Headquarters U.S. Air Force

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Part 1. Hydrus Modeling Hydrogeologic Factors

Former George Air Force Base
September 2017
Sacramento, CA

ED_003054_00003441-00001

Organization of Presentations

1. Overview of hydrogeologic factors affecting models in the SS030 (including ST054, ST057, & SS084 sub-areas), OU5 (SS083 & FT082), and OT071 areas
2. OU5, SS083 and FT082, Hydrus model approach. TCE modeling compound of concern.
3. SS030, including ST054, ST057, & SS084 sub-areas, Hydrus model setup, calibration, and results. Benzene modeling compound of concern.
4. OT071 Hydrus model approach. Dieldrin modeling compound of concern.

Site Management

- SS030—Petroleum hydrocarbon; benzene primary COC
  - Vadose zone soil contamination at and above the top of the Upper Aquifer water table addressed in Sites ST054, ST057, and SS084
  - LNAPL and groundwater contamination addressed in Site SS030
  - SS030 Hydrus model included in several reports
- OU5—Chlorinated hydrocarbons; TCE primary COC
  - Vadose zone contamination managed in SS083 and FT082
  - Groundwater managed in OT069e
  - SS083 and FT082 have separate TCE groundwater plumes and will be modeled separately
- OT071—Dieldrin contamination will be modeled from ground surface to the Lower Aquifer as colloidal-enhanced migration.

GAFB Models

- 3D data models
  - Developed using RockWorks 17 software
  - Used to develop data models of 3D data locations and values and 3D grid models ("cubes") of lithology, groundwater levels, groundwater and vapor plumes
  - Cross-sections and plan maps are "slices" thru the 3D "cubes"
  - Most models use 25'(X) by 25'(Y) by 5'(Z) grid spacing
- Hydrus models
  - Developed using Hydrus 2D/3D model code
  - Develop 2D vertical profile models
  - Finite element model code capable of simulating water flow and transport in the vadose and groundwater zones using basic input data on soils, contaminants, and meteorological data
  - Extensive capabilities for handling variable-saturation conditions in vadose zone for air-water flow and transport
- *LNAST* (LNAPL Dissolution and Transport Screening Tool) models
  - Simple analytical 1D model for LNAPL depletion and migration and dissolved plume transport
  - Used previously in SS030 and ST067b LNAPL evaluations

Use of Models

- Data models—Understand 3D distribution of data types and values to understand hydrogeology
- Hydrus models
  - Understand flow and contaminant migration from ground surface to the Upper Aquifer and migration in the groundwater zone including recharge and vadose zone contaminant flow rates
  - Assess long-term fate and transport of groundwater contamination
  - Determine vadose zone soil remediation concentration goals
  - Evaluate effectiveness of remedial alternatives
- *LNAST* models
  - LNAPL migration potential in SS030 and ST067b
  - Compare *LNAST* and Hydrus model results

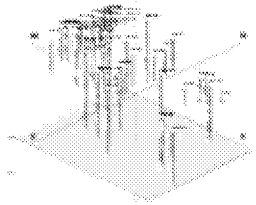
Overview of Factors Affecting Hydrus Modeling—SS030 Examples

- Hydrogeology
  - Lithology and 3D data modeling using RockWorks 17 software
  - Geotechnical properties of lithologic units that affect vadose zone and groundwater contaminant flow and transport
  - Recharge—natural and man-made
  - Groundwater flow directions and gradients
- LNAPL and vadose zone contaminant sources

3D Modeling Process

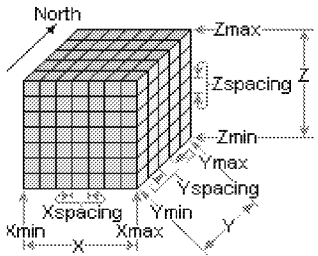
Compile data into 3D database

- Boring logs, analytical data, etc.



Construct 3D volumetric "cube"

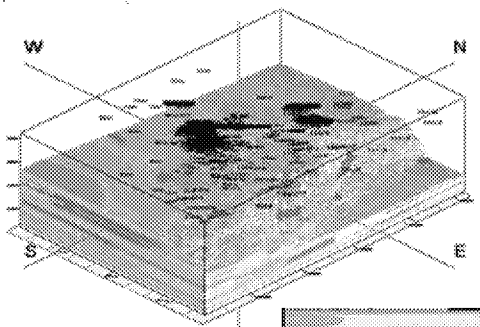
- 3D data gridding (various methods)



Integrate existing surfaces

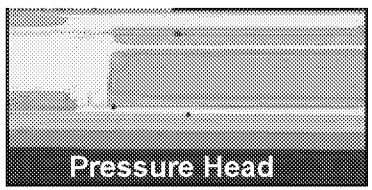
- Topography, water level elevations, structural surfaces, etc.

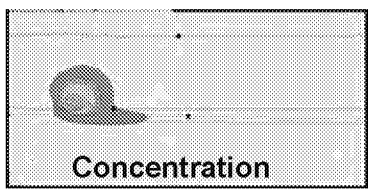
Final 3D "cubes"



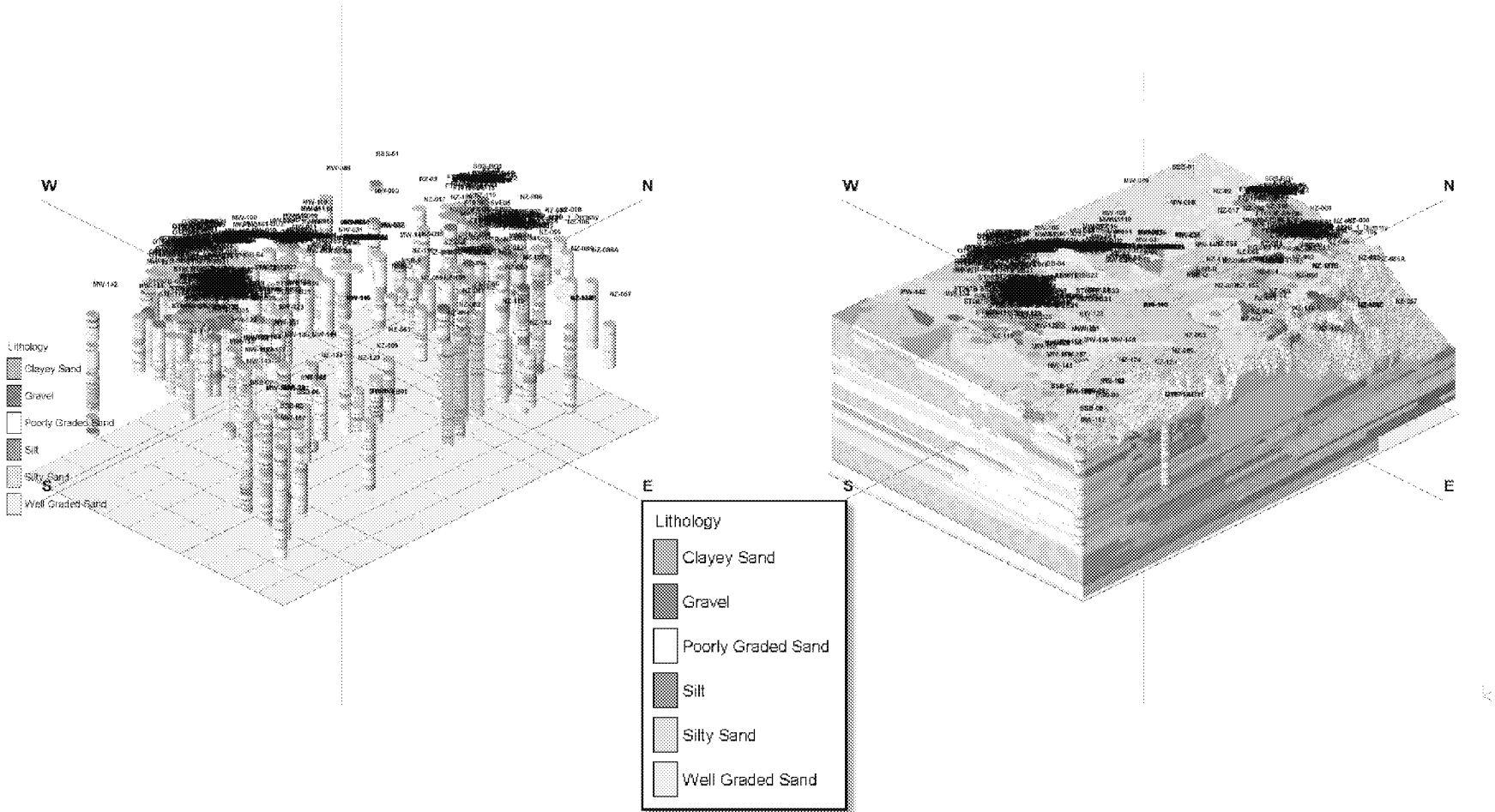
Generate maps and cross-sections

HYDRUS 2D Model





SS030 Boring Logs (n = 519) and Lithologic 3D Model



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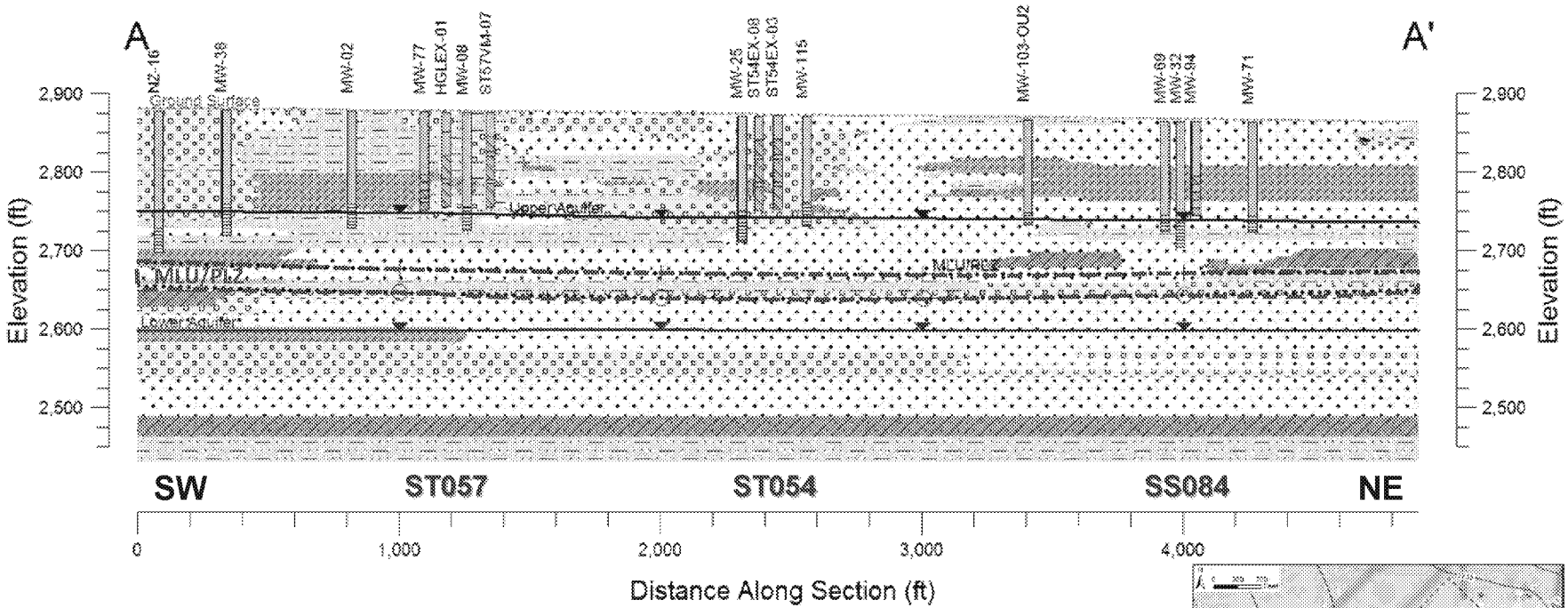
Cross-Sections from 3D Models

- All data in one XYZ coordinate system and one database
- Two types of cross-sections
  - Profile sections
    - Straight-line section between two selected points with a "swath" to post wells/borings along profile line
    - Swath width defined by user (e.g. 100 feet on either side of profile line)
  - Well-to-well section
    - Between wells/borings along section line. Line can "zig-zag" between wells
    - Only wells/borings intercepted are posted on cross-section
- Sections internally consistent no matter what is included
- Sections show well construction, concentrations, lithology, etc. at well/boring locations.
- Various surfaces, e.g. topography, water tables, structural surfaces, are in RockWorks database and can be shown along profile and well-to-well sections.

Lithology Profile Section A-A'



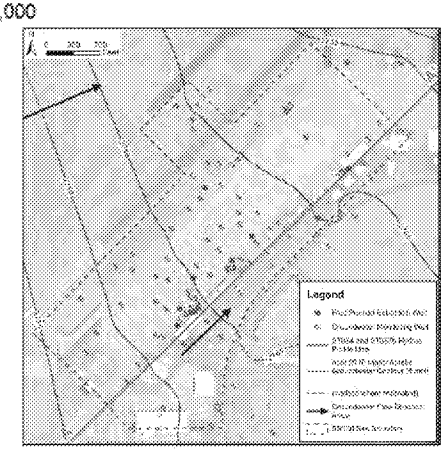
Lithology Index

- Clay + Sandy Clay
- Silt
- Silty Sand
- Poorly Graded Sand
- Well Graded Sand
- Gravel

Well Legend

- Casing
- Screen-Groundwater
- Screen-Vapor

Cross-Section Location Map



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High-Concentration Well-to-Well Benzene Plume Section

Benzene Plumes and Lithology

AZ

AZ'

Ground Surface

Upper Aquifer

Inset 1

Inset 2

Inset 3

70

100

Elevation (ft)

2,500

2,600

2,700

2,800

2,900

0

2,000

2,500

3,000

3,500

4,000

4,500

SW

NE

Distance Along Section (ft)

Lithology Index

Clay + Sandy Clay

Silt

Silty Sand

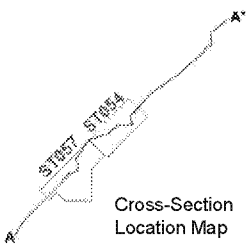
Poorly Graded Sand

Well Graded Sand

Gravel

Vapor Concentration (ppmv)

Groundwater Concentration (ug/L)



Cross-Section Location Map

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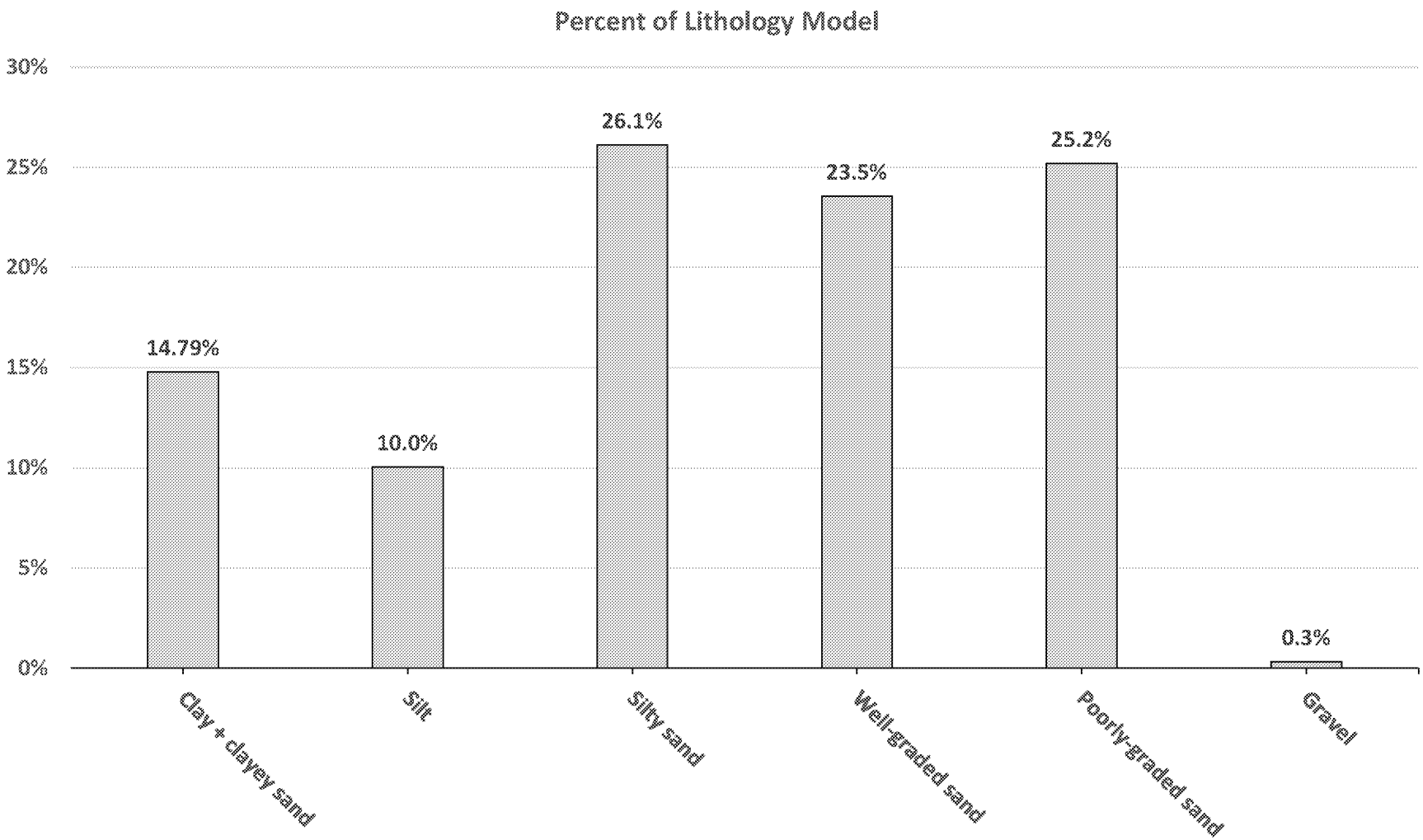
SS030 Lithology Distribution



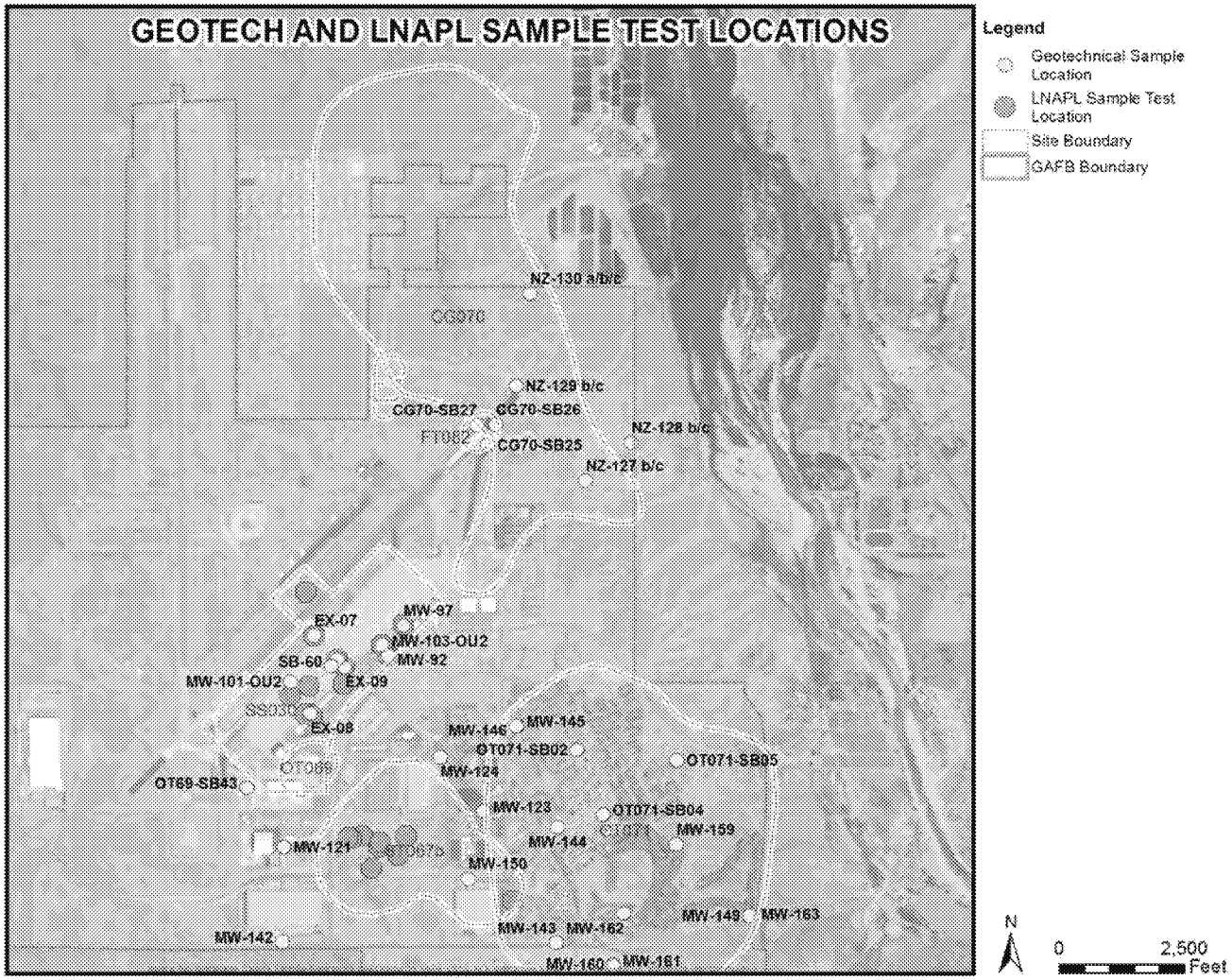
Lithologic Factors Affecting Model Development

- Lithologic modeling across GAFB shows that the MLU/PLZ is a zone of heterogeneous lithology (clay to sand) that has lower hydraulic conductivity than the Upper and Lower Aquifers.
- There are areas where the lithology is sand thus creating the PLZ.
- Large volumes of lower vadose zone are clays, silts, silty sands
- Based on the presence of TCE and Dieldrin in the Lower Aquifer, there are contaminant pathways through the MLU/PLZ. This is consistent with the lithologic model results.
- Detailed, heterogeneous lithology used to develop Hydrus model finite-element lithology compared to typical MODFLOW model layers
- Available software allows for relatively straight-forward model development.

