Comparison of LNAPL Transmissivity Derived from Baildown Tests and Recovery-Based Methods

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Site Background

- Petroleum Facility Located in the Midwest and Operated from the Early 1940's to Early 2000's
- Subsurface Geology
  - Large River Valley (~175 square miles)
  - Fine-Grained Alluvial Deposits Overlies Coarser Grained Glaciofluvial Deposits (Fining Upward Sequences)
- Hydrogeology
  - Localized Shallow, Unconsolidated Saturated Unit (T_w = ~8 to 420 ft^2/day)
  - Primary Unconsolidated Aquifer (T_w = ~700 to 75,000 ft^2/day)
  - River is the Primary Hydraulic Boundary
  - Groundwater Surface Fluctuates Across the Site ~3 to 14 feet
- Historic Releases of Petroleum Over the Period of Facility Operations

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Site Background

- ~1,800,000 Gallons LNAPL Recovered Since 1994
- LNAPL Primarily Recovered Using Skimmer Pumps (SPR) and Multiple-Phase Extraction (MPE) Systems (Fixed-Based and Mobile)
- Over 200 LNAPL Baildown (BDT) Tests Performed 2003 through 2015
  - 77 Well Locations
- LNAPL Tn Calculated by ASTM Recovery-Based Methods (RBM) Performed at 19 Well Locations
  - SPR at 18 Well Locations
  - MPE at 5 Well Locations (4 Previously Operated as SPR)

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Skimmer Pump Recovery (SPR) – Site Examples

- BDT Tn Data Analysis – Aquifer Testing Software and the *User Guide for API LNAPL Transmissivity Workbook and Spreadsheet: A Tool for Baildown Test Analysis* (Pre-Publication Drafts, 2012 and 2013)

- Skimming RBM Tn Data Analysis – *Standard Guide for Estimation of LNAPL Transmissivity* (ASTM E2856-13)

- Conditions/Assumptions:
  - Fluid Levels Continually Under Non- Equilibrium (River Stage Fluctuations)
  - SPR System Maintains Constant Drawdown and Zero LNAPL Thickness
  - Maximum Estimated Drawdown Based on Equations for Confined and Unconfined Conditions
  - $l_n(R_{oi}/r_w)$ = 4.6 (Charbeneau, 2007 and ASTM, 2013)

$$T_n = \frac{Q_n \ln\left(\frac{R_{oi}}{r_w}\right)}{2\prod s_n}$$

Equation 16(ASTM, 2013)

$$s_{n\_unconfined} = b_n(1 - p_n)$$

$$s_{n\_confined} = b_{nf}\,(1 - p_n)/p_n$$

T_n = LNAPL transmissivity (ft^2/day)
Q_n = Measured LNAPL removal rate (ft^3/day)
s_n = Estimated LNAPL drawdown (ft)
R_{oi} = radius of influence (ft)
r_w = well radius (ft)
b_n = LNAPL thickness in well (ft)
b_{nf} = LNAPL thickness in formation (ft)
p_n = LNAPL density

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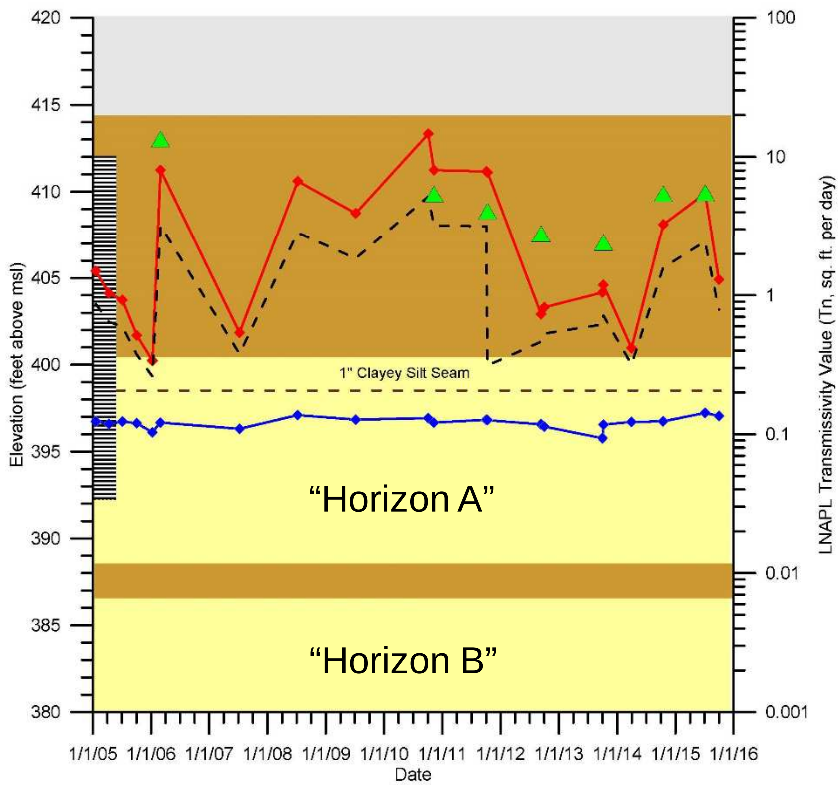
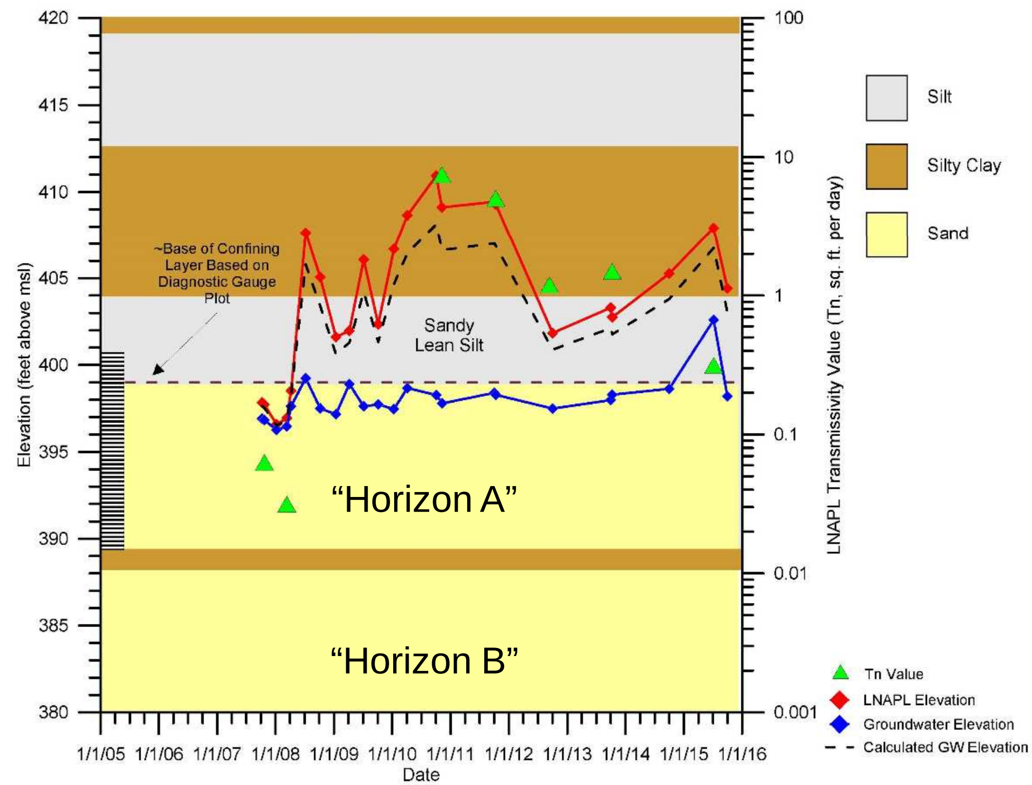
Skimmer Pump Recovery (SPR) – Site Examples

