Capture Zone Analyses For Pump and Treat Systems

Internet Seminar

Version: July 1, 2008

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Background

- Hydraulic containment of impacted ground water (i.e., "plume capture") is one of the remedy objectives at almost every site with a P&T system
  - Control the leading edge of the plume
  - Control source areas
- EPA Superfund Reforms: Pump and Treat Optimization
  - http://www.epa.gov/superfund/programs/reforms/docs/implem.pdf
  - Remediation System Evaluations (RSEs)
  - Recommendation to perform an improved capture zone analysis was made at 16 of the first 20 "Fund-lead" sites where a Remediation System Evaluation (RSE) was performed

Common Capture Zone Issues Observed During RSEs

- No Target Capture Zone defined, and/or capture not evaluated
- Pumping rates lower than design, but modeling never updated accordingly
- Relied on water levels measured at pumping wells when interpreting water levels
- Neglected potential for vertical transport
- Confused drawdown response with capture
- Not monitoring water levels at all measuring points, or not converting “depth to water” to “water level elevation”
- Model predictions from design not verified based on observed pumping rates and resulting drawdown observations

Dissemination of Information – Capture Zone Evaluation

- Published document in 2008
- Training sessions
  - EPA Regions
  - EPA NARPM meeting
  - States
- Internet training

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Key EPA Reference Documents

- ***A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems, January 2008*** *(*EPA 600/R-08/003*)*
  - *http://www.epa.gov/ada/download/reports/600R08003/600R08003-FM.pdf*
- ***Elements for Effective Management of Operating Pump and Treat Systems**, 2002* (EPA 542-R-02-009)
  - http://www.clu-in.org/download/remed/rse/factsheet.pdf *{a more general reference on management of P&T systems}*
- ***Methods for Monitoring Pump-and-Treat Performance**, 1994* (EPA/600/R-94/123)
  - http://www.epa.gov/r10earth/offices/oea/gwf/issue20.pdf

Outline

- Introduction
  - What is a capture zone, and why is it important to evaluate capture zones?
- Six Basic Steps for Capture Zone Analysis
  - Examples and schematics used to illustrate concepts

we are discussing systems that behave like a porous media, not addressing the added complexities of karst or fracture flow systems

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What is a "Capture Zone"?

- "Capture Zone" refers to the three-dimensional region that contributes the ground water extracted by one or more wells or drains
- Capture zone in this context is equivalent to zone of hydraulic containment

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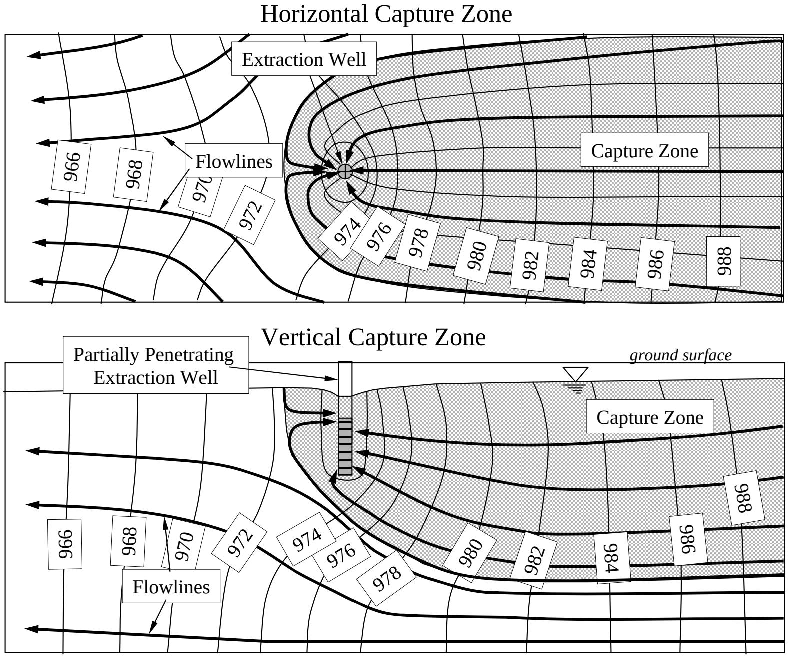

- *Vertical capture does not encompass the entire aquifer thickness for this partially penetrating well. The top figure does not convey this, which shows the need for three-dimensional analysis.*
- *The greater the vertical anisotropy (horizontal versus vertical hydraulic conductivity), the shallower the vertical capture zone will be.*

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Evaluating Capture

- For pump-and-treat (P&T) systems, there are two components that should be the focus of a project manager
  - Target Capture Zone
  - Actual Capture Zone
- “Capture zone analysis” is the process of interpreting the actual capture zone, and comparing it to the Target Capture Zone to determine if sufficient capture is achieved

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Items Where Actual System May Differ From Designed System

- Actual extraction well locations or rates differ from those in the design
- Design may not have accounted for
  - system down time (i.e., when wells are not pumping)
  - time-varying influences such as seasons, tides, irrigation, or transient off-site pumping
  - declining well yields due to fouling (need for proper well maintenance)
  - Geologic heterogeneities (such as zone of higher hydraulic conductivity due to a buried paleochannel)
  - Hydraulic boundary conditions (such as surface water boundary or hard rock boundary)