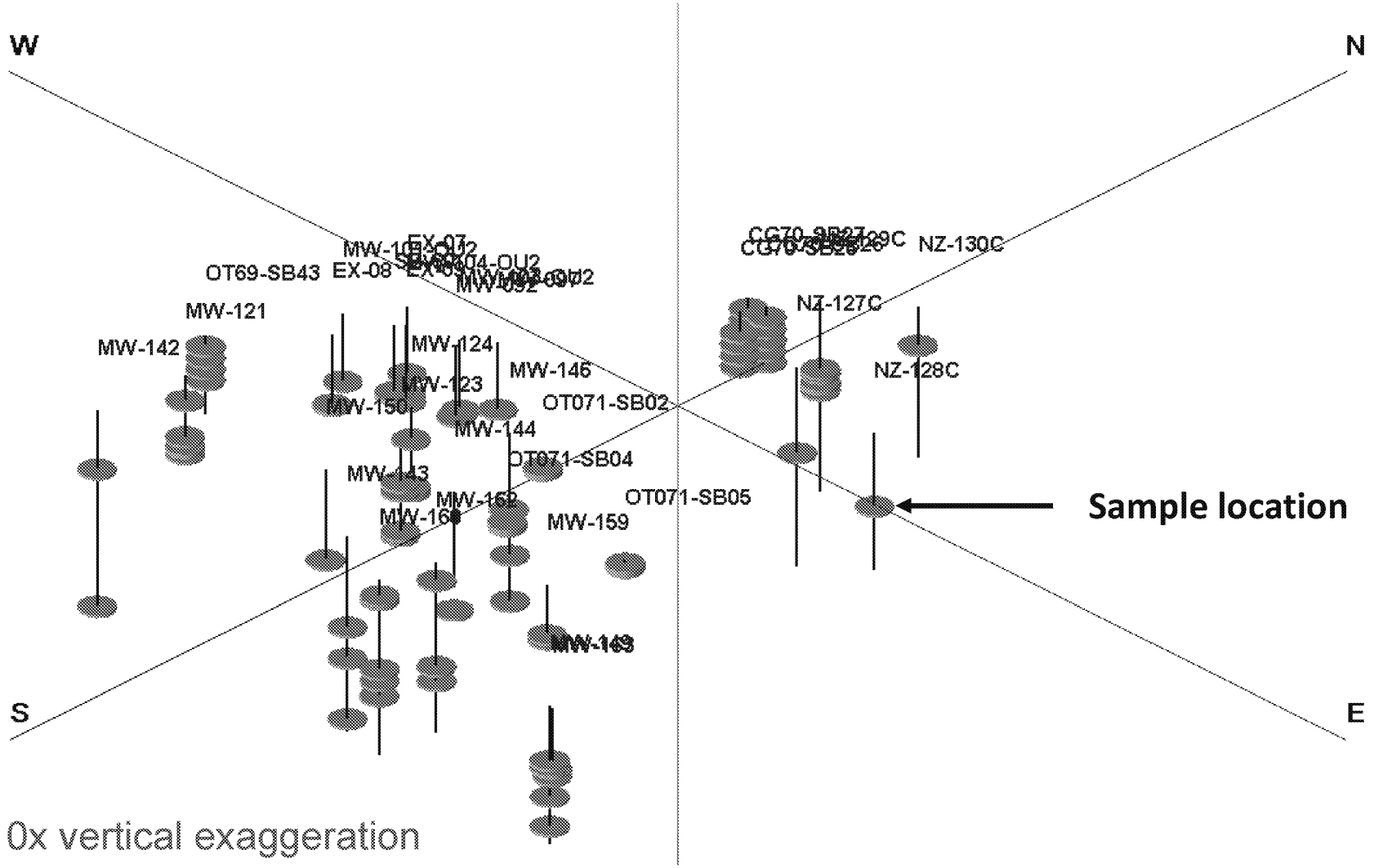
Geotechnical and Hydraulic Conductivity Data

82 geotechnical and 97 aquifer tests across GAFB

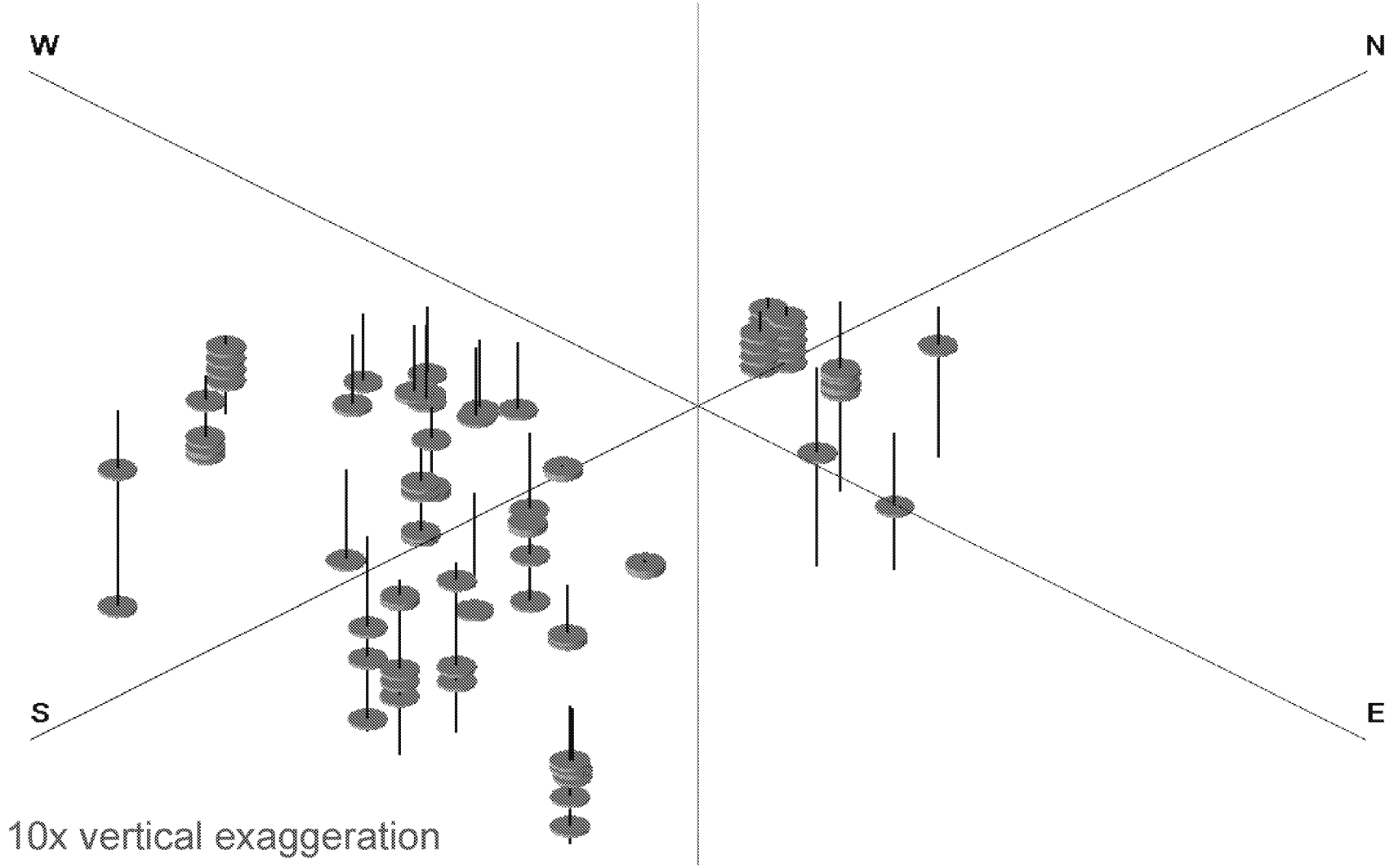
Geotechnical Soil and LNAPL Test Locations



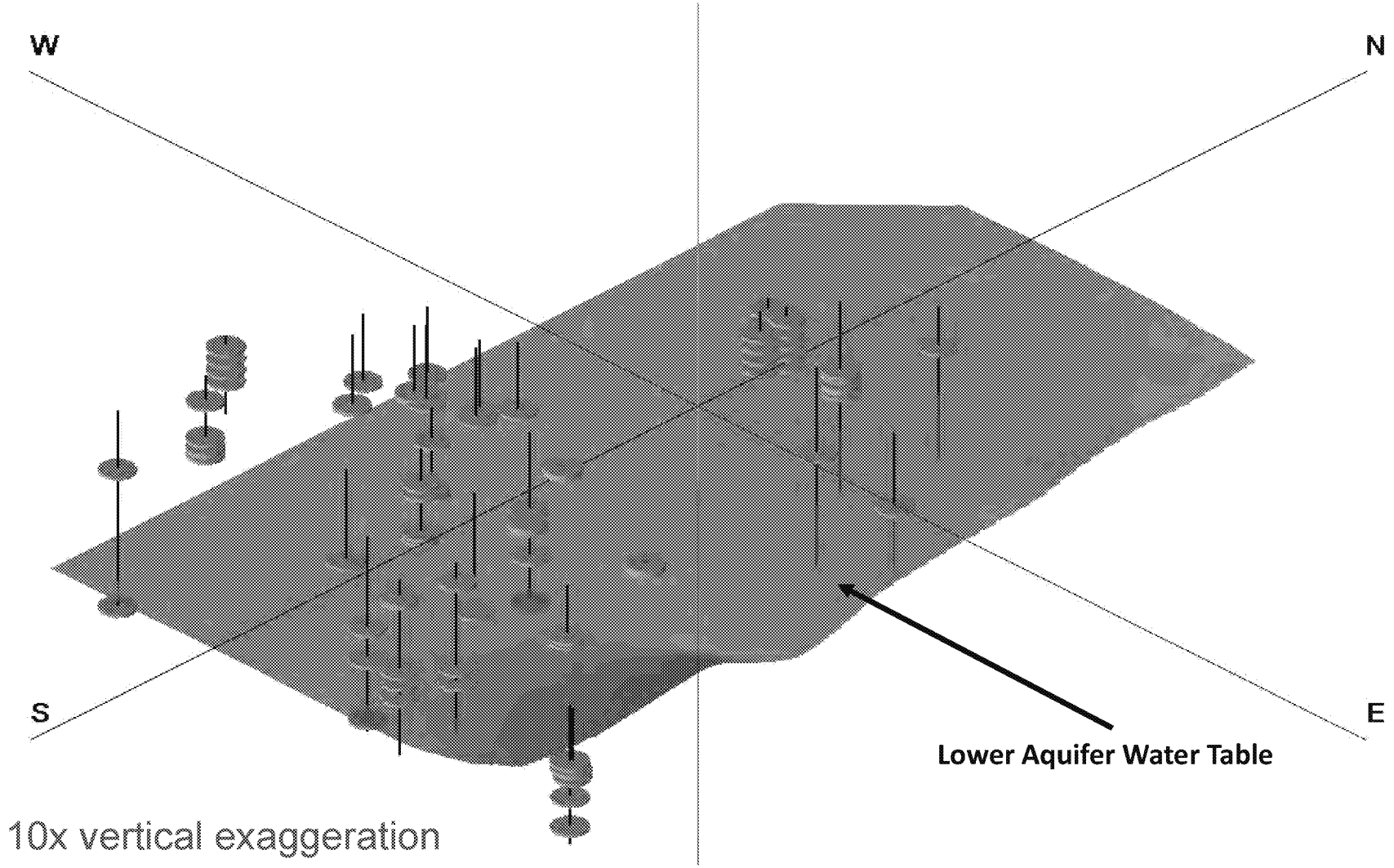
3D View of Geotechnical Sample Locations



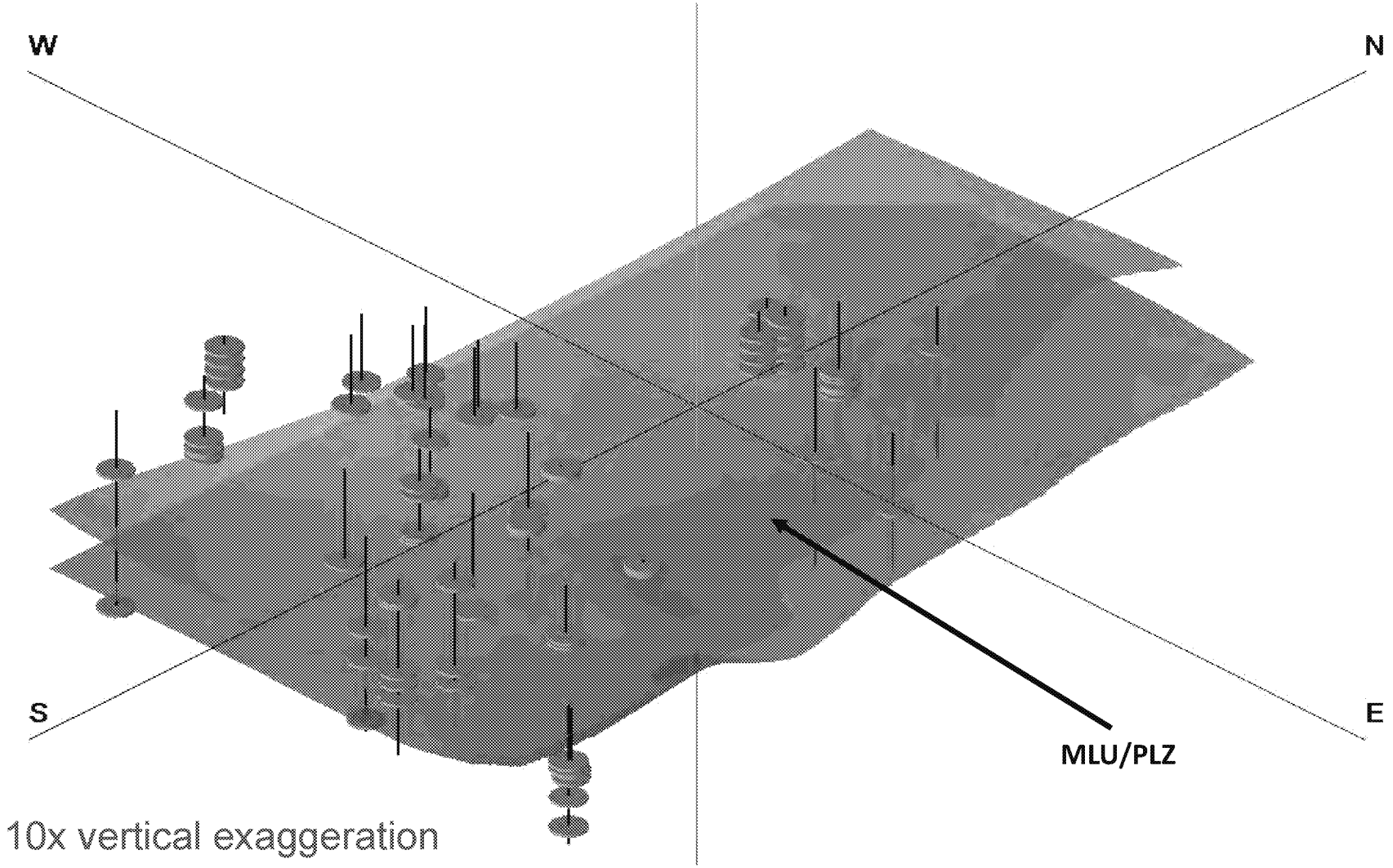
3D View of Geotechnical Sample Locations



3D View of Geotechnical Sample Locations



3D View of Geotechnical Sample Locations



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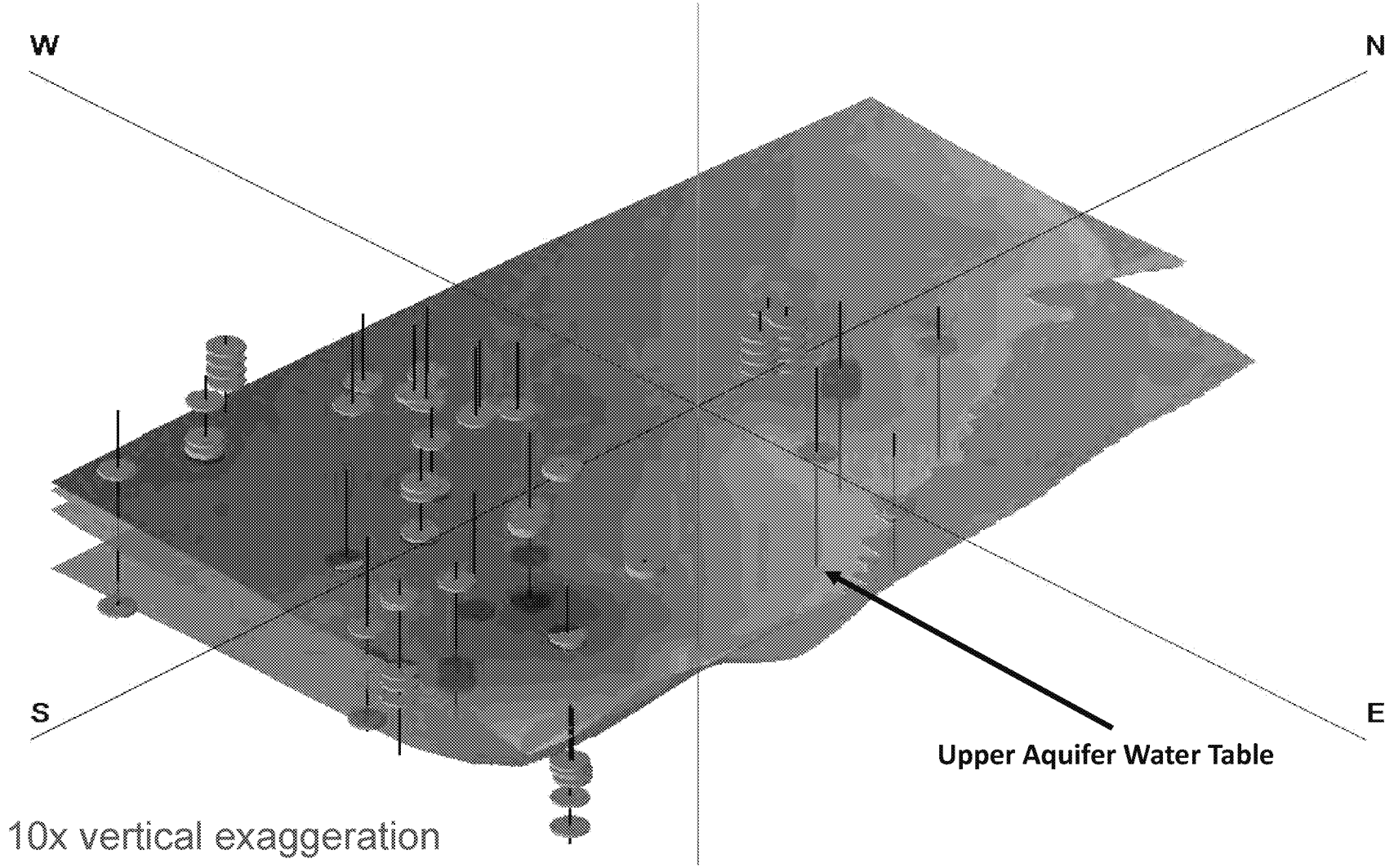

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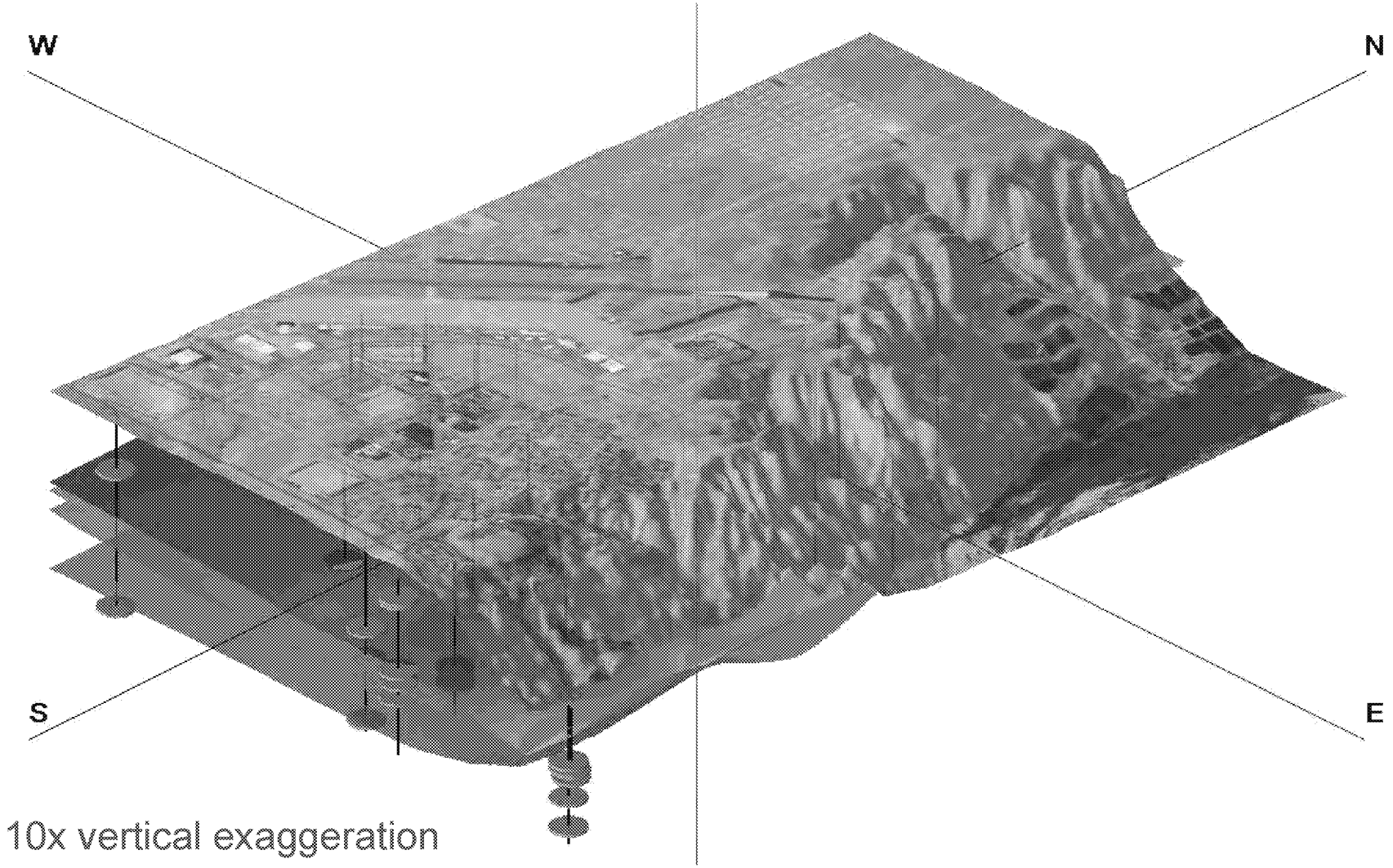
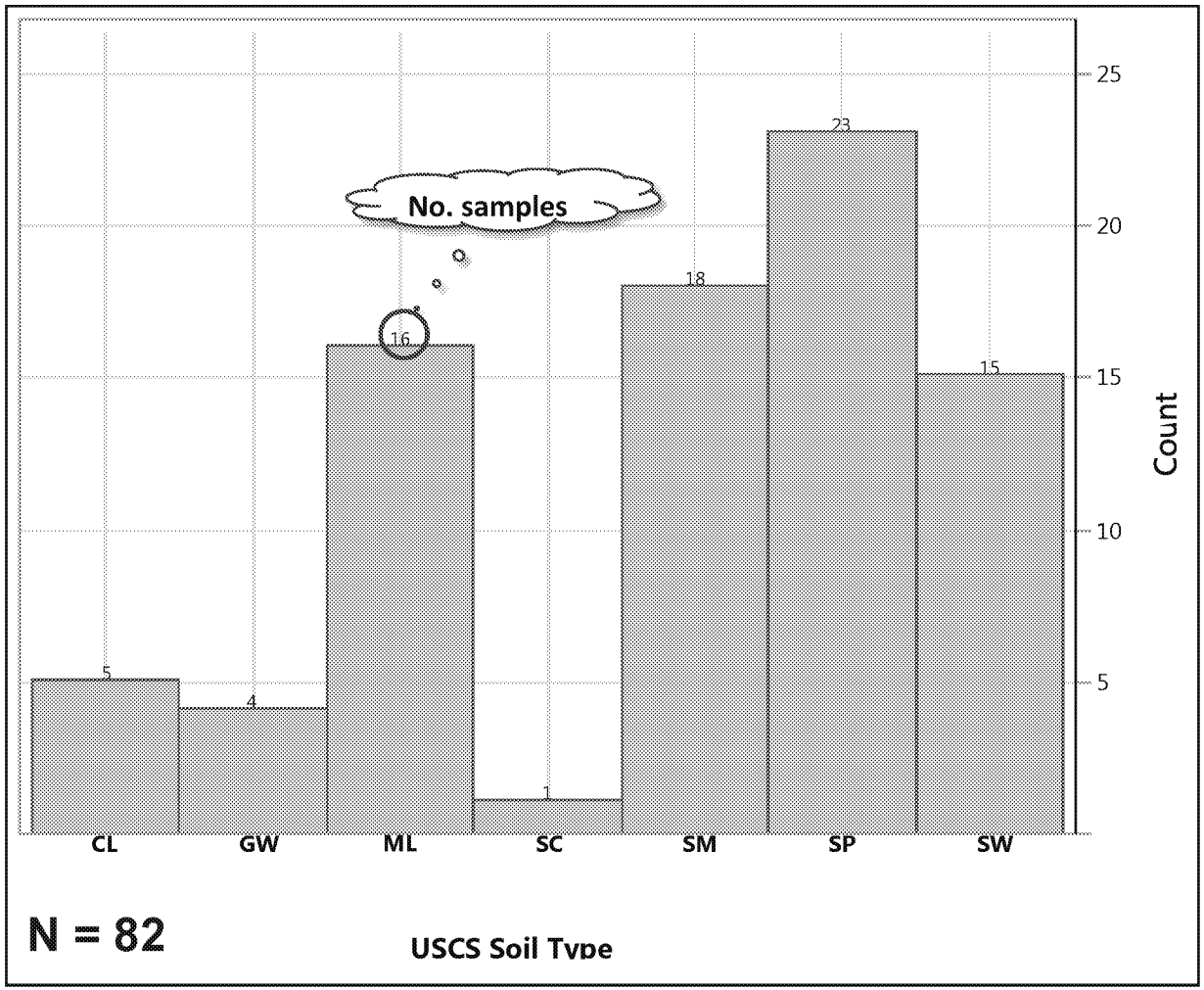