RW-002 LCSM



RW-005 LCSM



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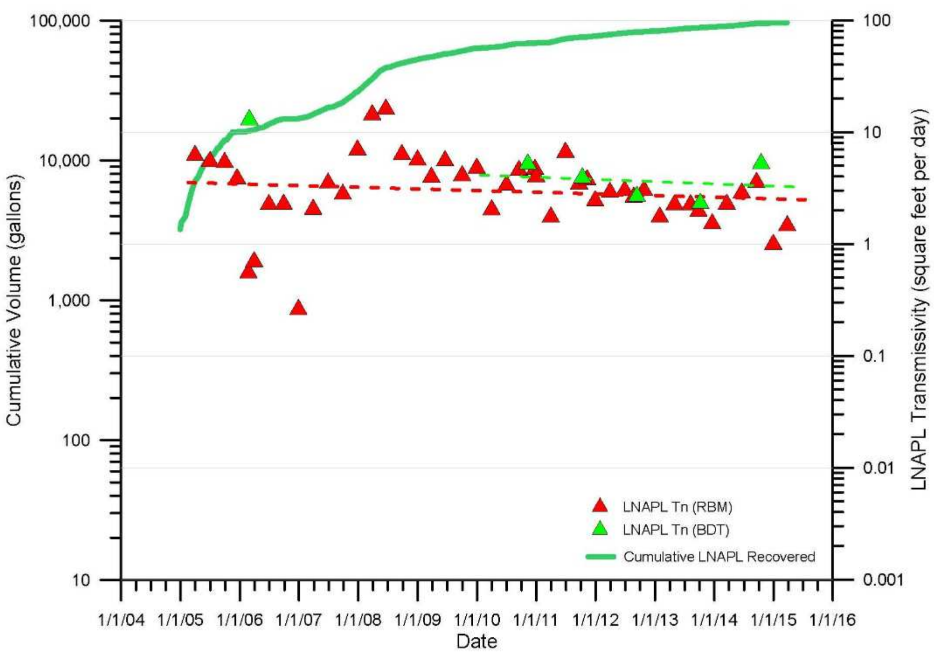
Skimmer Pump Recovery (SPR) – Site Examples

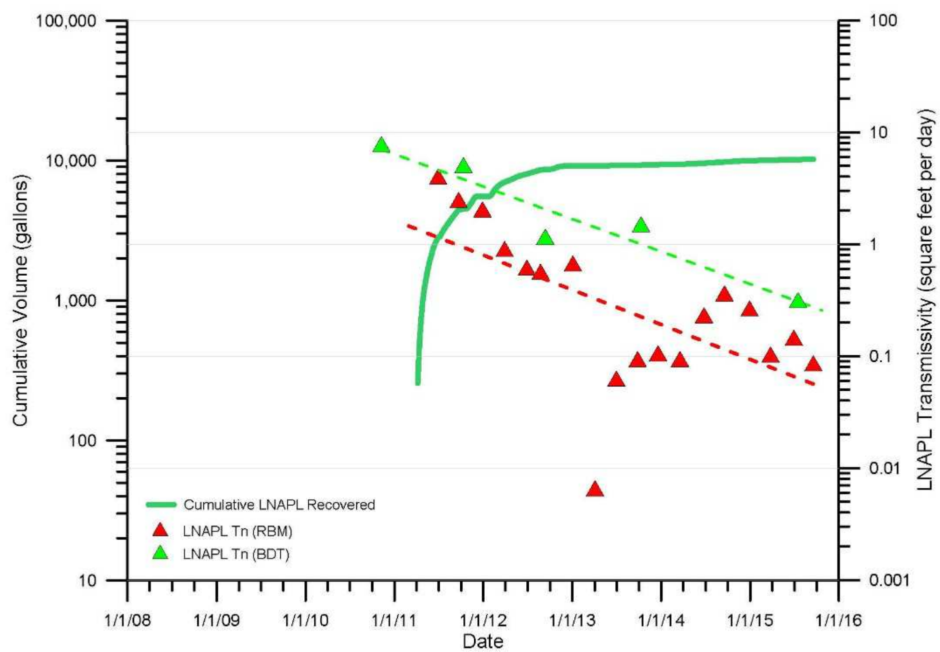
<u>RW-002 (SPR)</u>

LNAPL Confined
~10 Years of Operation
Volume ~96,400 gallons



<u>RW-005 (SPR)</u>

LNAPL Unconfined to Confined
~5 Years of Operation
Volume ~10,000 gallons



"<u>The Good</u>, The <u>Not So Bad</u>, …"

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Multiple Phase Extraction (MPE) – Site Examples

- MPE Recovery-Based Tn Data Analysis – *Standard Guide for Estimation of LNAPL Transmissivity* (ASTM E2856-13)

- Conditions/Assumptions:
  - Fluid Levels Continually Under Non-Equilibrium (River Stage Fluctuations)
  - Cannot Accurately Measure LNAPL/Groundwater Drawdown During Operation
  - LNAPL is Confined
  - No Open Well Screen Above LNAPL Level (b_a = 0 feet)
  - No Air Discharge From Vadose Zone or Formation ($Q_a = 0$ *ft³/day*)
  - Negligible Vacuum Induced Drawdown and Vacuum R_{oi}
  - LNAPL Tn Estimated Based on Fluid Recovery Ratios

$$T_n = \frac{Q_n p_r}{\frac{\mu_{ar} Q_a}{k_{ra} K_w b_a} + \frac{Q_w}{T_w}}$$

Equation 23 (ASTM, 2013)

or

$$T_n = \frac{Q_n p_r}{\frac{2\Pi s_n}{\ln\left(\frac{R_{oi}}{r_w}\right)} + \frac{Q_w}{T_w}}$$

Equation 24 (ASTM, 2013)

$$T_n = (Q_n/Q_w)\, T_w\, p_r$$

$$\text{where, } T_w = K_w\, L$$

(Hawthorne, 2013)

T_n = LNAPL transmissivity (ft²/day)
T_w = Aquifer transmissivity (ft²/day)
K_w = Aquifer conductivity (ft/day)
L = Wetted interval along well screen (ft)
Q_n = Measured LNAPL removal rate (ft³/day)
Q_w = Measured water discharge rate (ft³/day)
Q_a = Measured air discharge rate (ft³/day)
b_a = Screened interval above LNAPL (ft)
p_r = LNAPL-water density ratio
k_{ra} = Air-phase permeability
μ_{ar} = Air-water viscosity ratio

