# Groundwater Contaminant Plume Stability Analysis


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PREMIER
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# Ricker Plume Stability Analysis

- Background
- Ricker Plume Stability Analysis Methodology
- Example Site Analyses

# Plume Stability – MDNR Appendix H Definition

- **Stable Groundwater Plume:** a groundwater plume is "stable" when data representative of the entirety of the plume demonstrates that the plume is not expanding and that, overall, concentrations of chemicals of concern (COC) are not increasing.
- **Shrinking Groundwater Plume:** A groundwater plume is "shrinking" when data demonstrates that the areal extent of the plume is decreasing and concentrations of COCs, overall, are decreasing.
- **Expanding Groundwater Plume:** A groundwater plume is "expanding" when either the physical extent of the plume is increasing or concentrations of COCs are increasing.

# Plume Stability

- **A condition where the plume is no longer expanding in size, AND the plume footprint is not moving.**

- **Plume is at dynamic equilibrium**
  - ***Rate of chemical mass into the plume is equal to the rate of chemical mass lost from the plume***

# Why Evaluate Plume Stability?

- An increasing plume could migrate to sensitive receptors
- Evaluate remedial progress
- Answer Environmental Indicator Code (EI) CA 750 – "Has the migration of contaminated groundwater stabilized?"
- Primary line of evidence when implementing MNA
  - *"Historical groundwater …data that demonstrate a clear and meaningful trend of decreasing contaminant mass and/or concentration over time…"*

    - USEPA OSWER Directive 9200.4-17P

- Demonstrate low risk to close sites

# How is Plume Stability Determined?

- **Qualitative Methods**
  - ***Concentration vs. Time Plots***
  - ***Concentration vs. Distance Plots***
  - ***Concentration Isopleth Maps***
- **Statistical Methods**
  - ***Well by well trend analysis***
    - *Mann-Kendall*
    - *Linear Regression*
- **Plume-Based Methods**
  - ***Plume Area***
  - ***Plume Mass***
  - ***Plume Center of Mass (COM)***
  - ***Mass Flux***

# How is Plume Stability Determined?

## Qualitative Methods

| | Probability of Significant Risk | | |
|---|---|---|---|
| Plume Stability Analysis Method | High | Moderate | Low |
| Concentration vs. Time Plots | Trends in most wells visually stable and/or increasing | No discernable trends in many wells, trends in some relevant wells | Trends in all relevant wells visually decreasing |
| Concentration vs. Distance Plots | Moderate or no visual decrease in concentration along the plume centerline and generally stable trends in plots over time. Sentinel wells above DRCLs. | Moderate visual decrease in concentration along the plume centerline and generally stable trends in plots over time. Sentinel | Significant visual decrease in concentration along the plume centerline and general decreasing trends in plots over time. Sentinel wells with nondetects. |
| Concentration Isopleth Maps | Generally increasing plume size over time. Sentinel wells above DRCLs. | Relatively unchanged plume size and extent over time. Sentinel wells with less than | Discernable decrease in plume size and extent over time. Sentinel wells with nondetects. |

# How is Plume Stability Determined?

## Statistical Methods

| Plume Stability Analysis Method | Probability of Significant Risk | | |
|---|---|---|---|
| | High | Moderate | Low |
| Mann-Kendall | Concentrations trends in any relevant monitoring wells are statistically Increasing or Probably Increasing | Concentration trends in all relevant monitoring wells are statistically Decreasing, Probably | Concentration trends in all relevant monitoring wells are statistically Decreasing or Probably Decreasing |
| Linear Regression | | | |

**Mann-Kendall Trend Analysis Criteria**

| Mann-Kendal Statistic | Confidence in Trend | Concentration Trend |
|---|---|---|
| S>0 | > 95 % | Increasing |
| S>0 | 90-95 % | Probably Increasing |
| S>0 | < 90 % | No Trend |
| S<0 | < 90% and COV > 1 | No Trend |
| S<0 | < 90% and COV < 1 | Stable |
| S<0 | 90-95 % | Probably Decreasing |
| S<0 | 0.95 | Decreasing |

