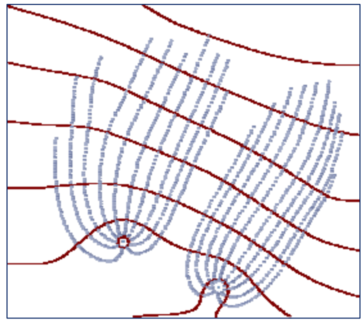
Hydraulic Capture Estimated Using Universal Kriging with Hydrologic Drift Terms



Rachel Shannon, Marinko Karanovic, Matt Tonkin
19th Annual Maryland Ground Water Symposium
Baltimore, Maryland 2010

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Introduction
Hydraulic capture (capture zones)

Estimates of hydraulic capture (capture zones) are used for

- Developing wellhead protection areas for supply wells
- Evaluating the performance of pump and treat systems

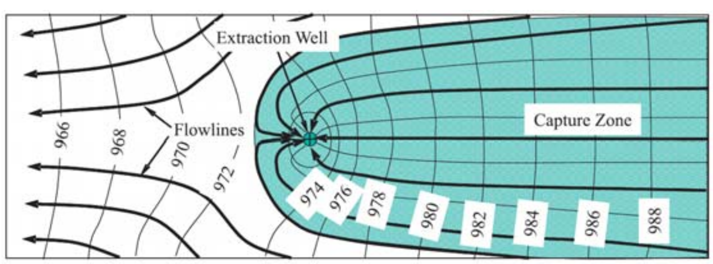

Figure from EPA/600/R-08/003: “A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems”, January 2008

Introduction
Hydraulic capture (capture zones)

Common methods used for this type of analysis:

- Interpolate water level measurements to a regular grid, producing a water level map (kriging)
- Use a groundwater flow model with particle tracking across the calculated water levels

Accuracy of the calculated capture zone depends on the accuracy of the water level map, whether obtained by interpolation or from a model

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Overview

- Discussion of the use of kriging and particle tracking to create water level maps and estimate hydraulic capture
- Incorporation of analytic elements to create more accurate water level maps
- Introduction to KT3D_H20: a free, open-source plug-in to MapWindow GIS which implements these methods.
- Presentation of an example project: the evaluation of a pump and treat system in EPA Region V

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KRIGING
Background and theory

- Interpolates from known data to intermediate locations
- Exact interpolator if no measurement error or replicates
- Universal kriging (UK):
  - Enables inclusion of an underlying trend
  - Trend coefficients estimated through mapping

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KRIGING
Background and theory

- Estimated value is a function of the surrounding, known data
- The weight given to the known data is proportional only to the separation distance of each known point from the estimation point

$$Z_{est} = f(R)$$

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KRIGING
With a trend - universal kriging

$$Z_{est} = f(X, Y, R)$$

- Kriging with linear trend is effective if regional patterns dominate

$$h(x,y) = A + BX + CY + \varepsilon(x,y)$$

- Where there are singularities – such as wells – severe local departures from this linear trend occur

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KRIGING
Using control points?

- Estimates of the gradient can be biased, hence estimates of velocities (direction and magnitude) can be biased
- One more control point → different result
- Maintaining the dataset gets clumsy
- With respect to pumped well water levels:
  - Are subject to uncertain and typically non-linear losses - the water level is not representative of aquifer conditions
  - Exaggerated drawdown and mounding often leads to erroneous (over-) estimates of the extent of capture

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ANALYTIC ELEMENTS
Introduction

- Analytical equations that describe water level changes in response to deterministic forcing functions
- Can be superimposed and combined with a universal “offset” to calculate groundwater levels
- Generally steady-state although transient elements are under development
- Generally two-dimensional although true-3D elements and quasi-3D analytic element models do exist (e.g., TimML)

ANALYTIC ELEMENTS
Integrating into kriging

Kriging with linear trend

$$h(x,y) = A + BX + CY + \varepsilon(x,y)$$

Add Terms for Analytic Elements:

- Point Sink/Source (Extraction/Injection Well)
- Line Sink/Source (Trench, River)
- Circular Source (Leaking Pond)

ANALYTIC ELEMENTS
Integrating into kriging

Kriging with a linear trend and point sink/sources:

$$h(x,y) = a + bx + cy + d\sum_{1}^{m} Q\log_{10}(r_i) + \varepsilon(x,y)$$

Kriging with a linear trend and line sink/sources:

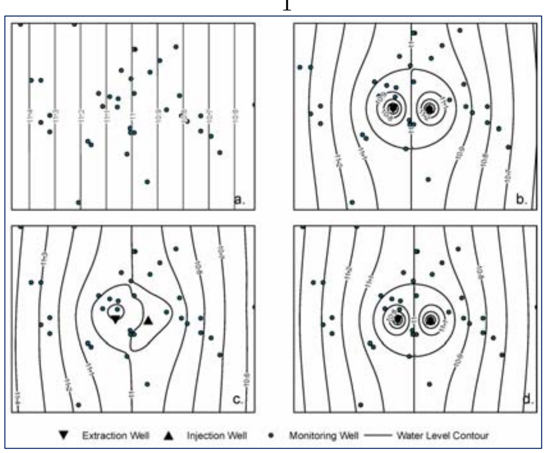
$$h(x,y) = a + bx + cy + e\sum_{1}^{n} L(r_i) + \varepsilon(x,y)$$

Kriging with a linear trend and circular sink/sources:

$$h(x,y) = a + bx + cy + f\sum_{1}^{o} P(r_i) + \varepsilon(x,y)$$

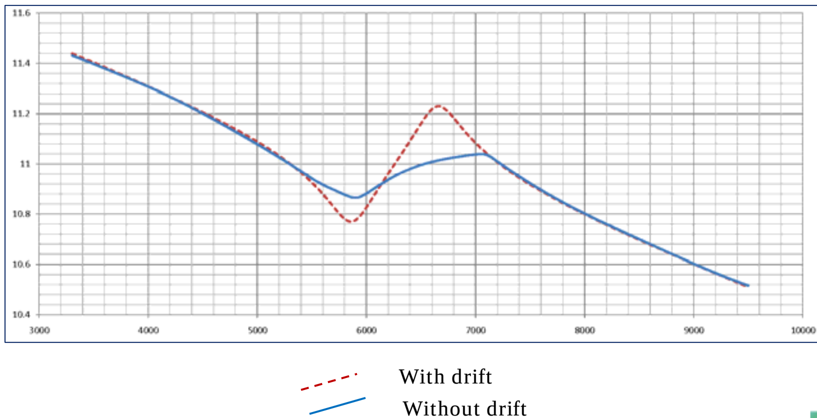
ANALYTIC ELEMENTS
Point sink/source

$$h(x,y) = a + bx + cy + d\sum_{1}^{m} Q\log_{10}(r_i) + \varepsilon(x,y)$$



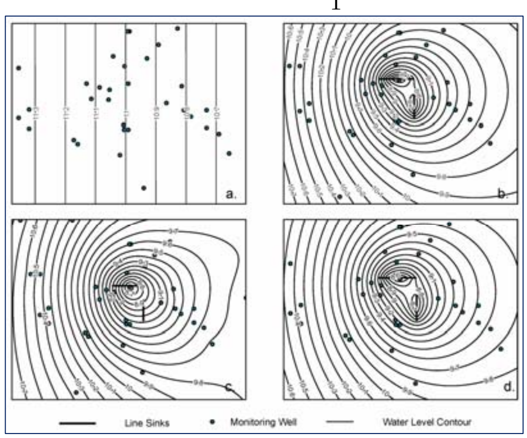
ANALYTIC ELEMENTS
Point sink/source

$$h(x,y) = a + bx + cy + d\sum_{1}^{m} Q\log_{10}(r_i) + \varepsilon(x,y)$$



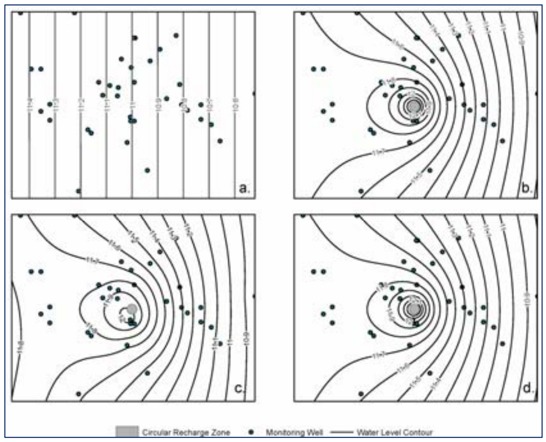
ANALYTIC ELEMENTS
Line sink/source

$$h(x,y) = a + bx + cy + e\sum_{1}^{n} L(r_i) + \varepsilon(x,y)$$



ANALYTIC ELEMENTS
Circular source

$$h(x,y) = a + bx + cy + f\sum_{1}^{o} P(r_i) + \varepsilon(x,y)$$



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ANALYTIC ELEMENTS
Integrating into kriging