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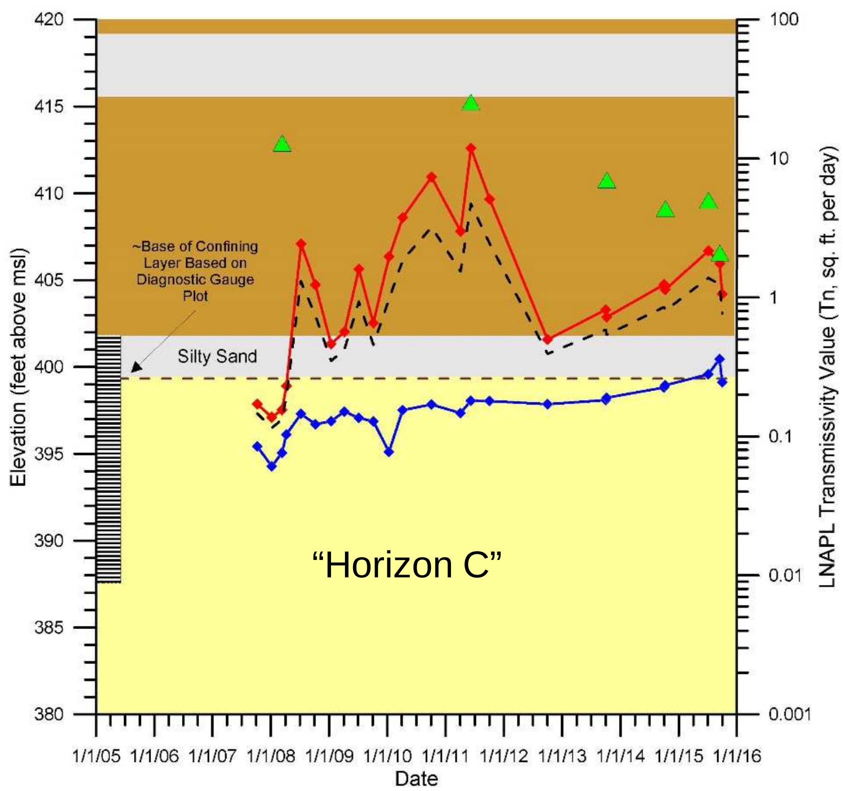
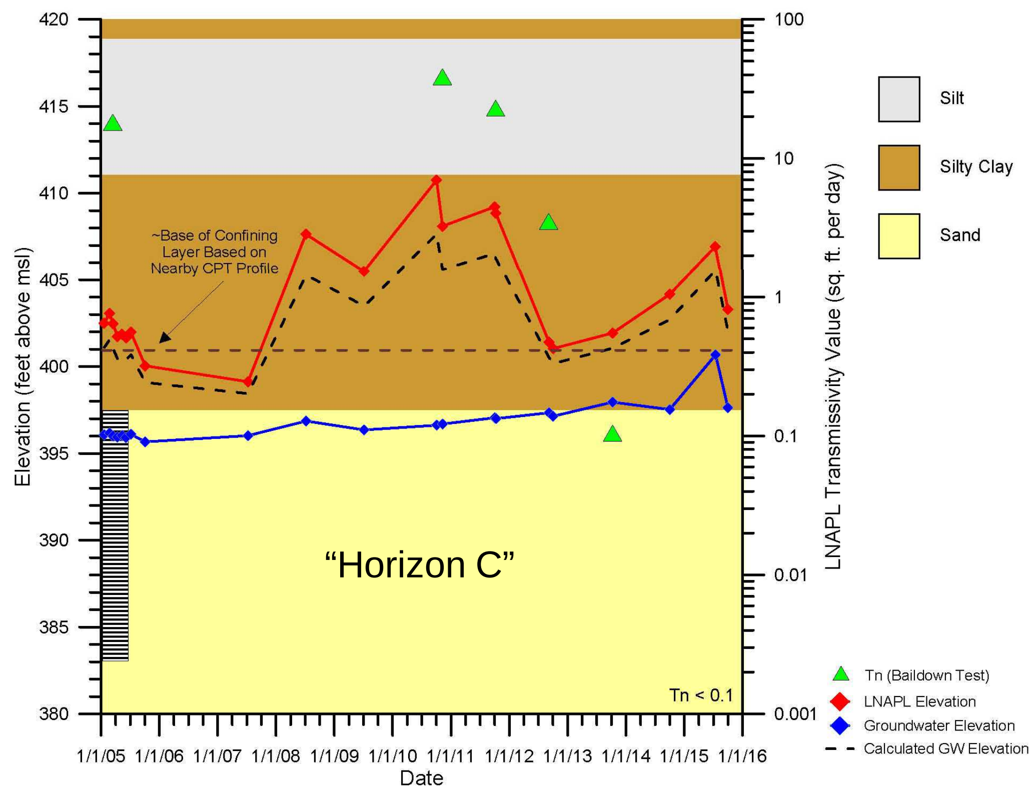
Multiple Phase Extraction (MPE) – Site Examples

RW-014 LCSM



RW-008 LCSM



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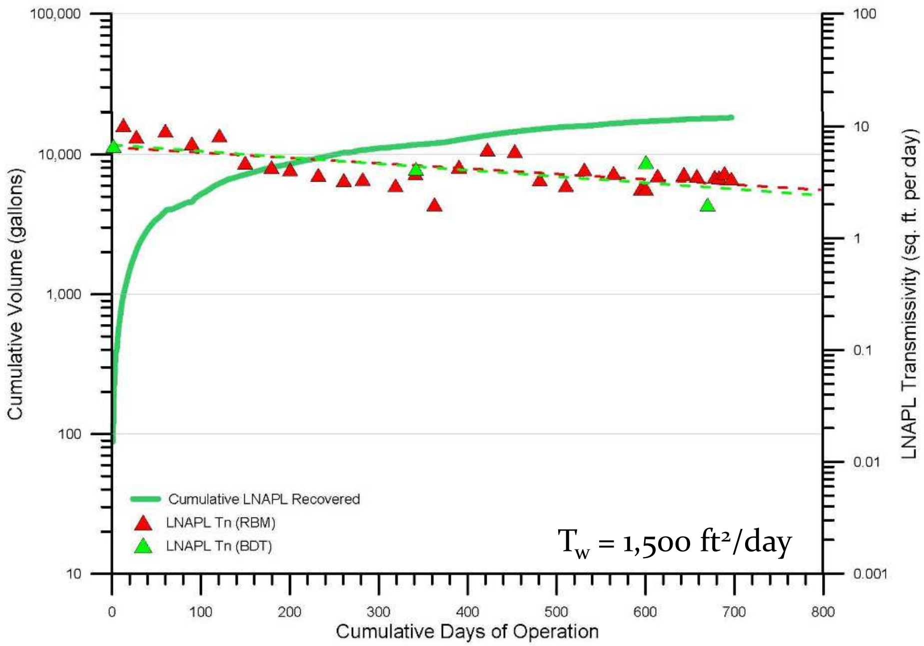
Multiple Phase Extraction (MPE) – Site Examples

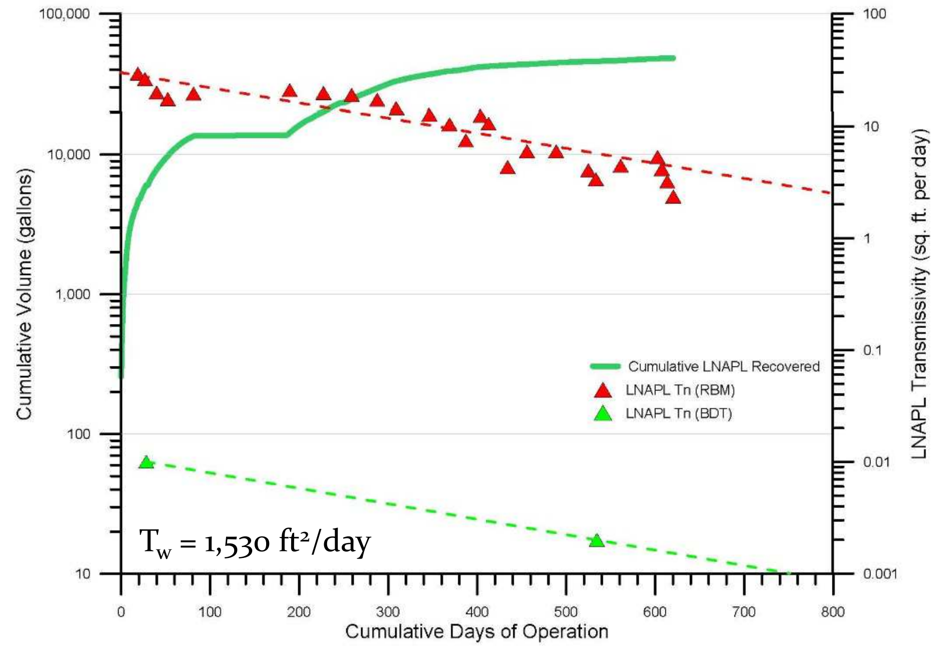
RW-014 (MPE)

