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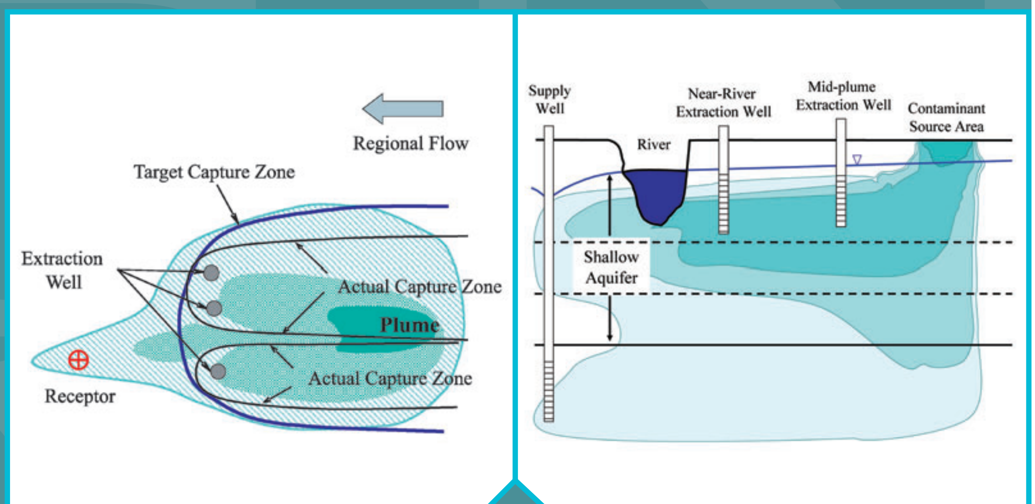
A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems

FINAL PROJECT REPORT



Office of Research and Development
National Risk Management Research Laboratory | Ground Water and Ecosystems Restoration Division

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January 2008

A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems

Project Officer
David S. Burden
Ground Water and Ecosystems Restoration Division
U.S. EPA, National Risk Management Research Laboratory
Ada, OK 74820

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH   45268

NOTICE

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This document describes a systematic approach for performing capture zone analysis associated with ground-water pump and treat (P&T) systems. The intended audience is technical professionals that actually perform capture zone analyses (i.e., hydrogeologists, engineers) as well as project managers who review those analyses and/or make decisions based on those analyses.

Stephen G. Schmelling, Director
Ground Water and Ecosystems Restoration Division
National Risk Management Research Laboratory

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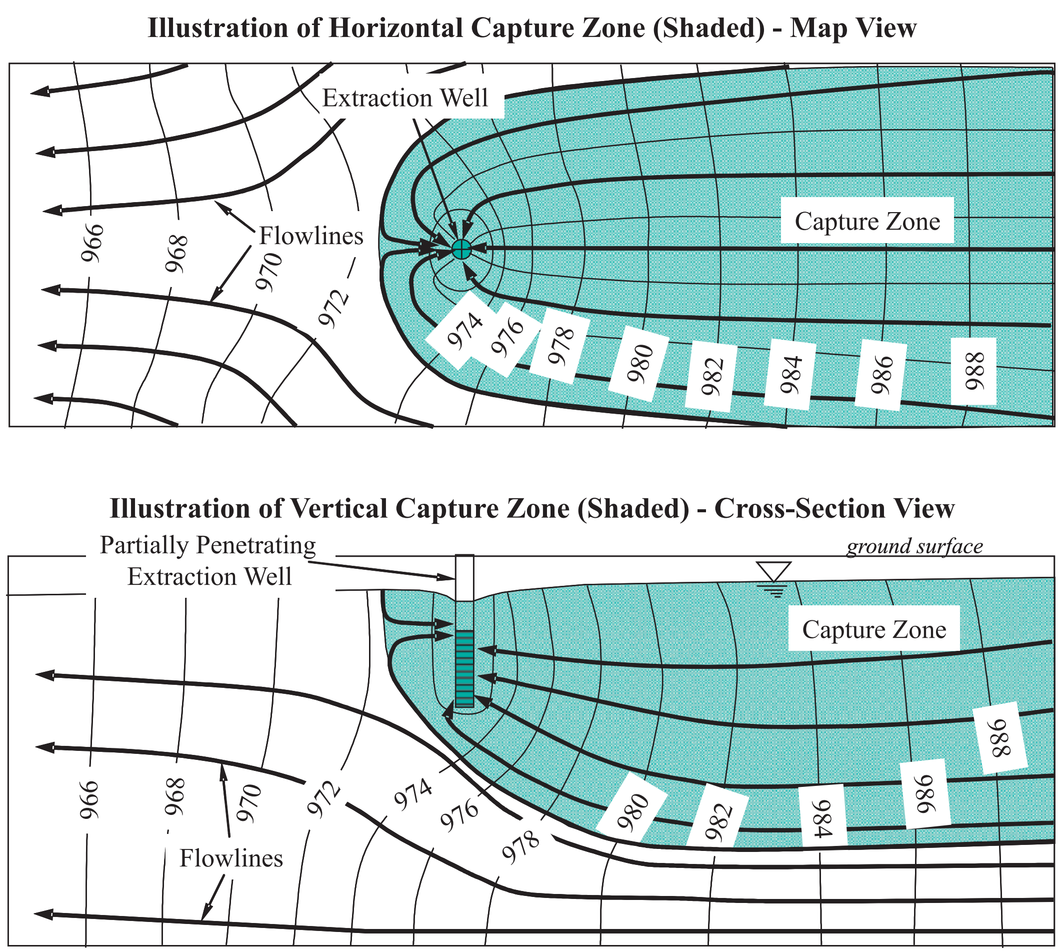
ACKNOWLEDGEMENTS

The U.S. EPA Office of Research and Development (ORD) wishes to express their appreciation to the U.S. EPA Ground Water Forum for their initial conception of the idea for this document and their helpful comments received during the writing. The Ground Water Forum was instrumental in the development and review of this document along with ORD scientists Mr. Steve Acree, Dr. David Burden, Dr. David Jewett, and Dr. Randall Ross.

A. INTRODUCTION

This document describes a systematic approach for performing capture zone analysis associated with ground-water pump and treat (P&T) systems. A "Capture Zone" refers to the three-dimensional region that contributes the ground water extracted by one or more wells or drains (see Figure 1). A capture zone in this context is equivalent to the "zone of hydraulic containment".



Vertical capture does not encompass the entire aquifer thickness for this partially penetrating well. The top figure does not convey this, which demonstrates the need to perform a three-dimensional analysis. If vertical anisotropy is present (Kx > Kz), then the greater the vertical anisotropy, the shallower the vertical capture zone will be.

Figure 1. Illustration of horizontal and vertical capture zones.

If a contaminant plume is hydraulically contained, contaminants moving with the ground water will not spread beyond the capture zone. Failed capture, illustrated schematically on Figure 2, can allow the plume to grow, which may cause harm to receptors and may increase the ultimate cost or duration of the ground-water remedy.

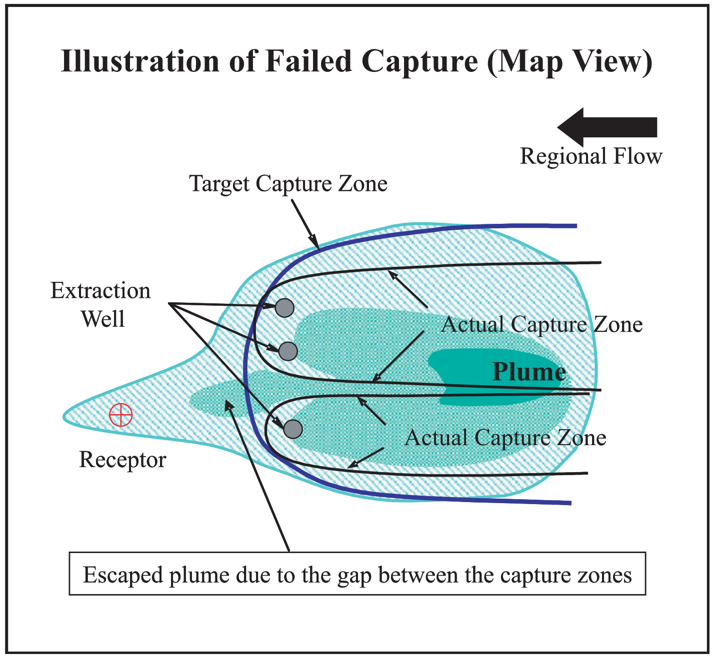


Figure 2. Illustration of failed capture.

The purpose of this document is to present a systematic approach to evaluating capture zones at P&T sites. The intended audience is technical professionals that actually perform capture zone analyses (i.e., hydrogeologists, engineers) as well as project managers who review those analyses and/or make decisions based on those analyses. The scope of this document is limited to evaluating capture in porous media and not necessarily karst or fractured rock settings. The methods and techniques presented here may be used for such settings, but other more intensive techniques may also be required.

EPA places considerable emphasis on P&T performance and determination of whether or not these systems are operating properly and successfully. As discussed in *Elements for Effective Management of Operating Pump and Treat Systems* (U.S. EPA, 2002b), protection of human health and the environment often requires hydraulic containment of contaminants. Capture zone analysis is the process of evaluating field observations of hydraulic heads and ground-water chemistry to interpret the actual capture zone, and then comparing the interpreted capture zone to a "Target Capture Zone" to determine if capture is sufficient.

An optimization study (U.S. EPA, 2002a) of 20 "Fund-lead" P&T systems at Superfund sites concluded that capture zones were not being adequately evaluated. At least 14 of the 20 sites did not have a clearly defined Target Capture Zone. About half of the 20 sites had not attempted to interpret actual capture based on water levels. Only eight of the 20 sites had a ground-water flow simulation model, and capture zone analysis was found to be inadequate or incomplete at six of those eight. Overall, a recommendation to improve the capture zone analysis was made for 16 of the 20 sites. The report also concluded there was a need for improved guidance and training with respect to capture zone analysis. This document is intended to partially address those needs.

This document is intended to be used as a companion document to *Methods for Monitoring Pump-and-Treat Performance* (U.S. EPA, 1994, link provided in "References" section) when evaluating capture zones. This document is intended to provide more detail regarding capture zone analysis, and includes more complex examples, relative to the previous document. This document is not intended to be a comprehensive reference for each topic presented herein nor is it a "how to" guide. However, a table provided at the beginning of the "References" section helps guide the reader to sources of information (cited within this document) according to specific topics.

The approach presented here should be considered iterative since few sites, if any, begin the process with sufficient field data to evaluate and confirm hydraulic containment. Monitoring wells and piezometers are usually installed at sites to develop the site conceptual model and determine the nature and extent of contamination. These sampling locations are typically installed prior to initiating a P&T remedy, and may not be appropriate for evaluating plume capture. The systematic approach advocated here is iterative in that it is advised that the practitioner obtain additional field information to address data gaps and ambiguities if present. The completeness of the data set, including the locations and construction of monitoring points for water levels and water quality, should be evaluated during remedial design and throughout the performance monitoring period. Additional monitoring points should be installed to address any data gaps that are identified.

This document primarily pertains to operating P&T systems. However, the concepts presented in this document should also be considered during system design. In particular, an appropriate methodology for evaluating plume capture, including requisite monitoring locations, should be developed as part of the system design. Also, the implemented P&T system may differ substantially from the system that was originally designed, and the following issues should be assessed:

- did the design account for system down time (i.e., when wells are not pumping)?
- did the design consider time-varying influences such as seasons, tides, irrigation, or transient off-site pumping?
- did the design account for declining well yields due to fouling, or provide for proper well maintenance?
- did the design address geologic heterogeneities?
- did the design take into account other hydraulic boundary conditions such as a surface water boundary or a hard rock boundary?

Such issues may impact the effectiveness of capture relative to the designed system, highlighting the need to conduct capture zone evaluations for the operating P&T system.

Capture zone analysis should be included in plans for remedial action, Operations and Maintenance (O&M), and/or long-term monitoring. Appropriate elements for inclusion in a performance monitoring plan for capture zone evaluations are outlined in Section 2.5 of U.S. EPA (1994). The monitoring plan should be evaluated and revised as appropriate as new data are collected and the site conceptual model is improved based on interpretation of new data.

The appropriate frequency for capture zone evaluations is site-specific. Factors that should be considered include changes in remedy pumping rates over time (and the associated time for the ground-water levels to stabilize), the temporal nature of stresses (on-site and off-site), and the travel-time of contaminants to potential receptors. Some examples of temporal stresses include off-site pumping wells (water supply or irrigation), tidal influences, seasonal changes in surface water levels, and seasonal changes in net recharge from precipitation or irrigation. Additional discussion of factors and strategies to consider when specifying monitoring frequency for water levels and water quality is provided in Sections 2.2.1.4 and 2.2.6.3 of U.S. EPA (1994), respectively. Capture should be evaluated throughout the first year of system operation, and on a routine basis thereafter as part of O&M. One or more capture zone evaluations per year is appropriate at many sites due to changing conditions.

This document highlights six key steps for systematically performing a capture zone evaluation (Exhibit 1). Specific techniques to interpret the extent of capture achieved by the ground-water extraction are applied in Steps 3 to 5. Each of these techniques is subject to limitations, and in most cases, no single line of evidence will conclusively differentiate between successful and failed capture. Therefore, developing "converging lines of evidence", by applying multiple techniques to evaluate capture, increases confidence in the conclusions of the capture zone analysis. In some cases, modifications and additions to the monitoring program may be required to provide sufficient data to conclusively differentiate between successful and failed capture.

Exhibit 1

Six Steps for Systematic Evaluation of Capture Zones

Step 1: Review site data, site conceptual model, and remedy objectives

Step 2: Define site-specific Target Capture Zone(s)

Step 3: Interpret water levels

- potentiometric surface maps (horizontal) and water level difference maps (vertical)
- water level pairs (gradient control points)

Step 4: Perform calculations

- estimated flow rate calculation
- capture zone width calculation (can include drawdown calculation)
- modeling (analytical or numerical) to simulate water levels, in conjunction with particle tracking and/or transport modeling

Step 5: Evaluate concentration trends

Step 6: Interpret actual capture based on Steps 1-5, compare to Target Capture Zone(s), assess uncertainties and data gaps

These six steps for systematically evaluating capture, and the use of converging lines of evidence, are illustrated in this document with five examples that vary in complexity. Appendix A contains three illustrative examples, based on hypothetical sites which were developed for this document. These hypothetical examples highlight some of the details associated with techniques for evaluating capture. Appendix B presents example capture zone evaluations for two actual sites and demonstrates the systematic application of the six steps. These examples are representative of many (but not all) sites. As mentioned, this document does not apply to fractured or karst systems.

B. A SYSTEMATIC APPROACH FOR CAPTURE ZONE ANALYSIS

Step 1: Review Site Data, Site Conceptual Model, and Remedy Objectives

The items listed in Exhibit 2 should be considered prerequisites for performing a capture zone analysis. If the plume is not adequately delineated (width and/or extent), it may not be possible to establish a meaningful Target Capture Zone (Step 2). Hydrogeologic data typically used as the basis for a capture zone evaluation include information on stratigraphy, hydraulic conductivity (values and distribution), hydraulic gradients (magnitude and direction), pumping/injection rates and locations, ground-water elevations, and ground-water quality. Well construction information is important for interpreting some of these data. In many cases, it is appropriate to review regional hydrogeologic data in addition to site-specific data. If hydrogeologic information such as hydraulic conductivity distribution and hydraulic gradient (magnitude and direction) are highly uncertain, then some of the techniques for evaluating capture may be subject to an unacceptable degree of uncertainty, and additional characterization may be appropriate.

Exhibit 2

Elements Associated with Step 1
(Prerequisites for a Capture Zone Evaluation)

- Is the plume adequately delineated in three dimensions?
- Is there adequate hydrogeologic information for performing capture zone evaluations?
  - hydraulic conductivity values and distribution
  - hydraulic gradient (magnitude and direction)
  - aquifer thickness and/or saturated thickness
  - pumping rates and locations
  - ground-water elevation measurements
  - water quality data and associated details
  - well construction details
- Is there a site conceptual model (not a numerical model) that adequately
  - indicates the source(s) of contaminants
  - describes geologic and hydrogeologic conditions
  - explains observed fate and transport of constituents
  - identifies potential receptors
- Is the objective of the remedy clearly stated?
  - complete hydraulic containment of the plume, or
  - partial hydraulic containment in conjunction with other remedies, such as Monitored Natural Attenuation (MNA), for portions of the plume outside the Target Capture Zone

In order to develop remedy objectives and associated performance criteria for a P&T system, and realistic means of evaluating capture zone performance with respect to these criteria, the Data Quality Objectives (DQO) process (U.S. EPA, 2000) should be followed. The DQO process is a systematic planning approach for data collection that is based on the scientific method. The DQO process involves identification of data gaps that may cause an erroneous decision to be made, and assessment of the cost-benefit ratio of filling those gaps to reduce uncertainty. By using the DQO process, one can clearly define what data and information about the remedy performance are needed and develop a data collection design to help obtain the right type, quantity, and quality of data needed to make a sound decision about whether or not the remedy is effective.

A site conceptual model (a text description, maps, and cross-sections that should not be confused with a “numerical model”, although a numerical model is based on a site conceptual model) should adequately accomplish the following:

- indicate the source(s) of contaminants
- describe geologic and hydrogeologic conditions
- explain observed fate and transport of constituents
- identify potential receptors

The objectives of the remedy regarding capture should then be established (Figure 3) so that an appropriate Target Capture Zone can be specified (Step 2). Specifically, it should be determined if there is a need for complete hydraulic containment (the definition of “capture” in this document), or if it is acceptable to have an uncaptured portion of the plume that is below cleanup levels or is addressed by another remedial technology. The type of remedy objective will dictate the specifics of the Target Capture Zone.

Step 2: Define Site-Specific “Target Capture Zone”

The Target Capture Zone is defined herein as the three-dimensional zone of ground water that must be captured by the remedy extraction wells for the hydraulic containment portion of the remedy to be considered successful. This will depend on the site-specific remedy objectives (Step 1). The Target Capture Zone should be clearly stated in site remedial action and monitoring plans, and illustrated on maps and/or cross-sections when feasible. An example is schematically presented on Figure 4, with the Target Capture Zone illustrated both horizontally and vertically.

The Target Capture Zone should be defined in terms of specific criteria, such as a specific concentration contour or a geographical boundary along which an inward hydraulic gradient is to be established. If the Target Capture Zone is based on a specific concentration contour, it may need to be updated over time as concentrations change. If a variety of contaminants of concern are present, the Target Capture Zone should consider each contaminant.

Step 3: Interpret Water Levels

Ground-water elevation measurements are used to:

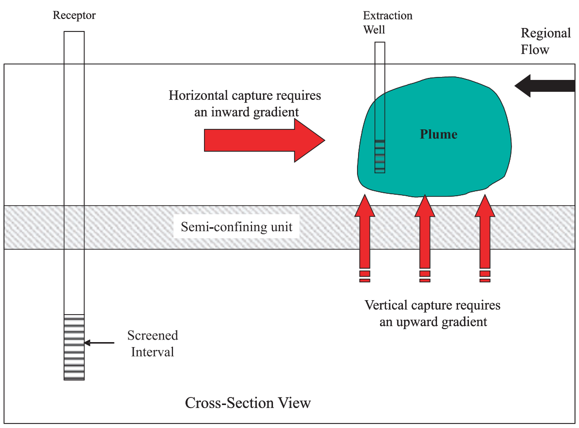
- evaluate flow directions based on water level maps (horizontal or vertical)
- evaluate flow directions based on water levels at paired locations (gradient control pairs)

Both types of evaluation listed above can provide evidence regarding the extent of capture.

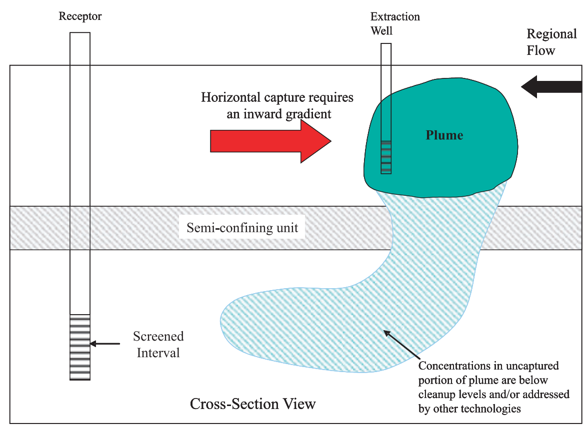
Remedy Objectives May or May Not Require Complete Hydraulic Capture

Site 1 (Cross Section View)

Case 1: Complete Horizontal and Vertical Capture



Case 2: Complete Horizontal Capture Only

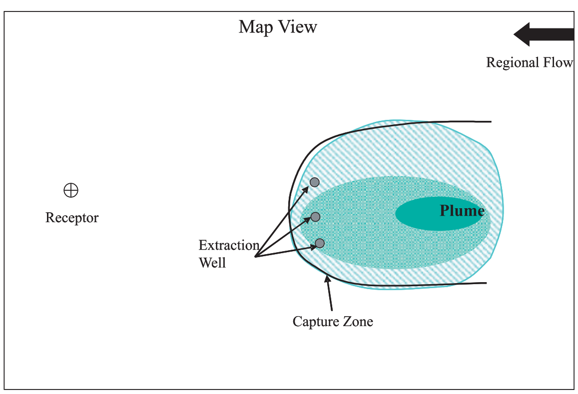


Case 1: Remedy objective is complete horizontal and vertical capture.

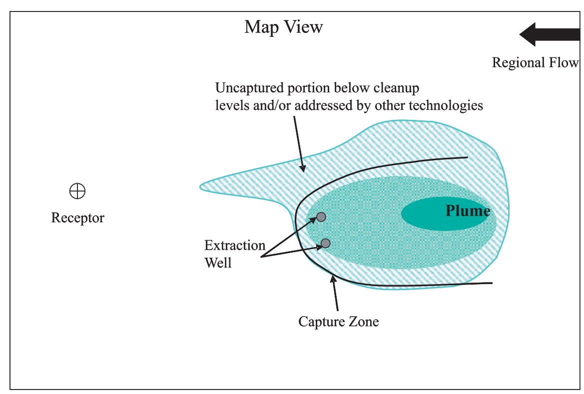
Case 2: Remedy objective is complete horizontal capture only, in conjunction with other remedial technologies for the deeper aquifer

Site 2 (Map View)

Case 1: Capture for Entire Plume Extent



Case 2: Capture for Portion of the Plume



Case 1: Remedy objective is horizontal containment of the entire plume

Case 2: Remedy objective is horizontal containment of the most contaminated portion of the plume, in conjunction with other remedial technologies for the uncaptured portion

Notes:
- Site 1 and Site 2 are distinct hypothetical sites and do not illustrate the same plume
- Performance monitoring wells are not depicted on these schematics to maintain figure clarity

Figure 3. Remedy objectives may or may not require complete hydraulic capture.

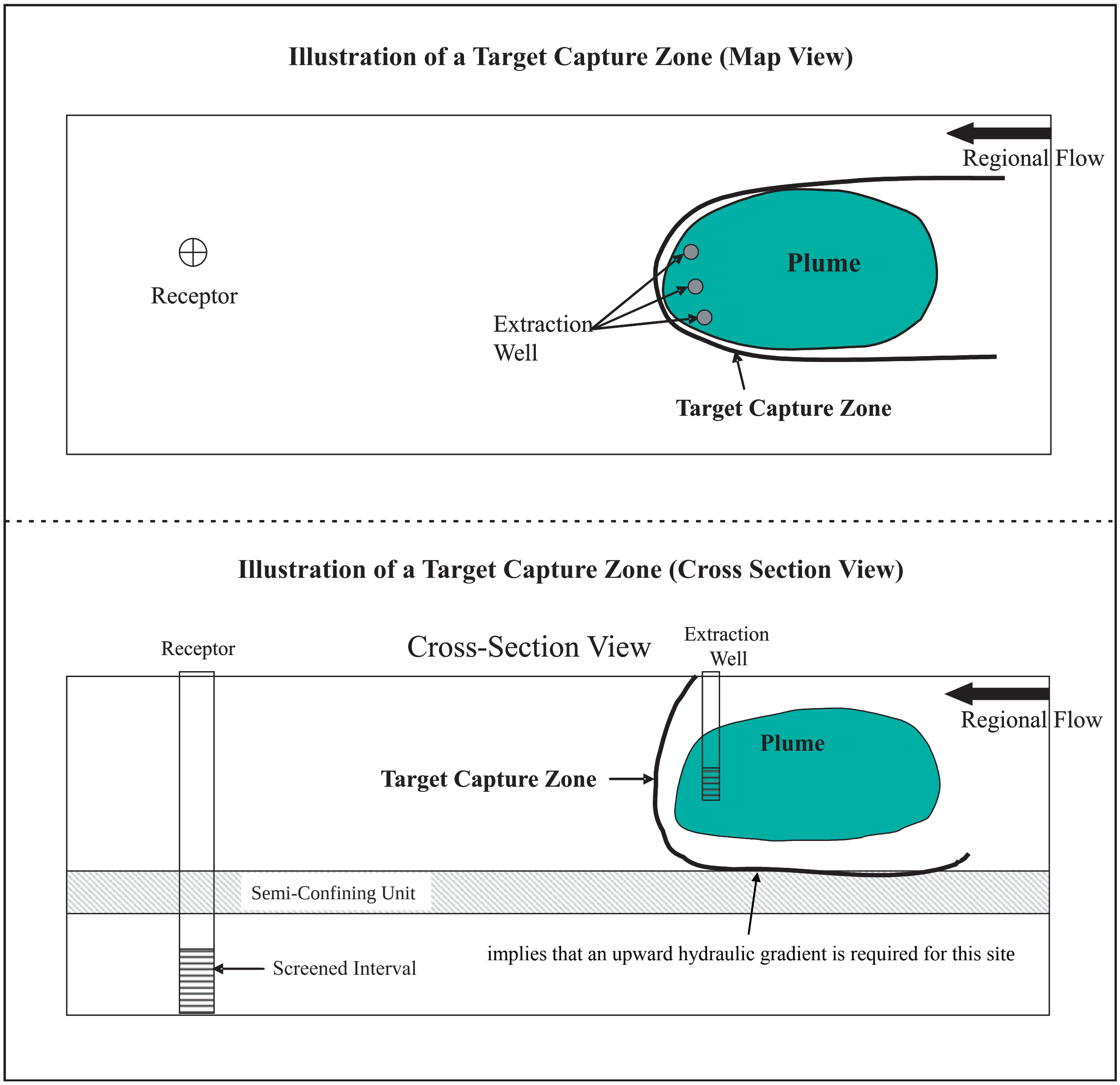


Figure 4. Illustration of a Target Capture Zone (map and cross-section views).

For most sites it is appropriate to analyze ground-water flow patterns in three dimensions (i.e., both horizontal and vertical). The potential for vertical transport of contaminants to underlying or overlying aquifers should be considered. Three-dimensionality of ground-water flow patterns in the vicinity of pumping wells should also be considered. For instance, in the presence of partially penetrating wells (see Figure 1), a flow divide will generally develop with respect to vertical flow, such that water at some depth below the well screen does not flow to the extraction well. The depth of this flow divide for a partially penetrating well depends on the vertical anisotropy. The greater the ratio of horizontal to vertical hydraulic conductivity, the shallower the vertical capture zone will be.

When water levels are collected, it is good practice to provide the field technician with historical depth to water data at each location, so that reasonableness of measurements can be evaluated in the field. When anomalous data are observed, a plan to resolve discrepancies with historical data can be developed while the technician is still in the field. It is also good practice to periodically survey measuring point elevations. For instance, changes in measuring point elevations can occur over time due to frost heaving. In other cases, wells installed by different contractors at different times may be surveyed inconsistently.

Water Level Maps

Horizontal water level maps indicate interpreted contours of water levels within an individual hydrostratigraphic unit. Vertical water level difference maps indicate vertical head differences or gradients between hydrostratigraphic units. The extent of horizontal or vertical capture can subsequently be interpreted on the basis of those maps (illustrated schematically in Figure 5):

- *Horizontal Capture Analysis*. Flow lines are interpreted as perpendicular lines to water level contours (strictly valid only for isotropic systems). Horizontal capture is defined by a bounding flow line, within which all other flow lines reach an extraction location. The delineation of the capture zone in this manner is a derived interpretation, since water level contours must first be interpreted from water level values.

- *Vertical Capture Analysis.* Water levels between adjacent hydrogeologic units are evaluated to indicate zones of upward versus downward flow. The analysis can be based on vertical head differences or vertical gradients (the head difference divided by the vertical distance between measurements).

Note that "water level" and "head" are used interchangeably in this document. Contour maps interpreted from water levels should generally include the following (some of which are not included on the schematic illustrations within Figure 5):

- the actual data values being contoured superimposed with the interpreted contour lines (whenever feasible)

- labels for the contour lines

- an indication of any water level measurements made at extraction wells, and whether or not they were corrected for well inefficiency and losses

- locations of pumping and injection wells, ideally with rates indicated for the time period just prior to the water level measurements

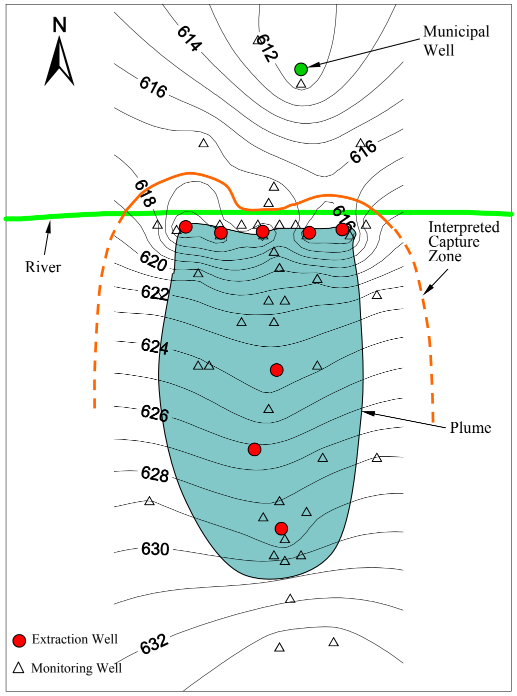
- enough basemap features to orient the reader, including the Target Capture Zone so the success of capture can be evaluated, plus a north arrow and a scale

- dashed (or otherwise identified) contour lines where data are sparse and contour lines are inferred

Interpreting horizontal capture from water level maps is subject to significant uncertainty. The issues listed in Exhibit 3 should all be considered when interpreting horizontal capture from water level maps. Many of these items also pertain to evaluation of vertical capture based on vertical head differences or vertical hydraulic gradients between hydrostratigraphic units. In light of these uncertainties EPA recommends using additional lines of evidence regarding capture to augment the evaluation of flow directions interpreted from water level maps.

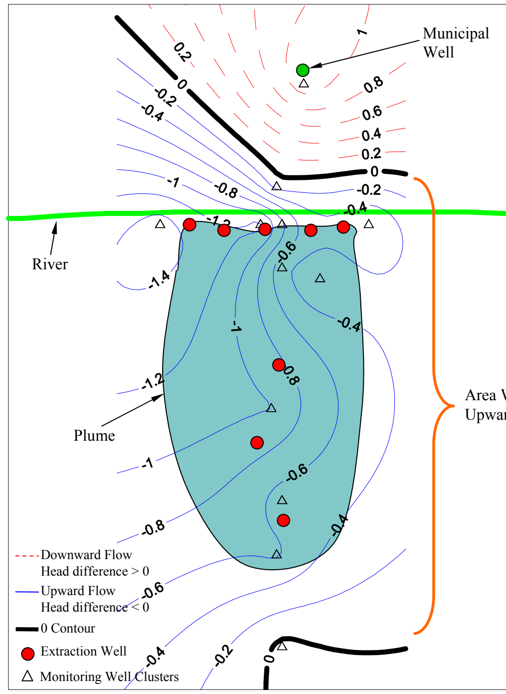
Interpreting Capture From Water Level Maps

Potentiometric Surface Map: Horizontal



Horizontal Capture: Can be interpreted from water level contours by approximating the location of a "bounding flowline", within which all other flowlines reach a pumping well. In this example the entire plume is within the interpreted horizontal capture zone, for the specific hydrostratigraphic horizon evaluated.

Water Level Difference Map: Vertical



Vertical Capture: Can be evaluated by interpreting areas of upward versus downward flow. In this example head differences at well clusters were contoured, and the entire footprint of the plume is within the area where upward flow is interpreted. Note the number of well clusters is quite limited.

In this example the Target Capture Zone corresponds to the plume boundary

Cross-Section Schematic for Illustrating Upward and Downward Head Differences

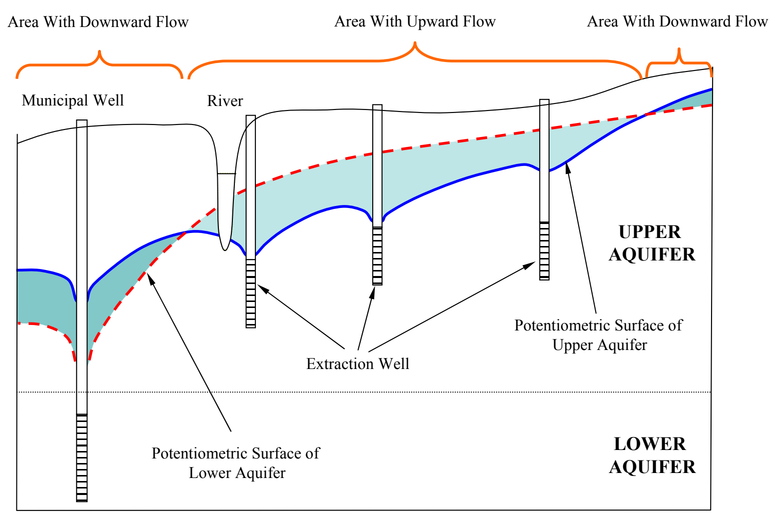


Figure 5. Interpreting capture from water level maps.

Exhibit 3

Issues When Evaluating Horizontal Capture from Water Level Contour Maps (Step 3)

- Are the number and distribution of measurement locations adequate?

  Contouring accuracy will generally increase as the number of data points increases.

- Are water levels included in vicinity of extraction wells (and have well inefficiency and losses been considered at extraction well locations)?

  Ideally, water level data representative of the aquifer are obtained from piezometers located near extraction wells. Water levels measured at an extraction well will be lower than in the surrounding aquifer material due to well inefficiency and losses, which can lead to incorrect interpretations of capture.

- Has the horizontal capture evaluation been performed individually for all pertinent horizontal units?

  Care should be taken to avoid combining water level observations from multiple hydrostratigraphic units to generate an overall water level map. Only observations collected from a specific unit should be used to generate a water level map for evaluating horizontal capture in that unit.

- Is there bias based on contouring algorithm?

  Multiple interpretations of water level contours and associated flow directions are possible for one data set by using a different contouring algorithm (or by having a different hydrogeologist contour the data manually). The potential for alternate interpretations of water level contours should be considered when evaluating capture based on the contours.

- Is representation of transient influences adequate?

  A water level map for one point in time may not be representative of water levels and flow directions at other points in time, which may be impacted by seasons, tides, or other pumping wells with time-varying pumping rates.

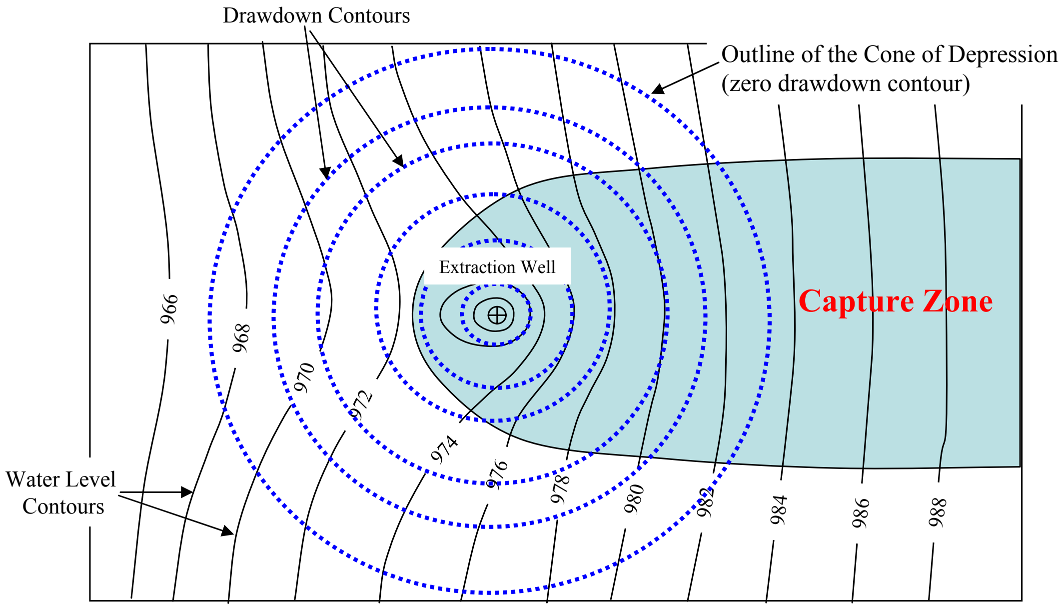
- Has potential for vertical transport been neglected when evaluating horizontal capture?

  Successful horizontal capture in one stratigraphic unit does not preclude impacted water from being transported vertically to other stratigraphic units.

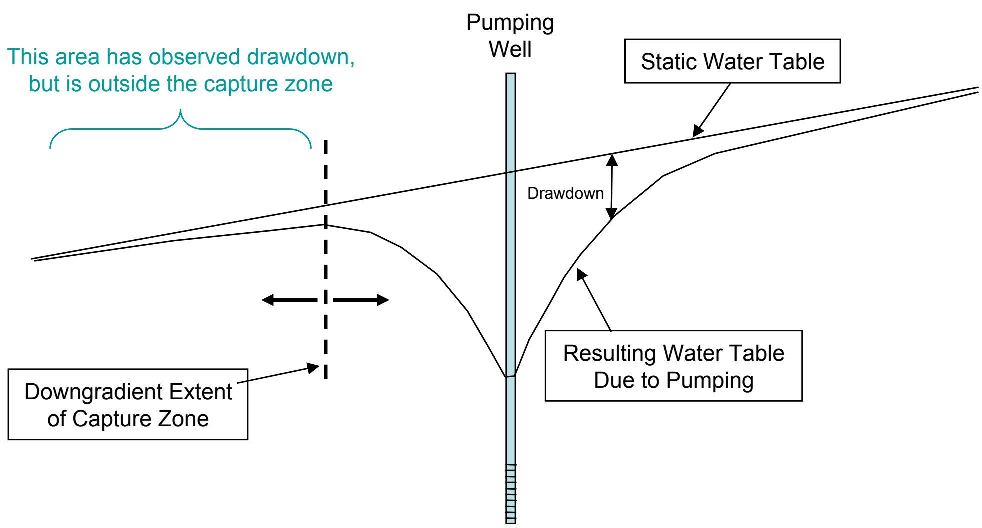
"Drawdown" Versus "Capture"

Drawdown is the change of water level due to ground-water extraction. It is calculated by subtracting the water level measured under pumping conditions from the water level measured without pumping. The "cone of depression" (i.e., the zone where drawdown is observed) caused by extraction from one or more locations should not be confused with the capture zone associated with that extraction. As illustrated on Figure 6, there are generally locations outside the capture zone where drawdown due to pumping is observed. The difference between the "cone of depression" and the "capture zone" is due to the impact of regional hydraulic gradients. The only case where the capture zone is the same as the entire area where drawdown is observed is when the background hydraulic gradient is perfectly flat.

Drawdown and Capture are Not the Same



Cross-Section View: Difference Between Drawdown and Capture



<u>Drawdown</u> is the change of water level due to pumping. It is calculated by subtracting water level under pumping conditions from the water level without pumping.

<u>Cone of Depression</u> is the region where drawdown due to pumping is observed.

<u>Capture Zone</u> is the region that contributes the ground water extracted by the extraction well(s). It is a function of the drawdown due to pumping and the background (i.e., without remedy pumping) hydraulic gradient. The capture zone will only coincide with the cone of depression if there is zero background hydraulic gradient.

Figure 6. Drawdown and capture are not the same.

Hand-Contouring versus Computer-Based Contouring

There are many different approaches to contouring measured water levels. The interpolation or mapping approach is probably most common. Some prefer contouring by hand, while others prefer using computer-based contouring algorithms (e.g., SURFER by Golden Software). In either case, vastly different (yet reasonable) interpretations of flow direction and capture may be inferred from the same water level data, based on the interpolations (between data points) and extrapolations (beyond data points) associated with the evaluation. Whether contouring is performed by hand or is computer-based, the results should be evaluated for hydrogeologic reasonableness.

An advantage of contouring by hand is that professional judgment and hydrogeologic insight (e.g., plume shape, orientation of hydrogeologic features) can be more easily incorporated into the contours. However, hand-contouring can be time consuming, and is not very reproducible. One approach is to have several different individuals contour the measured values, to potentially indicate different interpretations. Computer-based contouring is generally faster and is more reproducible. Many different algorithms are available, and each may yield different interpretations. If different algorithms cause different conclusions regarding the success or failure of capture, it may suggest a need for additional water level measurement points to resolve the uncertainties.

It is harder to incorporate professional judgment and hydrogeologic insight with computer-based contouring, but it can be accomplished by augmenting the measured data with assumed values at "pseudo-data points". The assumed values are used to force the computer-based algorithms to interpret the actual data in a manner consistent with the insight of the user.

Contour maps should indicate (either on the map or in related text):

- the software name and settings (if applicable) and specific algorithms applied
- the locations and values for "pseudo-data points" where data values were assumed to augment measured data
- any data distribution models (including trends and transformations) assumed or applied

Neither hand-contouring nor computer-based contouring using measured water levels strictly account for the physics-based ground-water flow equation, and the underlying principles such as mass balance. For instance, the contours interpreted from measured water level data may be inconsistent with known or assumed spatial variation of hydraulic conductivity. The resulting hydraulic gradients (magnitude and/or direction) interpreted from those contoured water levels may therefore also be inconsistent with the known or assumed spatial variation of aquifer parameters. A properly constructed flow net, whether obtained by hand or with software, leads to head contours that satisfy the ground-water flow equation and the principle of mass balance, although only for a highly idealized situation. Basic information on flow nets is given by Freeze and Cherry (1979) or Fetter (2001), and a more detailed presentation is provided in Cedargren (1997).

One approach to improve interpreted contours (Wilson and Dougherty, 2002; Dougherty and Wilson, 2003; Tonkin and Larson, 2002) is to condition computer-based contouring (based on current water level measurements and rates of extraction/injection) with assumed trends, or with the results of simulation models of ground-water flow (analytical or numerical) that incorporate physical principles and are consistent with the physics of ground-water flow.

Hydraulic Gradient Vector Maps

Many computer-based contouring programs can quickly generate hydraulic gradient vector maps based on the interpreted water level data. An example is provided in Figure 7. Such maps can make it easier to visualize flow directions and gradient magnitudes.

A form of particle tracking can also be performed based on computer-based contours of measured water levels, but such particle tracking is generally not consistent with the physics associated with the ground-water flow equation (unless the computer-based contours are conditioned with an underlying simulation model, as discussed above).

Number and Distribution of Water Level Measurements

Water level monitoring is conducted within, at the perimeter, and downgradient of the Target Capture Zone to interpret ground-water flow patterns and the associated capture zone. The number and distribution of ground-water elevation measurements are frequently not sufficient to interpret capture unambiguously. Additional water level observation points, located appropriately, may be required to resolve the uncertainty.

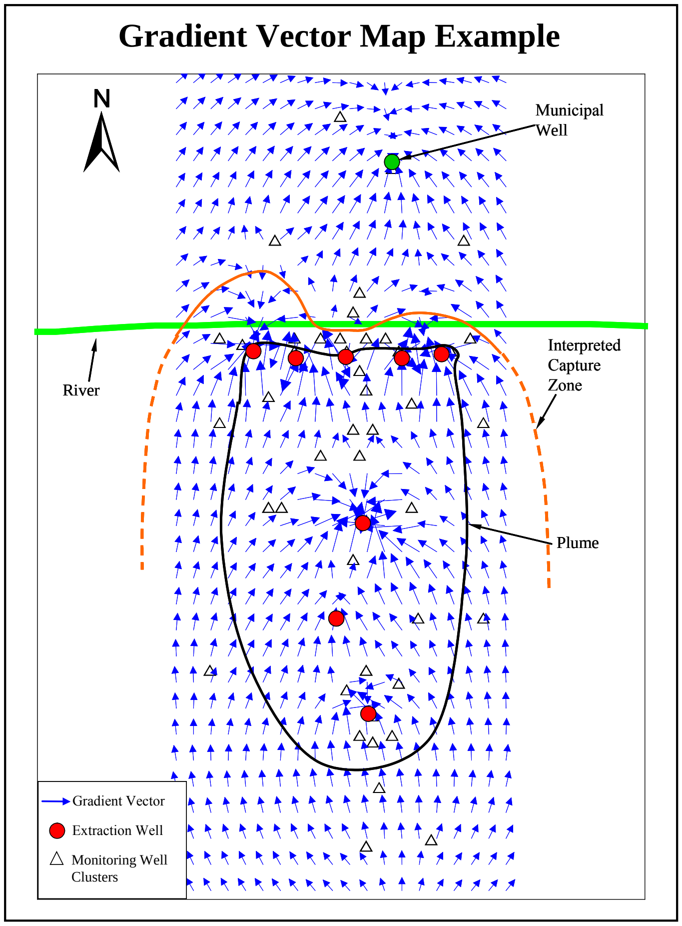


Figure 7. Gradient vector map example.

As discussed in Section 2.2.1.3 of U.S. EPA (1994), the number of observations needed to evaluate capture increases with site complexity and with decreasing hydraulic gradients around the perimeter of the Target Capture Zone. However, there is no rule regarding the "correct" amount of water level data. Contouring accuracy will generally increase as the number of data points increases. Installing piezometers (used herein to indicate locations where only water levels are measured) is inexpensive at many sites, and adding piezometers should be considered if the monitoring network is not sufficient to construct water level maps with confidence.

Water Levels at Extraction Wells (Well Inefficiency and Well Losses)

The water level measured in an extraction well is typically lower than the water level in the adjacent aquifer due to well inefficiency and well losses (see Driscoll, 1986 and Dawson and Istok, 1991). This is schematically illustrated in Figure 8.

Well inefficiency can be caused by the following:

- inappropriate drilling and/or installation of wells for the materials through which the well bore is advanced

- poor or inadequate development of new wells
- biofouling (e.g., iron-fixing or sulfur-fixing bacteria) and encrustation (e.g., scaling due to pH change or aeration) for extraction wells that have been operating for some time (usually months or years)

Additional well losses may occur due to turbulent flow inside the well bore and through the well screen slots.

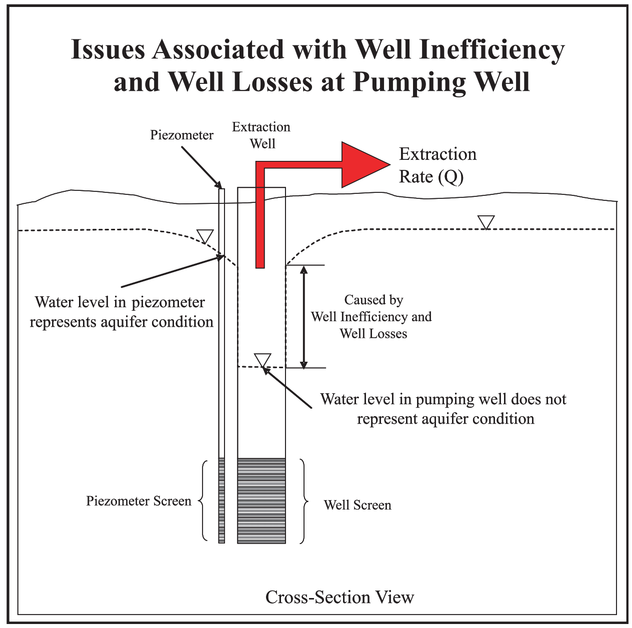


Figure 8. Issues associated with well inefficiency and well losses at pumping well.

Using water levels at extraction wells can bias the interpretation of capture, since the water levels at the extraction wells used for contouring may be much lower than water levels in the aquifer material just outside of the well bore. Thus, the capture zone may be interpreted to be larger than it actually is when water levels at the extraction wells are used for contouring. This is illustrated in Figure 9. It can be equally problematic to ignore water levels measured at extraction wells if no piezometers are located in the vicinity of the extraction wells. In that case, the capture zone often is interpreted to be smaller than it actually is. To avoid these problems, EPA recommends installing a piezometer near each extraction well. It is also possible to install piezometers in the filter pack of extraction wells, although some causes of well inefficiency (e.g., formation damage due to poor well construction) will not be mitigated by this approach.

If a piezometer is not available near a pumping well, a possible approach (until an appropriately located piezometer is available) is to estimate aquifer water levels at the extraction well by correcting the measured water level for well losses. Bierschenk (1964) and Hantush (1964) presented a graphical method (see Exhibit 4) for determining head loss coefficients for well losses caused by turbulent flow across the well screen, based on a plot of specific capacity versus pumping rate developed from a step-drawdown test. However, this approach incorporates the assumption that all well inefficiency results from turbulent flow near the well and in the well screen. Driscoll (1986) points out that other causes of well inefficiency are not accounted for in this approach. Dougherty (2003) presents another well loss estimation technique based on a recovery test in a pumping well. Note that well losses can change over time due to well fouling, further complicating the issue. Again, locating piezometers near extraction wells is much preferred to correcting water levels in extraction wells based on calculated well losses.

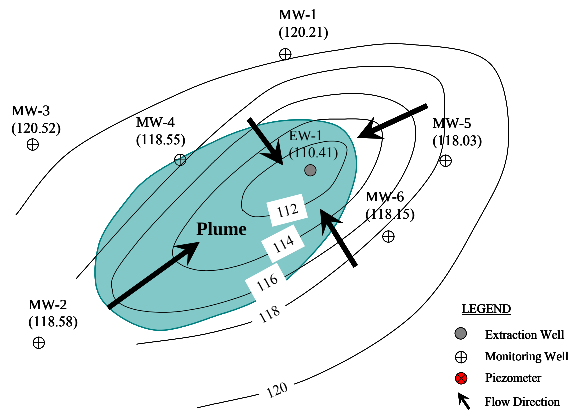
Vertical Head Differences versus Vertical Hydraulic Gradients

Vertical hydraulic gradient is the head difference divided by the vertical distance between measuring points. Vertical gradients provide more information than head differences because they account for the distance between measurements, but calculating vertical gradients can be confusing because the vertical distance between measurements is generally not clear (because of the length of each well screen). Also, the small numbers typically associated with gradients can be confusing. For those reasons, head differences are often easier to work with.

Head differences can be measured at specific well clusters, or they can be estimated over a region by subtracting interpreted water level surfaces created for each hydrogeologic unit using contouring software. Typically there are just a few locations at a site where clustered wells are available to provide measurements of vertical head difference, and contours based on just a few points are generally subject to a high degree of uncertainty.

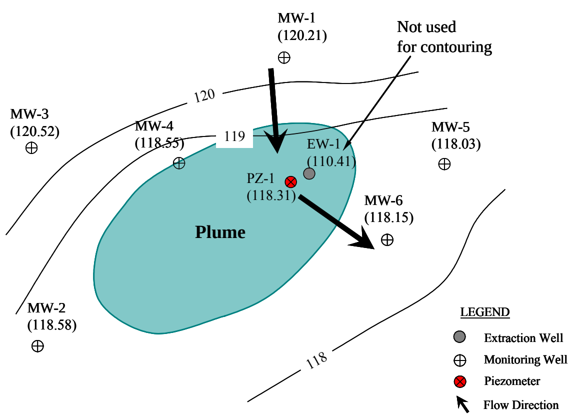
Water Level Interpretation with Measurement at Pumping Well versus Near Pumping Well

Measurement at Pumping Well



Using water level at the extraction well for developing contours biases interpretation to indicate extensive capture…

Measurement Near Pumping Well
(Not at Pumping Well)



The piezometer near the extraction well indicates that water level in the extraction well is not representative of water level in the aquifer. Using water levels measured at the extraction well will overestimate the capture. In this example, no clear-cut capture is in fact apparent when the water level measurement at the extraction well is excluded and a water level measurement at a piezometer near the extraction well is available.

Figure 9. Water level interpretation with measurement at pumping well versus near pumping well.

Other Potential Pitfalls Interpreting Capture from Water Level Maps

If transient influences are present, water level maps for multiple time periods may be required to sufficiently evaluate the capture zone. Examples of transient influences are seasons (e.g., changes in net recharge due to precipitation or irrigation), tides, or transient pumping at other nearby wells. Such transient influences can impact hydraulic gradients and, hence, capture effectiveness.

Water level data measured in different hydrostratigraphic units should generally not be combined to generate an overall water level map for the site. Only water level measurements from a specific unit should be used to generate a water level map for that unit. Also, it is important to remember that successful horizontal capture in one stratigraphic unit does not preclude impacted water from being transported vertically to other stratigraphic units where horizontal capture may not be achieved. Also, if extraction wells are partially penetrating, then the potential limitations of two-dimensional analysis of water levels should be evaluated.

<u>Water Level Pairs (Gradient Control Points)</u>

Pairs of water level elevations on either side of a boundary (horizontally or vertically) are used to demonstrate inward flow relative to that boundary. Examples include ground-water elevations on either side of a hydrogeologic boundary or property boundary, or stage measured in a creek relative to the ground-water elevation in the aquifer immediately adjacent to the creek (a higher creek stage indicates no discharge from the aquifer to the creek), or water levels on either side of Target Capture Zone boundary.

Exhibit 4

Using Specific Capacities From a Step-Drawdown Test to Estimate Well Losses at Extraction Wells

Ground water flow across the well screen is turbulent due to large hydraulic gradients. For this case Jacob (1950) proposed the following expression for drawdown inside the well casing, s_w:

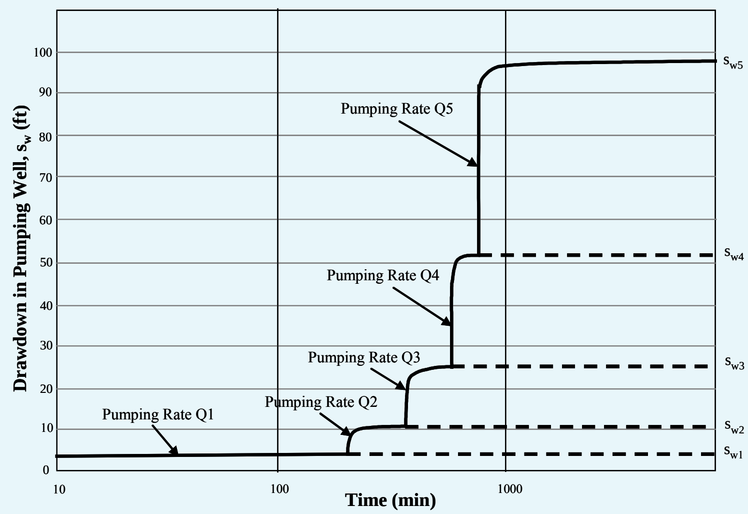
$$s_w = BQ + CQ^2$$
$$s_L = CQ^2$$

Where

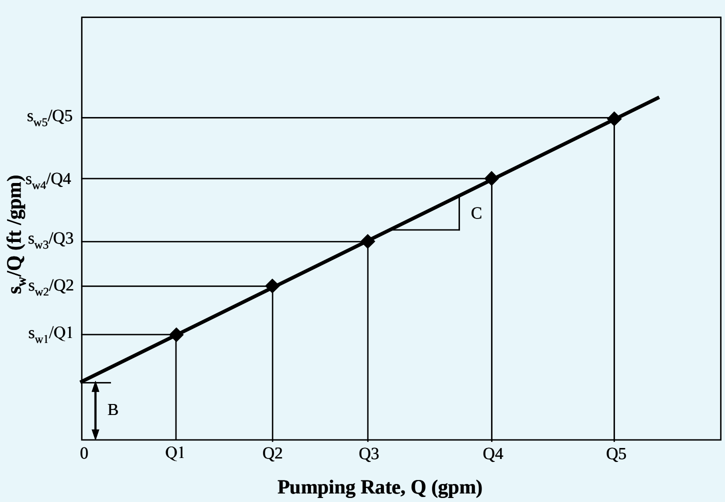
- s_w = drawdown inside the well casing
- s_L = well loss
- C = a "well coefficient", a measure of the head loss due to turbulent flow in the well screen and pump inlet
- B = an "aquifer coefficient", a measure of the head loss due to laminar (Darcy) flow in the aquifer
- Q = pumping rate

Bierschenk (1964) developed a graphical method for determining coefficients B and C. It is based on a plot of the inverse of specific capacity versus pumping rate from a step-drawdown test, which assumes that an equilibrium drawdown in the pumping well will be established during the step-drawdown test for several pumping rates. Rearranging the equation provided above yields:

$$s_w/Q = CQ + B$$



The step-by-step description of the procedure is as follows:



- Plot drawdown s_w versus log(time) as shown in the upper figure
- For each pumping rate, record the equilibrium drawdown at the pumping well (s_w)
- Plot s_w/Q versus Q on arithmetic scale as shown in the lower figure. Fit a straight line through the data and extend the fitted line to a zero pumping rate. The slope of the line is C and the y-intercept is B.
- Calculate the well loss associated with a specific pumping rate, $s_L = CQ^2$

Specific water level pairs used for gradient control points can appear to indicate a lack of inward flow, even when capture is actually achieved. This is illustrated for horizontal capture in Figure 10 and Figure 11.