Geotechnical Data Compilation and Analysis

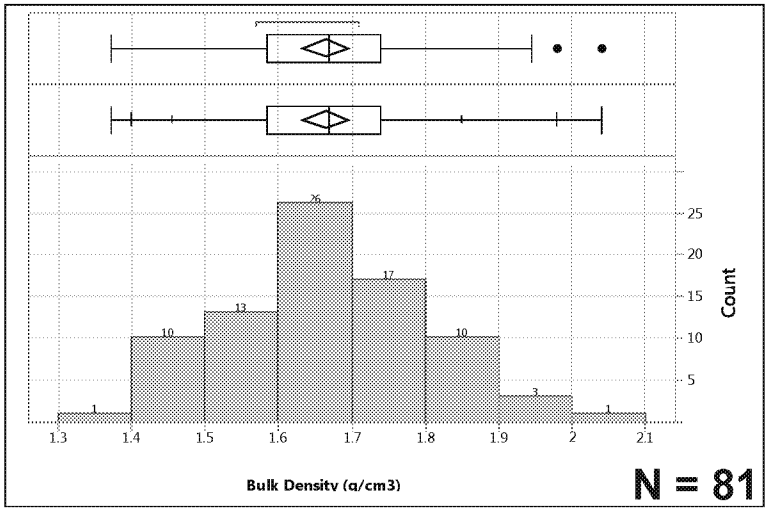
- Compiled data from 82 soils geotechnical tests into database (not all parameters measured on all samples)
  - Sample depths from 5 to 350 feet
  - Grain-size distribution and USCS soil classification
  - Bulk density
  - Porosity
    - Total porosity
    - Effective porosity
    - Air-filled porosity
    - Water-filled porosity
    - NAPL-filled porosity
  - Moisture content
  - Hydraulic conductivity
- Capillary curve pressure tests with van Genuchten curve-fit parameters (air displacing water)
- LNAPL physical properties—density, viscosity, interfacial tension

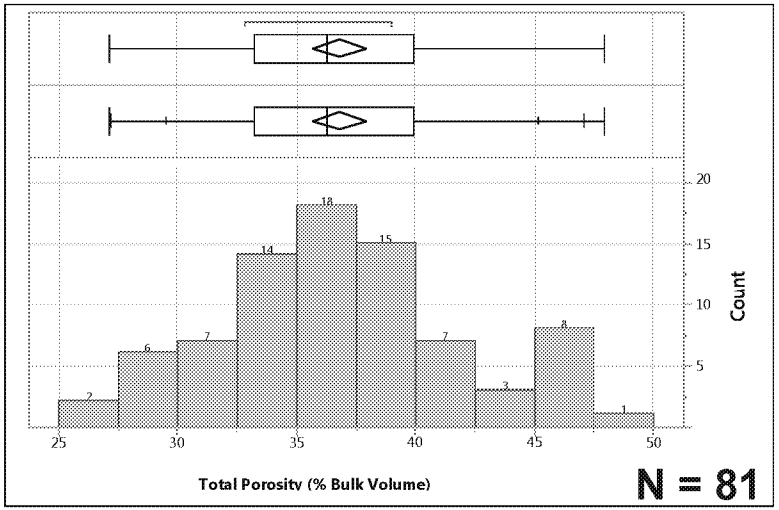
Geotechnical Test Soil Types

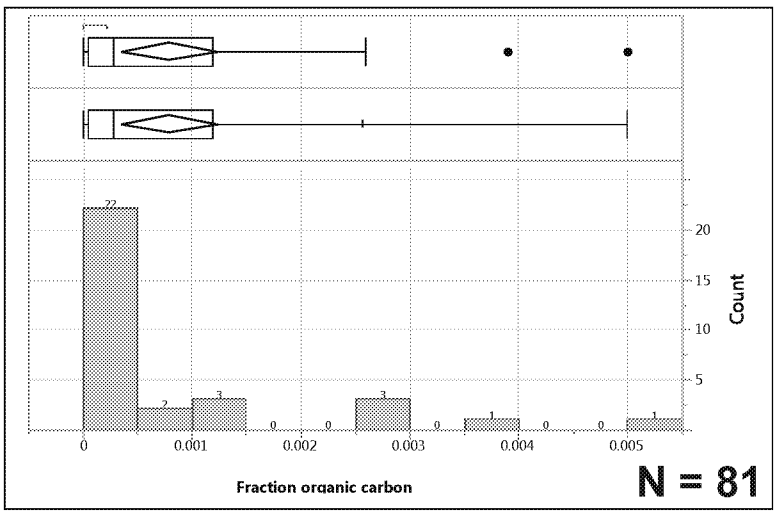


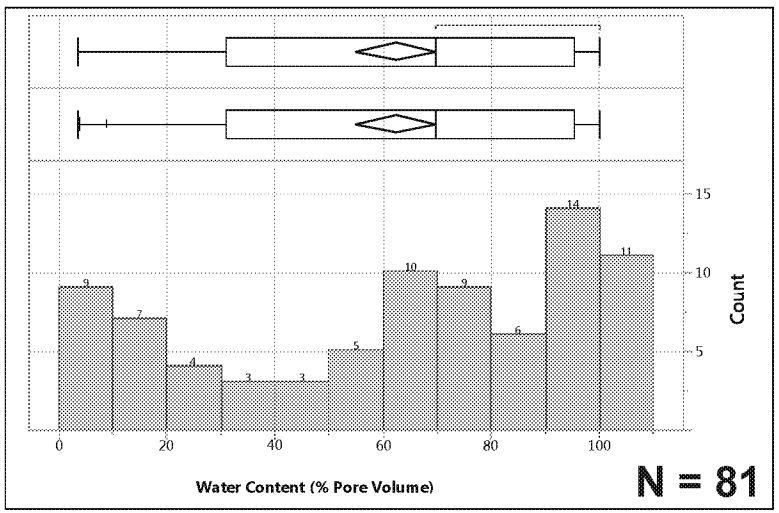
Soil classification based on grain-size distribution for 70 samples and boring log for 12 samples

Geotechnical Results—Density, Porosity, Water Content, foc









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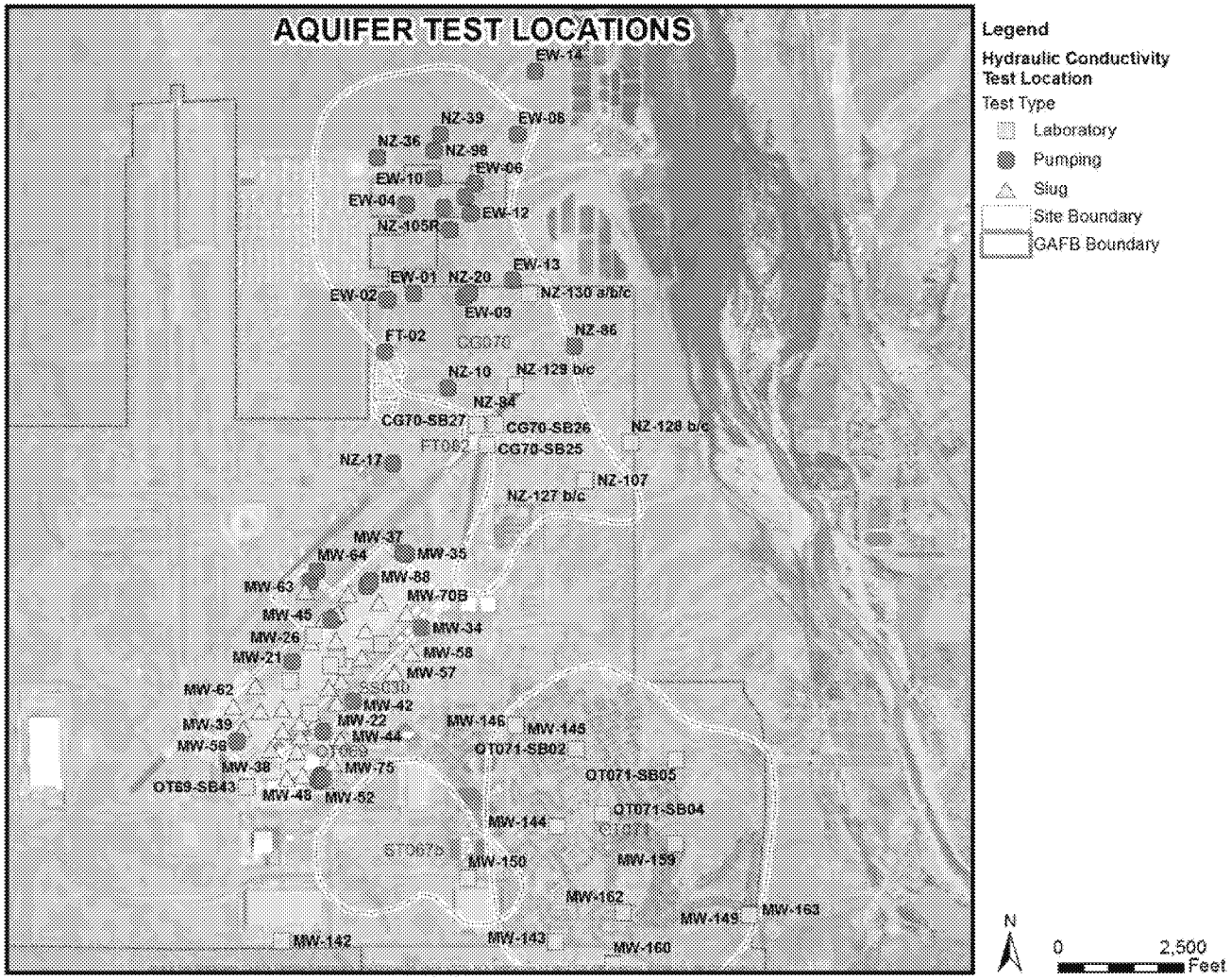
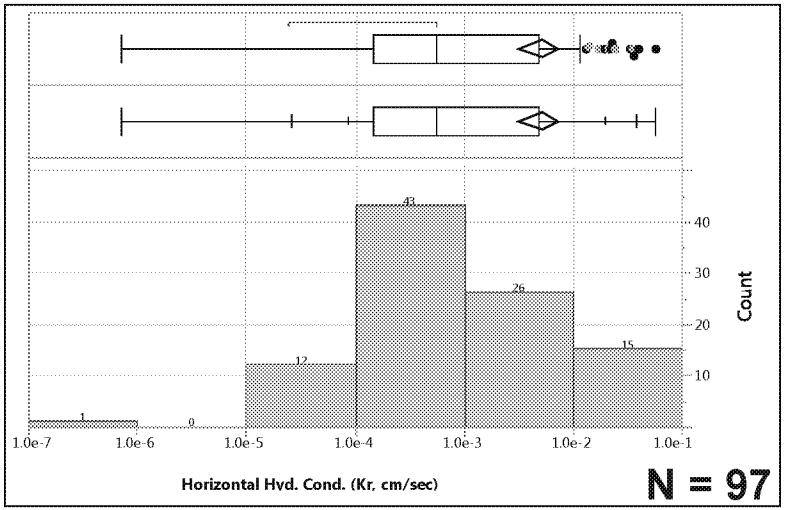
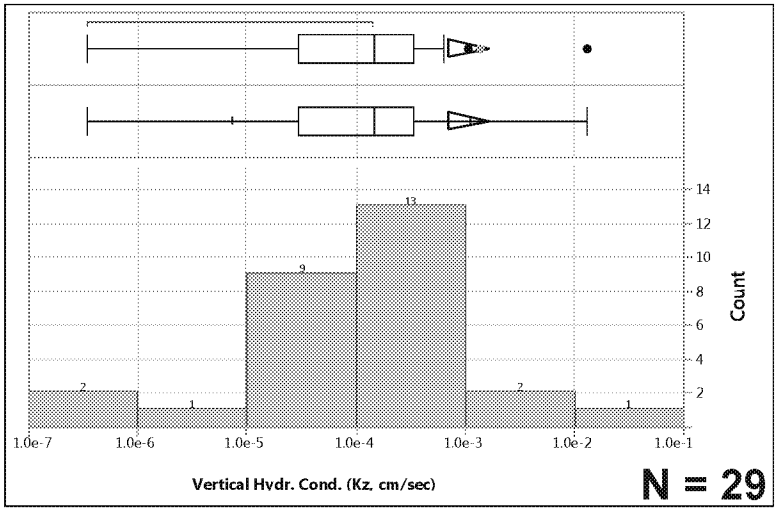
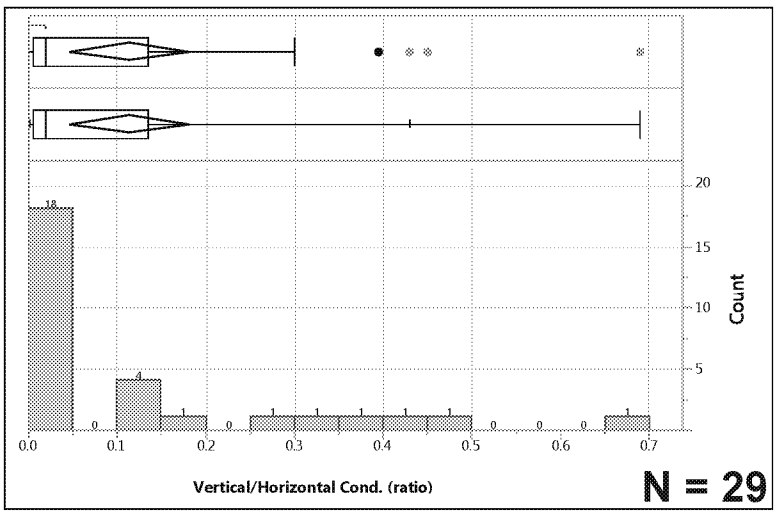
Hydraulic Conductivity Test Locations



Field Aquifer Test Results







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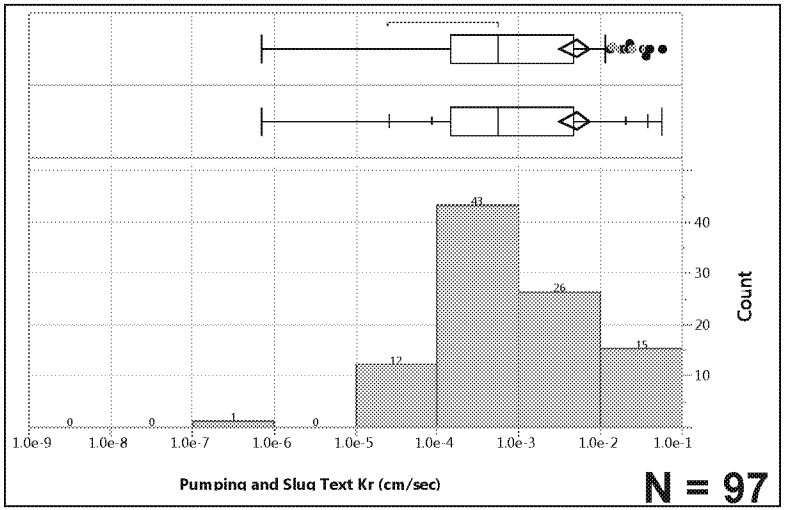
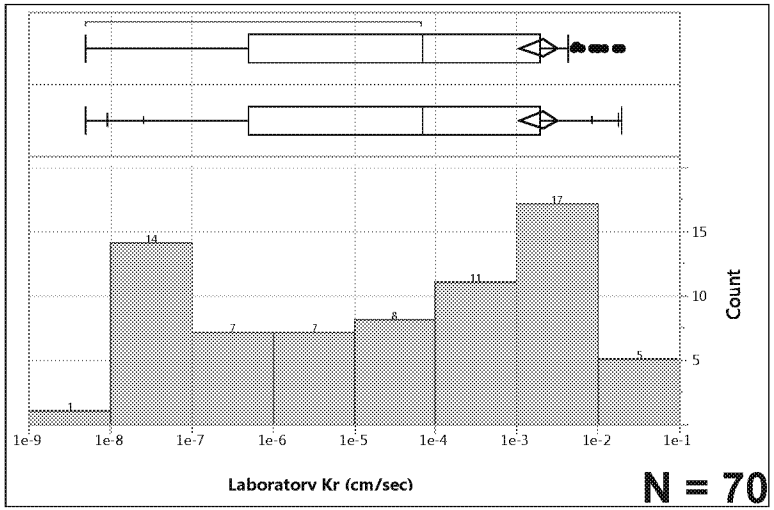
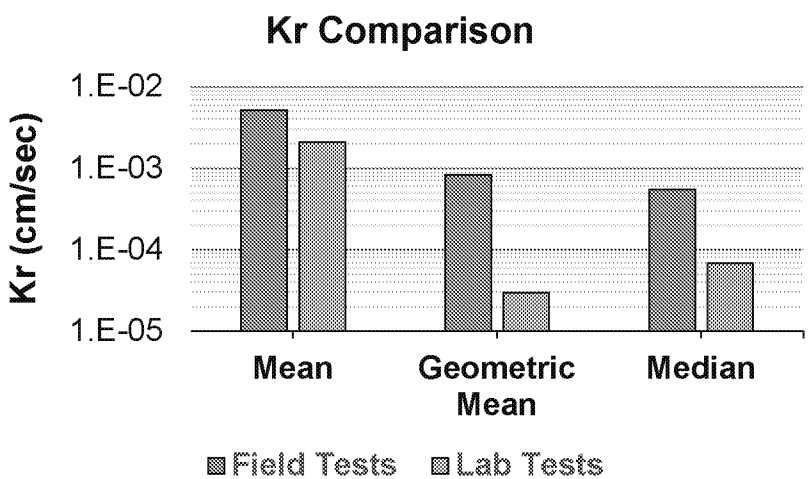
Field and Lab Horizontal Hydraulic Conductivity Compraison



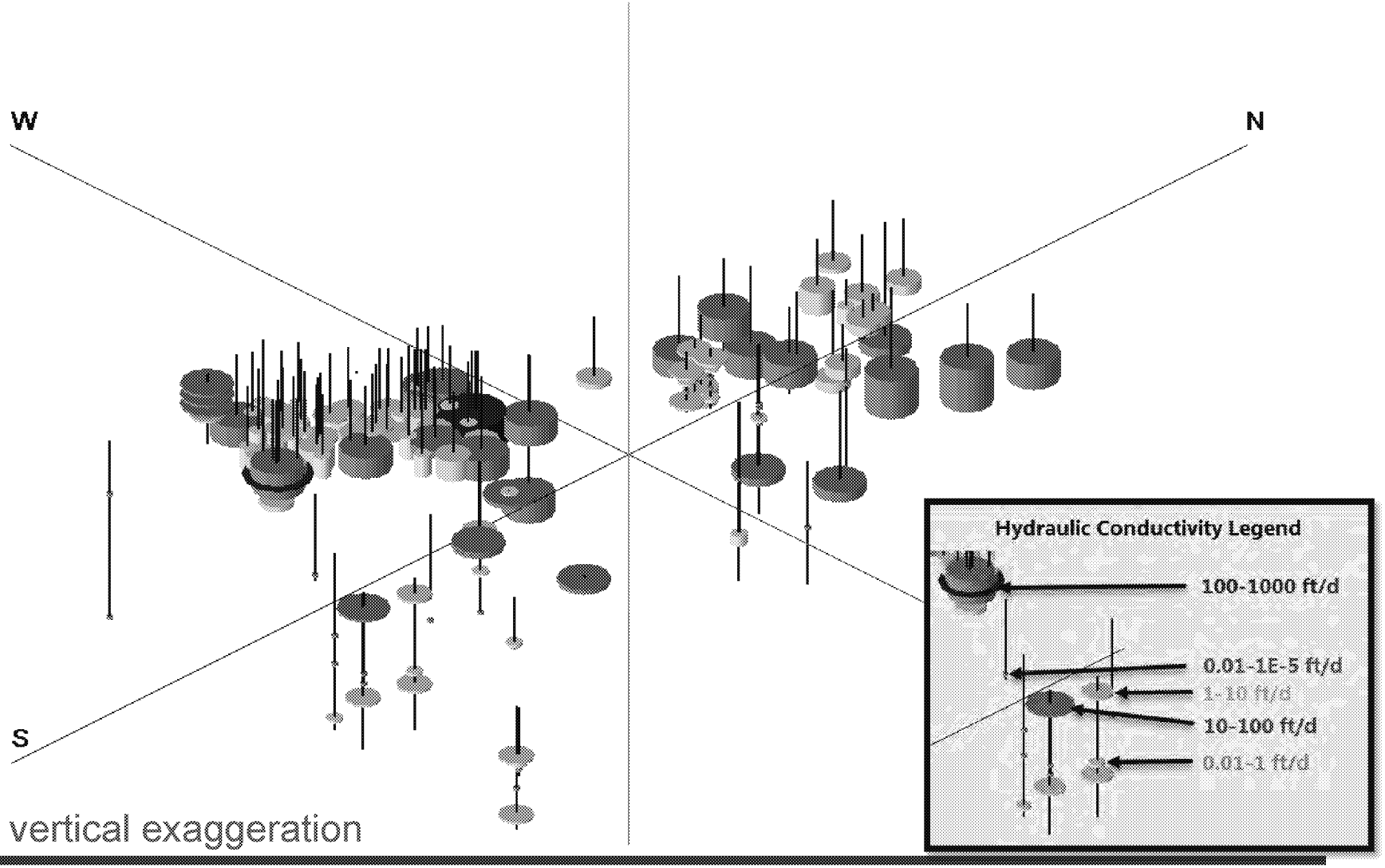




Parameter	Field Tests	Laboratory Tests
Mean	5.2e-3	2.1E-03
Geometric Mean	8.3e-4	3.0E-05
Median	5.5e-4	6.8E-05
Std Dev	1.0e-2	4.2E-03
N	97	70
Minimum	7.1e-7	4.9E-09
Maximum	5.7e-2	1.9E-02