Combine with superposition:

$$h(x,y) = a + bx + cy + d\sum_{1}^{m} Q\log_{10}(r_i) + e\sum_{1}^{n} L(r_i) + f\sum_{1}^{o} P(r_i) + \varepsilon(x,y)$$

These expressions contain variables assumed *constant for a set of drift terms* (e.g., transmissivity), and variables that can *change for each drift term* (e.g., extraction rate)

- Variables that are constant *for a set of drift terms* lie outside of summations
- Variables that can change *for each drift term* lie inside summations

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ANALYTIC ELEMENTS
Integrating into kriging

Terms can be grouped arbitrarily, which allows the Conceptual Site Model (CSM) to be incorporated. For example:

- Separate drift terms for two wells that are screened within aquifer units that exhibit different transmissivities
- Separate drift terms for two line sinks that exhibit different per-unit-length exchange rates with the groundwater system

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KT3D_H2O:
Introduction

- KT3D_H2O Version 3.0 is a graphical user interface (GUI) that combines various programs to generate
  - Gridded maps of water level elevations
  - Particle tracks
  - Capture zones
- Developed as a plug-in application under the open-source GIS foundation MapWindow.
- KT3D_H2O is free

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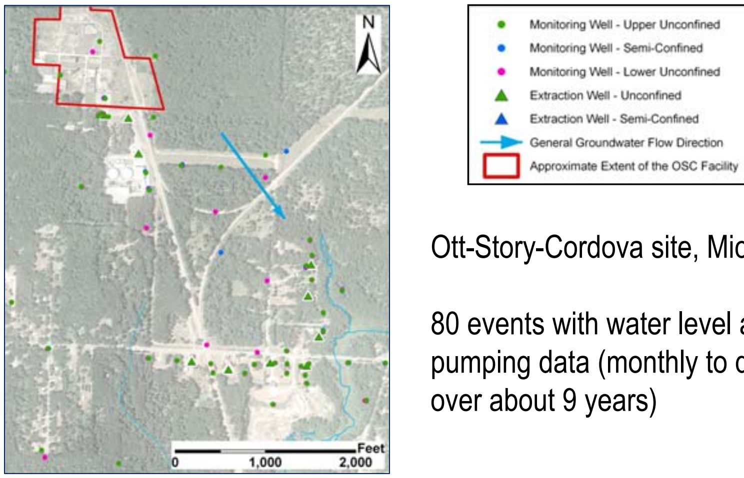
Example: EPA region V
Evaluation of a pump and treat system



Ott-Story-Cordova site, Michigan.

80 events with water level and pumping data (monthly to quarterly over about 9 years)

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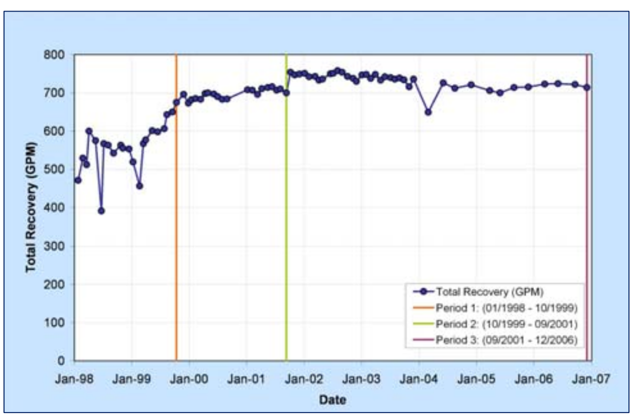
Example: EPA region V
Evaluation of a pump and treat system



What is the extent of hydraulic capture (capture zone) during each period?

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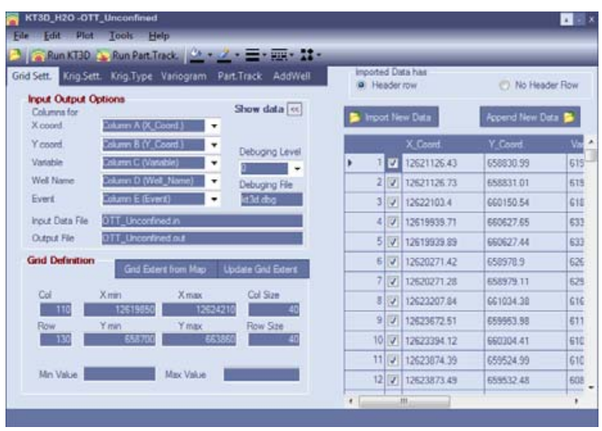
Example: EPA region V
Evaluation of a pump and treat system

