Assessment of Hydraulic Capture Through Interpolation of Measured Water Level Data

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Outline of This Presentation

- A **Problem Statement**
- Some **History** and **Motivation**
- A brief introduction to **Kriging**
- Some **Reality Checks** to be mindful of
- The inclusion of **Particle Tracking**
- A single illustrative **Example**

Background and Developments

- The basis of the approach described here – combining kriging and hydrology – is an area of extensive historical investigation and literature
- This presentation discusses one fairly recent development in particular
- **David Dougherty** will discuss extensions to the approach described here that he has developed and applied

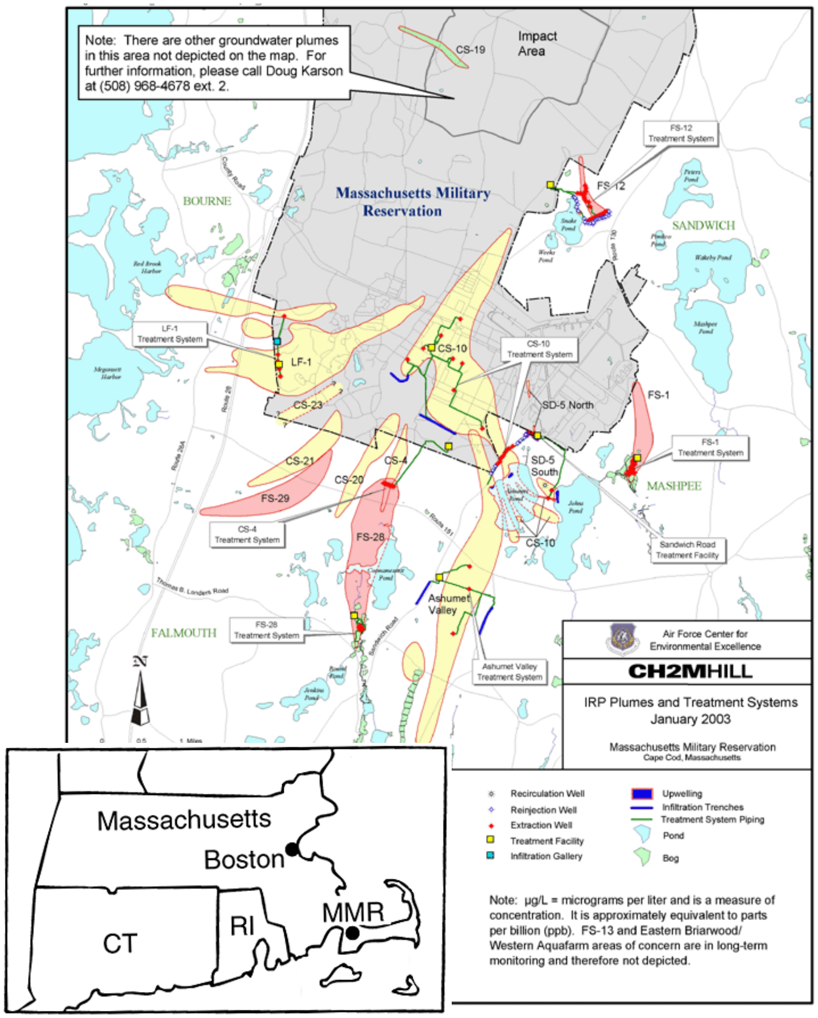
Problem Statement

- How do we improve the inference that can be drawn from a water level data set?

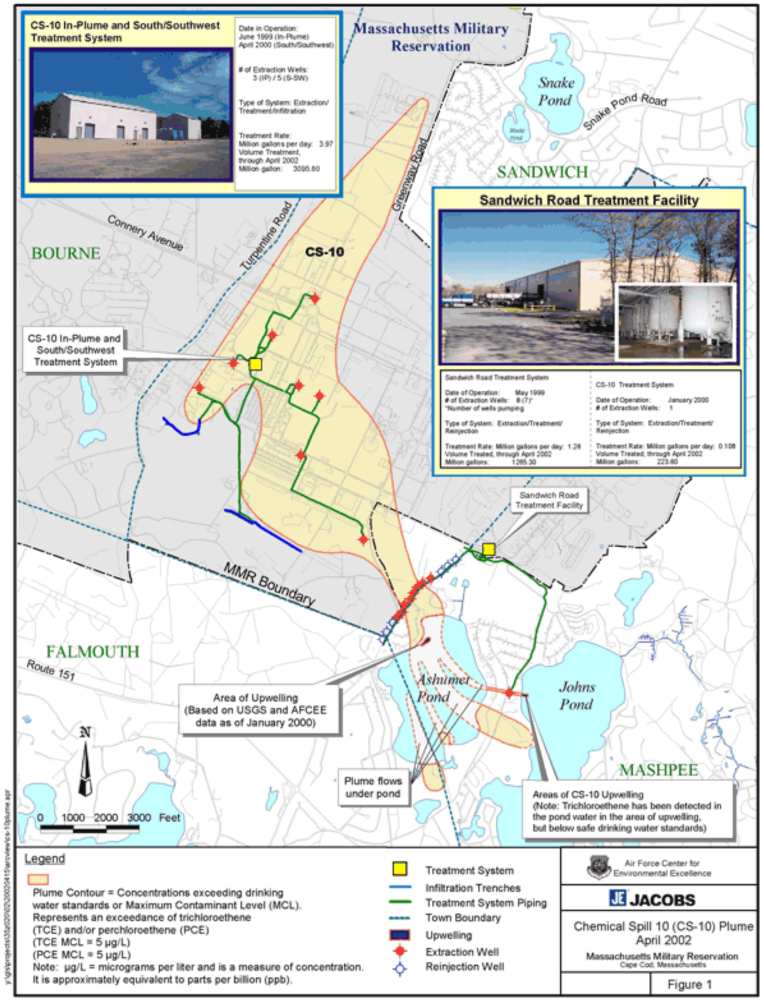
History

- OTIS-MMR, MA., 1998.
- Rapid development of several large-scale, multi-well pump-and-treat (P&T) remedies.
- Various options for returning treated water including injection, infiltration.
- Quarterly monitoring reports.
- Regular meetings.

History



Note: There are other groundwater plumes in this area not depicted on the map. For further information, please call Doug Karson at (508) 968-4678 ext. 2.
Impact Area
CS-19
FS-12 Treatment System
FS-12
Massachusetts Military Reservation
BOURNE
SANDWICH
LF-1 Treatment System
LF-1
CS-10
CS-10 Treatment System
SD-5 North
FS-1
CS-23
FS-1 Treatment System
CS-21
CS-4
SD-5 South
MASHPEE
CS-20
FS-29
CS-4 Treatment System
FS-28
CS-10
Sandwich Road Treatment Facility
Ashumet Valley
FALMOUTH
FS-28 Treatment System
Ashumet Valley Treatment System
Air Force Center for Environmental Excellence
CH2MHILL
IRP Plumes and Treatment Systems
January 2003
Massachusetts Military Reservation
Cape Cod, Massachusetts
Massachusetts
Boston
CT
RI
MMR
Recirculation Well
Reinjection Well
Extraction Well
Treatment Facility
Infiltration Gallery
Upwelling
Infiltration Trenches
Treatment System Piping
Pond
Bog
Note: µg/L = micrograms per liter and is a measure of concentration. It is approximately equivalent to parts per billion (ppb). FS-13 and Eastern Briarwood/ Western Aquafarm areas of concern are in long-term monitoring and therefore not depicted.



CS-10 In-Plume and South/Southwest Treatment System
Massachusetts Military Reservation
Snake Pond
Snake Pond Road
SANDWICH
Sandwich Road Treatment Facility
Connery Avenue
Turpentine Road
Greenway Road
BOURNE
CS-10
CS-10 In-Plume and South/Southwest Treatment System
Sandwich Road Treatment Facility
MMR Boundary
FALMOUTH
Route 151
Ashumet Pond
Johns Pond
Area of Upwelling (Based on USGS and AFCEE data as of January 2000)
Plume flows under pond
MASHPEE
Areas of CS-10 Upwelling (Note: Trichloroethene has been detected in the pond water in the area of upwelling, but below safe drinking water standards)
0 1000 2000 3000 Feet
Legend
Plume Contour = Concentrations exceeding drinking water standards or Maximum Contaminant Level (MCL). Represents an exceedance of trichloroethene (TCE) and/or perchloroethene (PCE)
(TCE MCL = 5 µg/L)
(PCE MCL = 5 µg/L)
Note: µg/L = micrograms per liter and is a measure of concentration. It is approximately equivalent to parts per billion (ppb).
Treatment System
Infiltration Trenches
Treatment System Piping
Town Boundary
Upwelling
Extraction Well
Reinjection Well
Air Force Center for Environmental Excellence
JACOBS
Chemical Spill 10 (CS-10) Plume
April 2002
Massachusetts Military Reservation
Cape Cod, Massachusetts
Figure 1

History

- Common questions asked at these meetings…..
  - *How is the system performing?*
  - *Is capture developing?*
- The contents of quarterly reports were not intended to include capture zones.