LNAPL Confined
~2.0 Years of Operation (2013 - 2015)
LNAPL Volume = ~18,600 gallons
Water Volume = ~4,620,000 gallons



RW-008 (MPE)

LNAPL Confined
1.6 Years of Operation (2013 - 2015)
LNAPL Volume = ~48,500 gallons
Water Volume = ~ 4,560,000 gallons



"The Good, The Bad, and The Ugly"

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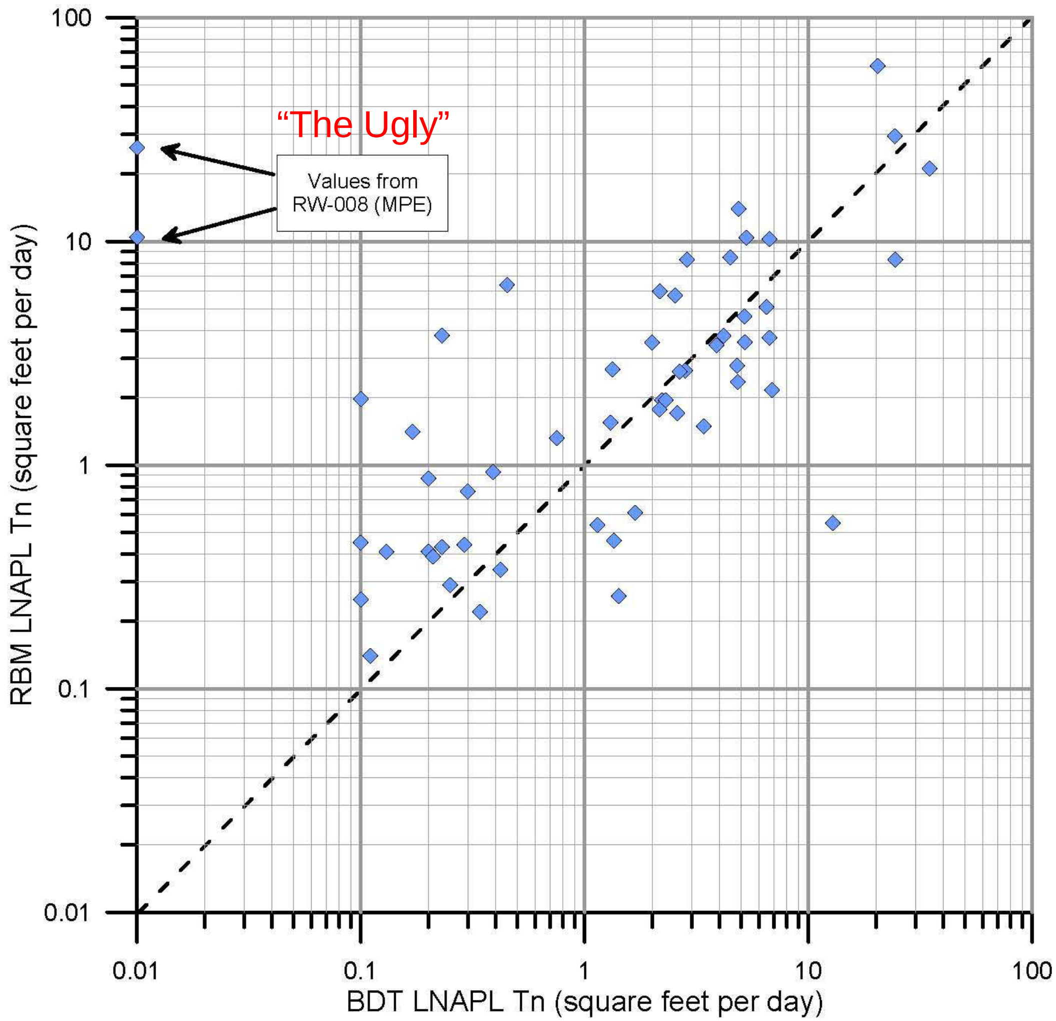
RBM and BDT Data Analysis – LNAPL Tn Value Comparison



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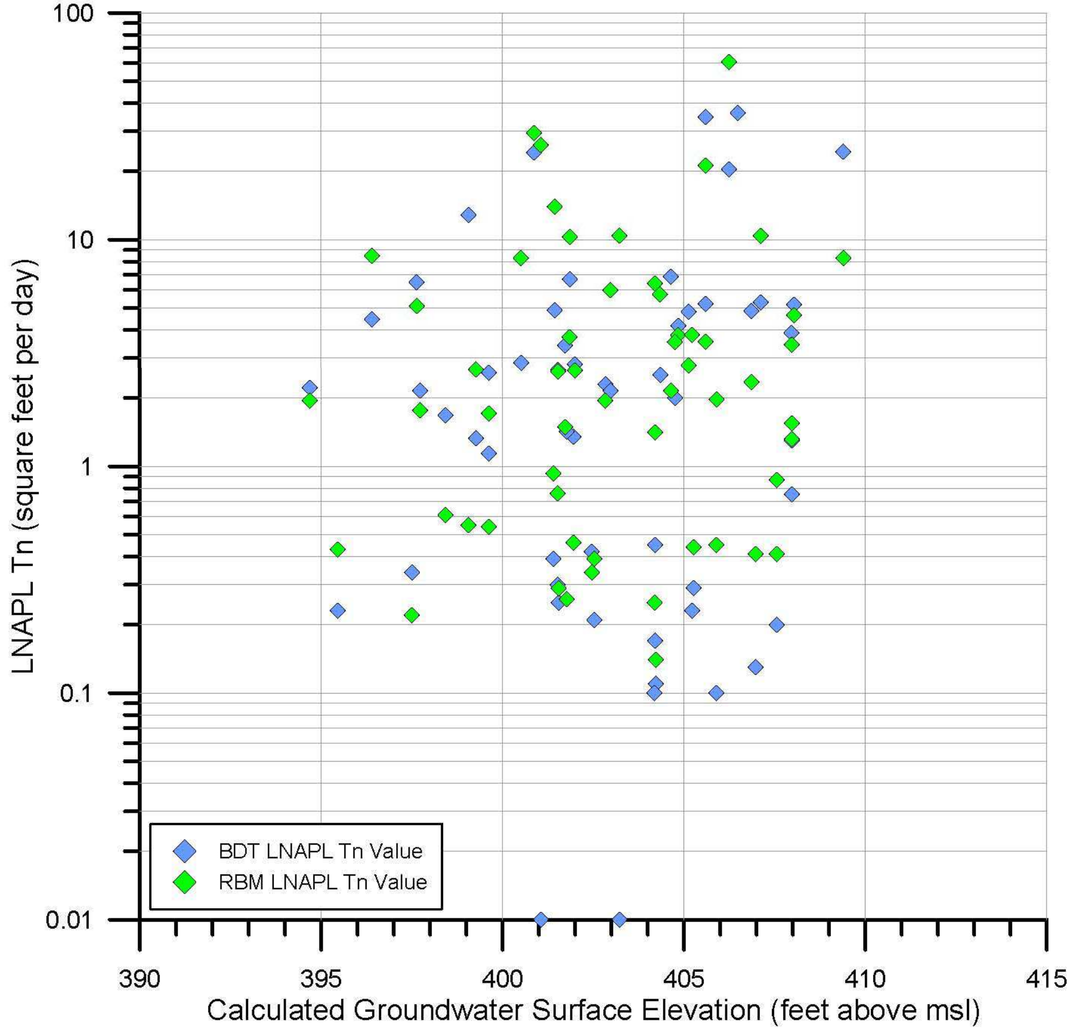
RBM and BDT Data Analysis – Calculated Groundwater Surface Elevation