**Linear Regression Trend Analysis Criteria**

| Confidence in Trend | Ln Slope | |
|---|---|---|
| | Positive | Negative |
| < 90% | No Trend | COV < 1 Stable<br>COV > 1 No Trend |
| 90-95 % | Probably Increasing | Probably Decreasing |
| > 95 % | Increasing | Decreasing |

# How is Plume Stability Determined?

## Plume-Based Methods

| Plume Stability Analysis Method | Probability of Significant Risk | | |
|---|---|---|---|
| | High | Moderate | Low |
| Plume Area | Increasing or probably increasing trend in plume area. | Stable trend in plume area. | Decreasing or probably decreasing trend in plume area. |
| Plume Mass | Increasing or probably increasing trend in plume mass. | Stable trend in plume mass. | Decreasing or probably decreasing trend in plume mass. |
| Plume Center of Mass (COM) | Increasing or probably increasing trend in COM location. Condition should be verified with visual analysis to verify that plume is truly | Stable trend in plume COM location. | Decreasing or probably decreasing trend in plume COM location. |
| Mass Flux | Increasing or probably increasing trend in mass flux at any transect location. | Decreasing, probably decreasing, or stable trend in mass flux at each transect. | Decreasing or probably decreasing trend in mass flux at each transect. |

# Plume Stability - Existing Methods

- **Most Common Method to Evaluate Plume Stability**
  - ***Well by well trend analysis***
    - *"The primary concern in a stability demonstration is whether COC concentrations are increasing or decreasing at individual monitoring wells."* **- Indiana RISC Technical Guide – Appendix 3**
    - *"…a stable or shrinking condition can be identified by a stable or decreasing concentration trends over time. For this analysis, an overall plume condition was determined for each COC based on a statistical trend analysis of concentrations at each well…"*