Making Maps

- Water levels are measured at a lot of wells – *but*,
- It is still necessary to interpolate between measured data in order to make maps - *and*,
- Most maps we make of water levels don’t convey much information.

Making Maps

- If we acknowledge that in order to make maps we must perform some form of interpolation – then,
- the question is which of the available methods is the most suitable for our needs?
    - inverse distance, kriging, radial basis functions, others?

Motivation

- To increase the inference that can be drawn from water levels measured in monitoring wells

in order to

- Assist with inferring pump-and-treat system performance.

Introduction to Kriging

- Kriging is a method for interpolating from known data to intermediate locations
- When rigorously implemented, interpolation weights are determined from the data
- Where there is assumed to be no measurement error, and there are no replicates, kriging is an exact interpolator
- Under certain assumptions about spatial statistics (variogram), kriging provides an estimate of the variance in the estimation error

Some Bases for Kriging

- The variogram – intuitively, a descriptor for how information diminishes with separation distance.
- Linear algebra – a method for solving the matrix equations to estimate a point.

Variography is fun - but can be taken too seriously .... data sets usually inadequate

Simple or Ordinary Kriging[1]

- 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

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

1. Assumptions about the mean of the quantify being estimated vary – for simple kriging, zero; for ordinary kriging, data average

Kriging With a Trend[1]

$$Z_{est} = A + BX + CY$$

A = ‘offset’ term

B = gradient in the X direction

C = gradient in the Y direction

Trend coefficients must be linear

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

1. Often termed ‘Universal Kriging’

Kriging With a Trend

- Kriging with linear trend has been shown to be effective in aquifer systems (e.g. Ogallala) where regional patterns are dominant.
- However – where we have singularities – such as wells – severe local departures from this linear trend occur.

The Cooper-Jacob Equation

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

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

The Cooper-Jacob Equation

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

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

Note – this is a function of time – but we wish to deal with steady state

The Cooper-Jacob Equation

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

This is a function of time

This is not

The Cooper-Jacob Equation

$$s = \frac{Q}{2\pi T} \ln(r) \quad + \textit{offset}$$

The Cooper-Jacob Equation

$$s = \frac{1}{2\pi T} Q \ln(r) \text{ + offset}$$

The Cooper-Jacob Equation

$$s = \underbrace{\frac{1}{2\pi T}}_{\text{Log trend coefficient}} Q \ln(r) + \text{offset}$$

Log trend coefficient

Multiple Extraction Wells

$$\mathbf{s_{ij}} = \frac{1}{2\pi T} \sum Q_n \, \mathrm{Ln}(r)_n$$

s_{ij} = drawdown at (*i*, *j*) due to extraction

Q_n = extraction rate at well *n*

$\mathrm{Ln}(r)_n$ = log of separation distance

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

Reality Checks - Aquifer

- The estimated transmissivity should correspond with other sources of information – e.g. pumping tests.

and

- The estimated capture zone width should correspond with the estimated transmissivity, pumping rate, and hydraulic gradient.

Capture Zone Width

$$W = Q \ / \ K\,B\,i$$

W = capture zone width
K = average hydraulic conductivity
Q = extraction rate
B = saturated thickness
i = hydraulic gradient

Note: Half-width at the recovery well

Stagnation Point

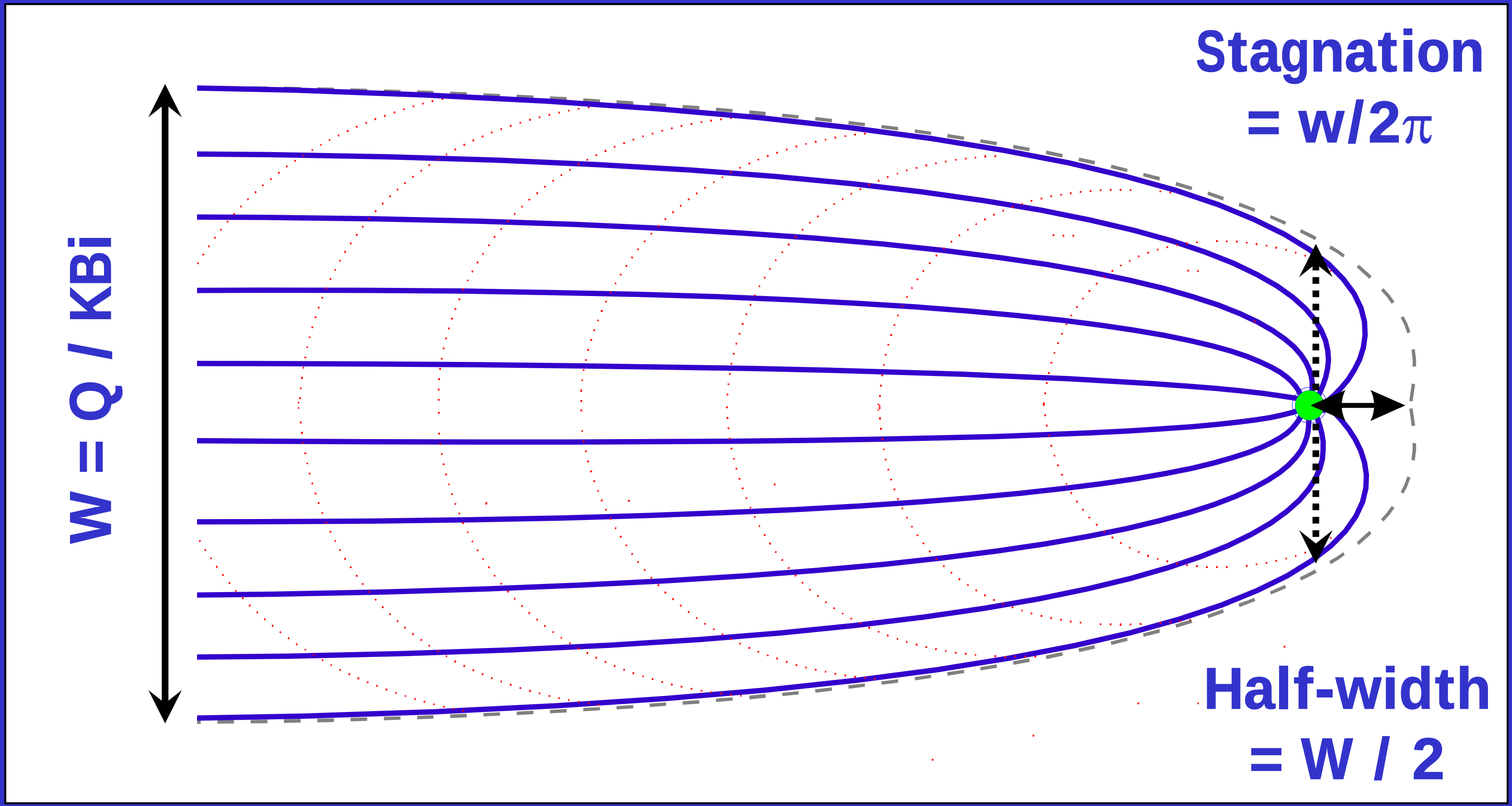
$$h = W / 2 \times PI$$

h = distance of stagnation point down gradient of the recovery well

W = capture zone width

PI = 3.14159...

Reality Checks - Aquifer



Reality Checks - Data

- Do the data meet the assumptions
- Are there ‘outliers’ that require additional explanation