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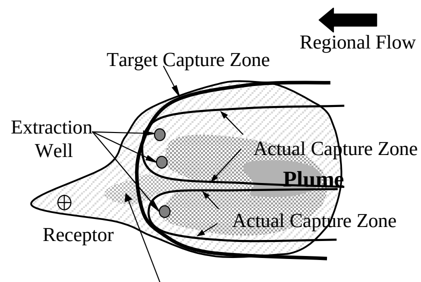
Potential Negative Impacts From Poor Capture Zone Analysis

- May compromise protectiveness with respect to receptors
- May allow plume to grow
  - May require expansion of extraction and/or monitoring network
  - May increase cleanup time
- Potentially wastes time and money



Escaped plume due to the gap between the capture zones

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Six Basic Steps for Capture Zone Analysis

- 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 (as appropriate based on site complexity)
  - Estimated flow rate calculation
  - Capture zone width calculation (can include drawdown calculation)
  - Modeling (analytical and/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), and assess uncertainties and data gaps

"Converging lines of evidence" increases confidence in the conclusions

Concept of
“Converging Lines of Evidence”

- Each technique for evaluating capture is subject to limitations
- “Converging lines of evidence”
  - Use multiple techniques to evaluate capture
  - Increases confidence in the conclusions

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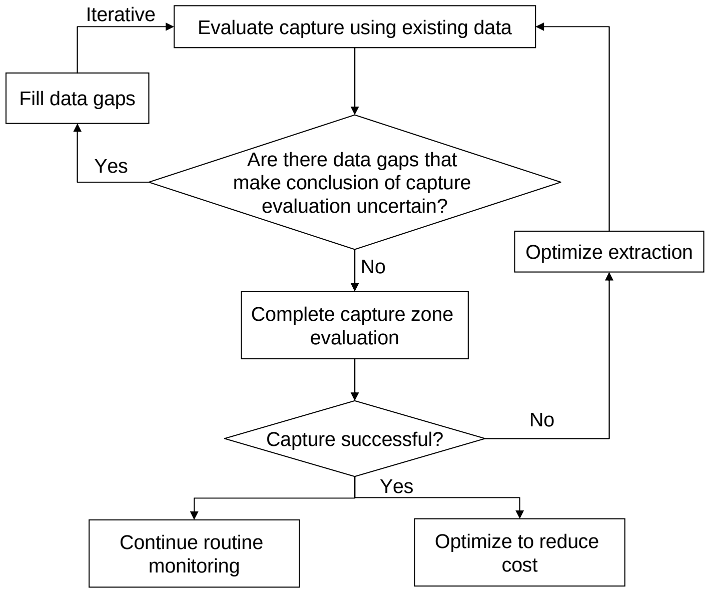
Capture Zone Analysis – Iterative Approach



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Questions so far?

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Six Basic Steps for Capture Zone Analysis

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Step 1: Review Site Data, SCM, and Remedy Objectives

- Is plume delineated adequately in three dimensions (technical judgment required)?

- Is there adequate hydrogeologic information to perform capture zone analysis (technical judgment required)?
  - 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 over time
  - Well construction data

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Step 1: Review Site Data, SCM, and Remedy Objectives

- Is there an adequate "site conceptual model (SCM)" (not to be confused with a numerical model) that
  - Indicates the source(s) of contaminants
  - Summarizes geologic and hydrogeologic conditions
  - Explains the observed fate and transport of constituents
  - Identifies potential receptors

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Step 1: Review Site Data, SCM, and Remedy Objectives

- Is the objective of the remedy clearly stated with respect to hydraulic containment?
  - Does it include complete hydraulic containment?

    – or –

  - Does it only require partial hydraulic containment with other remedy (e.g., MNA) for portion of the plume outside of the Target Capture Zone?
  - These question apply both horizontally and vertically

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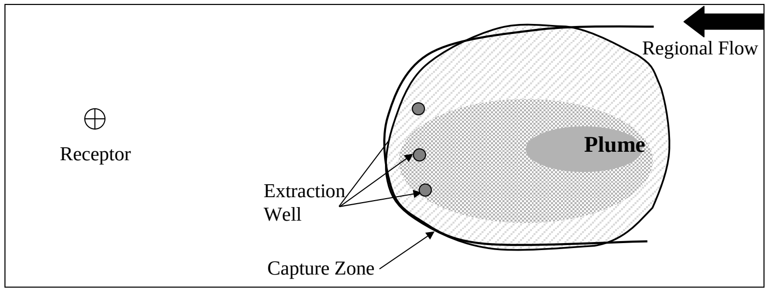
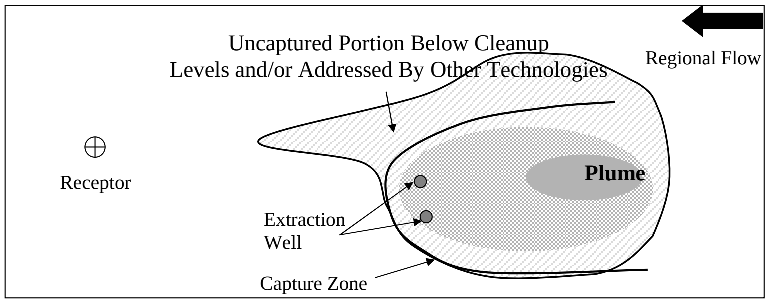
Goal is Capture for Entire Plume Extent – Map View