In Figure 10, water level pairs nearest the pumping wells show inward flow relative to the boundary, but water level pairs between the pumping wells show outward flow relative to the boundary. Nevertheless, the extraction wells fully capture ground water between locations A and A'.

In Figure 11, an adequate capture zone is established to contain the plume. However, water level pairs near the river show continued discharge from the aquifer to the river because the flow divide associated with the capture zone occurs between the extraction well and the river, and the water level pairs are located downgradient of that flow divide.

Figures 10 and 11 illustrate that achieving inward gradients at water level pairs used to monitor gradient control near a boundary generally requires more pumping than is actually required to simply achieve adequate capture. In each case, the water level pairs illustrated would all show inward gradients if the pumping rate was increased. That may add confidence in the analysis of capture, but may also increase the cost of treating and discharging the water and/or potentially cause other negative impacts (e.g., dewatering well screens or wetlands).

Figure 12 is a cross-section view that illustrates the types of interpretations that can be determined using water level pairs when enough water level data downgradient of the extraction well are available. The top schematic in Figure 12 definitively indicates flow towards the river, but a specific flow divide caused by the extraction well cannot be interpreted (though a flow divide caused by the extraction might still be present). The middle schematic in Figure 12 definitively indicates a flow divide between the extraction well and the river. The bottom schematic in Figure 12 definitively indicates inward flow from the river towards the extraction well. Note that measured water level at the extraction well is not used in these interpretations, for reasons discussed earlier.

Inward Flow at Boundary is Hardest to Achieve Half-Way Between the Pumping Wells

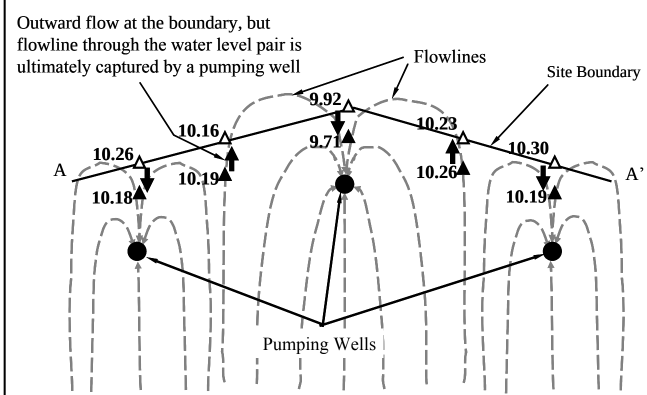
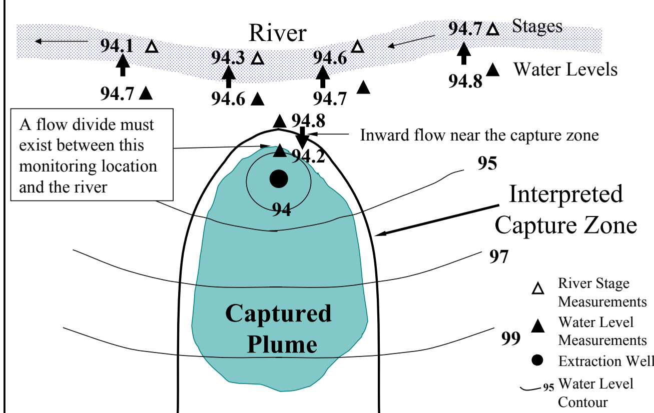


Figure 10. Inward flow at boundary is hardest to achieve half-way between the pumping wells.

Complication Associated with Water Level Pairs



Water level pairs may suggest lack of inward flow in cases where capture is actually successful. In this case, the flow divide caused by the well is located between the well and river. Using water level pairs at the river may cause an erroneous interpretation that capture is not achieved. More pumping is required to cause inward flow from the river to the aquifer, compared to the pumping required to achieve capture of the plume.

Figure 11. Complication associated with water level pairs.

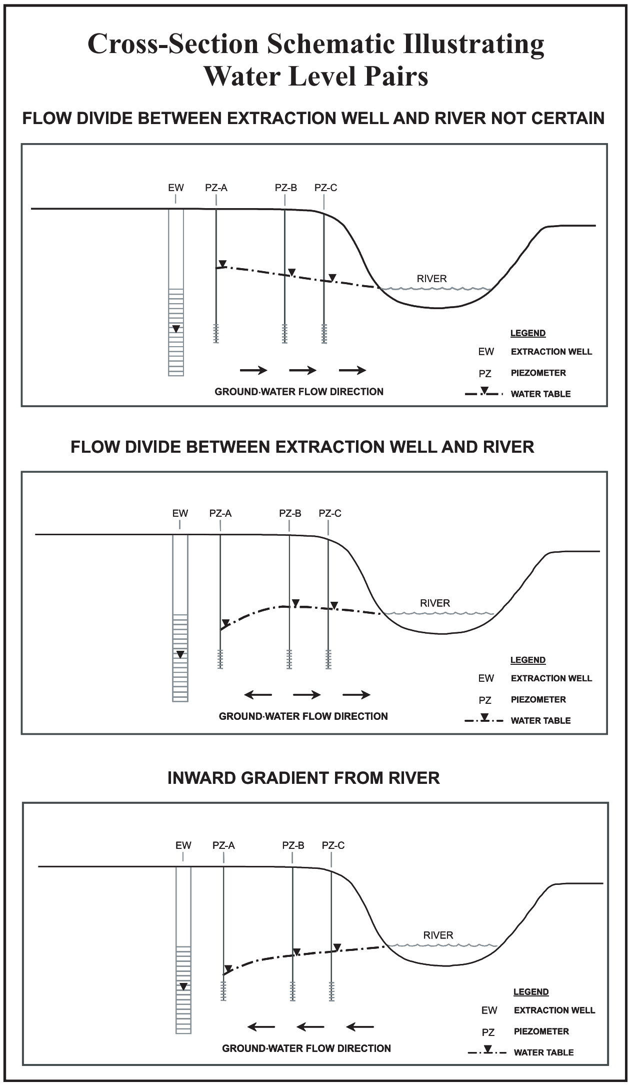


Figure 12. Cross-section schematic illustrating water level pairs.

If transient influences are present (e.g., seasonal pumping, tides), water level pairs for multiple time periods may be required for sufficient evaluation.

Step 4: Perform Calculations

Specific calculations can be performed to add additional lines of evidence regarding the extent of capture, including the following:

- simple horizontal analyses related to capture, such as estimated flow rate calculations and capture zone width calculations
- modeling (analytical or numerical) to simulate heads, in conjunction with particle tracking and/or contaminant transport modeling

Determining the appropriate types of calculations to perform should be based on site complexity. For instance, numerical simulation of heads for evaluating capture may not be necessary for sites with very simple hydrogeology and only minor heterogeneity of aquifer parameters.

<u>Simple Horizontal Analyses</u>

The simplest (and most commonly applied) horizontal capture zone analyses are estimated flow rate calculations and capture zone width calculations:

- *Estimated Flow Rate Calculations*, illustrated in Figure 13, provide an estimate of pumping rate required to capture the ground-water flux through the extent of the plume.

- *Capture Zone Width Calculations*, illustrated in Figure 14 for the case of one extraction well, provide an estimate of capture zone width for a specific pumping rate.

Simplifying assumptions for these methods include the following:

- homogeneous, isotropic aquifer of infinite extent

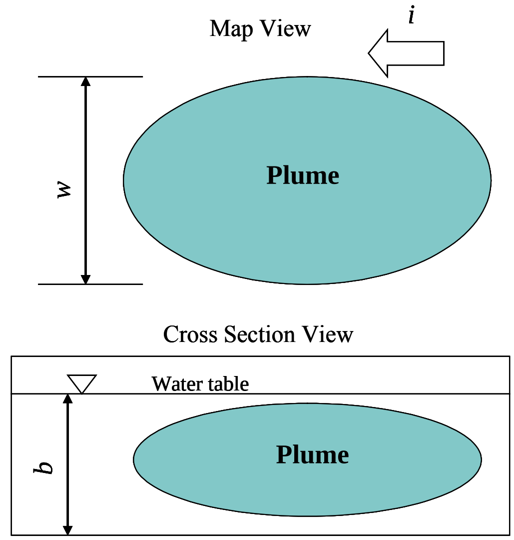
- confined aquifer, uniform aquifer thickness

- fully penetrating extraction well(s)

Estimated Flow Rate Calculation

Assumptions:

- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- no other sources of water introduced to aquifer due to extraction (e.g., from rivers or leakage from above or below)



$$Q = K \cdot (b \cdot w) \cdot i \cdot \ factor$$

(must use consistent units, such as "ft" for distance and "day" for time)

Where:

Q = extraction rate
K = hydraulic conductivity
b = saturated thickness
w = plume width
i = regional (i.e., without remedy pumping) hydraulic gradient
factor = "rule of thumb" is 1.5 to 2.0, intended to account for other contributions to the pumping well such as flux from a river or induced vertical flow from other stratigraphic unit

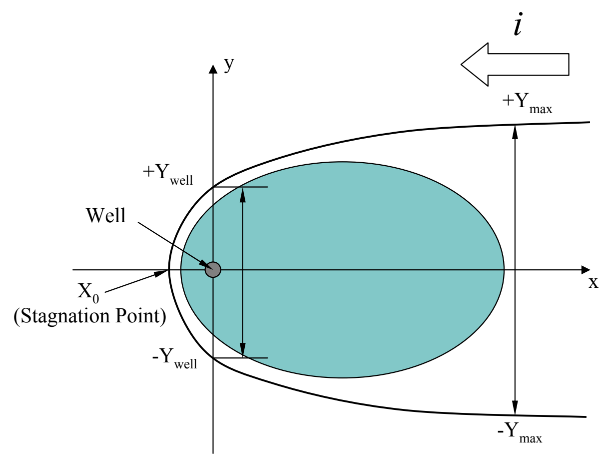
Figure 13. Estimated flow rate calculation.

- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in the regional hydraulic gradient
- no other sources of water to the extraction well (e.g., flux from rivers or from other aquifers), except as represented by the "factor" in the estimated flow rate calculation

One or more of these simplifying assumptions will be violated at most sites. However, these simple horizontal analyses can be performed in minutes, and force the practitioner to perform a basic assessment of hydrogeologic data (e.g., hydraulic parameter values, variation of hydrogeologic parameters over space and/or time). For those reasons, EPA recommends that these simple horizontal analyses be performed, even though in most cases one or more of the assumptions will be violated and additional lines of evidence from more sophisticated capture zone evaluation techniques will likely be appropriate to more rigorously account for site-specific conditions.

Capture Zone Width Calculation, One Extraction Well

Assumptions:
- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- no other sources of water introduced to aquifer due to extraction (e.g., from rivers or leakage from above or below)



$$x = \frac{-y}{\tan\left(\dfrac{2\pi Ti}{Q}y\right)} \quad - or - \quad y = \pm\left(\frac{Q}{2Ti}\right) - \left(\frac{Q}{2\pi Ti}\right)\tan^{-1}\left(\frac{y}{x}\right)$$

$$X_0 = -Q/2\pi Ti \quad ; \quad Y_{\max} = \pm Q/2Ti \quad ; \quad Y_{well} = \pm Q/4Ti$$

(must use consistent units, such as "ft" for distance and "day" for time)

Where:

Q	=	extraction rate
T	=	transmissivity, $K \cdot b$
K	=	hydraulic conductivity
b	=	saturated thickness
i	=	regional (i.e., pre-remedy-pumping) hydraulic gradient
X_0	=	distance from the well to the downgradient end of the capture zone along the central line of the flow direction
Y_{max}	=	maximum capture zone width from the central line of the plume
Y_{well}	=	capture zone width at the location of well from the central line of the plume

The above equation is used to calculate the outline of the capture zone. Solving the equation for $x = 0$ allows one to calculate the distance between the dividing streamlines at the line of wells ($2 \cdot Y_{well}$) and solving the equation for $x = \infty$ allows one to calculate the distance between the dividing streamlines far upstream from the wells ($2 \cdot Y_{max}$). One can also calculate the distance from the well to the stagnation point (X_0) that marks the downgradient end of the capture zone by solving for x at $y = 0$. For any value of y between 0 and Y_{max}, one can calculate the corresponding x value, allowing the outline of the capture zone to be calculated.

Figure 14. Capture zone width calculation, one extraction well.

The extraction rate "Q" in the estimated flow rate calculation incorporates a "factor" to account for other potential contributions of water to the extraction location, such as water from a nearby creek or water from an overlying or underlying unit. There is no scientific rule for assigning a value for the "factor", although common practice is to assign a value between 1.5 and 2.0. Note that the variability in hydraulic conductivity at many sites is as great or greater than the potential variability in this "factor". It is good practice to perform the estimated flow rate calculation with several different values assumed for the "factor" (e.g., 1.0, 1.5, and 2.0), to determine a range of values for the estimated flow rate required for capture. The extraction rate "Q" in the capture zone width calculation does not account for any such "factor".

These calculations require an estimate of the regional hydraulic gradient, without the influence of remedy pumping. Sometimes, the use of water level data obtained prior to the remedy is appropriate for determining the regional hydraulic gradient. However, regional hydraulic gradients often change with time. Accordingly, in some cases, the use of water level data obtained side gradient or even upgradient of the contaminated area, collected during the remedy, may be more appropriate than pre-remedy water level data for calculating regional hydraulic gradient.

Capture zone width calculations are most often performed assuming one extraction well. As illustrated in Figure 14, the capture zone width calculation for one extraction well provides an estimate of capture zone width near the extraction well (Y_{well}) and far upgradient of the extraction well (Y_{max}), and also provides the distance from the extraction well to the downgradient flow divide (X_0) that is often referred to as the "stagnation point".

For cases with more than one extraction well, the capture zone width is often estimated by assigning the total pumping rate at one centrally-located "equivalent well". Javandel and Tsang (1986) provided solutions for one-, two-, and three-well extraction systems for cases where there is too much drawdown if all of the extraction is applied at one well. These multi-well solutions assume the extraction wells are located along a line perpendicular to the regional flow direction, and also assume that the total pumping rate is divided equally among the extraction wells. Their solution provides the appropriate spacing for such wells. However, the capture zone width far upgradient of the pumping wells (Y_{max}) will be nearly identical to the case with all of the pumping assigned to one extraction well located in the center. Note that the assumptions for this multi-well calculation are not met in many field situations. Grubb (1993) provides a solution for a capture zone in an unconfined aquifer that can be utilized for multi-well calculations.

Although the calculations associated with these simple horizontal capture zone analyses are quite easy, deciding on the actual values to use for the calculations is not straightforward when the parameters (e.g., hydraulic conductivity, aquifer thickness, hydraulic gradient) are not uniform. Performing the calculations for reasonable ranges of parameter values can provide upper and lower bounds on the results.

The items highlighted in Exhibit 5 should be addressed when using these techniques. If answers to any of the questions in Exhibit 5 are "yes", then assumptions behind these calculations are violated and other lines of evidence regarding capture should be given higher priority.

It should be stressed that these simple horizontal capture zone calculations do not pertain in any manner to vertical capture.

Exhibit 5

Questions to Ask When Performing Simple Horizontal Capture Analyses (Step 4)

- Is there significant heterogeneity at this site, such as a wide range of hydraulic conductivity due to a buried paleochannel?
- Are there any other contributions of water to the extraction wells (e.g., leakage from a river, leakage from other stratigraphic units, clean water extracted from outside the plume)?
- Do transient conditions and/or off-site stresses exist, such as seasonal pumping at off-site production wells?

If any answers are "yes", the assumptions associated with these methods are violated, and additional lines of evidence should be examined.

Modeling (Analytical or Numerical) to Simulate Heads In Conjunction with Particle Tracking

Different types of simulation models, ranging from analytical to numerical, can be applied to calculate hydraulic heads and subsequently evaluate capture zones based on particle tracking. For instance, the analytical-based code CAPZONE (Ohio State University) can be used to analytically construct ground-water flow models of two-dimensional flow systems with isotropic and homogeneous confined, leaky-confined, or unconfined flow conditions, using either the Theis equation or the Hantush-Jacob equation. Particle tracking software (e.g., GWPATH by the Illinois State Water Survey) can then utilize the simulated flow field to draw capture zones. WhAEM^{2000} (U.S. EPA) is another analytical-based code that can be used for capture zone delineation. Numerical simulation codes such as MODFLOW (U.S. Geological Survey) allow for simulation of more complex systems (three dimensional geometry including aquifer heterogeneity and complex boundary conditions). Particle tracking codes (e.g., MODPATH by the U.S. Geological Survey) can then utilize the simulated flow field to draw capture zones. Please note that many codes are available for these types of applications, and the codes named herein are only mentioned as examples.

A general reference for ground-water modeling and particle tracking is Anderson and Woessner (1992). Ground water models should be calibrated to reasonably match field-measured heads and flow patterns. Calibration is accomplished by varying parameter values, boundary conditions, and stresses until an acceptable match with field-measured values is achieved.

Particle tracking based on simulation of heads can provide a precise delineation of both horizontal and vertical hydraulic capture (not accounting for dispersion). Precision, however, should not be confused with accuracy. The capture zone indicated by the particle tracking is only as accurate as the underlying head predictions from the simulation model, which are subject to many types of uncertainty (e.g., parameter values, boundary conditions). If the model inputs do not reasonably represent actual conditions, there is potential for “garbage in – garbage out”.

Ideally, the calibrated numerical model should subsequently be “verified” by simulating drawdown responses to different pumping conditions, and comparing those predicted responses to field measurements. This instills confidence that the model provides a reasonable representation of the physical system.

Another way to “verify” the numerical model is to run forward particle tracking to show that particles released at the location of the contaminant source reasonably account for the observed plume dimensions, and that the downgradient plume extent is consistent with the amount of elapsed time since contaminants were first introduced into the ground water. However, there are factors in addition to the prediction of the flow system (including contaminant source locations and timing, dispersion, and adsorption) that complicate such evaluations.

Tracking particles in reverse from initial locations around the extraction wells, to define the capture zone, is a commonly used approach. However, it can lead to erroneous interpretations in two and three dimensions. The apparent area of capture is highly controlled by the number of particles released, and the specific locations (horizontal and vertical) where particles are released. For instance, if particles are started at only one vertical location (e.g., the middle of the well screen) and tracked backwards, the results may indicate that all water captured by the well comes from the aquifer screened by the well, and may not show contributions to the well from water that may originate from aquifers above and/or below.

Another approach is to track particles backward from locations beyond the capture zone, to create a “shadow” plot of particles that escape the capture zone (the blank area represents the capture zone).

However, this method does not indicate the capture zone of each individual extraction well if there is more than one extraction well.

Tracking particles forward in space and time from a large variety of starting points (horizontally and vertically), and determining which of those particles reach each extraction location (i.e, wells or drains), is generally a better way to assess the three-dimensional capture zone. The initial particle locations can be plotted, using different symbols or colors to indicate the specific extraction location where each particle is ultimately captured. In this manner, the capture zone of each individual extraction location can be effectively illustrated. Producing multiple maps of this type, where each map illustrates particles starting at a different vertical elevation, is an effective approach for illustrating the vertical capture zone of each extraction location.

It is important to simulate pumping rates actually achieved with the P&T system, which in some cases differ substantially from design values. It is not appropriate to simulate the maximum pumping rate if that rate is not sustained in a continuous manner. In general, simulating the average pumping rate or a range of pumping rates is more appropriate for evaluating current capture zones than simulating the maximum extraction rate, except as a screening exercise.

It is also important to assess if the options selected for particle tracking, such as alternatives for removing particles, are biasing the interpretation of capture. For instance, the particle tracking code may allow the option of removing particles at “weak sinks” or allowing particles to pass through “weak sinks”. A “weak sink” is a model grid cell where some water is removed from the model, but where some water also flows into one or more adjacent model cells. This could occur if an extraction well is located in a relatively large grid cell and pumps relatively little water. The option selected by the user may greatly influence the resulting interpretation of capture. One approach is to evaluate capture using both options, and determine if the resulting interpretation is greatly influenced by the option selected. If so, both results can be reported or finer model grid spacing can be considered.

In addition to providing a basis for particle tracking, ground-water modeling can bring a higher level of understanding regarding the hydrogeology and contaminant transport at a site. Although ground-water model results are subject to uncertainty, and ground-water modeling is not warranted at many simple sites, EPA encourages the use of ground-water modeling at more complex sites as a tool for evaluating and improving the site conceptual model, predicting capture zones, and evaluating alternate remediation scenarios. However, actual field monitoring must be carried out in order to provide information necessary to evaluate model predictions. Capture zone effectiveness is ultimately determined by field monitoring that typically includes some combination of hydraulic head measurement and ground-water sampling and analysis, in conjunction with field confirmation of remedy pumping rates.

Step 5: Evaluate Concentration Trends

Contaminant concentrations can be monitored at two types of locations downgradient of the Target Capture Zone in an attempt to interpret capture (Figure 15):

- *sentinel wells* are located downgradient of the Target Capture Zone and are not currently impacted above background concentrations

- *downgradient performance monitoring wells* are located downgradient of the Target Capture Zone and are currently impacted above background concentrations

For sentinel wells, contaminant concentrations should remain at background levels over time if capture

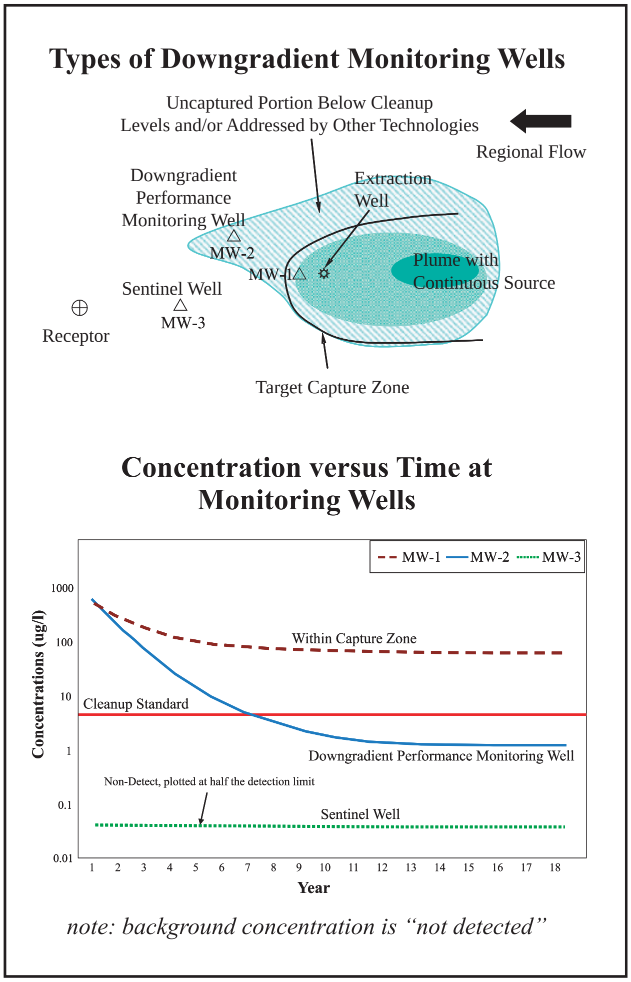


Figure 15. Types of downgradient monitoring wells.

is successful. For downgradient performance monitoring wells, contaminant concentrations should decline to background levels (or below cleanup levels) over time if capture is successful.

The term "downgradient performance monitoring well" is used herein to describe a specific subset of "performance monitoring wells" that are located downgradient of the Target Capture Zone and are impacted by chemicals above background concentrations. Other performance monitoring wells might be located within the Target Capture Zone, and might monitor hydraulic performance and/or concentration trends. A good understanding of contaminant release history and plume dynamics is needed to successfully position sentinel wells and "downgradient performance monitoring wells".

A primary issue complicating the use of concentration trends for evaluating capture is illustrated in Figure 15, which presents concentration versus time for the three monitoring well locations (MW-1 to MW-3) shown in the top portion of Figure 15.

This example pertains to a case with a continuing source of dissolved contamination. Concentrations at monitoring well MW-1 remain above background over time, because the monitoring well is actually within the capture zone (i.e., not downgradient of the Target Capture Zone), and therefore continues to be impacted by contaminated water from the continuing upgradient source. However, since the actual extent of the capture zone is not generally known, the concentration trend at MW-1 could be erroneously interpreted as failed capture (because concentrations downgradient of the extraction well remain above background).

Interpretation of capture based on concentration trends at monitoring wells located downgradient of the Target Capture Zone is complicated by several other factors:

- there may be limited concentration data since monitoring ground-water concentrations is far more expensive than monitoring water levels

- interpretations of concentration data related to capture may take years because ground-water flow velocities (and associated concentration changes) are generally quite slow

- for sites with multiple hydrogeologic units that are impacted or may become impacted, it is necessary to monitor wells in multiple hydrogeological units

- multiple releases of contaminants can result in multiple pulses in monitoring well concentration data, which means that decreasing concentrations may be misleading if a second pulse has not yet arrived

In Figure 15, concentrations do not fall below cleanup standards at the downgradient performance monitoring well (MW-2) until nearly eight years of monitoring have been completed. This is likely to be an unacceptably long period of time for use as the sole indication of capture, highlighting the need for other lines of evidence, such as those that measure hydraulic performance, to be used in conjunction with this line of evidence.

Although these issues complicate interpretation of capture from concentration trends, the concentration trends at these downgradient performance monitoring wells over time may ultimately provide the most solid and compelling line of evidence that successful capture has actually been achieved. Therefore, both hydraulic monitoring and chemical monitoring should usually be components of capture zone evaluations. Estimates of capture performance based on hydraulic data allow relatively rapid assessments of system performance that complement the more direct but longer term assessments provided by monitoring of ground-water chemistry.

Such chemical data may also be used to assess consistency with the site conceptual model and/or with other lines of evidence regarding interpretation of capture. In many cases, ambiguity associated with the interpretation of such concentration data will indicate data gaps, which in turn may suggest a need to collect additional field data to meet the data quality objectives of the capture zone evaluation.

Step 6: Interpret Actual Capture And Compare to Target Capture Zone(s)

Once multiple lines of evidence regarding capture have been evaluated, actual capture achieved by the extraction wells should be interpreted, and the items in Exhibit 6 should be addressed. To avoid bias, the actual capture should be interpreted independent of the Target Capture Zone (i.e., they should be compared after the actual capture zone is interpreted).

Exhibit 6

Items to Address after
Actual Capture is Interpreted (Step 6)

- Compare the interpreted capture zone to the Target Capture Zone

  Does the current system achieve remedy objectives with respect to plume capture, both horizontally and vertically?

- Assess uncertainties in the interpretation of the actual capture zone

  Are alternate interpretations possible that would change the conclusions as to whether or not sufficient capture is achieved?

- Assess the need for additional characterization and/or monitoring

  Is there a need for additional plume delineation or additional piezometer locations to determine convincingly whether or not actual capture is sufficient?

- Evaluate the need to reduce or increase extraction rates

  Should extraction rates, number of extraction wells, and/or locations be modified based on the results of the capture zone analysis?

Capture zone analysis should be an iterative process that includes the following:

- evaluate capture based on existing data
- identify any data gaps that create uncertainty in the conclusions of the capture zone analysis
- fill any data gaps that are identified (e.g., add new piezometers), and re-evaluate capture
- continue monitoring capture over time
- if capture is ever determined to not be sufficient, optimize the extraction system until capture is sufficient
- if capture is determined to be sufficient, continue routine monitoring and consider the potential to optimize extraction locations and/or rates to reduce cost

The iterative process described above is illustrated in Exhibit 7. Increasing the pumping rates may add confidence in the analysis of capture, but may also increase the cost of treating and discharging the water and/or potentially cause other negative impacts (e.g., dewatering well screens or wetlands).

Exhibit 7

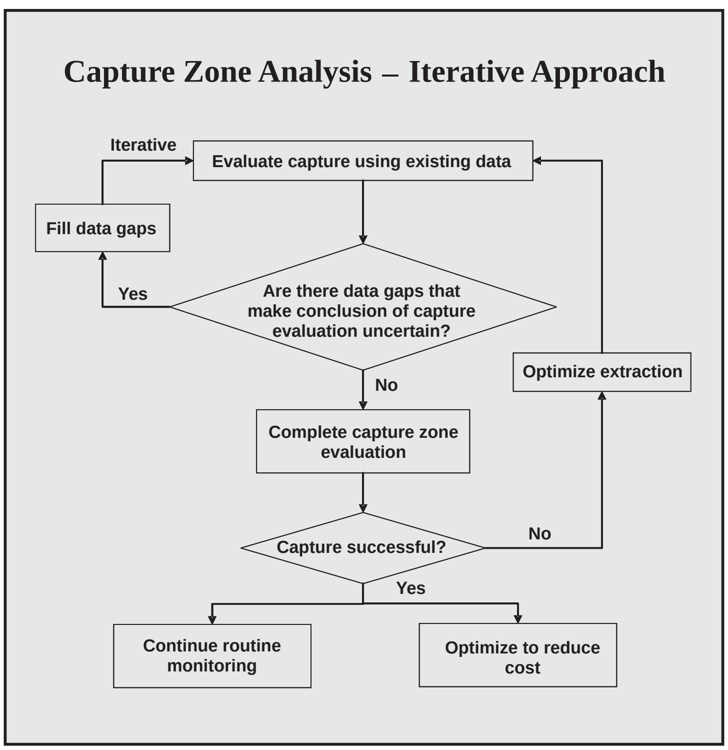


Exhibit 8 presents one possible format for summarizing the results of a capture zone evaluation. It is organized in a manner that provides the conclusions from different lines of evidence regarding capture, and then presents overall conclusions regarding the adequacy of capture, uncertainties and data gaps, and recommendations for future action. In most cases, the required level of detail cannot be presented in one simple table such as Exhibit 8, and will actually be included in chapters or appendices of a report.

Exhibit 9 is an example of a similar format for summarizing capture zone evaluations with two cases: one where capture is likely successful and one where capture is not convincingly demonstrated.

Exhibit 8

Possible Format for Presenting Results of a Capture Zone Evaluation

Line of Evidence	Is Capture Sufficient?	Comments
<u>Water Levels</u> • Potentiometric surface maps • Vertical head difference maps • Water level pairs		
<u>Calculations</u> • Estimated flow rate calculations • Capture zone width calculations • Ground-water flow modeling with particle tracking		
<u>Concentration Trends</u> • Sentinel wells • Downgradient performance monitoring wells		
<u>Overall Conclusion</u> • Is capture sufficient, based on “converging lines of evidence”? • Key uncertainties/data gaps • Recommendations to collect additional data, install new monitoring wells, change current extraction rates, change number/location of extraction wells, etc.		

Exhibit 9

Examples of Summaries for Systematic Capture Zone Evaluations

Example Where Capture Appears Successful

Step 1: Review site data, site conceptual model, remedy objectives	Completed, all determined to be up-to-date and adequate
Step 2: Define “Target Capture Zone(s)”	Updated based on revised plume map, illustrated on maps
Step 3: Water level maps	Adequate monitoring well network exists to determine capture; water levels indicate capture zone larger than the Target Capture Zone, piezometers are available near each extraction well for accurate water levels
Step 3: Water level pairs	Inward flow at all pairs along property boundary, and vertical water level differences indicate hydraulic control
Step 4: Simple horizontal capture zone analyses	Estimated flow rate calculation suggests 50-100 gpm should be sufficient, system currently at 100 gpm
Step 4: Particle tracking	Model calibration updated based on actual pumping rates and drawdowns, particle tracks indicate successful horizontal and vertical capture
Step 5: Concentration trends	Not relied upon for short term, concentrations do not increase at sentinel wells in long term
Step 6: Interpret actual capture and compare to Target Capture Zone	Actual capture zone is interpreted to be larger than the Target Capture Zone, all lines of evidence support that conclusion, some reduction in pumping rates/locations might be considered

Example With Many “Red Flags” - No Confidence That Capture is Successful

Step 1: Review site data, site conceptual model, remedy objectives	Last plume delineation 5 years ago, unclear if remedy objective is “cleanup” or containment
Step 2: Define “Target Capture Zone(s)”	Not clearly defined, objective is simply “hydraulic containment”
Step 3: Water level maps	Inadequate monitoring well network exists to determine capture, water levels indicate a “large” capture zone, however, water levels are used at extraction wells with no correction for well inefficiencies and losses (no piezometers near extraction wells)
Step 3: Water level pairs	Vertical water level differences are not evaluated
Step 4: Simple horizontal capture zone analyses	Done during system design, estimated flow rate calculation indicated 50-100 gpm would be required, current pumping rate is 40 gpm
Step 4: Particle tracking	Not performed, no ground-water model being utilized
Step 5: Concentration trends	Evaluated but with inconclusive results
Step 6: Interpret actual capture and compare to Target Capture Zone	Not even possible since Target Capture Zone is not clearly defined, conclusion of capture zone analysis should be that there is a need to adequately address Steps 1 to 5, so that success of capture can be meaningfully evaluated

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C. SUMMARY

Capture zone analysis is the process of evaluating field observations of hydraulic heads and ground-water chemistry to interpret the actual capture zone, and then comparing the interpreted capture zone to a “Target Capture Zone” to determine if capture is sufficient. This document presents a systematic approach to evaluating capture zones at P&T sites.

Six steps are suggested for a systematic capture zone evaluation:

Step 1: Review site data, site conceptual model, and remedy objectives

Step 2: Define site-specific Target Capture Zone(s)

Step 3: Interpret water levels

- *potentiometric surface maps (horizontal) and water level difference maps (vertical)*
- *water level pairs (gradient control points)*

Step 4: Perform calculations

- *estimated flow rate calculation*
- *capture zone width calculation (can include drawdown calculation)*
- *modeling (analytical or numerical) to simulate water levels, in conjunction with particle tracking and/or transport modeling*

Step 5: Evaluate concentration trends

Step 6: Interpret actual capture based on steps 1-5, compare to Target Capture Zone(s), assess uncertainties and data gaps

Specific techniques to assess the extent of capture achieved by the extraction wells are applied in Steps 3 to 5. Each of these techniques is subject to limitations, and in most cases no single line of evidence will conclusively differentiate between successful and failed capture. Therefore, developing “converging lines of evidence”, by applying multiple techniques to evaluate capture, increases confidence in the conclusions of the capture zone analysis.

The systematic approach advocated here is iterative in that it is advised that the practitioner obtain additional field information to address data gaps and ambiguities if present. Along each step of the process, the practitioner should evaluate the completeness of the data set and how to address uncertainty.

This document is intended to be used as a companion document to *Methods for Monitoring Pump-and-Treat Performance* (U.S. EPA, 1994, link provided in “References” section) when evaluating capture zones. This document is intended to provide more detail regarding capture zone analysis and includes more complex examples than are discussed in that previous document. This document is not intended to be a comprehensive reference for each topic presented herein nor is it a “how to” guide. However, a table provided at the beginning of the “References” section helps guide the reader to sources of information (cited within this document) according to specific topics.

Some of the important "big-picture" considerations when performing a capture zone evaluation include the following:

- there should be a clearly stated remedy objective based on a site conceptual model, and an associated three-dimensional "Target Capture Zone" that is clearly defined both horizontally and vertically

- the evaluation should utilize as many "converging lines of evidence" as practicable (i.e., use of multiple techniques to evaluate capture)

- the success of capture (relative to the Target Capture Zone) should be summarized in a format that conveys the results of the different lines of evidence, identifies data gaps, and provides recommendations (Exhibit 8 is an example of one such format)

- many of the components of a capture zone evaluation require hydrogeologic insight and expertise, and practitioners should use the assistance of support personnel if they lack that expertise

The appropriate frequency for capture zone evaluations is site-specific. Factors that should be considered include changes in remedy pumping rates over time (and the associated time for the ground-water levels to stabilize), the temporal nature of stresses (on-site and off-site), and the travel-time of contaminants to potential receptors. Capture zone analysis should be considered during system design, and should be performed throughout the first year of system operation and on a routine basis thereafter as part of O&M. One or more capture zone evaluations per year is appropriate at many sites due to changing conditions.

D. GLOSSARY AND SELECTED ABBREVIATIONS

Capture Zone. A three-dimensional region that contributes the ground water extracted by one or more wells or drains.

Converging Lines of Evidence. Applying multiple techniques to evaluate capture, such that confidence in the conclusions of the capture zone analysis is increased.

Downgradient Performance Monitoring Well. Monitoring well located downgradient of the Target Capture Zone and currently impacted by contaminants above background concentrations. This well can be used to monitor concentration reductions that are expected if capture is successful (note that the more general term "performance monitoring well" may pertain to wells in other locations, such as within the Target Capture Zone, that may monitor hydraulic performance and/or chemical performance).

Estimated Flow Rate Calculation. Used herein to refer to a calculation of ground-water flux that requires capture, based on plume width and a set of simplifying assumptions.

Gradient Control Points. See "water level pairs".

Gradient Vector Map. A map that uses arrows to illustrate the direction of ground-water flow, and optionally uses the length of the arrow to indicate the magnitude of the hydraulic gradient.

Head. Used interchangeably with "water level" in this document (see "Water Level").

Hydraulic Gradient. The change in head over a distance (the "magnitude") in the direction that represents the maximum rate of head decline ("the direction").

MNA (Monitored Natural Attenuation). Refers herein to remediation of contaminants, actively monitored, without use of an active remedy such as P&T.

Monitoring Well. Used herein to refer to a well which is used for measurement of water levels and contaminant concentrations.

O&M. Operations and maintenance, used herein to refer to activities associated with operating and maintaining a P&T system (does not refer to any specific period of time or regulatory status associated with the remedy).

P&T. Pump and treat, used herein to refer to remediation systems where ground water is extracted and treated and/or appropriately discharged

Particle Tracking. Tracing the movement of a particle of a conservative solute as it flows within the ground-water flow system, not influenced by hydrodynamic dispersion.

Piezometer. A well used to measure hydraulic water level in the subsurface, with a relatively short screen or slotted interval such that the water level represents the specific location within the aquifer. Used in this document to refer to a well which is used for measurement of water levels only (i.e., not for contaminant concentrations).

Preferential Pathway. Used herein to refer to a continuous zone where ground water flows faster relative to surrounding zones, due to aquifer heterogeneity.

Sentinel Well. Monitoring well located downgradient of the Target Capture Zone that is not currently impacted by contaminants above background concentrations.

Stagnation Point. Distance from the extraction well to the flow divide that indicates the downgradient extent of the capture zone (in the direction of uniform background flow).

Target Capture Zone. The three-dimensional zone of ground water that must be captured by the remedy extraction for the hydraulic containment portion of the remedy to be considered successful.

Water Level. Calcuated by subtracting depth to water from a datum with a surveyed elevation, such as the top of well casing.

Water Level Pairs. Pairs of water level elevations on either side of a boundary (horizontally or vertically) that are used to demonstrate the direction of flow relative to that boundary.

Well Inefficiency and Well Losses. Refers to the difference between the water level in the extraction well (lower) versus the water level in the aquifer immediately adjacent to the extraction well (higher) that may result from a variety of factors.

E. REFERENCES

Table 1 indicates the cited references in this document for specific topics.

Table 1. Topics Associated with Cited References

Topic	Cited Reference #
Previous EPA guidance	15, 16, 17, 18
Flow nets	3, 8, 9
Water level maps/contouring	6, 14, 19
Well losses	2, 4, 5, 7, 11, 12
Capture zone width calculation	10, 13
Particle tracking based on numerical modeling	1

The "Reference #" pertains to the number of the reference in the following "Cited References" section. This is not intended as a comprehensive set of references for each topic, and some of the references cited for one topic may also be valuable for other topics. This table is only intended to link the cited references to the topics they were cited for in this document.

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18. U.S. EPA, 2002b. Elements of Effective Management of Operating P&T Systems, EPA 542-R-02-009.

19. Wilson, D.A. and D.E. Dougherty, 2002. Optimizing Pump and Treat Systems: Data Assimilation, Federal Remediation Technologies Roundtable Meeting, Arlington, VA, December 18, 2002 (http://www.frtr.gov/meetings2.htm)

Codes/Software Cited (as Examples)

These codes have been cited in this document:

CAPZONE (Ohio State University)
GWPATH (Illinois State Water Survey)
MODFLOW (U.S. Geological Survey)
MODPATH (U.S. Geological Survey)
SURFER (Golden Software)
WhAEM (U.S. EPA)

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

EPA Web Sites With Links to Modeling Software

Center for Subsurface Modeling Support (CSMoS): www.epa.gov/ada/csmos.html

Center for Exposure Assessment Modeling (CEAM): www.epa.gov/ceampubl/ceamhome.htm

Council for Regulatory Environmental Modeling (CREM): http://cfpub.epa.gov/crem/

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Varljen, M.D. and J.M. Shafer, 1991. Assessment of uncertainty in time-related capture zones using conditional simulation of hydraulic conductivity. *Ground Water*, vol. 29, no. 5, pp. 737-748.

Wilson, J.L., 1986. Induced infiltration in aquifers with ambient flow. *EOS* Transactions of the American Geophysical Union, vol. 67, p. 966.

APPENDIX A:

EXAMPLES FROM THREE HYPOTHETICAL SITES

INTRODUCTION TO APPENDIX A:
EXAMPLES FROM THREE HYPOTHETICAL SITES

To illustrate the systematic approach to capture zone analysis, and to highlight some of the details associated with specific techniques for evaluating capture, examples for three hypothetical sites were developed for this document. Each hypothetical site is represented by a numerical flow and transport model that is intended to portray "actual conditions" for operating P&T systems. Each example site has a different degree of complexity, to represent a variety of real world conditions. In addition, each example site highlights a specific issue related to capture zone analysis:

- Example A1: highlights complications of evaluating capture when significant vertical flow and vertical contaminant transport are present
- Example A2: highlights complications of evaluating horizontal capture when preferential flow pathways are present
- Example A3: highlights complications of evaluating capture when off-site stresses are present

For each example, at least one pumping scenario that achieves successful capture and one pumping scenario that does not achieve successful capture is presented.

The pumping scenarios for these examples should not be confused with pre-remedy design options. Instead, these scenarios are intended to represent different examples of operating P&T systems.

Example A1 is presented in the greatest detail, and is used to demonstrate the entire systematic process for capture zone evaluation. Example A2 and Example A3 are then used to illustrate specific aspects of capture zone analysis.

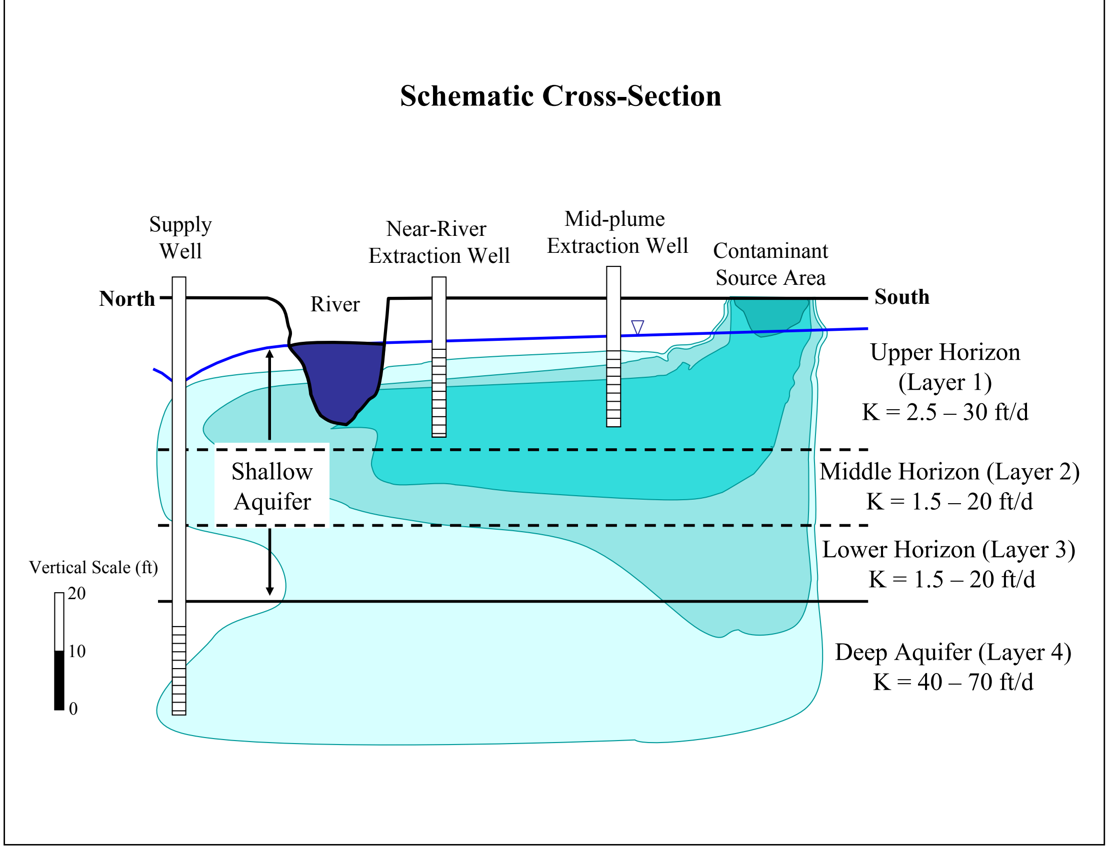
EXAMPLE A1

This example, for a hypothetical site, highlights complications of evaluating capture when significant vertical flow and vertical contaminant transport are present.

Example Setup

The stratigraphy of the site contains two heterogeneous aquifers: a shallow aquifer and a deep aquifer (Figure A1-1). These aquifers are differentiated based on geologic description, and there is no aquitard separating these aquifers. In general, the deep aquifer material has a higher hydraulic conductivity than the shallow aquifer material.

Figure A1-1



The shallow aquifer is further divided into three distinct horizons (upper, middle, lower) to better represent the following observations:

- there are partially penetrating wells
- only the upper horizon of the shallow aquifer is hydraulically connected to the river
- observed contaminant levels decrease with depth within the shallow aquifer

For ease of presentation, the subsequent discussion refers to “layers” as follows:

Layer 1: shallow aquifer, upper horizon
Layer 2: shallow aquifer, middle horizon
Layer 3: shallow aquifer, lower horizon
Layer 4: deep aquifer

Figure A1-2 indicates the actual hydraulic conductivity distribution of each layer in this hypothetical heterogeneous system. In reality, site managers would only have drilling logs, cores, slug test, or pumping test data at a limited number of locations, and maps similar to those in Figure A1-2 might be created from those data. Uncertainty in the hydraulic conductivity distributions is an important issue that should be considered and addressed, as it directly affects ground-water flow, velocity vectors, and capture zones.

The contaminant of concern is dissolved TCE. Figure A1-3 indicates the actual pre-remedy TCE concentrations in each layer. The ground-water standard for TCE at this site is 5 ppb. There is a continuing source of TCE (in the unsaturated zone) that has not yet been fully identified or delineated, and it is being investigated further with the hope that the continuing source can be remediated in the future.

Historically, dissolved TCE has discharged to the river from the south. In addition, there are two water supply wells screened in the deep aquifer across the river from the contaminant source (i.e., north of the river). These water supply wells have caused contaminated ground water to flow beneath the river, and these water supply wells are impacted by TCE. The wells continue to pump and have wellhead treatment.

The TCE concentrations decrease with depth, and the lowest concentrations of TCE are observed in the deep aquifer. For this hypothetical example, the distribution of TCE is known at all locations. In reality site managers would only have data at locations where monitoring wells exist, and maps similar to Figure A1-3 would be created based on those sparse data using interpolation and/or extrapolation.

Scenarios Illustrated

Three pumping scenarios are evaluated with respect to capture (Figure A1-4).

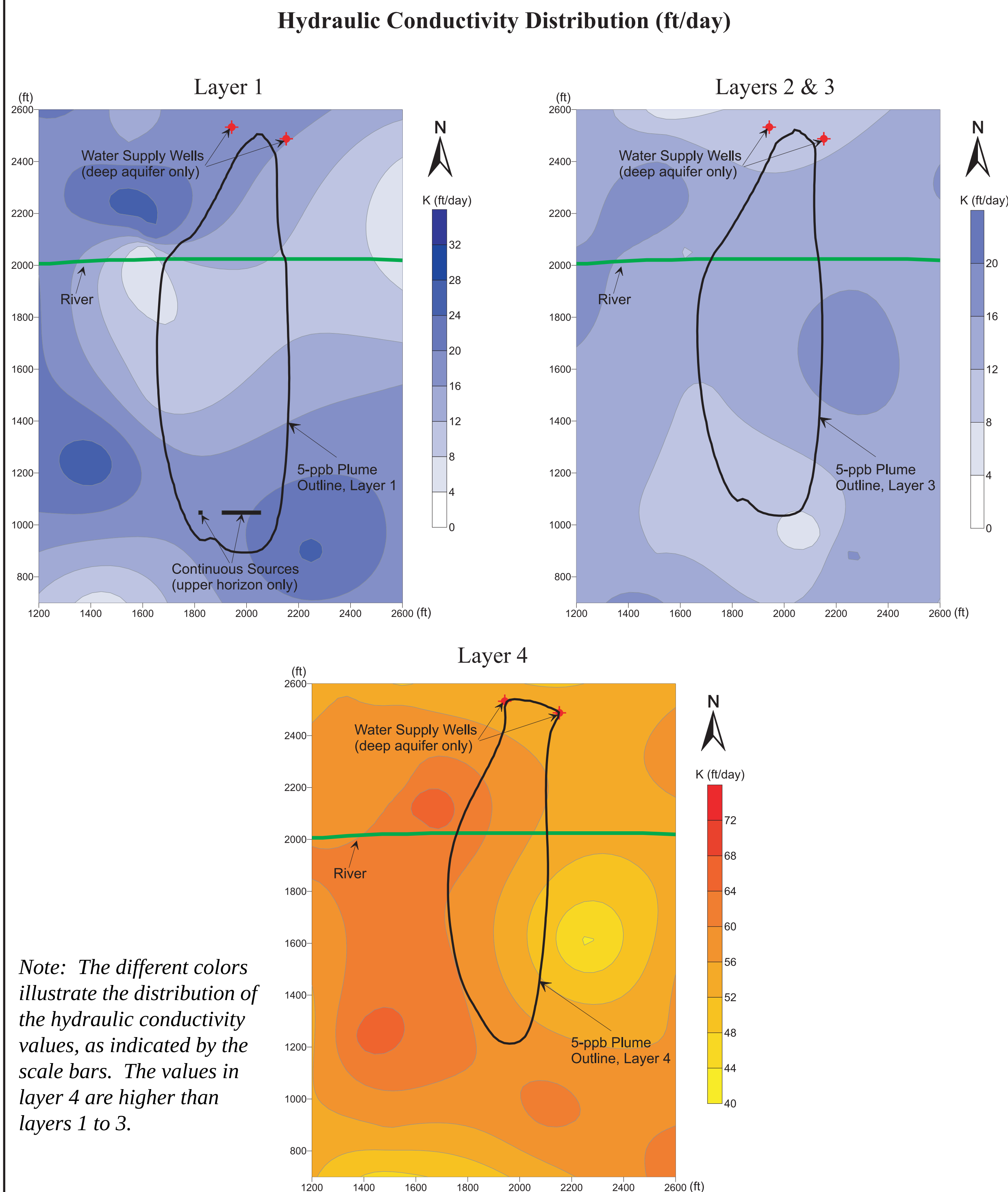
- Scenario 1 has three remedy pumping wells screened in the upper horizon of the shallow aquifer (Layer 1) near the river, with a total pumping rate of 22.5 gpm.

- Scenario 2 has five remedy pumping wells in the upper horizon of the shallow aquifer (Layer 1), with a total pumping rate of 44 gpm. Three of the five wells are located near the river, and the other two are mid-plume or source-area wells.

- Scenario 3 has nine remedy pumping wells in the upper horizon of the shallow aquifer (Layer 1), with a total pumping rate of 107 gpm. Five of the nine wells are located near the river, and the other four are mid-plume or source-area wells.

None of the scenarios for this example have remedy pumping in the deeper layers.

Figure A1-2



Note: The different colors illustrate the distribution of the hydraulic conductivity values, as indicated by the scale bars. The values in layer 4 are higher than layers 1 to 3.

Figure A1-3

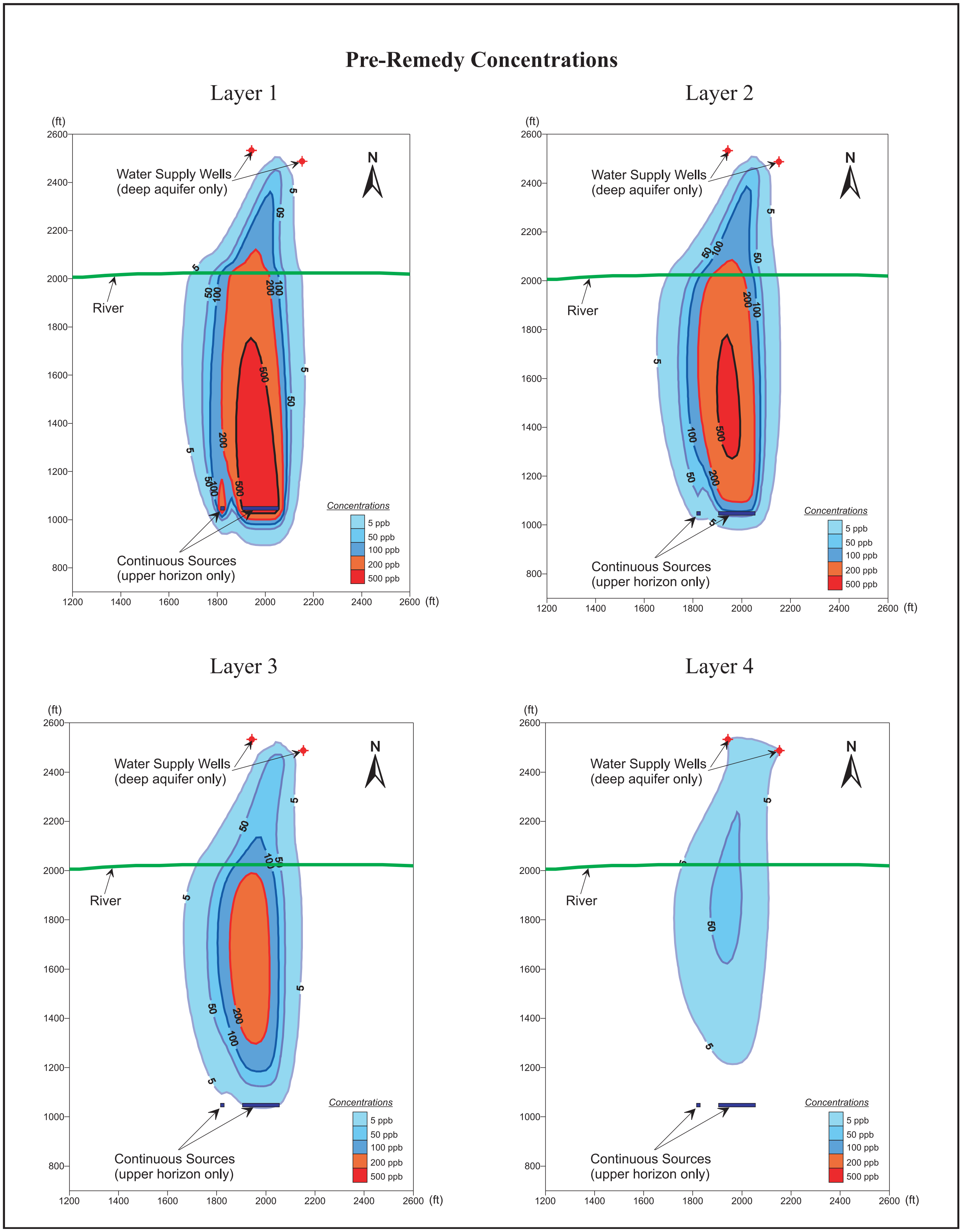
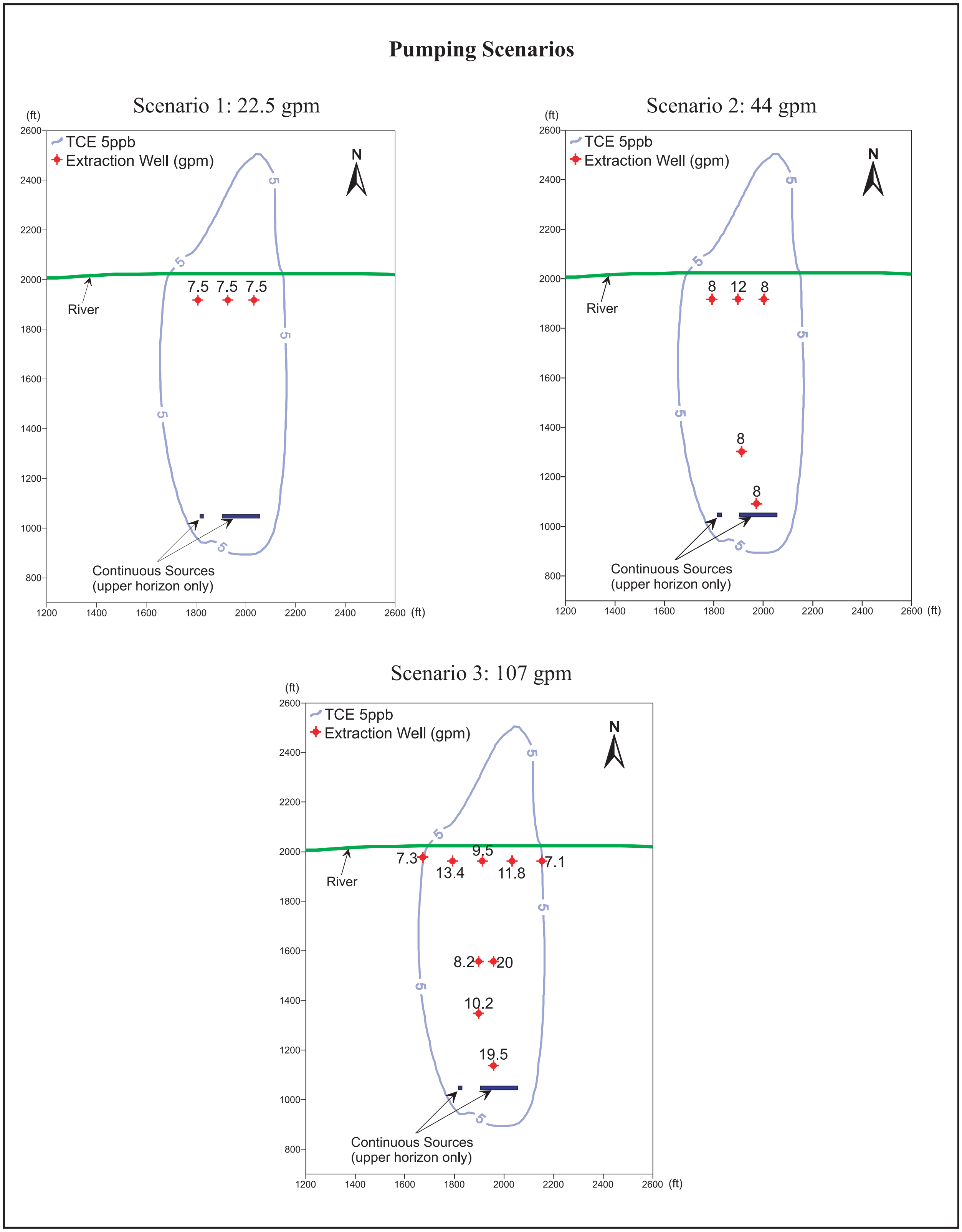

Pre-Remedy Concentrations
Layer 1
Layer 2
Layer 3
Layer 4
Water Supply Wells
(deep aquifer only)
River
Continuous Sources
(upper horizon only)
N
Concentrations
5 ppb
50 ppb
100 ppb
200 ppb
500 ppb
(ft)
1200
1400
1600
1800
2000
2200
2400
2600

Figure A1-4


Pumping Scenarios
Scenario 1: 22.5 gpm
TCE 5ppb
Extraction Well (gpm)
N
7.5 7.5 7.5
River
Continuous Sources
(upper horizon only)
(ft)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
1200 1400 1600 1800 2000 2200 2400 2600 (ft)
Scenario 2: 44 gpm
TCE 5ppb
Extraction Well (gpm)
N
8 12 8
8
8
River
Continuous Sources
(upper horizon only)
Scenario 3: 107 gpm
TCE 5ppb
Extraction Well (gpm)
N
7.3 13.4 9.5 11.8 7.1
8.2 20
10.2
19.5
River
Continuous Sources
(upper horizon only)

Step 1 - Review Site Data, Site Conceptual Model, and Remedy Objectives

- Is the plume delineated adequately in three dimensions?