  - Jacknifing
  - Single-point cross-validation

Σ²Π

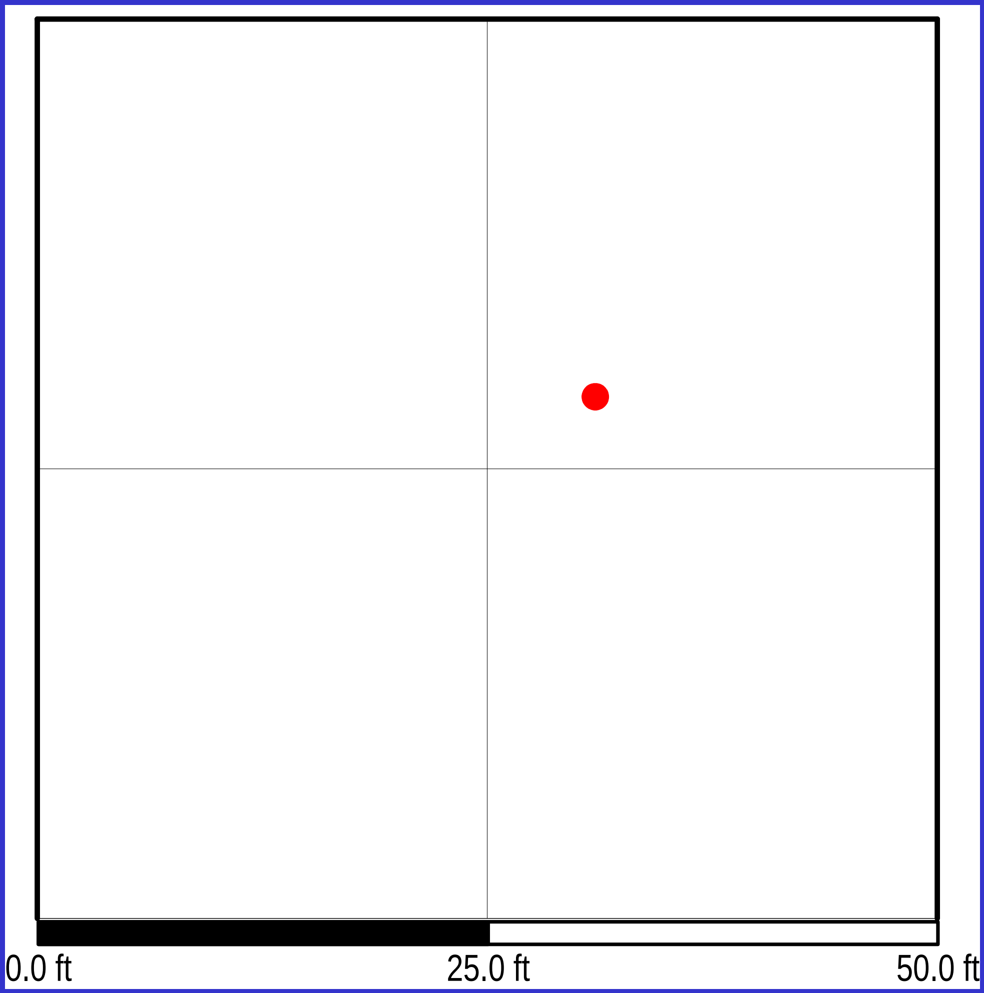
Particle Tracking

Build directly from the kriging routine

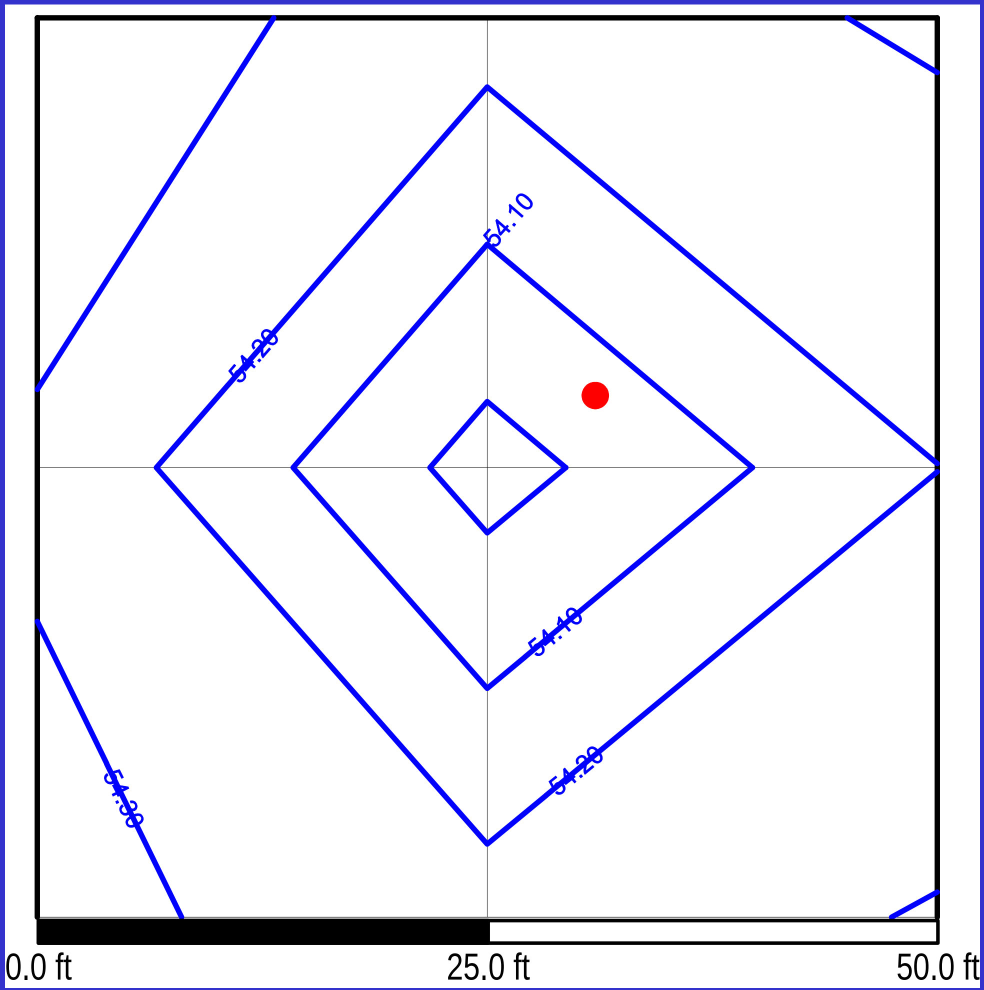
- Once the kriging matrix has been constructed the kriging weights that pertain to the estimation of any point are estimable
- The benefit of this approach is that the gradient and seepage velocity are calculated on the basis of the kriging estimate exactly at the location of the particle