Goal is Capture for Portion of Plume – Map View



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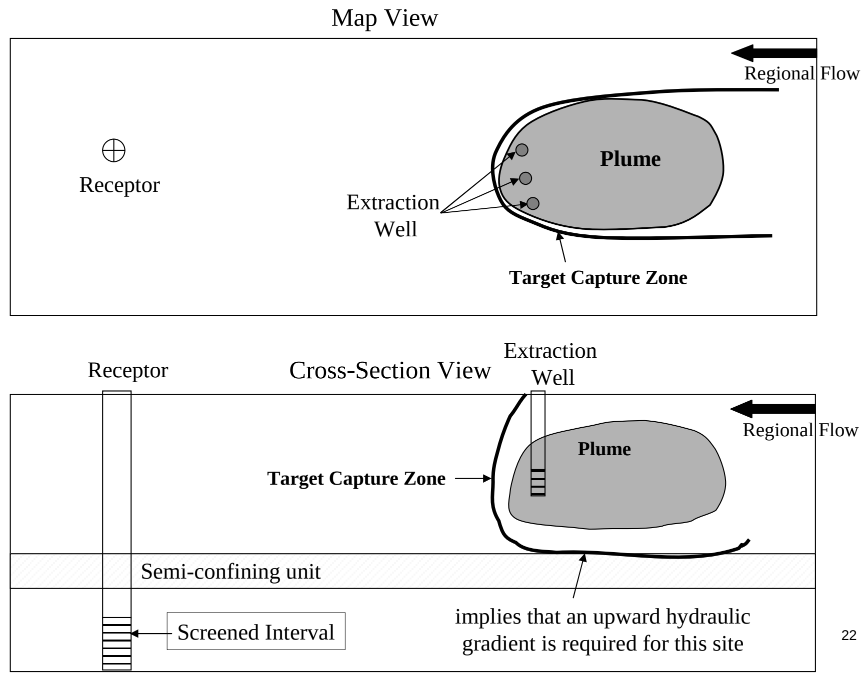
**Performance monitoring wells are not depicted on these schematics to maintain figure clarity*

Step 2:
Define Target Capture Zone

- Where specifically is hydraulic capture required?
  - Horizontally
  - Vertically
  - Any related conditions that must be met
- Should be consistent with remedy objectives (Step 1)
- Should be clearly stated on maps and/or cross-sections when possible
- May be defined by a geographical boundary or a concentration contour
  - Note that concentration contours can change over time
  - If multiple contaminants, all should be considered

Target Capture Zone: Should Be 3-Dimensional



Step 3: Interpretation of Water Levels

- Potentiometric surface maps
  - Extent of capture interpreted from water level contours
  - To evaluate horizontal capture
- Head difference maps
  - To evaluate vertical capture
- Water level pairs (gradient control points)
  - Confirm inward flow across a boundary, or from a river or creek into an aquifer, at specific locations
  - Confirm vertical flow is upward or downward at specific locations

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Step 3: Notes about Water Level Measurements

- Installing water level measurement points is generally inexpensive at most (but not all) sites
  - If data gaps exist, installing new "piezometers" should be considered
  - We refer to "piezometer" as a location with a relatively short screen or open interval where *only water levels* are measured
- Historical depth to water at each well should be available in the field so sampling technician can identify (and ideally reconcile) anomalies during sampling
- Performing periodic well surveys is recommended to verify the measuring point elevations

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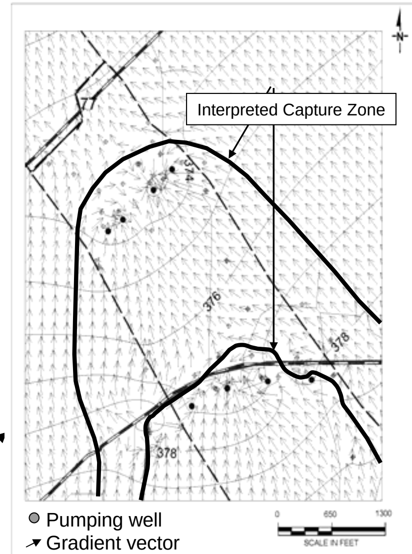
Step 3: Notes about Water Level Measurements

- Contouring can be done by hand or with software
  - By hand incorporates the insight of the hydrogeologist
  - Software can allow vectors of flowlines to be created and displayed