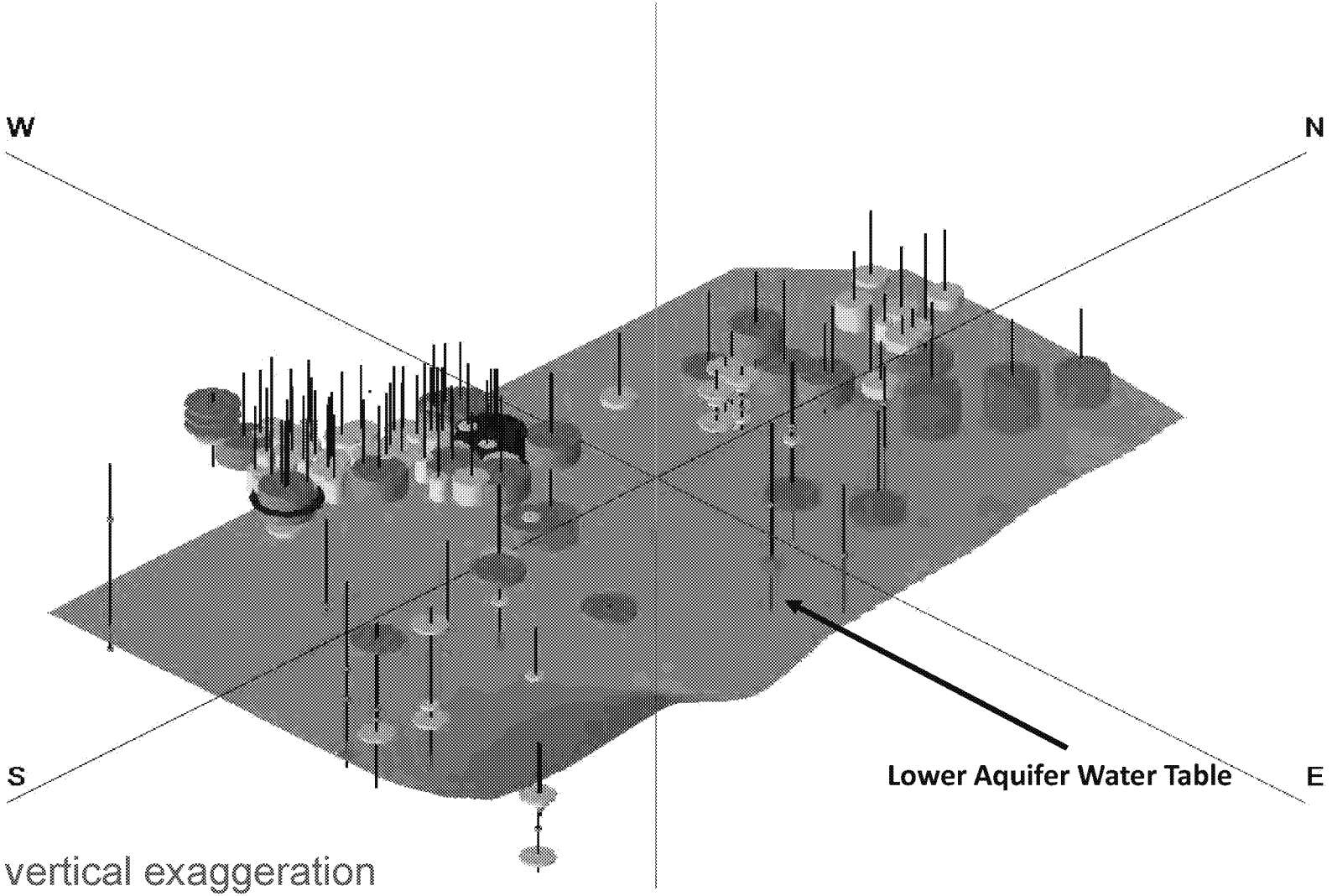
Summary Statistics Comparison

3D View of Hydraulic Conductivity Test Results



10x vertical exaggeration

3D View of Hydraulic Conductivity Test Results



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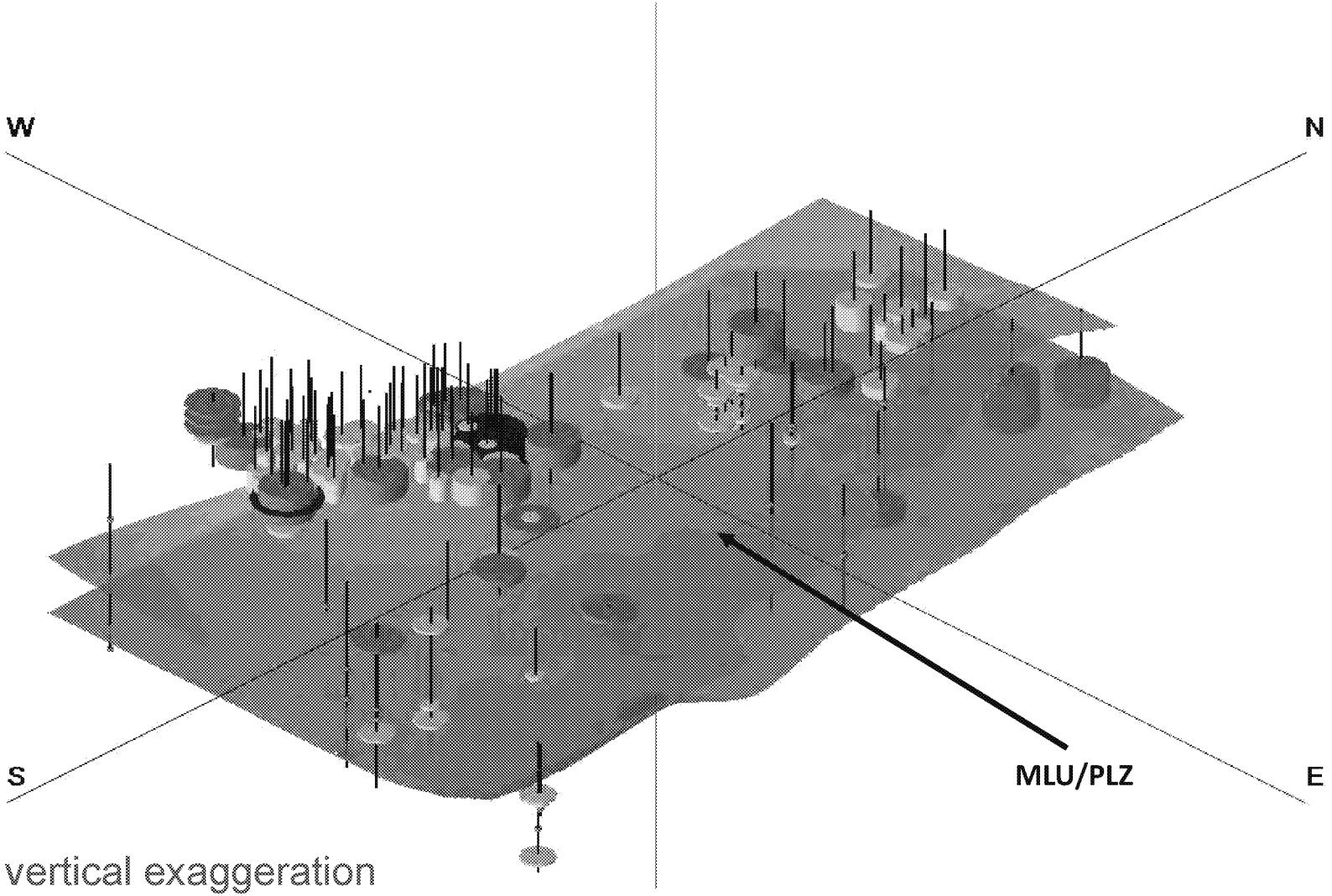

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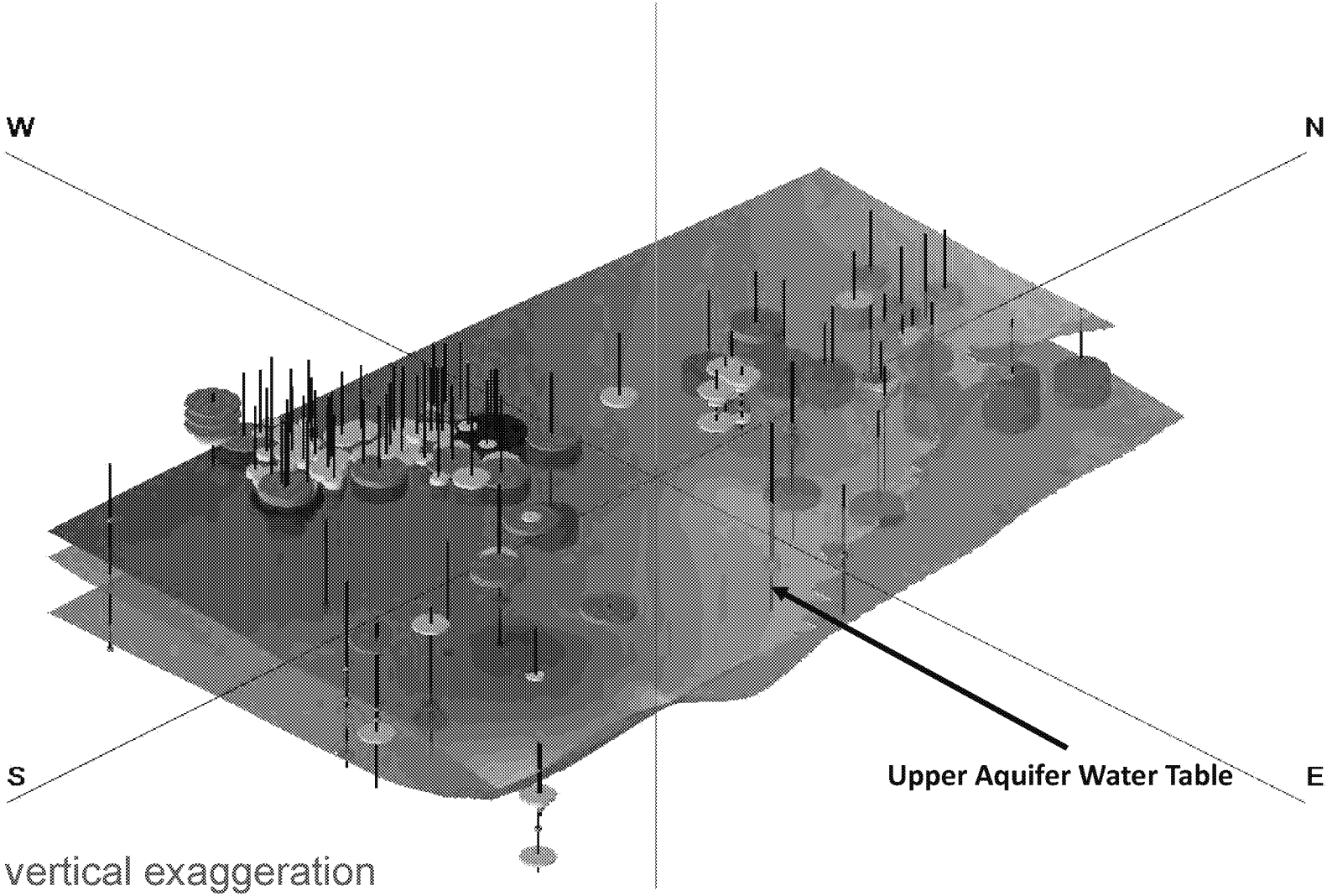

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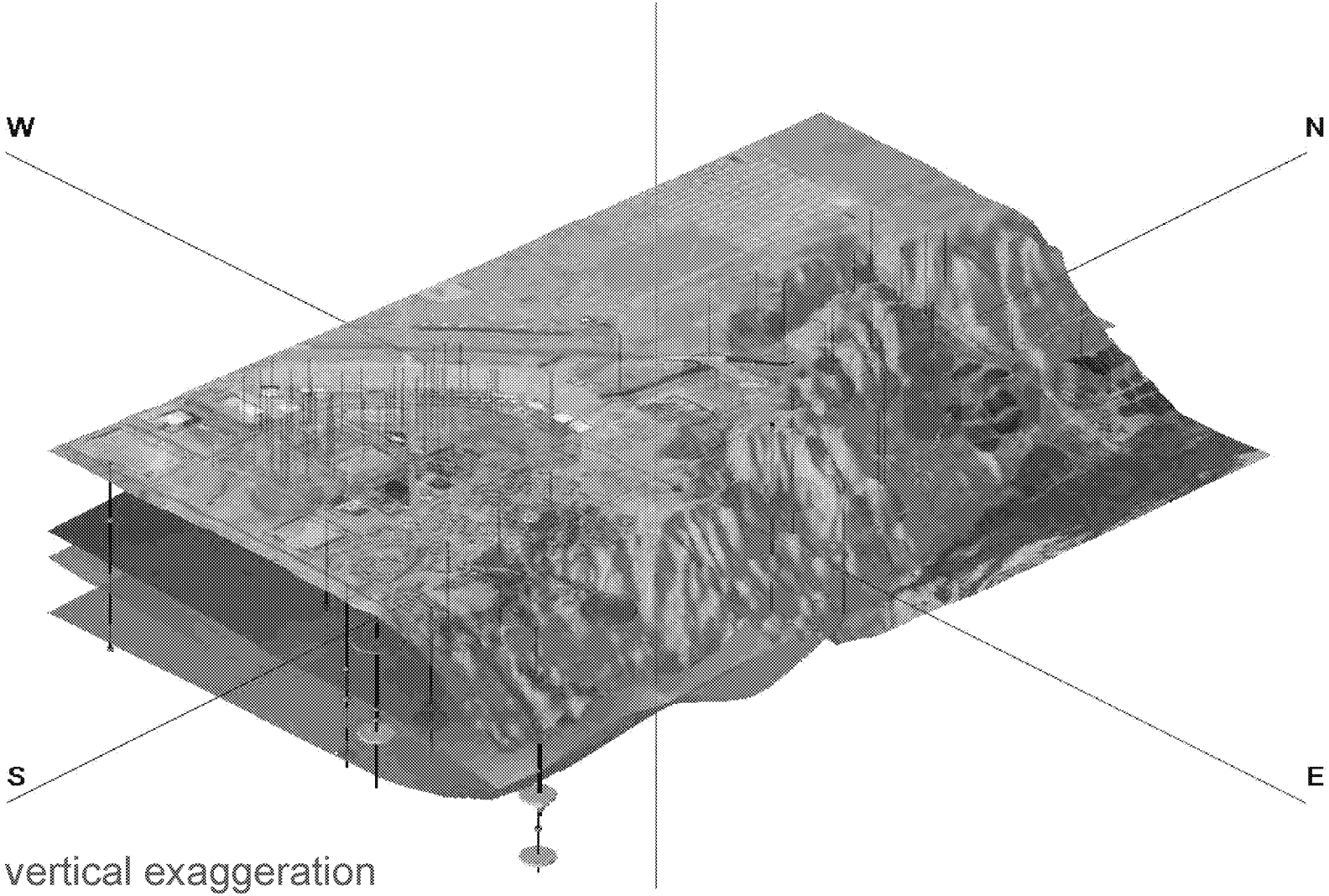


van Genuchten Values from GAFB Capillary Pressure Tests

Sample ID	Depth (ft)	Median grain-size	USCS Soil Type	Total Porosity (fraction)	Alpha (α, 1/cm)	n (unitless)	Sr (frac)	Hydraulic Conductivity (cm/sec)
SB-60-127	127	Silt	ML	0.42	2.01E-03	1.80	0.30	6.93E-05
MW-104-126	126	Fine sand	SM	0.37	7.55E-03	1.95	0.12	8.05E-04
EX-8-129	129	Medium sand	SP	0.45	8.70E-03	2.72	0.03	3.48E-03
MW-101-126	126	Fine sand	SP	0.36	1.69E-02	2.06	0.10	2.20E-03
SB-60-123	123	Medium sand	SP	0.38	5.12E-03	1.95	0.18	7.00E-04
EX-7-123	123	Medium sand	SW	0.34	1.64E-02	1.69	0.13	1.85E-03
EX-8-130.5	131	Medium sand	SW	0.40	1.74E-02	2.17	0.11	3.59E-03
EX-9-127.5	128	Fine sand	SW	0.35	1.25E-02	1.74	0.12	1.22E-03
MW-103-128	128	Fine sand	SW	0.34	1.27E-02	2.41	0.08	2.18E-03
MW-104-132.5	133	Fine sand	SW	0.34	1.72E-02	1.96	0.11	1.68E-03

α van Genuchten alpha parameter

n van Genuchten n parameter

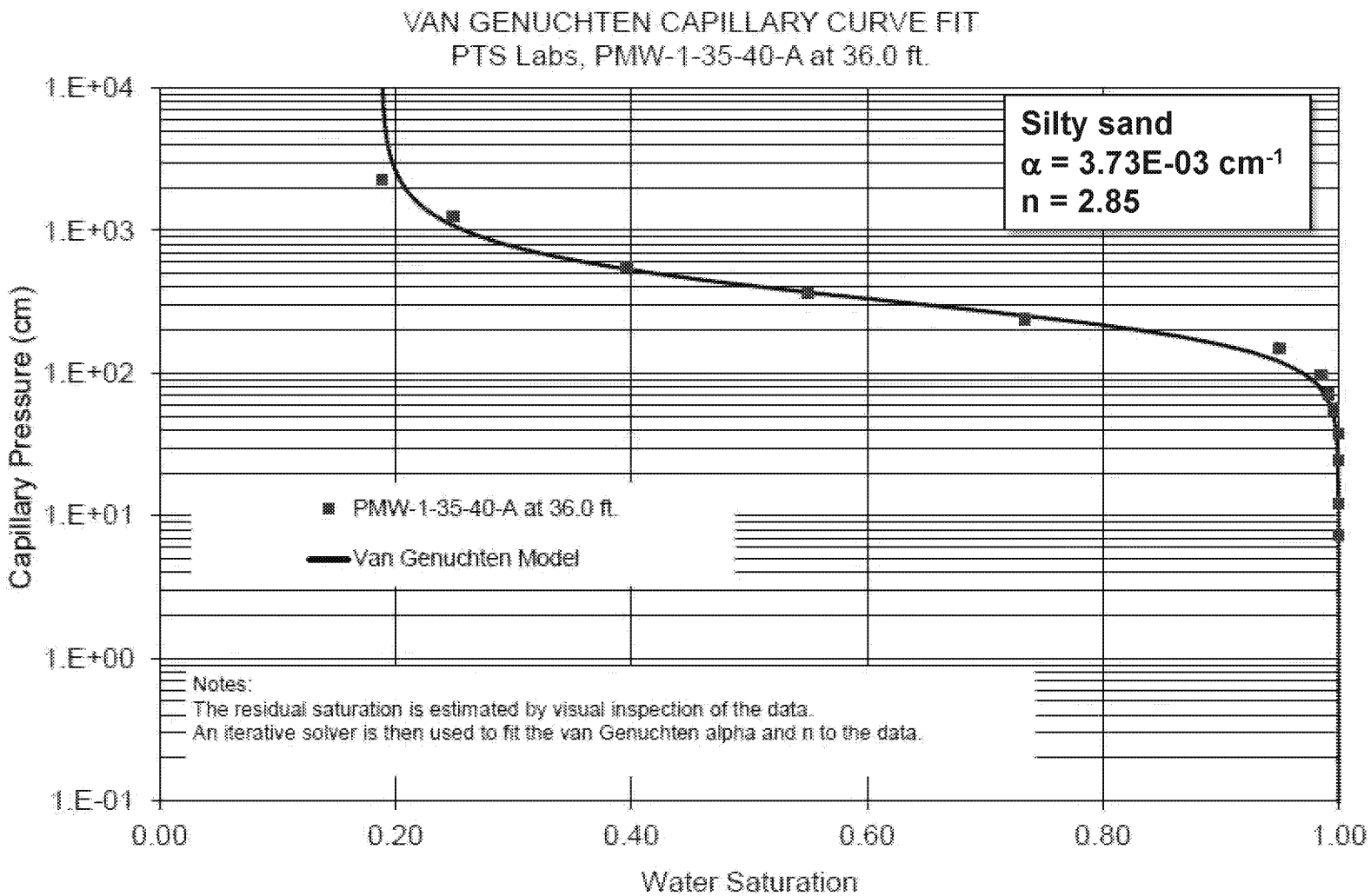
Sr Residual saturation

Additional van Genuchten parameter values are obtained from API database.

van Genuchten Parameters

- van Genuchten equation developed by Martinus Th. Van Genuchten in 1980 to improve on the Brooks-Corey equation at low water saturation values
- Relates water content to capillary pressure in air-water variably-saturated conditions
- Extended to other two-phase systems
  - NAPL-water
  - NAPL-air
- Determined by curve fit to capillary pressure tests
- Relative permeability determined by substituting van Genuchten parameters into Mualem (1976) equation that determines relative permeability to the capillary pressure curve
- Widely used in vadose zone and NAPL model codes