$\Sigma^2\Pi$

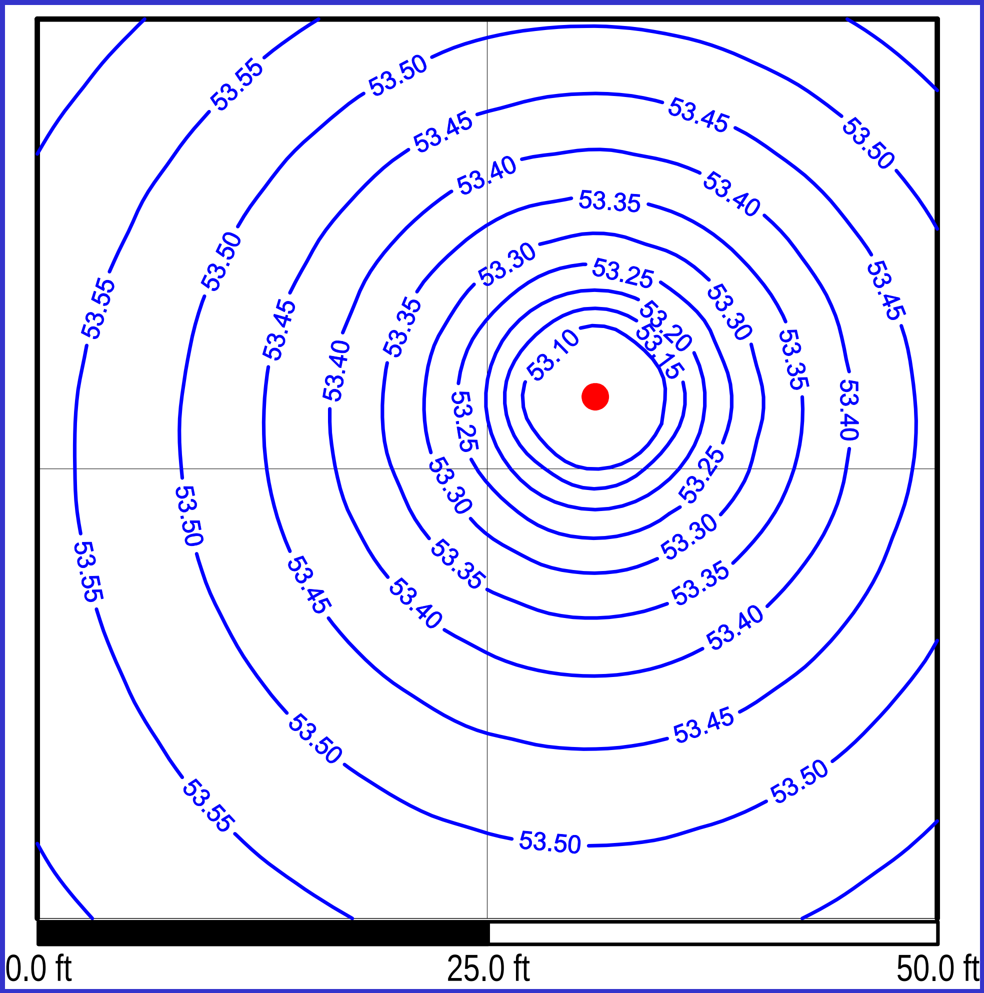
Particle Tracking



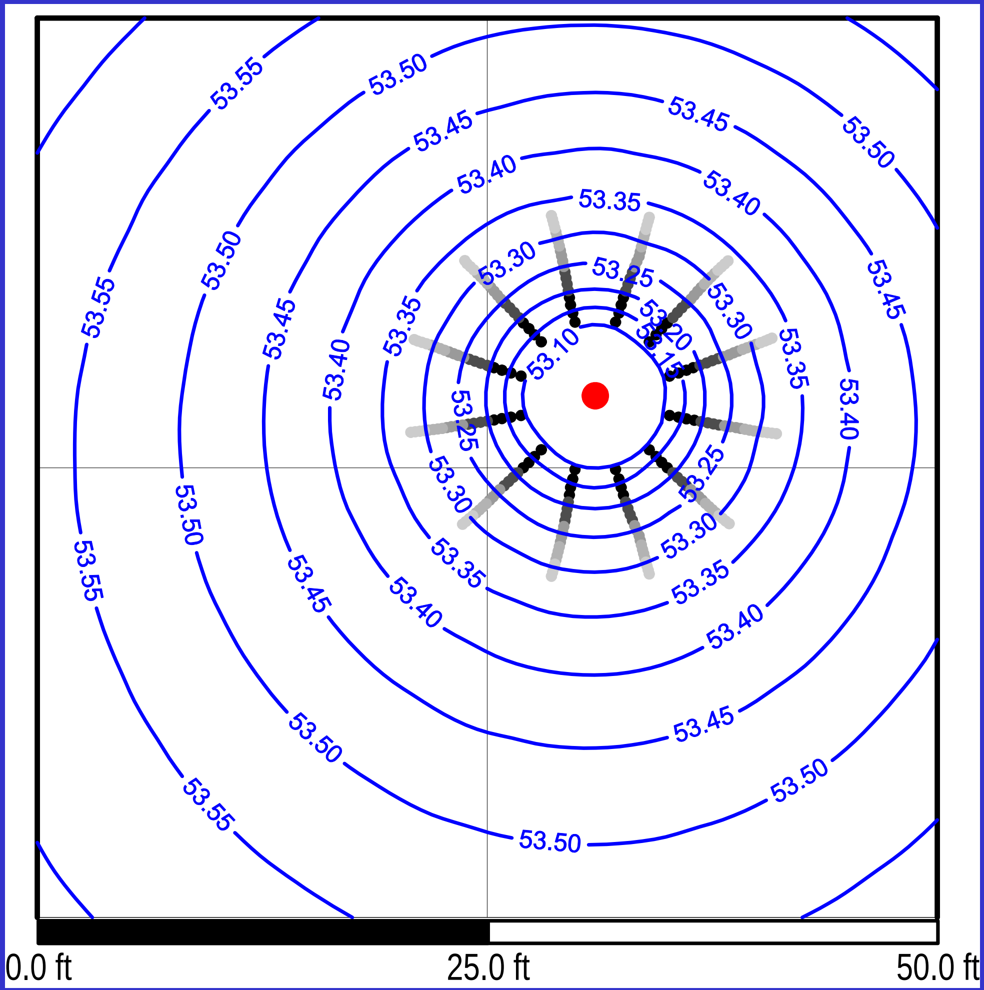
Particle Tracking



Particle Tracking



Particle Tracking



Example Application

Cape Cod, MA.

- Described in the paper by Tonkin and Larson, 2002.

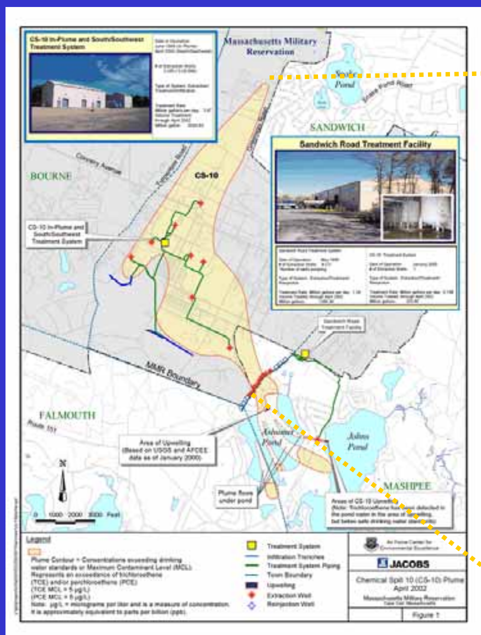
Tonkin, M.J., and Larson, S.P., 2002. Kriging Water Levels with a Regional –linear and Point-logarithmic Drift, Ground Water, 40 (2), 185-193, March-April 2002.

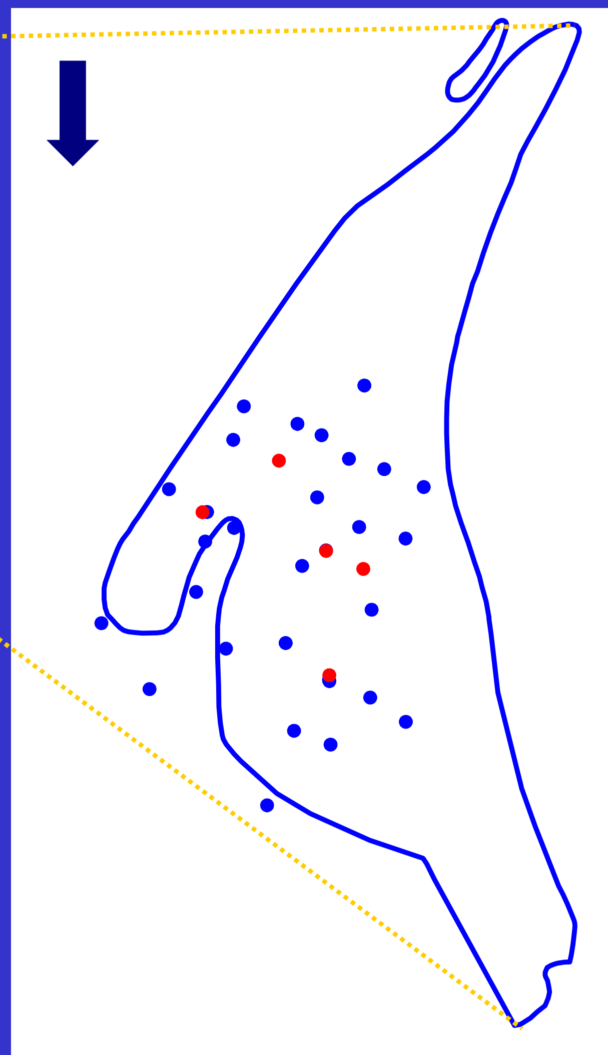
$\Sigma^2\Pi$

Cape Cod

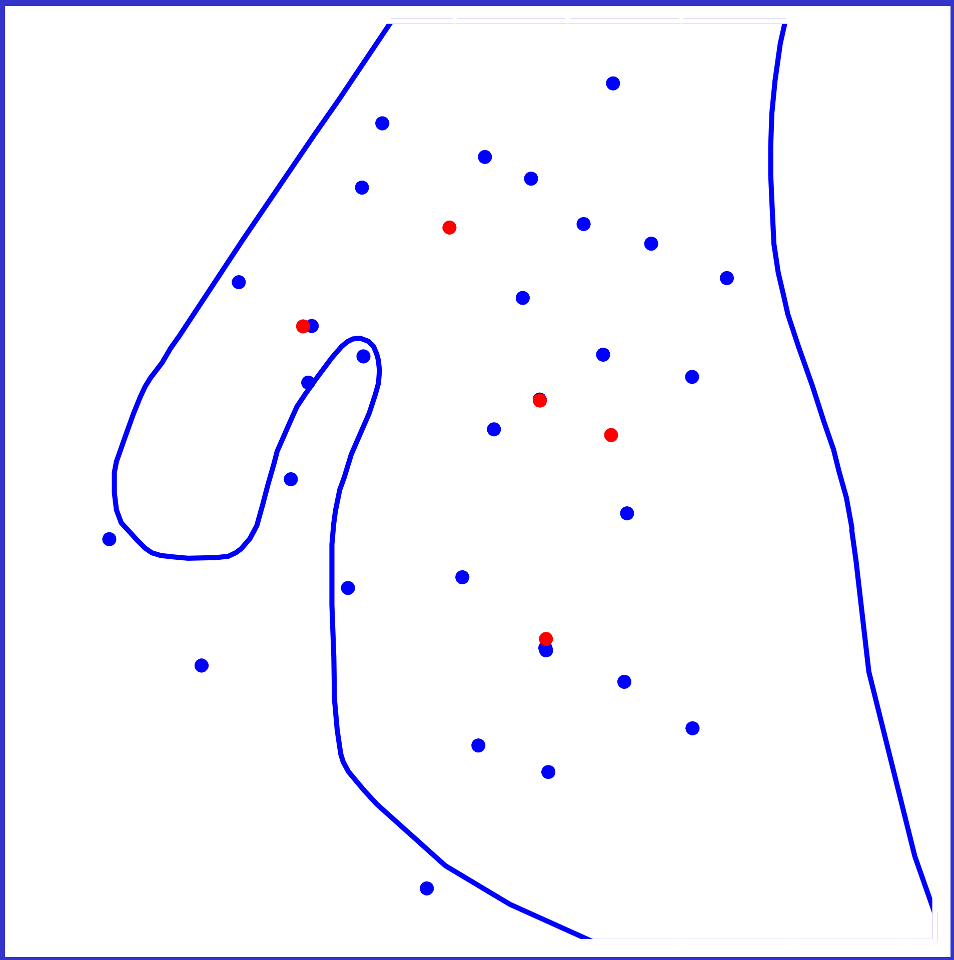
- CS-10 In-Plume System
- Mass recovery objective
- 5 extraction wells
- Peripheral infiltration galleries
- About 40 monitoring wells
- *Aim to infer if capture is developing*