Contours and vectors are interpreted from measured water levels

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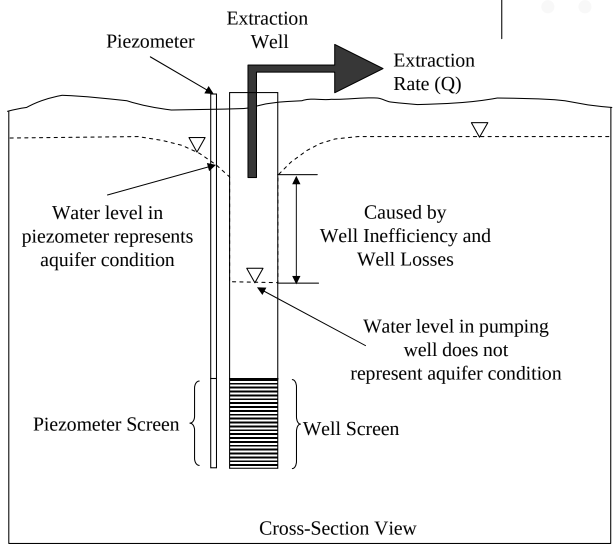
Critical Pitfall: Water Levels at Pumping Wells

- Water levels at extraction wells are generally *<u>not representative</u>* of the aquifer just outside the well bore due to well losses
  - Well inefficiencies and losses caused by
    - Poor or inadequate development of well
    - Biofouling and encrustation
    - Turbulent flow across the well screen
- Best to have piezometer(s) near each extraction well



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Issues with Evaluating Potentiometric Surfaces

Issue	Comments
Are 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?	Water levels measured at extraction wells should not be used directly due to well inefficiencies and losses. Preferably, water level data representative of the aquifer should be obtained from locations near extraction wells. If not, water levels near pumping wells can be estimated.
Has horizontal capture evaluation been performed for all pertinent horizontal units?	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?	There may be valid alternate interpretations of water level contours that indicate a different capture zone
Is representation of transient influences adequate?	A water level map for one point in time may not be representative for other points in time

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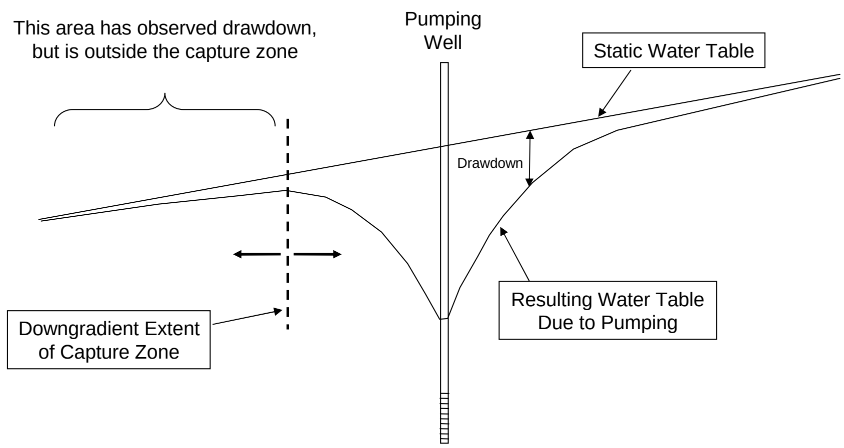
Drawdown and Capture Are Not The Same Thing (section view)



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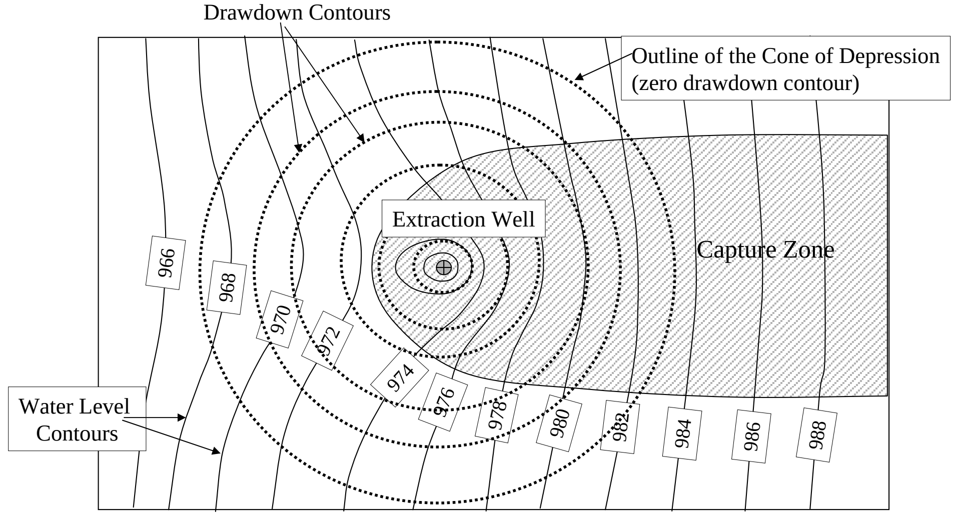
Drawdown and Capture Are Not The Same Thing