      **- AFCEE MAROS User's Guide**

# Plume Stability - Existing Methods

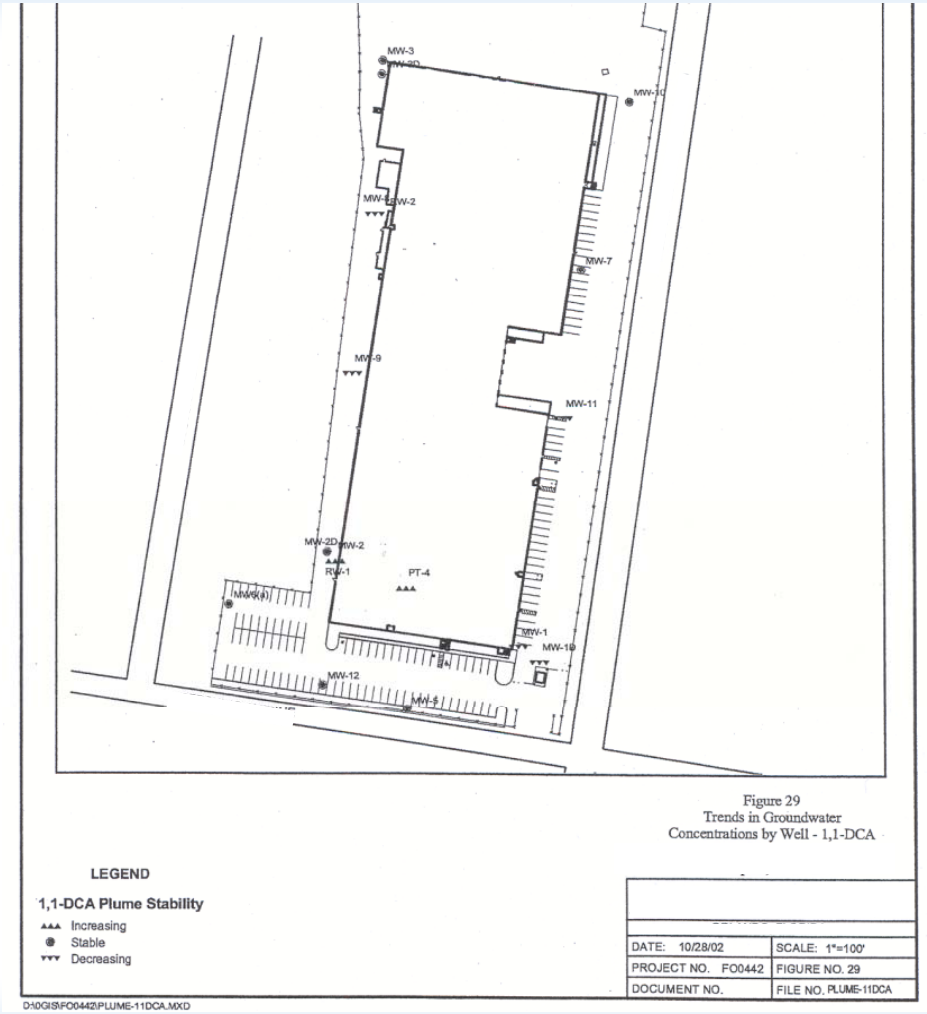
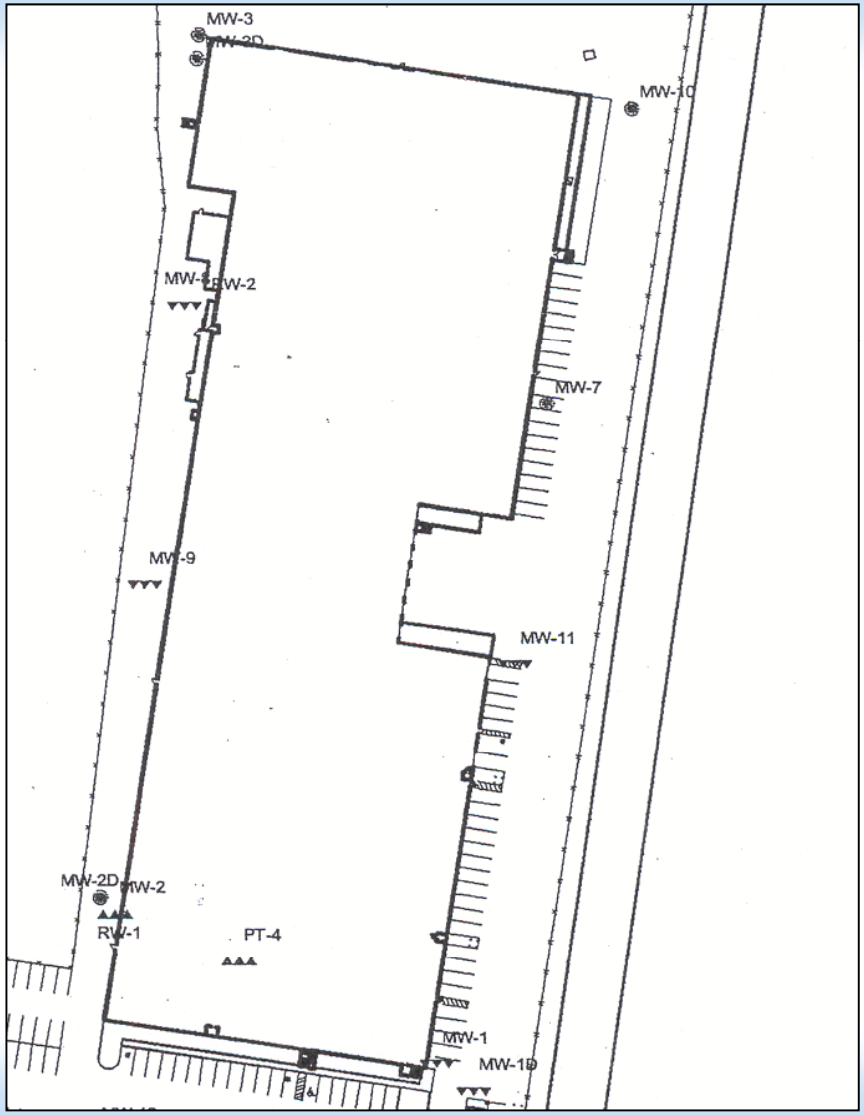