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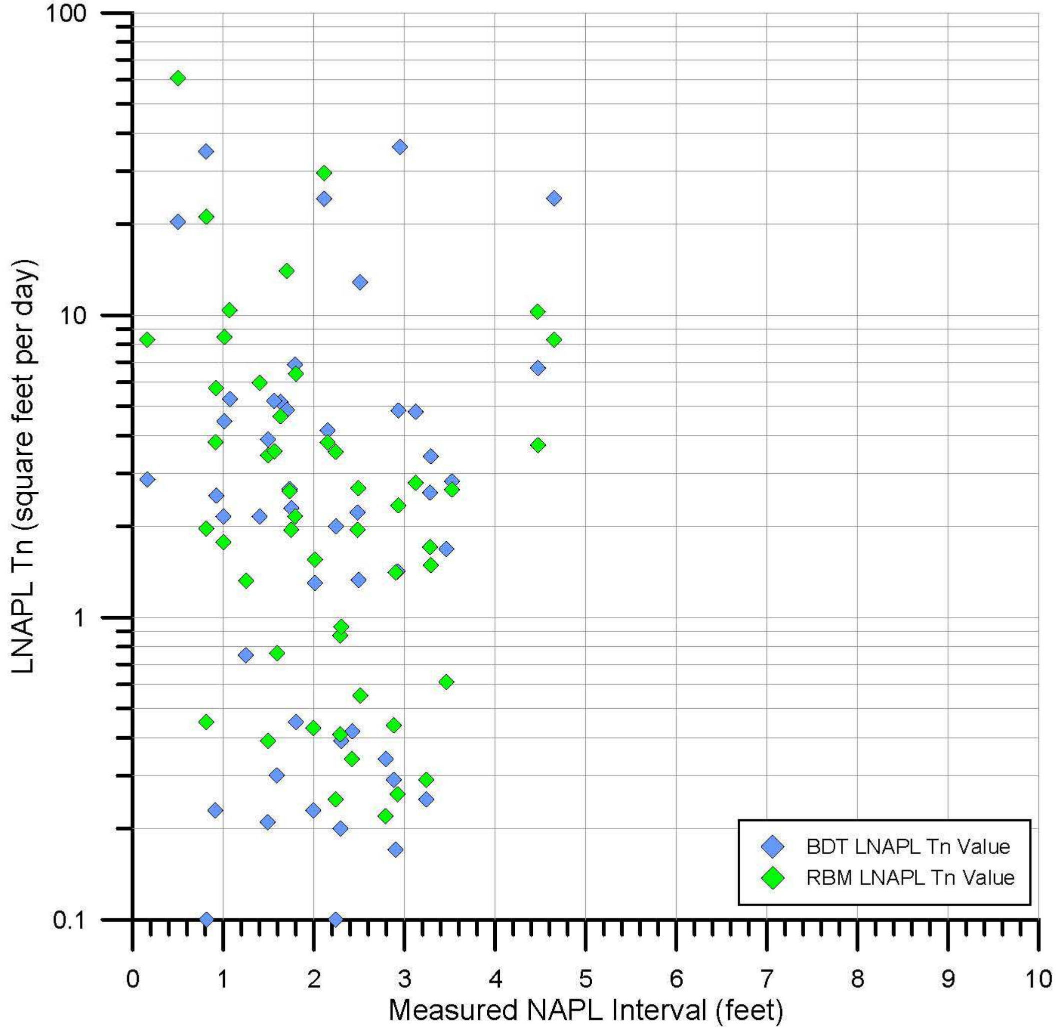
RBM and BDT Data Analysis – Measured NAPL Interval (MNI)



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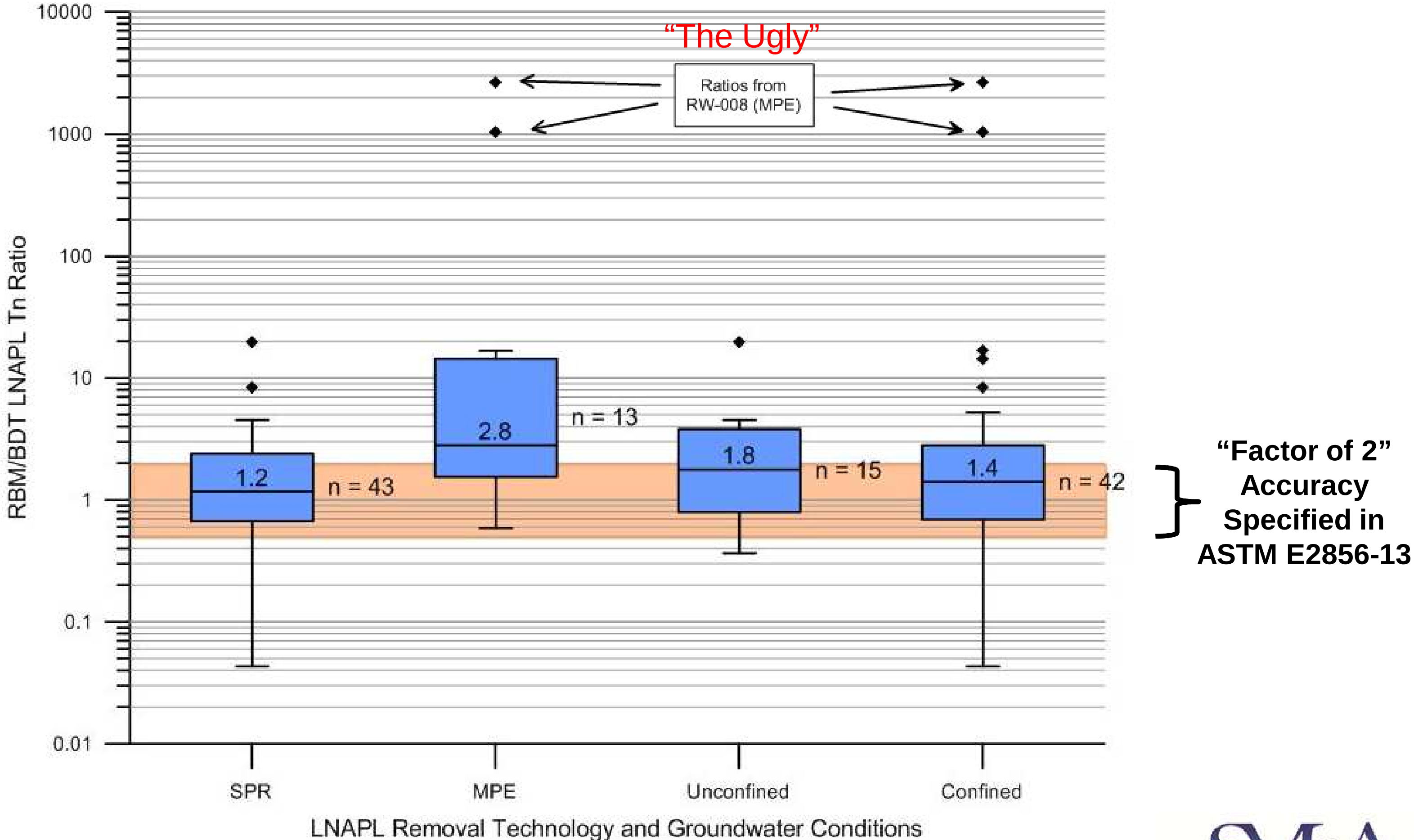
RBM/BDT Ratio Analysis – Removal Technology and Hydraulic Conditions