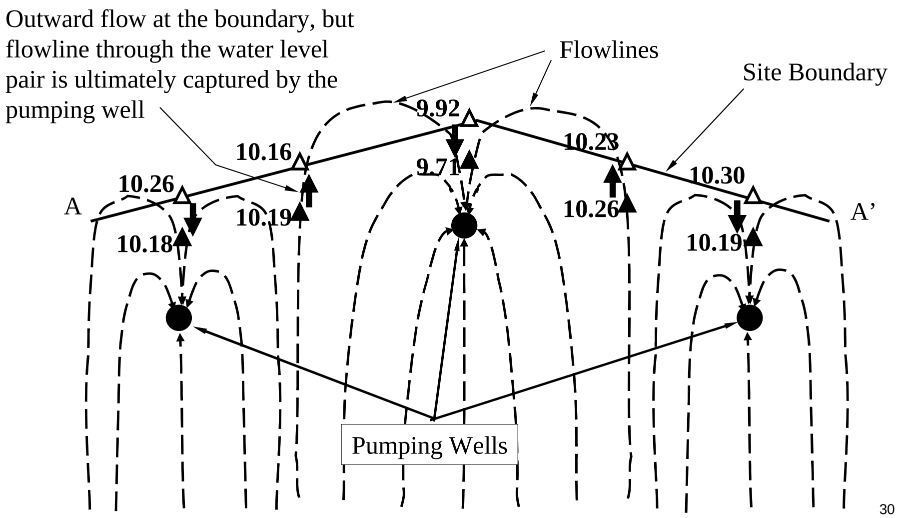


Drawdown is the change of water level due to pumping. It is calculated by subtracting water level under pumping conditions from the water level without pumping.

Cone of Depression is the region where drawdown due to pumping is observed.

Capture Zone 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.

Step 3 (cont.): Water Level Pairs (Gradient Control Points)



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Step 3 (cont.): Water Level Pairs (Gradient Control Points)

- Water level pairs (gradient control points)
  - Are most likely to indicate "outward flow" when located between pumping wells
  - Increasing pumping rates to achieve "inward gradients" can increase confidence that capture is achieved, but there may be increased cost associated with that
  - Water level pairs at well clusters with different screen intervals can be used to indicate areas of upward or downward flow
    - usually only a few clustered locations are available and locations between those clusters must be interpreted

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Questions so far?

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Step 4:
Perform Calculations

- Specific calculations can be performed to add additional lines of evidence regarding extent of capture
  - ➢ Simple horizontal analyses
    - Estimated flow rate calculation
    - Capture zone width calculation (can include drawdown calculation)
  - ➢ Modeling to simulate heads, in conjunction with particle tracking and/or transport modeling
    - Modeling of heads may be analytical or numerical
    - Numerical modeling is more appropriate for sites with significant heterogeneity and/or multiple aquifers
- Not suggesting that numerical modeling is appropriate at all sites

Step 4a: Simple Horizontal Analyses

- Estimated Flow Rate Calculation: calculate estimated pumping required for capture based on flow through the plume extent

and/or

- Capture Zone Width Calculation: evaluate analytical solution for specific values of pumping to determine if capture zone width is likely sufficient

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Simple Horizontal Capture Zone Analyses

- These methods require simplifying assumptions:
  - Homogeneous, isotropic, confined aquifer of infinite extent
  - Uniform aquifer thickness
  - Fully penetrating extraction wells
  - 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)

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Estimated Flow Rate Calculation

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

(*Must use consistent units*)

Where:

Q = extraction rate

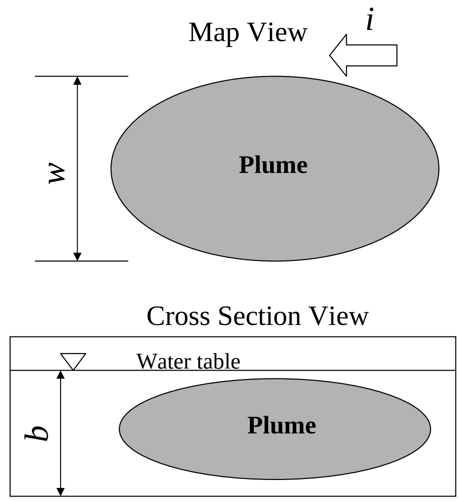
K = hydraulic conductivity

b = saturated thickness

w = plume width

i = regional 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 unit



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Flow Rate Calculation – Example

- Parameters
  - K = 28 ft/d {hydraulic conductivity}
  - b = 31 ft {saturated thickness}
  - w = 1000 ft {plume width to be captured}
  - i = 0.0033 ft/ft {hydraulic gradient}

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

Q = 28 ft/day * 31 ft * 1000 ft * .0033 ft/ft * factor * 7.48 gal/ft3 * 1 day/1440 min
= 15 gpm * factor

If factor = 1.0, then 15 gpm is estimated to capture the plume
If factor = 1.5, then 22.5 gpm is estimated to capture the plume
If factor = 2.0, then 30 gpm is estimated to capture the plume