  The plume is bounded by monitoring wells with concentrations below standards in each hydrostratigraphic unit, based on recent concentration data (for example, Figure A1-5 illustrates plume delineation in Layer 1). Thus, the plume delineation is considered adequate.

- Is there sufficient hydrogeologic information?

  Numerous well logs are available to evaluate stratigraphy. Slug test and pumping test data exist for multiple locations (Table A1-1). Pre-remediation water level maps are available for calculating regional gradients (Figure A1-5). Thus, the hydrogeologic information is considered sufficient.

- Is there a site conceptual model that adequately explains the contaminant source and constituents?

  Currently there exists a continuing source of contaminants to shallow ground water. Shallow ground water flows north to the river, and the water supply wells on the other side of the river cause some contaminated ground water to flow beneath the river to the supply wells.

- Is the objective of the remedy clearly stated?

  The remedy objective for this site is to prevent contaminants at concentrations above standards from discharging to the river, and to prevent contaminants at concentrations above standards from continuing to flow under the river towards the water supply wells.

Figure A1-5

Plume Delineation, Model Layer 1 | **Pre-Remedy Water Levels, Layer 1**

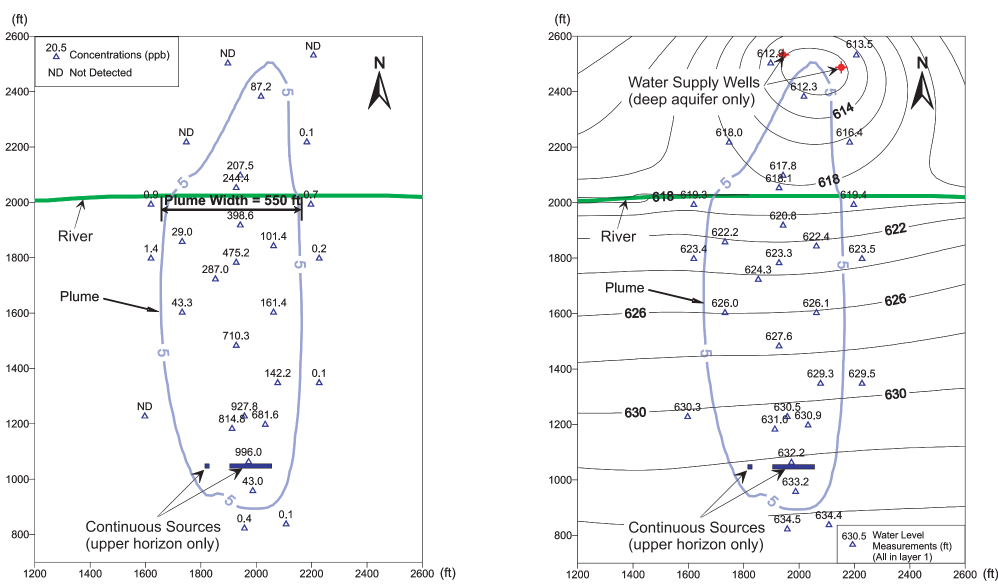


Table A1-1. Slug/Pumping Test Results

Layer	Test Type	K Range (ft/day)
Layer 1:		
MW-6s	slug	1.7 - 9
MW-9s	pumping	25 - 30
MW-15s	slug	7 - 110
MW-20s	slug	0.6 - 50
MW-31s	pumping	8 - 22
MW-33s	slug	90 - 130
EW-1	pumping	18 - 20
EW-2	pumping	15 - 30
EW-3	pumping	15 - 18
	representative value	15
	range from regional pumping test data	10-40
Layer 2:		
MW-6m	slug	12 - 60
MW-20m	slug	1.2 - 85
MW-31m	slug	7 - 75
	representative value	30
	range from regional pumping test data	15-30
Layer 3:		
MW-3m	slug	12 - 20
MW-12m	slug	70 - 115
MW-17m	pumping	20 - 30
MW-26m	slug	1.2 - 28
MW-37m	slug	0.7 - 12
	representative value	20
	range from regional pumping test data	10 - 35
Layer 4:		
MW-3d	slug	25 - 120
MW-12d	slug	50 - 560
MW-18d	pumping	50 - 80
MW-21d	slug	29 - 130
MW-28d	slug	50 - 620
MW-37d	pumping	40 - 70
	representative value	60
	range from regional pumping test data	20 - 100

Step 2 - Define Target Capture Zone(s)

As discussed in the main document, the Target Capture Zone can be defined based on: (1) complete hydraulic capture of the entire plume (horizontal and/or vertical); or (2) capture of a specific portion of the plume in conjunction with another remedial technology for the uncaptured portion. Two options for defining the Target Capture Zone at this site are presented below and are illustrated in Figure A1-6:

Option 1 (More Conservative)

- to prevent continuing discharge of TCE to the river, inward flow from the river to the aquifer (i.e., to the south) will be established over the width of the plume exceeding 5 ppb

- vertical hydraulic containment is required south of the river within the 5 ppb plume, by demonstrating upward flow to Layer 1 (where the continuing source is located) from underlying hydrogeologic units

Option 2 (Less Conservative)

- to prevent continuing discharge of TCE to the river, a flow divide will be established between the extraction wells and the river, over the width of the plume exceeding 5 ppb

- vertical hydraulic containment is not required south of the river as long as concentrations on the north side of the river decrease below 5 ppb over time as a result of the shallow extraction south of the river in conjunction with Monitored Natural Attenuation (MNA)

For the purpose of illustrating the process of capture zone analysis, the discussion below will consider both of these options for defining the Target Capture Zone. Note that the requirement for demonstrating horizontal capture is more conservative for Option 1 than for Option 2. The requirement for demonstrating vertical capture is also more conservative for Option 1. Other options for defining Target Capture Zone are possible, but are not presented herein.

Step 3 - Interpret Water Levels

Horizontal and/or vertical capture can be interpreted from water level maps that are constructed from measured water levels. In addition, flow directions can be analyzed from water level pairs (gradient control points) to aid in interpretation of capture. The discussion below illustrates some of the analyses that can be performed at this site based on water levels, for each of the three defined pumping scenarios, to evaluate the extent of capture.

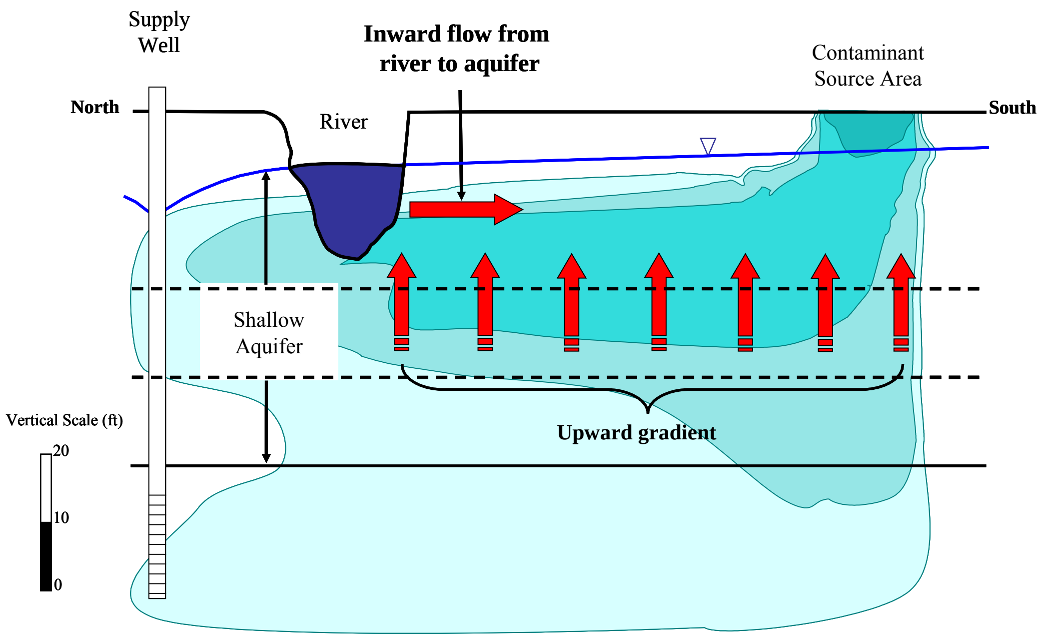
Water Level Maps: Horizontal Capture Analysis

The following figures present constructed water level maps for Layer 1 (the upper horizon of the shallow aquifer where the extraction wells are screened), for each of the three pumping scenarios defined for this example:

- Figure A1-7: Scenario 1 (22.5 gpm)
- Figure A1-8: Scenario 2 (44 gpm)
- Figure A1-9: Scenario 3 (107 gpm)

Figure A1-6

Target Capture Zone, Option 1 – More Conservative



Target Capture Zone, Option 2 – Less Conservative

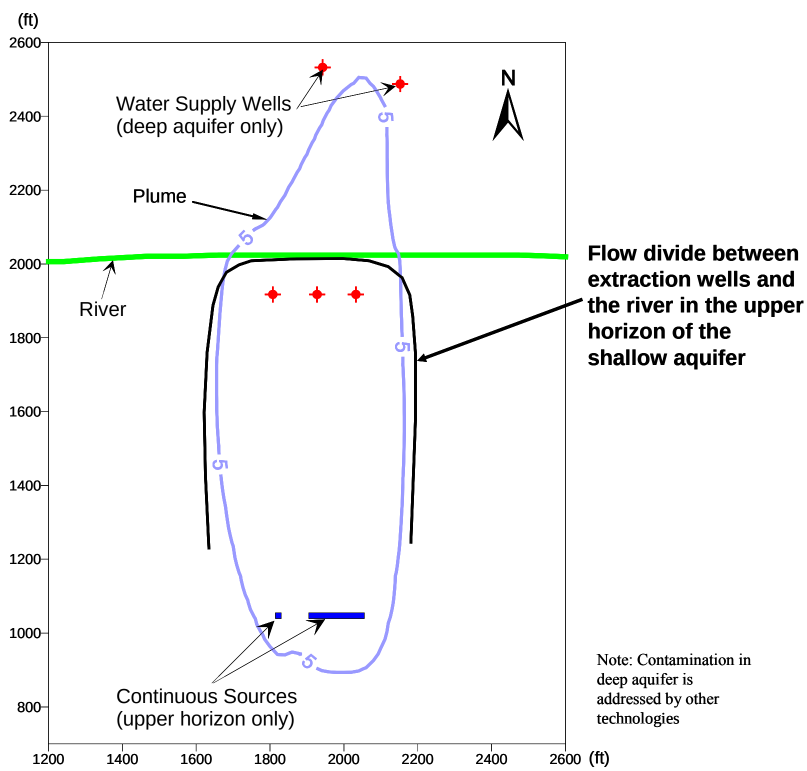


Figure A1-7

Horizontal Interpretation of Water Level Maps, Layer 1, Pumping Scenario 1 (22.5 gpm)

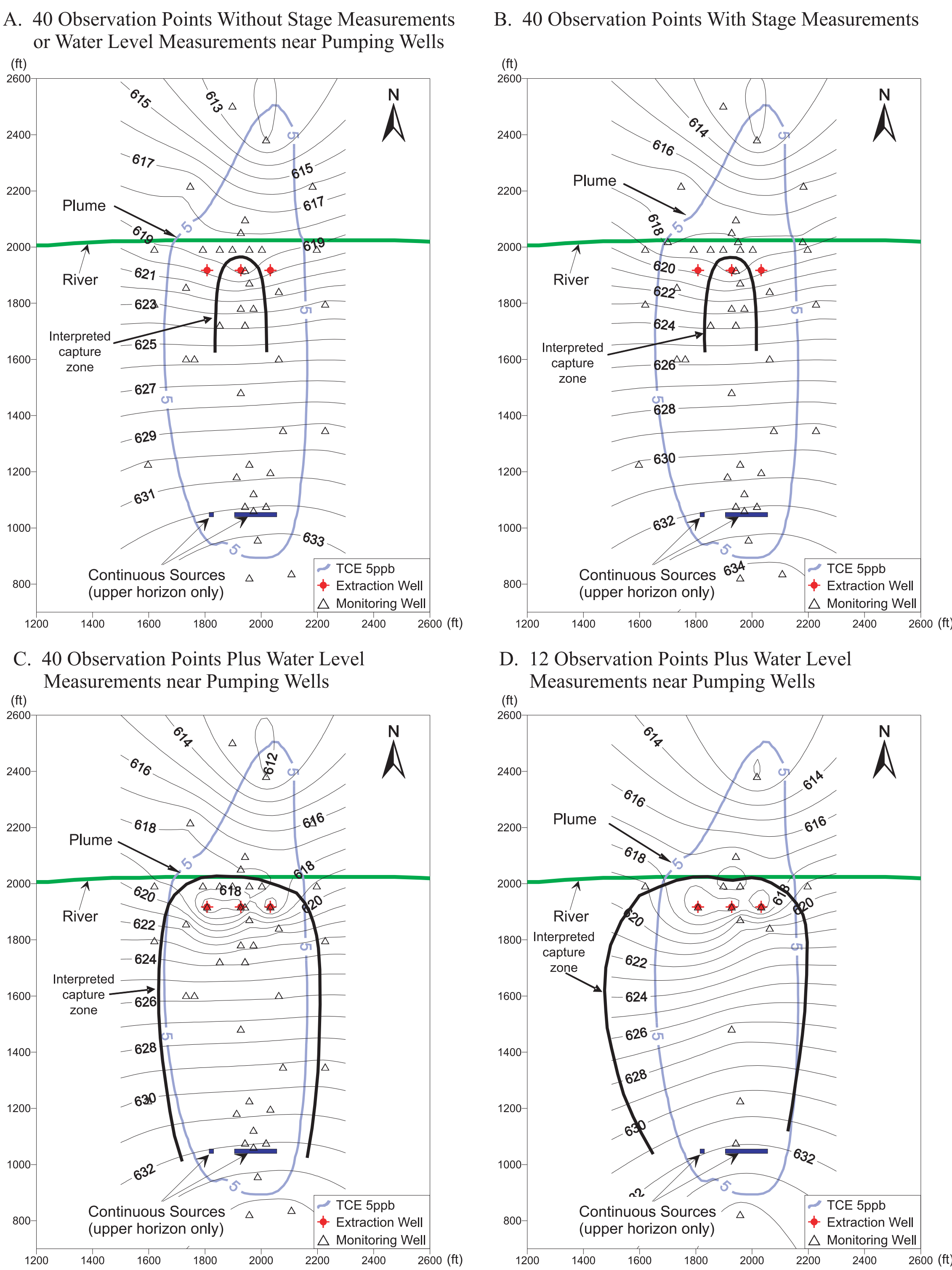


Figure A1-8

Horizontal Interpretation of Water Level Maps, Layer 1, Pumping Scenario 2 (44 gpm)

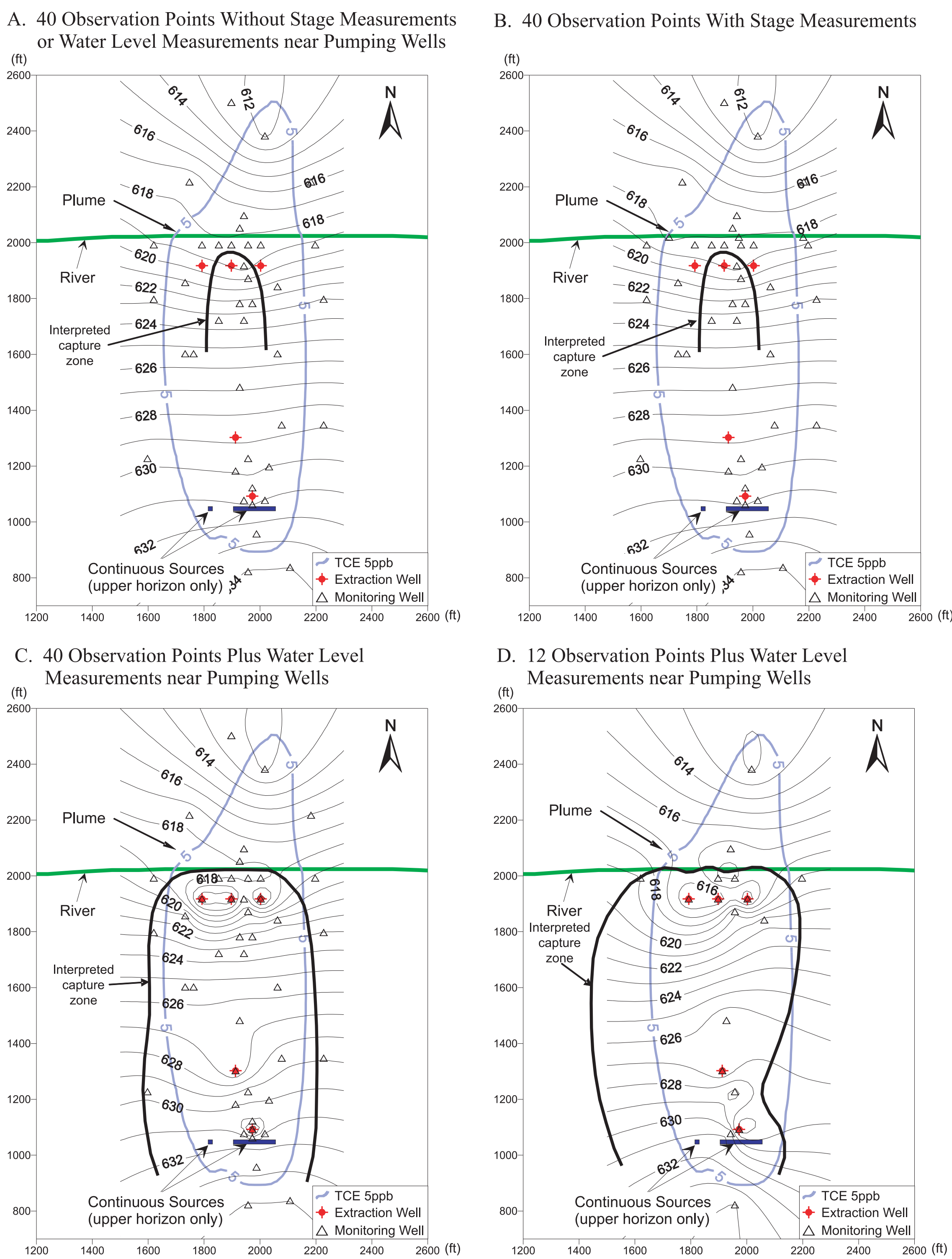
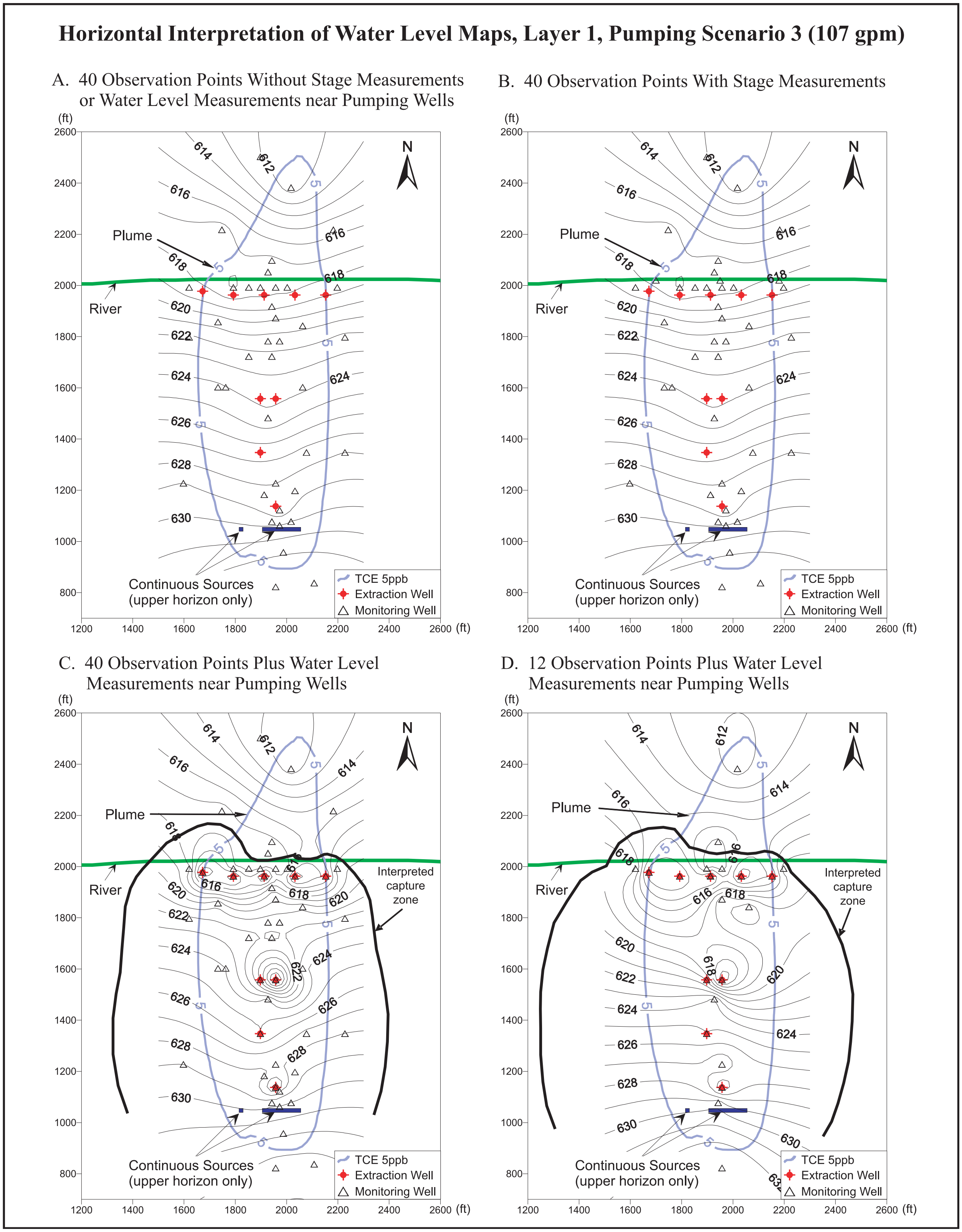


Figure A1-9



Horizontal Interpretation of Water Level Maps, Layer 1, Pumping Scenario 3 (107 gpm)
A. 40 Observation Points Without Stage Measurements or Water Level Measurements near Pumping Wells
B. 40 Observation Points With Stage Measurements
C. 40 Observation Points Plus Water Level Measurements near Pumping Wells
D. 12 Observation Points Plus Water Level Measurements near Pumping Wells
Plume
River
Continuous Sources (upper horizon only)
Interpreted capture zone
TCE 5ppb
Extraction Well
Monitoring Well
N
(ft)

In these figures several potential water level maps are presented for each pumping scenario, to compare the following situations:

- with/without water level measurements near the pumping wells
- larger/smaller amounts of water level data
- with/without river stage measurements

These different water level maps for Layer 1 illustrate how interpretations of horizontal capture can vary depending on the availability of water level measurements near the extraction wells:

- with a large number of water level measurements, but no water level measurements near the pumping wells (map "A" of Figures A1-7 to A1-9), horizontal capture is not clearly apparent and successful capture is not interpreted even for Scenario 3 (107 gpm)
- with the same number of water level measurements, plus water level measurements near the pumping wells (map "C" of Figures A1-7 to A1-9), horizontal capture is apparent and the extent of capture can be interpreted

Water levels at extraction wells are typically lower than water levels in the surrounding aquifer due to well inefficiency and well losses. For this reason, water levels measured at extraction wells should generally not be utilized to construct water level maps, because they potentially bias the interpretation of capture (to be more extensive than is actually achieved). However, Figures A1-7 to A1-9 illustrate that if no water level measurements are available near the extraction wells, interpretation of horizontal capture will likely be biased towards an interpretation of poor capture. To avoid this problem, EPA recommends installing a piezometer near each extraction well. However, if such piezometers do not exist, a possible approach is to estimate aquifer water levels at the extraction wells by correcting the measured water levels for well losses, until appropriately located piezometers are available. However, such calculations do not account for all components of well inefficiency, and locating piezometers near extraction wells is much preferred to correcting water levels in extraction wells based on calculated well losses.

For this site, the inclusion of river stage measurements in addition to the water level measurement is also illustrated (map "B" on Figures A1-7 to A1-9), for the situation without water level measurements near the pumping wells. These maps indicate that the addition of stage measurements at this site has little impact on the interpretation of horizontal capture. For this site, including river stage measurements is not as important as including water level measurements near the extraction wells. This is likely because of the availability of water level measurements at several locations between the extraction wells and the river at this example site. River stage measurements might impact the interpretation of capture more substantially if these water level data from measuring points near the river were not available.

For Layer 1 in Figures A1-7 to A1-9, a water level map and associated interpretation of horizontal capture are also provided for a case with many fewer water level measurements (map "D" on Figures A1-7 to A1-9), and where water level measurements near the extraction wells are available. With fewer water level measurements a larger zone of capture is interpreted. This illustrates that the number of available water level measurements will impact the interpretation of capture. In general, the accuracy of the interpreted capture extent will increase as the number of water level measurement locations increases. As discussed earlier, availability of water level measurement points located near and around the extraction wells are very important for accurately depicting capture zones from water level maps.

For Scenario 3, the interpreted capture zones with water levels near the extraction wells (maps “C” and “D” on Figure A1-9) indicate that the extraction wells south of the river are potentially capturing water from north of the river. This suggests that the pumping rate associated with Scenario 3 (107 gpm) may be more than is necessary to simply prevent water from discharging to the river from the south.

It is also observed that the capture zone widths on maps “C” and “D” of Figure A1-8 (total pumping of 44 gpm) are only slightly greater than the capture zone widths on maps “C” and “D” of Figure A1-7 (total pumping of 22.5 gpm), despite the fact that the pumping rate is nearly double. The capture zone width would be nearly double under very simplified hydrogeologic conditions, because the total extraction rate is nearly double. However, that simple relationship does not hold when the hydrogeology is complex, such as with this example, which includes a river that serves as a potential source of water to the extraction wells and/or underlying strata that also provide water to the partially-penetrating extraction wells.

In summary, a variety of potential water level maps can be constructed depending on the data available, leading to a variety of potential interpretations regarding the extent of horizontal capture. For each of the three pumping scenarios (Figures A1-7 to A1-9), at least one potential water level map is presented that suggests potential for “failed” horizontal capture in Layer 1, and at least one potential water level map is presented that suggests “successful” horizontal capture in Layer 1.

The most important consideration appears to be the existence of water level measurements near each extraction well (or an estimate of water levels in the aquifer near each extraction well). Without such measurements, horizontal capture is biased towards interpretation of poor capture. However, the number of available data points away from the extraction wells also impacts the interpreted extent of horizontal capture. The more water level points that are available, the more accurate the interpretation of capture.

Constructed water level maps for Layer 3 (lower horizon of the shallow aquifer) and Layer 4 (deep aquifer) are presented on the following figures:

- Figure A1-10: Scenario 1 (22.5 gpm)
- Figure A1-11: Scenario 2 (44 gpm)
- Figure A1-12: Scenario 3 (107 gpm)

The water level maps for Layers 3 and 4 do not indicate any discernable capture from the extraction wells that are screened in Layer 1, for any of the pumping scenarios. That is because no water level measurements or estimates for these depths are available in the vicinity of the extraction wells.

If piezometers screening these deeper horizons were installed in the vicinity of the extraction wells, some horizontal capture in these layers would likely be apparent, even though the extraction wells are screened only in the upper horizon of the shallow aquifer. This again illustrates the importance of having water level measurements near extraction wells when interpreting horizontal capture using water level maps. For a multi-aquifer or multi-layer problem, multi-level monitoring wells (or well clusters) near the extraction wells are recommended.

Figure A1-10

Horizontal Interpretation of Water Level Maps, Layers 3-4, Pumping Scenario 1 (22.5 gpm)

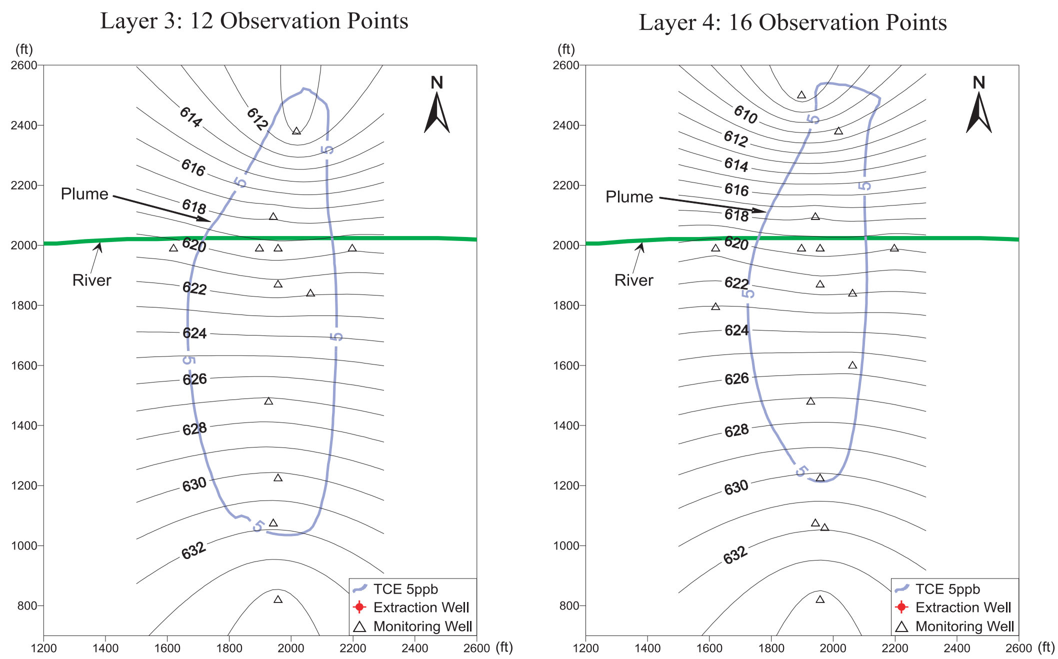


Figure A1-11

Horizontal Interpretation of Water Level Maps, Layers 3-4, Pumping Scenario 2 (44 gpm)

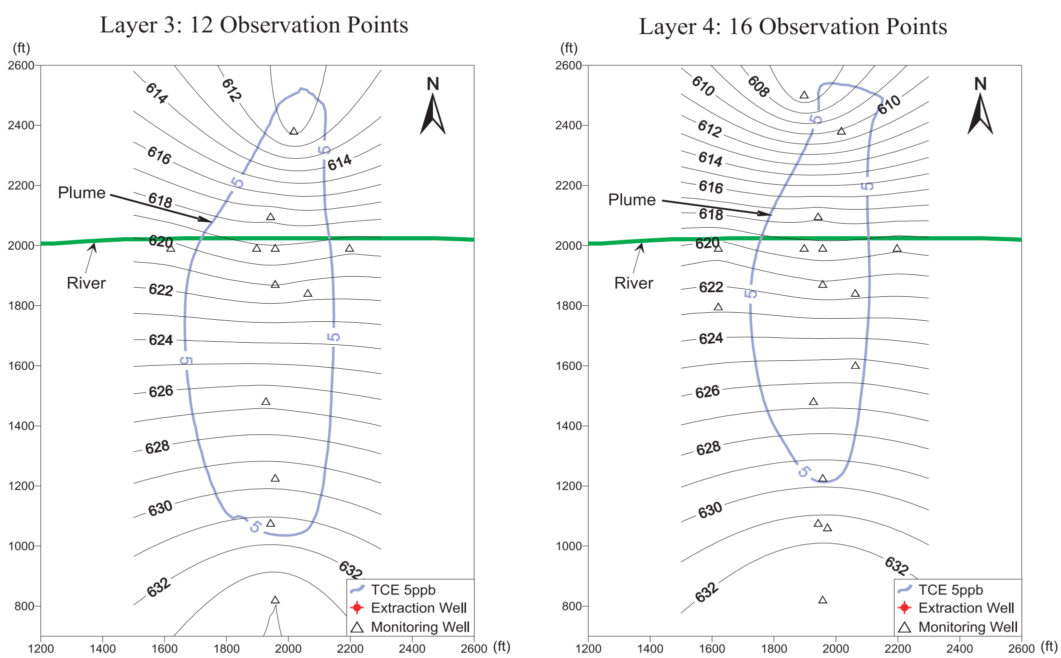
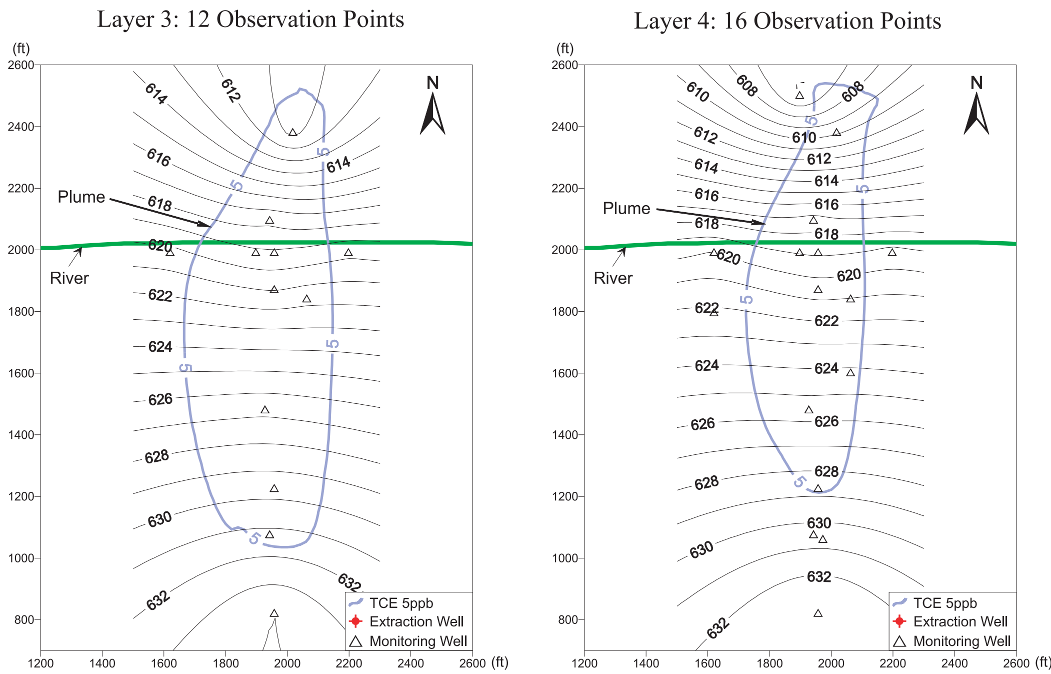


Figure A1-12

Horizontal Interpretation of Water Level Maps, Layers 3-4, Pumping Scenario 3 (107 gpm)



Water Level Maps: Vertical Capture Analysis

This site has a continuous source of TCE in the upper horizon of the shallow aquifer (Layer 1). By evaluating head difference between the upper and lower horizons of the shallow aquifer (Layer 1 versus Layers 2 and 3), the potential for downward flow from the contaminant source area can be evaluated. If vertical gradients are upward at all locations, then dissolved contaminants will not be transported by advection from the source area to underlying horizons. Note that at DNAPL sites there is a potential for DNAPL to migrate downward even in the presence of upward hydraulic gradients. However, at this site TCE concentrations at depth are too low relative to the solubility limit to be indicative of DNAPL at depth.

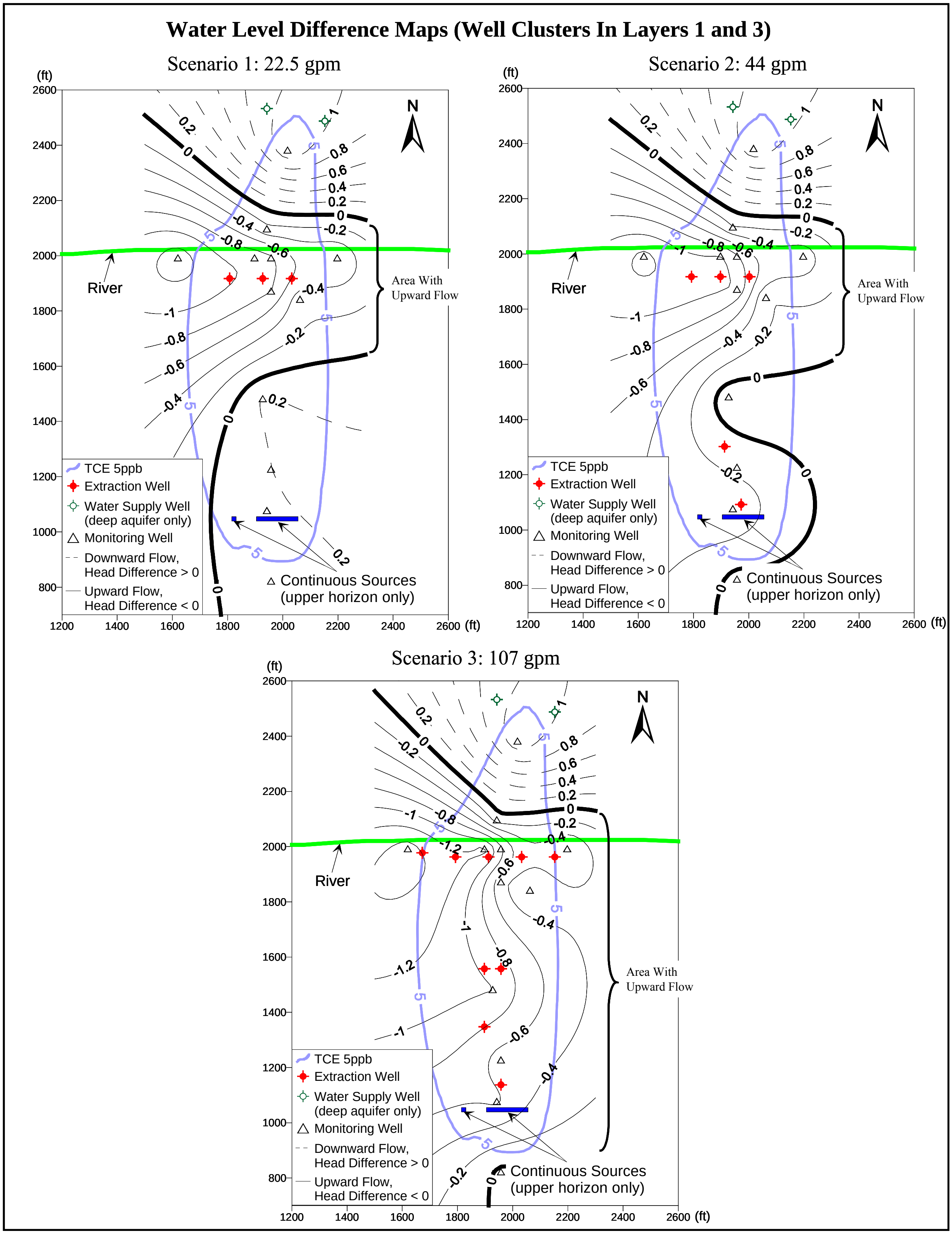
Figure A1-13 illustrates interpretation of vertical head differences at existing well clusters, for each of the three pumping scenarios:

- for Scenario 1 (22.5 gpm) there are downward vertical gradients interpreted near the contaminant source and in the central portion of the plume south of the river, suggesting the potential for downward advection of dissolved TCE

- for Scenario 2 (44 gpm) there is a much greater area where upward vertical gradients are interpreted, largely due to the existence of the mid-plume extraction wells, although some areas of downward vertical gradients are interpreted within the footprint of the plume south of the river

- for Scenario 3 (107 gpm) upward vertical gradients are interpreted within the entire footprint of the plume south of the river

Figure A1-13



Water Level Difference Maps (Well Clusters In Layers 1 and 3)
Scenario 1: 22.5 gpm
Scenario 2: 44 gpm
Scenario 3: 107 gpm
(ft)
N
River
Area With
Upward Flow
TCE 5ppb
Extraction Well
Water Supply Well
(deep aquifer only)
Monitoring Well
Downward Flow,
Head Difference > 0
Upward Flow,
Head Difference < 0
Continuous Sources
(upper horizon only)

These vertical head difference figures were created by contouring the measured head differences from locations where water level data were available at multiple depths (i.e., clustered monitoring wells).

For Scenarios 1 and 2, the downward vertical gradients within the footprint of the plume suggest a potential for dissolved TCE to migrate downward, and potentially beneath the river to the water supply wells. However, the level of detail associated with this water level analysis cannot determine if such transport beneath the river ultimately occurs, or if TCE transported downward near the contaminant source area is ultimately captured (or adequately attenuated) by the shallow extraction wells near the river (note there are upward vertical gradients near the river caused by the remedy extraction wells for all three pumping scenarios).

<u>Water Level Pairs (Gradient Control Points)</u>

Two types of water level pairs are analyzed for this site:

- river stage measurements are compared to water level measurements in the aquifer immediately south of the river to evaluate horizontal hydraulic containment at the river (at this site the upper horizon of the shallow aquifer is hydraulically connected to the river, so head differences between the river stage and the aquifer water level indicate if flow direction is to or from the river)

- water levels are compared between the upper and lower horizons of the shallow aquifer (Layer 1 and Layer 3), to evaluate vertical hydraulic containment for the upper horizon of the shallow aquifer that contains the continuing source of dissolved TCE

Figure A1-14 illustrates results for a large number of potential horizontal gradient control pairs (many more than would typically be available at most sites) in the vicinity of the river, for each of the three pumping scenarios. The use of so many data points is to highlight the details of the actual flow system for this example, and should not be confused with the number of monitoring wells in this hypothetical example illustrated earlier (i.e., many fewer locations, which is more realistic). The interpretations regarding horizontal hydraulic containment at the river, based on Figure A1-14, are as follows:

- for Scenario 1 (22.5 gpm), ground water in the aquifer discharges to the river at all locations, and the downgradient extent of capture cannot be determined from these data

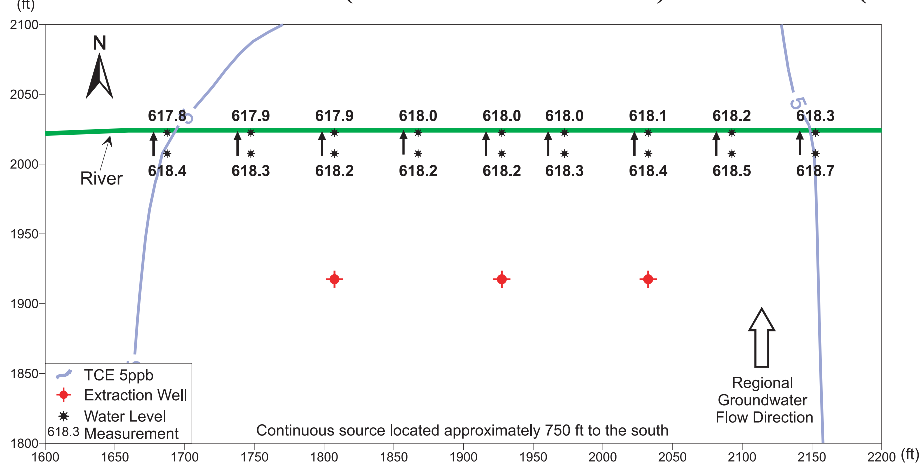
- for Scenario 2 (44 gpm), ground water in the aquifer discharges to the river at all locations, and the downgradient extent of capture cannot be determined from these data

- for Scenario 3 (107 gpm), the river discharges to the aquifer at all locations, indicating successful hydraulic containment at the river

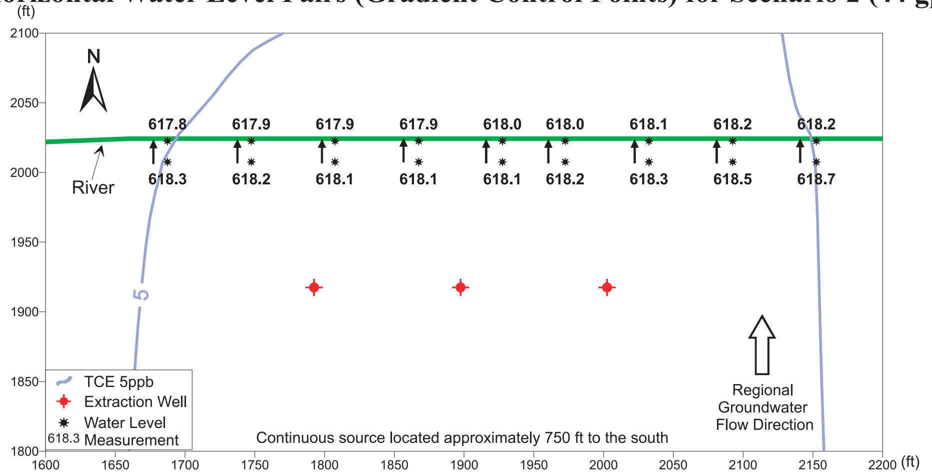
As discussed earlier (see Figure 11 of main document), the lack of demonstrated hydraulic containment at the river in Scenarios 1 and 2 does not prove that a capture zone is not achieved. It is possible that horizontal capture of the plume is successful but the flow divide associated with the capture zone is established upgradient of the river. The hydraulic containment achieved at the river in Scenario 3 should be viewed as a conservative measure of horizontal capture because achieving inward gradients at the river along the entire plume width requires more pumping than simply achieving an adequate flow divide between the extraction wells and the river.

Figure A1-14

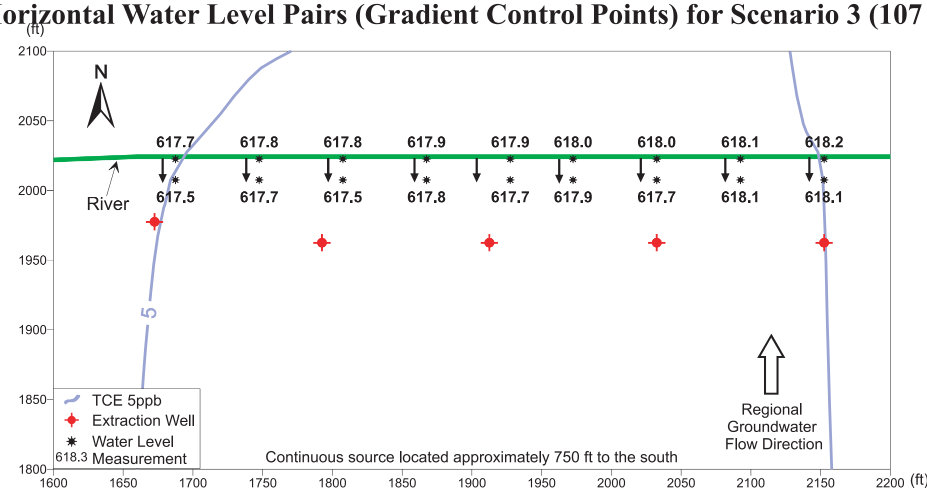
Horizontal Water Level Pairs (Gradient Control Points) for Scenario 1 (22.5 gpm)



Horizontal Water Level Pairs (Gradient Control Points) for Scenario 2 (44 gpm)



Horizontal Water Level Pairs (Gradient Control Points) for Scenario 3 (107 gpm)



Figures A1-15 to A1-17 illustrate results for a large number of potential vertical gradient control pairs (again, many more than would typically be available at most sites), for each of the three pumping scenarios, respectively. The interpretations regarding vertical hydraulic containment of Layer 1, south of the river, are as follows:

- for Scenario 1 (22.5 gpm), downward flow exists in most of the area within the plume footprint except near the extraction wells and the river, indicating potential for failed hydraulic containment in the vertical (Figure A1-15)

- for Scenario 2 (44 gpm), upward flow occurs near the contaminant source area where the mid-plume extraction wells are installed, but downward flow occurs in the central portion of the plume, indicating potential for failed hydraulic containment in the vertical (Figure A1-16)

- for Scenario 3 (107 gpm) upward flow occurs within the entire footprint of the plume, indicating successful hydraulic containment in the vertical (Figure A1-17)

Again, please note that at most sites a much smaller number of water level pairs are typically available for the interpretation of horizontal and/or vertical containment than are illustrated in this example.

Step 4 - Perform Calculations

Specific calculations can be performed to add additional lines of evidence regarding the extent of capture, including the following:

- simple horizontal analyses, such as estimated flow rate calculations and capture zone width calculations

- modeling (analytical or numerical) to simulate heads, in conjunction with particle tracking and/or transport modeling

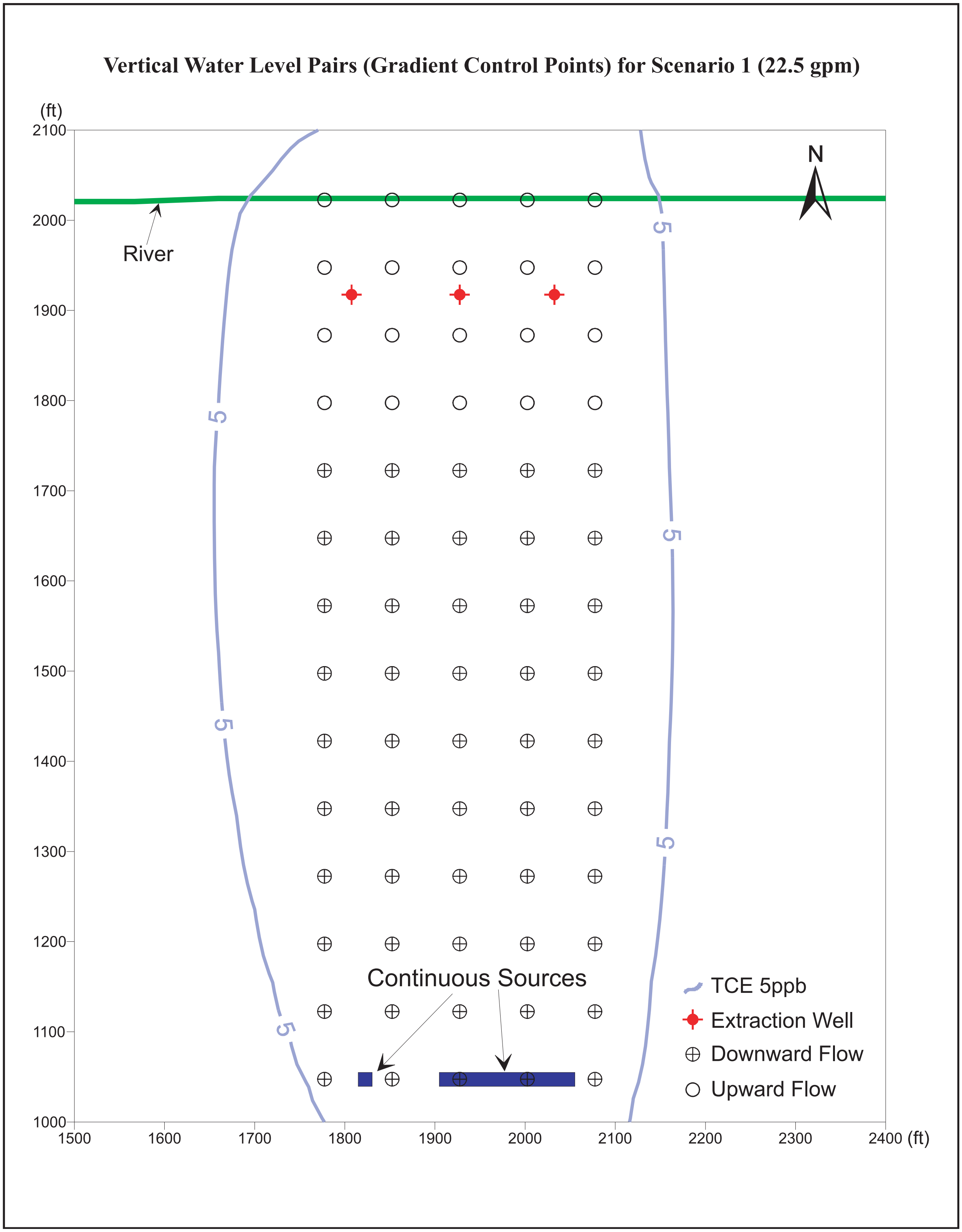
The discussion below illustrates some of the calculations that can be performed at this site, for each of the three defined pumping scenarios, to evaluate the extent of capture.

<u>Simple Horizontal Calculations</u>

Although the calculations associated with these analyses are quite simple, deciding on the actual values to use for the calculations is not straightforward for this site because some of the parameters (e.g., aquifer thickness, hydraulic conductivity, magnitude of the hydraulic gradient) vary in space.

One complication pertains to aquifer thickness. The shallow aquifer is unconfined, so the thickness of the aquifer is variable and depends on the actual water levels. Also, the extraction wells are only screened in the upper horizon of the shallow aquifer (Layer 1), but the wells are partially penetrating wells and likely draw water from all horizons of the shallow aquifer (Layers 1-3), and perhaps from the deep aquifer as well because there is no aquitard separating the shallow and deep aquifers.