Cape Cod – CS-10

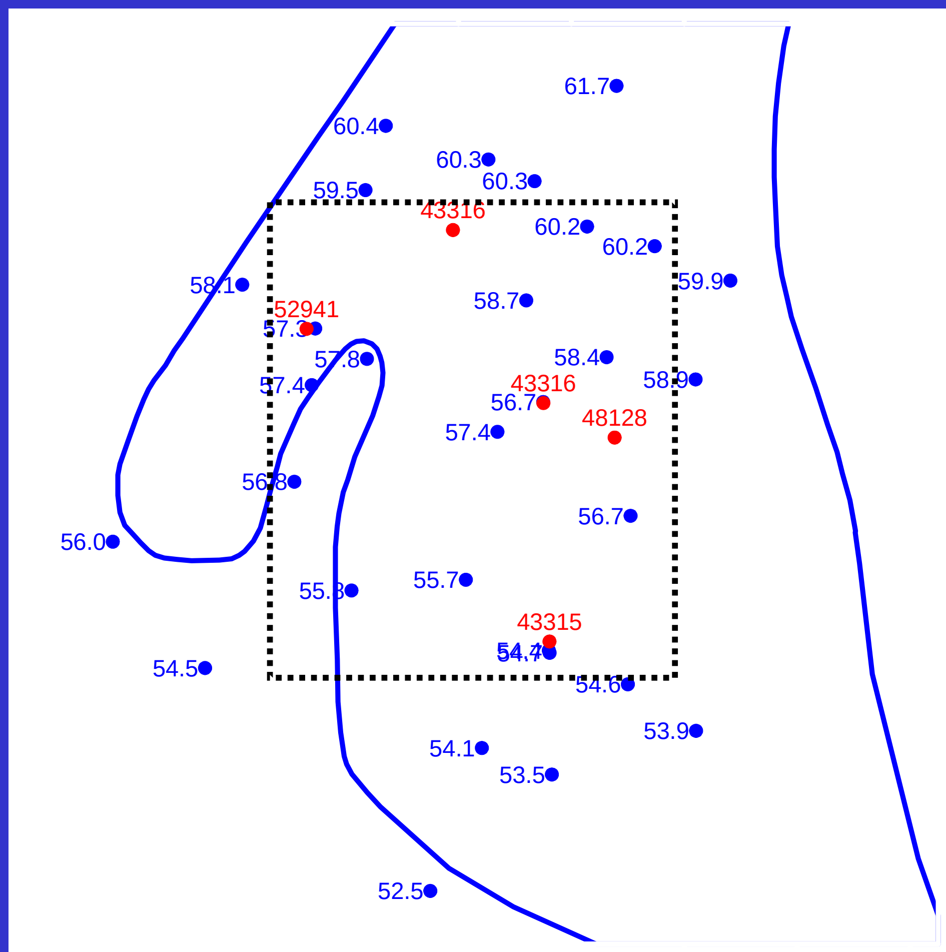




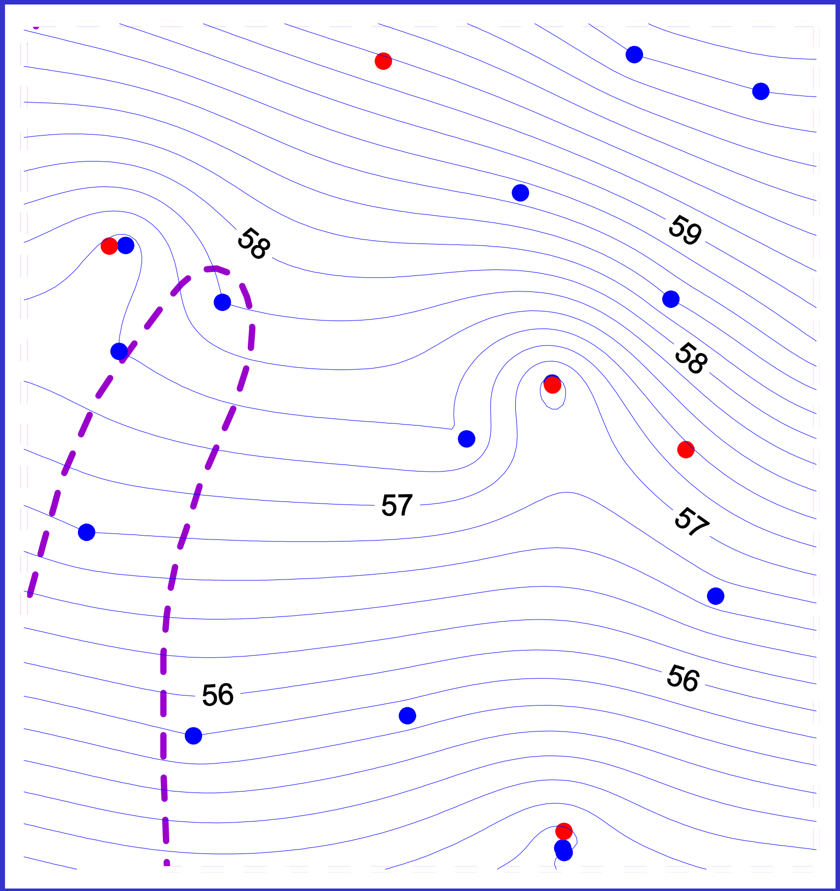
CS10 - Zoom



CS10 - Zoom

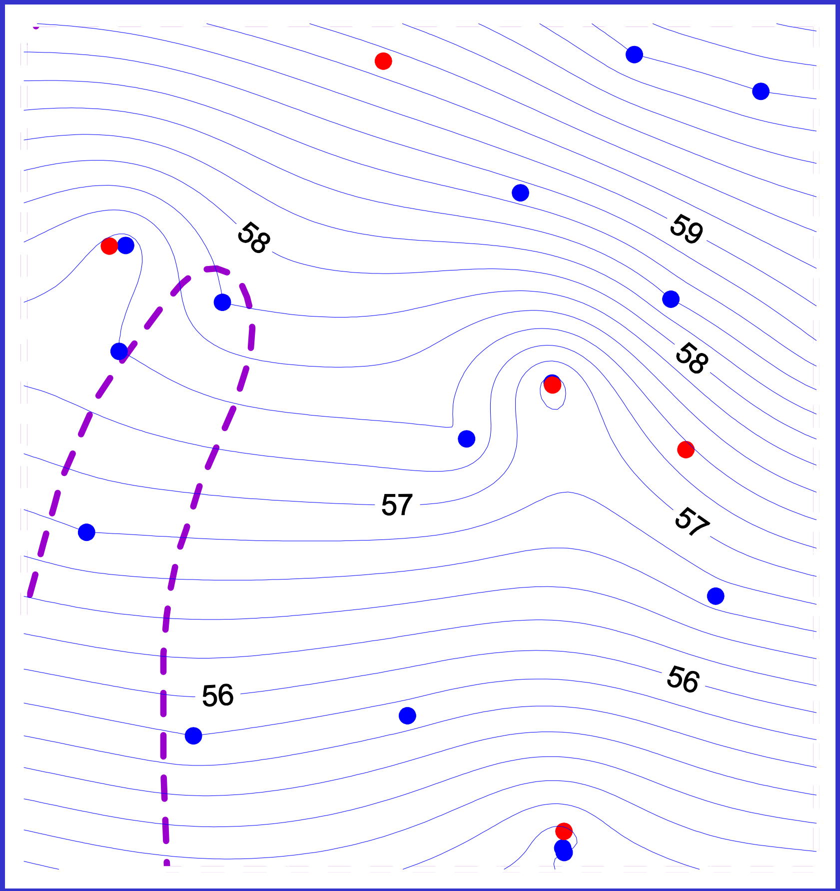

61.7
60.4
60.3
60.3
59.5
43316
60.2
60.2
59.9
58.1
58.7
52941
58.4
57.4
43316
56.7
48128
57.4
56.7
56.0
55.7
43315
54.5
54.6
53.9
54.1
53.5
52.5