Capture Zone Width Calculation

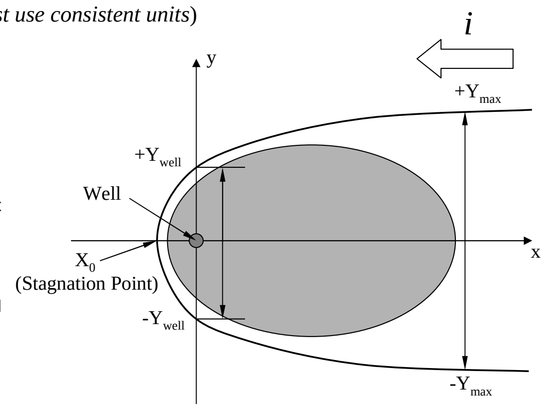
$$x = -y \Big/ \tan\left(\frac{2\pi Ti}{Q}\, y\right) \quad - or - \quad y = \pm\left(\frac{Q}{2Ti}\right) - \left(\frac{Q}{2\pi Ti}\right)\tan^{-1}\left(\frac{y}{x}\right)$$

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

(*Must use consistent units*)

Where:

- Q = extraction rate
- T = transmissivity, K·b
- K = hydraulic conductivity
- b = saturated thickness
- i = 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



This simple calculation can also applied for multiple wells (in some cases) based on simplifying assumptions 38

Capture Zone Width Calculation - Example

- Parameters
  - Q = 21 gpm {pumping rate – note units are not consistent!}
  - K = 28 ft/d {hydraulic conductivity}
  - b = 31 ft {saturated thickness}
  - i = 0.0033 ft/ft {hydraulic gradient}

X_0 = -Q/2πKbi = -(21 gpm * 1440 min/day * 0.1337 ft^3/gal) / (2 * 3.14 * 28 ft/day * 31 ft * .0033 ft/ft) = -225 ft

Y_{max} = Q/2Kbi = (21 gpm * 1440 min/day * 0.1337 ft^3/gal) / (2 * 28 ft/day * 31 ft * .0033 ft/ft) = 706 ft

Y_{well} = Q/4Kbi = (21 gpm * 1440 min/day * 0.1337 ft^3/gal) / (4 * 28 ft/day * 31 ft * .0033 ft/ft) = 353 ft

Units conversion must be incorporated due to inconsistent units for pumping rate 39

Simple Horizontal Capture Zone Analyses

- Easy to apply quickly, and forces basic review of conceptual model
- Clearly indicates relationship between capture zone width and other parameters
  - Capture zone width decreases if hydraulic conductivity or hydraulic gradient is lower, or if aquifer thickness is higher
- One or more assumptions are typically violated, but often are still useful as scoping calculations and/or to evaluate ranges of possible outcomes based on reasonable variations of parameters
- Vertical capture not addressed by these simple methods

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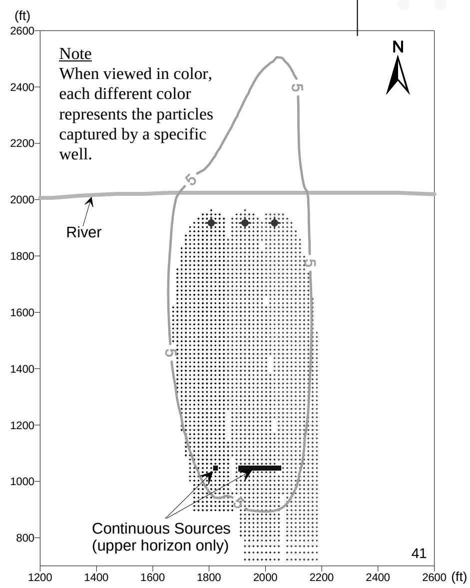
Step 4b: Modeling plus Particle Tracking

- Can be used to evaluate both horizontal and vertical aspects of capture
- It is easy to be misled by a picture made with particle tracking, it is important to have the particle tracking approach evaluated by someone with adequate experience with those techniques
- Evaluation of capture with a numerical model is "precise" if performed properly, *but is still only as "accurate" as the water levels simulated by the model (if model inputs do not reasonably represent actual conditions, there is potential for "garbage in – garbage out")*
- Model predictions are subject to many uncertainties, and the model should be calibrated and then verified with field data to the extent possible (usually verify drawdown responses to pumping)



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Step 5: Evaluate Concentration Trends

- Concentration Trends
  - Sentinel wells
    - downgradient of Target Capture Zone
    - not currently impacted above background concentrations
  - Downgradient performance monitoring wells
    - downgradient of Target Capture Zone
    - currently impacted above background concentrations