Strategy:

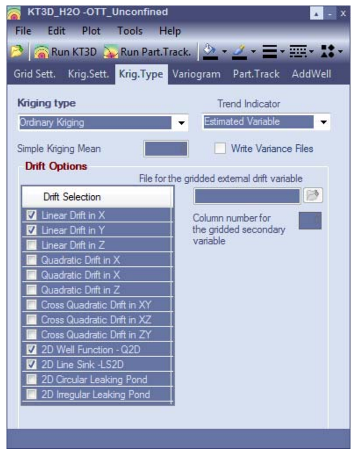
1. Create water level maps for each of the 80 sampling events, using kriging with analytic elements.
2. Use particle tracking to estimate extent of hydraulic capture (capture zone) for each event.
3. Combine the capture zone maps for all events during each period to estimate overall hydraulic capture extent during each period using a Capture Frequency Map (CFM).

KT3D_H20
Create water level maps



Import water level measurements for multiple events.

KT3D_H20
Create water level maps



Select analytic elements (drifts) to be included in kriging.

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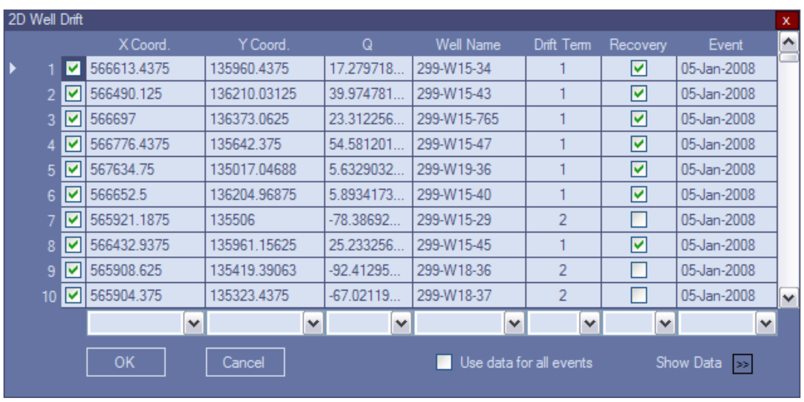
KT3D_H20
Create water level maps



2D Well Drift

	X Coord.	Y Coord.	Q	Well Name	Drift Term	Recovery	Event
1	566613.4375	135960.4375	17.279718...	299-W15-34	1	☑	05-Jan-2008
2	566490.125	136210.03125	39.974781...	299-W15-43	1	☑	05-Jan-2008
3	566697	136373.0625	23.312256...	299-W15-765	1	☑	05-Jan-2008
4	566776.4375	135642.375	54.581201...	299-W15-47	1	☑	05-Jan-2008
5	567634.75	135017.04688	5.6329032...	299-W19-36	1	☑	05-Jan-2008
6	566652.5	136204.96875	5.8934173...	299-W15-40	1	☑	05-Jan-2008
7	565921.1875	135506	-78.38692...	299-W15-29	2	☐	05-Jan-2008
8	566432.9375	135961.15625	25.233256...	299-W15-45	1	☑	05-Jan-2008
9	565908.625	135419.39063	-92.41295...	299-W18-36	2	☐	05-Jan-2008
10	565904.375	135323.4375	-67.02119...	299-W18-37	2	☐	05-Jan-2008

OK Cancel Use data for all events Show Data >>

Import injection and extraction rates for multiple events.
Specify drift term for each well.

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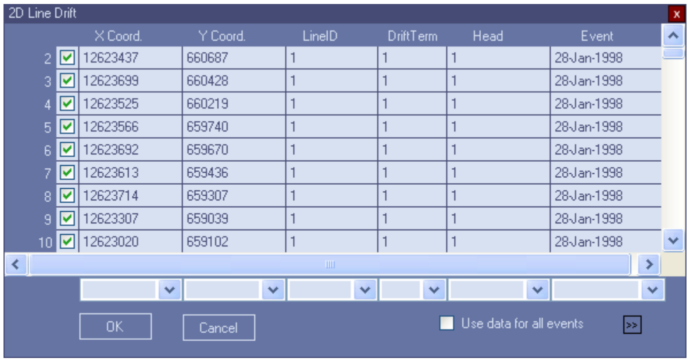
Create water level maps



Import line sink (river) location.
Specify drift terms for each segment.