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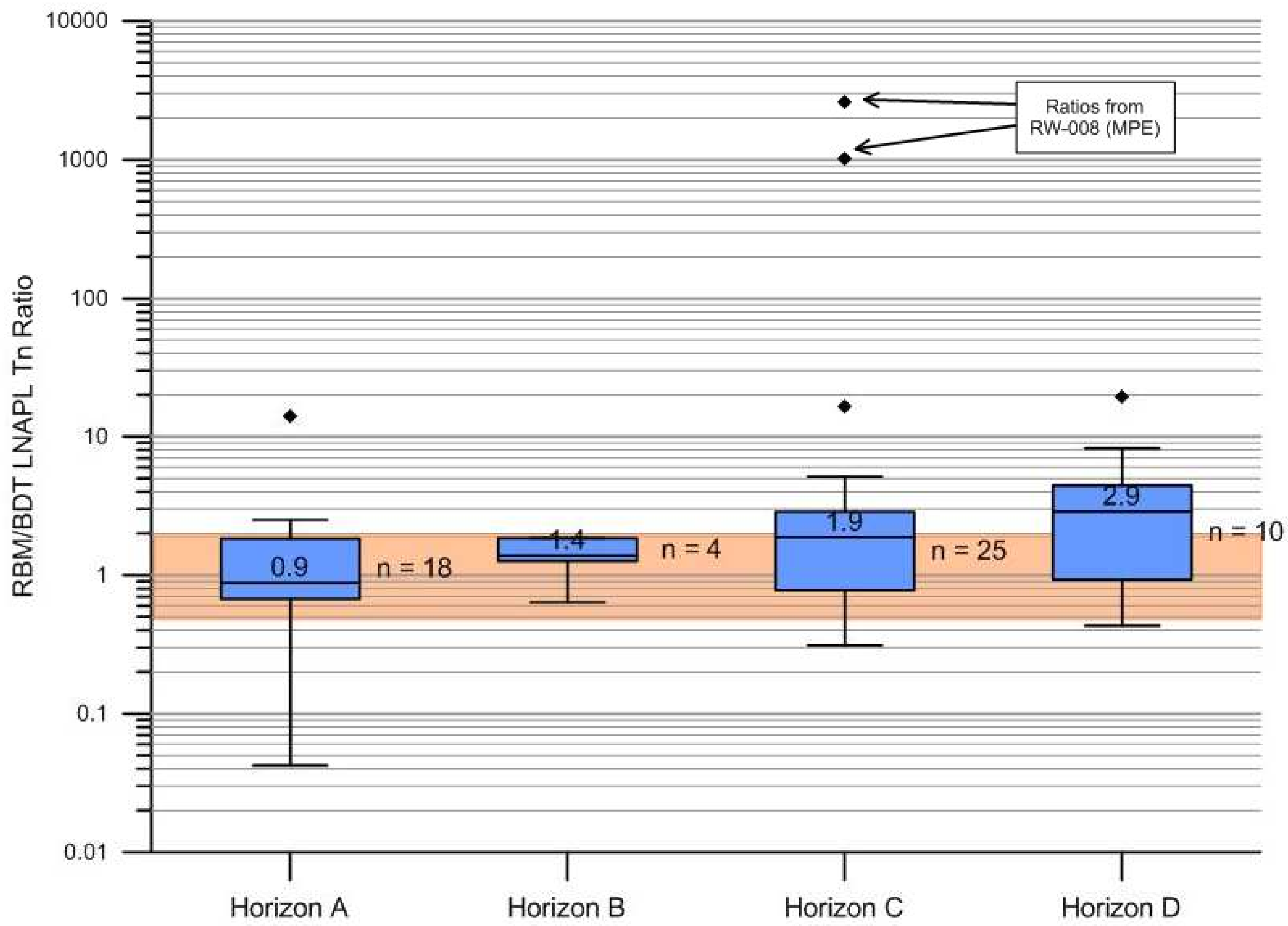
RBM/BDT Ratio Analysis – Geologic Setting and Horizon



"Factor of 2" Accuracy Specified in ASTM E2856-13

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Overview of RBM/BDT Ratio Data

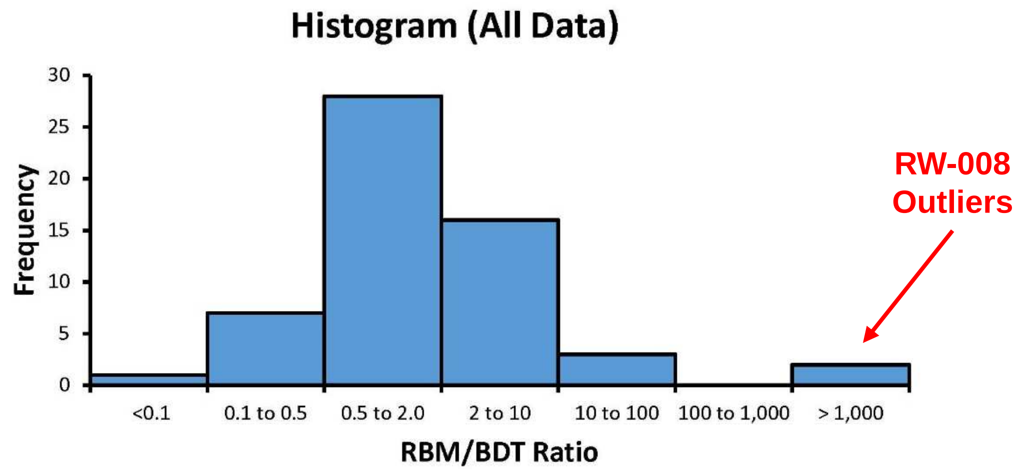
n = 57

Minimum = 0.04

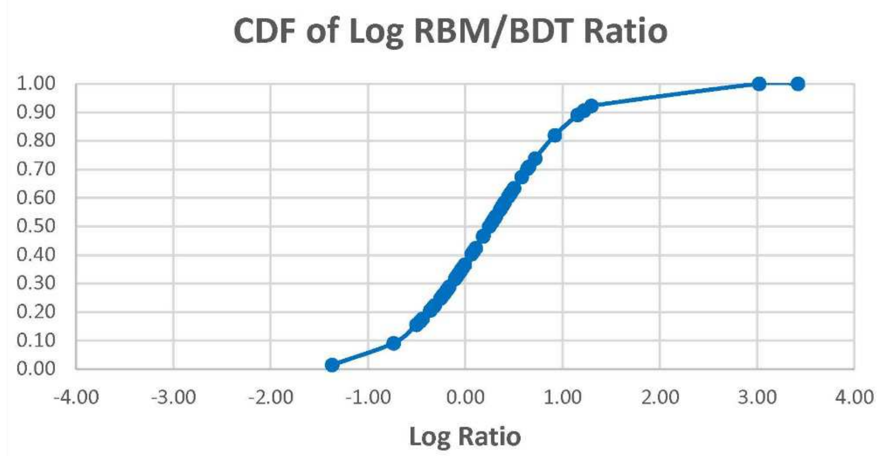
Maximum = 2,620

Mean = 66.7

Median = 1.52



85%	< 10
53%	< 2
23%	< 0.5
5%	< 0.1



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Overview of RBM/BDT Ratio Data