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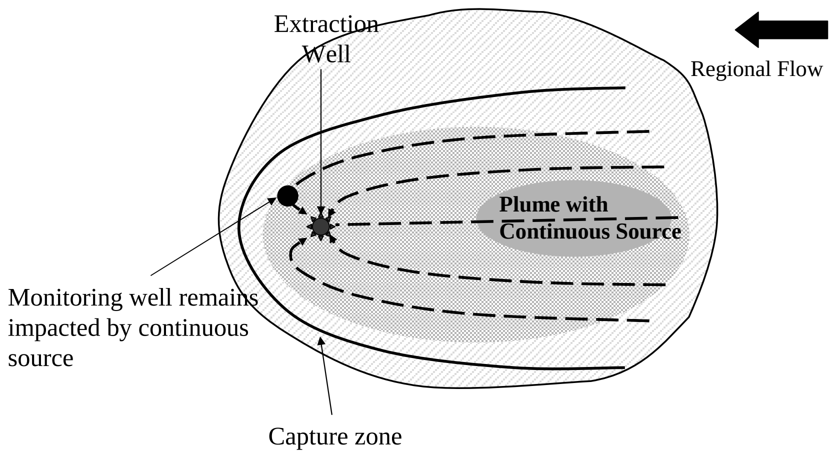
Complication:
Concentration Trend at Monitoring Well Located Within Capture Zone



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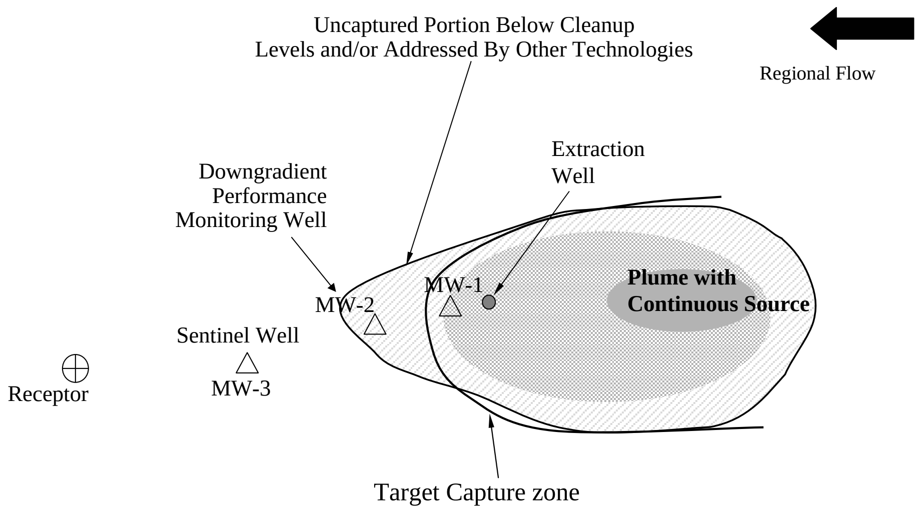
Monitoring Wells for Concentration Measurement



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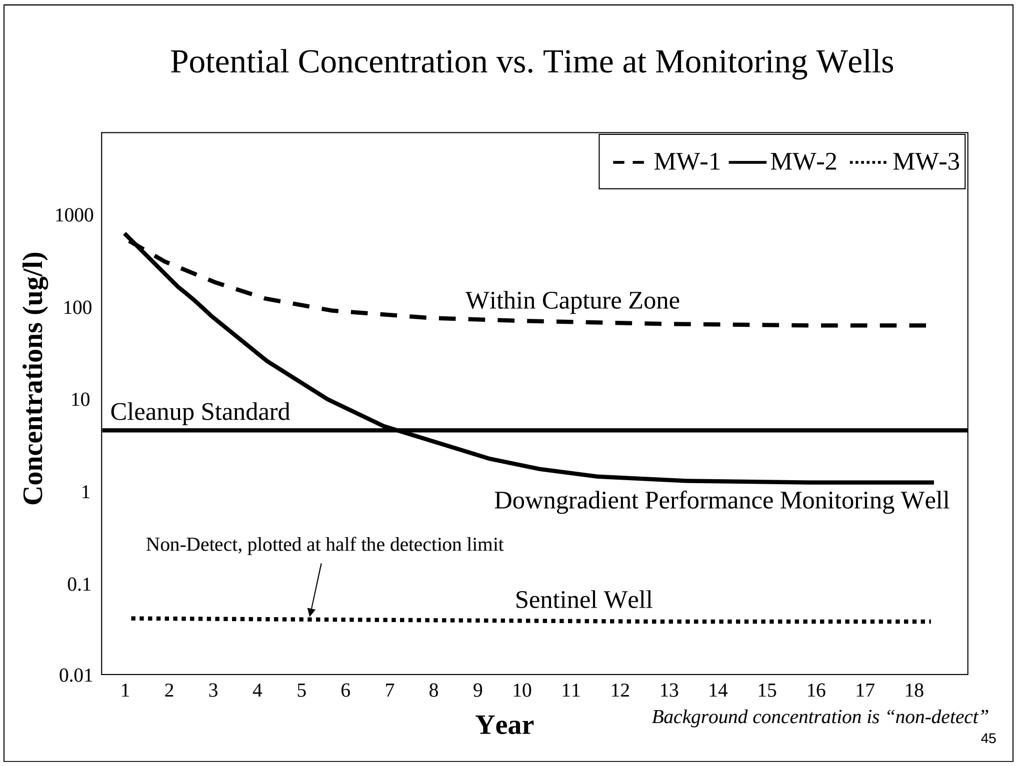
Potential Concentration vs. Time at Monitoring Wells
MW-1
MW-2
MW-3
Concentrations (ug/l)
1000
100
10
1
0.1
0.01
Within Capture Zone
Cleanup Standard
Downgradient Performance Monitoring Well
Non-Detect, plotted at half the detection limit
Sentinel Well
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Year
Background concentration is "non-detect"
45

Step 5a: Concentration Trends

- Wells must be located properly to provide useful evidence of capture
  - If located within the capture zone…may show early declines but then stabilize above cleanup levels if there is a continuing source
  - In some cases adding additional monitoring points may be appropriate
- Even if located properly (i.e., beyond the actual capture zone), usually takes a long time (typically years) to indicate successful capture.