Example van Genuchten Curve Fit and Data



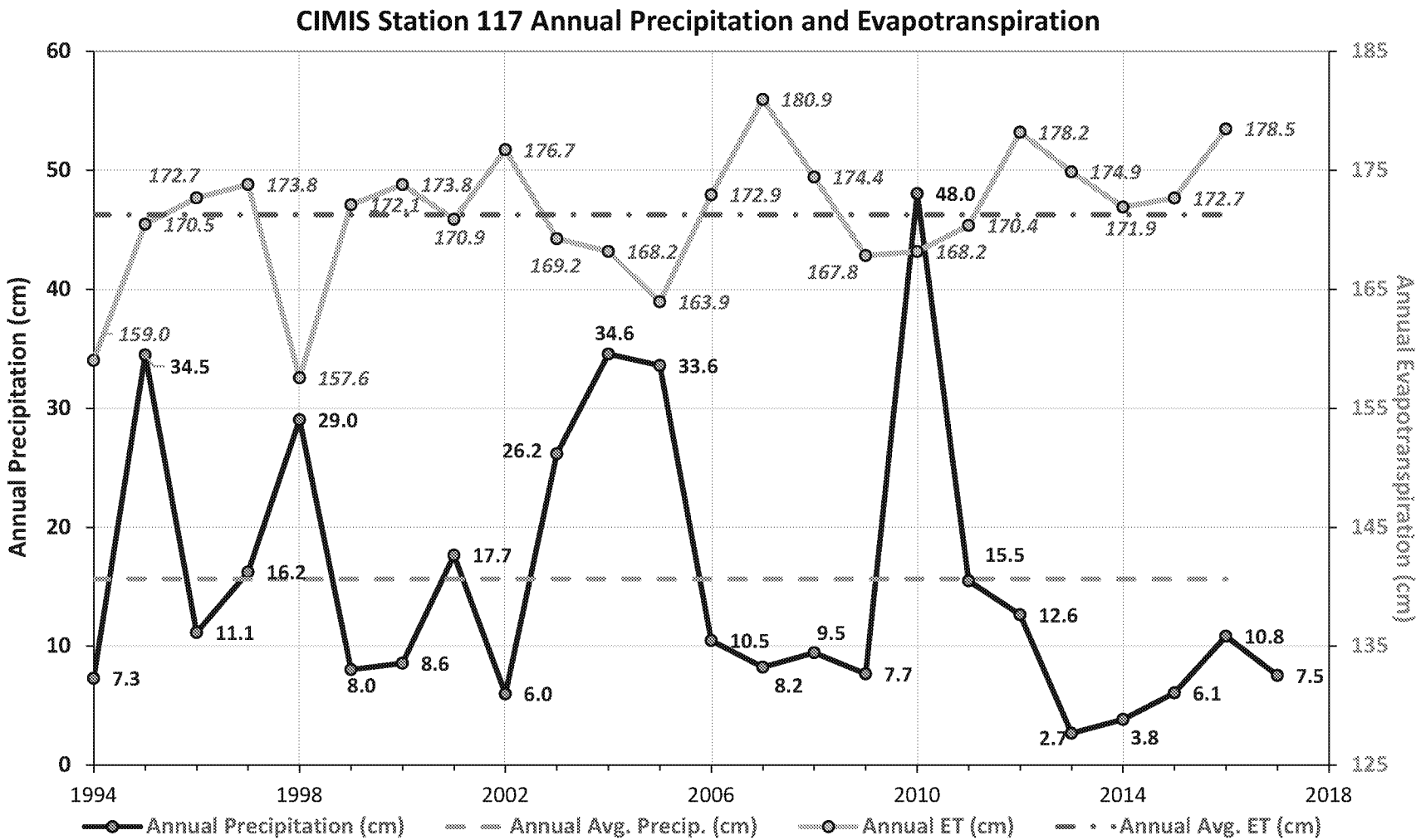
Recharge

Natural and Artificial

Recharge from Precipitation

- Comparing average annual precipitation of 15.7 cm/yr (6.2 in/yr) to average annual evapotranspiration (ET) of 171.3 cm/yr (67.4 in/yr) may lead to erroneous conclusion that recharge is negligible
- Examination of daily data shows that most precipitation events occur in winter when ET is low and highest ET is in summer when precipitation is low
- Hydrus modeling indicates that the annual recharge to the Upper Aquifer water table is ~3 cm/yr (~1 in/yr)
- Multiple precipitation events over a short period of time can generate shallow recharge "pulses" that are smoothed out deeper in vadose zone
- In following slides, flux = volume of water/time period; e.g. cm^2/d = Daily precipitation (cm^3/d)/model width (cm)

CIMIS Station 117 Annual Precipitation



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CIMIS Station 117 Precipitation and Evapotranspiration

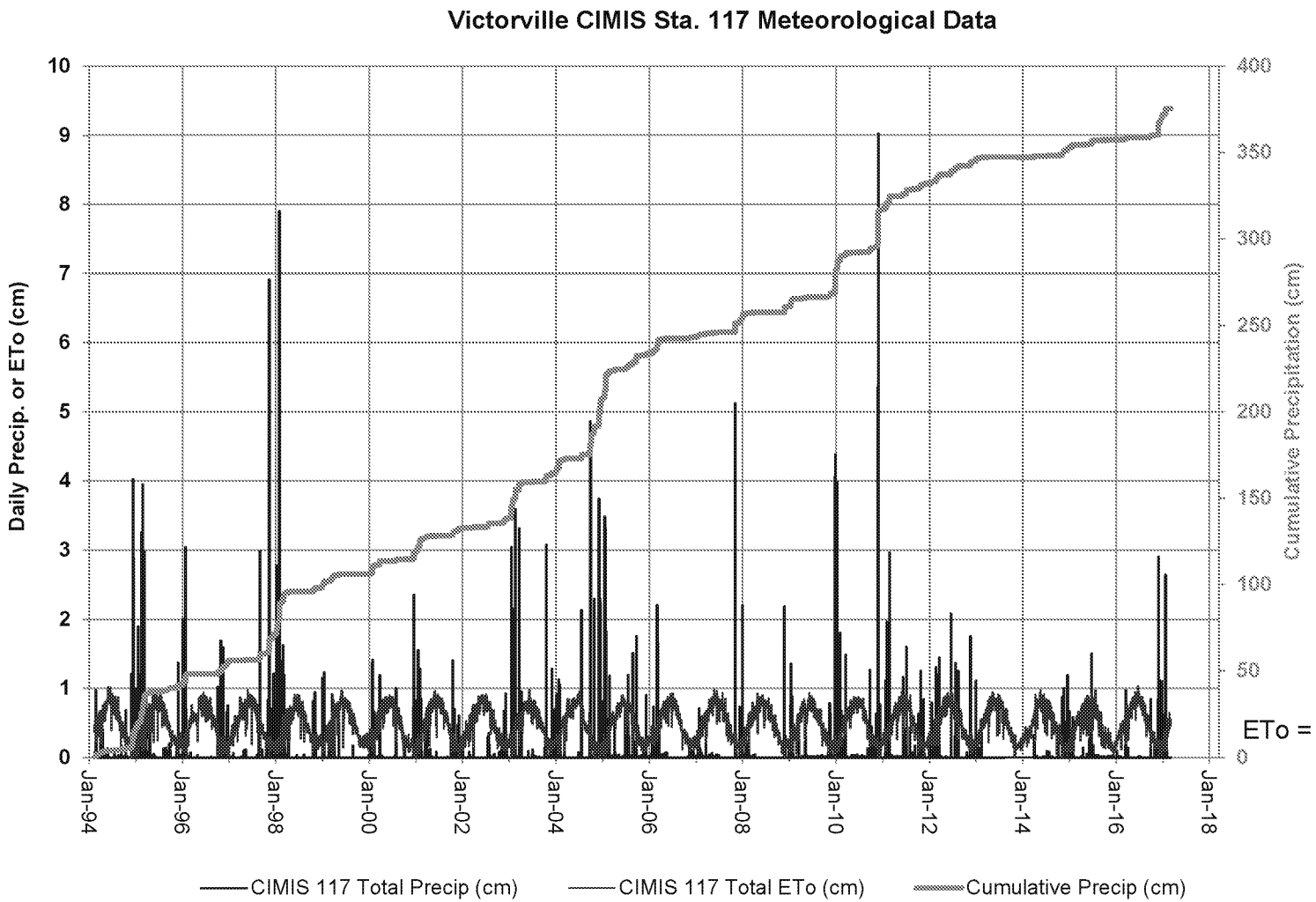
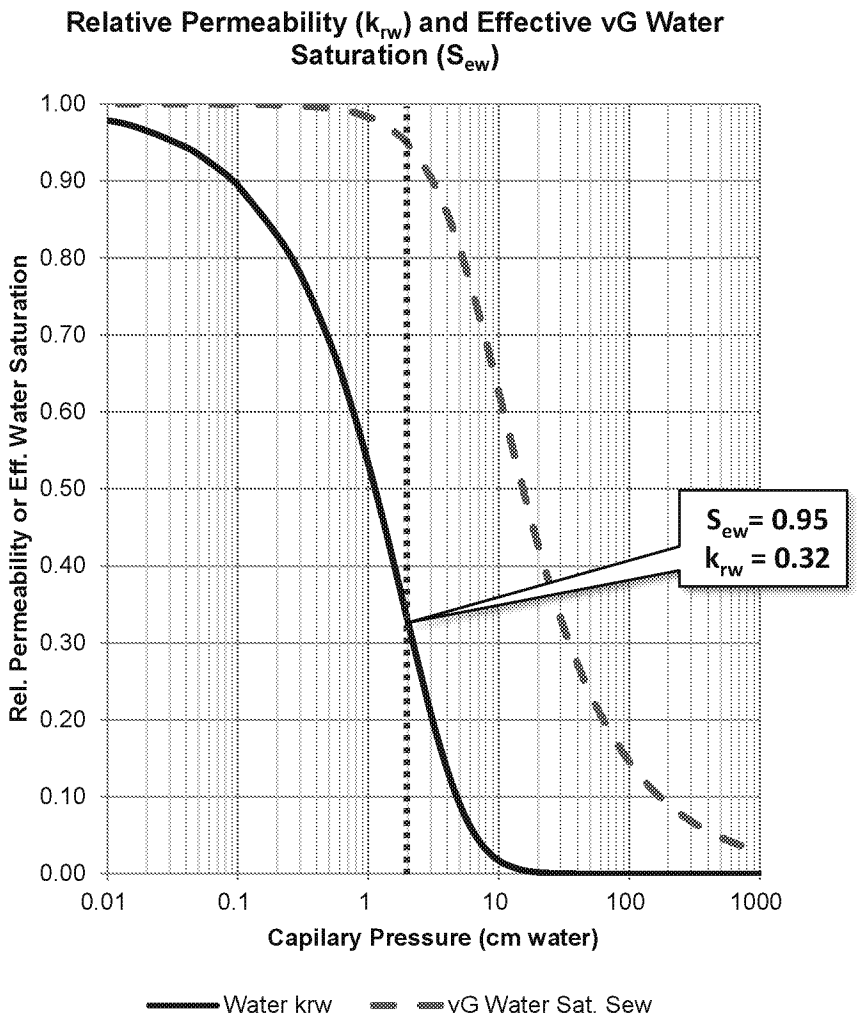


Illustration of How Recharge Propagates thru Subsurface

- **Many factors affect calculated recharge to water table**
  - Precipitation frequency and amounts
  - Season
  - Antecedent soil moisture
  - Daily evapotranspiration
  - Lithology
  - Relative permeability
    - Ratio of effective permeability to saturated permeability, scale 0 to 1, non-linear, function of transient water content
    - Defined by van Genuchten/Mualem, Brooks-Corey, or Kosugi parameters (in Hydrus)



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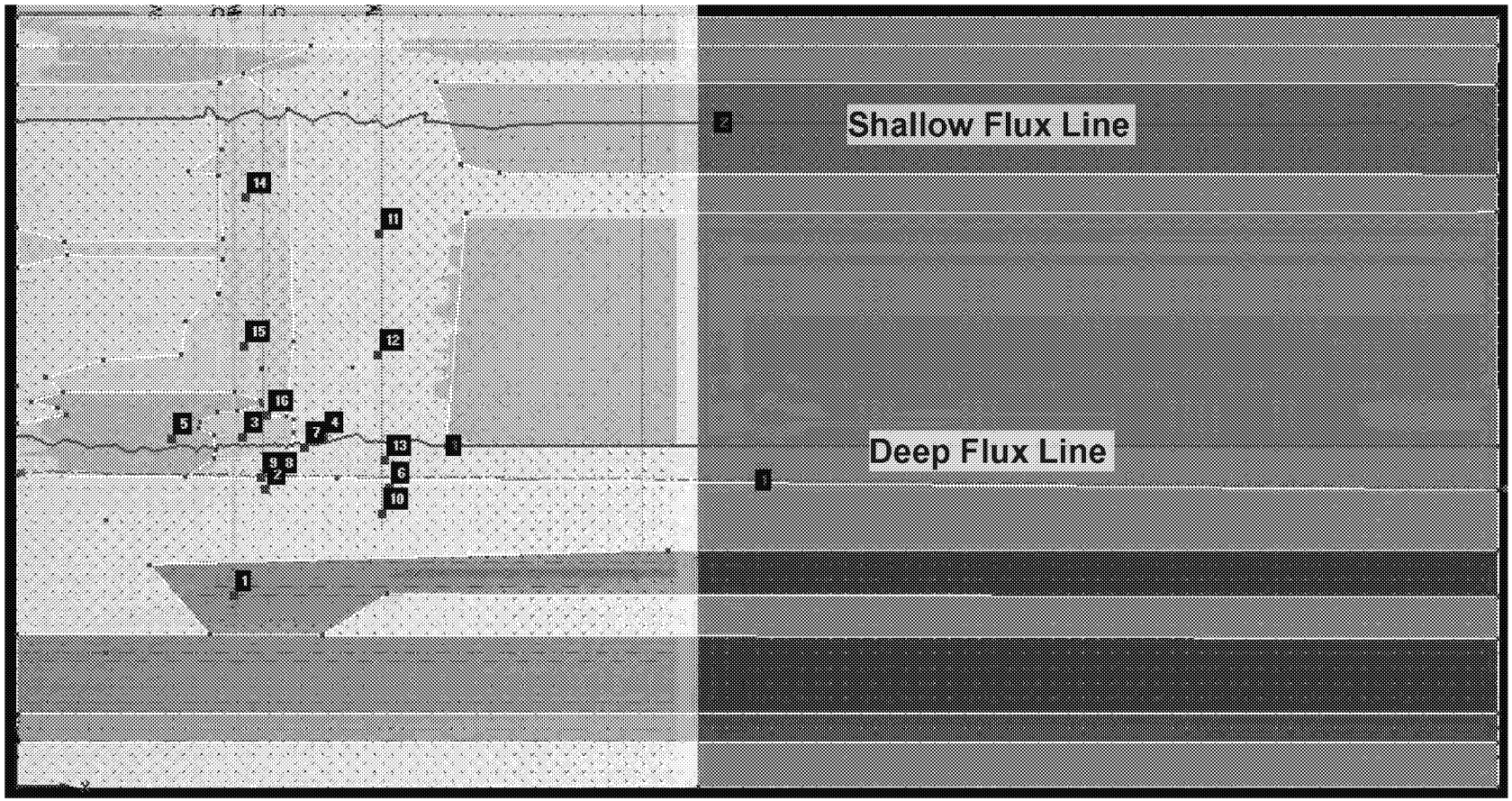
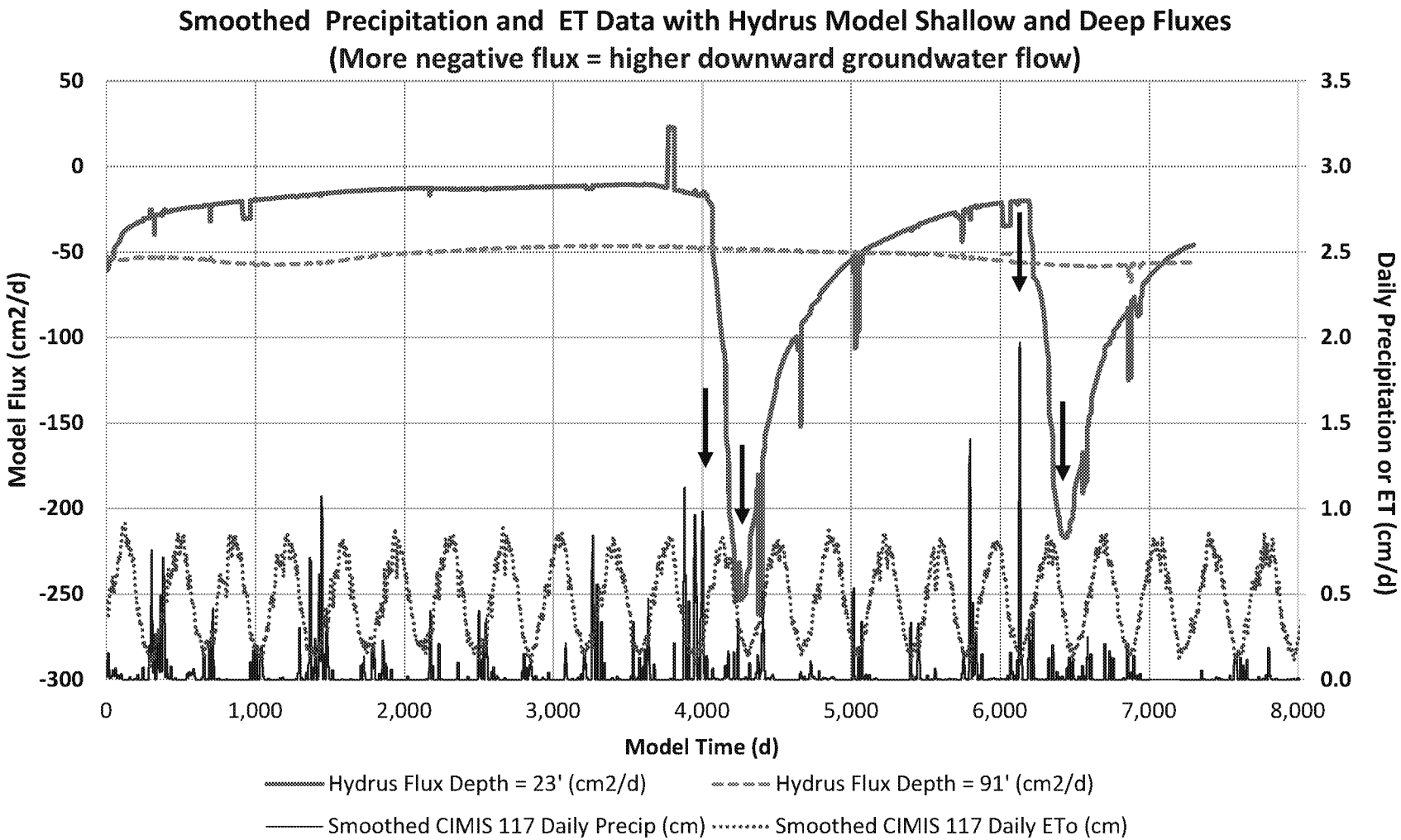
Hydrus Recharge Example

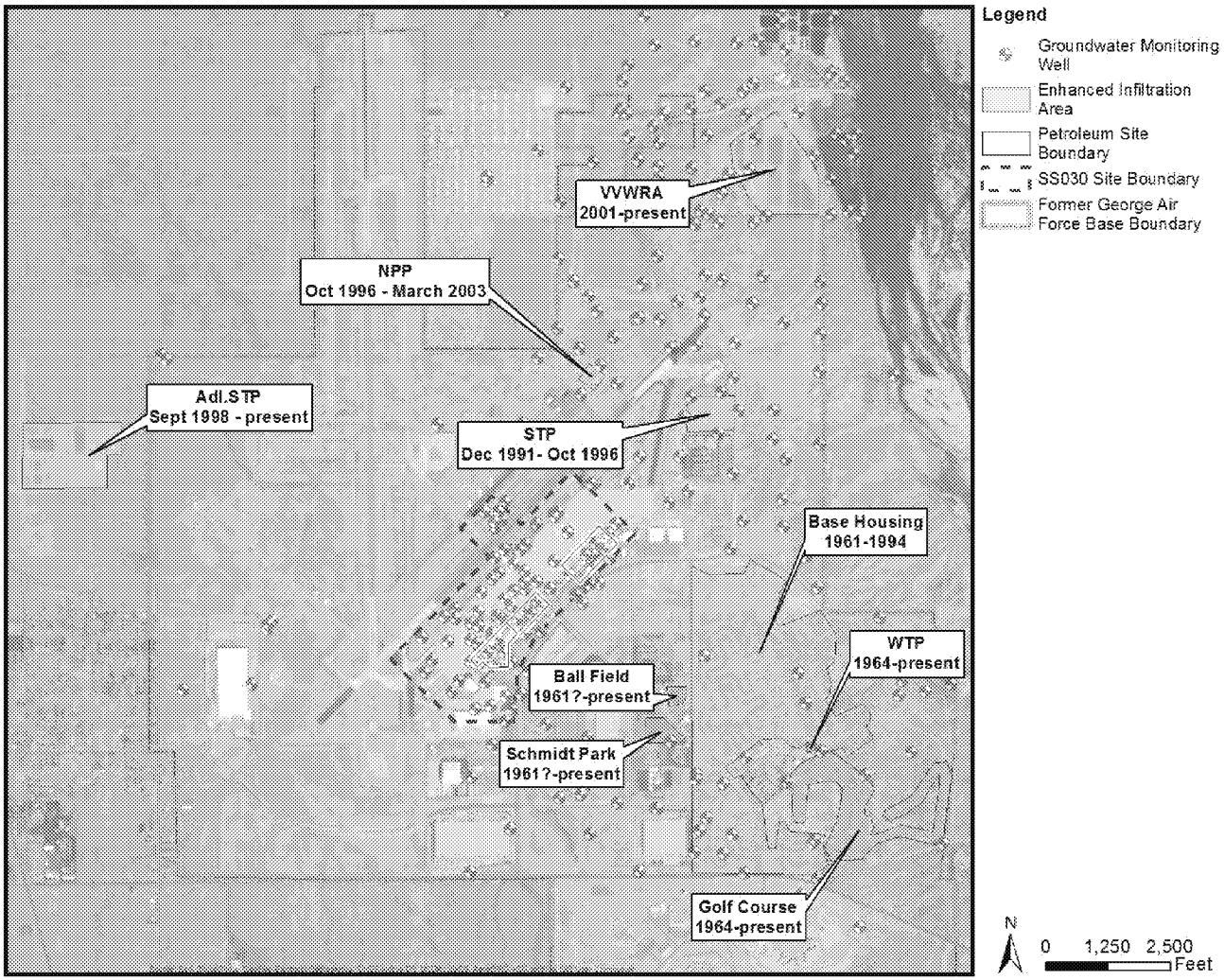


Example from OT051

Precipitation Events Generate Recharge "Pulses" in Hydrus



Enhanced Infiltration Areas

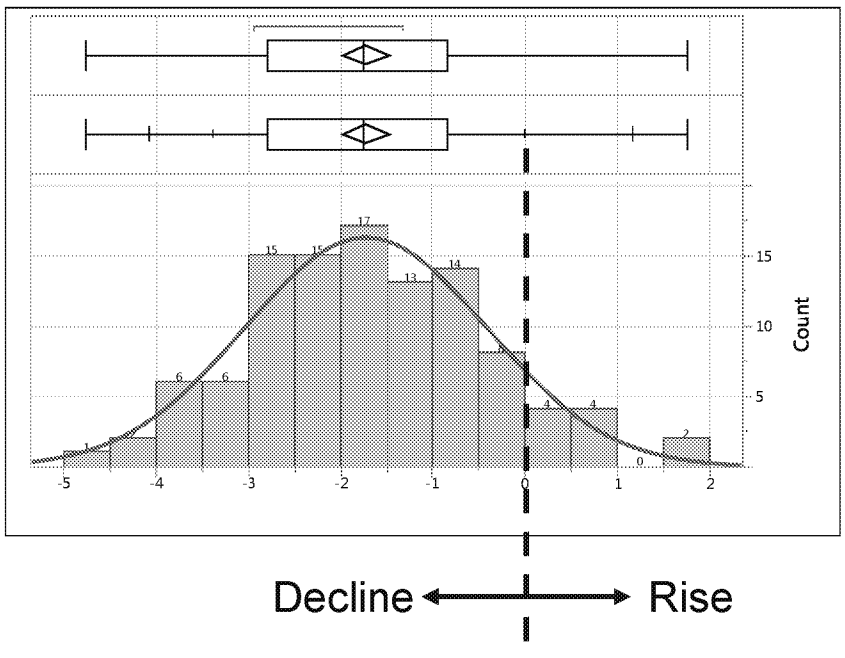


Enhanced Recharge Impacts

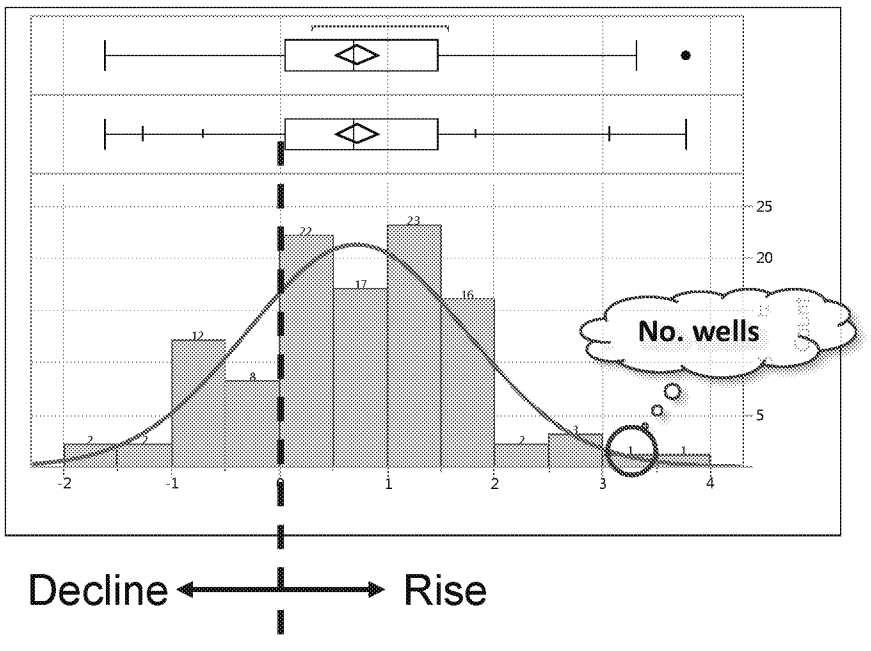
- Upper Aquifer—Major water level impacts on SS030
  - New percolation ponds (NPP)—1996 to 2003
  - Adelanto sewage treatment plan (Adl. STP)—1998 to present
- Upper Aquifer—Major water level impacts on other areas
  - Base housing—1961 to 1994
  - Golf course—1964 to present
  - Golf course/water tower pond—1964 to present
- Upper Aquifer—Minor water level effects
  - Sewage treatment plant (STP)—1991 to 1996
  - Ball field—1961? to present
  - Schmidt Park—1961? to present
- Lower Aquifer—Major water level effects
  - VVWRA ponds—2001 to present
  - Potentially Adelanto sewage treatment plant