Figure 29
Trends in Groundwater
Concentrations by Well - 1,1-DCA

# Plume Stability - Existing Methods



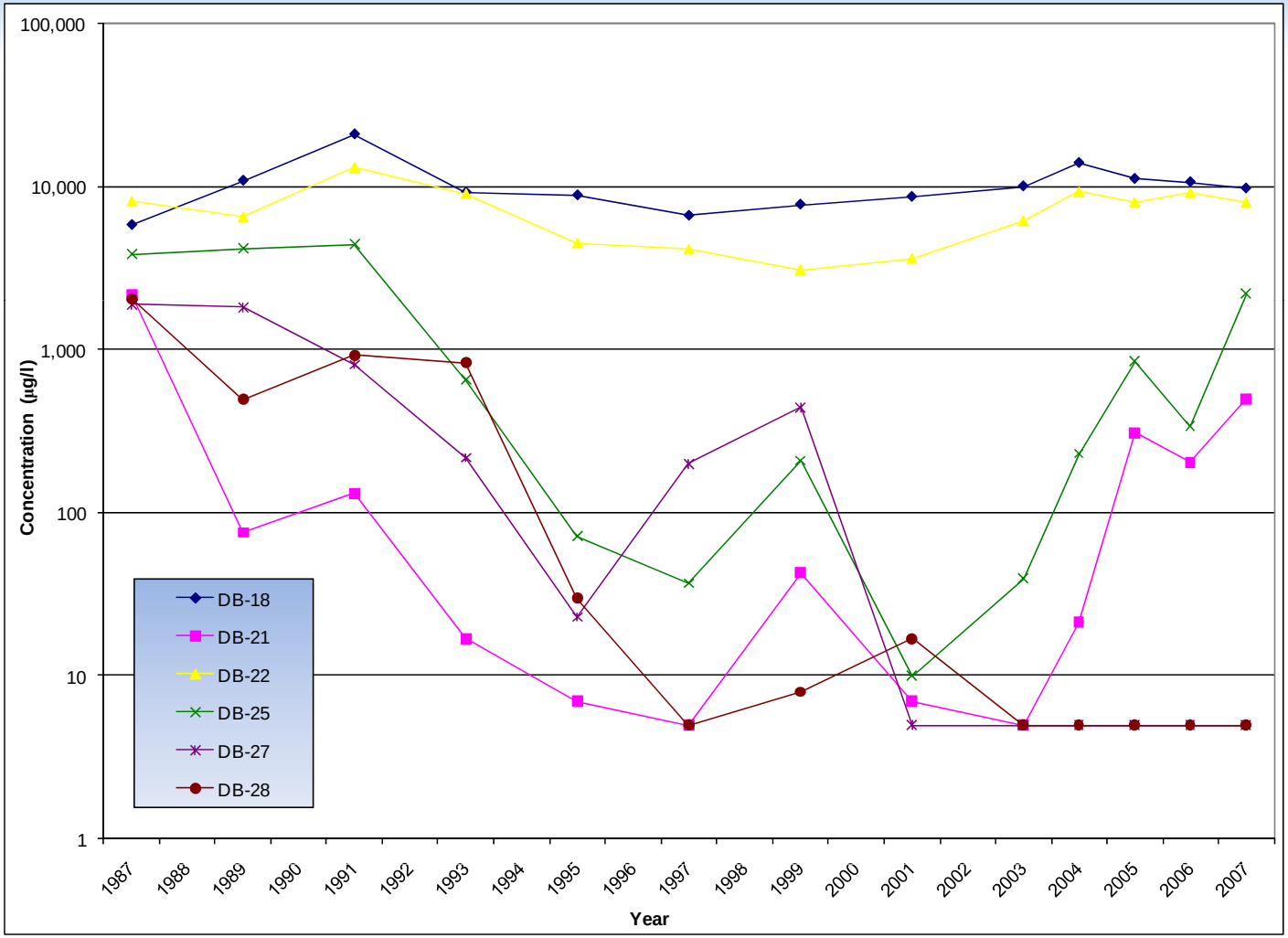

**LEGEND**

**1,1-DCA Plume Stability**

- ▲▲▲ Increasing
- ● Stable