Cape Cod - No Trend



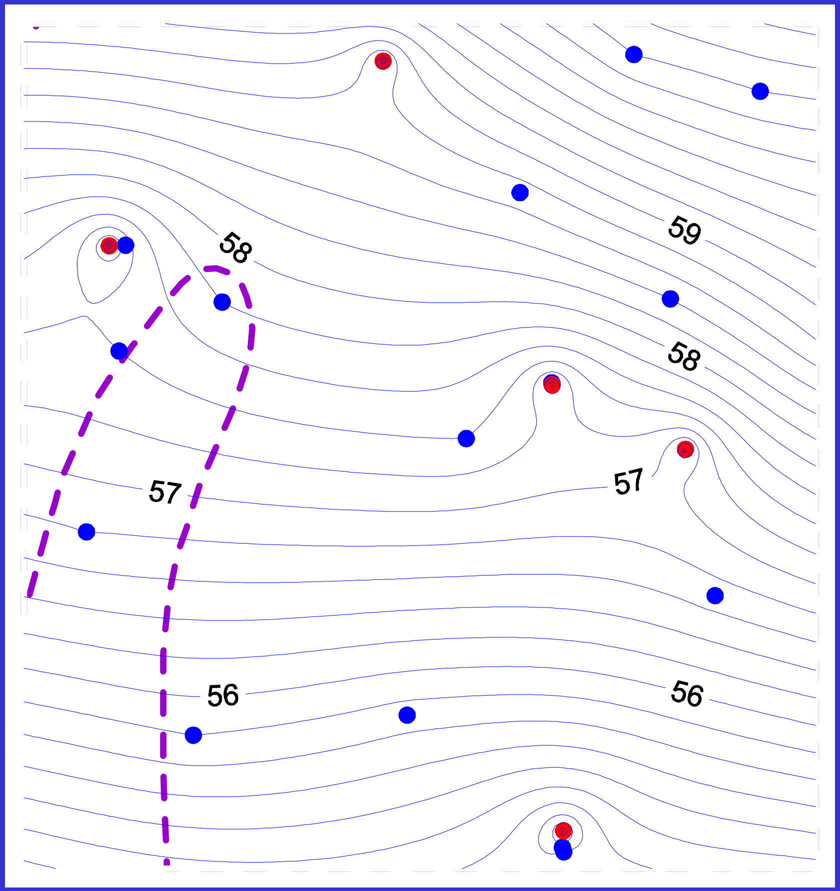
$$Z_{est} = f(R)$$

Cape Cod - Linear Trend



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

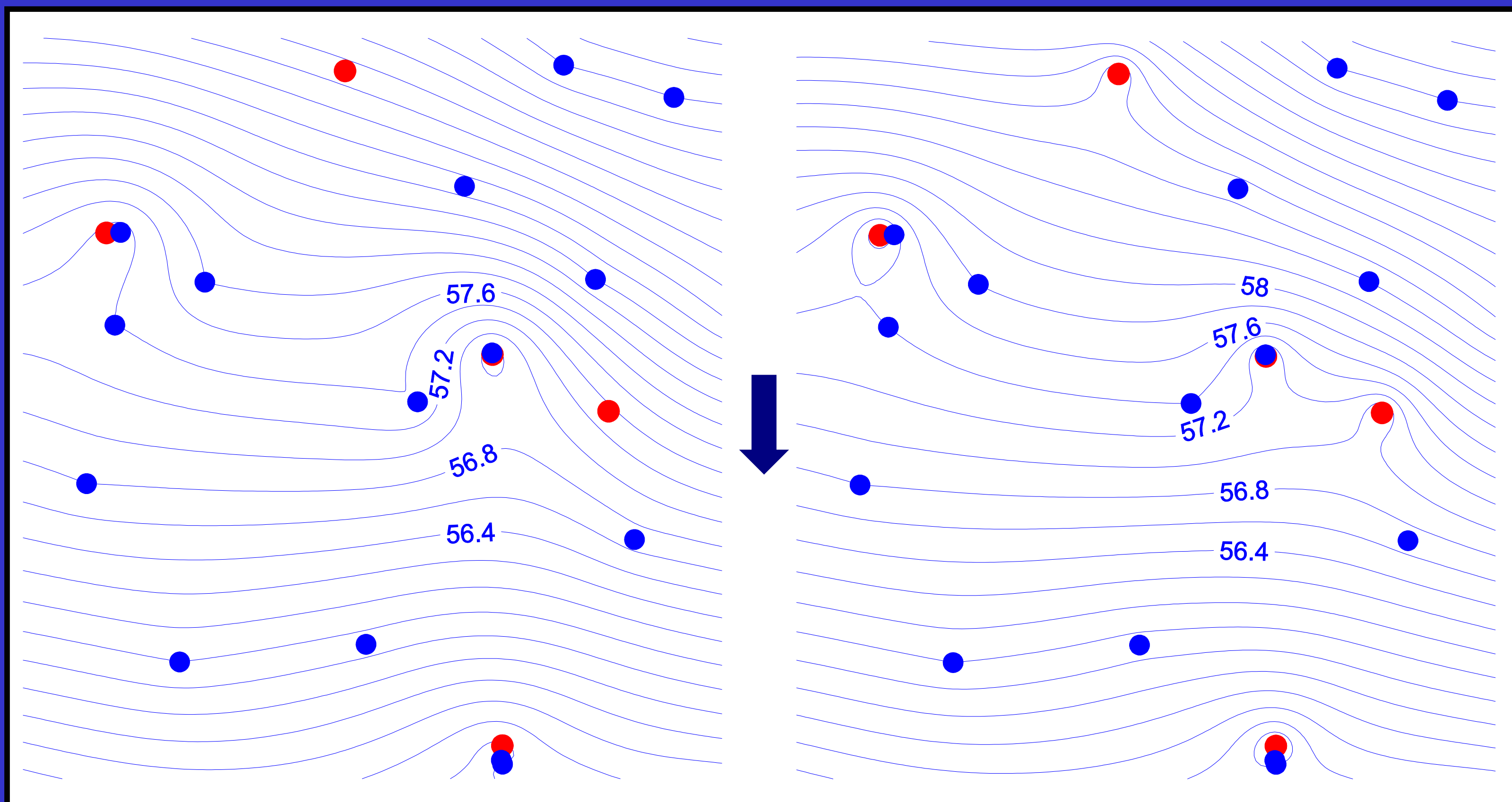
Cape Cod - Linear-log Trend



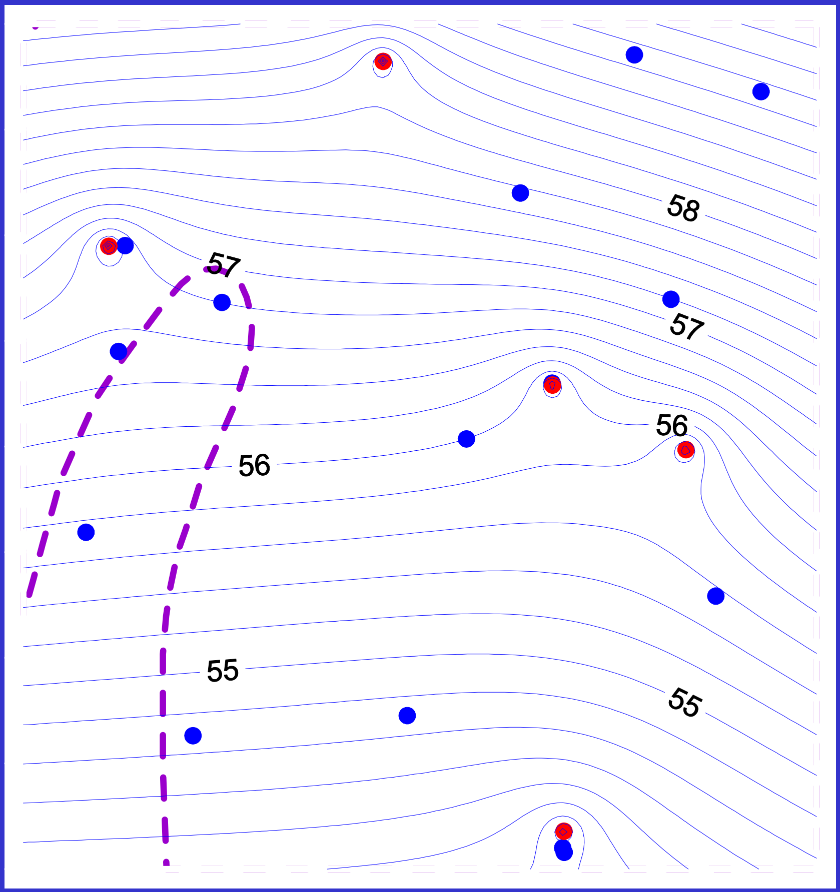
$$Z_{est} = f(Q, X, Y, R)$$

Cape Cod - Comparison

Linear drift | Linear-log drift