SS030 Water Level Changes—1996 to 2016

Change 1996/2003 to 2005/2010

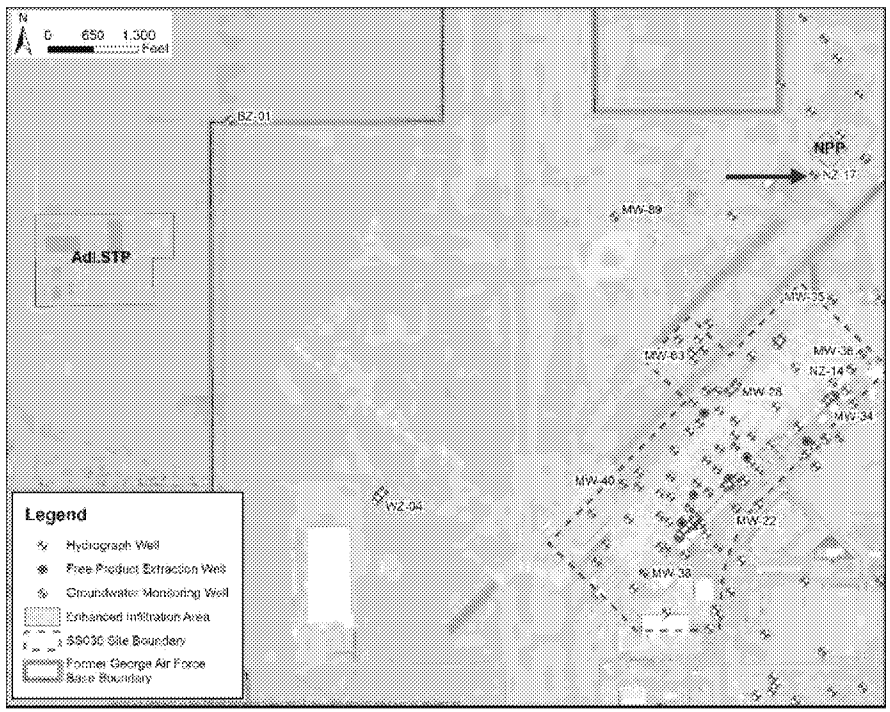


Change 2005/2010 to 2016

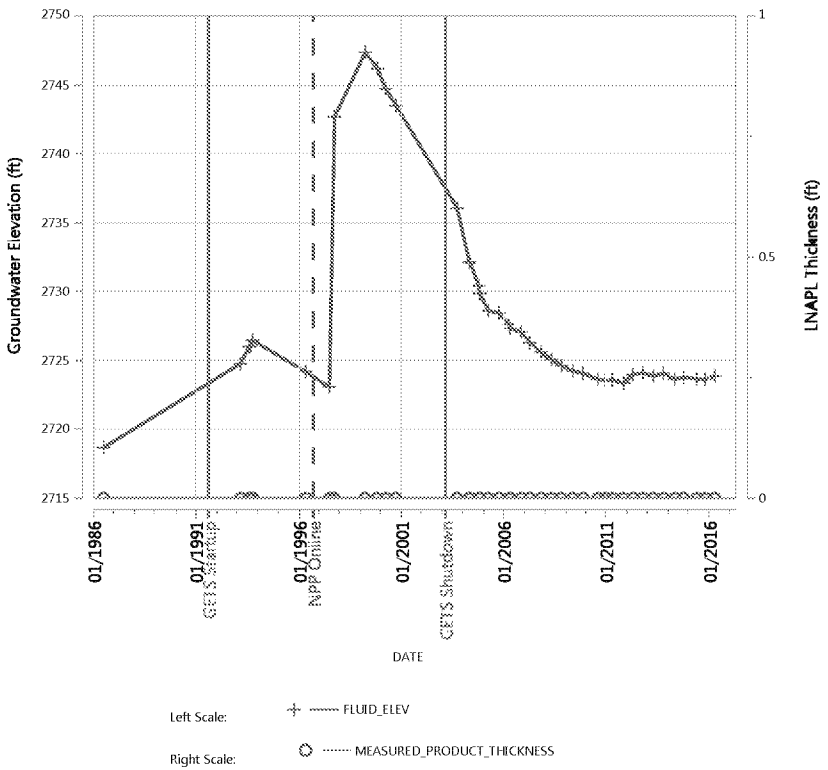


- Positive (+) values represent water level rise
- Negative (-) value represent water level decline
- Range of dates used because of time-lag in water level response from various events

NPP-Related SS030 Water Level Changes

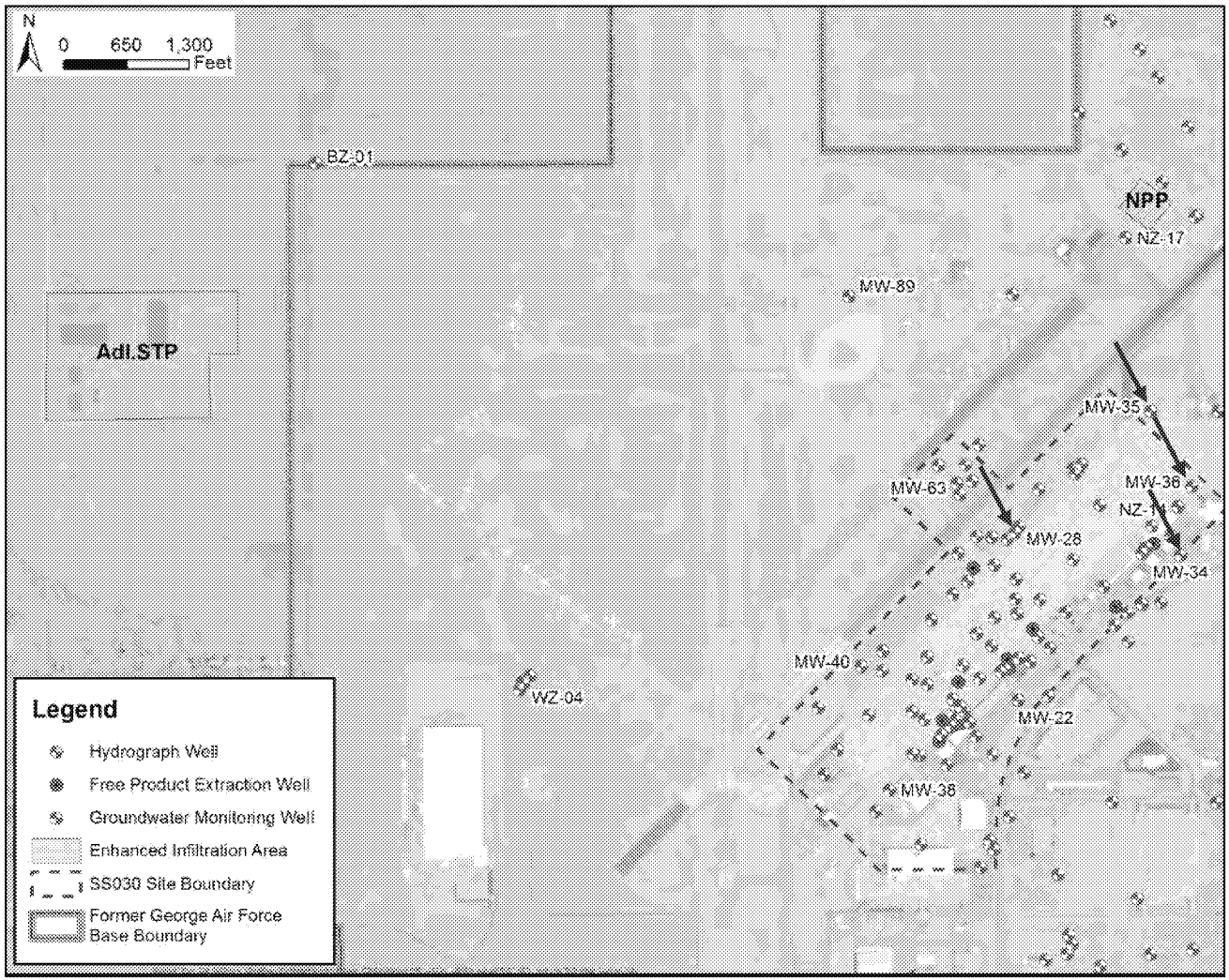


NZ-17 Hydrograph

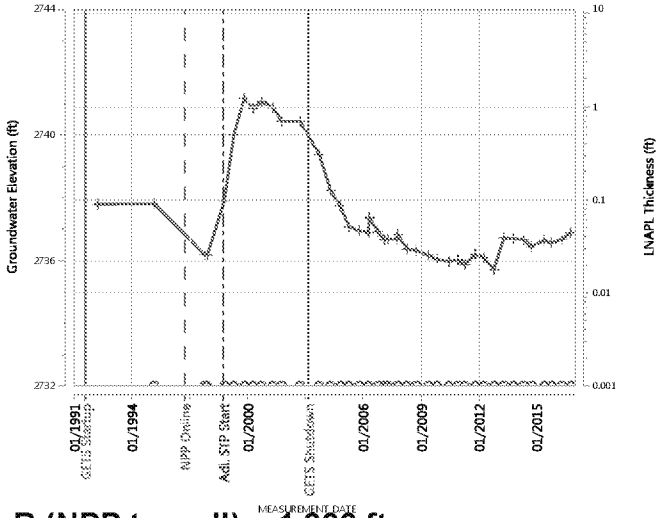


~30-foot rise near ponds

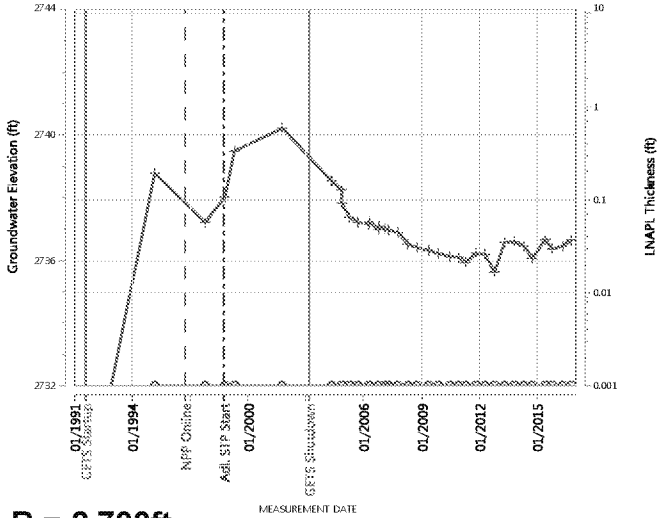
NPP-Related Hydrographs



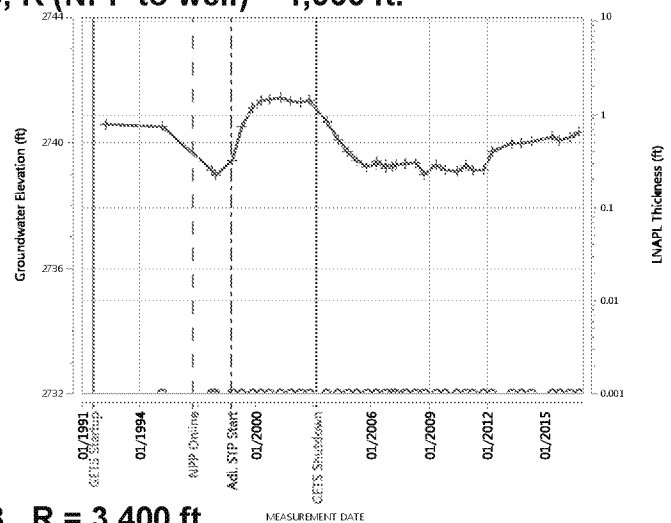
NPP Related Hydrographs



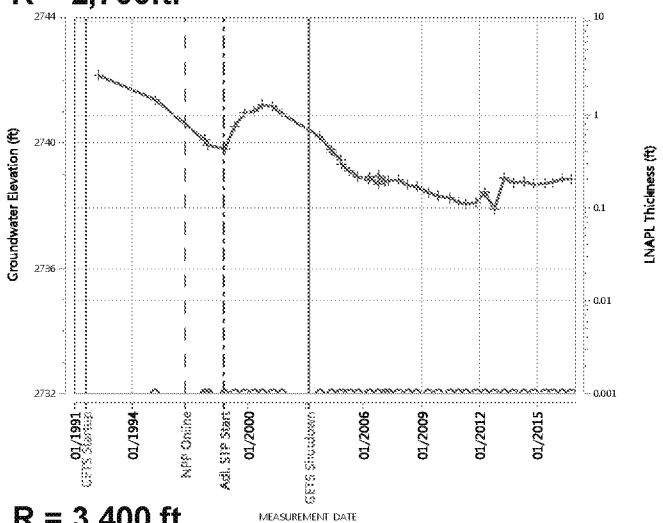
MW-35, R (NPP to well) = 1,900 ft.



MW-36, R = 2,700ft.



MW-28 , R = 3,400 ft.



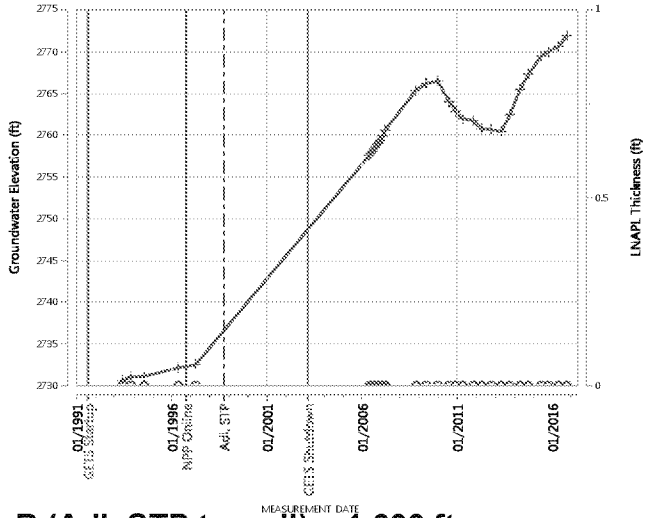
MW-34, R = 3,400 ft.

Impact of Adelanto STP Infiltration on Upper Aquifer

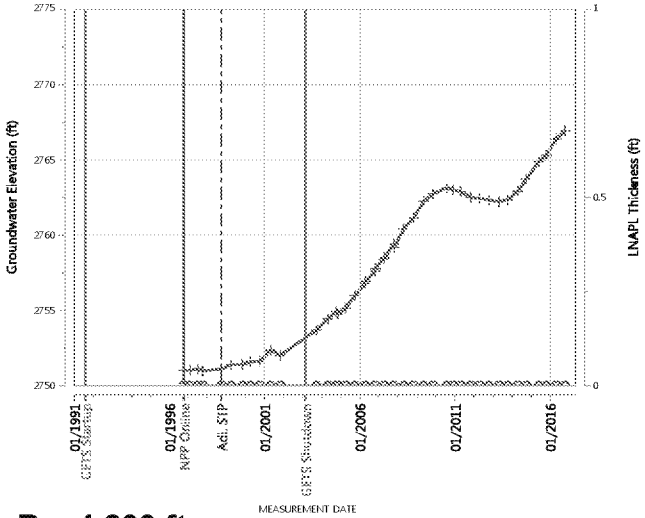
- Water levels have risen 40+ feet on west side of GAFB with gradient away from ponds (0.005, rise extends ~ mile)
- Water levels have risen 3 to 5 feet at south end of SS030
- No obvious rise at north end of SS030
- Major impact on groundwater gradient across SS030
  - 0.0016 to northeast in 2000
  - 0.0017 to east/northeast in 2003
  - 0.0022 to east/northeast in 2005
  - 0.0034 to northeast in 2010
  - 0.0043 to east/northeast in 2016
- Used 2016 gradient in Hydrus modeling

Hydrographs Illustrating Impact of Adelanto STP on Water Levels

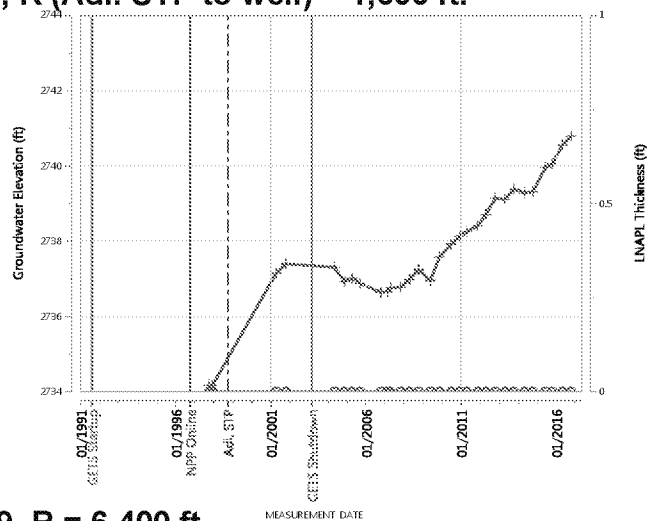
Adelanto Sewage Treatment Plant Hydrographs



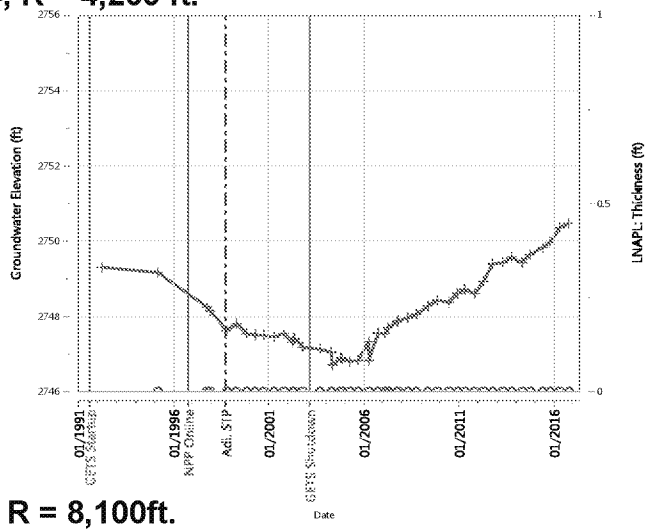
BZ-01, R (Adl. STP to well) = 1,600 ft.



WZ-04, R = 4,200 ft.

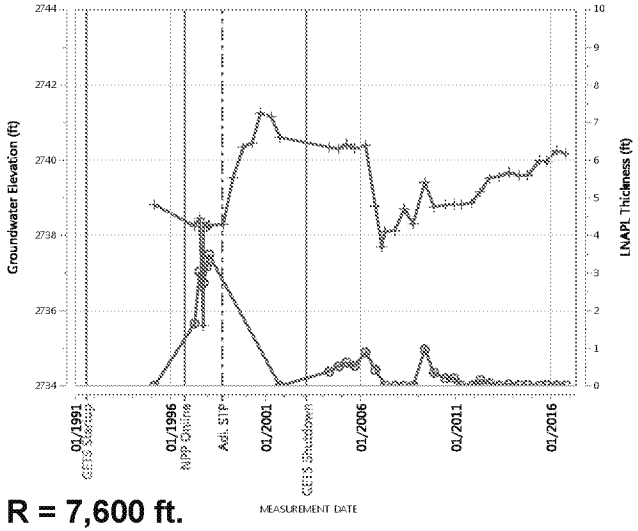


MW-89, R = 6,400 ft.

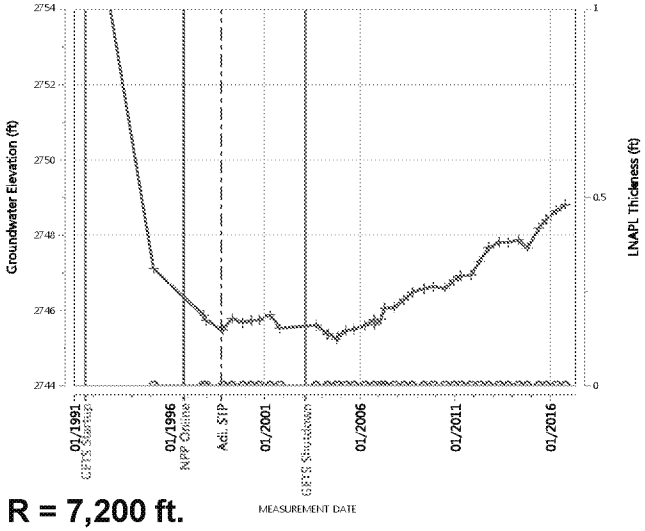


MW-38, R = 8,100ft.