Figure A1-15



Vertical Water Level Pairs (Gradient Control Points) for Scenario 1 (22.5 gpm)
(ft)
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400 (ft)
N
River
5
Continuous Sources
TCE 5ppb
Extraction Well
Downward Flow
Upward Flow

Figure A1-16

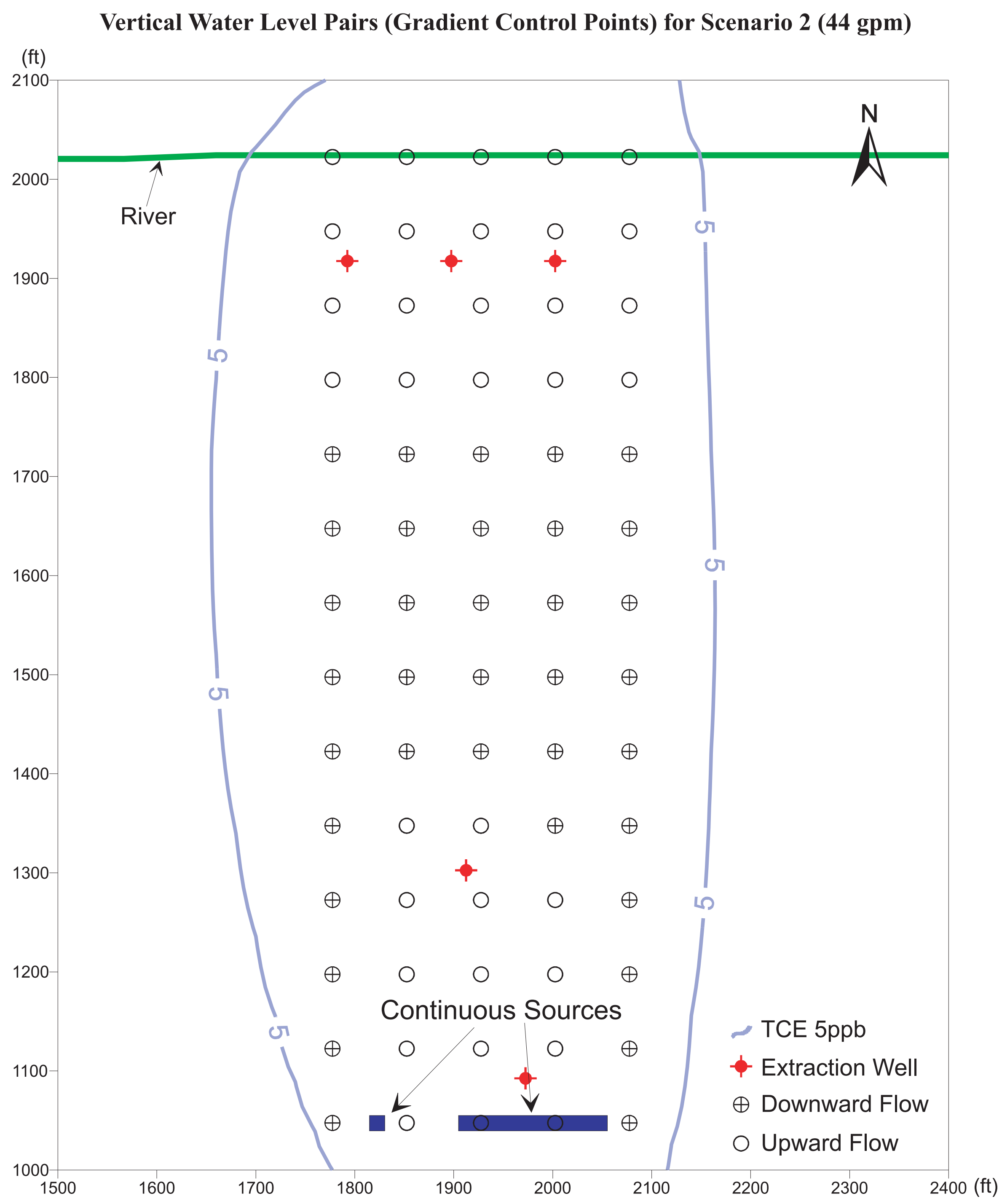
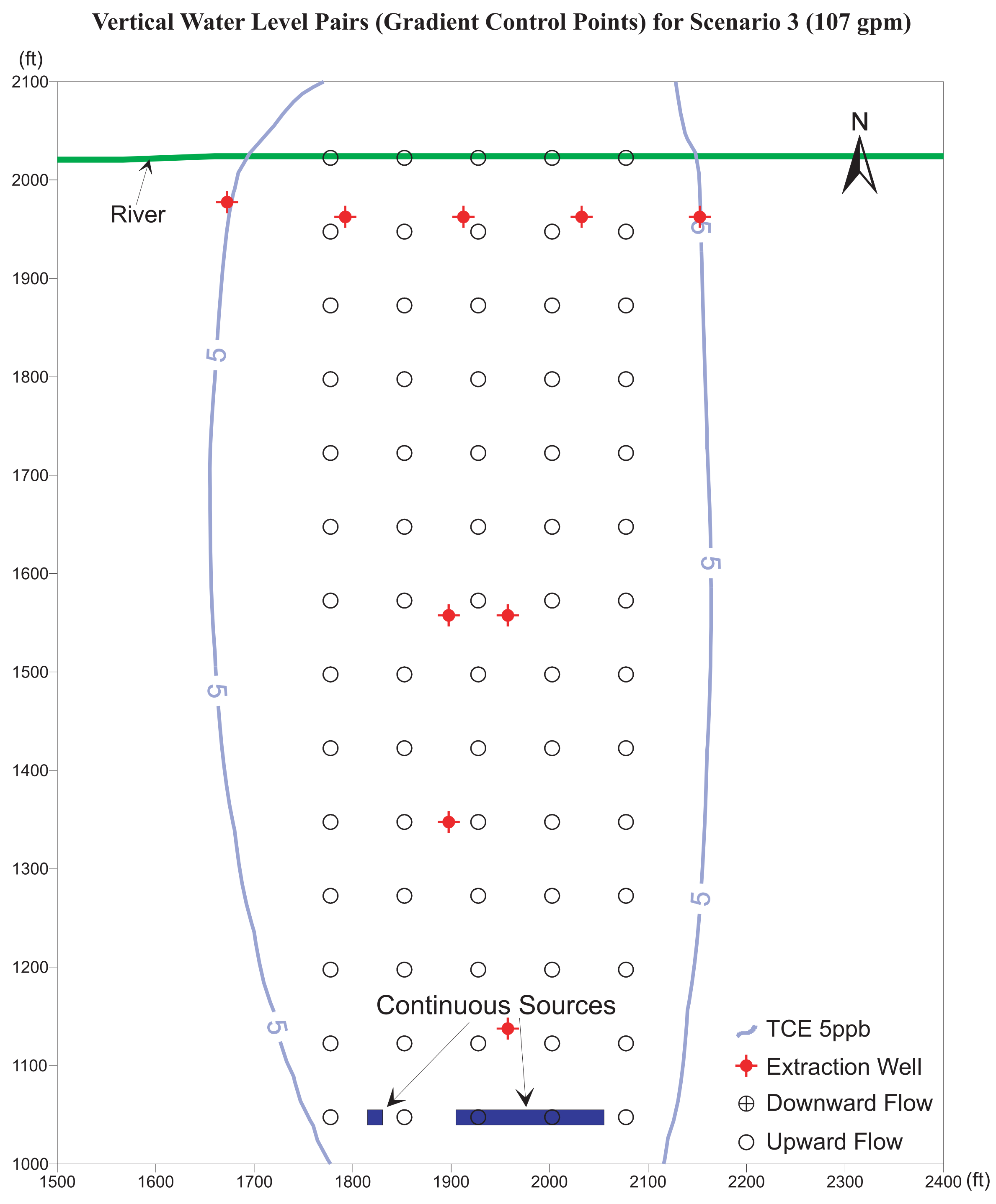

Vertical Water Level Pairs (Gradient Control Points) for Scenario 2 (44 gpm)
(ft)
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
(ft)
N
River
5
Continuous Sources
TCE 5ppb
Extraction Well
Downward Flow
Upward Flow

Figure A1-17


Vertical Water Level Pairs (Gradient Control Points) for Scenario 3 (107 gpm)
(ft)
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400 (ft)
N
River
5
5
5
5
5
5
5
Continuous Sources
TCE 5ppb
Extraction Well
Downward Flow
Upward Flow

Some possible options for assigning aquifer thickness are:

- ~ 25 ft (saturated thickness of Layer 1)
- ~ 50 ft (saturated thickness of Layers 1-3)
- ~ 75 ft (saturated thickness of Layers 1-4)

Based on the equations presented in Figure 13 (estimated flow rate calculation) and Figure 14 (capture zone width calculation) of the main document, assigning a higher value for aquifer thickness would suggest that more water flows through the plume, which would, in turn, require more pumping to achieve a specific width of capture.

Another complication pertains to hydraulic conductivity. The slug test and pumping test data (Table A1-1) suggest that heterogeneities exist within each aquifer, and from aquifer to aquifer. However, these simple calculations require a uniform value for hydraulic conductivity. Some possible options for assigning hydraulic conductivity are:

- 15 ft/day (representative value for Layer 1)
- 30 ft/day (conservatively high value, Layers 1-3)

Based on the equations presented in Figure 13 (estimated flow rate calculation) and Figure 14 (capture zone width calculation) of the main document, assigning a higher value for hydraulic conductivity would suggest that more water flows through the plume, which would in turn require more pumping to achieve a specific width of capture. Also note that lower hydraulic conductivity (at some sites) may dictate a need for more wells, at a lower discharge rate per well, to achieve the required total flow rate due to potential for lower sustained yields at each well.

A third complication pertains to regional hydraulic gradient. One of the assumptions of these simple calculations is that regional hydraulic gradient is uniform, which is not true for most actual sites due to aquifer heterogeneity, sources or sinks of water, or other factors. For this example, the magnitude of the hydraulic gradient ranges from 0.01 ft/ft (near the contaminant source) to 0.025 ft/ft (just south of the river). For the calculations presented below, only one value for hydraulic gradient (0.016 ft/ft) is utilized, which is a simplification based on the hydraulic gradient in the immediate vicinity of remedy wells located upgradient of the river.

To perform these calculations, a uniform value must also be assigned for the width of the plume requiring capture. For this site, the width of the 5 ppb plume is approximately 550 ft (Figure A1-5).

Estimated Flow Rate Calculation

Some combinations of parameter values that can be inserted into the equation presented in Figure 13 of the main document, for estimating the flow rate required for capture, are listed below:

- K = 15 ft/day or 30 ft/day (discussed above)
- b = 25 ft or 50 ft (discussed above)
- w = 550 ft
- i = 0.016 (simplification, discussed above)

The estimated flux (Q) through the plume, with “factor” of 1.0 (i.e., not accounting for other sources of water to the extraction wells), for various combinations of parameter values, is given in Table A1-2:

Table A1-2. Flux Through Plume, “Factor” = 1.0

K (ft/day)	b (ft)	Q (ft^3/day)	Q (gpm)
15	25	3,300	17.1
	50	6,600	34.3
30	25	6,600	34.3
	50	13,200	68.6

Applying values for “factor” of 1.5 and 2.0, to attempt to account for other sources of water to the extraction wells, increases the estimate of pumping required to capture the plume width, as indicated in Tables A1-3 and A1-4.

Table A1-3. Estimated Pumping Required, “Factor” = 1.5

K (ft/day)	b (ft)	Q (ft^3/day)	Q (gpm)
15	25	4,950	25.7
	50	9,900	51.4
30	25	9,900	51.4
	50	19,800	102.8

Table A1-4. Estimated Pumping Required, “Factor” = 2.0

K (ft/day)	b (ft)	Q (ft^3/day)	Q (gpm)
15	25	6,600	34.3
	50	13,200	68.6
30	25	13,200	68.6
	50	26,400	137.1

These results illustrate how the assignment of parameter values impacts the results of this simple calculation. It suggests that anywhere from 17.1 gpm to 137.1 gpm is required to capture the plume at this site, given the simplification for uniform hydraulic gradient, based on different estimates for hydraulic conductivity, aquifer thickness, and “factor”.

The results of the estimated flow rate calculations, which suggests anywhere from 17.1 gpm to 137.1 gpm might be required to capture the plume at this example site, can then be compared to the pumping rate for each of the three pumping scenarios defined for this example (Figure A1-4), to interpret whether or not the pumping rate associated with each scenario is likely sufficient to provide capture:

- Scenario 1 (22.5 gpm): likely not enough pumping
- Scenario 2 (44 gpm): possibly enough pumping
- Scenario 3 (107 gpm): likely enough pumping

These interpretations are semi-quantitative. They are quantitative in that they compare existing pumping rates to calculated values for pumping that might be required for successful capture, but they are also somewhat subjective because the calculated values are in the form of a range due to the significant uncertainty in the underlying parameters (for the reasons discussed earlier). Note that these flow-rate calculations do not provide any insight regarding vertical capture.

Capture Zone Width Calculation

As with the estimated flow rate calculations, a range of parameter values must be considered for transmissivity (T = K * b) since a range of possible values for both hydraulic conductivity and aquifer thickness are possible. For the calculations presented below, only one value for hydraulic gradient (0.016 ft/ft) is utilized, which is a simplification based on the hydraulic gradient in the immediate vicinity of remedy wells located upgradient of the river (as discussed earlier with respect to the estimated flow rate calculation).

Each of the three pumping scenarios defined for this example have more than one extraction well. The capture zone width calculation is generally performed by assigning the total extraction rate to one "equivalent well". The location of the equivalent well for each of the three pumping scenarios defined for this example is illustrated in Figure A1-18. The location of the equivalent well is generally selected visually so it is centrally located with respect to the plume width and/or extraction well locations, and located at the most downgradient position of the actual extraction wells. This often represents a significant level of simplification for a multi-well extraction system.

Capture zone widths calculated for the three pumping scenarios defined for this example, assuming one centrally located extraction well, are illustrated in Figure A1-18.

As discussed in Section B of the main document (see Figure 14 of the main document), Y_{max} is the capture zone width far upgradient of the equivalent well, and Y_{well} is the capture zone width at the location of the well. Both should be considered. For the purpose of this example, the full capture zone that includes both Y_{max} and Y_{well} is illustrated graphically (Figure A1-18), and calculations of Y_{max} are evaluated in detail below. Since the plume width at this site is 550 ft, and Y_{max} is measured from the plume centerline, Y_{max} should be greater than 275 ft to suggest successful capture.

Calculations for Y_{max} for each of the three pumping scenarios defined for this example are presented in Tables A1-5, A1-6, and A1-7. These calculations account for some of the variations of parameter values discussed previously. As noted in Figure 14 of the main document, these capture zone width calculations require that consistent units be used. Therefore, pumping rate (Q) is converted from gpm to ft^3/day prior to the calculation.

Figure A1-18

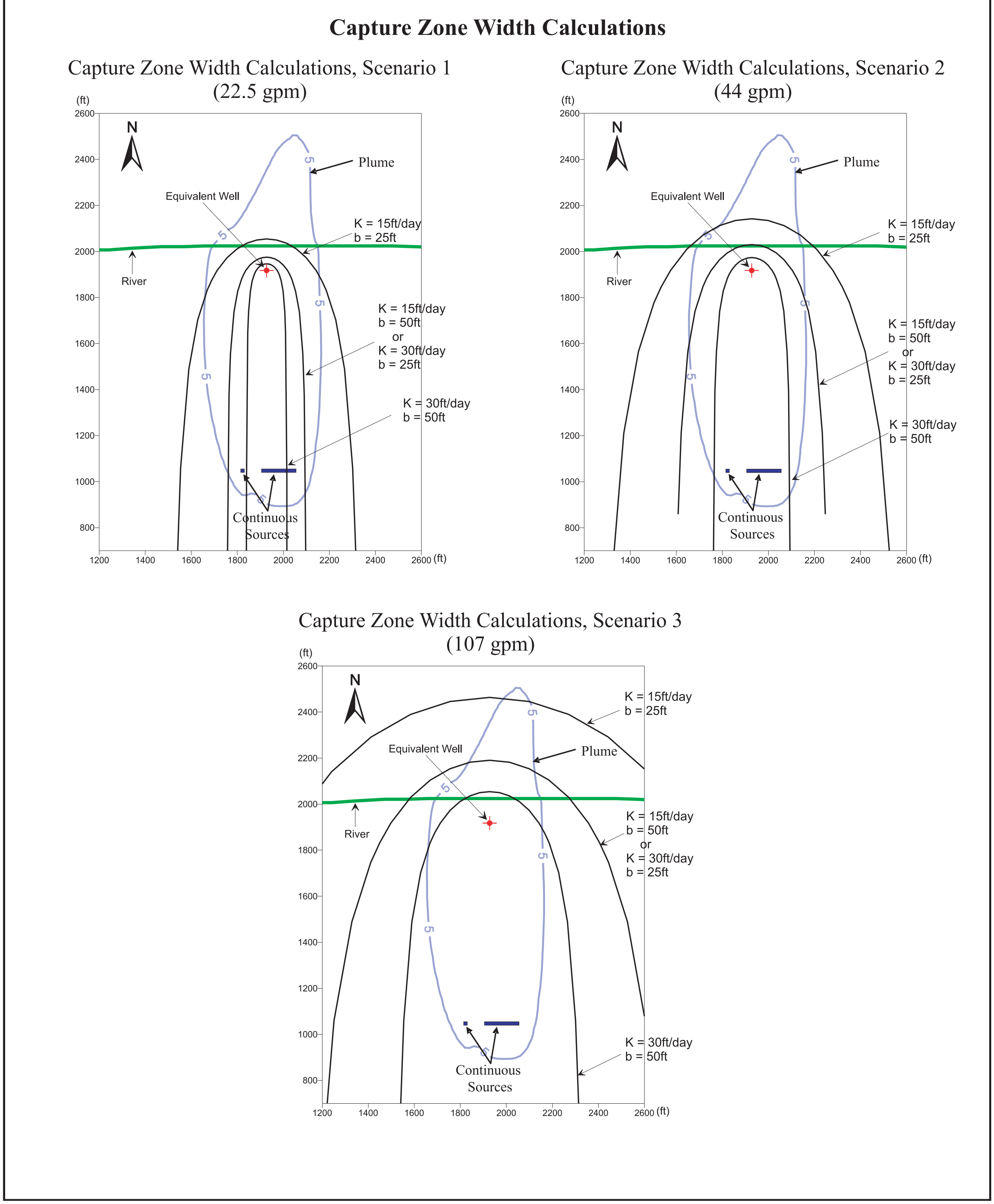

Capture Zone Width Calculations
Capture Zone Width Calculations, Scenario 1
(22.5 gpm)
Capture Zone Width Calculations, Scenario 2
(44 gpm)
Capture Zone Width Calculations, Scenario 3
(107 gpm)
N
Plume
Equivalent Well
River
Continuous Sources
K = 15ft/day
b = 25ft
K = 15ft/day
b = 50ft
or
K = 30ft/day
b = 25ft
K = 30ft/day
b = 50ft
(ft)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
1200
1400
1600
1800
2000
2200
2400
2600

Table A1-5. Capture Width from Plume Centerline
Scenario 1 (22.5 gpm, or 4,331 ft^3/day)

K (ft/day)	b (ft)	T (ft^2/day)	Y_{max} (ft)
15	25	375	360
	50	750	180
30	25	750	180
	50	1500	90

Table A1-6. Capture Width from Plume Centerline
Scenario 2 (44 gpm, or 8,470 ft^3/day)

K (ft/day)	b (ft)	T (ft^2/day)	Y_{max} (ft)
15	25	375	706
	50	750	353
30	25	750	353
	50	1500	176

Table A1-7. Capture Width from Plume Centerline
Scenario 3 (107 gpm, or 20,597 ft^3/day)

K (ft/day)	b (ft)	T (ft^2/day)	Y_{max} (ft)
15	25	375	1,715
	50	750	858
30	25	750	858
	50	1500	429

For each pumping scenario, the calculated value for Y_{max} can be compared to the target capture width on either side of the plume centerline (275 ft). As with the estimated flow rate calculations presented earlier, the calculated capture zone width for each of the defined pumping scenarios is actually a range, due to the uncertainty in assigning a uniform value for some of the parameters. The following semi-quantitative interpretations are made with respect to horizontal capture (based on the range of calculated values for Y_{max}):

- Scenario 1 (22.5 gpm): likely not enough pumping (Y_{max} generally less than 275 ft)
- Scenario 2 (44 gpm): possibly enough pumping (Y_{max} generally more than 275 ft)
- Scenario 3 (107 gpm): likely enough pumping (Y_{max} always more than 275 ft)

Similar detailed evaluations could also be performed for $Y_{well.}$

Note in Figure A1-18 that the calculated capture zone boundary in some cases crosses the river, because the analytical solution does not account for the river contributing water to the remedy well located south of the river. This highlights one of the limitations of these simple calculations (i.e., they do not account for other sources or sinks of water).

Exhibit A1-1 highlights questions that should be asked when performing these simple analyses, plus answers to those questions, for this example. Based on the answers to those questions, other lines of evidence are needed at this site to adequately assess capture for each of the three pumping scenarios.

Exhibit A1-1

Questions Asked When Performing Simple Horizontal Capture Analyses

- Is using a single "representative value" for hydraulic conductivity adequate?

  Probably not in this hypothetical example

- Are other contributions to the extraction wells adequately considered?

  Flux from a river: extraction wells are close to the river, there is high potential for the river to contribute water to the extraction wells

  Flux from other stratigraphic units: there is already uncertainty in thickness (b) to use for the shallow aquifer, there is also potential for extraction well(s) to capture water from the deep aquifer because no aquitard exists

- Is potential for vertical transport of contaminants being considered by these methods?

  No, and it is a potential concern in this hypothetical example due to the presence of water supply wells screened in the deep aquifer

Particle Tracking Based on Numerical Ground-Water Flow Modeling

For this example, particle tracking was performed with the existing numerical flow model upon which the example was generated (the "actual condition"). The following approach to particle tracking was employed:

- in each model layer, one particle was initially located in each model grid cell, at the vertical midpoint of the layer, and tracked forward in space to the location where it was removed (such as a well or the river)

- for each particle removed by one of the remedy extraction wells, a symbol was plotted at the initial location of that particle, to identify the specific well that captured the particle

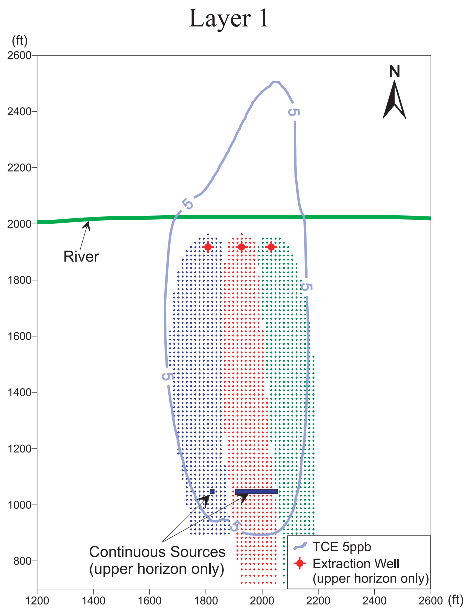
This is a very effective particle tracking approach to illustrate three-dimensional capture zones.

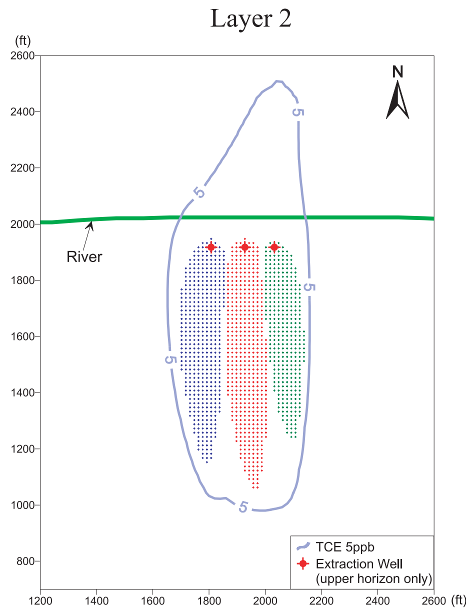
The particle tracking results for each of the three pumping scenarios are presented in Figures A1-19 to A1-21. For each pumping scenario, capture zone maps are provided for particles starting at the vertical

Figure A1-19

Particle Tracking Results, Scenario 1 (22.5 gpm)

Note: All the extraction wells are screened in layer 1





Note: When this figure is viewed in black-and-white, the extent of the total capture zone is illustrated. When this figure is viewed in color (such as from within the PDF digital version), the colors additionally highlight the capture zones of individual wells.

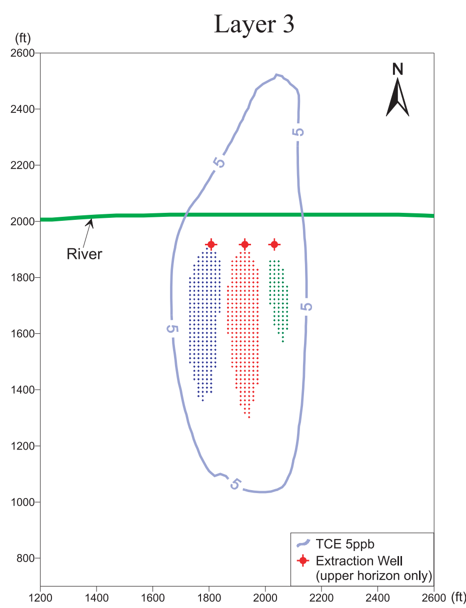
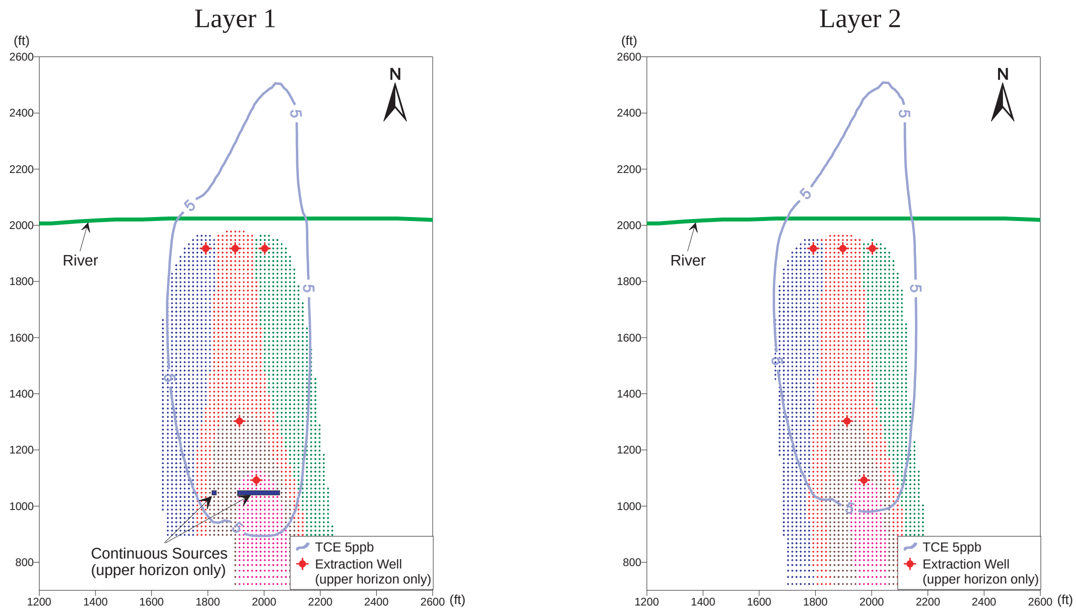
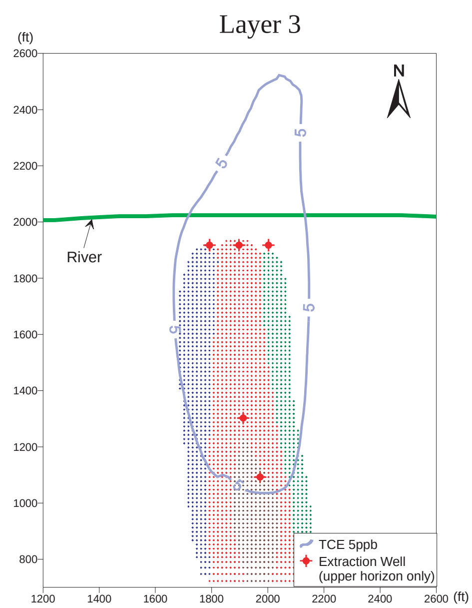


Figure A1-20

Particle Tracking Results, Scenario 2 (44 gpm)

Note: All the extraction wells are screened in layer 1



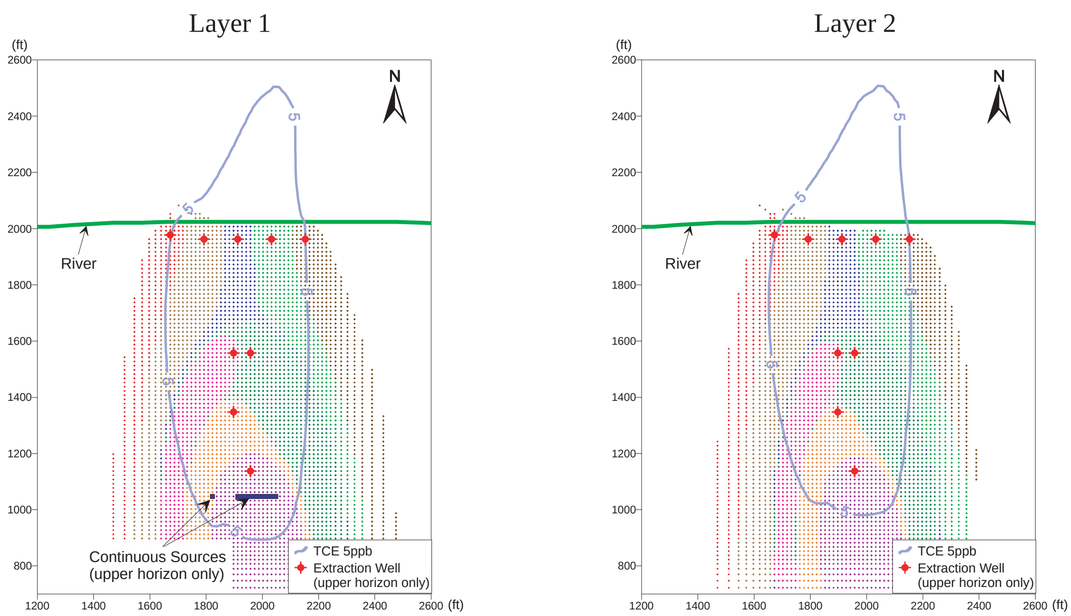


Note: When this figure is viewed in black-and-white, the extent of the total capture zone is illustrated. When this figure is viewed in color (such as from within the PDF digital version), the colors additionally highlight the capture zones of individual wells.

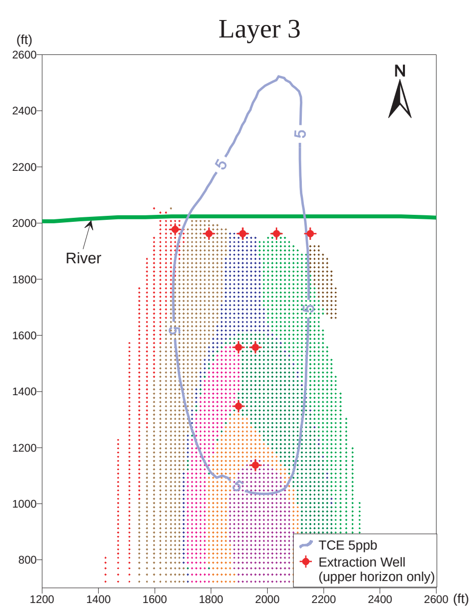
Figure A1-21

Particle Tracking Results, Scenario 3 (107 gpm)

Note: All the extraction wells are screened in layer 1



Note: When this figure is viewed in black-and-white, the extent of the total capture zone is illustrated. When this figure is viewed in color (such as from within the PDF digital version), the colors additionally highlight the capture zones of individual wells.



midpoint of Layer 1, Layer 2, and Layer 3 (i.e., each horizon of the shallow aquifer). No particles starting at the vertical midpoint of Layer 4 (the deep aquifer) are removed by any of the remedy extraction wells. Although these shallow extraction wells may help prevent contaminants from migrating down to the deep aquifer in the future, the particle tracking results indicate that they will not remove contamination that has already migrated down to the deep aquifer.

The particle tracking results for this example are summarized below:

- for Scenario 1 (22.5 gpm), illustrated in Figure A1-19, the 5-ppb plume in Layer 1 is mostly captured, but the 5-ppb plumes in Layers 2 and 3 are largely not captured, and TCE-impacted ground water likely discharges to the river or flows beneath the river
- for Scenario 2 (44 gpm), illustrated in Figure A1-20, effective capture is indicated for Layer 1, and nearly complete capture is indicated for Layers 2 and 3
- for Scenario 3 (107 gpm), illustrated in Figure A1-21, complete capture is indicated for Layers 1 to 3, and the capture extends well beyond the 5 ppb plume boundary, indicating that there is more pumping than is actually required to capture the plume

The particle tracking results present a more comprehensive and precise illustration of the extent of horizontal and vertical capture than the evaluations of water level maps or water level pairs. However, the reliability of this line of evidence for interpreting actual capture depends on the reliability of the model predictions, which are typically subject to uncertainty based on the presence of heterogeneity in natural systems that can be difficult to characterize and represent in the model.

For the example presented herein, the particle tracking evaluations were performed with a model known to be an accurate representation of ground-water flow conditions for the site. At actual sites, that will never be the case. Ideally, a numerical model used for particle tracking should be “verified” by reproducing measured drawdown responses to various pumping scenarios, increasing confidence in the model’s ability to accurately predict capture. Another way to “verify” the numerical model is to run forward particle tracking to show that particles released at the source actually account for the observed plume dimensions. However, there are factors in addition to the prediction of the flow system (including contaminant source location and timing, dispersion, and adsorption) that complicate such evaluations.

Sensitivity analysis can be performed to evaluate how changes in model parameter values might impact the particle tracking results. The best way to perform such sensitivity analysis is to make sure the alternate runs are performed using parameter values in the ground-water flow model that still provide an acceptable model calibration.

Step 5 - Evaluate Concentration Trends

At this site, the use of concentration trends at monitoring wells that are located between the extraction wells and the river is difficult with respect to evaluation of capture. Sentinel wells (i.e., wells that are currently clean) cannot be located between the extraction wells and the river, because that area is already impacted by TCE. “Downgradient performance monitoring wells” should be located beyond the Target Capture Zone, because monitoring wells located within the capture zone will often remain impacted if there is a continuing source of contamination (see Figure 15 of the main document and associated discussion). For this example, it is not clear that any monitoring wells between the extraction wells and the river could be known to be located outside the Target Capture Zone, since the capture zone might extend all the way to the river. However, declining concentrations at performance monitoring wells located north of the river could, over time, provide evidence of successful vertical capture from the extraction wells located south of the river (i.e., successfully preventing continued migration of contaminants beneath the river). Other types of performance monitoring, such as stream bed wells or pore water samplers, could be used to establish concentration trends in ground water immediately adjacent to the river that would provide evidence regarding the success of horizontal capture in the shallow aquifer.

Figure A1-22 illustrates the locations of several potential monitoring wells in Layer 1 (i.e., screened in the upper horizon of the shallow aquifer), located between the extraction wells and the river (more than would typically be available at most sites). Some are located closer to the extraction wells, and some are located closer to the river. Also, some are located immediately north of the extraction wells (i.e., directly downgradient of the extraction wells), while some are located between extraction wells (i.e., north of, but not directly downgradient of, the extraction wells).

Figure A1-23 illustrates concentration trends observed at these locations, for each of the three defined pumping scenarios.

Figure A1-22

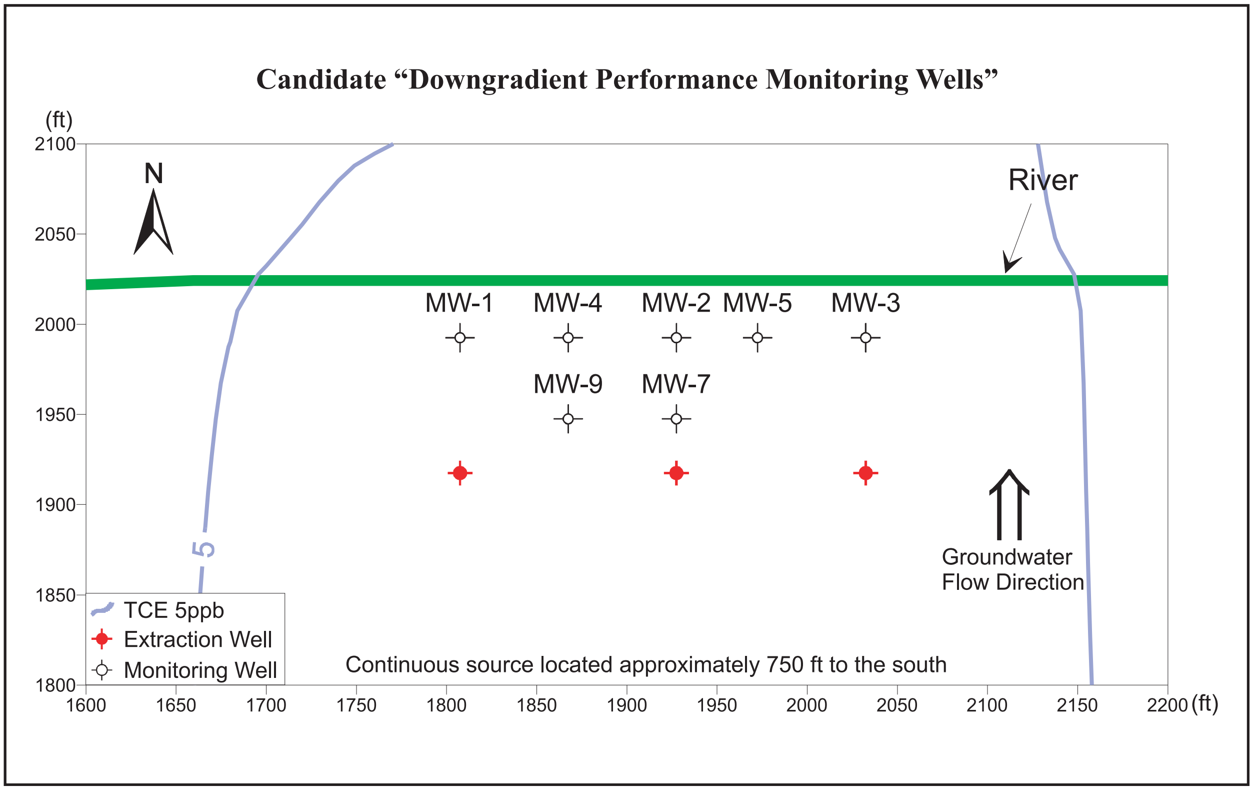
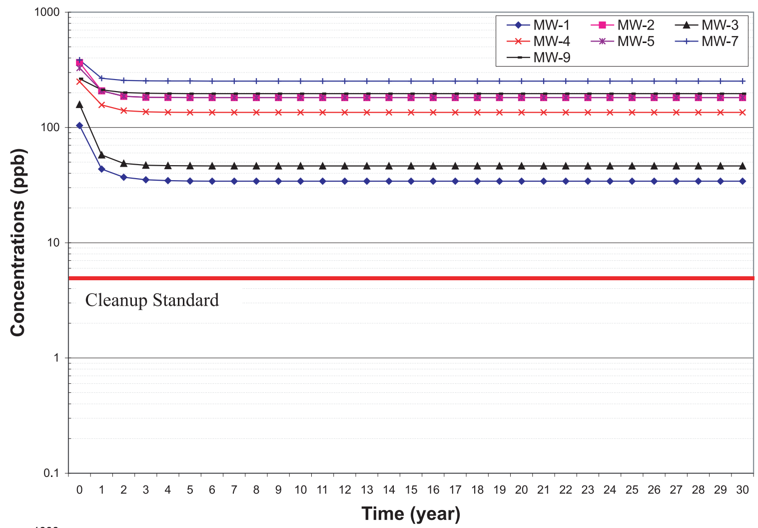


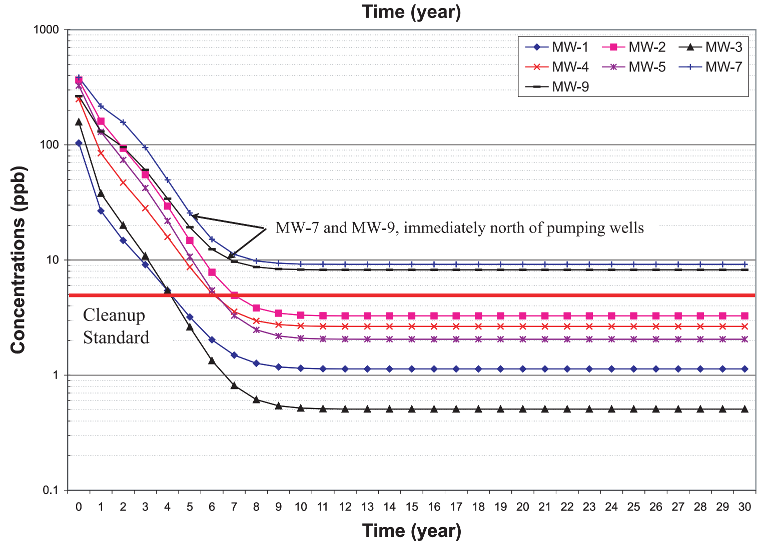
Figure A1-23

Concentration Trends

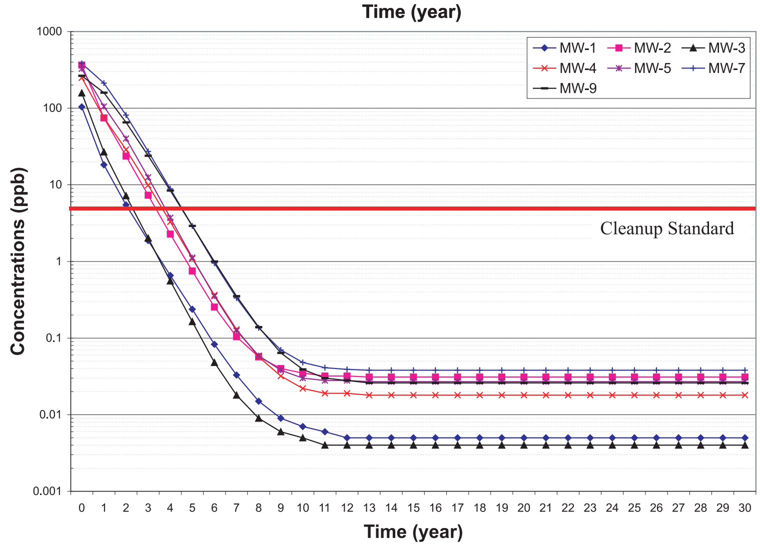
A. Concentrations vs. Time:
Scenario 1 (22.5gpm)



B. Concentrations vs. Time:
Scenario 2 (44 gpm)



C. Concentrations vs. Time:
Scenario 3 (107 gpm)



Interpretations of the contaminant concentration trends presented in Figure A1-23 are as follows:

- for Scenario 1 (22.5 gpm), concentrations remain above 5 ppb at all the monitoring wells, possibly because capture fails, but possibly because all are within the capture zone and are subject to continued impacts as a result of the continuing contaminant source

- for Scenario 2 (44 gpm), concentrations over time decline at all of the monitoring wells, but only decline below 5 ppb at some of the wells

- for Scenario 3 (107 gpm), concentrations decline below cleanup levels at all the monitoring wells, likely because the upgradient source is controlled by mid-plume wells and clean water is being pulled towards the monitoring wells from the river

At most sites only a subset of these data would actually be available, making interpretations regarding capture even more difficult. Also, for monitoring wells where the concentrations do ultimately decrease below 5 ppb, that result is not observed for a number of years (i.e., not a timely evaluation of capture effectiveness). It is also apparent that monitoring wells can initially show a decline in concentrations but then level off at a concentration higher than the cleanup level of 5 ppb, making it difficult or impossible to make conclusions about capture based on declining concentration trends in early time periods.

Interestingly, the monitoring wells in this group that remain above the 5 ppb cleanup limit in Scenario 2 (MW-7 and MW-9) are those located closest to the extraction wells. This could be because those wells are within the capture zone of the extraction wells and the wells closer to the river are not. It could also be because that all the monitoring wells are within the capture zone of the extraction wells, and those monitoring wells closest to the extraction wells experience higher concentrations than those located closer to the river. The particle tracking results provide an additional line of evidence for determining which is more likely.

Step 6 - Interpret Capture

Once multiple lines of evidence are developed based on technical evaluations such as those presented above, the next step is to use “converging lines of evidence” to interpret the actual capture zone, and to compare it to the Target Capture Zone. Exhibit A1-2 provides a brief summary of each line of evidence regarding horizontal and vertical capture, for each of the three pumping scenarios. Exhibit A1-2 also provides an interpretation of capture effectiveness relative to the two options presented earlier for Target Capture Zone. A summary table such as the one presented in Exhibit A1-2 is an effective way to summarize a capture zone evaluation.

Target Capture Zone Option 1 is the more conservative option. It requires inward flow from the river to aquifer, and also requires upward flow to the upper horizon of the shallow aquifer. Only Scenario 3 achieves these more conservative conditions.

Target Capture Zone Option 2 is the less conservative option. It requires that a flow divide be established between the extraction wells and the river, but does not require inward flow from the river to the aquifer and does not require complete vertical containment (but will require monitoring in the deeper aquifer on the north side of the river to make sure the remedy is allowing adequate attenuation of constituents previously flowing beneath the river).

Exhibit A1-2

Lines of Evidence Regarding Capture for Example A1, for Each Pumping Scenario

Method	Scenario 1: 22.5 gpm	Scenario 2: 44 gpm	Scenario 3: 107 gpm
Water Level Maps	• Horizontal capture may or may not be achieved • Using water levels measured near extraction wells, appears horizontal capture in Layer 1 is achieved • Downward flow from Layer 1 near source area and most of the plume	• Horizontal capture may or may not be achieved • Using water levels measured near extraction wells, appears horizontal capture in Layer 1 is achieved • Downward flow from Layer 1 in the mid-plume area	• Horizontal capture may or may not be achieved • Using water levels measured near extraction wells, appears horizontal capture in Layer 1 is achieved • Upward flow within the entire footprint of the plume
Water Level Pairs	• Discharge from aquifer to river across entire plume width between the extraction wells and river, presence of divide cannot be determined • Downward flow in most areas except area near the extraction wells	• Discharge from aquifer to river across entire plume width, presence of divide between the extraction wells and river cannot be determined • Downward flow in some portions of the plume	• Discharge from river to aquifer across entire plume width, indicating horizontal hydraulic containment at river • Upward flow in all portions of the plume, indicating vertical hydraulic containment
Estimated Flow Rate & Capture Zone Width Calculations	• Likely insufficient for horizontal capture	• Potentially sufficient for horizontal capture	• Likely sufficient for horizontal capture
Particle Tracking with Ground-water Flow Modeling	• Nearly complete capture in upper horizon of shallow aquifer, poor capture in lower horizons of shallow aquifer	• Complete capture in upper horizon of shallow aquifer, nearly complete capture in lower horizons of shallow aquifer	• Complete capture in all portions of the shallow aquifer
Monitoring Well Concentration Trends Between the Extraction Wells and the River	• Concentrations do not reach cleanup level of 5 ppb at any of the monitoring wells • Interpretation ambiguous	• Concentrations reach cleanup level of 5 ppb at some monitoring wells in 4-7 years • Interpretation ambiguous	• Concentrations reach cleanup level of 5 ppb at all the monitoring wells within approximately 5 years

Exhibit A1-2 Continued

Lines of Evidence Regarding Capture for Example #1, for Each Pumping Scenario

Method	Scenario 1: 22.5 gpm	Scenario 2: 44 gpm	Scenario 3: 107 gpm
Interpretation for Target Capture Zone Option 1 (More Conservative)	• Horizontal condition is not achieved • Vertical condition is not achieved	• Horizontal condition is not achieved • Vertical condition is not achieved	• Horizontal condition is very likely achieved • Vertical condition is very likely achieved
Interpretation for Target Capture Zone Option 2 (Less Conservative)	• Horizontal condition is possibly, but not likely, achieved • Vertical condition is likely not achieved, but hard to evaluate without transport modeling and/or long-term concentration trends on the other side of the river	• Horizontal condition is likely achieved • Vertical condition is possibly achieved, but hard to evaluate without transport modeling and/or long-term concentration trends on the other side of the river	• Horizontal condition is very likely achieved • Vertical condition is very likely achieved

Note that interpretations with respect to the two options for Target Capture Zone are based on all lines of evidence presented, and the interpretation might be different if one or more of the lines of evidence was not available.

For Target Capture Zone Option 2 (less conservative), based on all the lines of evidence presented, the interpretations are as follows:

- For Scenario 1 (22.5 gpm), the horizontal condition possibly is achieved for the upper horizon of the shallow aquifer (based on water level maps and particle tracking results), but likely is not achieved for the lower horizon of the shallow aquifer because there are downward hydraulic gradients in the shallow aquifer near the source area that will continue to cause impacts to deeper ground water, and horizontal ground-water capture appears to be incomplete in the deeper ground-water units primarily based on particle tracking results. The vertical condition will require monitoring in the deeper aquifer on the north side of the river to make sure the remedy is allowing adequate attenuation of constituents previously flowing beneath the river. Monitoring will likely indicate failed capture due to the potential for downward contaminant transport indicated by water level pairs and subsequent contaminant transport beneath the river (it may take years of monitoring to reach a conclusion, and transport modeling could augment the evaluation).

- For Scenario 2 (44 gpm) the horizontal condition is likely met based on the water level maps and particle tracking results. The vertical condition will require monitoring in the deeper aquifer on the north side of the river to make sure the remedy is allowing adequate attenuation of constituents previously flowing beneath the river, and that monitoring may or may not indicate successful capture (it may take years of monitoring to reach a conclusion, and transport modeling could augment the evaluation).

- For Scenario 3 (107 gpm), horizontal capture is achieved based on water level maps, particle tracking results, and especially based on inward flow at the river across the entire plume width. The vertical condition will require monitoring in the deeper aquifer on the north side of the river to make sure the remedy is allowing adequate attenuation of constituents previously flowing beneath the river (it may take years of monitoring to reach a conclusion). Monitoring is likely to indicate successful capture based on the upward head differences observed south of the river within the footprint of the plume, which adds confidence that remedy objectives will be achieved.

It should be noted that the interpretations of capture presented above are based on multiple lines of evidence determined from a variety of technical analyses. If some of those lines of evidence were not developed, the evaluation of capture might differ for one or more of the pumping scenarios. In all of the cases discussed above, periodic water quality monitoring of the deep aquifer south of the river and north of the river will be appropriate to confirm that concentrations decrease over time as a result of the remedy. This is especially important given the presence of water supply wells that extract deep ground water on the other side of the river. Also, in all cases stream bed wells or pore water samplers might be considered to monitor concentration trends in pore water immediately adjacent to the river, which could provide additional evidence regarding the success of horizontal capture.

Once the extent of actual capture zone has been interpreted, and that interpretation has been compared to the Target Capture Zone, the following issues should be addressed:

- compare the interpreted capture zone to remedy objectives
- assess uncertainties in the capture zone analysis
- assess the need for additional characterization or monitoring
- determine if extraction (rates and/or locations) or monitoring should be modified

The remedy objective in this example is to prevent contaminants at concentrations above standards from discharging to the river and/or flowing under the river. Scenario 3 appears very likely to achieve these remedy objectives.

For Scenarios 1 and 2, it is difficult to establish if these remedy objectives are likely to be achieved. The capture zone analysis for Scenario 1 (22.5 gpm) indicates that the remedy objectives will likely not be achieved because downward hydraulic gradients are observed near the source area, and there is a high potential (based on the particle tracking results) for contaminants in the deeper horizons of the shallow aquifer to not be captured by the pumping wells. Nevertheless, it is possible that attenuation of TCE concentrations due to the remedy, in conjunction with other attenuation mechanisms, may still help achieve remedy objectives. The capture zone analysis for Scenario 2 (44 gpm) indicates the remedy objectives will likely be achieved, particularly based on the particle tracking results that indicate nearly complete capture of ground water within the plume footprint in all horizons of the shallow aquifer. However, this assessment would be much more uncertain without the particle tracking analysis (or if there was a high degree of uncertainty associated with the accuracy of the model upon which the particle tracking results are based).

There will always be uncertainties regarding aspects of the capture zone analysis. In general, the more conservative the pumping strategy, the more certain each individual line of evidence is likely to be. For this example, the interpretation of Scenario 3 (107 gpm) is subject to the least uncertainty, because it satisfies even the more conservative requirements such as inward hydraulic gradients from the river to the aquifer and upward flow at all available well clusters. The extra pumping associated with Scenario 3 (both in terms of the total rate and the use of mid-plume and source area wells) is more conservative, and therefore reduces uncertainty in the capture zone analysis. In general, the reliability of the assessment of capture often increases as the total pumping rate increases, even if uncertainty in some aspects of the capture zone analysis remains.

At this example site, no need for additional characterization appears necessary. However, the evaluation of water level maps illustrates that water level measurements (or estimates of water levels) near the extraction wells are vital to interpreting capture from the water level maps, and if piezometers are not available near the extraction wells, installing piezometers in those locations is strongly recommended.

If pumping for Scenario 1 is in place, the capture zone evaluation suggests that more pumping is likely required mid-plume and/or near the source area, to improve control of downward gradients. Installing remediation wells near the river with deeper well screens could also be considered, which allows water to be drawn from a different (i.e., deeper) portion of the aquifer, which in turn might also sustain greater pumping rates if designed properly. However, the deeper pumping near the river could risk drawing more of the plume into the deeper layers, making more plume mass available for capture by water supply wells located north of the river. Thus, pumping from deeper levels may not be prudent.

If pumping for Scenario 2 is in place, increasing pumping rate (mid-plume or near the river) could be considered to improve confidence that remedy objectives are met, especially if cost impacts associated with that action are reasonable (site-specific). If pumping for Scenario 3 is in place, consideration could be given to reducing pumping rates, especially if the cost of operating individual wells and/or treating more water is reasonably high (site specific).

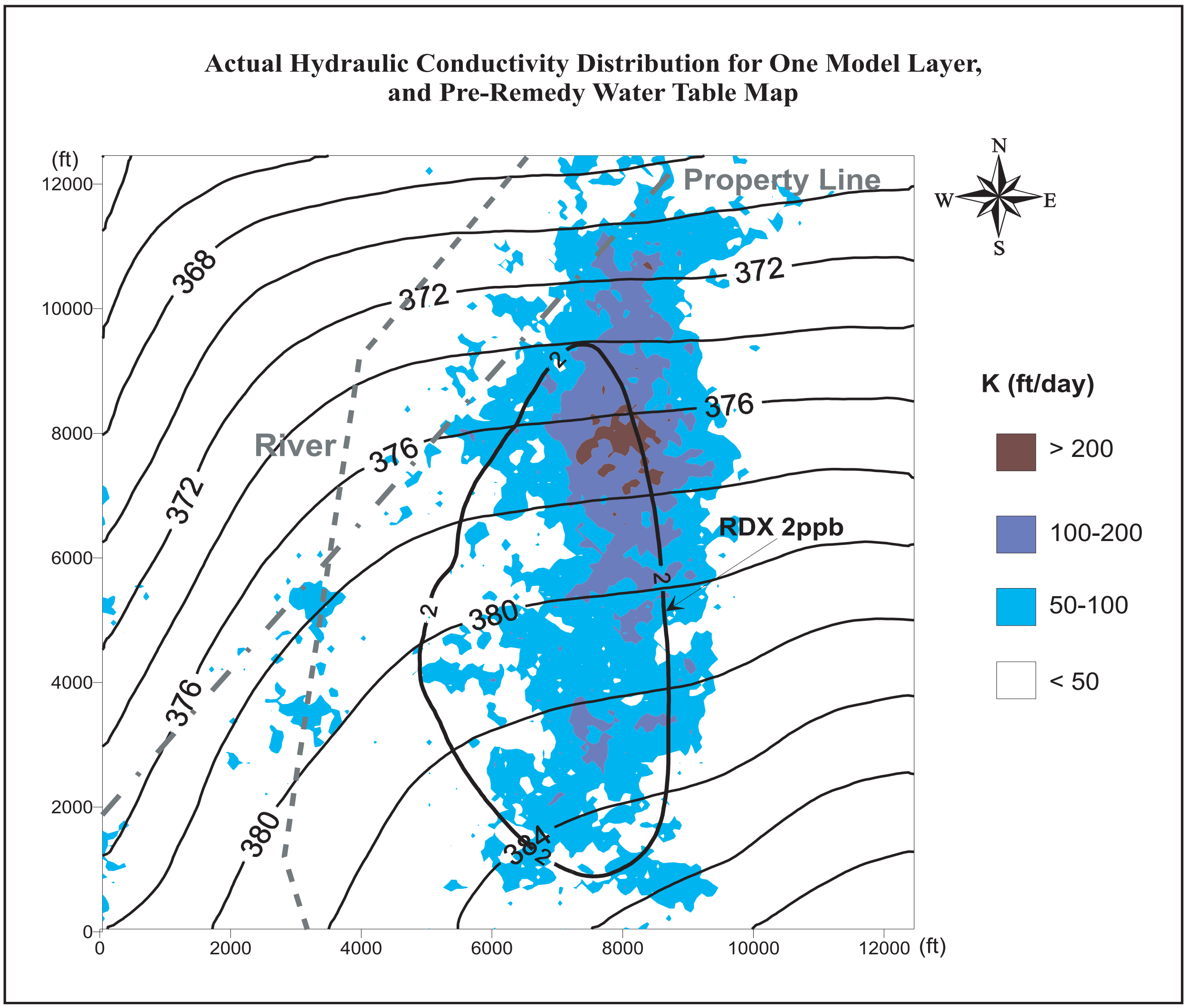
EXAMPLE A2

This example highlights complications of evaluating capture when preferential flow pathways are present. For this hypothetical site, not all six steps associated with the systematic evaluation of capture are fully demonstrated. Instead, specific items that demonstrate important aspects of capture zone analyses are highlighted.