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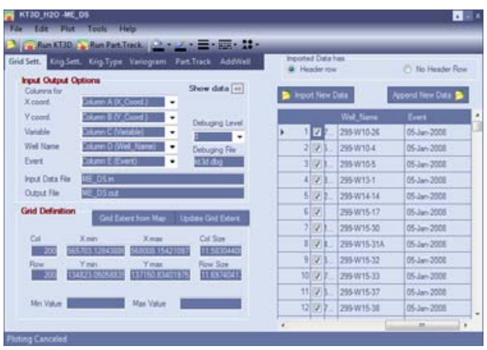
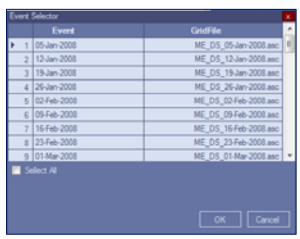
KT3D_H20
Create water level maps





Select events and run KT3D. Grids are created for each event.

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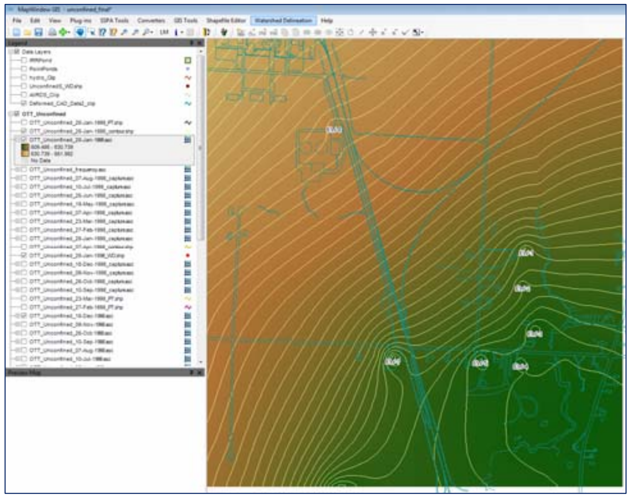
KT3D_H20
Create water level maps



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KT3D_H20
Particle tracking/capture zones

- Particle tracking records the fate of individual particles released anywhere on a single water level grid.
- Hydraulic Capture Zone analysis records the fate of many particles released across a single water level grid.
  - The program records the fate of particles in an ASCII summary file. The contents of this file is used by KT3D_H2O to illustrate capture zone maps
- TransientTracker tracks a particle across multiple water level grids.

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KT3D_H20
Particle tracking/capture zones

Particles may be tracked for a single event water level map and specified amount of time; or transient tracker may be used to track a particle across multiple events/water level maps

Set aquifer parameters, timesteps, and particle tracking type

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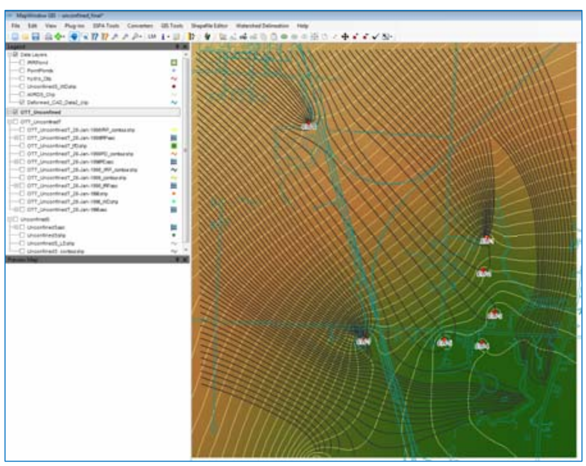
Particle tracks



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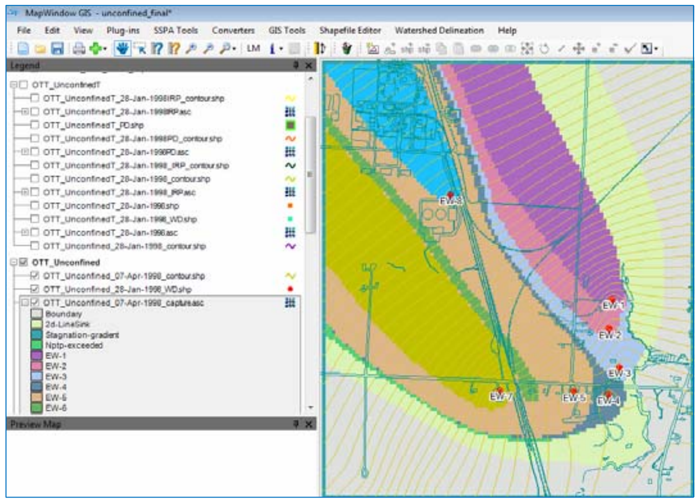
Capture zones