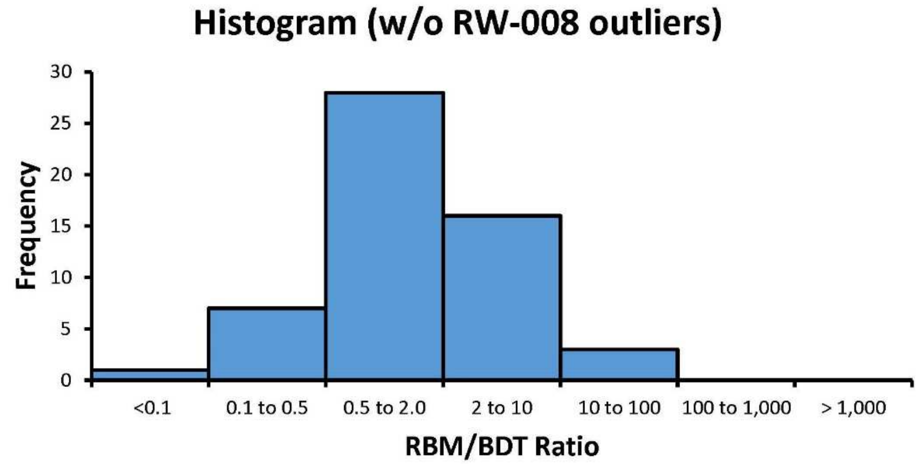
n = 55

Minimum = 0.04

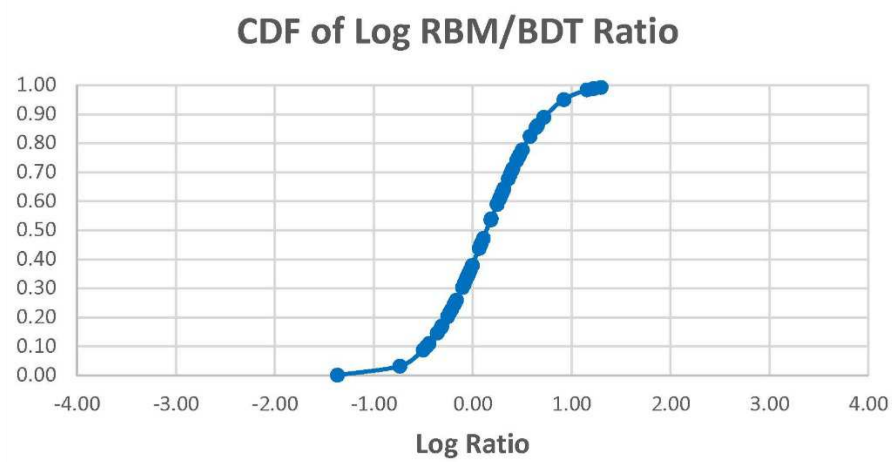
Maximum = 19.7

Mean = 2.53

Median = 1.27



97%	< 10
63%	< 2
18%	< 0.5
1%	< 0.1



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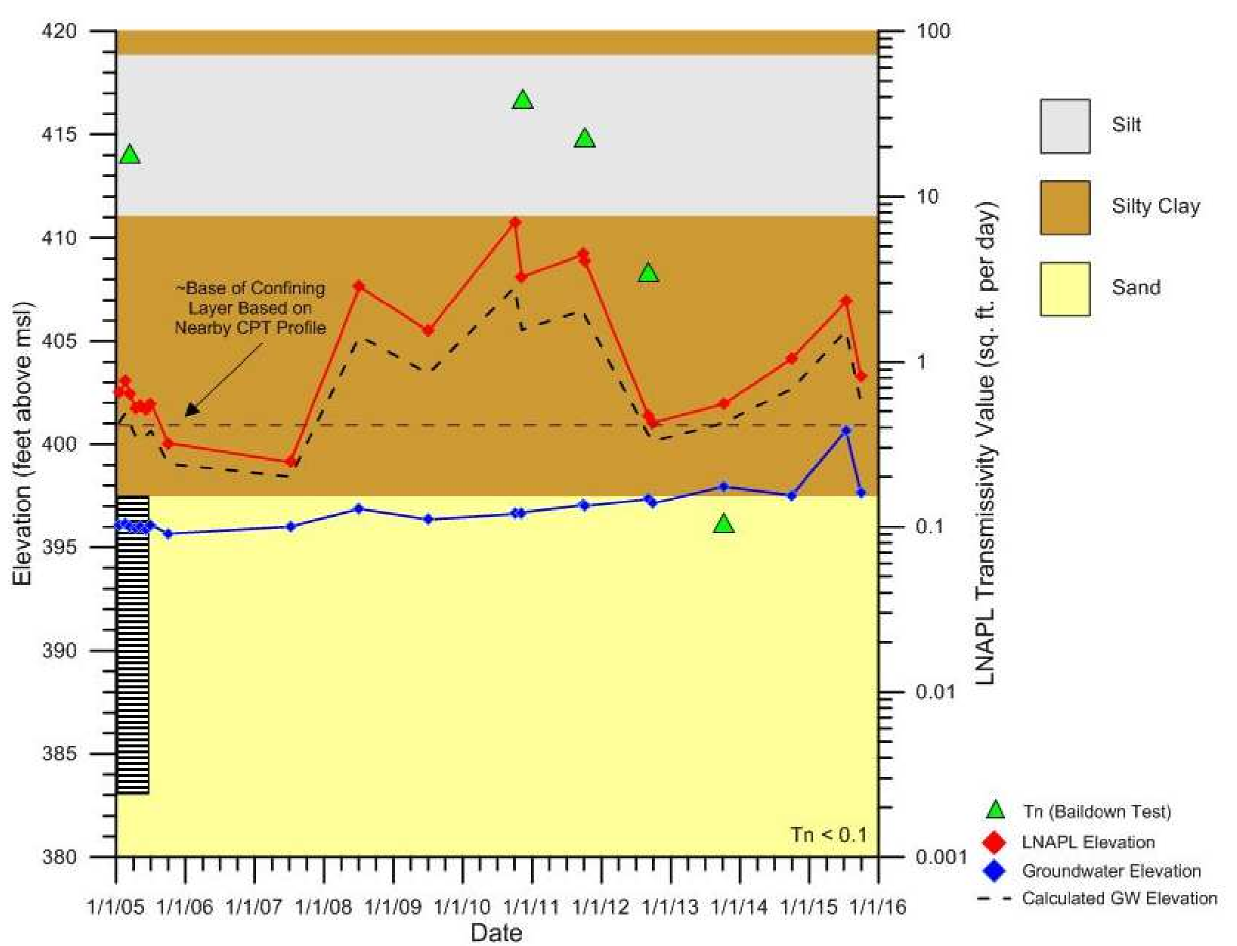
Summary

- LNAPL Transmissivity is a Useful Metric for Evaluating Recoverability of LNAPL and the Performance of a Variety of Hydraulic Recovery Systems
- ~ 51% of RBM/BDT Ratios (Excluding Outliers from RW-008) were within a Factor of 2 (ASTM E2856-13)
- ~93% of the RBM/BDT Ratios (Excluding the Outliers from RW-008) were within a Factor of 10 (Order of Magnitude)
- Evaluation of RBM/BDT Ratios Provides a Good Quality Assurance Check of the Derived LNAPL Tn Values and Trends
- Ratios Outside a “Factor of 2 Accuracy” May Require a Re-Evaluation of the LSCM, Operation of the Recovery System, Data Collection Methods, and/or Calculation Method of LNAPL Tn Values

Thank You!
Any Questions?

RBM/BDT Ratio Outliers at RW-008



Note: RW-008 is located along a flank of a stratigraphic trap.