Example Setup

The area of interest is several square miles (Figure A2-1). The stratigraphy of this site consists of an aquifer approximately 300 ft thick that overlies a competent aquitard. The aquifer primarily consists of coastal plain sand. According to regional data, net recharge from precipitation at the site is expected to be 12 to 16 inches per year. Based on regional data and site-specific slug test data, the horizontal hydraulic conductivity of the aquifer is heterogeneous and varies from 2 ft/day to 300 ft/day. Regionally, preferential pathways associated with historic stream channel deposits are known to exist.

Figure A2-1



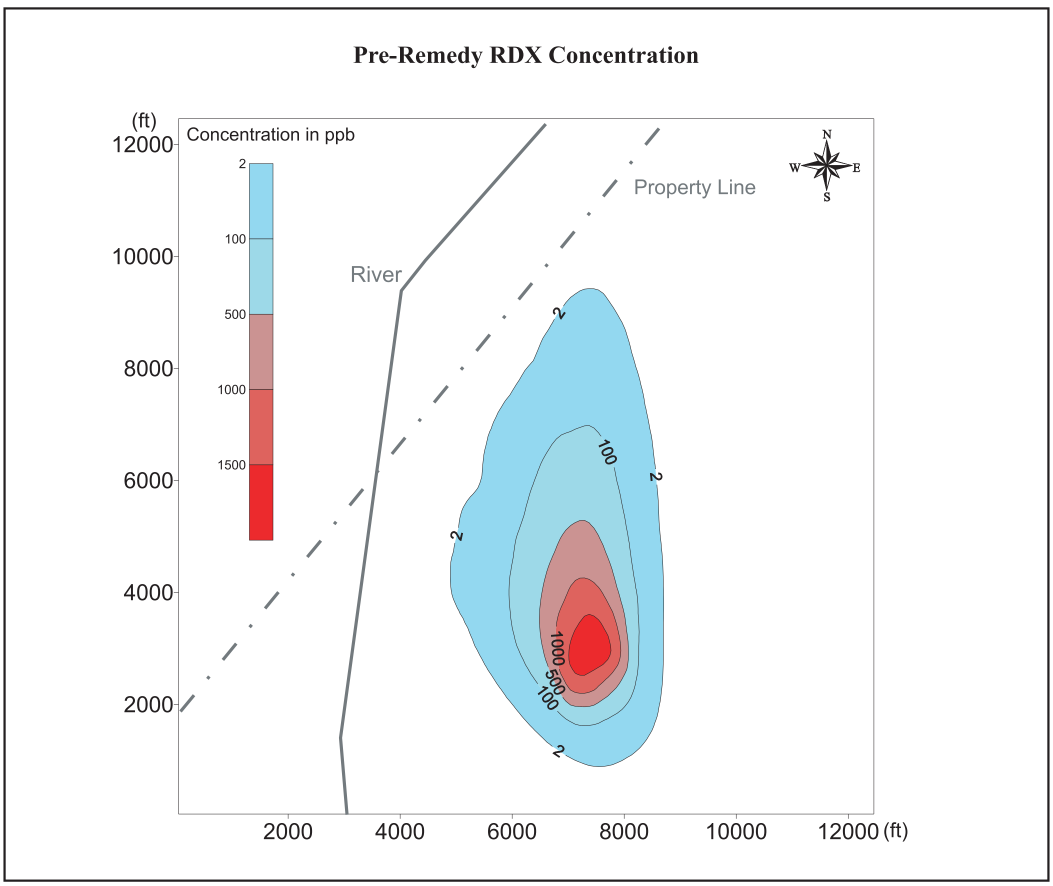
A river located west of the site flows from southwest to northeast. Pre-remediation measurements for the water table are also illustrated in Figure A2-1, and they indicate that ground-water flow directions are somewhat variable (to the northwest and the north). The river does not influence the head contour map because the impacted aquifer is not in hydraulic connection with the river.

A ground-water flow model was used to generate this hypothetical example. The aquifer is represented in the model with 12 layers, each of which has a heterogeneous hydraulic conductivity. Figure A2-1 indicates the assumed hydraulic conductivity distribution for one layer of this heterogeneous system. There is a zone of generally higher hydraulic conductivity associated with a preferential pathway, running north-south, that is apparent in Figure A2-1. In reality, site managers would only have slug test or pumping test data at a limited number of locations and depths (plus information such as well borings, well records from nearby wells, and regional hydrogeology reports), and the existence of this preferential pathway might or might not be evident.

At this site the aquifer has been impacted by dissolved RDX, a contaminant associated with manufacture of explosives. Dissolved RDX is mobile in the subsurface. The RDX leached into the ground water from a drainage ditch over a 15-year period, after which the contaminant source was excavated.

Figure A2-2 indicates the pre-remedy concentrations of RDX in the model (maximum concentration at any vertical depth within the aquifer). The remedy objective for this site is to hydraulically contain the plume along the property boundary at all depths. The Target Capture Zone is to create a flow divide between the remedy extraction wells and the property boundary for the entire aquifer thickness, across the entire width of the plume (defined by the 2 ppb contour for RDX).

Figure A2-2



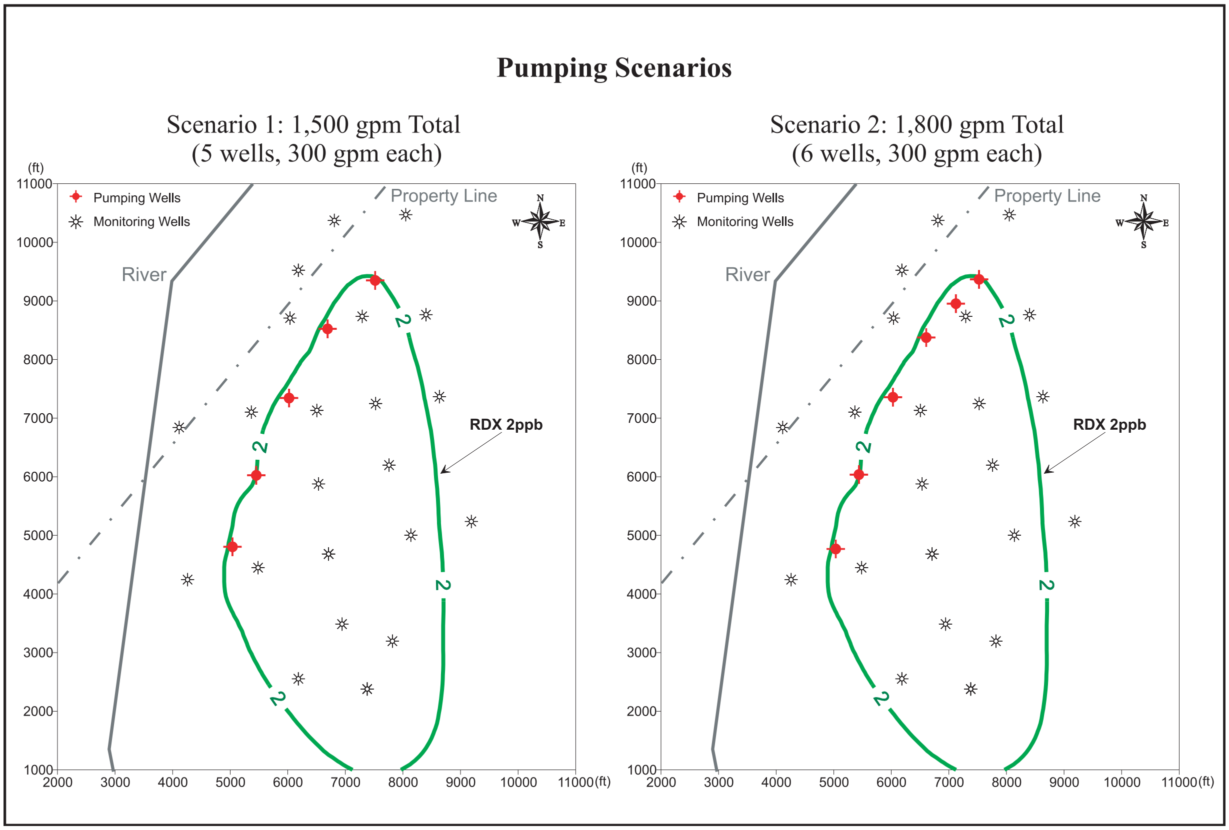
Scenarios Illustrated

Figure A2-3 illustrates two pumping scenarios for this site:

- *Scenario 1* has 5 pumping wells with the total pumping rate of 1,500 gpm.
- *Scenario 2* has 6 pumping wells with the total pumping rate of 1,800 gpm.

In each scenario, the pumping rate at each individual well is 300 gpm. The extraction wells are screened over the entire thickness of the aquifer.

Figure A2-3



Items Highlighted for this Example

For this example, the following items pertaining to capture zone are presented:

- the impact that the number of monitoring locations can have on plume delineation, which impacts the width of the Target Capture Zone
- the impact that a variable regional flow direction can have on capture zone width calculations
- the impact that multiple extraction wells that are not oriented perpendicular to ground-water flow direction can have on capture zone width calculations

- the impact that the absence of water level data at or near extraction wells can have on interpretation of capture from water level maps
- the impact that heterogeneous aquifer conditions (e.g., preferential pathways) can have on capture zone evaluation
- the use of gradient vector maps

Each of these items is presented below.

Plume Delineation

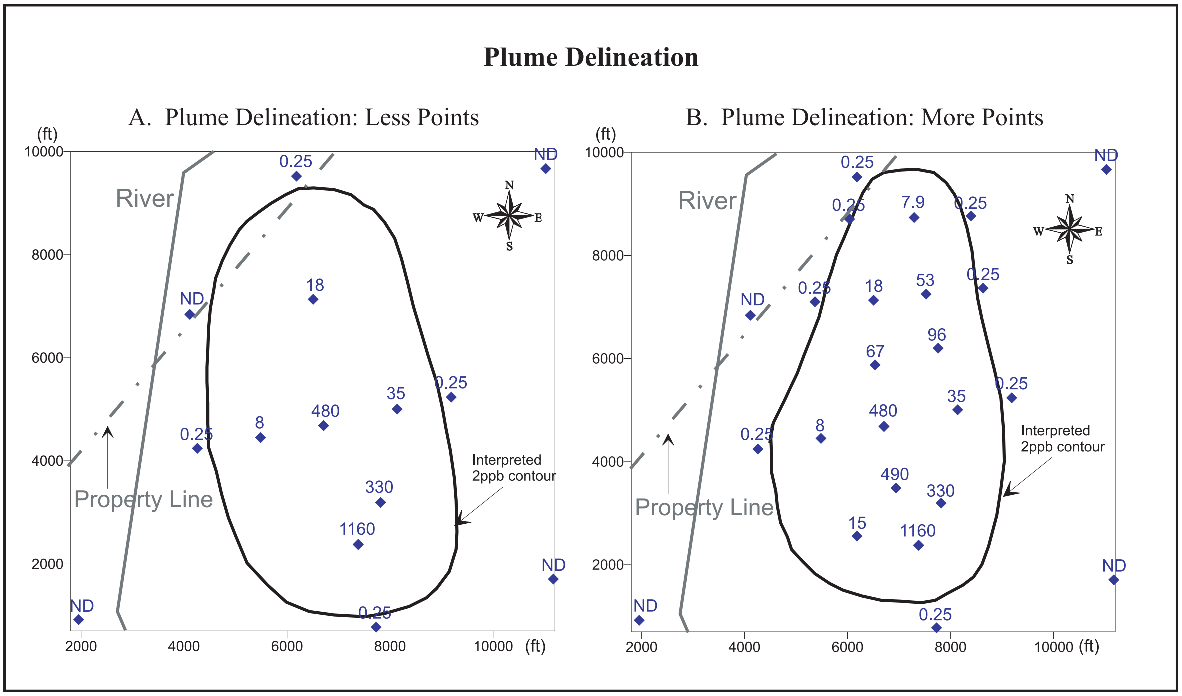
Plume delineation is associated with Step 1 of capture zone analysis. The plume delineation impacts the definition of the Target Capture Zone (Step 2), which for this site is based on the extent of the plume defined by the 2-ppb contour.

Figure A2-4 includes an illustration of the interpreted 2-ppb plume boundary, based on two different sets of available monitoring data:

- the figure on the left has fewer available points, such that the plume width is more uncertain (such as in the northeast portion of the plume)
- the figure on the right has more available points, so the delineation of the plume is more certain

For this site, the interpreted plume based on fewer points has greater width, which in turn would increase the size of the Target Capture Zone.

Figure A2-4



Impact of Regional Flow Direction on Capture Zone Width Calculations

Capture zone width calculations are associated with Step 4 of a systematic capture zone analysis. One assumption associated with these calculations is that regional hydraulic gradient is uniform (in both magnitude and direction).

As illustrated in Figure A2-1, regional hydraulic gradient at this site is variable with respect to direction, so it is not clear which direction is most appropriate for orienting the calculated capture zone for comparison to the plume boundary. In this case, the best option might be to use the flow direction closest to the toe of the plume where the extraction wells are located, which is more northerly than in some other portions of the plume.

Impact on Capture Zone Width Calculations When Extraction Wells are not Oriented Perpendicular to Ground-Water Flow

The estimated capture zone width for multiple extraction well scenarios will generally be similar to a single "representative well" case if all wells are oriented perpendicular to direction of regional flow and the pumping is evenly split between the wells. For this example, the pumping rate is split evenly among multiple extraction wells, but the wells are not oriented perpendicular to regional flow direction (compare water levels in Figure A2-1 with the orientation of extraction wells for each scenario in Figure A2-3). The well locations are more closely aligned with the property boundary than with the direction of ground-water flow. Therefore, a primary assumption of the capture zone width calculation for multiple wells is violated. In this case, an "equivalent well" will never accurately represent the actual multi-well capture zone due to the mis-alignment of the wells with the regional hydraulic gradient (in this case they are instead aligned with the property boundary). This again illustrates that these simple calculations are often of limited use because the simplifying assumptions they are based on do not allow the complexity of the actual system to be adequately represented.

Impact of Water Level Data At/Near Extraction Wells on Interpretation of Water Level Maps

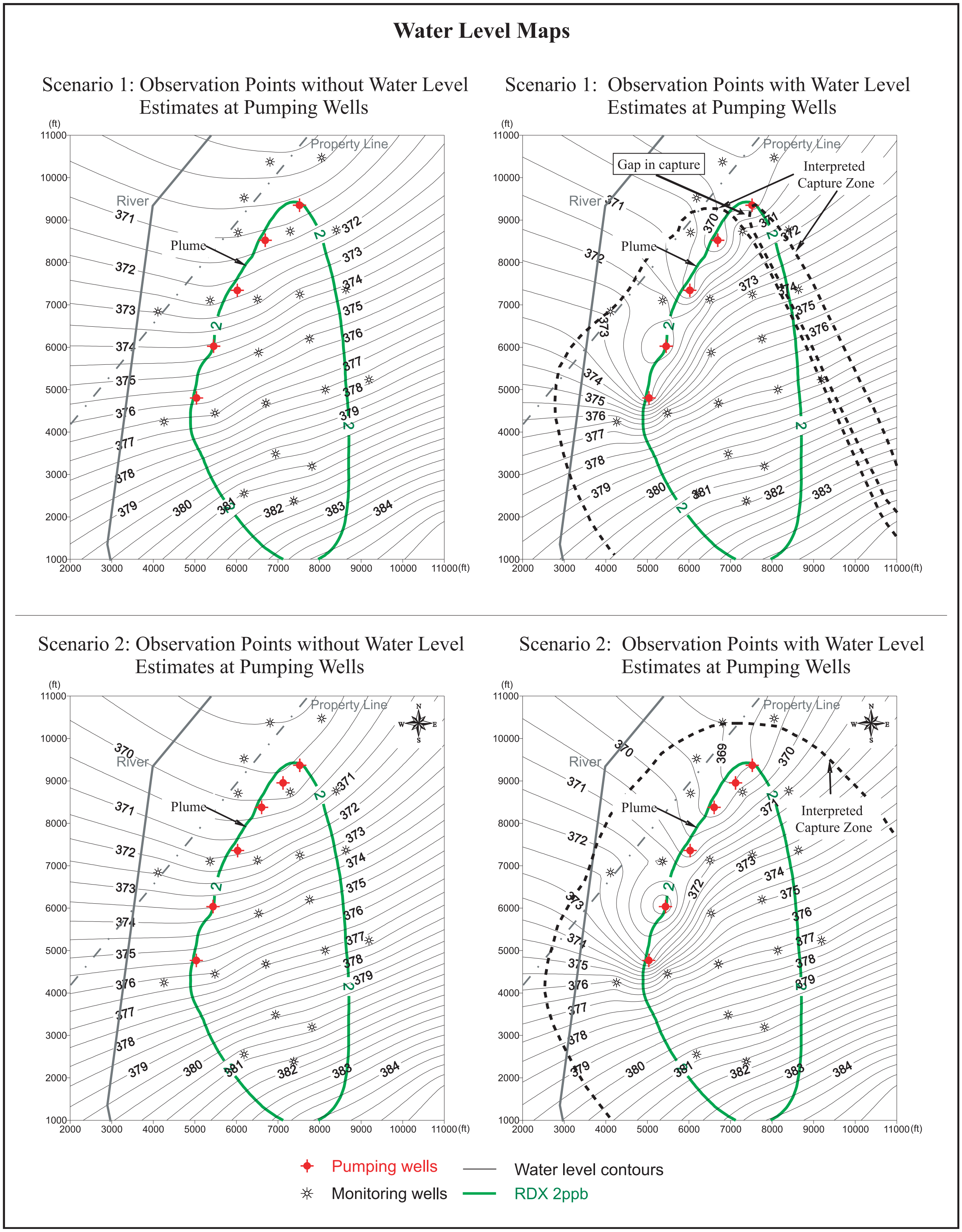
Interpreting capture based on water level maps is associated with Step 3 of a capture zone analysis. Figure A2-5 illustrates two water level maps for each pumping scenario at this site. One of the water level maps for each pumping scenario includes water level estimates at the extraction wells, and the other water level map for each scenario does not include water level estimates at the extraction wells.

When water levels near the extraction wells are not available, capture is not apparent or easily interpreted. Interpretation in those cases is biased towards an interpretation of poor capture. When water levels near the extraction wells are available, a completely different interpretation of capture can occur.

Impact of Heterogeneous Conditions (e.g., Preferential Pathways) on Capture Zone Evaluation

For this site, a potential supporting evaluation of capture is particle tracking in conjunction with a numerical model. Figure A2-6 illustrates simulated particle pathlines for each of the two pumping scenarios. Particles are released at the plume boundary in different layers, and tracked forward. For Scenario 1 (1,500 gpm) capture appears to fail in the area of the preferential pathway. For Scenario 2 (1,800 gpm), which includes an additional extraction well in that area, capture appears to succeed.

Figure A2-5

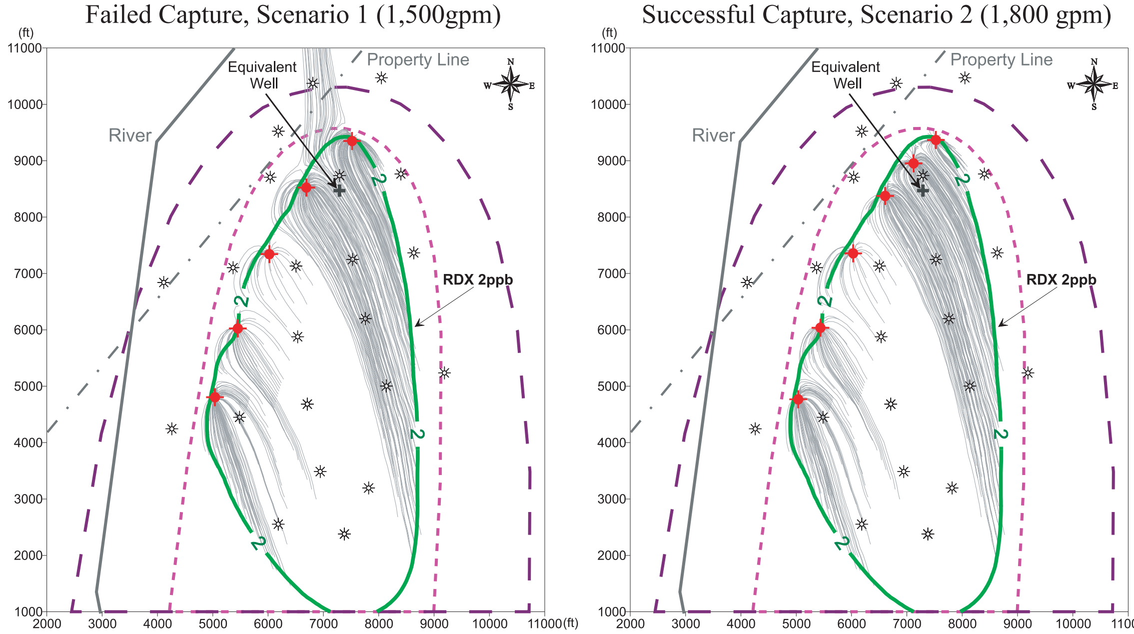


Water Level Maps
Scenario 1: Observation Points without Water Level Estimates at Pumping Wells
Scenario 1: Observation Points with Water Level Estimates at Pumping Wells
Scenario 2: Observation Points without Water Level Estimates at Pumping Wells
Scenario 2: Observation Points with Water Level Estimates at Pumping Wells
Property Line
River
Plume
Gap in capture
Interpreted Capture Zone
(ft)
Pumping wells
Monitoring wells
Water level contours
RDX 2ppb

Figure A2-6

Capture Zone Width Calculation and Particle Tracking Results

Failed Capture, Scenario 1 (1,500gpm)   Successful Capture, Scenario 2 (1,800 gpm)



<u>For performing capture zone width calculation:</u>
Q = 800 gpm or 1,500 gpm
K = 75 ft/day (representative value)
b = 300 ft
i = 0.013

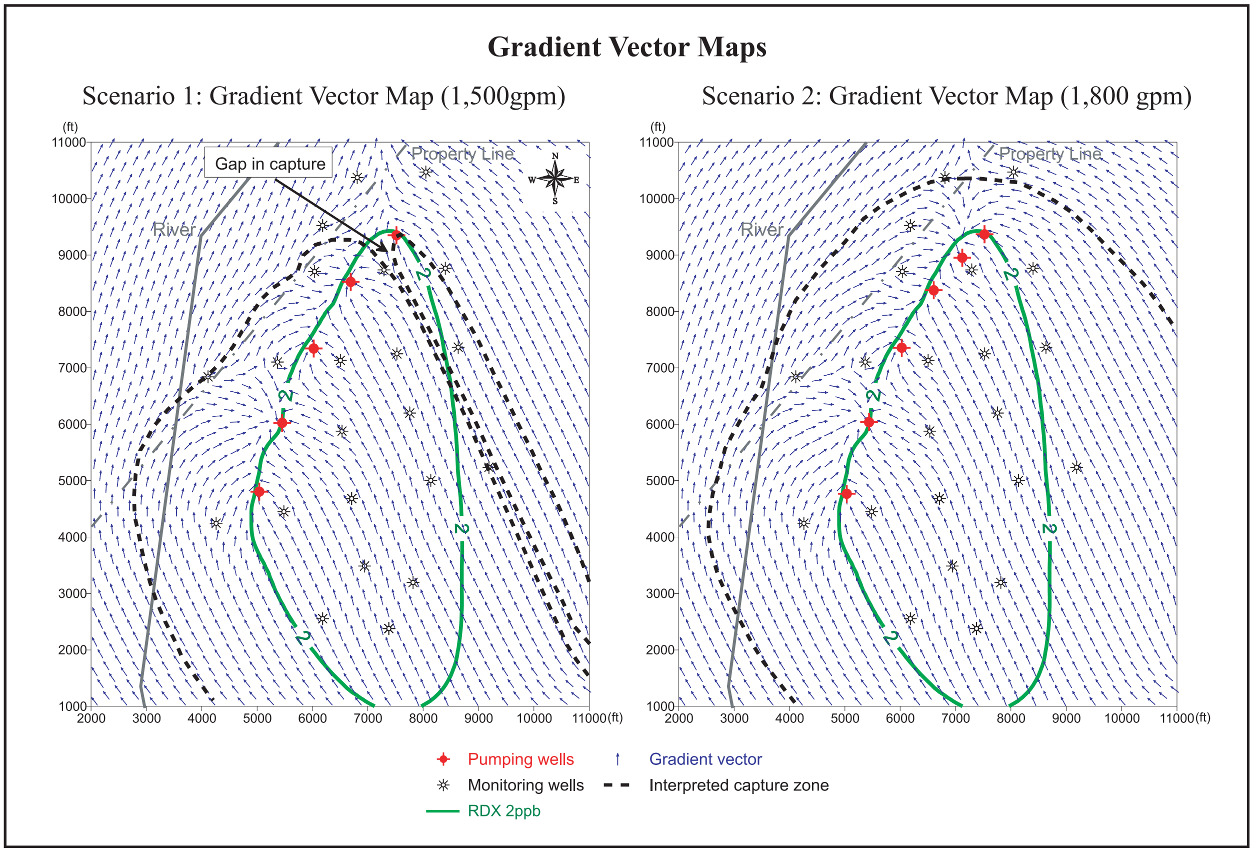
Capture zone widths (Figure A2-6) were calculated for 800 gpm (arbitrarily selected) and 1,500 gpm (same pumping rate as Scenario 1). This was done assuming one “equivalent well” and a regional flow direction orientated slightly east of north. There is no specific method for selecting the location of the “equivalent well”, and it was somewhat arbitrarily selected. The regional flow direction was selected qualitatively based on the measured water levels (Figure A2-1, which pertains to one point in time) plus the orientation of the interpreted plume. Selecting other orientations for uniform flow direction would lead to different orientations of the illustrated capture zones. Again, there is no easy or “correct” way to determine the location of the “equivalent well” or the uniform flow direction to utilize, because of the complexity of the actual system relative to the simplified assumptions associated with the calculation.

For Scenario 1 (1,500 gpm), the capture zone width from particle tracking is much smaller than the corresponding capture zone width calculation, probably because the calculation of capture zone width uses a uniform value of hydraulic conductivity. This does not accurately represent the aquifer, particularly in the area of the preferential pathway. To be more conservative, the calculation of capture zone width could use a hydraulic conductivity value at the high end of the expected range, but it still might overestimate capture near the preferential pathway.

Use of Gradient Vector Maps to Interpret Capture

Figure A2-7 presents a gradient vector map for the water level maps presented on the right-hand side of Figure A2-5. These maps were produced using the same software that produced the water level contours (i.e., the software produces the gradient vectors based on the contours). Note that the gradient vectors for Scenario 1 (left-hand side of Figure A2-7) indicate a potential gap in capture, consistent with the particle tracking results.

Figure A2-7



EXAMPLE A3

This example highlights complications of evaluating capture when off-site stresses are present. For this hypothetical example, not all six steps for capture zone analysis are fully demonstrated. Instead, specific items that demonstrate important aspects of capture zone analyses are highlighted.

Example Setup

The location of hypothetical site is illustrated in Figure A3-1. Land surface is generally flat. The stratigraphy consists of two aquifers (a surficial aquifer and a deeper aquifer) separated by an aquitard that is regionally discontinuous. However, the aquitard has been identified in all site borings to date. The site is not located close to any surface water bodies.

Based on regional data, the hydraulic conductivity in the surficial aquifer varies over a narrow range (approximately 28 ft/day). Regionally, the net recharge to the aquifer from precipitation is estimated at 9 to 15 inches per year.

The contaminant of concern at the site is dissolved TCE (Figure A3-1). Regional ground-water flow direction in both aquifers is to the north. Pre-remedy water levels in the surficial aquifer are illustrated in Figure A3-1. The plume extends approximately 1000 feet downgradient (i.e., north) of the site boundary in the surficial aquifer. The sources of contamination are located in the unsaturated zone, and the plume primarily impacts the surficial aquifer. Several sources of the TCE have been identified, and those sources have not yet been removed (further source area characterization is ongoing in advance of future source area remediation).

The site currently has an interim remedy. The objective of the interim remedy for this site is to prevent contaminants at concentrations above standards (5 ppb) from migrating beyond the property boundary in the future using extraction wells located on the site property. Ground-water quality in the shallow aquifer beyond the property boundary will continue to be monitored during the operation of the interim remedy. No active remediation for the deep aquifer is anticipated as part of this interim remedy, and long-term monitoring in the deep aquifer will continue to be performed to determine if concentrations in the deep aquifer decline over time based on the performance of the interim remedy in the shallow aquifer.

Based on these remedy objectives, the Target Capture Zone for the interim remedy only applies to horizontal capture in the shallow aquifer, and is defined for this site as a flow divide downgradient of the extraction wells over the entire width of the 5-ppb TCE plume. One representation of a Target Capture Zone is illustrated in Figure A3-2.

Scenarios Illustrated

This example is used to demonstrate the impact of off-site stresses on capture zone analysis for the interim remedy. Two pumping scenarios are presented (Figure A3-3):

- *Scenario 1* has 3 pumping wells screened in the surficial aquifer, with a combined pumping rate of 21 gpm.
- *Scenario 2* has the same 3 pumping wells (21 gpm combined) as Scenario 1, plus an off-site well pumping at 30 gpm that has recently been installed on a neighboring property (i.e., after the remedial design for the interim remedy was implemented).

Figure A3-1

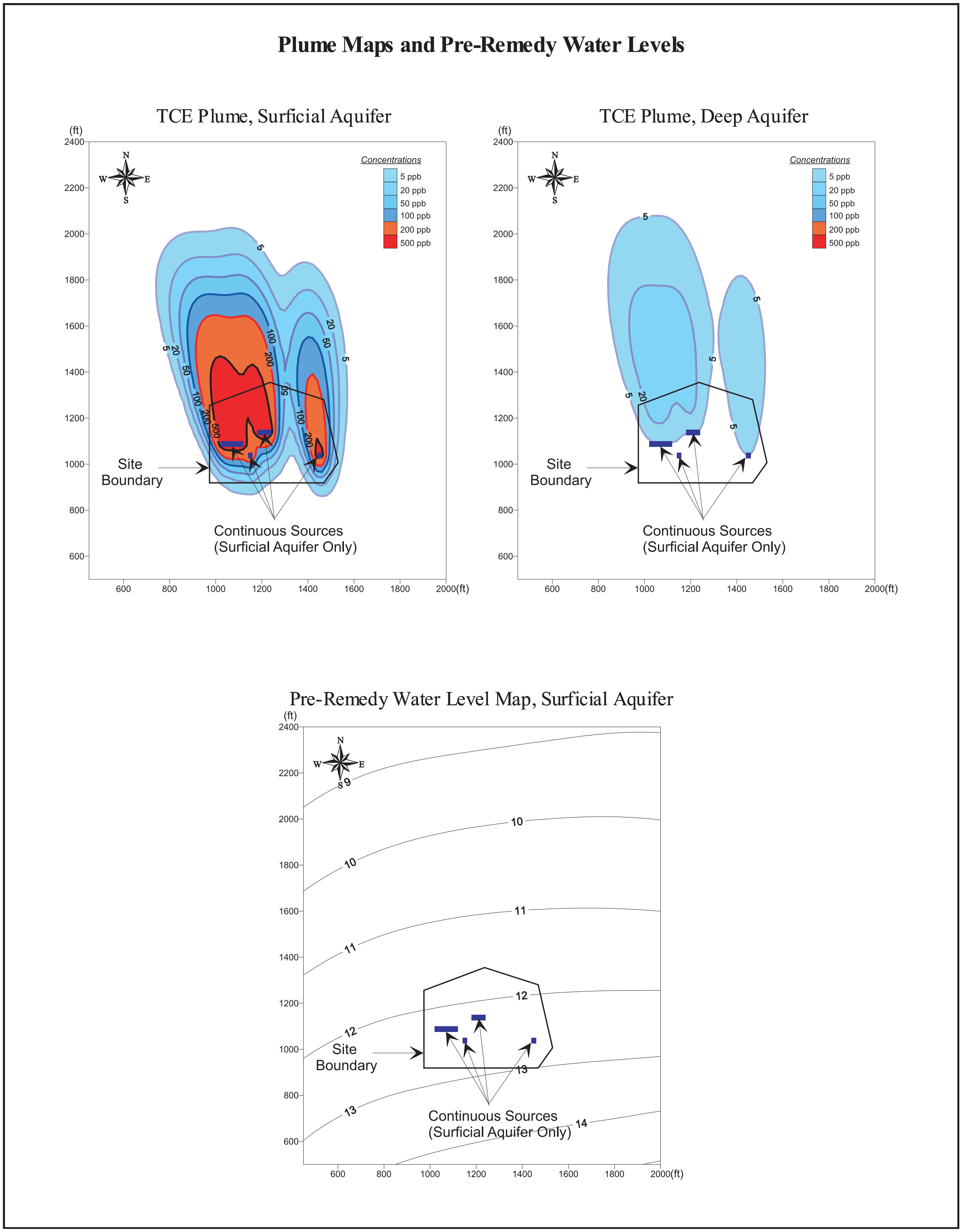

Plume Maps and Pre-Remedy Water Levels
TCE Plume, Surficial Aquifer
Concentrations
5 ppb
20 ppb
50 ppb
100 ppb
200 ppb
500 ppb
Site Boundary
Continuous Sources (Surficial Aquifer Only)
TCE Plume, Deep Aquifer
Pre-Remedy Water Level Map, Surficial Aquifer
(ft)
2000(ft)

Figure A3-2

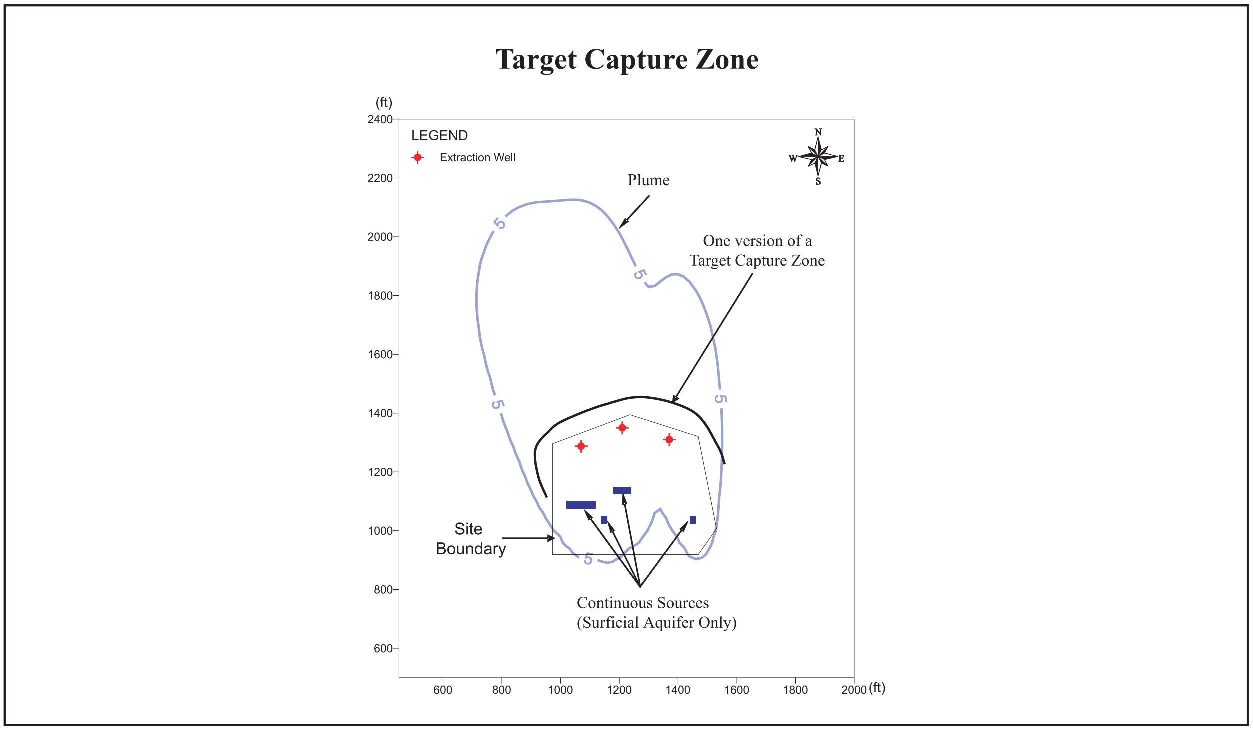
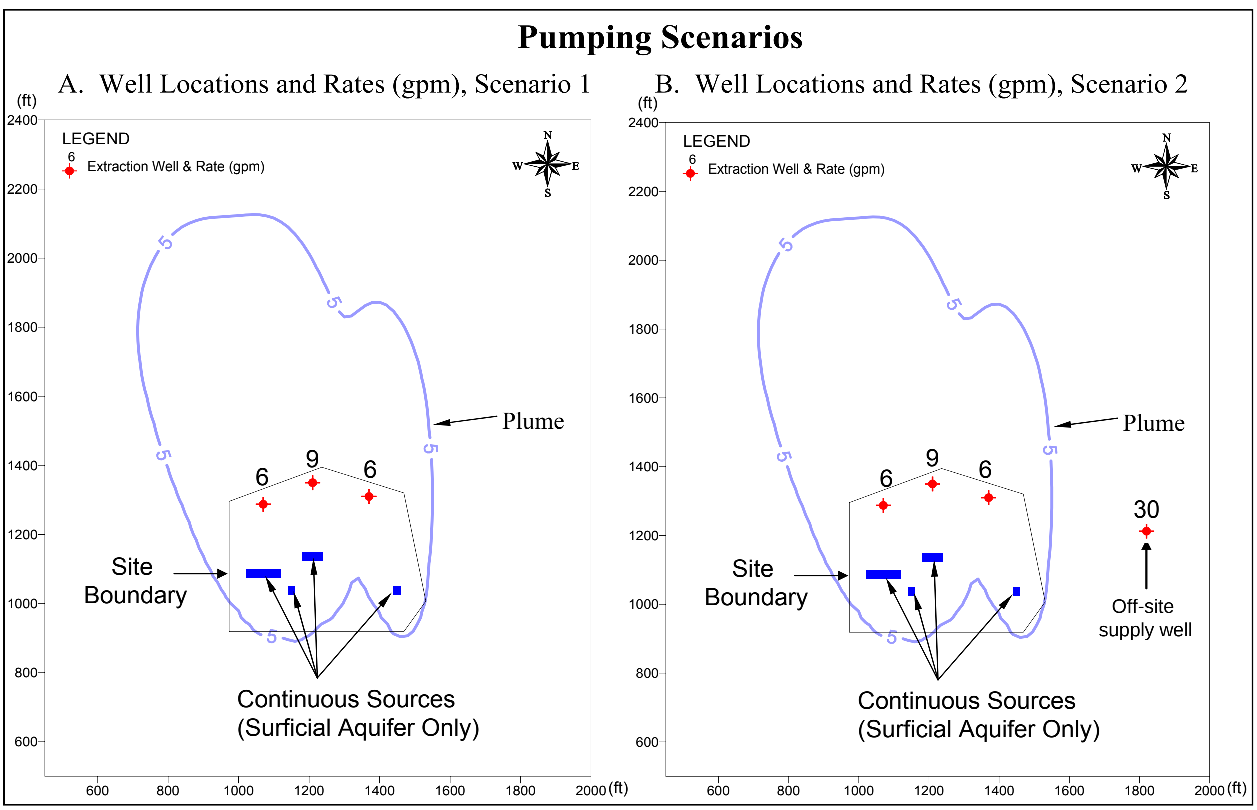


Figure A3-3



Items Highlighted for this Example

For this example, the following items pertaining to capture zone analysis are presented:

- the similarity of the capture zone width calculation to the particle tracking results at this site
- the importance of monitoring well location with respect to interpretation of capture based on water level pairs
- the impact an off-site stress can have on the capture zone (and associated capture zone analysis)
- an illustration of using a sentinel well to indicate failed capture, and the importance of locating sentinel wells in critical locations

Similarity of the Capture Zone Width Calculation to the Particle Tracking Result at this Example Site

Capture zone width calculations are associated with Step 4 of a systematic capture zone analysis. Such calculations are often of limited utility because one or more of the simplifying assumptions is typically not met. For this site, however, the surficial aquifer is reasonably homogeneous, there is poor connection to other aquifers, and there are no nearby surface water bodies to provide water to the extraction wells. Therefore, a capture zone width calculation would be expected to be more reliable at this type of site.

Figure A3-4 illustrates the comparison of a capture zone width calculation for this site with the simulated particle tracking results for pumping Scenario 1. To perform the particle tracking, one particle was initially located in selected model grid cells in the model layer representing the surficial aquifer, vertically in the middle of the layer, and tracked forward in space to the location where it was removed. For each particle removed by one of the remedy extraction wells, a symbol was plotted at the initial location of that particle, to identify the specific well that captured the particle.

For this site the capture zone width calculation approximates the capture zone reasonably well, for the reasons discussed above.

Importance of Monitoring Well Locations for Water Level Pairs

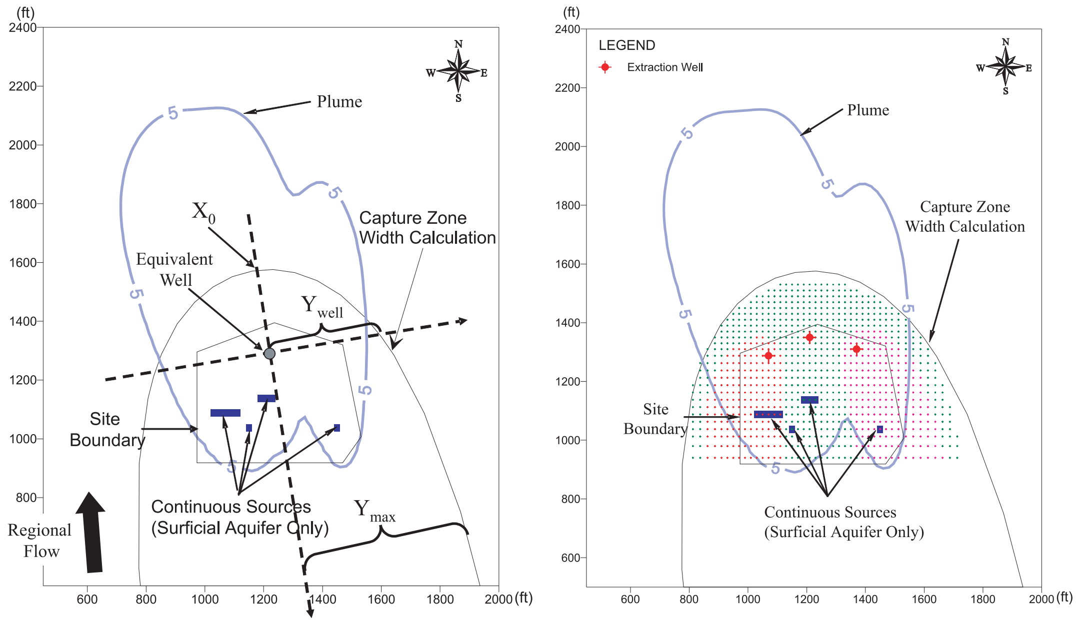
Figure A3-5 illustrates water level measurements at monitoring well pairs for Scenario 1 (without off-site pumping) and Scenario 2 (with off-site pumping), respectively. Two sets of water level pairs are illustrated for each pumping scenario:

- water level pairs along the northern property boundary, downgradient of on-site ground-water extraction wells associated with the interim remedy
- water level pairs along the eastern property boundary, between the on-site extraction wells and the off-site well

For Scenario 1, with no off-site pumping, some of the water level pairs suggest inward flow at the northern property boundary, and some of the water level pairs suggest outward flow at the northern property boundary. Note that the locations indicating inward flow are those immediately downgradient of the extraction wells, and the locations indicating outward flow are those in between the extraction wells.

Figure A3-4

Particle Tracking versus Capture Zone Width Calculation, Scenario 1



<u>For performing capture zone width calculation:</u>

- Q = 21 gpm
- K = 28 ft/day (based on average of slug test)
- b = 31 ft (based on well logs)
- I = 0.0033 (based on pre-pumping water level maps)

<u>Capture zone width calculation results:</u>

- X_0 = -225 ft
- Y_{well} = 353 ft
- Y_{max} = 706 ft

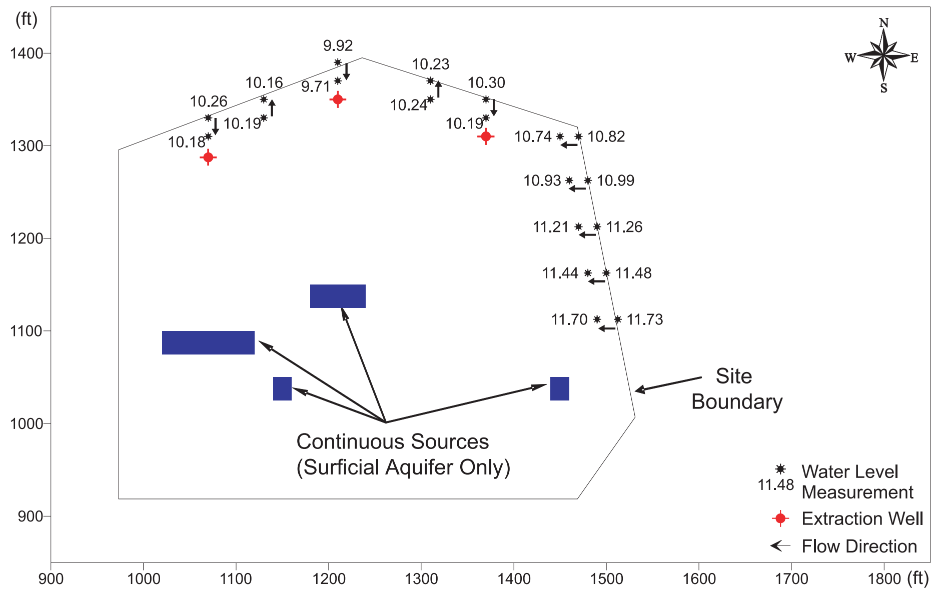
Note: When this figure is viewed in black-and-white, the extent of the total capture zone is illustrated. When this figure is viewed in color (such as from within the PDF digital version), the colors additionally highlight the capture zones of individual wells.

This illustrates that it is more likely to observe inward hydraulic gradients immediately downgradient of the extraction wells. As illustrated in Figure 10 in the main document, the outward gradients at some locations along the northern property boundary do not specifically indicate failed capture. It is possible that water flows outward between the wells at the property boundary but eventually flows inward and reaches the wells. Some potential interpretations regarding outward flow observed at a property boundary are illustrated schematically in Figure A3-6. In that figure, the top interpretation represents failed capture, but the bottom two interpretations represent successful capture despite the outward hydraulic gradients at the boundary.

Figure A3-5

Water Level Pairs

Head Differences at Water Level Pairs, Scenario 1



Head Differences at Water Level Pairs, Scenario 2

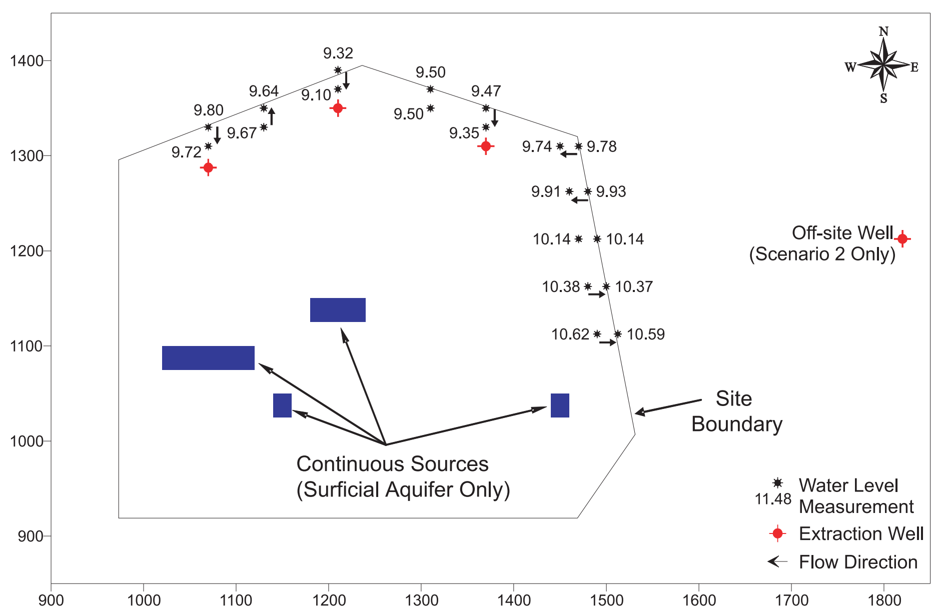
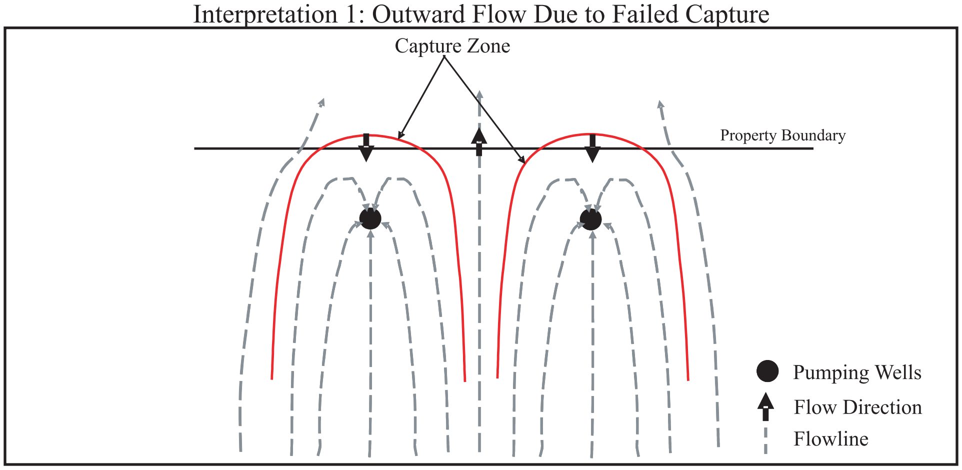


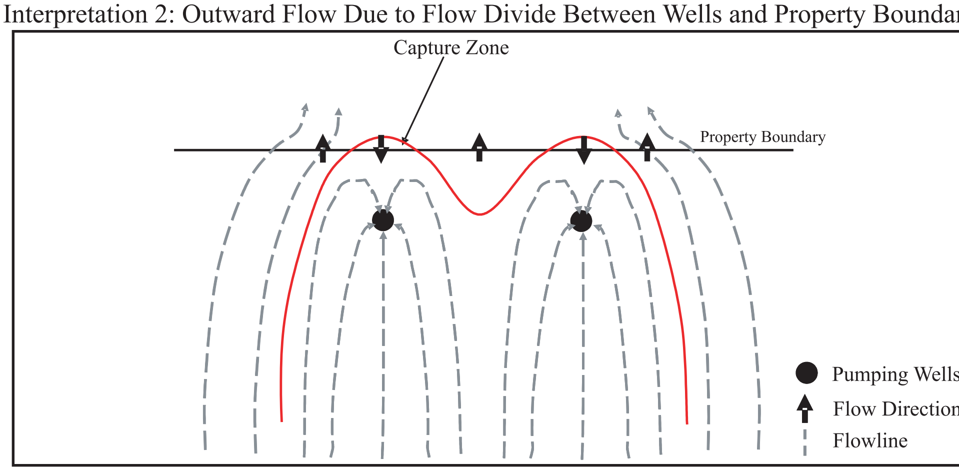
Figure A3-6

Potential Interpretations of Outward Flow Between Extraction Wells

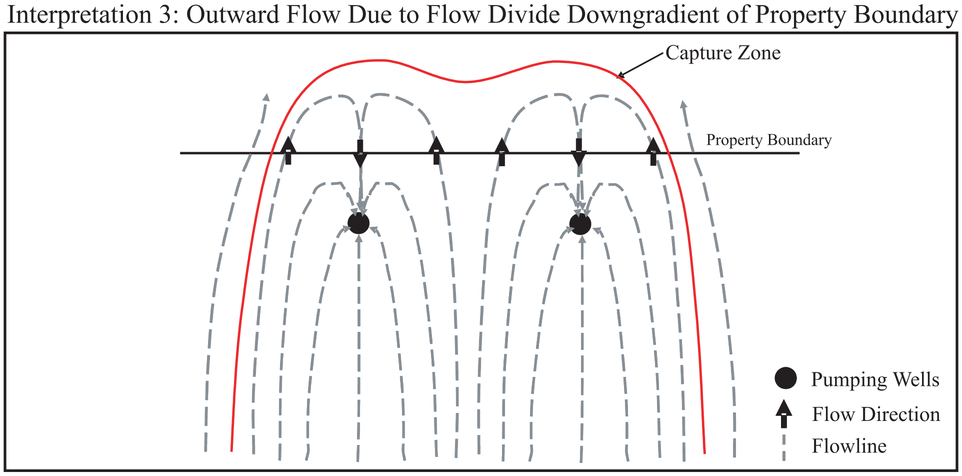
Interpretation 1: Outward Flow Due to Failed Capture



Interpretation 2: Outward Flow Due to Flow Divide Between Wells and Property Boundary



Interpretation 3: Outward Flow Due to Flow Divide Downgradient of Property Boundary



The capture zone width calculation and the particle tracking results for this example site (Figure A3-4) suggest that hydraulic containment is in fact achieved for Scenario 1, despite the outward hydraulic gradients observed between some water level pairs at the northern property boundary (Figure A3-5). To add conservatism, pumping rates could be increased to provide inward gradients at all water level pairs.

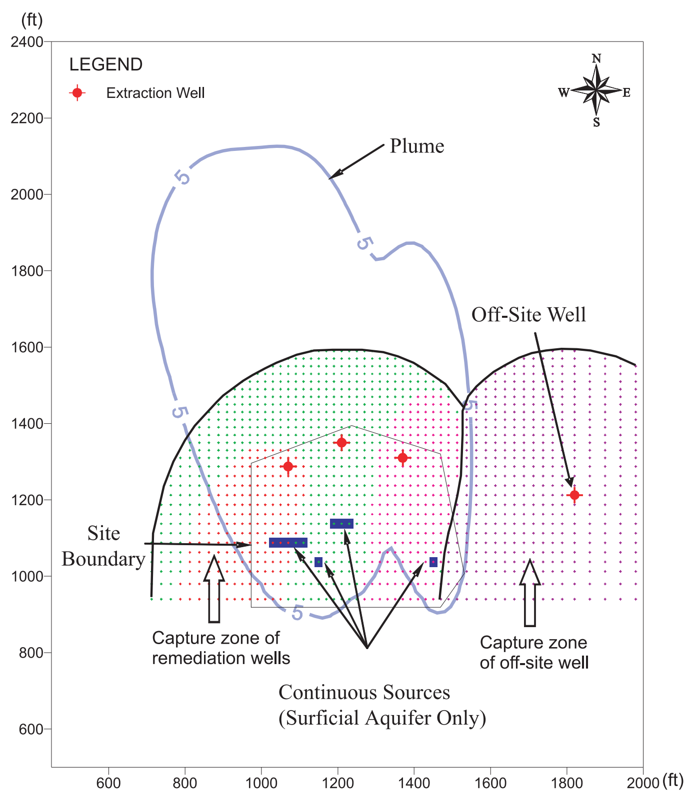
Also note in Figure A3-5, for Scenario 1, that inward gradients are established at every pair along the eastern property boundary. In general, it is harder to achieve inward gradients at locations downgradient of extraction wells compared to locations to the side of the extraction wells, due to the influence of the regional hydraulic gradient.

For Scenario 2, where an off-site well is added after remediation is initiated, the data from the water level pairs (bottom of Figure A3-5) indicate similar results along the northern property boundary, but also indicate a potential for outward flow along the eastern property boundary. Particle tracking results for Scenario 2 are illustrated in Figure A3-7, and add an additional line of evidence that horizontal capture fails when the off-site pumping is added, because some on-site water reaches the off-site well.

This example illustrates that water level pairs are a useful line of evidence regarding capture, but generally should be supplemented by other lines of evidence. Also, the analysis of water level pairs along

Figure A3-7

Particle Tracking Results, Scenario 2



Note: When this figure is viewed in black-and-white, the extent of the total capture zone is illustrated. When this figure is viewed in color (such as from within the PDF digital version), the colors additionally highlight the capture zones of individual wells.

the eastern property boundary, indicating the impacts from the off-site well, is only possible if water level pairs are located in that area. This illustrates that selection of locations for water level pairs, and the schedule for evaluating water levels at those locations, should take into account the potential for current and/or future off-site stresses.