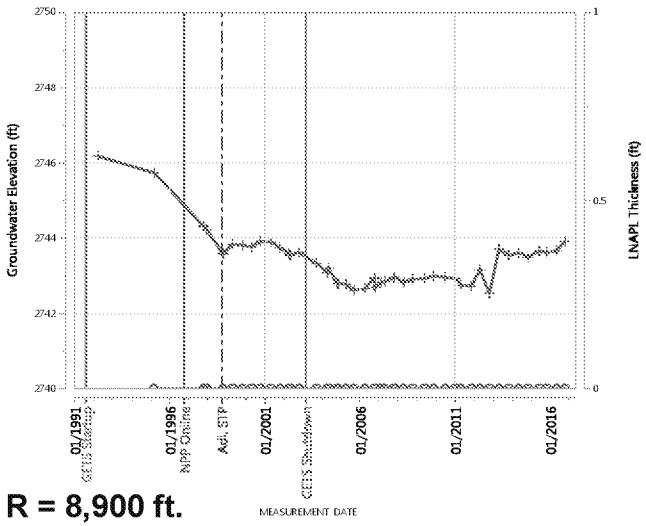
Adelanto Sewage Treatment Plant Hydrographs—2



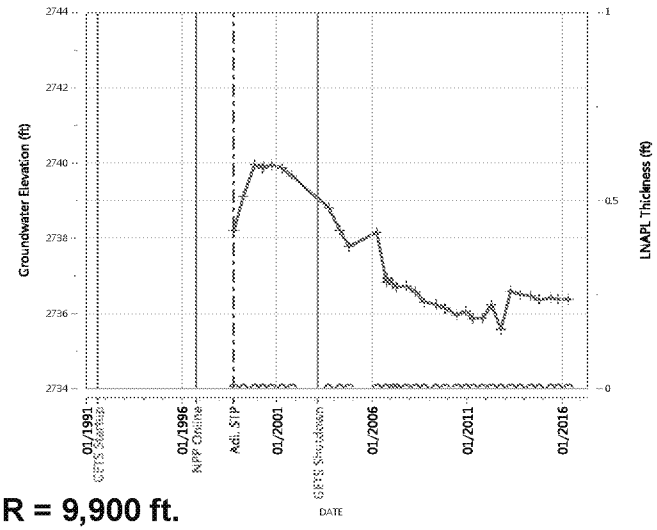
MW-63, R = 7,600 ft.



MW-40, R = 7,200 ft.



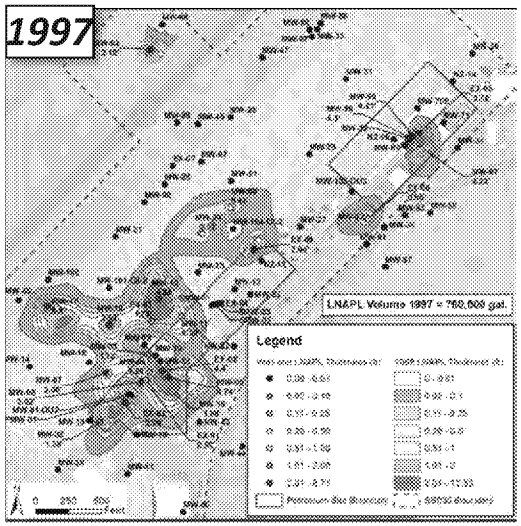
MW-22, R = 8,900 ft.

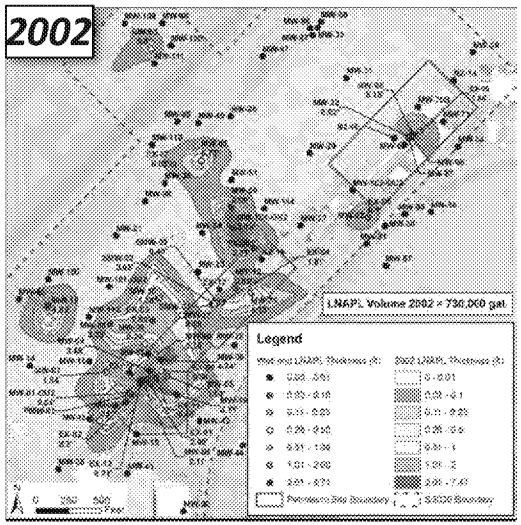


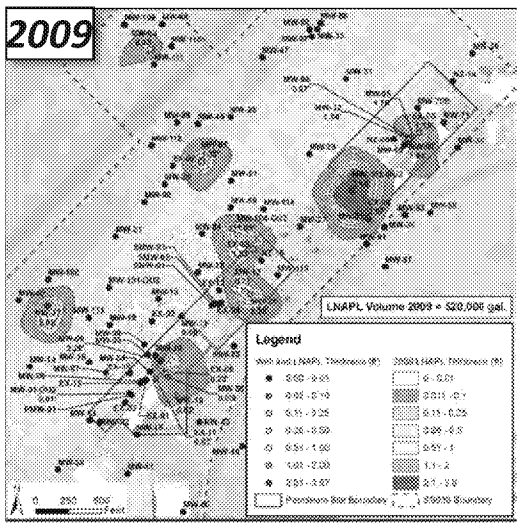
NZ-14, R = 9,900 ft.

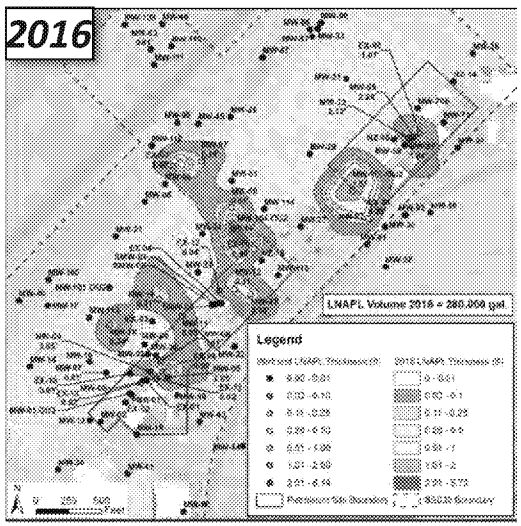
SS030 LNAPL Plume

SS030 LNAPL Thickness over Time

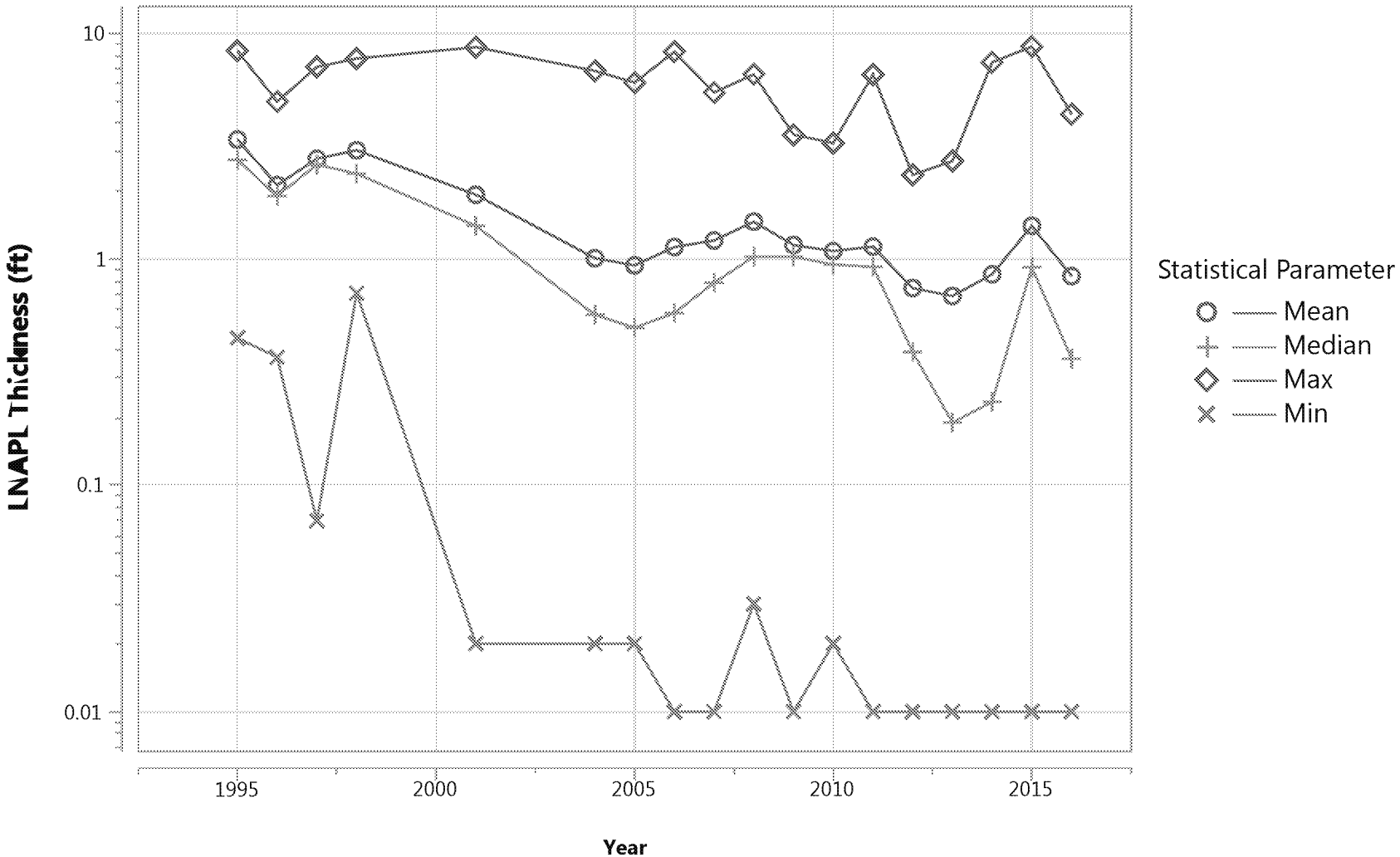








LNAPL Thickness Over Time (LNAPL wells only)



LNAPL Volume Update

- Historical volume calculations
  - 832,000 gallons in 1998 (using 1997 data) vs 2.3 million gallons in 2002 vs 2.1 million gallons in 2009
  - All three using same basic LNAPL specific volume and kriging methods
  - 1998 calculations used site-specific van Genuchten parameter values while 2002 and 2009 calculations used literature values
- 2016 Re-estimate
  - van Genuchten parameters
    - Site-specific values for SW & SP sands, silty sand, and silt
    - API database values for clays and clayey sands
  - Updated and consistent lithology along Upper Aquifer water table
  - Same basic specific volume (LDRM) and kriging routines as previous estimates
  - 10' spacing point grid GIS methods instead of contour-area interpolations for volume calculations

LNAPL Volume and Mobility Variables

van Genuchten-Mualem Model of LNAPL Distribution and Relative Permeability

Enter Data in Yellow Region

Maximum Monitoring Well LNAPL Thickness [feet]	
b_o =	3.000

Soil Characteristic		
n =	0.420	porosity
N =	2.060	van Genuchten "N"
α =	1.240	van Genuchten "α" [ft^{-1}]
S_{wr} =	0.240	irreducible water saturation
S_{orv} =	0.050	residual LNAPL saturation (vadose)
S_{ors} =	0.110	residual LNAPL saturation (saturated)

Different values for each soil type

Fluid Characteristics:		
ρ_o =	0.790	LNAPL density [gm/cc]
σ_{aw} =	71.000	air/water surface tension [dyne/cm]
σ_{ao} =	24.000	air/LNAPL surface tension [dyne/cm]
σ_{ow} =	28.000	LNAPL/water surface tension [dyne/cm]

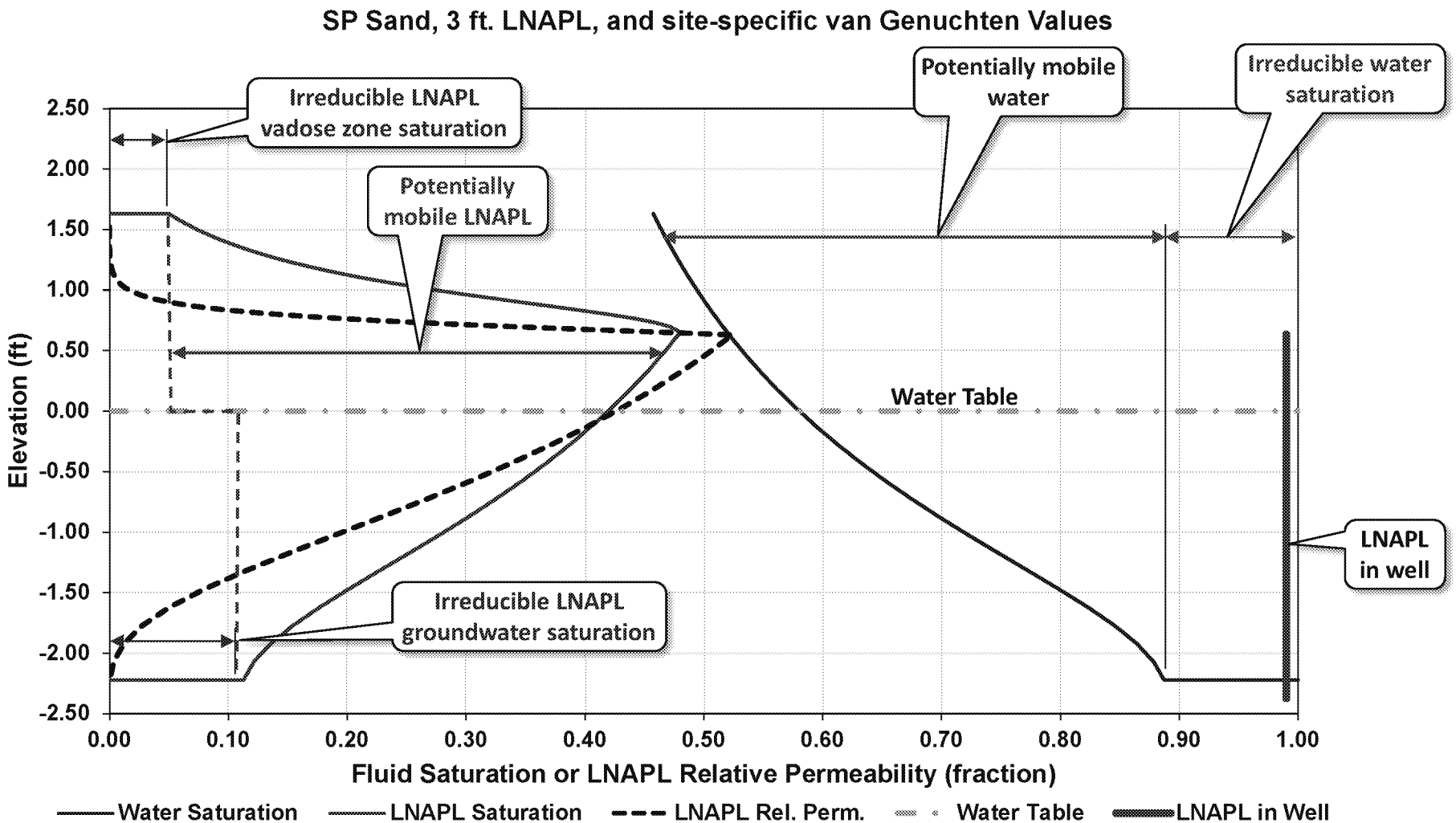
Calculated Parameters		
M =	0.515	van Genuchten "M"
α_{ao} =	2.898	air/LNAPL "α" [ft^{-1}]
α_{ow} =	0.660	LNAPL/water "α" [ft^{-1}]
z_{ao} =	0.630	elevation of air-LNAPL interface [ft]
z_{ow} =	-2.370	elevation of LNAPL-water interface [ft]
z_{max} =	1.630	maximum free-product elevation [ft]
λ =	0.784	pore-size distribution index
ψ_c =	0.502	B-C displacement pressure head [ft]

Data from site-specific capillarity tests preferable or API database

Set Tools> Op "Manual."

Press Ctrl+Shift

LNAPL Saturation Curves



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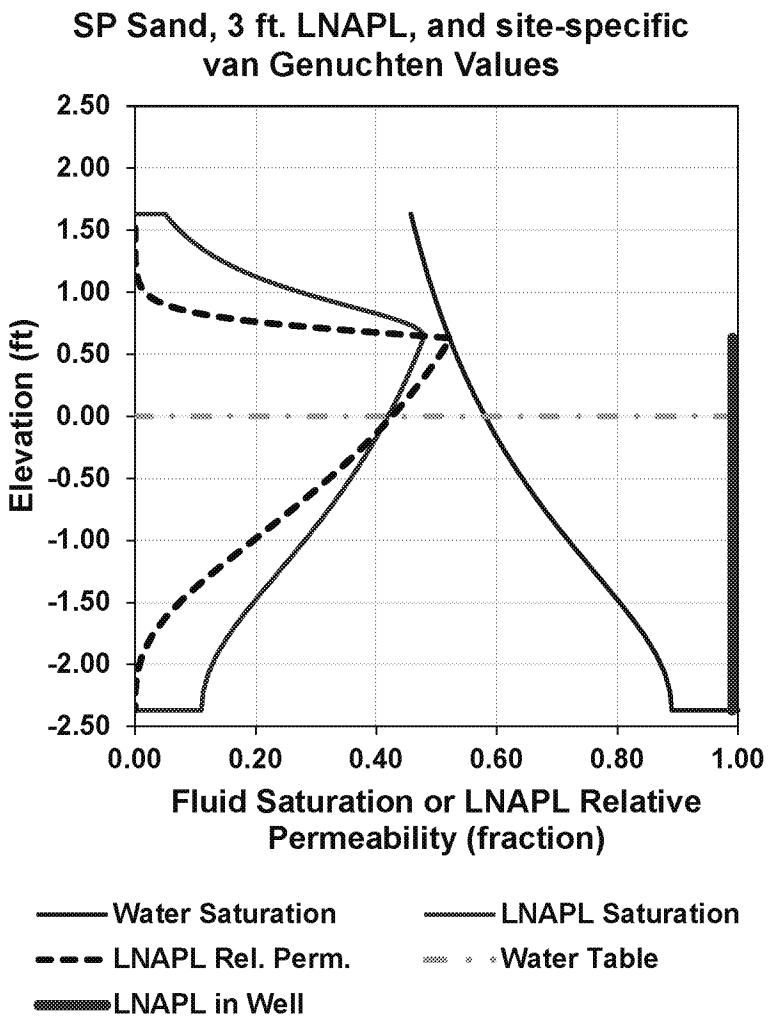
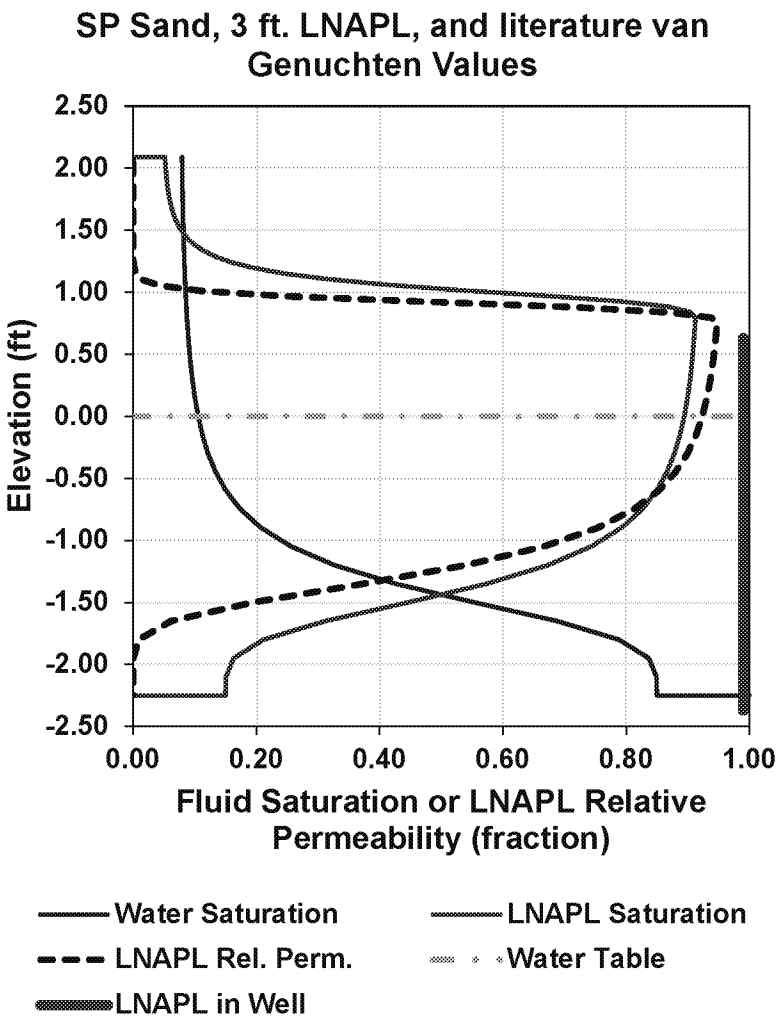
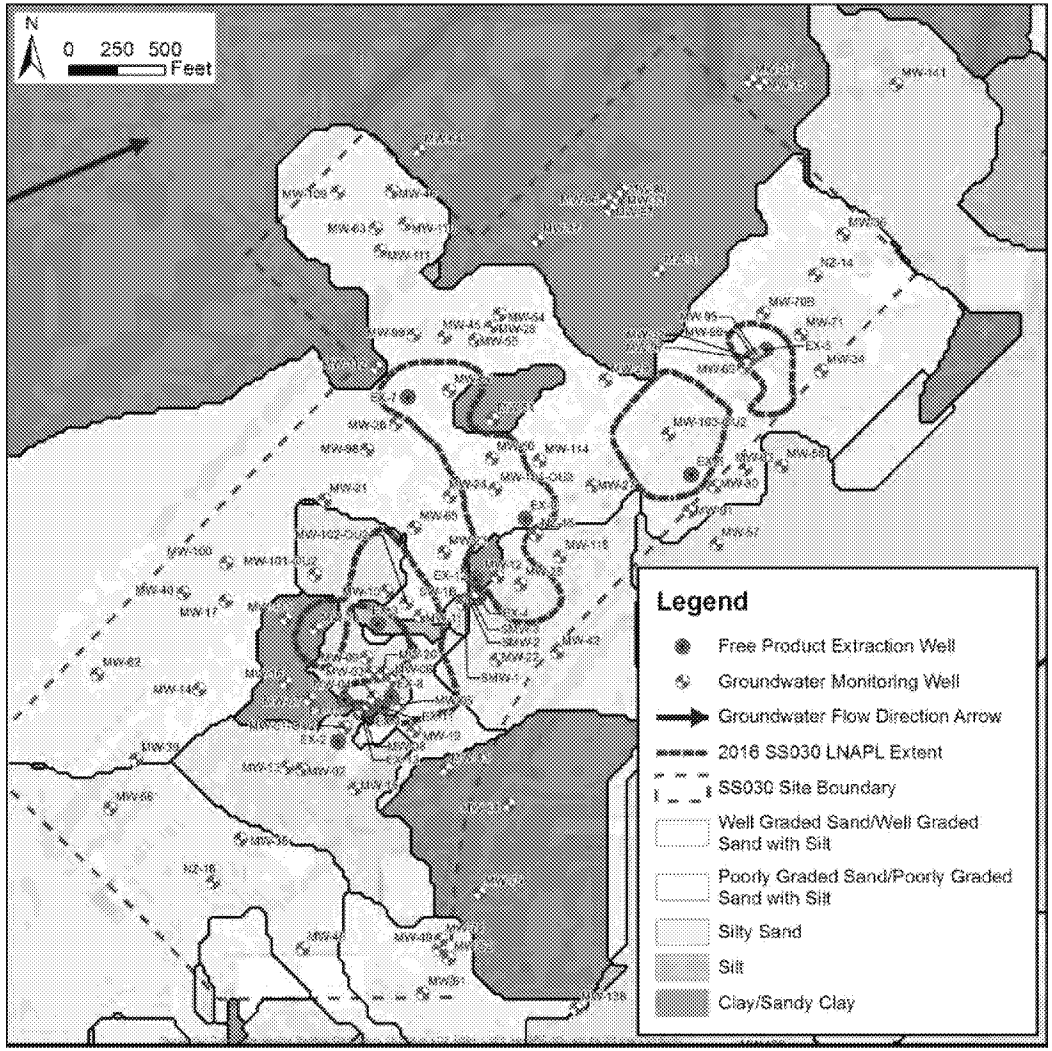
Difference in LNAPL Saturation: Site vs Literature van Genuchten Values