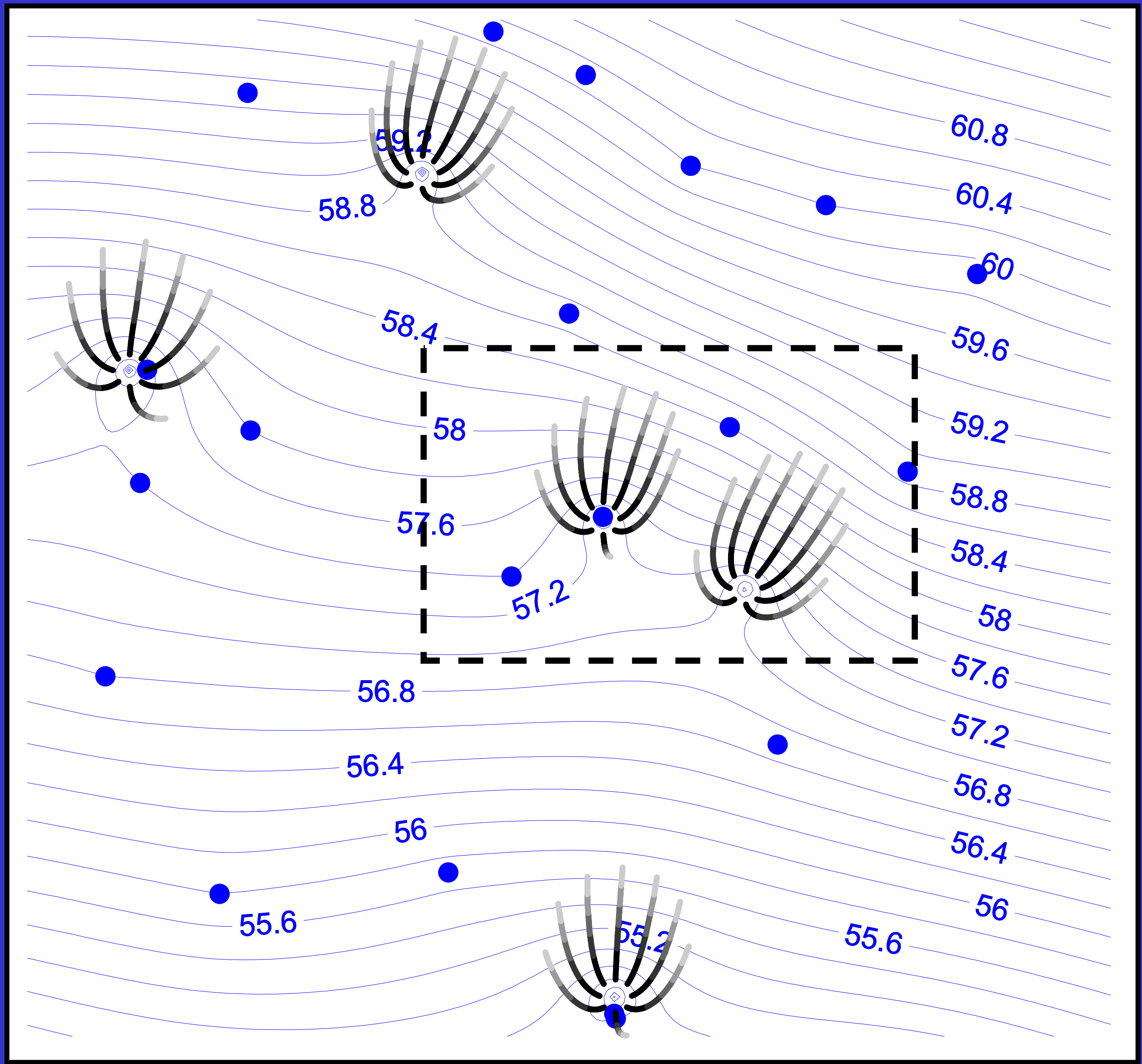


Cape Cod - Trend Pattern



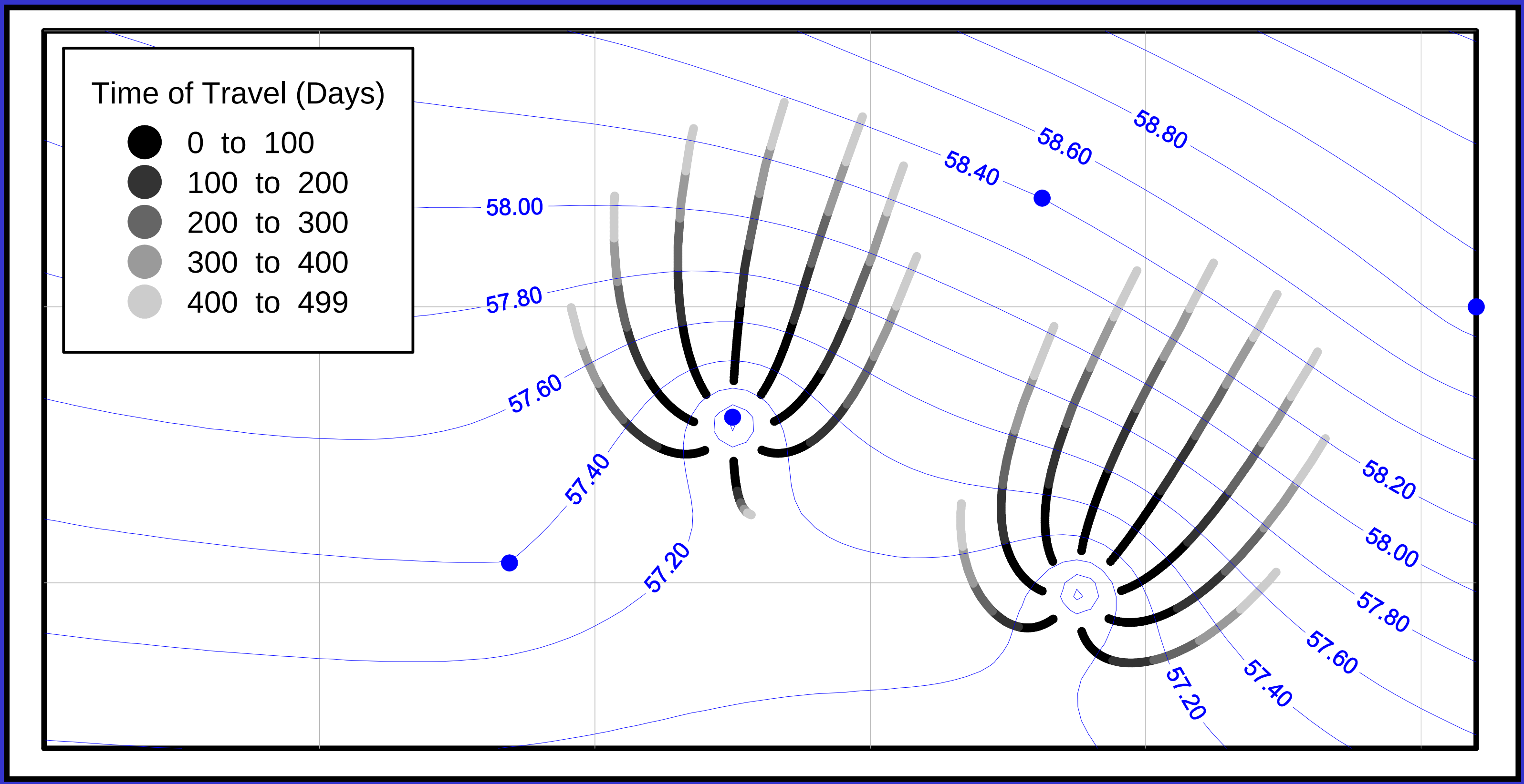
NOTE – estimated T was 56,000 ft^2/d; from pump tests – 35,000 – 60,000 ft^2/d

Cape Cod

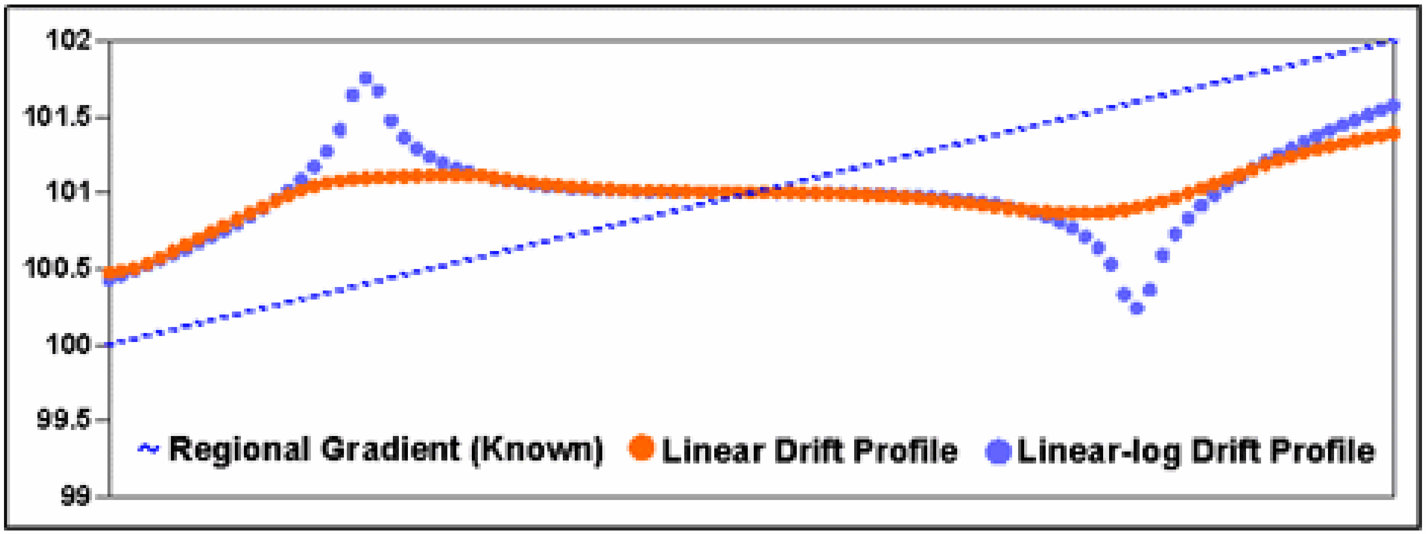


60.8
60.4
60
59.6
59.2
58.8
58.4
58
57.6
57.2
56.8
56.4
56
55.6
59.2
58.8
58.4
58
57.6
57.2
56.8
56.4
56
55.6
55.2