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KT3D_H20
Capture Frequency Map (CFM)

Capture Frequency Map (CFM) depicts capture from multiple events:

- Describes the number of times a particle was removed at an extraction well compared to the number of events calculated (i.e., the fraction of capture for each particle).
- Plots frequency with which a particle terminates at a well, calculated independently over all mapped events
- Can empirically reflect the transient development of capture

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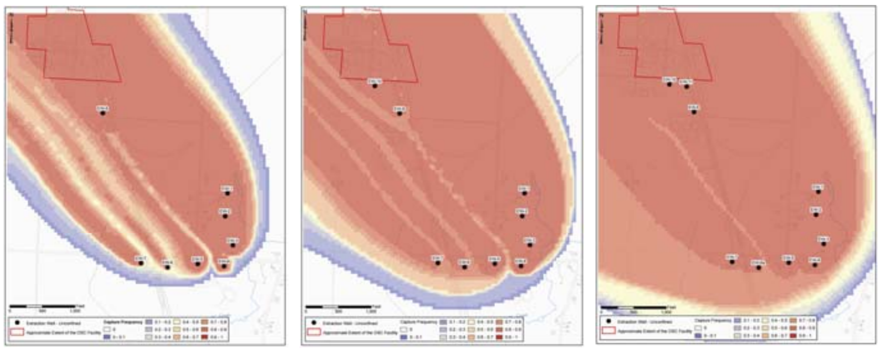
Example: EPA region V
Capture Frequency Maps (CFM)

Period 1 | Period 2 | Period 3



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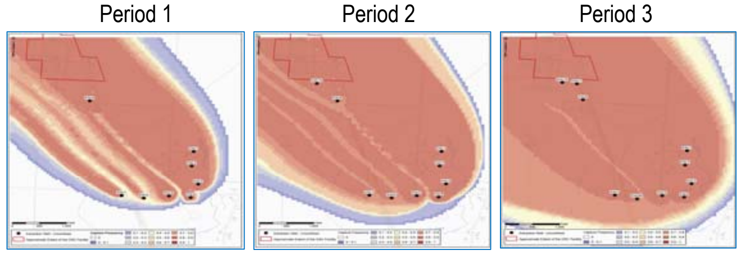
Example: EPA region V
Conclusion

Adjustments to pumping rates effectively increased overall extent of hydraulic capture (capture zone) and closed gaps.

Period 1 | Period 2 | Period 3



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Summary

- Incorporation of analytic elements into kriging produces a more accurate water elevation map, resulting in better estimates of hydraulic capture (capture zones)
- A Capture Frequency Map (CFM), which represents the combination of capture zone maps for multiple events, illustrates the transient development of capture
- KT3D_H20, a free, open-source plug-in for MapWindows GIS, provides a simple user interface for the implementation of these analysis methods.

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To Download KT3D_H20:
http://www.sspa.com/Software/kt3d.shtml

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Extra Slides

PARTICLE TRACKING Background

- Particle tracking has been implemented in TransientTracker (program developed by SSPA) to:
  - support approximate evaluations of historic and future contaminant migration; of hydraulic capture zones developed by pump-and-treat type remedies;
  - and other analyses that benefit from the ability to track particles on a surface.
- Particle tracking is implemented using the fourth-order Runge-Kutta (RK4: Press et al. 1992) numerical integration (particle tracking) scheme, calculated upon hydraulic head surfaces that have been generated using any number of methods including analytical solutions

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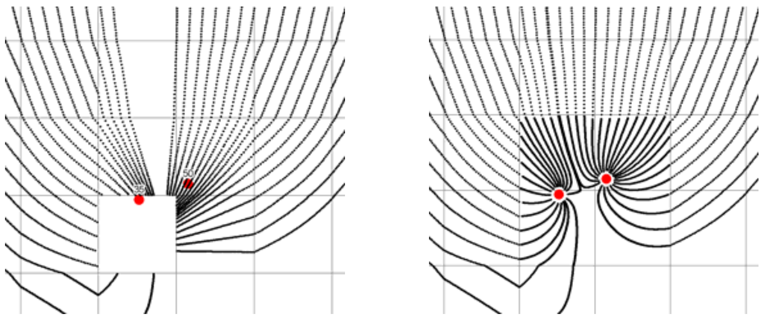
PARTICLE TRACKING
Background

- Far-field: RK4 with linear interpolation is appropriate
- Near-field: RK4 supplemented with iterative re-kriging using point sink/source drift