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Step 5a: Concentration Trends

- Although these issues complicate interpretation of capture from concentration trends, concentration trends downgradient of the capture zone 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
  - hydraulic data allow for relatively rapid assessment of system performance
  - monitoring of ground water chemistry allows for long-term assessment

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Step 6: Interpret Capture Based on Steps 1-5

- Compare the interpreted capture 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 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 monitoring to fill data gaps (iterative approach)
  - Do data gaps make assessment of capture effectiveness uncertain?
  - If so, fill data gaps (e.g., installation of additional piezometers), and re-evaluate capture
- Evaluate the need to reduce or increase extraction rates
  - Should extraction rates and/or locations be modified?

Converging Lines of Evidence

- In many cases the interpretation of capture is difficult
  - Best approach is to have multiple lines of evidence that each support the same conclusion regarding the success of capture
  - Each additional line of evidence adds confidence in the conclusions
  - By pumping more, the evidence for capture can be made less ambiguous, such as creating inward gradients relative to a boundary or very noticeable capture on a water level map… this is generally a good thing unless the additional pumping is…
    - prohibitively expensive
    - not feasible
    - causes other negative impacts (e.g., dewatering well screens or wetlands)

Step 6a: Potential Format for Presenting Results of Analysis

Line Of Evidence	Is Capture Sufficient?	Comments
Water Levels • Potentiometric surface maps • Vertical head difference maps • Water level pairs		
Calculations • Estimated flow rate calculations • Capture zone width calculations • Modeling of heads/particle tracking		
Concentration Trends • Sentinel wells • Downgradient performance MW's		
Overall Conclusion • Capture is (is not) sufficient, based on "converging lines of evidence" • Key uncertainties/data gaps • Recommendations to collect additional data, change current extraction rates, change number/locations of extraction wells, etc.		

Converging Lines of Evidence: Failed Capture

- Example with many “red flags”

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 not evaluated

Converging Lines of Evidence: Failed Capture

- Example with many "red flags" (continued)

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

Summary: Key Concepts For a Project Manager

- The suggested six steps provide a systematic approach for evaluating capture, can serve as a general checklist
- Need to have a clearly stated remedy objective
- Need to clearly define a “Target Capture Zone” that
  - Considers potential for both horizontal and vertical transport
  - Is consistent with the remedy objectives
  - May change over time as plume grows/shrinks
- “Converging lines of evidence” (i.e., use of multiple techniques to evaluate capture) should be used, and should primarily rely on field-collected data that indicates capture and/or validates model predictions that indicate capture

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Summary: Key Concepts For a Project Manager

- Need for additional field data to reduce uncertainties in the capture zone analysis should be routinely evaluated, and any such data gaps should be addressed

- Frequency of capture zone evaluation is site-specific, factors include time to reach quasi-steady state, temporal nature of stresses (on-site, off-site), travel-time to potential receptors, etc.

  - Throughout first year of system operation (hydraulic evaluation)
  - One or more evaluations per year is appropriate at many sites

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Summary: Key Concepts For a Project Manager

- Many aspects of capture zone analysis require hydrogeologic expertise…project managers should use the assistance of support personnel and/or contractors if they lack that expertise
  - Simple calculations usually not sufficient because underlying assumptions are not valid
  - Scrutinize the interpretation of each line of evidence (e.g., the availability of water levels at or near the extraction wells)

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Questions?

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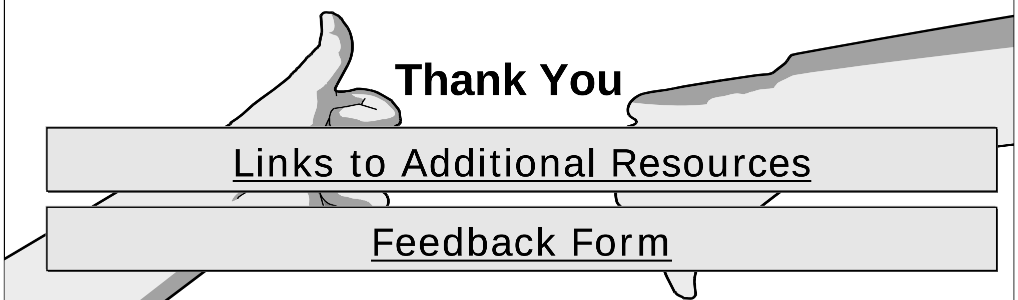
After viewing the links to additional resources, please complete our online feedback form.



Thank You

Links to Additional Resources

Feedback Form

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