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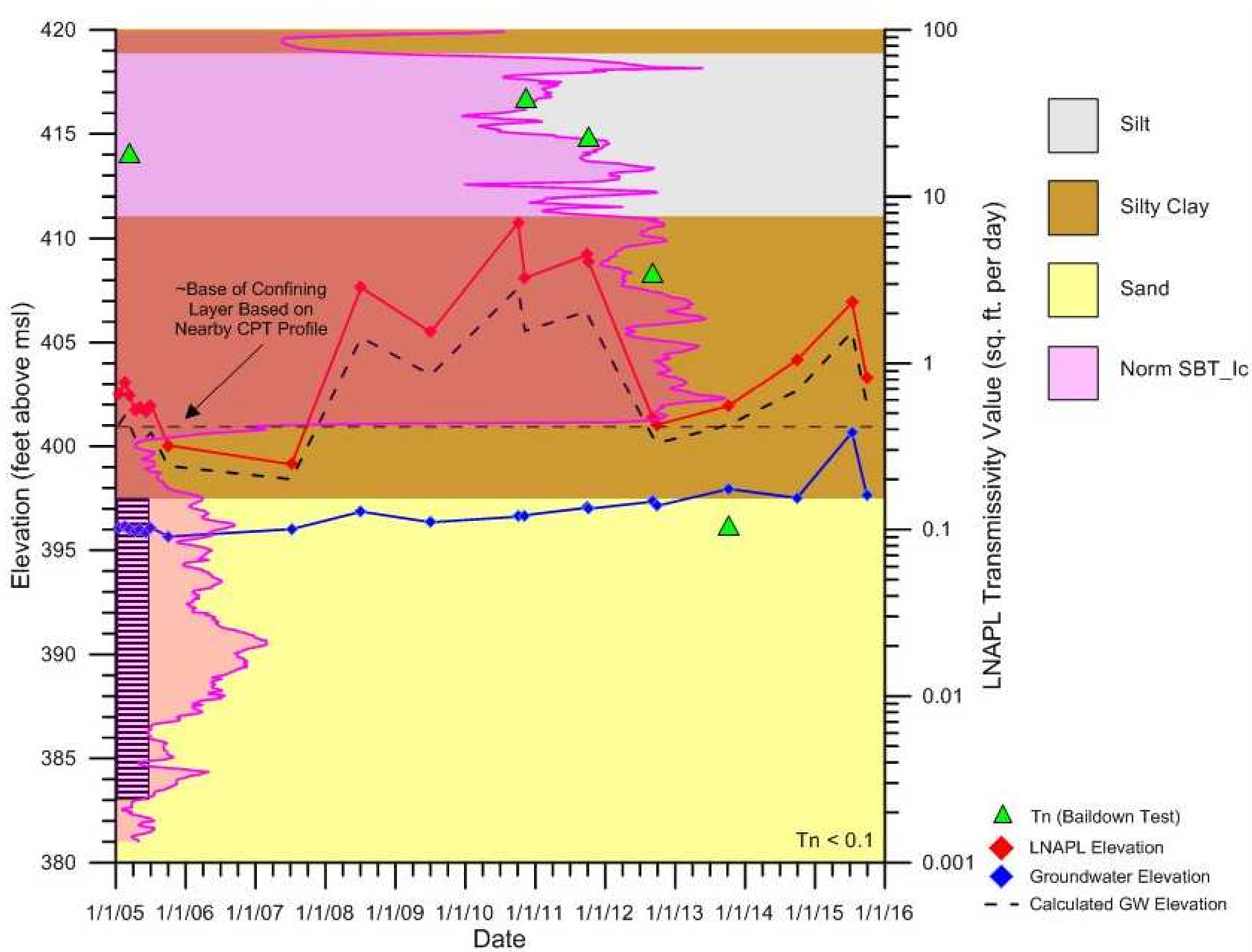
RBM/BDT Ratio Outliers at RW-008



Note: CPT-001 Located ~28 feet from RW-008.

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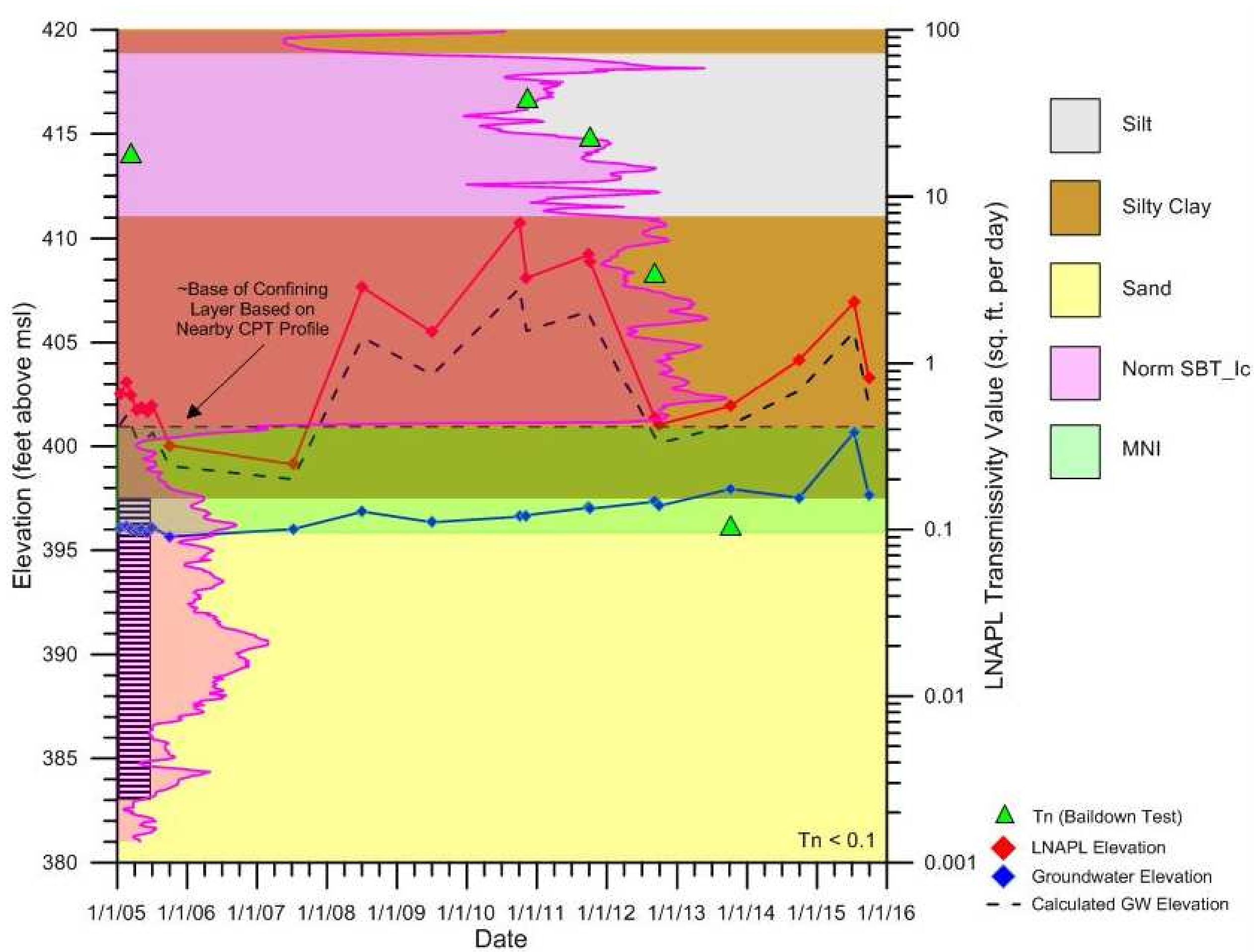
RBM/BDT Ratio Outliers at RW-008



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