Cape Cod


Time of Travel (Days)
0 to 100
100 to 200
200 to 300
300 to 400
400 to 499
58.80
58.60
58.40
58.20
58.00
57.80
57.60
57.40
57.20

Profile Example



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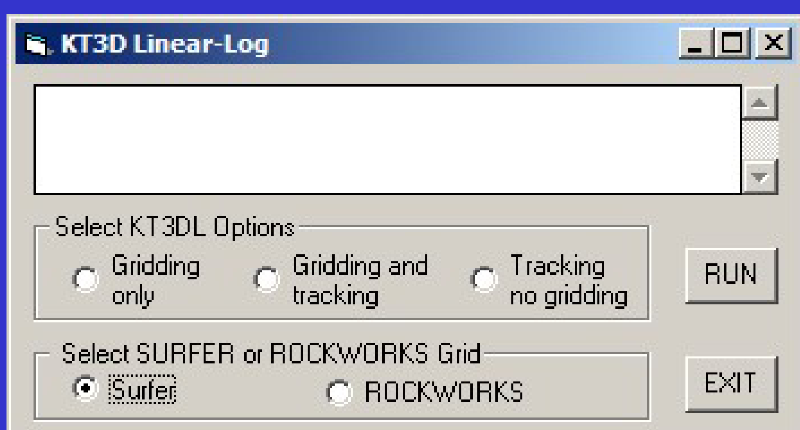
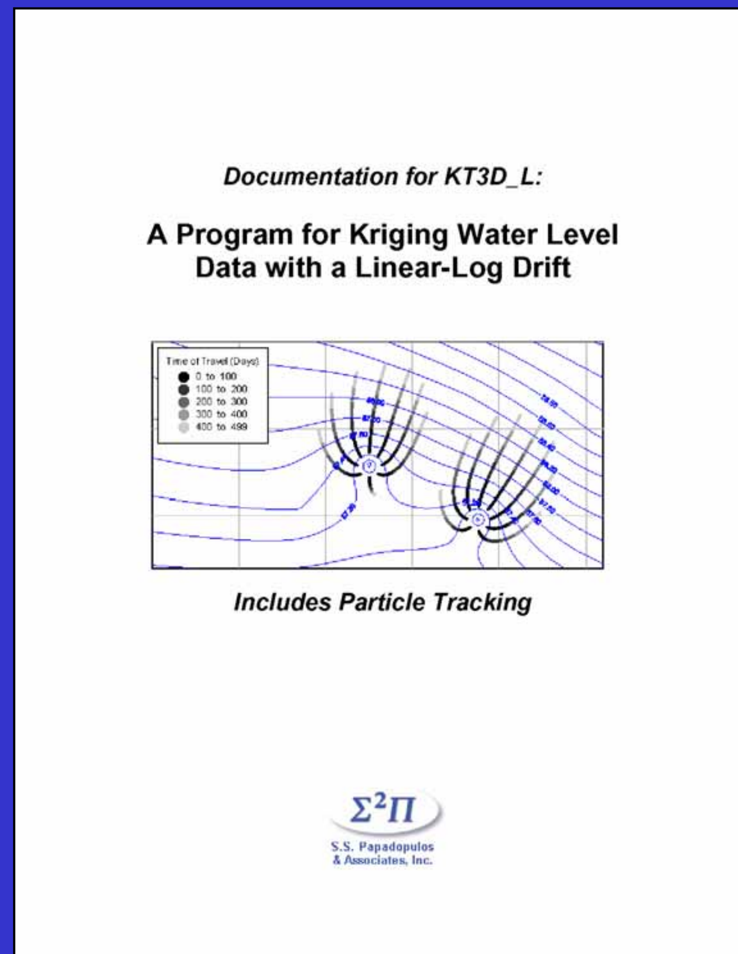
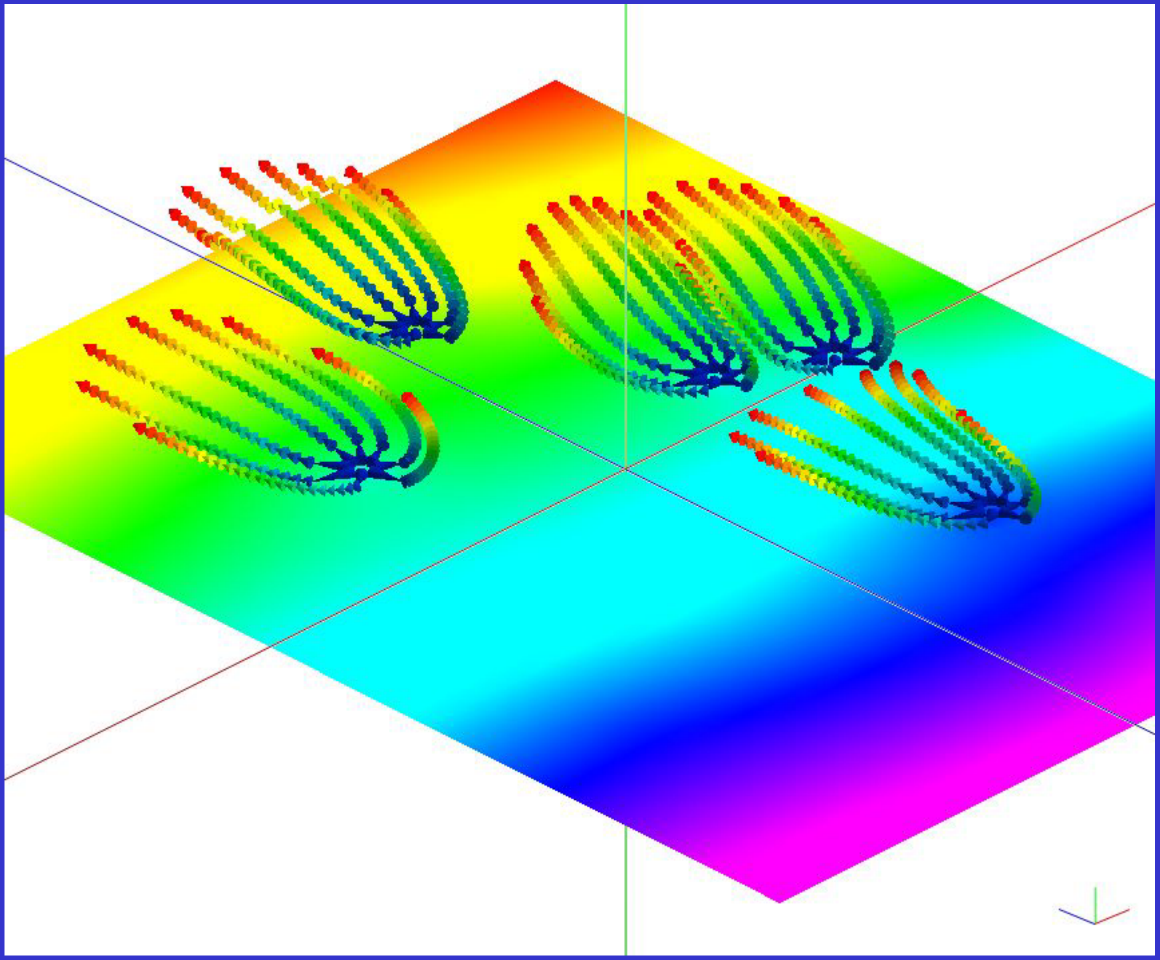
Software

- Based on GSLIB program KT3D.
- GUI drives KT3D_L1 including particle tracking.
- Surfer™ or Rockware™





Rockworks



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  - In particular, Rose Forbes

- Jacobs Engineering Group
  - In particular, Mike Goydas, Dave Ward