Impact an Off-Site Stress Can Have on the Capture Zone (and Associated Capture Zone Analysis)

The particle tracking results for the two pumping scenarios (Figures A3-4 and A3-7) illustrate that the addition of an off-site stress can impact the capture zone of an extraction system. This suggests that it is important for site managers to stay abreast of developments at neighboring properties, or in some cases changes in pumping at regional water supply wells. Similar impacts to capture zones can occur due to transient influences such as irrigation pumping or irrigation recharge.

Illustration of a Sentinel Well for Evaluating Capture

Figure A3-8 illustrates several monitoring wells located beyond the property boundary, and concentration trends over time at those wells for each of the two pumping scenarios. Monitoring wells MW-1s and MW-2s are already impacted prior to the remedy. MW-5s is a sentinel well, because it is located in an area not yet impacted by the site.

For Scenario 1, the concentration trends at MW-1s and MW-2s are similar to those observed for the other examples in this document. At the location closest to the extraction wells (MW-1s) the concentration remains above cleanup levels, but without other lines of evidence it is hard to interpret if that is because capture is incomplete, or if it is because MW-1s is within the capture zone. MW-2s, located further downgradient, eventually cleans up below the 5 ppb cleanup level, but it takes more than 15 years for that to occur. This example again illustrates the complications of evaluating downgradient performance monitoring wells to demonstrate successful capture in the absence of hydraulic monitoring data. Each line of evidence plays a role in the overall evaluation. In this case, the chemical monitoring data over a long period of time support interpretations from the hydraulic monitoring. The chemical data provide direct evidence that the interim remedy goals are ultimately achieved (based on long-term concentration trends at MW-2s) and suggest that MW-1s is likely located within the capture zone.

For Scenario 2, there is a concentration increase above the cleanup level at sentinel well MW-5s within one year. This type of monitoring would immediately indicate the potential for failed hydraulic containment. It could also be due to an off-site contaminant source, and further investigation would be appropriate. By using other lines of evidence regarding capture (such as the water level pairs illustrated in Figure A3-5 and the particle tracking results illustrated in Figure A3-7), it seems likely that the concentration increase observed in the sentinel well is due to failed capture. Also, MW-2s does not reach the cleanup level for Scenario 2, likely because it is within the capture zone of the extraction wells, whereas it is located downgradient of the capture zone in Scenario 1.

Note that the location of this sentinel well (MW-5s) is not immediately downgradient of the defined plume, based on background-water levels. A sentinel well would only be placed in the vicinity of MW-5s if site managers are aware of the potential off-site stress at the neighboring property. This again illustrates the importance of being aware of potential off-site stresses that may impact the capture zone.

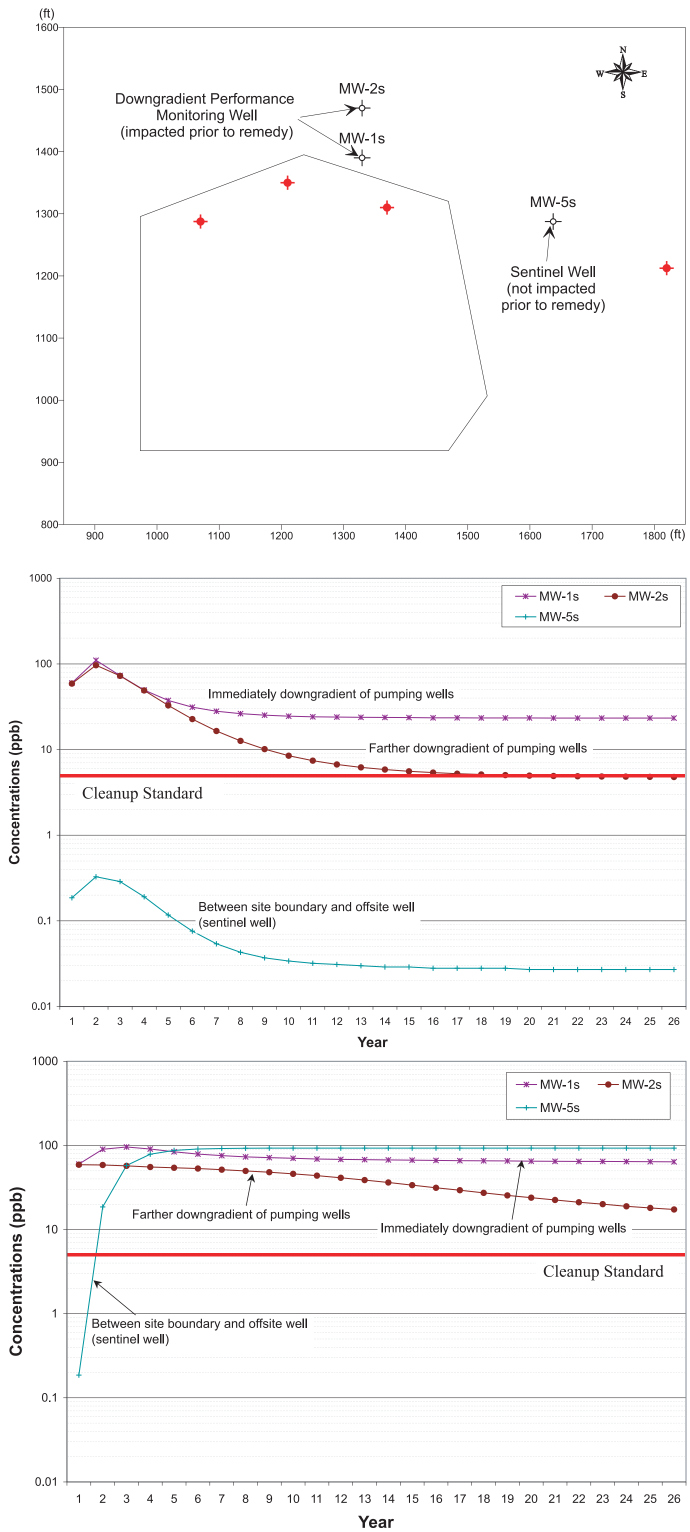
Figure A3-8

Concentration Trends

A. Candidate Locations for Downgradient Performance Monitoring Wells

B. Concentration vs. Time, Scenario 1

C. Concentration vs. Time, Scenario 2



APPENDIX B:

EXAMPLES FROM TWO ACTUAL SITES

INTRODUCTION TO APPENDIX B:
EXAMPLES FROM TWO ACTUAL SITES

The following examples present capture zone evaluations for two actual sites to demonstrate the application of the systematic approach presented in the main document. The example sites are as follows:

- Example B1: East Canal Creek Area (ECCA), Aberdeen Proving Grounds, Maryland

- Example B2: Milan Army Ammunition Plant, Operable Unit #4, Tennessee

The sole purpose of these examples is to demonstrate the application of the systematic approach to capture zone analysis at actual sites by applying the suggested steps in the guidance document to the sites using the existing site data, maps, and records. No attempt is made to present, reproduce, or discuss all site data or all previous work products associated with these example sites. There was no evaluation made of overall remedy performance or any portion of remedy performance beyond the hydraulic capture being discussed. Statements regarding suitability or adequacy of the performance monitoring system and sampling, achievement of performance goals, or any other aspects of the performance of the system are expressly not made here. Inclusion of these examples does not imply any endorsement of the remedy or of the performance monitoring of the remedy.

EXAMPLE B1
Example Capture Zone Evaluation, ECCA Site

SITE BACKGROUND INFORMATION

Location and Physical Setting

The East Canal Creek Area (ECCA) represents the eastern portion of the 700-acre Canal Creek Study Area (CCSA), which is located within the Aberdeen Proving Grounds (APG). APG is a 72,000-acre Army installation located in southeastern Baltimore County and southern Harford County, Maryland, on the western shore of the upper Chesapeake Bay (see Figure B1-1). The East Branch Canal Creek is a small stream that flows southward in the western portion of the ECCA (see Figure B1-2 for a more detailed view of the ECCA). Kings Creek is located in the eastern portion of the ECCA. The land surface is characterized as low-rolling terrain. The topographic elevation is near sea level in the vicinity of Kings Creek, and is less than 30 feet above mean sea level (msl) throughout the ECCA.

Site Geology and Hydrogeology

The study area lies within the Atlantic Coastal Plain physiographic province. The regional geology consists of unconsolidated sediments of sand, silt, clay, and gravel in a complex network of interbeds and discontinuous lenses that thicken to the east. Crystalline basement rock occurs approximately 500 feet below ground surface. The hydrostratigraphic units are as follows (see generalized cross section presented in Figure B1-3, and detailed west-to-east cross section presented in Figure B1-4):

- Surficial Aquifer (discontinuous, up to 35 ft thick)
- Upper Confining Unit (10 to 50 ft thick)
- Canal Creek Aquifer (10 to 70 ft thick)
- Lower Confining Unit (35 to 65 ft thick)
- Lower Confined Aquifer

The Canal Creek Aquifer is the primary aquifer in the area, and as discussed later, it has been impacted by site contaminants. In the general location of the East Branch Canal Creek, a paleochannel of Pleistocene age eroded the Upper Confining Unit, and in that area the Surficial Aquifer is in direct contact with the Canal Creek Aquifer (see Figure B1-3). Based on Figure B1-3, East Branch Canal Creek is a gaining creek due to discharge of ground water from the surficial aquifer.

In the Surficial Aquifer, ground-water flow direction is generally away from topographic highs towards the surface water bodies where ground-water discharges (i.e., within the study area illustrated in Figure B1-1, ground-water flow in the Surficial Aquifer is to the west in the vicinity of East Branch Canal Creek and to the east in the vicinity of Kings Creek). In the deeper aquifers (Canal Creek Aquifer and the Lower Confined Aquifer) ground-water flow direction in the ECCA is generally to the southeast, and does not discharge to Kings Creek due to the presence of the Upper Confining Unit.

Figure B1-1. Location of Canal Creek Study Area

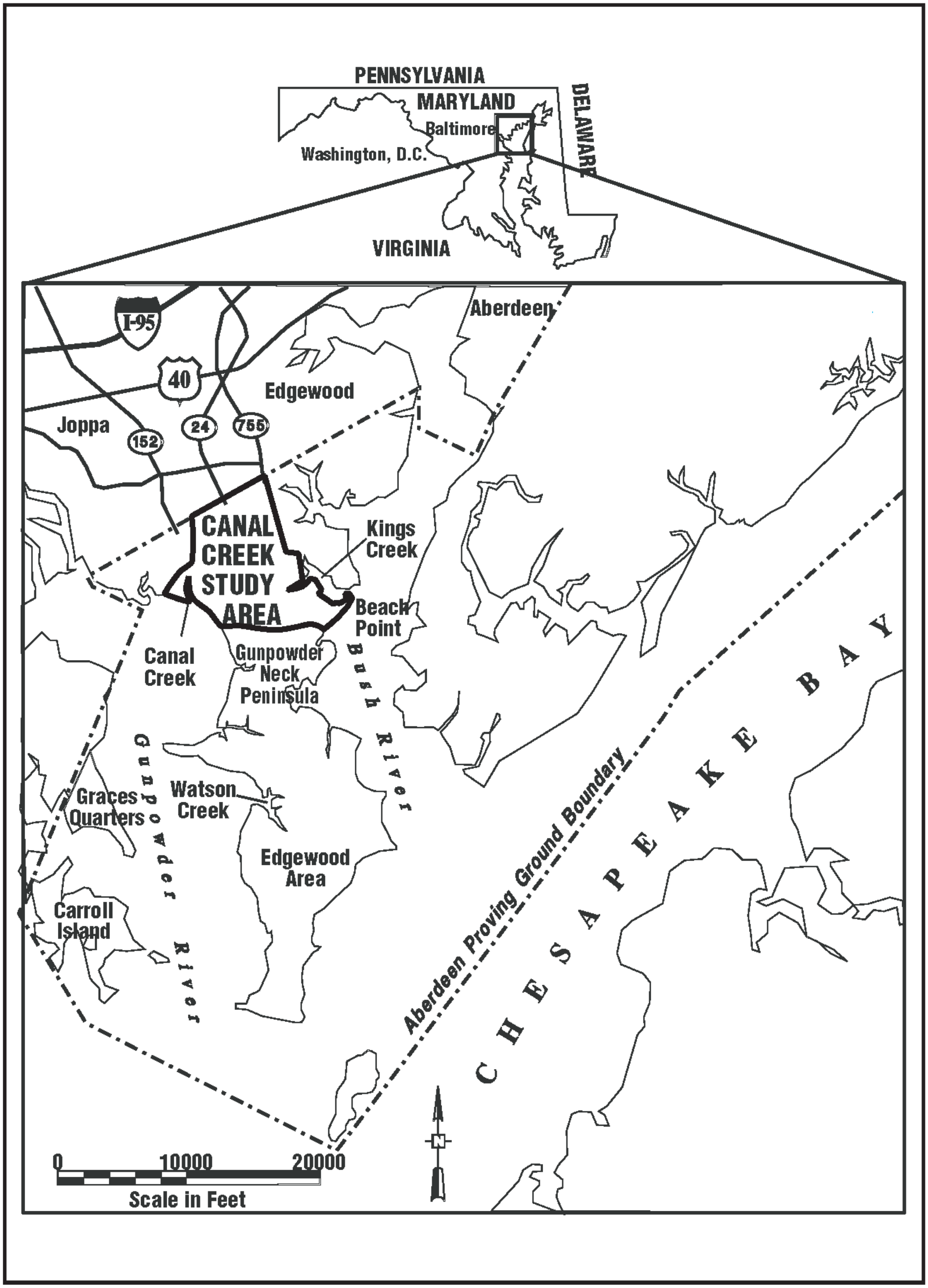


Figure B1-2. ECCA Study Area with VOC Plume and Extraction System

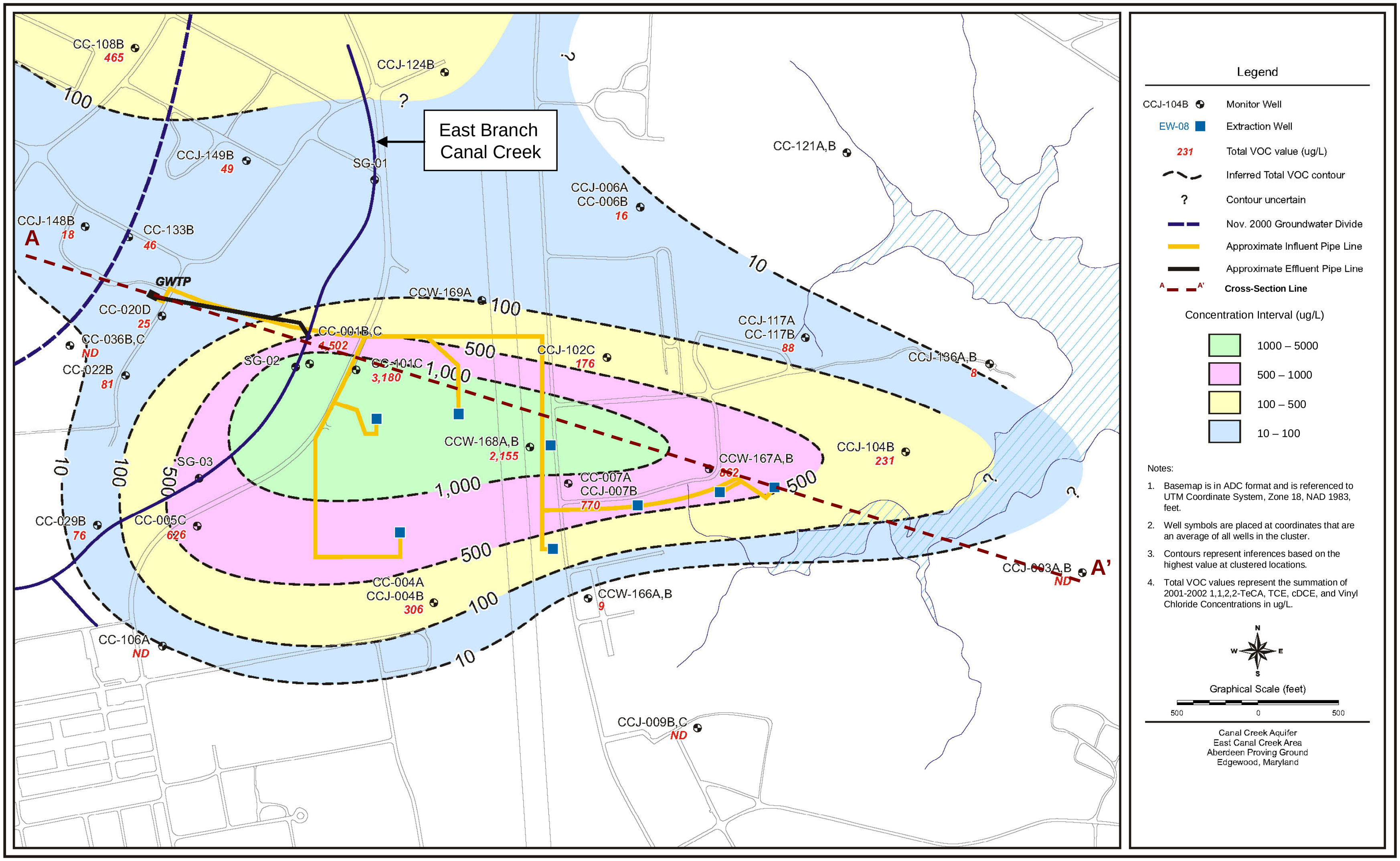
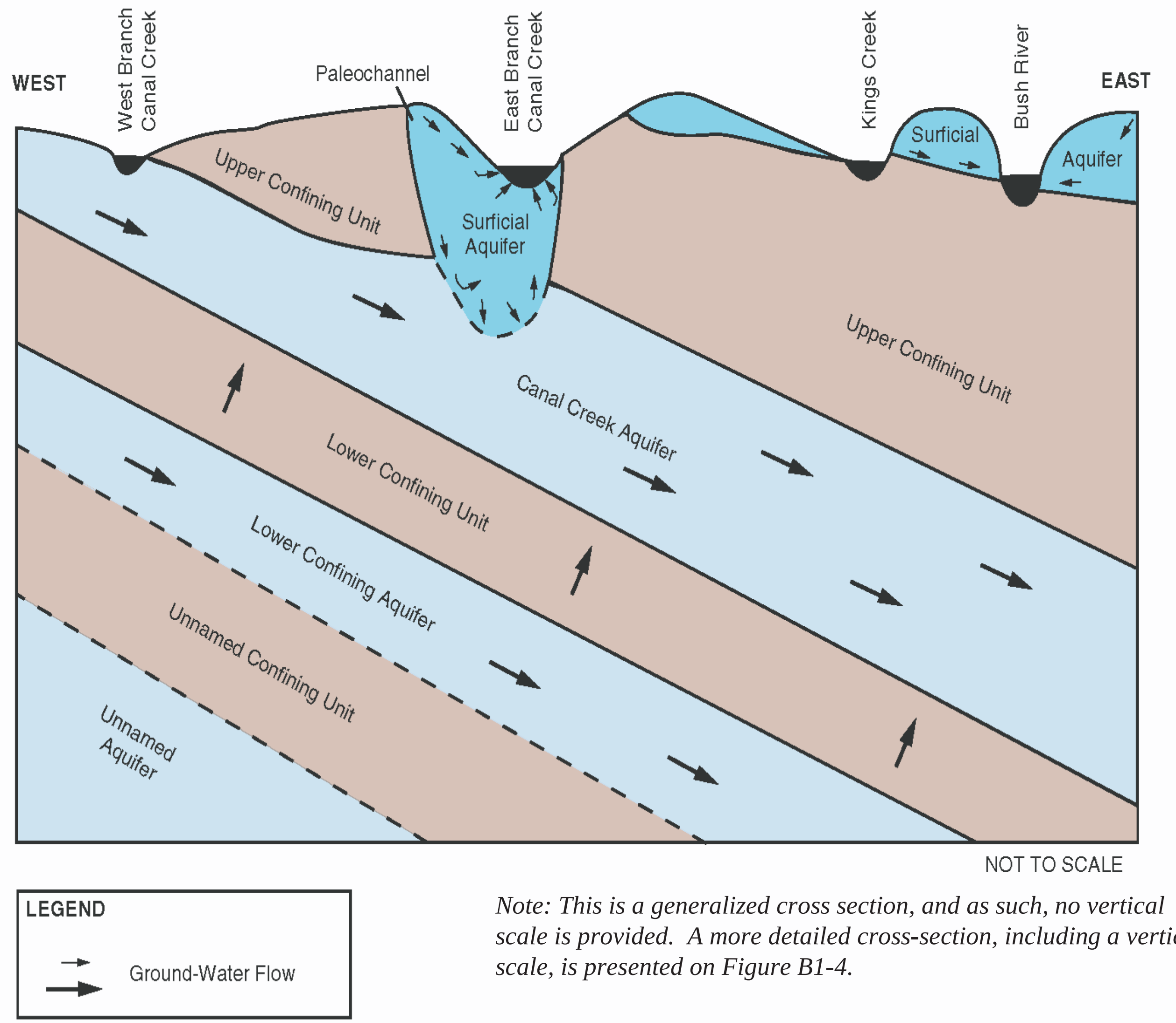
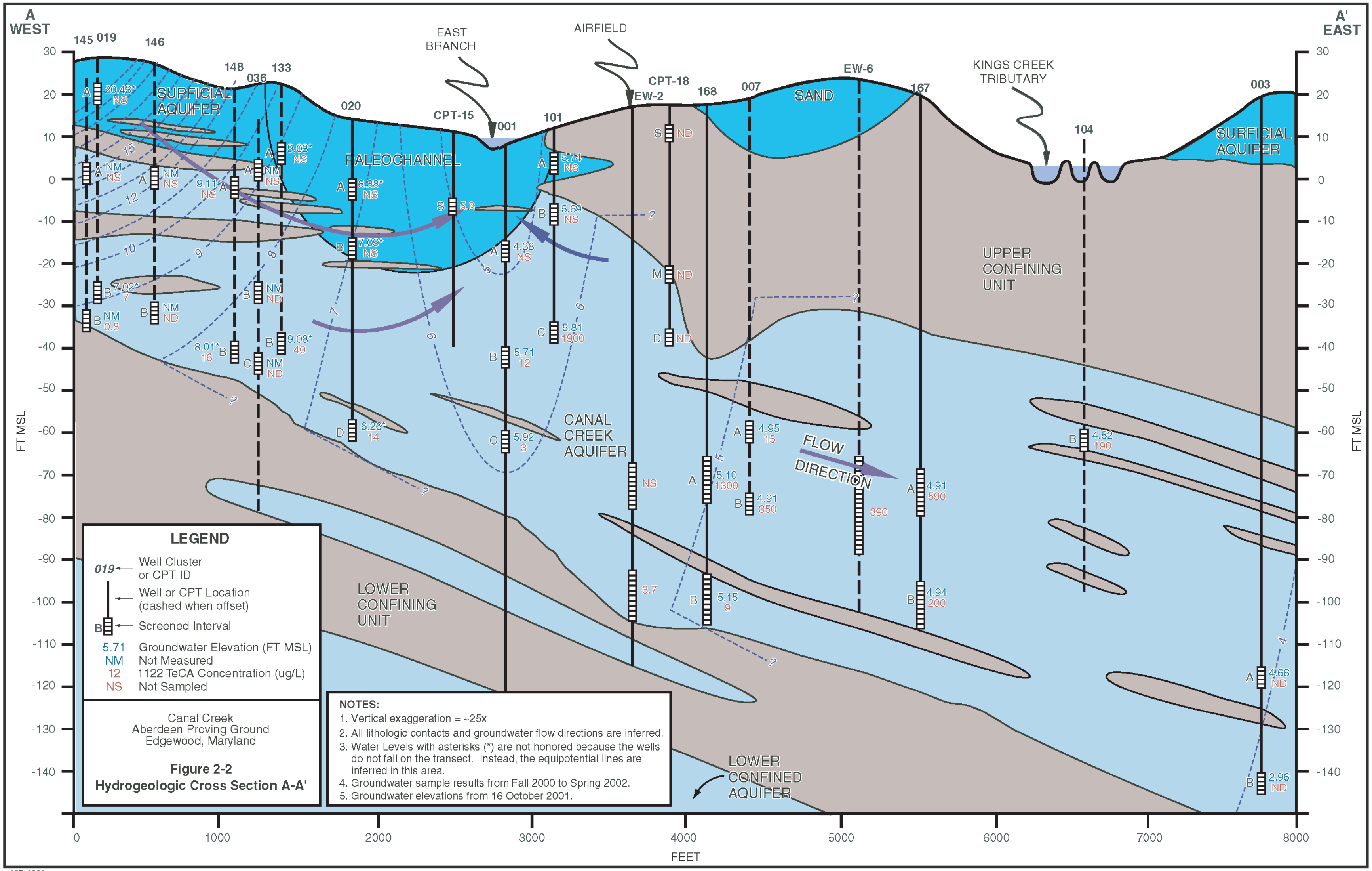


Figure B1-3. Generalized Hydrogeologic Cross Section



Note: This is a generalized cross section, and as such, no vertical scale is provided. A more detailed cross-section, including a vertical scale, is presented on Figure B1-4.

Figure B1-4. Detailed West-to-East Cross Section



Vertical hydraulic gradients are generally upward from the Lower Confined Aquifer to the Canal Creek Aquifer. Vertical hydraulic gradients between the Surficial Aquifer and the Canal Creek Aquifer vary in direction. In many areas hydraulic gradients are downward from the Surficial Aquifer to the Canal Creek Aquifer. In the paleochannel area near the East Branch Canal Creek, however, hydraulic gradient is generally upwards from the Canal Creek Aquifer to the Surficial Aquifer.

Transmissivity and hydraulic conductivity of the Canal Creek Aquifer in the vicinity of the extraction wells were estimated from aquifer tests at each of the eight individual extraction wells (locations of extraction wells are illustrated in Figure B1-2). A representative value for transmissivity is approximately 2,200 ft^2/d, and based on a typical thickness of 55 ft for the Canal Creek Aquifer in the vicinity of the extraction wells, the average hydraulic conductivity is approximately 40 ft/d. Transmissivity varies from this average value due to variations of hydraulic conductivity and aquifer thickness. The aquifer testing yielded a transmissivity range of 965 ft^2/d to 3,753 ft^2/d.

Contaminants of Concern

Historically, the Canal Creek Area was a former manufacturing center of military-related chemicals and agents. Previous ground-water investigations identified a large (approximately 5,000 ft long and 2,500 ft wide) dissolved-phase chlorinated VOC plume in the Canal Creek Aquifer in the ECCA. Pre-remediation concentrations for total VOCs are presented in Figure B1-2. Chlorinated solvents 1,1,2,2-tetrachloroethane (1122-TeCA) and trichloroethene (TCE) were identified as the primary contaminants. Elevated concentrations of VOC daughter products dichloroethene (DCE) and vinyl chloride (VC) were also detected. The shape of the contaminant plume likely has been influenced by historical water supply pumping from the Canal Creek Aquifer, which elongated the plume in an east-west direction.

Contaminants are found throughout the vertical extent of the Canal Creek Aquifer, but concentrations are lower near the bottom of the aquifer. For example, as presented in Figure B1-4, the 1122-TeCA concentration at location 168 is 1,300 ug/l in the middle of the aquifer, but only 9 ug/l near the bottom of the aquifer. Due to the upward hydraulic gradient from the aquifer below the Canal Creek Aquifer, further downward migration is not expected. Existing monitoring wells in the deep aquifer confirm that downward migration is not occurring.

Ground-Water Remedial System

The Record of Decision (ROD) was issued for the ECCA plume on July 17, 2000. It specified ground-water extraction and treatment as the selected remedy for the main part of the plume, with institutional controls and natural processes for the distal portion of the plume. Based on several site-specific constraints, the primary objectives include the following: (1) maintain hydraulic capture of the 100 µg/L composite VOC isocontour; and (2) provide mass removal for the VOC source area.

The extraction wells and treatment system were completed in 2002-2003. The ground-water treatment plant (GWTP) is designed to handle a flow rate up to 305 gpm. The effluent is discharged to East Branch Canal Creek. The system started operation on April 7, 2003.

The approved design utilized eight extraction wells with a total yield of 197 gpm. Extraction well locations are illustrated in Figure B1-2 (extraction well names are provided in Figures B1-6 to B1-9, which are presented later). The extraction wells are six-inches in diameter with depths ranging from 70 to 118 ft below ground surface (bgs). Well depths and screen intervals for two of the extraction wells (EW-2 and EW-6) are illustrated in Figure B1-4. EW-2 has two screen intervals, one in the middle of the Canal

Creek Aquifer and one near the bottom of the Canal Creek Aquifer. EW-6 has one screen interval, in the lower portion of the Canal Creek Aquifer. In general, the extraction wells are screened in the lower portion of the Canal Creek Aquifer. Each of the eight extraction wells are equipped with electric submersible pumps that continuously pump ground water to the GWTP. The pumping rates, which vary from 10 to 40 gpm at individual wells, are based on ground-water flow modeling that was conducted prior to GWTP start-up. The design flow rate at each individual extraction well is listed in Table B1-1.

Table B1-1. Design Rate at Each Extraction Well

Extraction Well	Design Flow Rate (gpm)
EW-1	16
EW-2	10
EW-3	10
EW-4	40
EW-5	26
EW-6	26
EW-7	29
EW-8	40
Total	*197*

Extraction wells typically pump at the design flow rate, and when that occurs the total system extraction rate is similar to the design system flow rate of 197 gpm. However, due to periodic downtime of individual wells or the entire system, the average flow rate achieved over each quarter is generally less. The average total flow rate for each quarter from mid-2003 to early-2005 is illustrated in Figure B1-5. Excluding first quarter of 2005, when considerable downtime was experienced, the long-term average pumping rate actually achieved is approximately 150 gpm.

CAPTURE ZONE EVALUATION

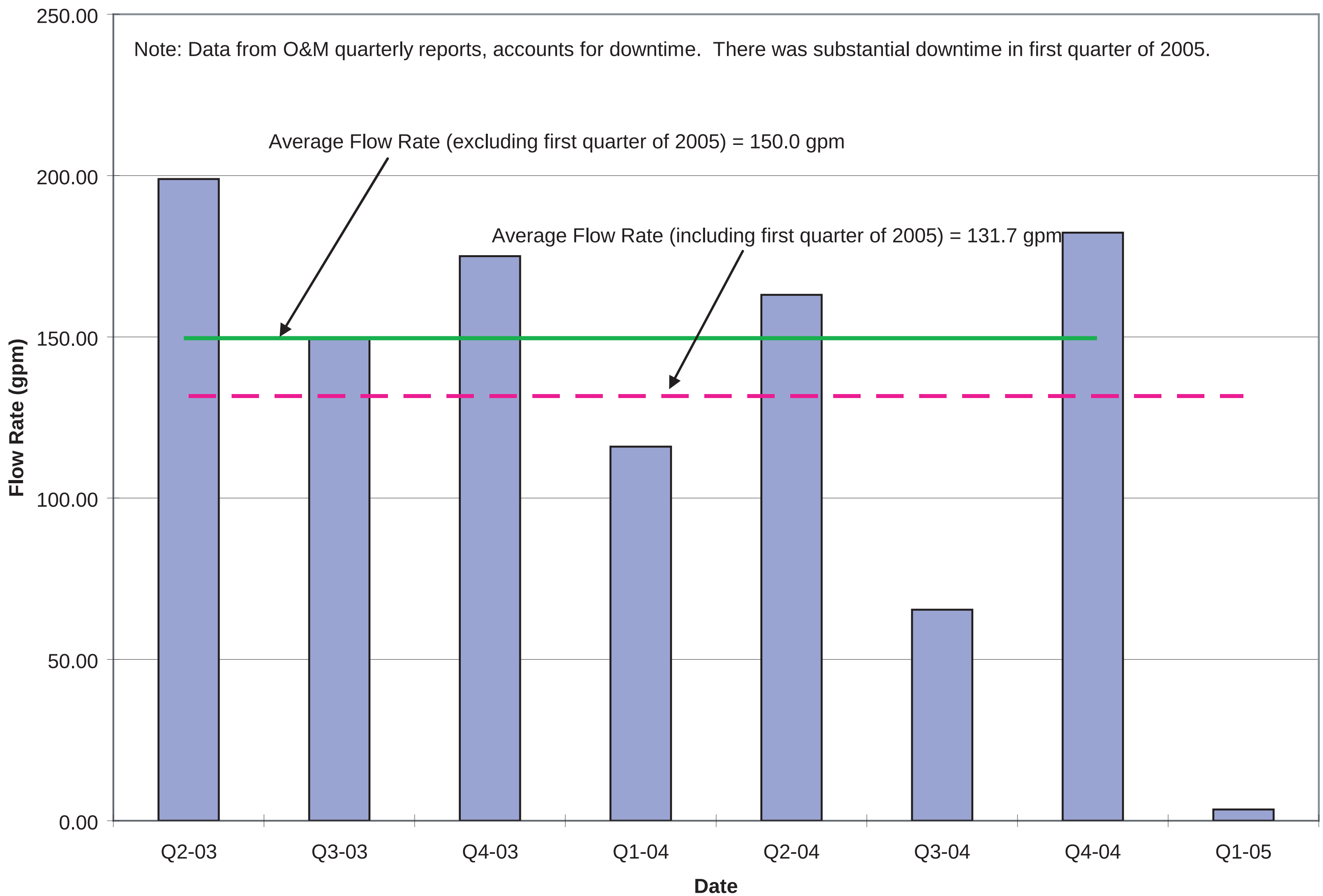
Step 1 - Review Site Data, Site Conceptual Model, and Remedy Objectives

Initial aspects of the capture zone evaluation should determine if the following issues are adequately addressed:

- Is the plume adequately delineated in three dimensions?
- Is there adequate hydrogeologic information for performing capture zone evaluations?
- Is there an adequate site conceptual model?
- Is the objective of the remedy clearly stated?

The important conclusion is whether or not all of these issues are addressed to an extent that allows the remaining steps of the capture zone evaluation to be performed with an acceptable level of uncertainty.

Figure B1-5. Average Total Flow Rate per Quarter



Is Plume Delineation Adequate?

It is important that the plume delineation be adequate so that a Target Capture Zone can be established in Step 2. An interpretation of the pre-remedy plume for total VOCs in the Canal Creek Aquifer is presented in Figure B1-2. The pre-remedy plume appears to have been well delineated with respect to the 100 ug/l contour in the vicinity of the extraction wells, which is the hydraulic containment boundary for this site. The exception may be at the extreme eastern portion of the plume, to the east of well CCJ-104B. However, given that the ground-water flow direction is observed to be to the south and southeast, the pre-remedy plume delineation appears adequate with respect to the 100 ug/L contour for the purpose of defining a Target Capture Zone.

Figure B1-6 presents the most recent available plume map that has been interpreted, corresponding to approximately 10 months after system start-up. This includes a comparison of the interpreted 100 ug/L contour for total VOCs before system start-up and after system start-up. Based on this comparison, the interpreted 100 ug/L contour for total VOCs did not change substantially within 10 months of system start-up. It should be noted that these contours are interpreted based on a limited number of data points, and different interpretations are possible. However, for the purpose of conducting a capture zone evaluation, the horizontal delineation of the total VOC plume to the 100 ug/L contour appears to still be appropriate.

As discussed earlier, contaminants are found throughout the vertical extent of the Canal Creek Aquifer, but concentrations are lower near the bottom of the aquifer. Due to the upward hydraulic gradient from the aquifer below the Canal Creek Aquifer, further downward migration is not expected. Existing monitoring wells in the deep aquifer confirm that downward migration is not occurring. Therefore, vertical delineation is considered to be complete (i.e., the plume is assumed to extend to the base of the Canal Creek Aquifer, but not below).

Is There Adequate Hydrogeologic Information?

The following brief summary is provided:

- The site has had extensive documentation of the geology and hydrostratigraphy.

- There have been numerous water level maps interpreted for the Canal Creek Aquifer (the aquifer of interest) in the vicinity of the extraction wells, both with and without pumping.

- Two water level maps, interpreted for two different time periods without pumping and generally referred as “static conditions” by the site documents, are illustrated in Figure B1-7 (March 2004, after six weeks with no pumping) and Figure B1-8 (April 2003, prior to system startup). These figures provide information regarding the direction and magnitude of the hydraulic gradient in the absence of remedy pumping. Note that the water level map presented in Figure B1-8 also highlights the interpretation of flow directions using arrows. Based on other information, background flow conditions do not vary substantially by season.

- Vertical hydraulic gradients have been evaluated between the Canal Creek Aquifer and the overlying Surficial Aquifer and underlying Lower Confined Aquifer.

- Individual pump tests were conducted at each extraction well to estimate hydraulic parameters.

Figure B1-6. Total VOC Plume Map Post-Start-Up Conditions, Jan/Feb 2004

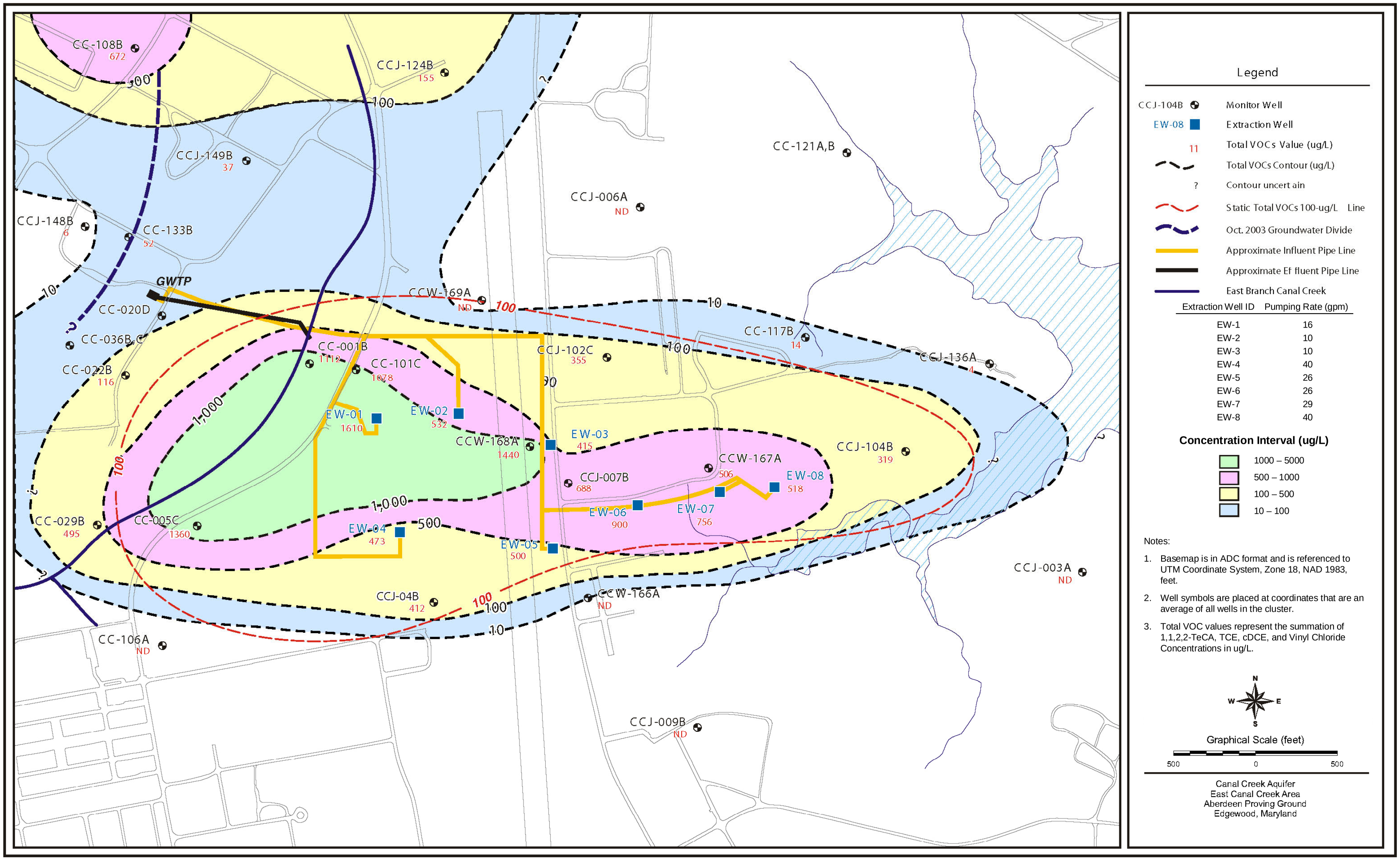


Figure B1-7. Static Groundwater Potentiometric Surface Map 3/16/2004

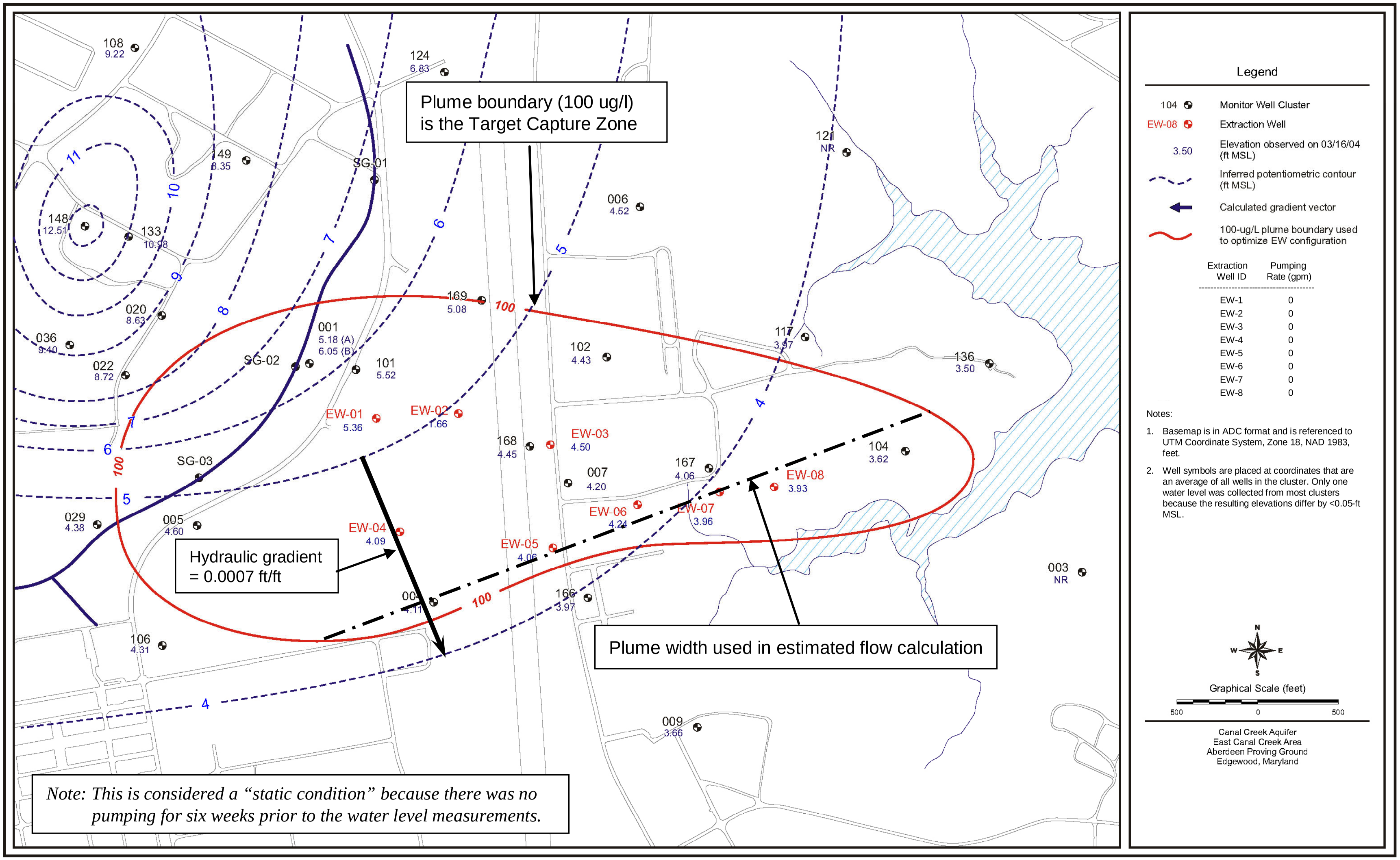
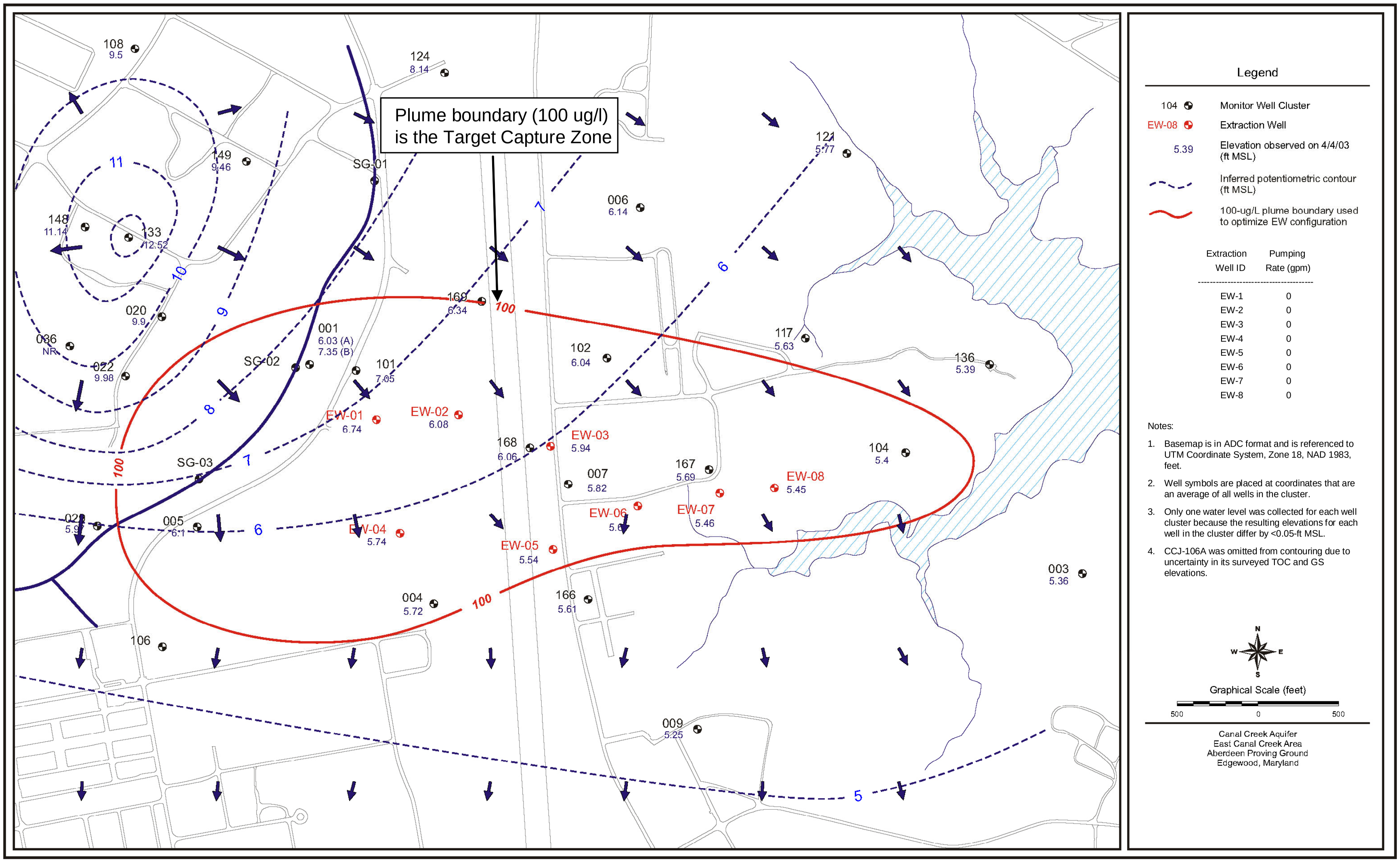


Figure B1-8. Static Groundwater Potentiometric Surface Map 4/4/2003



- Water quality data have been collected prior to system start-up and after system start-up, allowing for interpretation of spatial plume extent as well as concentration trends at individual wells. The density of spatial measurements appears to be adequate to horizontally delineate the 100 ug/L contour for the total VOC plume.

- Total pumping rate for the system is well documented over time. It is also documented that wells operate at their design rates during operation, and those design rates have been documented.

- Well construction data, including measuring point elevations and screen intervals, are documented.

Although all of the details regarding each of the above items are not provided in this report, the amount of available hydrogeologic information appears to be adequate.

Is There an Adequate Site Conceptual Model?

A site conceptual model (a text description, maps, and cross-sections that should not be confused with a "numerical model") should adequately accomplish the following:

- indicate the source(s) of contaminants

- describe geologic and hydrogeologic conditions

- explain observed fate and transport of constituents

- identify potential receptors

At this site, extensive work has been done to determine the sources of contaminants. For the ECCA, the primary sources of contamination were sewer discharge points, located near wells CC-001 and CC-101. Other sources of contamination exist to the north and northwest, and likely migrate towards the eight extraction wells associated with the remedy. Although discharged wastes may have included DNAPLs, no DNAPLs have been detected in ground water, and the dissolved-phase concentrations of the individual constituents in ground water are lower than those that typically exist when DNAPL is present.

Hydrogeologic conditions have been adequately defined, as discussed earlier. Contaminants in the Canal Creek Aquifer, in the absence of pumping, flow to the south and southeast. The shape of the plume was likely influenced by historical water supply pumping from the Canal Creek Aquifer. These water supply wells trended on an east-west line across the ECCA, which likely caused contamination to spread more to the east than would be expected based on the static (i.e., non-pumping) ground-water flow conditions.

The full thickness of the Canal Creek Aquifer is assumed to be impacted and targeted for horizontal hydraulic containment. Vertical hydraulic gradients between the Lower Confined Aquifer and the Canal Creek Aquifer are upward. Therefore, any dissolved contaminants present in the Canal Creek Aquifer are unlikely to migrate downward to the Lower Confined Aquifer. Existing monitoring wells in the deep aquifer confirm that downward migration is not occurring.

There is observed degradation of the VOCs, based on the presence of daughter products of the primary contaminants. It is also expected that the plume may be in a steady-state configuration towards the south due to dilution from net recharge and dispersion. The ROD noted that there was no observed VOC plume movement between investigations in the late 1980s and subsequent studies in the mid 1990s.

Currently, there is no potable use of ground water within the area impacted by the ECCA plume. An ecological risk assessment indicated no unacceptable ecological risks.

In summary, there appears to be an adequate site conceptual model for performing a capture zone evaluation.

Is Remedy Objective Clearly Stated with Respect to Plume Capture?

According to the ROD, "the goal of this remedy is to reduce the toxicity, mobility, and volume of contaminated media in the East Canal Creek Area plume to meet Applicable or Relevant and Appropriate Requirements (ARARs) in the plume by containing, capturing, and treating the contaminated ground water in the main body of the plume and to eliminate exposure to the ground water through implementation of institutional controls". The ROD also states that "implementation of the remedy for the East Canal Creek Area plume would involve plume containment and capture and treatment to reduce the toxicity, mobility, and volume of the contaminated media in the main body of the plume. The downgradient portion of the plume will be evaluated and monitored to ensure that the natural processes are protective and that downgradient contamination levels are being reduced as expected". The remedy goal with respect to plume capture is to provide horizontal hydraulic containment of the 100 ug/L contour for total VOCs in the Canal Creek Aquifer, for the entire thickness of the Canal Creek Aquifer.

Step 2 - Define Site-Specific Target Capture Zone(s)

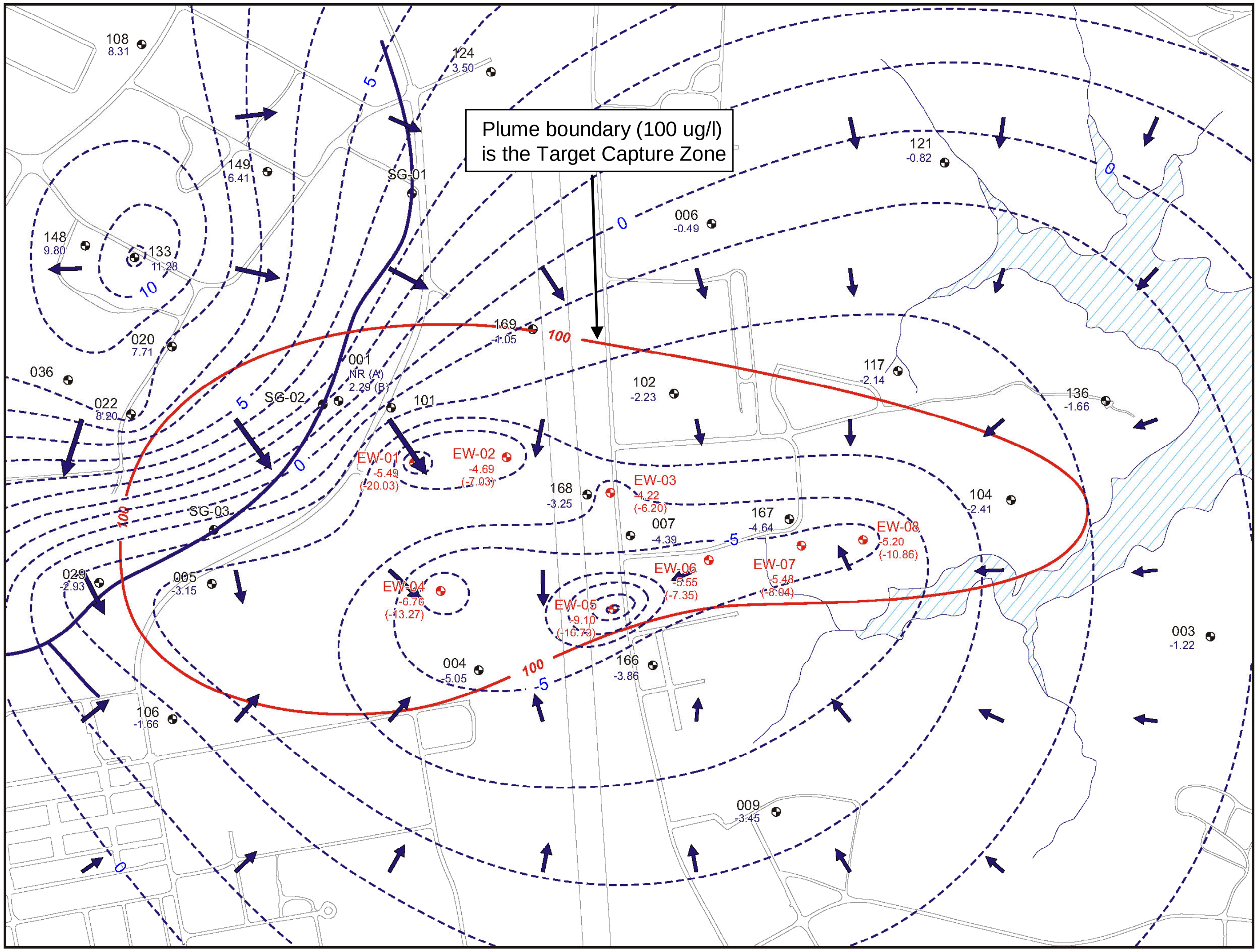
The Target Capture Zone is the three-dimensional zone of ground water that must be captured by the remedy extraction wells for the containment portion of the remedy to be considered successful. As discussed above, the remedy goal with respect to plume capture is to provide horizontal hydraulic containment of the 100 ug/L contour for total VOCs in the Canal Creek Aquifer, for the entire thickness of the Canal Creek Aquifer. More specifically, the site documents generally refer to the Target Capture Zone as the "static conditions" for the 100 ug/l total VOC contour, based on summation of 2001-2002 concentrations for 1122-TeCA, TCE, cis-DCE, and VC (see Figures B1-2 and B1-7). The Target Capture Zone extends the entire thickness of the Canal Creek aquifer. There is an awareness expressed in site documents that the horizontal extent of a Target Capture Zone defined in this manner may change over time, but interpretations to date indicate that the 100 ug/L contour for total VOCs has not changed significantly since remediation pumping began, and the Target Capture Zone is still appropriate.

Step 3 - Interpret Water Levels

Potentiometric Surface Maps

Ground-water elevations have been routinely measured, and ground-water potentiometric maps have been routinely constructed, after the system started operation. These water level maps indicate generally consistent results. The water level map for October 20, 2003, approximately six months after system operation began, is presented as Figure B1-9.