ANALYTIC ELEMENTS
Assumptions and limitations

- Assumptions common to the Thiem and Cooper-Jacob equations are implicit, principally:
  - The aquifer is homogeneous, isotropic, and of infinite areal extent
  - The aquifer is confined, or drawdowns are a reasonably small fraction of the aquifer saturated thickness
  - Features penetrate the entire saturated thickness of the aquifer (exception: circular source)
- The system has reached a (quasi-) steady-state condition and/or the rate of change in gradients should approach zero

ANALYTIC ELEMENTS: Point sink/source

- Can be described many ways
- Instructive to derive from Cooper-Jacob equation

$$s = \frac{Q}{4\pi T}\left(\ln\left(\frac{2.25Tt}{r^2 S}\right)\right)$$

$$s = \frac{Q}{4\pi T}\left(\ln\left(\frac{2.25Tt}{S}\right) + \ln\left(\frac{1}{r^2}\right)\right)$$

s = drawdown
Q = pumping rate
T = transmissivity
S = storage
r = separation distance
t = time

This is a function of time

This is not

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ANALYTIC ELEMENTS Line sink/source

- Typically used to represent trenches and rivers
- The complex potential representing a line sink/source of known strength is described by (Strack, 1989; Fitts, 2004; Bakker, 2008)

$$\Omega = \frac{\sigma L}{4\pi}\left((Z+1)Ln(Z+1) - (Z-1)Ln(Z-1)\right)$$

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ANALYTIC ELEMENTS
Circular sink/source

- Typically used to represent leaking ponds
- Mounding in response to infiltration from a circular feature is described by (Strack, 1989):

$$G\,(x, y, x_j, y_j, R_j) = -\frac{1}{4}\left[(x - x_j)^2 + (y - y_j)^2 + R_j^{\,2}\right] \qquad 0 \le r_j \le R_j$$

$$G\,(x, y, x_j, y_j, R) = -\frac{R_j^{\,2}}{4}\,Ln\,\frac{(x - x_j)^2 + (y - y_j)^2}{R_j^{\,2}} \qquad R_j \le r_j < \infty$$

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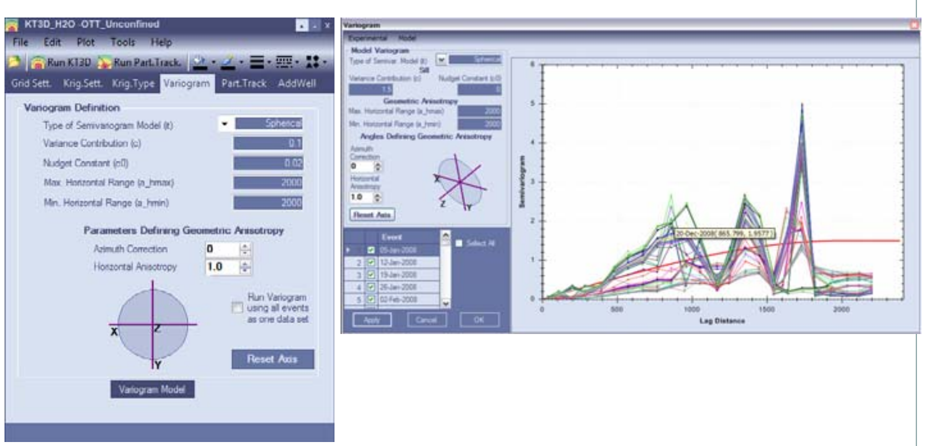
Variogram Modeling



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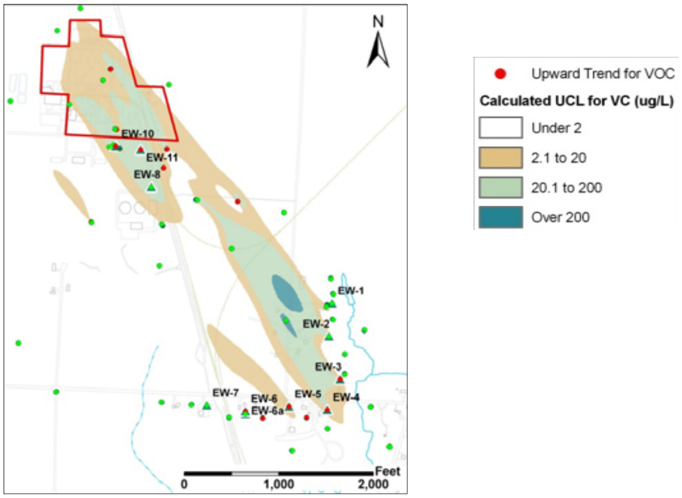
Example: EPA region V Plume Map



