %	104	8. ' - 18. ' (TW-1)	43	8. ' - 18. ' (TW-11) *
104	WI Lions Camp	10	3 (30 %)	2 (20 %)	0 (0 %)	3 (30 %)	67 %	50.1	29. ' - 39. ' (TW-2) *	190	29. ' - 39. ' (TW-2) *
108	City of Racine Parks Dept	12	2 (17 %)	2 (17 %)	6 (50 %)	3 (25 %)	67 %	166	6. ' - 16. ' (TW-13)	5.2	6. ' - 16. ' (TW-13)
126	UW Oshkosh Field Studies Building	10	8 (80 %)	6 (60 %)	1 (10 %)	3 (30 %)	100 %	806	3. ' - 13. ' (TW-1) *	63.7	3. ' - 13. ' (TW-2)

Red indicates higher detection frequency at post closure wells compared to SI.

Red indicates higher post-closure level than level at closure.

* Asterisk denotes a water-table well that is different from the high-BTEX well. For SiteMapID 104 (WI Lions Camp), no construction info on MW-2 was found in the case file, so we assumed it to be the same as MW-1.

Table 12: Detection Frequency in Piezometers at the Field Sites

Previous Site Investigation

			Detections					PZ Benzene		PZ Naphthalene	
SiteMap ID	Site Name	Total Number of SI Piezometers	PZs w/ BTEX detection	PZs w/ B detection	PZs w/ MTBE detection	PZs w/ N detection	Percent of PZs w/ N that also had B detections	Historical High B ug/l	Screen Depth	Historical High N ug/l	Screen Depth
33	Martin Oil	3	1 (33 %)	0 (0 %)	0 (0 %)	0 (0 %)		ND		ND	70' - 75' (MW-1P)
36	Woods Garage	6	3 (50 %)	3 (50 %)	0 (0 %)	2 (33 %)	100 %	22.1	20' - 22' (PZ-9A)	198	20' - 22' (PZ-9A)
55	Former Grandma's Restaurant	4	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)		ND (<0.5)	50' - 55' (PW-8)	ND (<1.0)	50' - 55' (PW-8)
63	Packard Charles Property	0									
9	Brown County Reforestation Camp	0									
34	Rutland Town Garage	1	1 (100 %)	1 (100 %)	0 (0 %)	0 (0 %)		4.97	35' - 40' (MW-5B)	ND (<1.0)	35' - 40' (MW-5B)
103	Grafton DPW Hickory St. Garage	0									
104	WI Lions Camp	1	1 (100 %)	1 (100 %)	0 (0 %)	1 (100 %)	100 %	180	50' (PZ-1 bottom)	25	50' (PZ-1 bottom)
108	City of Racine Parks Dept	0									
126	UW Oshkosh Field Studies Building	0									

Post-Closure Investigation

			Detections					PZ Benzene		PZ Naphthalene	
SiteMap ID	Site Name	Total Number of Post-C Piezometers**	PZs w/ BTEX detection	PZs w/ B detection	PZs w/ MTBE detection	PZs w/ N detection	Percent of PZs w/ N that also had B detections	Max B ug/l	Screen Depth	Max N ug/l	Screen Depth
33	Martin Oil	2	1 (50 %)	0 (0 %)	0 (0 %)	1 (50 %)	0 %	< 0.5		242.2	37' - 38' (TP-2)
36	Woods Garage	4	3 (75 %)	3 (75 %)	1 (25 %)	3 (75 %)	100 %	26.9	31' - 32' (TW-7A)	137	32' - 33' (TW-3A)
55	Former Grandma's Restaurant	2	1 (50 %)	1 (50 %)	1 (50 %)	2 (100 %)	50 %	72.3	40' - 45' (TW-2P)	7.8	40' - 45' (TW-2P)
63	Packard Charles Property	2	1 (50 %)	0 (0 %)	0 (0 %)	2 (100 %)	0 %	< 0.5		1.4	24.5' - 29.5' (P-7)
9	Brown County Reforestation Camp	3	2 (67 %)	0 (0 %)	0 (0 %)	1 (33 %)	0 %	< 0.5		0.7	16.5' - 21.5' (TW-2P)
34	Rutland Town Garage	0									
103	Grafton DPW Hickory St. Garage	1	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)		< 0.5		< 0.5	20' - 25' (TW-1P)
104	WI Lions Camp	2	0 (0 %)	0 (0 %)	0 (0 %)	1 (50 %)	0 %	< 0.5	50' - 55' (TW-2P)	0.8	50' - 55' (TW-2P)
108	City of Racine Parks Dept	0									
126	UW Oshkosh Field Studies Building	1	1 (100 %)	1 (100 %)	0 (0 %)	0 (0 %)		1.1	23'-28'(TWEX-1P)	< 0.5	

Orange denotes that well-screen depth range is different from SI.