Figure B1-9. Groundwater Potentiometric Surface Map Under Pumping Condition, 10/30/2003



Legend

104 Monitor Well Cluster
EW-08 Extraction Well
-1.66 Elevation observed on 10/20/03 (ft MSL)
Inferred potentiometric contour (ft MSL)
Calculated gradient vector
100-ug/L plume boundary used to optimize EW configuration

Extraction Well ID	Pumping Rate (gpm)
EW-1	16
EW-2	10
EW-3	10
EW-4	40
EW-5	26
EW-6	26
EW-7	29
EW-8	40

Notes:

1. Basemap is in ADC format and is referenced to UTM Coordinate System, Zone 18, NAD 1983, feet.
2. Well symbols are placed at coordinates that are an average of all wells in the cluster. Only one water level was collected for most clusters because the resulting elevations differ by <0.05-ft MSL.
3. Elevations posted at EWs while they are pumping are theoretical values calculated by subtracting the sum of the Theis-predicted influences from all EWs on the well in question from the static elevation recorded on 4/4/03. A variety of T and S values, one for each possible pair of EWs, were used in the Theis equation to calculate these values. Values in () are the observed values, which include well losses.

N W E S

Graphical Scale (feet)

500 0 500

Canal Creek Aquifer
East Canal Creek Area
Aberdeen Proving Ground
Edgewood, Maryland

Review of Figure B1-9 indicates that there are not many water level measurement points available near the extraction wells. Using water levels measured at extraction wells for constructing water level maps can bias the interpretation of capture, since the water levels at the extraction wells may be much lower than water levels in the aquifer material just outside the well bore. It can be equally problematic if no water level measurement points are located in the vicinity of the extraction wells. To avoid these problems, EPA recommends installing a water level measurement point near each extraction well. However, if such measurement points are not available near the pumping well, a possible approach is to estimate aquifer water levels at the extraction wells. The latter approach is utilized here. Figure B1-9 presents two water levels at each extraction well. One is a measured value, but that is not used for contouring water levels. The other is an estimated value that is calculated by subtracting Theis-predicted drawdowns from the static water levels (using superposition to account for drawdown due to pumping from each of the extraction wells). The water level contours are based on the estimated value at each of the extraction wells, rather than the measured value which is likely impacted by well inefficiencies and well losses.

Other noteworthy features associated with the water level map presented in Figure B1-9 include the following:

- measured water levels are posted
- a Target Capture Zone is identified on the map (the 100 ug/l contour)
- interpreted flow directions are highlighted using arrows
- pumping rates are identified
- there is a scale and a north arrow

The interpretation of the water level map presented in Figure B1-9, based on the arrows illustrated in the figure, is that the capture zone extends beyond the Target Capture Zone. There is some level of ambiguity regarding the interpretation, since much of it is based on the estimated values of water levels at the extraction wells (which was necessary due to lack of water level measurement points near the extraction wells). However, there are some water level measurement points near the extraction wells, and quick inspection of these values (i.e., excluding the values at the extraction wells) suggests qualitatively that the interpretation of the extent of capture is likely still valid. This can be evaluated more quantitatively by looking at specific water level pairs.

Water Level Pairs (Gradient Control Points)

Pairs of water level elevations, located on either side of a real or conceptual boundary, can be used to demonstrate inward flow relative to that boundary. For this demonstration site, this approach is somewhat limited because of the relatively large distance between potential water level pairs. However, calculation of water level differences between selected water level pairs, presented in Table B1-2, still provides for a useful line of evidence regarding capture.

Note some, but not all, of the water levels pairs presented in Table B1-2 utilize estimated water levels at extraction wells. More emphasis on the results for pairs that do not involve extraction well locations is likely appropriate. In this particular case, all of the pairs yield a consistent interpretation of inward flow relative to the Target Capture Zone boundary.

Table B1-2. Water Level Differences for Selected Water Level Pairs

Water Level Pairs	Apr 2003	Jun 2003	Jul 2003	Aug 2003	Sep 2003	Oct 2003	Nov 2003	Dec 2003	Mar 2004	Apr 2004
Pairs that do not involve extraction wells:										
003 to104	0.87	1.25	1.21	1.37	1.23	1.19	1.09	1.23	NA	NA
009 to 167	0.22	0.40	0.44	0.57	1.23	0.41	0.81	0.44	0.16	0.30
009 to 166	0.51	1.18	1.19	1.57	1.23	0.41	1.19	1.18	1.09	1.18
106 to 005	NA	NA	NA	NA	NA	1.49	1.57	1.56	1.22	1.24
106 to 004	NA	NA	NA	NA	NA	3.39	3.68	3.63	2.85	3.37
Pairs that involve extraction wells (using estimated water levels at the extraction wells):										
003 to EW-08	3.84	4.01	3.91	2.51	3.35	3.98	3.39	4.05	NA	NA
009 to EW-07	1.61	1.27	0.71	0.51	1.46	2.03	1.76	2.06	5.01	4.12
166 to EW-05	0.63	0.53	3.23	2.52	3.84	5.24	4.20	4.52	7.59	6.60
106 to EW-04	NA	NA	NA	NA	NA	5.10	5.12	5.34	7.50	6.66

Note: Positive values suggest the inward flow relative to the Target Capture Zone.

Step 4 - Perform Calculations

Estimated Flow Rate Calculation

As discussed in the main document, the estimated flow rate calculation provides an estimate for the pumping required to capture a plume, based on flow through the plume extent. This approach is summarized in Figure 13 in the main document. Assumptions for this approach include the following:

- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- other sources of water introduced to aquifer due to extraction are represented by the “factor”

Assignment of specific values for these parameters is typically difficult, due to heterogeneities. For instance, the hydrogeologic summary presented earlier indicates variation in aquifer thickness as well as hydraulic conductivity determined with pump tests. Furthermore, based on the static water level map presented in Figure B1-7, the direction of background hydraulic gradient varies spatially, complicating estimation of plume width. Therefore, the results from this line of evidence must be considered with knowledge of these limitations. Nevertheless, it is useful to perform the calculation using best estimates and/or ranges of values for specific parameters. For this demonstration, the following approach was utilized:

- transmissivity (hydraulic conductivity multiplied by thickness) was assigned as three potential values:
  - 1,000 ft^2/d (low estimate)
  - 2,200 ft^2/d (representative value)
  - 4,000 ft^2/d (high estimate)

- based on Figure B1-7 (static water levels) a plume width of 4,000 ft was estimated based on the width of the 100 ug/l contour (that defines that Target Capture Zone) in the vicinity of the southernmost extraction wells, in a direction perpendicular to the static ground-water flow direction interpreted in that vicinity

- recognizing that hydraulic gradients are variable in space and time, the hydraulic gradient was assigned as two potential values, 0.0007 ft/ft (representative value near extraction wells) and 0.001 ft/ft (conservatively high value for vicinity of extraction wells), based on water level contours for non-pumping conditions illustrated in Figures B1-7 and B1-8

- "factor" was assigned as three potential values (1.0, 1.5, and 2.0) to assess sensitivity of the results to different degrees of potential capture of water from surface water and/or adjacent aquifers

The flow rate calculation results, which estimate the amount of pumping that would be required to capture a plume width of 4,000 ft based on the various combinations of parameter assignments, are presented in Table B1-3.

These results are then compared to the actual pumping rate, which as discussed earlier, is typically 197 gpm when all wells are operating, with a long-term average of approximately 150 gpm. All of the calculations of the pumping rate required to capture the plume are less than the 197 gpm the wells typically operate at, indicating that a pumping rate of 197 gpm is likely more than enough for successful capture. In fact, all but one of the calculated values is less than the long-term average of 150 gpm, indicating capture is likely successful at the average long-term rate as well. The only exception is when all the assigned parameters (transmissivity, hydraulic gradient, and the "factor") are assigned at the high end of the range considered. By utilizing a range of values for the various input parameters, some of the simplifications associated with this calculation are addressed. The consistent results for different ranges of parameter values suggest that actual pumping at this site is likely sufficient for successful capture.

Table B1-3. Estimated Flow Rate Calculation*

Factor	Transmissivity (ft^2/day)	Hydraulic Gradient (ft/ft)	Estimated Flow Rate (ft^3/day)	Estimated Flow Rate (gpm)
1.0	1000	0.0007	2,800	14.54
		0.001	4,000	20.78
	2200	0.0007	6,160	32.00
		0.001	8,800	45.71
	4000	0.0007	11,200	58.18
		0.001	16,000	83.12
1.5	1000	0.0007	4,200	21.82
		0.001	6,000	31.17
	2200	0.0007	9,240	48.00
		0.001	13,200	68.57
	4000	0.0007	16,800	87.27
		0.001	24,000	124.68
2.0	1000	0.0007	5,600	29.09
		0.001	8,000	41.56
	2200	0.0007	12,320	64.00
		0.001	17,600	91.43
	4000	0.0007	22,400	116.36
		0.001	32,000	166.23

** based on estimated plume width of 4,000 ft*

Capture Zone Width Calculation

As discussed in the main document, this line of evidence utilizes an analytical solution (illustrated in Figure 14 in the main document), for a specific pumping rate, to determine if capture zone width is likely sufficient. Assumptions for this approach include the following:

- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient

- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- no other sources of water are introduced to aquifer due to extraction

Note that this calculation assumes no other sources of water are introduced to the aquifer due to induced flow, such as from surface water or from an adjacent aquifer. This differs from the estimated flow rate calculation, which accounts for other potential sources of water through the "factor" term.

When multiple extraction wells are present, this capture zone width calculation is typically applied by assigning the total extraction rate to one "equivalent well". The location of the equivalent well is generally selected visually so it is centrally located with respect to the plume width and/or extraction well locations, and located at the most downgradient position of the actual extraction wells. This represents a significant level of simplification for a multi-well extraction system.

For this site, the typical instantaneous pumping rate is 197 gpm, and the long term average pumping rate (accounting for down time) is approximately 150 gpm. The conservative analysis of capture zone width used here is based on 150 gpm, recognizing that much of the time a larger capture zone is present. Calculations for Y_{well}, Y_{max}, and X_0 for different possible combinations of transmissivity and hydraulic gradient values are presented in Table B1-4.

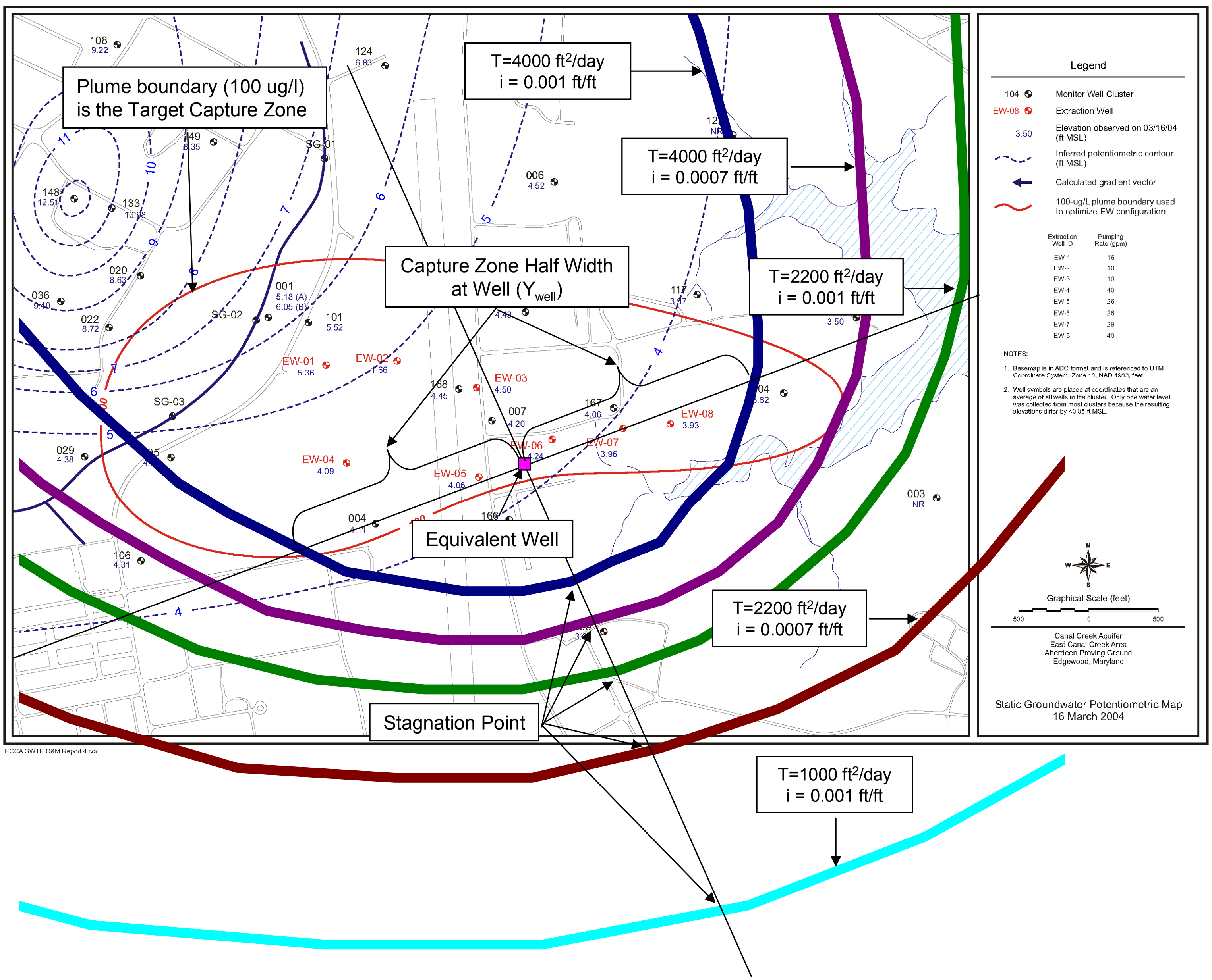
Table B1-4. Capture Width Calculation (150 gpm*)

Transmissivity (ft^2/day)	Hydraulic Gradient (ft/ft)	Distance from Well to Stagnation Point X_0 (ft)	Y_{well} (ft)	Capture Zone Width At Wells (ft)	Y_{max} (ft)	Max Capture Zone Width Upgradient (ft)
1000	0.0007	6,565	10,313	20,625	20,625	41,250
	0.001	4,596	7,219	14,438	14,438	28,876
2200	0.0007	2,984	4,688	9,375	9,375	18,750
	0.001	2,089	3,281	6,563	6,563	13,125
4000	0.0007	1,641	2,578	5,156	5,156	10,313
	0.001	1,149	1,805	3,609	3,609	7,218

**consistent units are feet and days - pumping rate of 150 gpm is equal to 28,877 ft^3/day*

Figure B1-10 illustrates the results. Note that results are illustrated based on the direction of background hydraulic gradient. As discussed earlier, the background hydraulic gradient at this site varies spatially (see Figure B1-7). The approach utilized herein was to orient the calculated capture zone based on the approximate static ground-water flow direction in the vicinity of the southernmost extraction wells.

Figure B1-10. Capture Zone Width Calculation Results



It is apparent that the calculated capture zone widths are larger than the target capture width, which is approximately 4,000 ft (as discussed earlier), except for the case where the transmissivity and hydraulic gradient are both at the high end of the range. By utilizing a range of values for the various input parameters, some of the simplifications associated with this calculation are addressed. Consistent results that capture zone width is sufficient for many different ranges of parameter values suggest that actual long-term average pumping rate at this site (150 gpm) is likely sufficient for successful capture. Also note that calculated capture zone widths would be approximately 25% larger than presented in Table B1-4 if the typical instantaneous pumping rate of 197 gpm was used rather than the long-term average pumping rate of 150 gpm.

Ground-Water Flow Model with Particle Tracking

The start-up of the GWTP and the extraction wells was implemented in a sequential fashion that consisted of consecutive 2-day periods of well performance tests (step-testing and constant-rate 8-hour design flow testing) at each well. A rigorous analysis of the hydraulic data was performed to correct for barometric, tidal and competing pumping influences. The transmissivity estimates from the aquifer testing were incorporated into a modified three-dimensional ground-water flow model, to predict the steady-state zone of capture generated by the eight extraction wells. Manual water levels collected on July 28, 2003 (several months after pumping was initiated) were used as head targets during active pumping to recalibrate the model versus observed drawdown. Simulation target summary statistics were compared between the original and the final models to illustrate the model improvements.

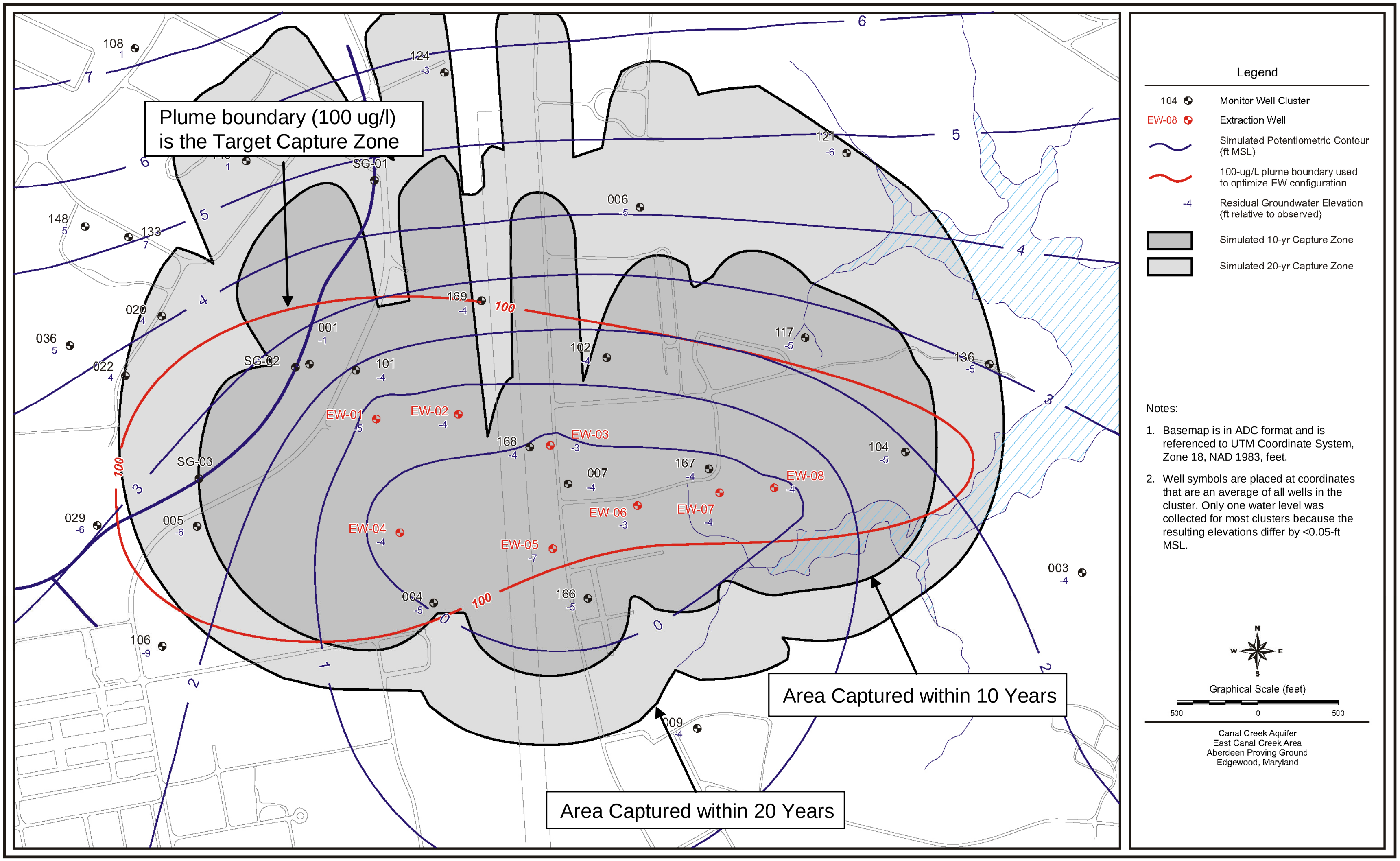
Reverse particle tracking was performed, in conjunction with the revised model, to evaluate the simulated capture zone for the typical instantaneous pumping rate of 197 gpm. The simulated capture zones associated with 10 year time-of-travel and 20 year time-of-travel are summarized in Figure B1-11. The complete capture zone would be larger. This simulated capture zone encompasses the entire Target Capture Zone, with the possible exception of a very small area at the extreme western edge. It should be noted that a simulation performed with the long-term average pumping rate of 150 gpm would have a smaller simulated capture zone than this illustration, which is based on 197 gpm.

It should also be noted that specific details about the model construction and particle tracking approach were not provided in the summary report that was reviewed. It is likely that these details were provided in other reports, but if not, an improved analysis would include simulations for the 150 gpm case and more details regarding model construction and the particle tracking approach.

Step 5 - Evaluate Concentration Trends

Based on the water level map interpretation (Figure B1-9) and capture width calculation (Figure B1-10) it appears possible (or likely) that all of the monitoring wells located downgradient of the extraction wells are within the capture zone of the extraction wells. Since there are continuing sources of ground-water impacts, monitoring wells that are impacted and are located within the capture zone would be expected to remain impacted. Therefore, this line of evidence would provide ambiguous interpretations (i.e., these wells might not clean up over time whether or not capture is sufficient), and therefore this line of evidence is not utilized for this capture zone evaluation.

Figure B1-11. Simulated Capture Zones Based on Particle Tracking



Step 6 - Interpret Actual Capture Based on Steps 1-5, Compare to Target Capture Zone(s), Assess Uncertainties and Data Gaps

Based on evaluations of multiple lines of evidence discussed in Step 3 to Step 5, the actual capture achieved by the extraction wells is interpreted in Step 6, and the following items are addressed:

- compare the interpreted capture zone to the Target Capture Zone
- assess uncertainties in the interpretation of the actual capture zone
- assess the need for additional characterization and/or monitoring
- evaluate the need to reduce or increase extraction rates

Table B1-5 presents the summary of the capture zone evaluation for this site.

Table B1-5. Summary of Capture Zone Evaluation

Step	Summary/Conclusions
Step 1: Review site data, site conceptual model, remedy objectives	Completed, all determined to be up-to-date and adequate.
Step 2: Define “Target Capture Zone(s)”	Clearly defined, illustrated on maps. Pertains to entire thickness of Canal Creek Aquifer.
Step 3a: Water level maps	Interpreted capture zone is larger than the Target Capture Zone. Estimated water levels at extraction wells are utilized when constructing potentiometric surface maps due to lack of water level measurement points near the extraction wells. This is an improvement over using water levels measured at the extraction wells, but actual water level measurements near the extraction wells would be preferred.
Step 3b: Water level pairs	Inward flow at all pairs along the Target Capture Zone boundary.
Step 4a: Simple horizontal capture zone analyses	Estimated flow rate calculation indicates the long-term average pumping rate of 150 gpm is likely sufficient. Capture zone width calculation indicates the long-term average pumping rate of 150 gpm likely provides for sufficient capture zone width.
Step 4b: Ground-water flow modeling with particle tracking	Model calibration was updated after system operation based on observed system performance. Particle tracking results indicate successful capture for typical instantaneous pumping rate of 197 gpm, but results for the long-term average pumping rate of 150 gpm were not simulated. An improved analysis would include simulations for the 150 gpm case and more details regarding model construction and the particle tracking approach.
Step 5: Concentration trends	Not relied upon for short-term evaluation of capture.
Step 6: Interpret actual capture and compare to Target Capture Zone	The actual capture zone is interpreted to be sufficient relative to the Target Capture Zone. Particle tracking was not performed for long-term average pumping rate of 150 gpm, but all other lines of evidence suggest that capture is sufficient. Adding a water level measurement point near each extraction well would improve the analysis.

As discussed in Exhibit 8 of the main document, a summary of the following items is appropriate:

- *Is capture sufficient, based on "converging lines of evidence"?*

  The capture zone analysis indicates that capture is sufficient, and the zone of capture is larger than the Target Capture Zone, based on water level maps, gradient pairs, simple calculations for estimated flow rate and capture zone width, and particle tracking results based on numerical modeling. This provides a safety factor that accounts for uncertainties.

- *Key uncertainties/data gaps*

  There is some uncertainty in the analysis of water levels due to the use of estimated water levels at the extraction wells. Also, an improved analysis would include particle tracking simulations for the 150 gpm case and more details regarding model construction and the particle tracking approach. However, because multiple lines of evidence regarding capture are available (as mentioned above), none of these issues likely impacts the conclusion that capture is sufficient.

- *Recommendations to collect additional data, install new monitoring wells, change current extraction rates, change number/location of extraction wells, etc.*

  It is possible that adequate capture could be achieved with a lower total pumping rate. Further evaluation to attempt to optimize pumping rates could potentially be considered, if it is determined that a lower total pumping would significantly lower the cost of the remedy while providing an adequate level of protection. Also, as stated earlier, adding water level measurement points near each extraction well would improve the analysis.

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EXAMPLE B2
Example Capture Zone Evaluation, Milan OU4 Site

SITE BACKGROUND INFORMATION

Location and Physical Setting

The Milan Army Ammunition Plant (MAAP) is located in the western portion of Tennessee (see Figure B2-1). The vicinity of the pre-remedy plume associated with Operable Unit 4 Region 1 (OU4) is illustrated in Figure B2-2. Highway 104 is located just outside the plant boundary and Highway 77 is located approximately 3,000 ft northwest of the plant boundary. There are no significant surface water bodies in the immediate vicinity of the OU4 plume, although there are several small surface ditches or creeks. Topography in the vicinity of the OU4 plume is relatively flat and slopes gently to the west.

Site Geology and Hydrogeology

The study area lies within the Gulf Coastal Plain physiographic province, on the eastern flank of the Upper Mississippi River Embayment. The regional geology consists of sediments that include sand, gravel, lignite, clay, chalk, and limestone. A generalized cross-section of the plant vicinity is presented in Figure B2-3. The upper unit is the Memphis Sand, which is several hundred feet thick and consists of sand with some layers of silt and clay. The Flour Island Formation serves as a confining clay layer below the Memphis Sand. The plume associated with OU4 is located within the Memphis Sand.

In the aquifer of concern, ground-water flow is generally to the northwest. Vertical hydraulic gradients are generally downward, and contamination is found to depths of more than 200 feet as a result (contaminant distribution with depth is discussed in more detail later).

Hydraulic conductivity of the Memphis Sand in the vicinity of OU4 is within the range of 70 to 110 ft/day, based on a combination of aquifer test results and flow model calibration (both regional and local flow models). Given an approximate aquifer thickness of 270 ft, the transmissivity of the Memphis Sand is approximately 20,000 to 30,000 ft^2/day.

Contaminants of Concern and Contaminant Distribution

The primary contaminants of concern for the OU4 plume are explosives. Water quality data are typically presented for total explosives. The explosive with the highest concentrations is RDX.

Discrete depth sampling in conjunction with rotosonic drilling was performed to vertically delineate the plume. Table B2-1 presents depth discrete sampling results for location MI-533 (between Route 77 and Route 104) and for location MI-527 (near Route 77). These data illustrate that the contaminants are located deeper within the Memphis Sand towards the northwest due to downward vertical hydraulic gradients. The interpreted plume depth, based on similar data from other locations, is illustrated in Figure B2-4.

Figure B2-1. Location of Milan Army Ammunition Depot

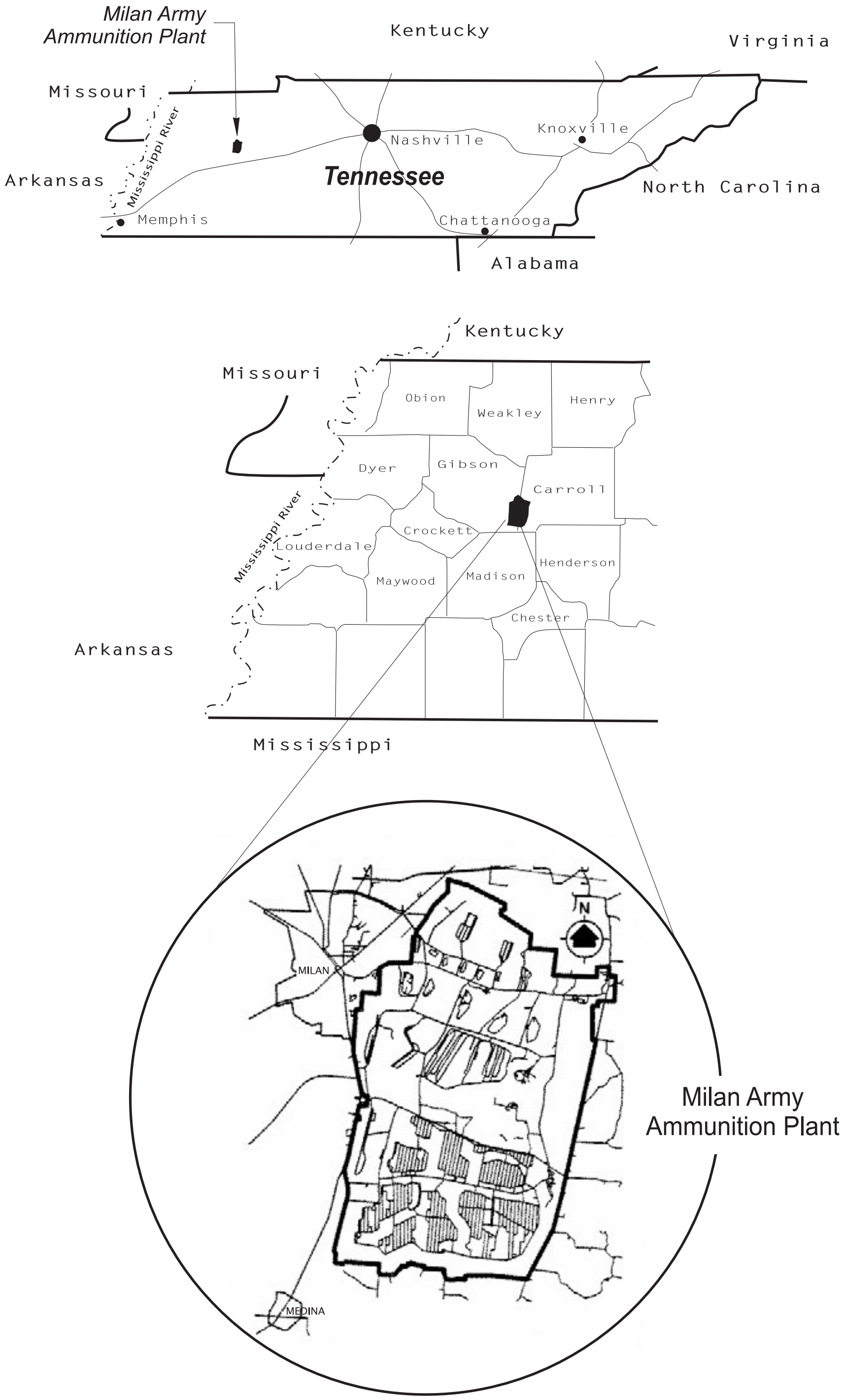
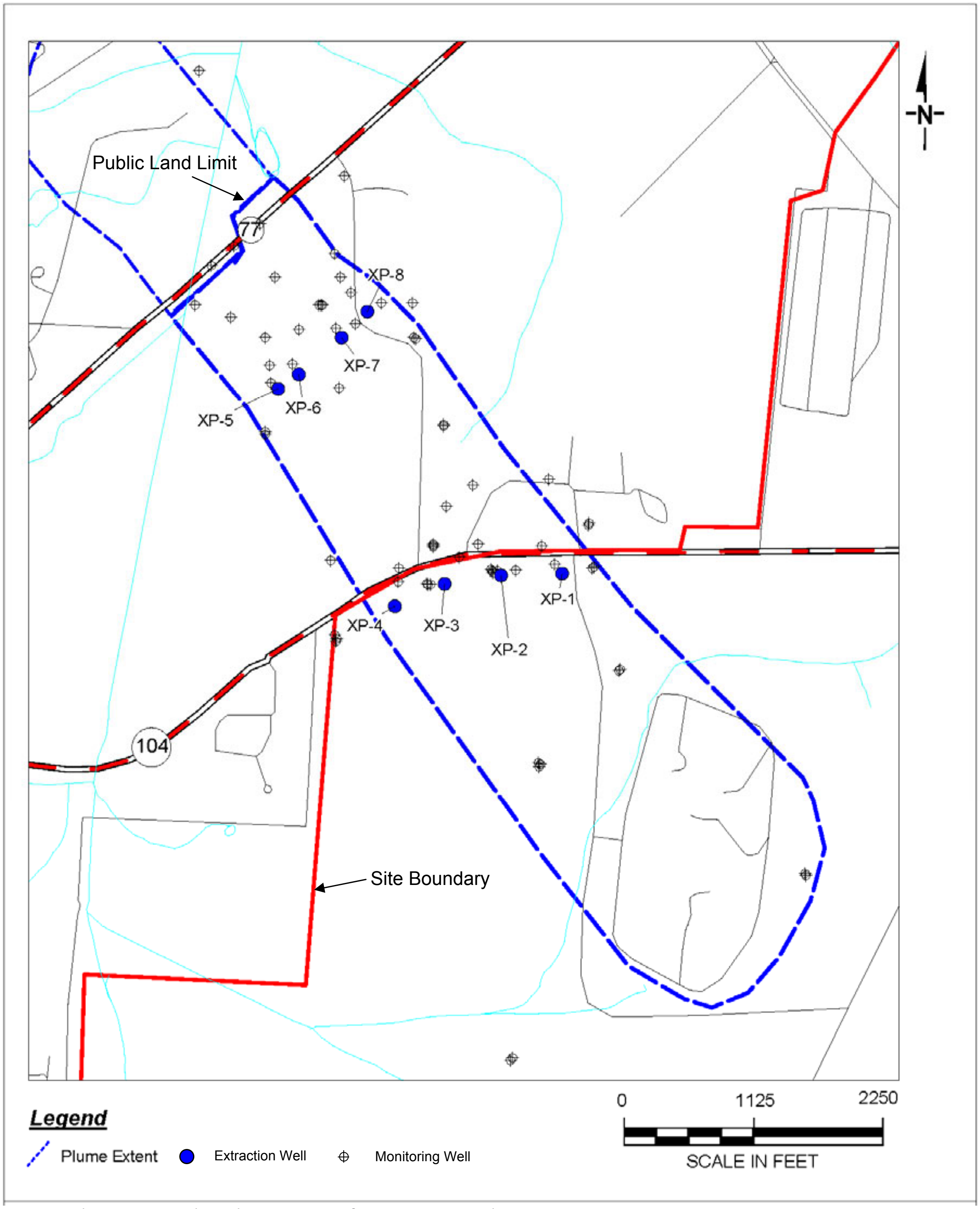


Figure B2-2. Vicinity of Milan OU4 and Extent of Explosive Plume



Note: "Plume Extent" based on site-specific concentration limit

Figure B2-3. Generalized Stratigraphic Cross Section

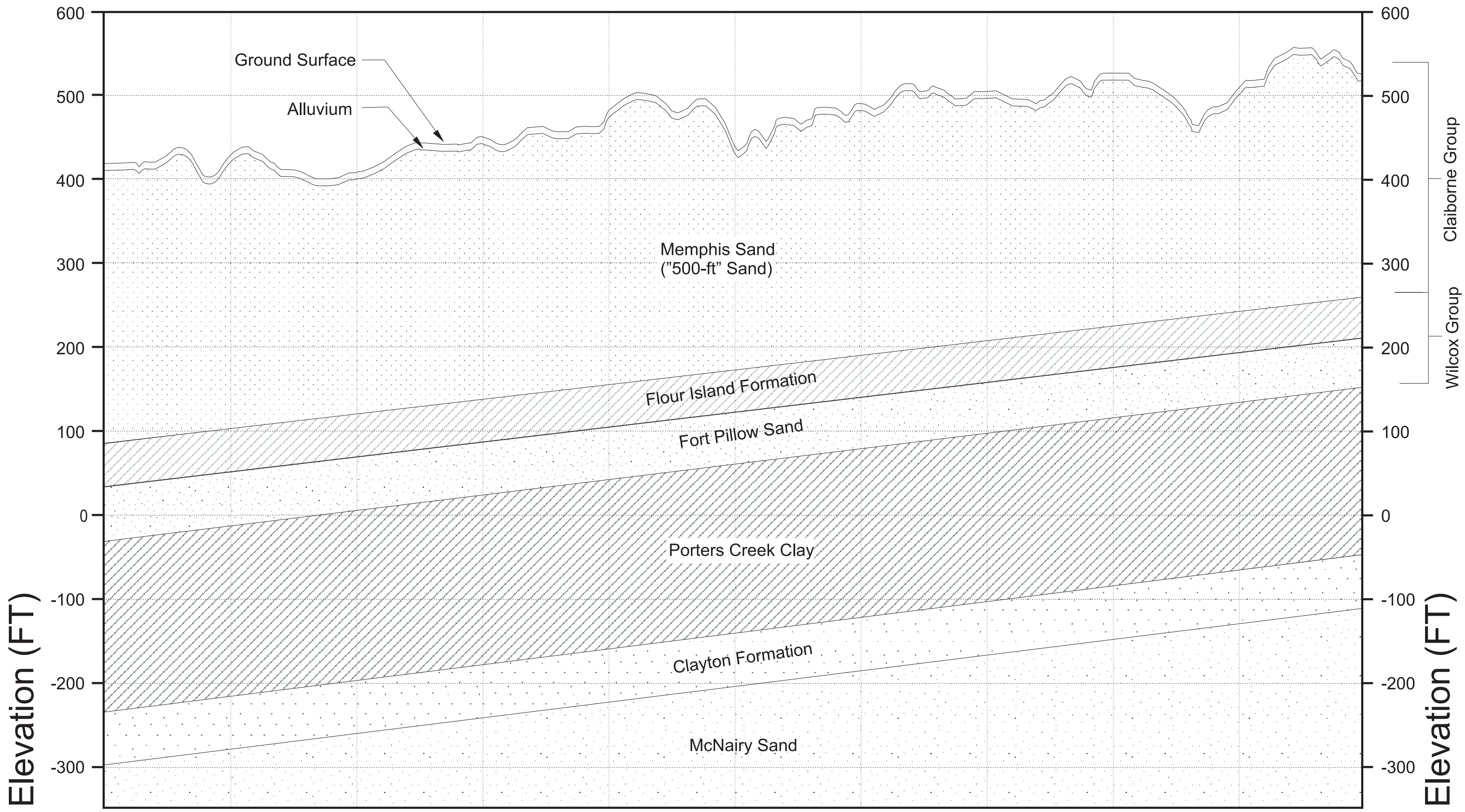


Figure B2-4. Vertical Extent of Contaminant

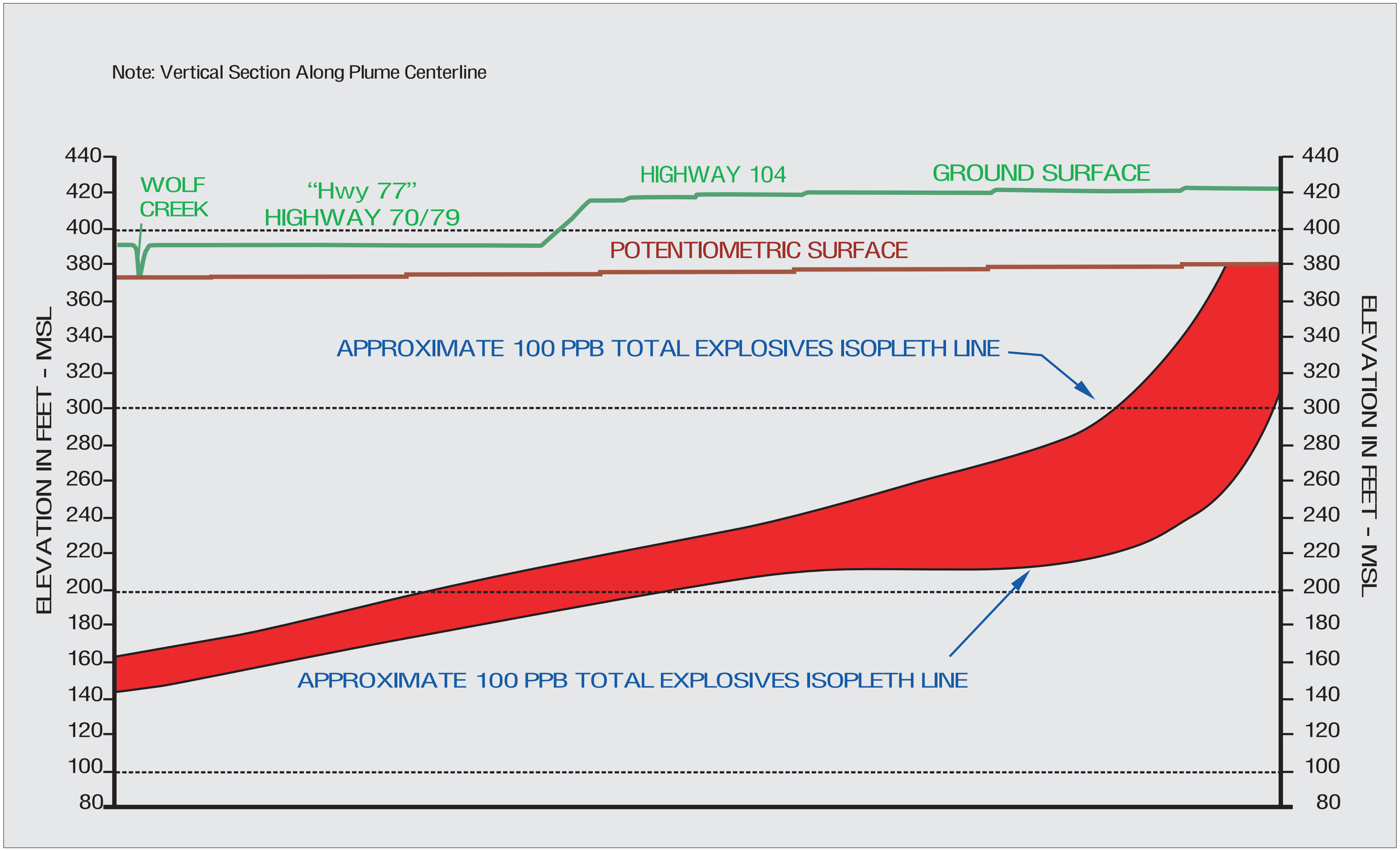


Table B2-1. Discrete Depth Sampling for Plume Delineation

Depth (ft)	Elevation (ft MSL)	Lab 1 Results* (ppb)	Lab 2 Results* (ppb)
Location MI-533 (Between Hwy 77 and Hwy 104):			
165-175	250-260	200	135
185-195	230-240	960	623
205-215	210-220	1725	971
225-235	190-200	ND	ND
Location MI-527 (Near Hwy 77):			
135 -145	252-262	ND	ND
165-175	222-232	ND	ND
195-205	192-202	81	73
225-235	162-172	242	212
255-265	132-142	ND	ND

**Results represent concentrations of total explosives. Lab 1 was a contract lab, Lab 2 was an on-site lab.*

Ground-Water Remedial System

A ground-water extraction and treatment system to address the plume of explosives was designed and built in 2001, and began operation in June, 2002. Operation has been more or less continuous since that time.

The extraction system consists of two lines of extraction wells (see Figure B2-2). A line of four extraction wells, referred to as XP-1 through XP-4 and located along Highway 104, is intended to provide hydraulic containment of the on-site part of the plume and prevent further off-site migration. A second line of four extraction wells located closer to Highway 77, referred to as XP-5 through XP-8, is intended to provide hydraulic containment of the off-site part of the plume that has been characterized.

The actual flow rate of each extraction well is presented in Table B2-2. Actual extraction rates total 1,135 gpm, which exceeds the original design flow rate of approximately 700 to 900 gpm. Higher flow rates were implemented to add conservatism regarding capture, given that the extraction wells could produce at least that much water. When the system was constructed, it was recognized that additional extraction wells might be required further to the northwest to contain the remainder of the plume, but the extent of contamination in this area was not fully characterized at the time.

Table B2-2. Actual Flow Rate at Each Extraction Well

Extraction Well	Actual Flow Rate (gpm)
XP-1	100
XP-2	190
XP-3	190
XP-4	100
XP-5	100
XP-6	190
XP-7	190
XP-8	75
Total	*1,135*

CAPTURE ZONE EVALUATION

<u>Step 1 - Review Site Data, Site Conceptual Model, and Remedy Objectives</u>

Initial aspects of the capture zone evaluation should determine if the following issues are adequately addressed:

- Is the plume adequately delineated in three dimensions?
- Is there adequate hydrogeologic information for performing capture zone evaluations?
- Is there an adequate site conceptual model?
- Is the objective of the remedy clearly stated?

The important conclusion is whether or not all of these issues are addressed to an extent that allows the remaining steps of the capture zone evaluation to be performed with an acceptable level of uncertainty.

<u>Is Plume Delineation Adequate?</u>

It is important that the plume delineation be adequate so that a Target Capture Zone can be established in Step 2. An interpretation of the pre-remedy plume extent is presented in Figure B2-2, along with the monitoring network. The actual concentration data from which the plume extent was determined is not shown here. There are some monitoring locations outside the interpreted plume map that provide a basis for delineating the plume width, which is interpreted to be approximately 1,800 feet wide. These monitoring wells were supplemented by numerous exploratory borings during the remedial investigation. Also, depth discrete sampling was performed to vertically delineate the plume. Review of site records indicates that the pre-remedy plume delineation is adequate for the purpose of defining a Target Capture Zone.

Is There Adequate Hydrogeologic Information?

The following brief summary is provided:

- The site has had extensive documentation of the geology and hydrostratigraphy.

- A series of monitoring wells was installed relatively close to the extraction wells, which allows for detailed characterization of water levels and water quality in the aquifer at locations near the extraction wells.

- For this capture zone evaluation, which was performed approximately one year after system startup, additional water levels were collected as part of a planned short-term system shutdown, as follows:

    - first, water levels were collected during operation of the system at a total extraction rate of 1,135 gpm

    - then, water levels were collected after the system had been operating for approximately 72 hours at a reduced total extraction rate of 775 gpm (to evaluate the extent of capture for a potentially reduced total pumping rate)

    - then, water levels were collected after the system had been shut down for a period of 72 hours

- Vertical gradients have been evaluated and are downward, consistent with the plume reaching depths of more than 200 feet.

- Hydraulic parameters were estimated from aquifer testing and ground-water flow model calibration at both the regional scale and local scale.

- Numerous ground-water monitoring wells and exploratory borings with depth discrete sampling were used to define the horizontal and vertical extent of the explosives plume during characterization investigations.

- A baseline water quality sampling event for explosives concentrations in monitoring wells was conducted prior to startup of the system. Data were then collected again in May and June of 2003, approximately one year after extraction was initiated.

- Total pumping rate for the system is well documented over time, and exceeds the design values.

- Well construction data, including measuring point elevations and screen intervals, are well documented.

Although details regarding each of the above items are not provided in this report, review of site records indicates that the amount of available hydrogeologic data is adequate.

Is There an Adequate Site Conceptual Model?

A site conceptual model (a text description, maps, and cross-sections that should not be confused with a "numerical model") should adequately accomplish the following:

- indicate the source(s) of contaminants
- describe geologic and hydrogeologic conditions
- explain observed fate and transport of constituents
- identify potential receptors

At this site, the source of contaminants is from a manufacturing facility located south of Highway 104, where wastewater from operations was placed into surface ditches. Hydrogeologic conditions and contaminant movement (horizontally and vertically) have been well documented. Contaminant transport patterns are consistent with ground-water flow patterns. Institutional controls have been implemented to prevent impacts to potential receptors. Although all of the details are not provided herein, review of site records indicates that there is an adequate site conceptual model for performing a capture zone evaluation.

Is Remedy Objective Clearly Stated with Respect to Plume Capture?

A line of four extraction wells (XP-1 through XP-4) located along Highway 104 is intended to provide hydraulic containment of the on-site part of the plume and prevent further off-site migration. A second line of four extraction wells (XP-5 through XP-8) is intended to provide hydraulic containment of the off-site part of the plume that has been characterized. The objective with respect to depth is to capture water from the impacted depths, and not necessarily the entire thickness of the Memphis Sand. The extraction wells were screened to include the most impacted portions of the aquifer with respect to depth (based on the sampling with depth discussed earlier), and were screened across approximately 75% of the impacted aquifer zone near the extraction wells (with respect to depth). Based on calculations and theory regarding partially penetrating wells (not presented herein), given the sandy nature of the aquifer, the vertical extent of capture would extend below the impacted portions of the aquifer.

Step 2 - Define Site-Specific Target Capture Zone(s)

The Target Capture Zone is the three-dimensional zone of ground water that must be captured by the remedy extraction wells for the hydraulic containment portion of the remedy to be considered successful. Based on the remedy goal with respect to plume capture described above, the Target Capture Zone is stated as follows: "Provide horizontal hydraulic containment of ground water at each of the two lines of extraction wells across the full width of the total explosives plume that is indicated in Figure B2-2". The Target Capture Zone does not indicate any specific distance down-gradient from each line of extraction wells that the capture zone needs to include, so long as a capture zone of appropriate width is achieved by each line of extraction wells.

With respect to depth, there is no explicit Target Capture Zone that pertains to vertical hydraulic capture (i.e., no specific depth where upward flow is required). However, as discussed earlier, design of the extraction system took into account the increasing depth of the plume towards the northwest, such that horizontal capture would be achieved for the depth intervals where the aquifer is impacted. Long-term ground-water monitoring is being conducted to verify that further plume migration with depth does not occur.

Step 3 - Interpret Water Levels

Potentiometric Surface Maps

For this capture zone evaluation, which was performed approximately one year after system startup, water levels were collected as part of a planned short-term system shutdown, as follows:

- first, during operation of the system at a total extraction rate of 1,135 gpm
- then, after the system had been operating for approximately 72 hours at a reduced total extraction rate of 775 gpm
- then, after the system had been shut down for a period of 72 hours

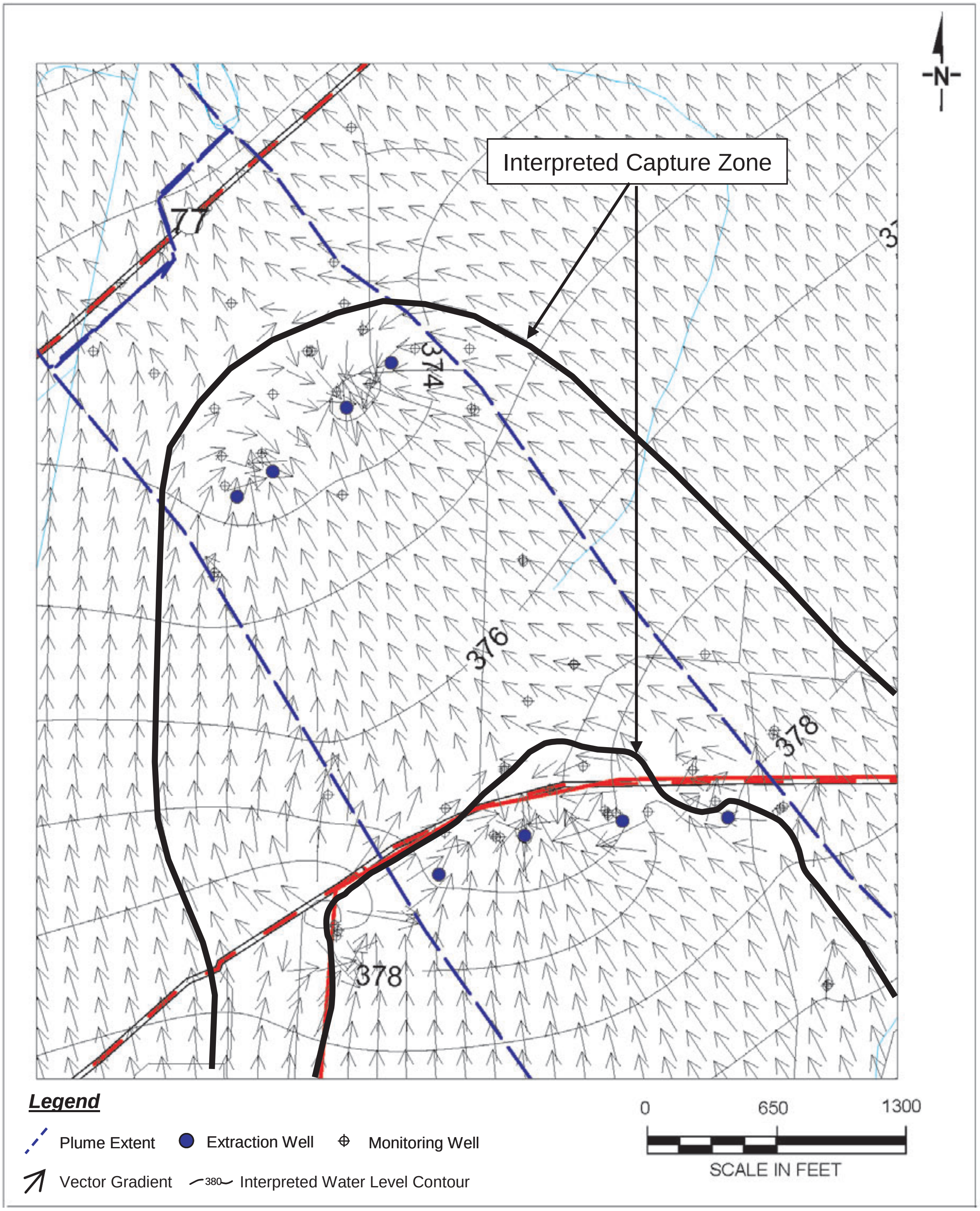
For this site, water levels collected for a specific range of aquifer depths are utilized to represent the flow patterns for the overall aquifer. The site-specific details of this approach are not discussed herein. As noted earlier, a series of monitoring wells was installed relatively close to the extraction wells, which allows for detailed characterization of water levels in the aquifer at locations near the extraction wells, which improves the ability to interpret water levels.

Figure B2-5 is a contour map of measured water levels that are based on the data for an extraction rate of 1,135 gpm. This map was constructed using a kriging algorithm. For this presentation, actual water level values are not posted on the figure, and it is noted that a more complete presentation would include posted water level measurements. Also shown in Figure B2-5 are vectors that depict the magnitude and horizontal direction of the hydraulic gradient based on the water levels. These vectors were produced by the software package that was used to develop the contours. The northern line of extraction wells appear to be capturing more water than is necessary based on the flow vectors outside the plume that form a trajectory toward the extraction wells. There appears to be a small area on the far eastern side of the plume, at the southern line of extraction wells, where there may be a lack of capture. However, there is some uncertainty regarding the quality of the measured water level at one location in that vicinity (i.e, east of extraction well XP-1), and it is possible that this value is causing an erroneous interpretation regarding water level contours. It should also be noted that the area potentially not captured at the southern line of extraction wells is within the interpreted zone of capture for the northern line of extraction wells, and thus within the capture zone of the overall system.

Figure B2-6 is a similarly-constructed contour map for water level measurements that were made when the system was operating at 775 gpm. The results are generally similar compared to the results for 1,135 gpm, except that there appears to be less clean water captured by the northern line of extraction wells. Once again, there appears to be a small area on the far eastern side of the plume, at the southern line of extraction wells, where there may be a lack of capture, and this interpretation may be due to a questionable water level measurement at one location east of extraction well XP-1.