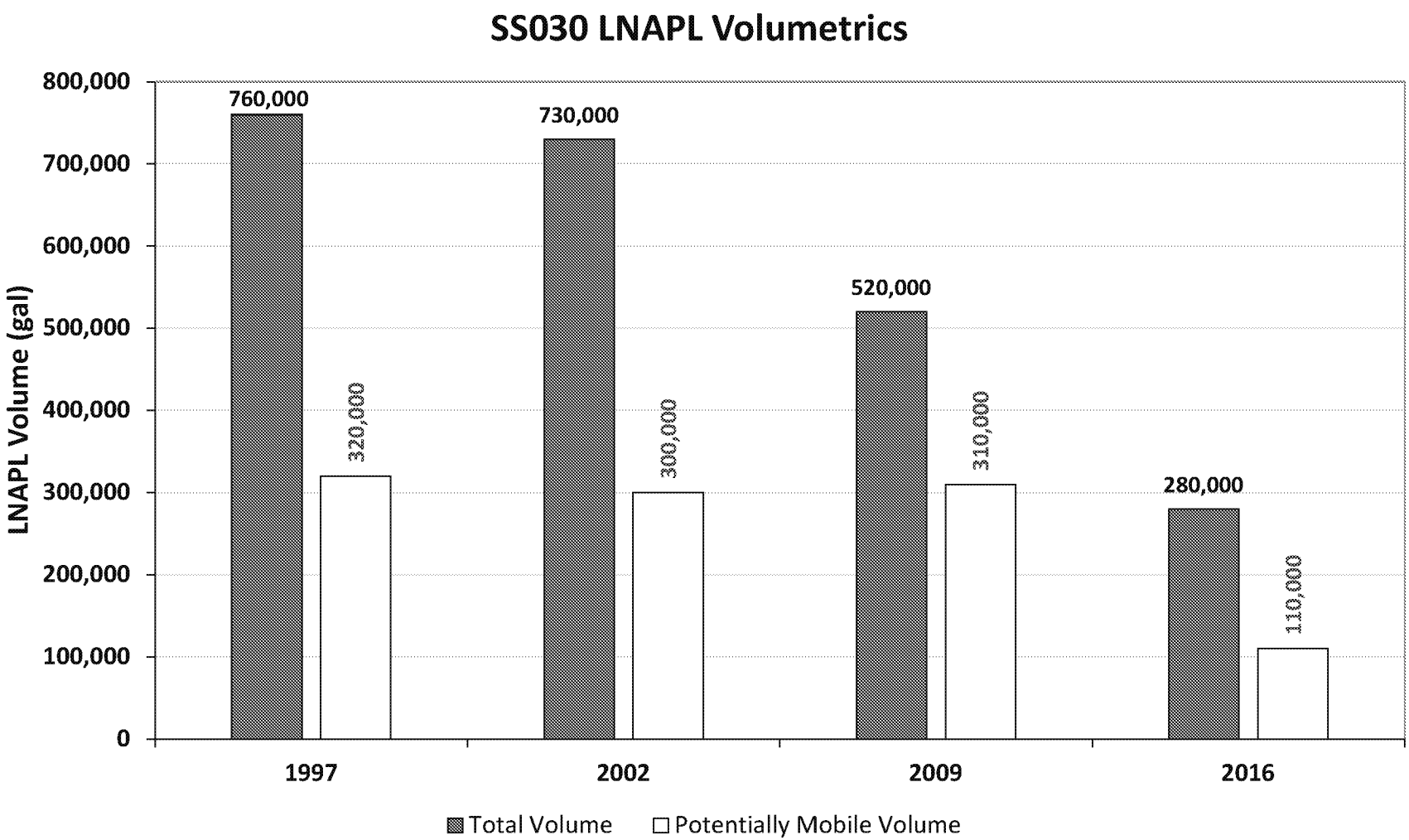




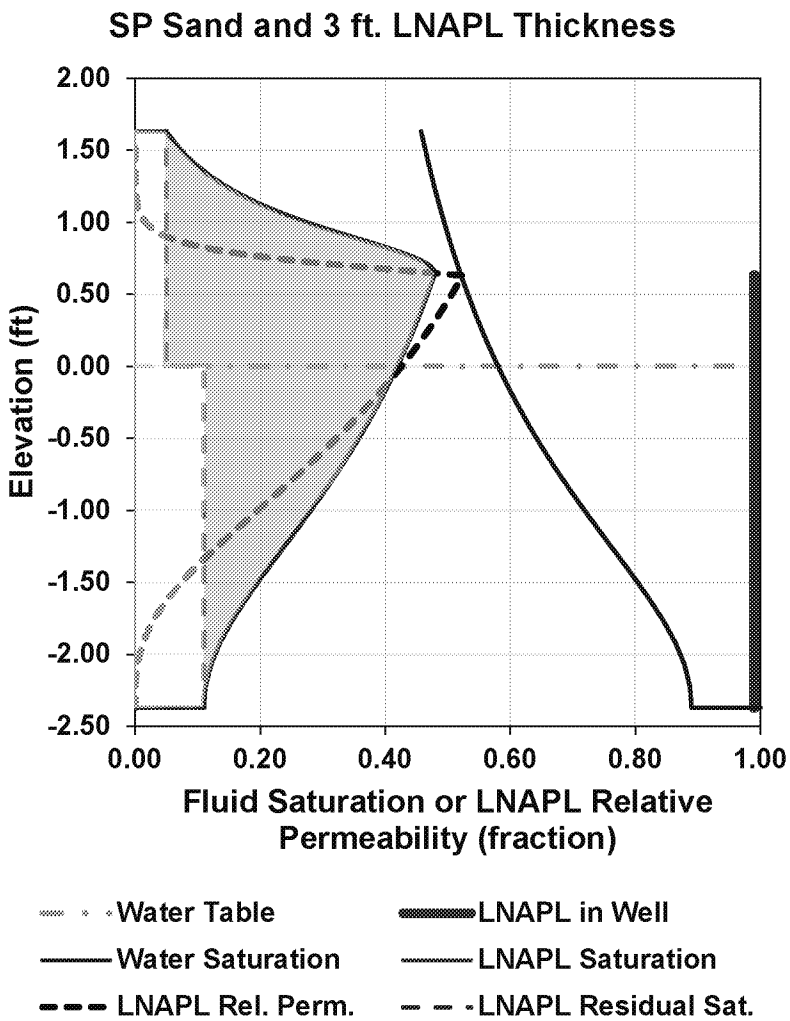
Lithology at Upper Aquifer Water Table

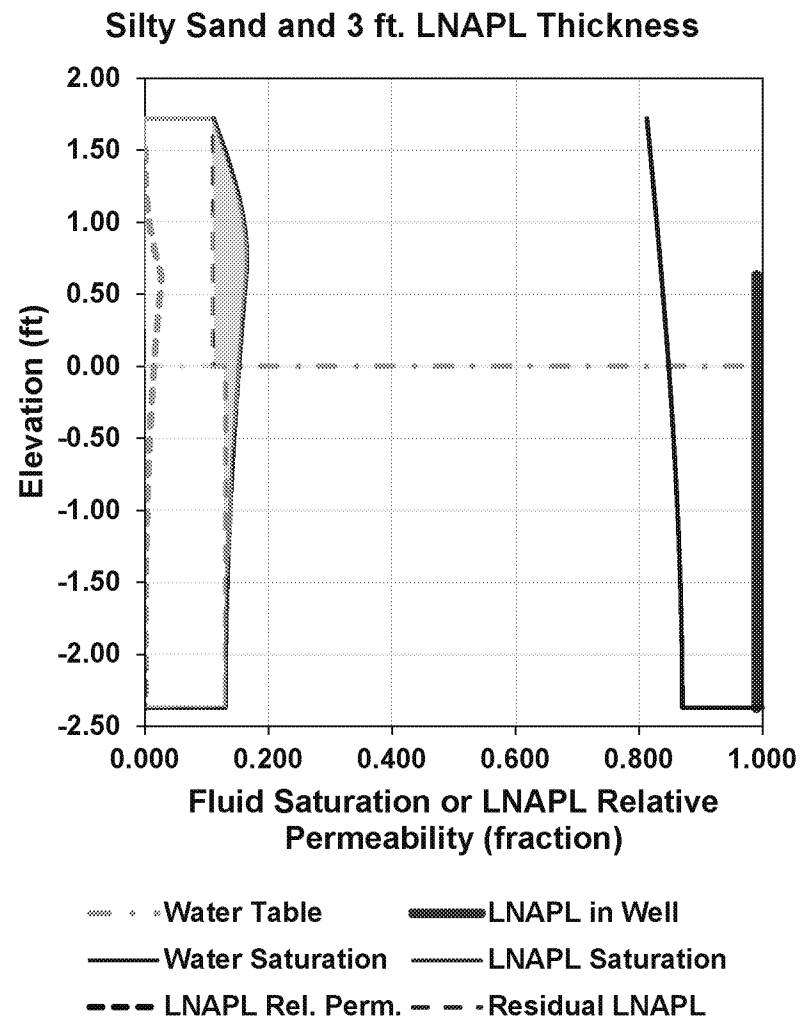


2016 SS030 LNAPL Volume Estimates

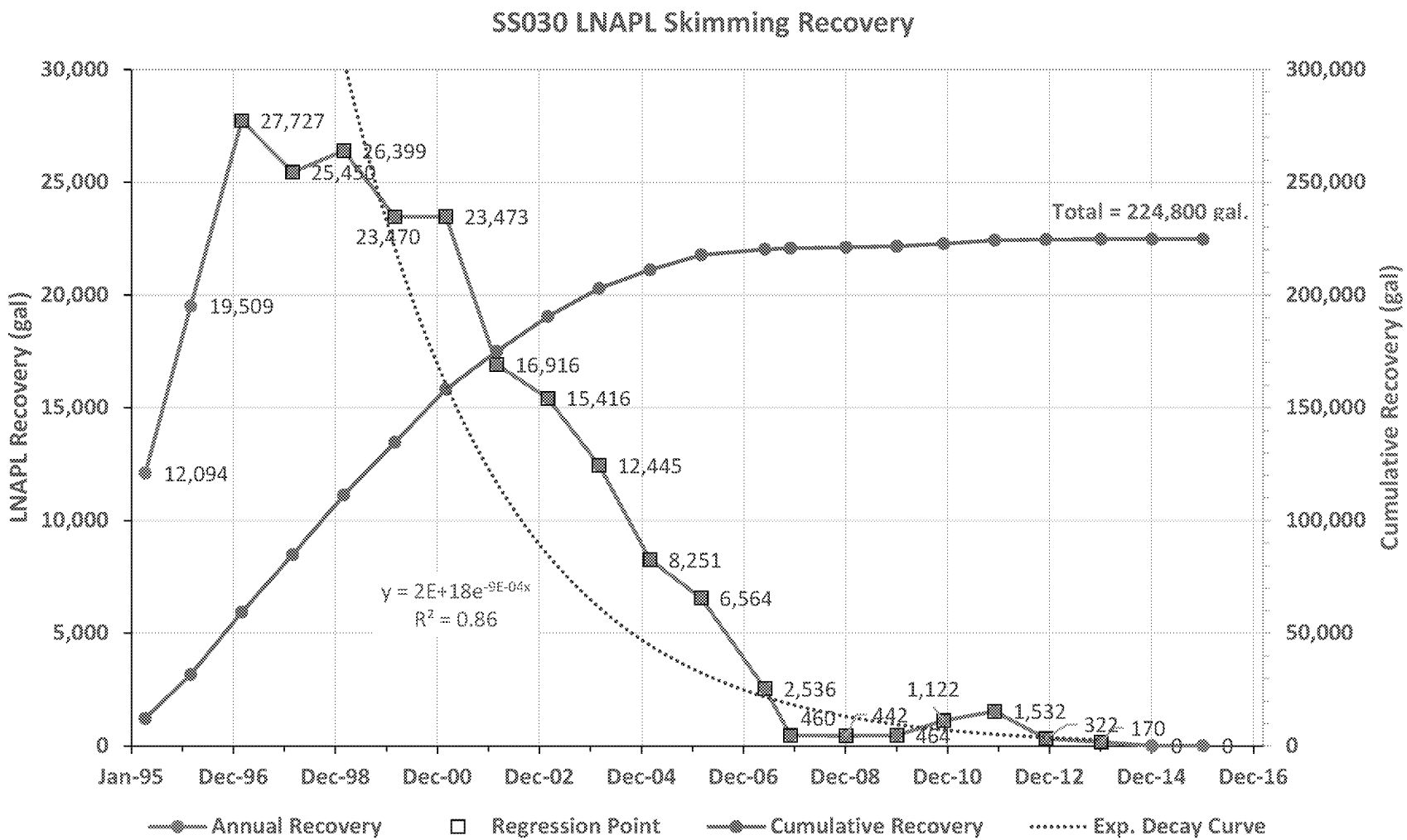


Difference in LNAPL Saturation: Site vs Literature van Genuchten Values





SS030 LNAPL Skimming Mass Recovery



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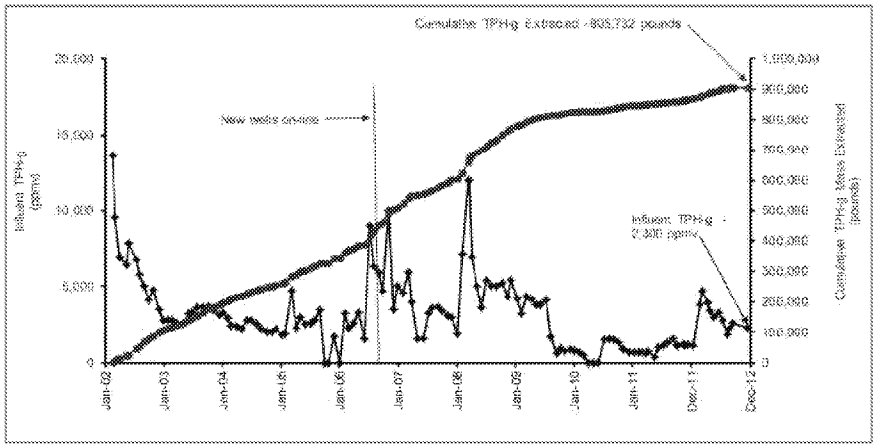
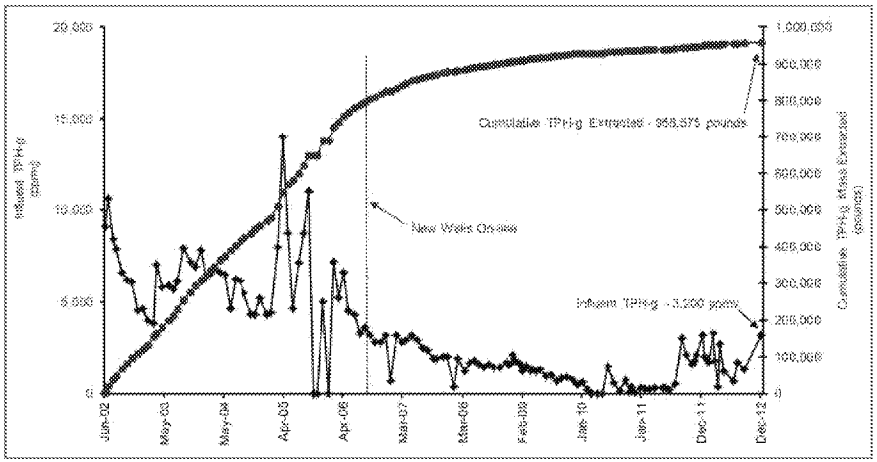
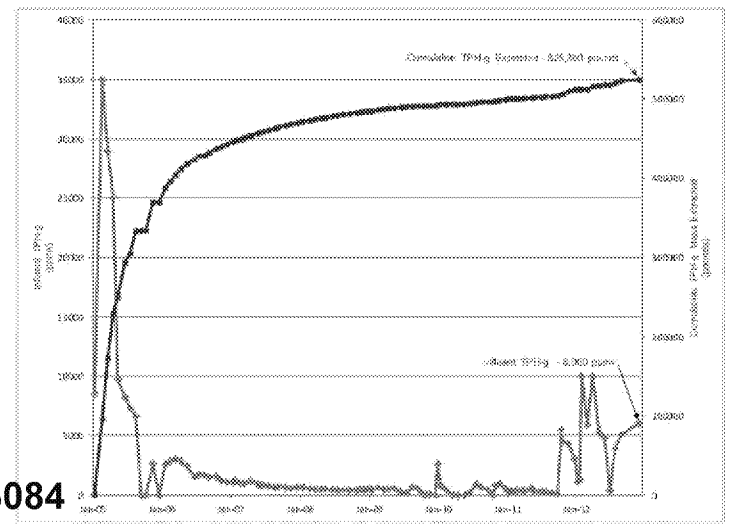
SVE Mass Recovery—Mostly LNAPL



ST054



ST057



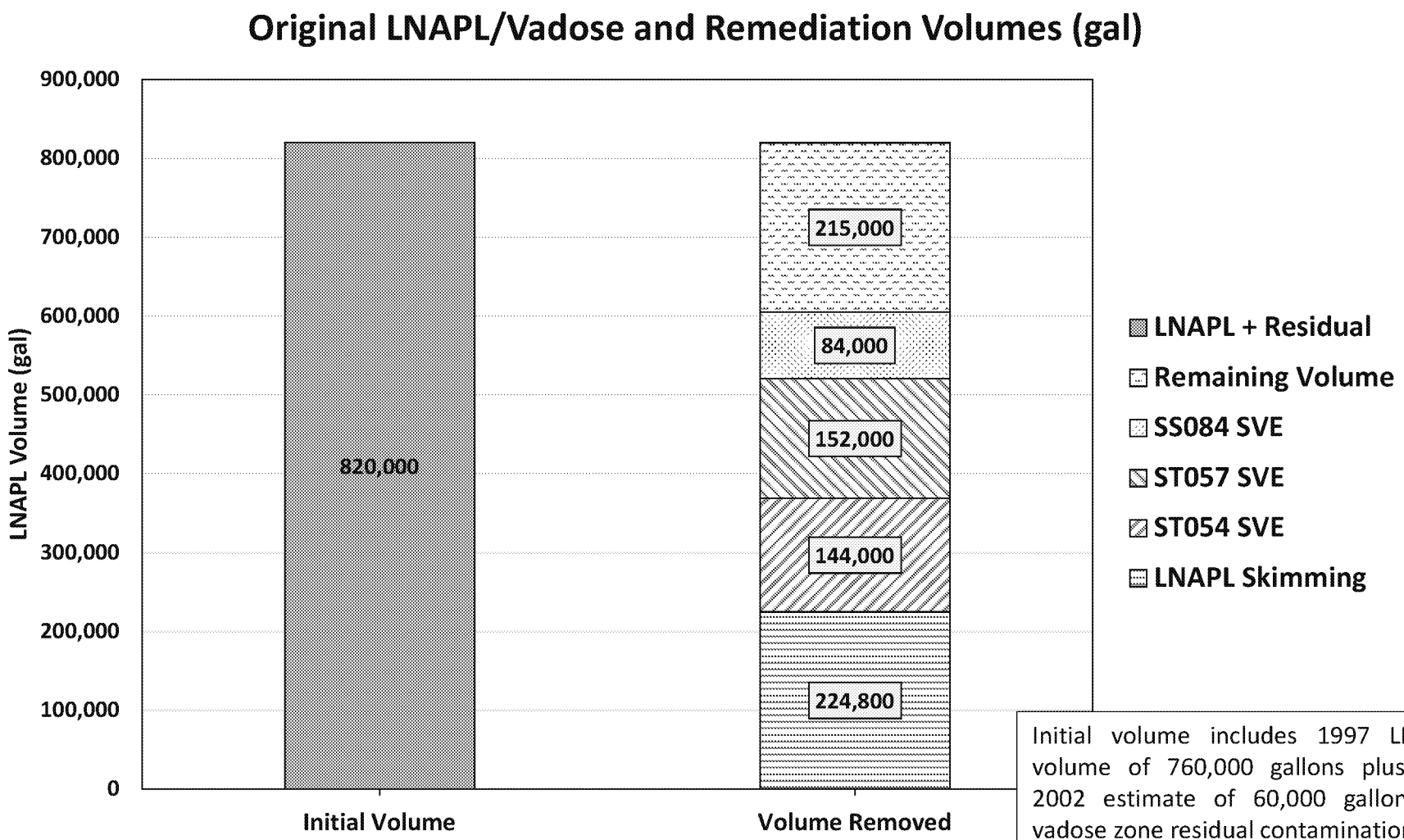
SS084

LNAPL Equivalent Volumes

- ST054—144,000 gal.
- ST057—152,000 gal.
- SS084—84,000 gal.
- Used 6.3 lb/gal for LNAPL density

Original vadose zone mass estimated as 60,000 gal (HGL,2002)

LNAPL Volume Mass Balance



Initial volume includes 1997 LNAPL volume of 760,000 gallons plus the 2002 estimate of 60,000 gallons of vadose zone residual contamination.

SS030 LNAPL Volume Summary

- Remaining LNAPL volume between 215,000 (mass balance) and 280,000 (2016 estimate) gallons
- Primary difference between historical volume estimates related to selection of van Genuchten parameters—literature vs site-specific

Questions / Comments