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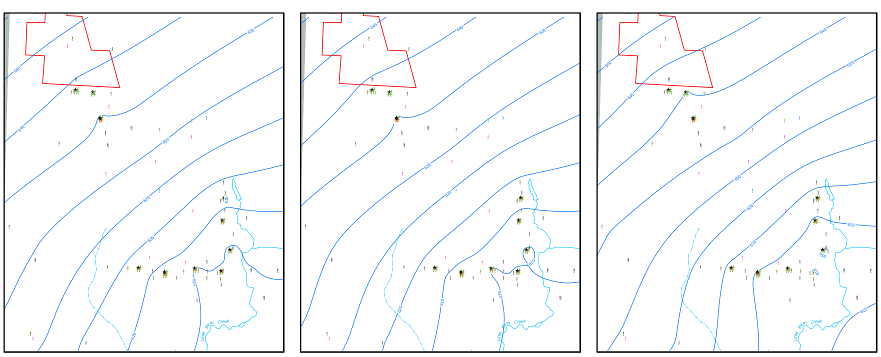
KT3D_H20 Create Water Level Maps



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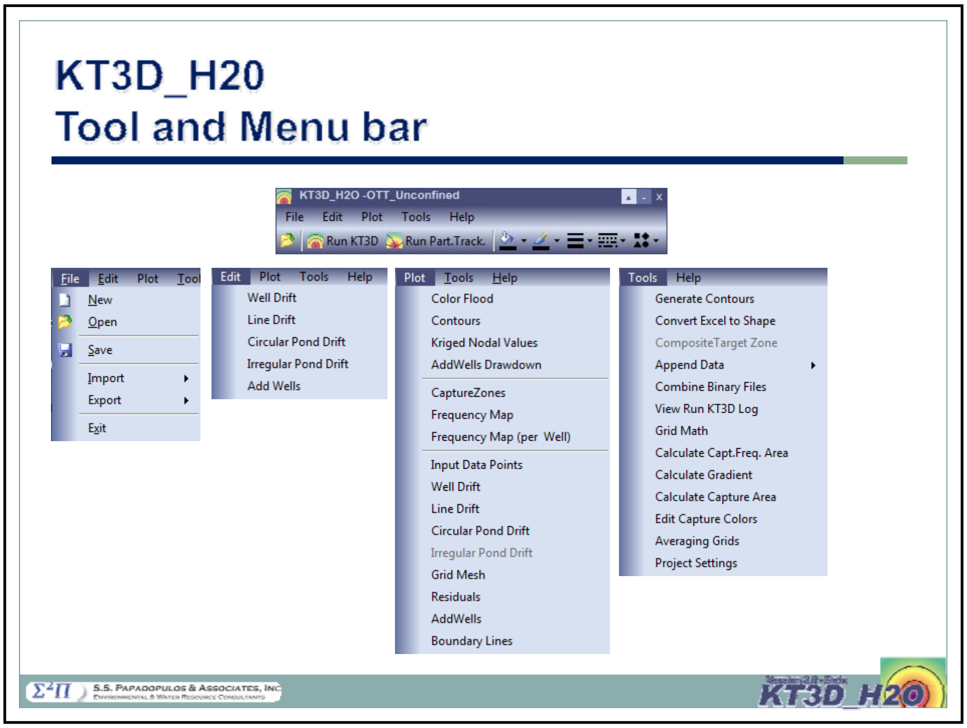
KT3D_H20
Tool and Menu bar
KT3D_H2O -OTT_Unconfined
File Edit Plot Tools Help
Run KT3D Run Part.Track.
File Edit Plot Tool
New
Open
Save
Import
Export
Exit
Edit Plot Tools Help
Well Drift
Line Drift
Circular Pond Drift
Irregular Pond Drift
Add Wells
Plot Tools Help
Color Flood
Contours
Kriged Nodal Values
AddWells Drawdown
CaptureZones
Frequency Map
Frequency Map (per Well)
Input Data Points
Well Drift
Line Drift
Circular Pond Drift
Irregular Pond Drift
Grid Mesh
Residuals
AddWells
Boundary Lines
Tools Help
Generate Contours
Convert Excel to Shape
CompositeTarget Zone
Append Data
Combine Binary Files
View Run KT3D Log
Grid Math
Calculate Capt.Freq. Area
Calculate Gradient
Calculate Capture Area
Edit Capture Colors
Averaging Grids
Project Settings
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