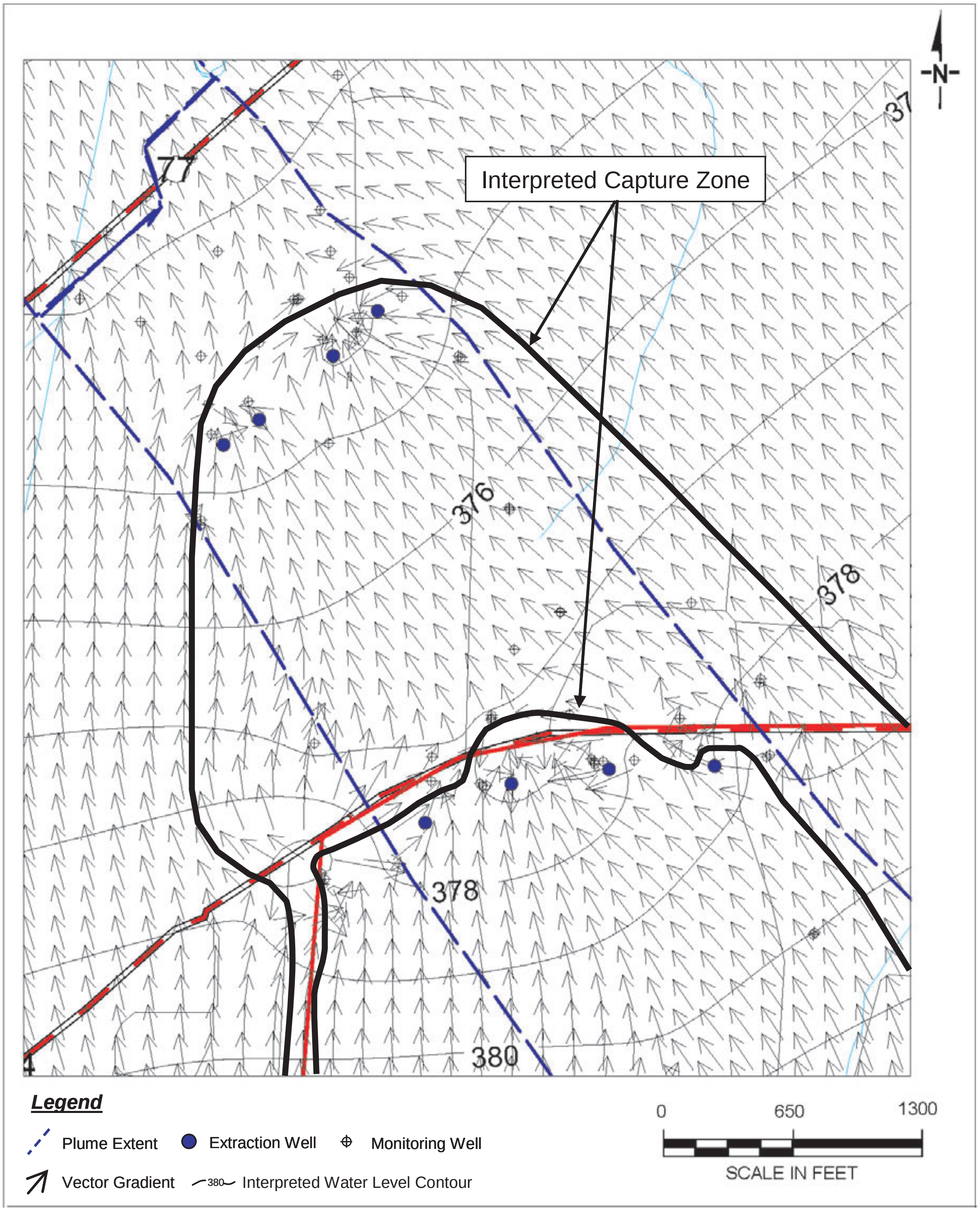
Figure B2-7 is a similarly-constructed contour map for water level measurements that were collected with the extraction system not operating. Comparing these water levels (without pumping) to the previous two figures (with pumping) clearly illustrates the impact of pumping. Figure B2-7 also highlights that some monitoring wells may have erroneous measurements or datums, because the flow vectors indicate complications in the ground-water flow patterns that would not be expected in the absence of pumping. Datums for these wells should be reviewed or re-surveyed; however it should be noted that the magnitude of possible error is on the order of inches. Some of these errors could also be

Figure B2-5. Interpreted Water Level Map, Current Pumping Rate of 1,135 gpm



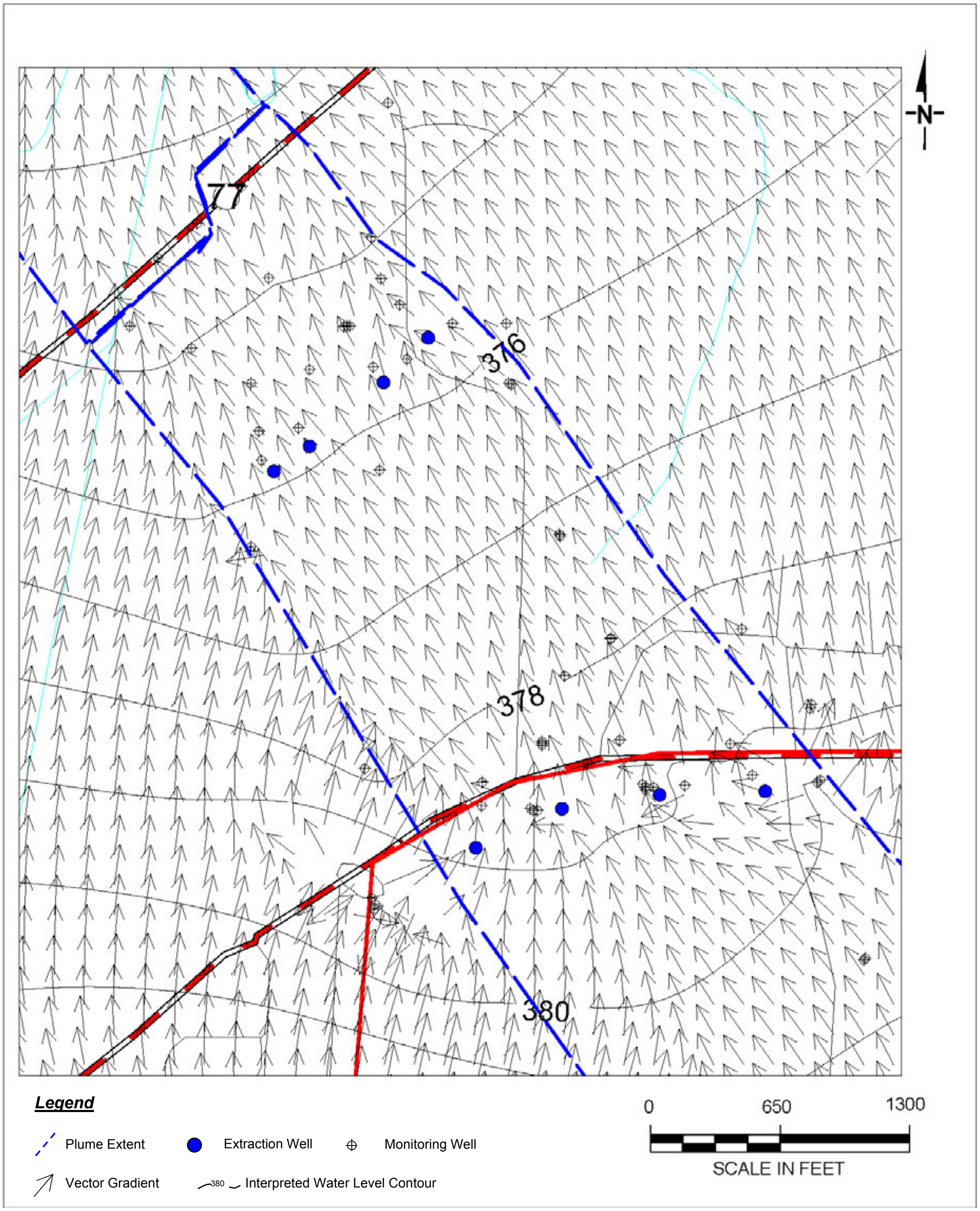
Note: contours and vectors are interpreted from measured water levels

Figure B2-6. Interpreted Water Level Map, Reduced Pumping Rate of 775 gpm



Note: contours and vectors are interpreted from measured water levels

Figure B2-7. Interpreted Water Level Map, with No Pumping



Note: contours and vectors are interpreted from measured water levels

due to 1) heterogeneity, 2) vertical head differences in well clusters, and 3) differing time frame for water levels to reach equilibrium after pumping was terminated.

Noteworthy features associated with the water level maps presented in Figures B2-5 to B2-7 include the following:

- measured water levels are not posted. Posting the water levels would allow the reader to better evaluate whether or not the interpreted water level contours are reasonable
- the width of the total explosives plume that is the basis for the width of the Target Capture Zone is identified on the map
- although total pumping rate is identified on each figure, pumping rates at the individual extraction rates are not identified, and adding those would improve the presentation
- there is a scale and a north arrow

It is also noted that the use of vectors that are created by the contouring software makes flow directions much easier to interpret.

Water Level Pairs (Gradient Control Points)

Pairs of water level elevations, located on either side of a real or conceptual boundary, can be used to demonstrate inward flow relative to that boundary. For this demonstration site, a more sophisticated approach using triangles was utilized. This approach utilized data from monitoring wells which were installed near the extraction wells for this purpose. This method mathematically determines a hydraulic gradient and flow direction from three water levels that form vertices of a triangle. Assumptions with this method include a homogeneous aquifer between wells, a linear change in head between wells, and that vertical head differences are small within the vertical interval from which water levels are used. A total of 17 “triangles” formed by wells that appear to satisfy these assumptions were used to evaluate ground-water flow directions for different rates of extraction.

The interpreted results for each of the three pumping scenarios are as follows:

- Figure B2-8 illustrates the flow directions derived from the two lines of extraction wells for a total extraction rate of 1,135 gpm. According to Figure B2-8, ground-water flow is generally towards the extraction wells, and flow divides downgradient of the extraction wells are indicated.
- Figure B2-9 illustrates that the magnitude of velocity is less when the pumping rate is lowered to 775 gpm, as depicted by the smaller arrows in Figure B2-9 compared to Figure B2-8, but flow directions do not change appreciably, again indicating the creation of flow divides downgradient of the extraction wells.
- Figure B2-10 presents the results for the case with no pumping. As expected, the flow directions change significantly when the extraction wells are turned off, with flow returning to background conditions (flow toward the northwest).

These evaluations of water levels pairs, while only based on a few measurement points, can be used to augment the conclusions from other lines of evidence regarding capture.

Figure B2-8. Interpreted Water Level "Triangles", Current Pumping Rate of 1,135 gpm

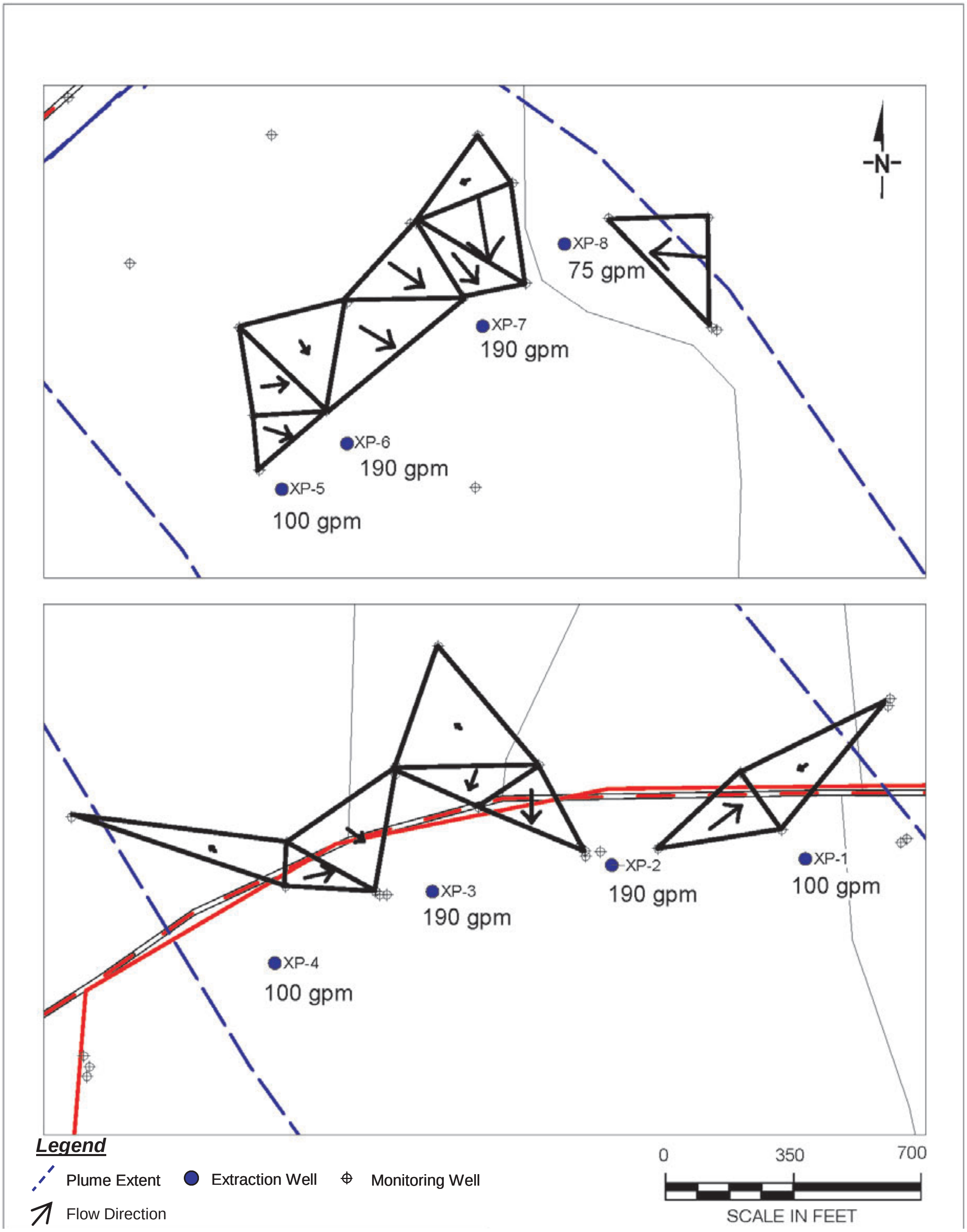


Figure B2-9. Interpreted Water Level “Triangles”, Reduced Pumping Rate of 775 gpm

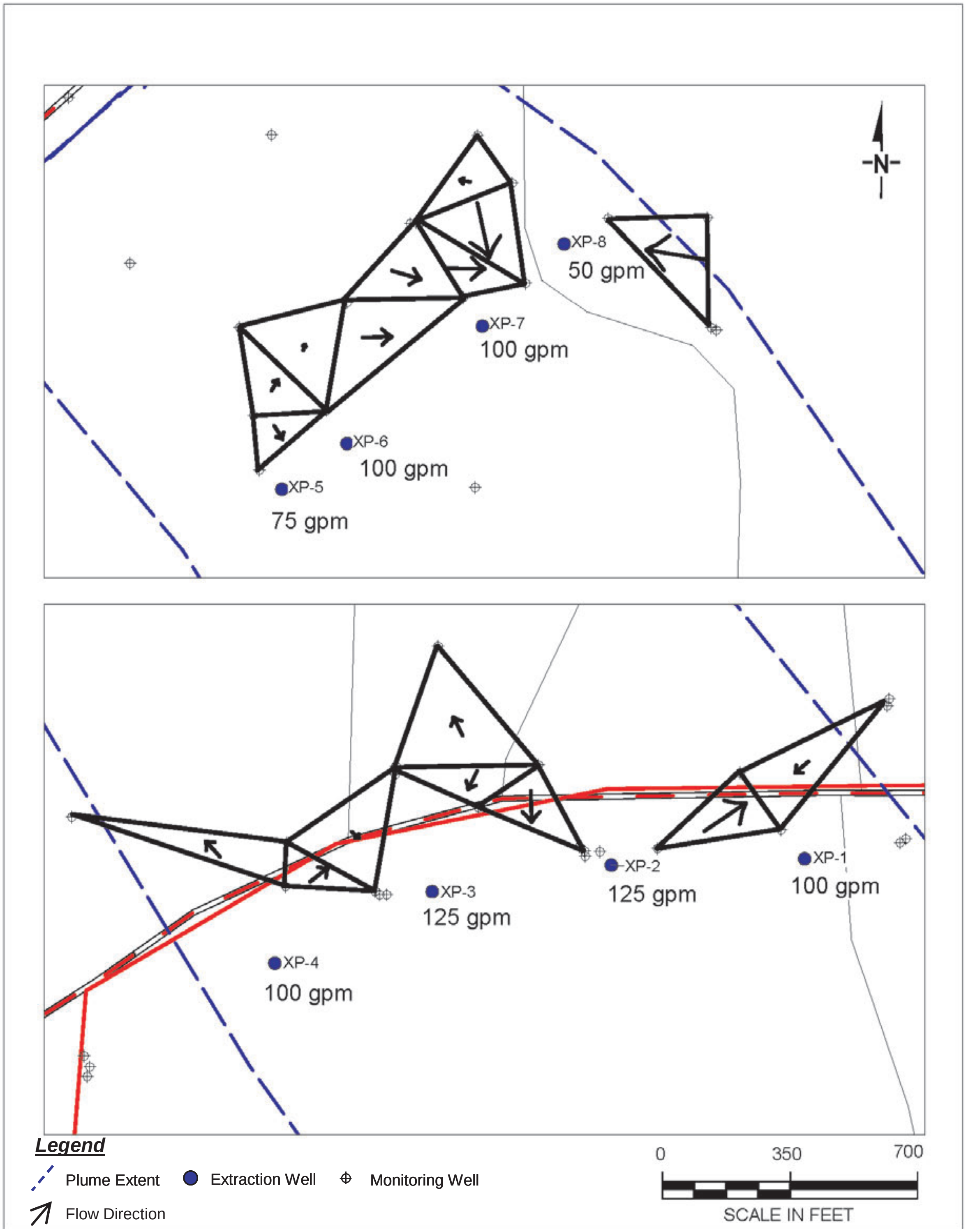
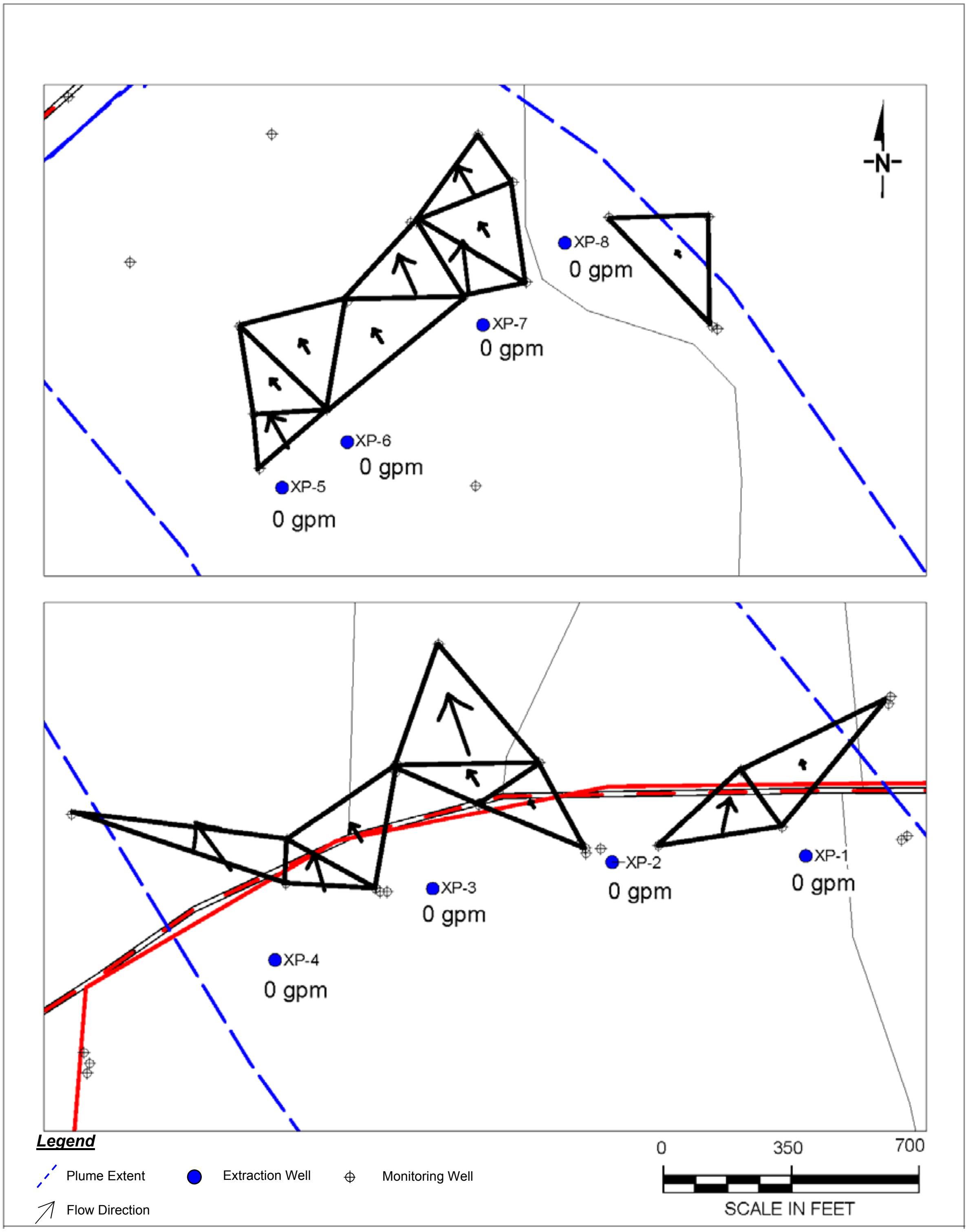


Figure B2-10. Interpreted Water Level "Triangles", with No Pumping



Step 4 - Perform Calculations

Estimated Flow Rate Calculation

As discussed in the main document, the estimated flow rate calculation provides an estimate for the pumping required to capture a plume, based on flow through the plume extent. This approach is summarized in Figure 13 in the main document. Assumptions for this approach include the following:

- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- other sources of water introduced to aquifer due to extraction are represented by the “factor”

Assignment of specific values for these parameters is typically difficult, due to heterogeneities. For instance, the hydrogeologic summary presented earlier indicates variation in hydraulic conductivity. Therefore, the results from this line of evidence must be considered with knowledge of these limitations. Nevertheless, it is useful to perform the calculation using best estimates and/or ranges of values for specific parameters. For this demonstration, the following approach was utilized:

- hydraulic conductivity was assigned as two potential values:
  - 70 ft/d (low estimate)
  - 110 ft/d (high estimate)
- aquifer thickness was assigned as 270 ft, therefore transmissivity ranges from:
  - 18,900 ft^2/d (low estimate)
  - 29,700 ft^2/d (high estimate)
- based on Figure B2-7 (static water levels) a hydraulic gradient of approximately 0.0012 was assigned
- plume width of 1,800 ft was estimated based on the width of the explosives plume (that defines that Target Capture Zone)
- “factor” was assigned as three potential values (1.0, 1.5, and 2.0) to assess sensitivity of the results to different degrees of potential capture of water from surface water and/or adjacent aquifers.

The flow rate calculation results, which estimate the amount of pumping that would be required to capture a plume width of 1,800 ft based on the various combinations of parameter assignments, are presented in Table B2-3.

Table B2-3. Estimated Flow Rate Calculation*

Factor	Transmissivity (ft^2/day)	Hydraulic Gradient (ft/ft)	Estimated Flow Rate (ft^3/day)	Estimated Flow Rate (gpm)
1.0	18,900	0.0012	40,824	212
	29,700	0.0012	64,152	333
1.5	18,900	0.0012	61,236	318
	29,700	0.0012	96,228	500
2.0	18,900	0.0012	81,648	424
	29,700	0.0012	128,304	666

** based on estimated plume width of 1,800 ft*

These results are then compared to the actual pumping rate. In this case, the actual pumping rate for each line of extraction wells should be considered. For the southern line of extraction wells (XP-1 to XP-4) the actual extraction rate is 580 gpm, and for the northern line of extraction wells (XP-5 to XP-8) the actual extraction rate is 555 gpm. Based on this simple calculation, it would appear that the total rate at each line of extraction is likely sufficient for successful capture, since the estimated flow rate required for capture is generally less than these actual pumping rates. The only exception is for the high value of transmissivity coupled with the high value of "factor". By utilizing a range of values for the various input parameters, some of the simplifications associated with this calculation are addressed. The consistent results for different ranges of parameter values adds confidence in the conclusion that the actual pumping rate is likely sufficient.

For the reduced pumping rate of 775 gpm being evaluated as an option, the pumping rate for each line of extraction wells should again be considered. For the southern line of extraction wells (XP-1 to XP-4) the extraction rate during the "shut-down" test was 450 gpm, and for the northern line of extraction wells (XP-5 to XP-8) the extraction rate during the "shut-down" test was 325 gpm. The results for estimated flow rates calculated in Table B2-3 indicate that pumping at each line of extraction may or may not be sufficient, because for several combinations of parameter values in Table B2-3 the estimated flow rate required for capture exceeds these actual pumping rates. It should be noted that the hydraulic gradient used at the northern line of the extraction wells (XP-5 to XP-8) may be an overestimate, because pumping at the southern line of extraction wells would likely flatten the background hydraulic gradient at the northern line of extraction wells. Thus, the simple analysis performed here may overestimate the pumping required at the northern line of extraction wells.

Capture Zone Width Calculation

As discussed in the main document, this line of evidence utilizes an analytical solution (illustrated in Figure 14 of the main document), for a specific pumping rate, to determine if capture zone width is likely sufficient. Assumptions for this approach include the following:

- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- no other sources of water are introduced to aquifer due to extraction

Note that this calculation assumes no other sources of water are introduced to the aquifer due to induced flow, such as from surface water or from an adjacent aquifer. This differs from the estimated flow rate calculation, which accounts for other potential sources of water through the "factor" term.

When multiple extraction wells are present, this capture zone width calculation is typically applied by assigning the total extraction rate to one "equivalent well". The location of the equivalent well is generally selected visually so it is centrally located with respect to the plume width and/or extraction well locations, and located at the most downgradient position of the actual extraction wells. This represents a significant level of simplification for a multi-well extraction system. For this site, a further complication is that there are two lines of extraction. For this analysis, one "equivalent well" is utilized for each line of extraction, and the capture zone width calculation is performed independently for each line of extraction (ignoring potential interference between the two lines of extraction).

Calculations for Y_{well} ,Y_{max}, and X_0 for different possible combinations of hydraulic gradient and transmissivity values are presented in Table B2-4, for the current pumping rate of 1,135 gpm, with the southern line of extraction wells (XP-1 to XP-4) at 580 gpm and the northern line of extraction wells (XP-5 to XP-8) at 555 gpm. Figure B2-11 illustrates these results for the current pumping rates (1,135 gpm). Note that results are illustrated based on the direction of background hydraulic gradient. The results indicate that this level of pumping provides sufficient capture at both lines of extraction, relative to the plume width of 1,800 feet that defines the Target Capture Zone.

A lower pumping rate of 775 gpm was also evaluated. Calculations for Y_{well} ,Y_{max}, and X_0 for different possible combinations of hydraulic gradient and transmissivity values are presented in Table B2-5, for the lower pumping rate of 775 gpm, with the southern line of extraction (XP-1 to XP-4) at 450 gpm and the northern line of extraction (XP-5 to XP-8) at 325 gpm, based on rates during the "shut-down" test. The results indicate that this level of pumping may not provide sufficient capture at the northern line of extraction wells (XP-5 to XP-8), for the higher value of transmissivity (i.e., maximum capture zone width of 1,755 ft upgradient of the extraction wells, versus plume width of approximately 1,800 feet). Figure B2-12 illustrates the results for the reduced pumping rates. For the low value of transmissivity, capture is sufficient at both lines of extraction wells. However, for the high value of transmissivity, capture is not quite sufficient across the full plume extent at the northern line of extraction wells. This suggests capture is likely sufficient for this pumping scenario, but with less certainty than at the current (higher) pumping rates.

Table B2-4. Capture Zone Width Calculation (Current Pumping)

XP-1 to XP-4 (580 gpm*)

Hydraulic Gradient (ft/ft)	Transmissivity (ft^2/d)	Distance from Well to Stagnation Point X_0 (ft)	Y_{well} (ft)	Capture Zone Width at Wells (ft)	Y_{max} (ft)	Max Capture Zone Width Upgradient (ft)
0.0012	18,900	783	1,231	2,461	2,461	4,923
	29,700	499	783	1,566	1,566	3,133

**consistent units are feet and days - pumping rate of 580 gpm is equal to 111,658 ft^3/day*

XP-5 to XP-8 (555 gpm*)

Hydraulic Gradient (ft/ft)	Transmissivity (ft^2/d)	Distance from Well to Stagnation Point X_0 (ft)	Y_{well} (ft)	Capture Zone Width at Wells (ft)	Y_{max} (ft)	Max Capture Zone Width Upgradient (ft)
0.0012	18,900	750	1,178	2,355	2,355	4,711
	29,700	477	749	1,499	1,499	3,998

**consistent units are feet and days - pumping rate of 555 gpm is equal to 106,845 ft^3/day*

Table B2-5. Capture Zone Width Calculation (Reduced Pumping)

XP-1 to XP-4 (450 gpm*)

Hydraulic Gradient (ft/ft)	Transmissivity (ft^2/d)	Distance from Well to Stagnation Point X_0 (ft)	Y_{well} (ft)	Capture Zone Width at Wells (ft)	Y_{max} (ft)	Max Capture Zone Width Upgradient (ft)
0.0012	18,900	608	955	1,910	1,910	3,819
	29,700	387	608	1,215	1,215	2,431

**consistent units are feet and days - pumping rate of 450 gpm is equal to 86,631 ft^3/day*

XP-5 to XP-8 (325 gpm*)

Hydraulic Gradient (ft/ft)	Transmissivity (ft^2/d)	Distance from Well to Stagnation Point X_0 (ft)	Y_{well} (ft)	Capture Zone Width at Wells (ft)	Y_{max} (ft)	Max Capture Zone Width Upgradient (ft)
0.0012	18,900	439	690	1,379	1,379	2,758
	29,700	279	439	878	878	1,755

**consistent units are feet and days - pumping rate of 325 gpm is equal to 62,567 ft^3/day*

Figure B2-11. Results for Capture Zone Width Calculation, Current Pumping Rate of 1,135 gpm

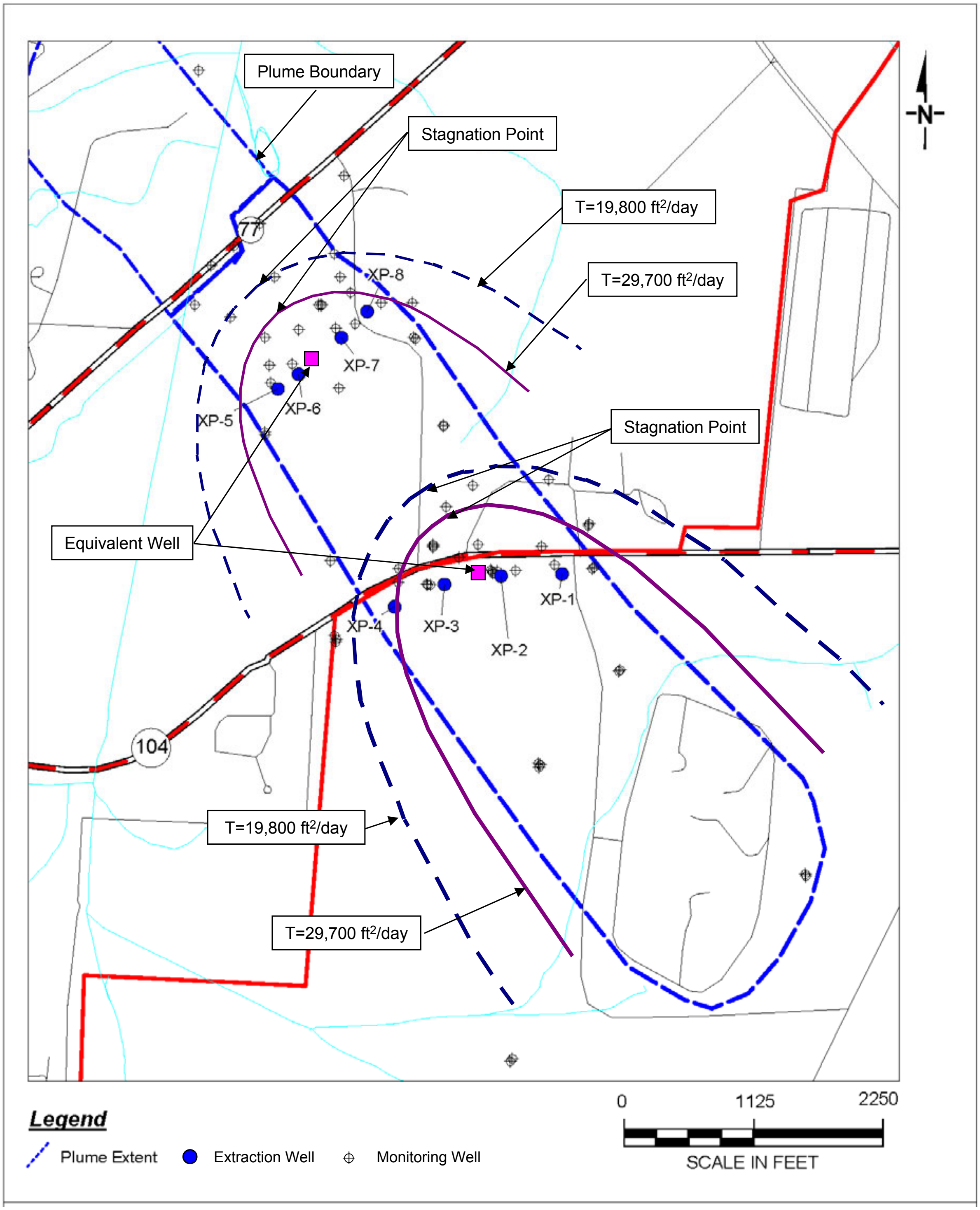
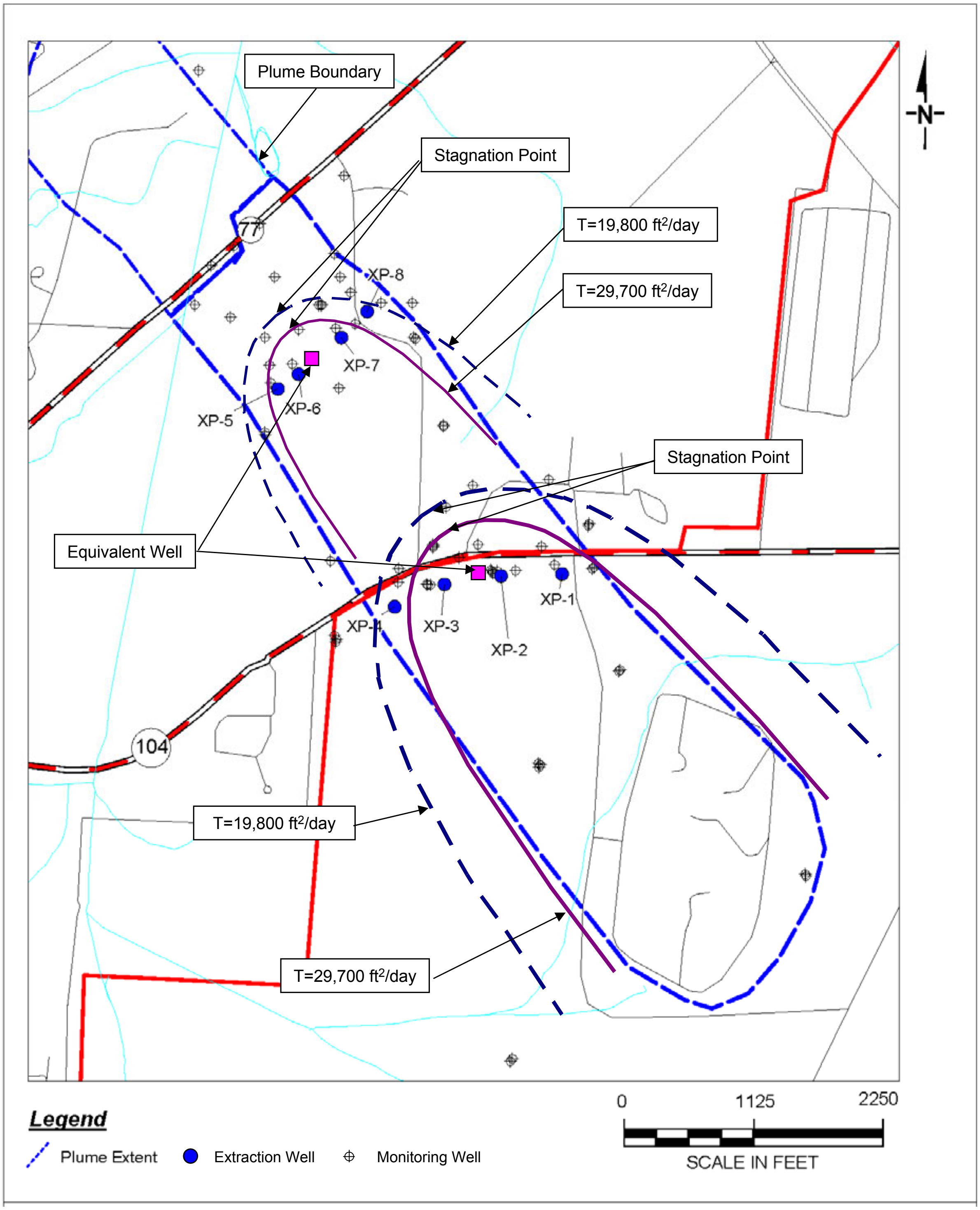


Figure B2-12. Results for Capture Zone Width Calculation, Reduced Pumping Rate of 775 gpm



Ground-Water Flow Model with Particle Tracking

After the start-up of the P&T system, the ground-water flow model used to design the extraction system was run to determine how well it predicted the drawdown response to known stresses. The two sets of extraction rates (1,135 and 775 gpm) were input to the model to compute water levels and drawdown (pumping versus no pumping). The model-computed output was then compared to the observed drawdown data. It was determined that the model had a tendency to over-predict drawdown (see Figure B2-13, part “a”), and the model was re-calibrated such that it predicted drawdown more accurately (see Figure B2-13, part “b”).

Capture zones derived by the model for each well, for the current extraction rate of 1,135 gpm, are shown in Figure B2-14. This figure was generated by color-coding each cell in the model by the final destination of a particle originating in that cell, as determined from the particle tracking. Although full details are not provided herein, this particle tracking analysis did consider the three-dimensionality of the problem. The initial particles were placed at different depths (i.e., model layers) where the aquifer is impacted. Figure B2-14 illustrates the results for one such depth interval. These results indicate that extraction of 1,135 gpm sufficiently captures the plume, plus a significant amount of clean water. Similar results were achieved for other depth intervals where the aquifer is impacted (not presented herein). It is also noted that a small area on the far eastern side of the plume may not be captured at the southern line of extraction wells, but is subsequently captured at the northern line of extraction wells. This could potentially be due to a slight discrepancy between the simulated ground-water flow direction in the model versus the actual flow direction suggested by the shape of the plume outline.

At 775 gpm, the particle tracking results (Figure B2-15) indicate that the overall plume is still captured. Again, Figure B2-15 illustrates the results for one depth interval where the aquifer is impacted, and similar results were achieved for other depth intervals where the aquifer is impacted (not presented herein). Again, there is a small area on the far eastern side of the plume that may not be captured at the southern line of extraction wells, but is subsequently captured at the northern line of extraction wells.

Step 5 - Evaluate Concentration Trends

A baseline sampling event for explosives concentrations in monitoring wells was conducted prior to startup of the system. Water quality data were collected again in May and June of 2003, approximately one year after extraction was initiated, primarily to monitor progress of aquifer restoration. These data are not relied upon for evaluating capture because this evaluation of capture was done so soon after pumping was initiated. However, continued water quality monitoring will provide data from which long-term trends can be determined and evaluated to provide additional evidence regarding capture.

Step 6 - Interpret Actual Capture Based on Steps 1-5, Compare to Target Capture Zone(s), Assess Uncertainties and Data Gaps

Based on evaluations of multiple lines of evidence discussed in Step 3 to Step 5, the actual capture achieved by the extraction wells is interpreted in Step 6, and the following items are addressed:

- Compare the interpreted capture zone to the Target Capture Zone
- Assess uncertainties in the interpretation of the actual capture zone
- Assess the need for additional characterization and/or monitoring
- Evaluate the need to reduce or increase extraction rates

Table B2-6 presents the summary of the capture zone evaluation for this site.

Figure B2-13. Summary of Drawdown Response to Pumping: Original Model (a) and Re-Calibrated Model (b)

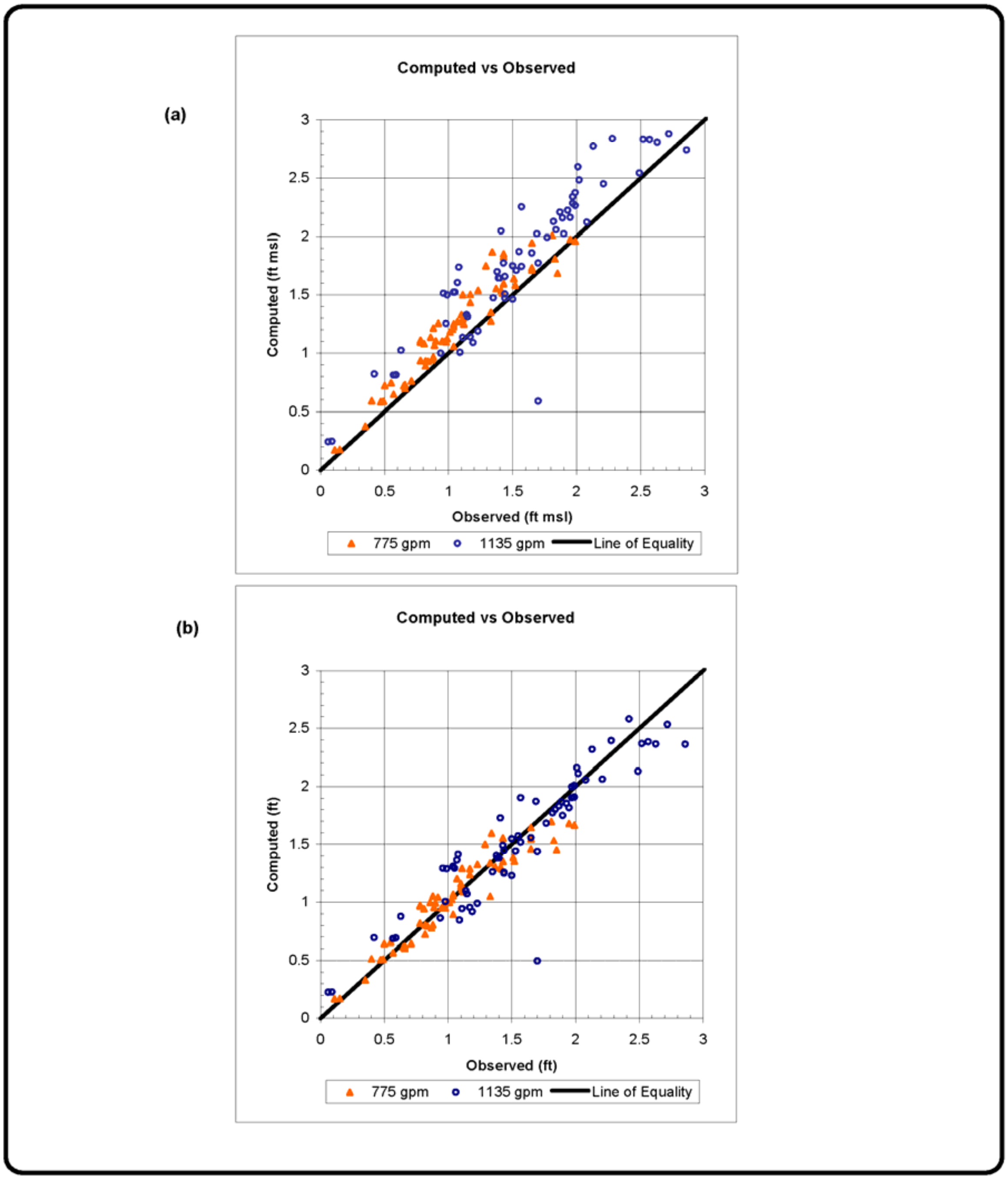


Figure B2-14. Summary of Particle Tracking Results, Current Pumping Rate of 1,135 gpm

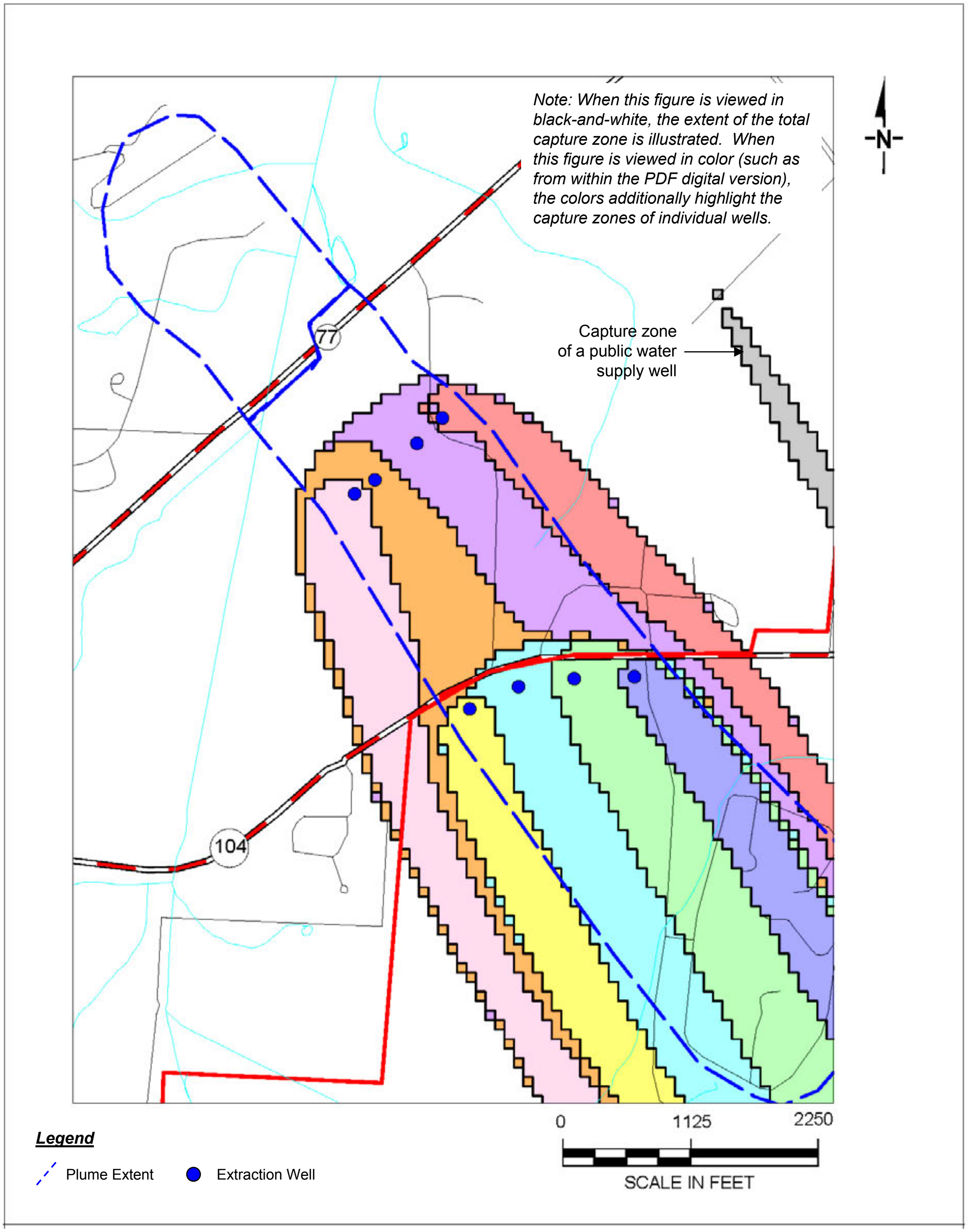


Figure B2-15. Summary of Particle Tracking Results, Current Pumping Rate of 775 gpm

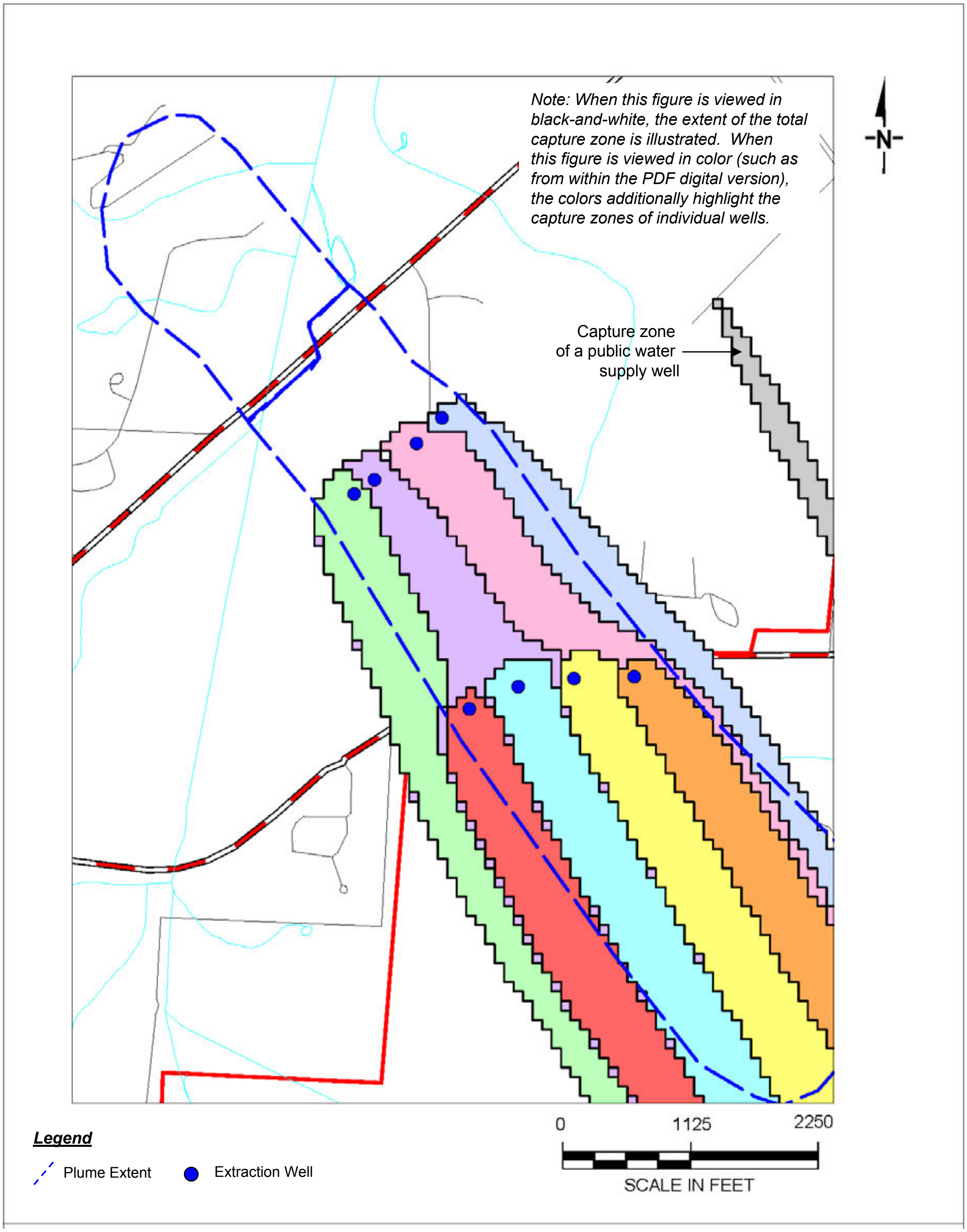


Table B2-6. Summary of Capture Zone Evaluation

Step	Summary/Conclusions
Step 1: Review site data, site conceptual model, remedy objectives	Completed, all determined to be up-to-date and adequate.
Step 2: Define "Target Capture Zone(s)"	Clearly defined horizontally and illustrated on maps, no vertical Target Capture Zone specified (however, as discussed, extraction well screens were designed to sufficiently provide horizontal hydraulic containment for all impacted depths).
Step 3a: Water level maps	Contours and flow vectors indicate successful capture for the overall system for the current extraction rate (1,135 gpm) and the reduced extraction rate (775 gpm). There appears to be a small area on far eastern side of the plume, at the southern line of extraction wells, where there may be a lack of capture. This could be the result of an uncertain water level measured east of extraction well XP-1. Also, that area is within the interpreted zone of capture for the northern extraction wells, and thus within the capture zone of the overall system. Water level measurements are available from locations near the extraction wells so the evaluation is not biased by water levels at extraction wells.
Step 3b: Water level pairs	Actually uses triangles rather than pairs, results suggest inward flow and successful creation of a flow divide for both the current extraction rate (1,135 gpm) and the reduced extraction rate (775 gpm).
Step 4a: Simple horizontal capture zone analyses	Estimated flow rate calculation suggests the current pumping rate of 1,135 gpm is likely sufficient at both lines of extraction, and the reduced pumping rate of 775 gpm may or may not be sufficient. Capture zone width calculation suggests the long-term average pumping rate of 1,135 gpm is sufficient at both lines of extraction, and the reduced pumping rate of 775 gpm is sufficient for the low value of transmissivity but potentially not sufficient for the high value of transmissivity. This suggests capture is likely sufficient, but with somewhat less certainty than with the current (higher) pumping rates.
Step 4b: Ground-water flow modeling with particle tracking	Model calibration was updated after the system began operating based on observed system performance, and particle tracking results indicate successful capture for both the current extraction rate (1,135 gpm) and the reduced extraction rate (775 gpm). A small area on far eastern side of the plume may not be captured at the southern line of extraction wells, but is subsequently captured at the northern line of extraction wells. This could potentially be due to a slight discrepancy between the simulated ground-water flow direction in the model versus the actual flow direction suggested by the shape of the plume outline.
Step 5: Concentration trends	Not relied upon for short-term evaluation of capture.
Step 6: Interpret actual capture and compare to Target Capture Zone	The actual capture zone is interpreted to be sufficient for the current extraction rate (1,135 pm). However, there is some uncertainty regarding capture on the far eastern side of the plume, along the southern line of extraction wells, for some lines of evidence (i.e., water levels and particle tracking). Actual capture is nearly complete and may be sufficient for the reduced extraction rate (775 gpm), although the capture zone width calculation indicates that capture may not be sufficient for the high value of transmissivity. Again, there is some uncertainty regarding capture on the far eastern side of the plume, along the southern line of extraction wells, for some lines of evidence (i.e, water levels and particle tracking).

As discussed in Exhibit 8 of the main document, a summary of the following items is appropriate:

- *Is capture sufficient, based on "converging lines of evidence"?*

  The actual capture zone is interpreted to be sufficient for the current extraction rate (1,135 pm). It appears that the zone of capture is larger than the Target Capture Zone at the northern line of extraction wells, based on multiple lines of evidence. This provides a safety factor that accounts for uncertainties, and is likely due to a flattening of the hydraulic gradient caused by the pumping at the southern line of extraction wells. There is some uncertainty regarding capture on the far eastern side of the plume, at the southern line of extraction wells, for some lines of evidence (i.e., water levels and particle tracking). Therefore, there is uncertainty as to whether or not the Target Capture Zone is fully satisfied for the southern line of extraction wells. The causes of this uncertainty are discussed below. However, multiple lines of evidence indicate that if there is a lack of capture in that area at the southern line of extraction wells, the water in that area of the plume would be subsequently captured at the northern line of extraction wells.

  Actual capture is nearly complete and may be sufficient for the reduced extraction rate (775 gpm), although the capture zone width calculation indicates that capture may not be sufficient for the high value of transmissivity. This issue is probably best resolved through calibration and verification of the ground-water flow model. The results of the particle tracking analysis, based on the ground-water flow model, indicate that the simulated extent of capture is greater than indicated by the simple capture zone width calculation using the high value of transmissivity. Thus, the high value of transmissivity used in the simple calculations is probably higher than the calibrated value of transmissivity. Again, there is some uncertainty regarding capture on the far eastern side of the plume for some lines of evidence (i.e, water levels and particle tracking).

- *Key uncertainties/data gaps*

  The water level map constructed for the case with no pumping (Figure B2-7) indicated that some monitoring wells may have erroneous measurements or datums, because the flow vectors indicate complications in the ground-water flow patterns that would not be expected in the absence of pumping. Datums for these wells should be reviewed or re-surveyed; however it should be noted that the magnitude of possible error is on the order of inches.

  As noted above, water level maps indicate some uncertainties in the capture zone evaluation along the far eastern plume boundary at the southern line of extraction wells. In particular, there is a potential water level data point east of extraction well XP-1 that might be errant. A potential approach is to confirm that the measurement is accurate in the field. Another approach is to re-contour the water levels without that value, or with a potentially different value, to determine if the interpretation of water level contours east of extraction well XP-1 changes as a result. Additional water level monitoring locations in that area might also help resolve this issue.

  It was noted in the analysis of particle tracking results that a small area on the far eastern side of the plume may not be captured at the southern line of extraction wells, but is subsequently captured at the northern line of extraction wells. This could potentially be due to a slight discrepancy between the simulated ground-water flow direction in the model versus the actual flow direction suggested by the shape of the plume outline. This flow model could be evaluated to determine if small changes to the model boundaries or parameter values might lead to a slightly different simulated flow direction, such that the orientation of the simulated capture zones more closely aligns with the interpreted plume shape.

- *Recommendations to collect additional data, install new monitoring wells, change current extraction rates, change number/location of extraction wells, etc.*

  The capture zone evaluation summarized herein concluded that the current system (1,135 gpm) was pumping more water than was required for successful capture. It also concluded that the reduced pumping rate of 775 gpm appeared to capture the plume in most areas (i.e., nearly complete capture), but with some uncertainty regarding capture near XP-1 (the easternmost extraction well along Highway 104) and also some uncertainty at the northern line of extraction wells. At this site, a recommendation resulting from the capture zone evaluation was to reduce the total pumping rate from 1,135 gpm to 900 gpm to capture less clean water (specific rates at individual wells were recommended, but those details are not presented herein). This provided a "safety factor" relative to the 775 gpm scenario. The recommendation also suggested subsequent capture zone evaluations after the new extraction rates were implemented, to verify with field data that capture continued to be sufficient under the new pumping strategy. Long-term evaluation of concentration trends at performance monitoring wells located downgradient of the capture zone associated with each line of extraction wells will allow the success of the extraction wells to prevent plume migration (horizontally and vertically) to be verified. Uncertainties identified above could be addressed by reviewing and/or re-surveying the datums for several wells where anomalous water levels were indicated, adding water level measurement locations near extraction well XP-1, and potentially making slight modifications to the ground-water flow model so that the simulated capture zones more closely align with the interpreted plume shape.

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