- ▼▼▼ Decreasing

# Plume Stability - Existing Methods

- Naphthalene Plume
- 52 Wells

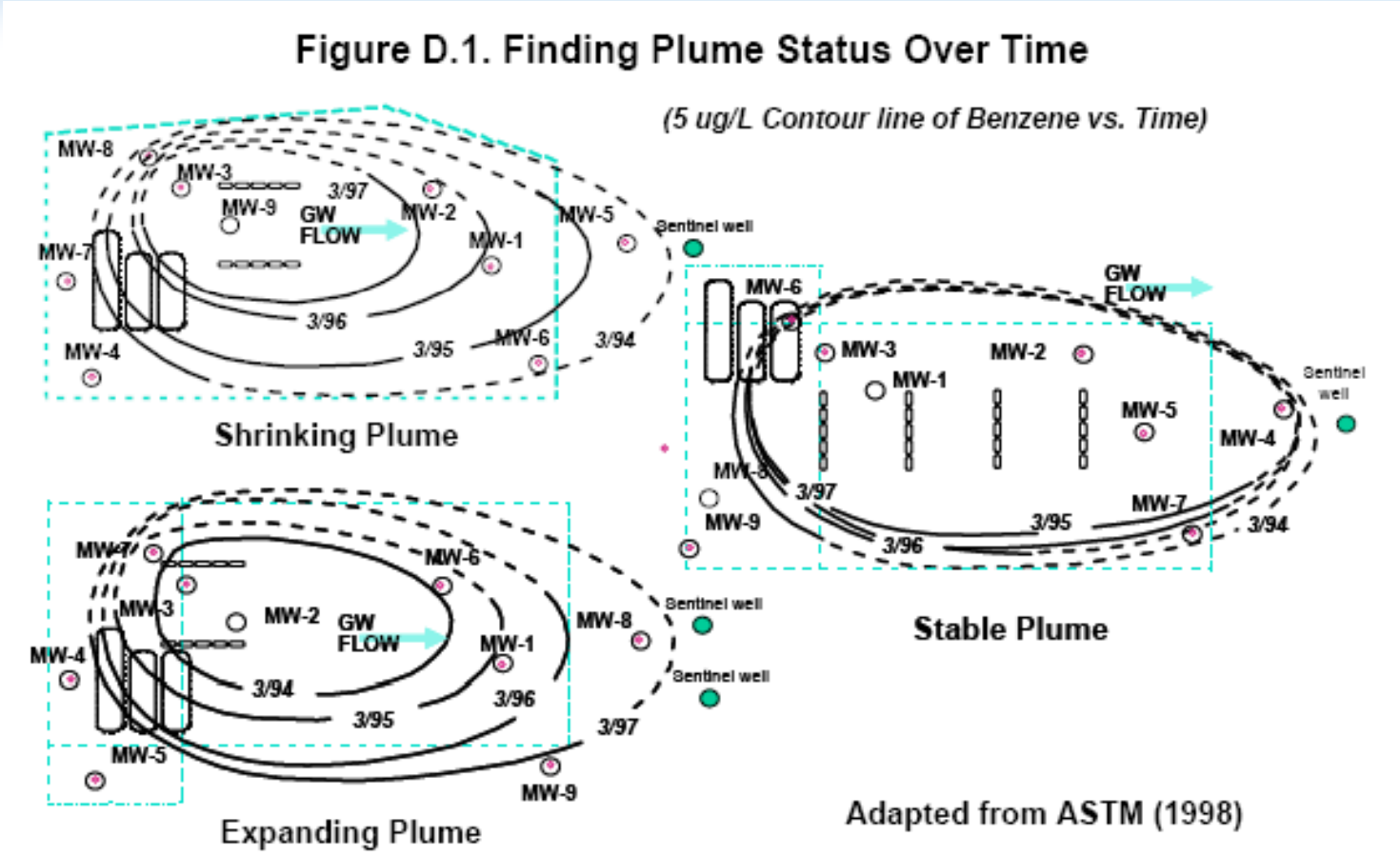


# Plume Stability - Existing Methods

- **Other Common Method to Evaluate Plume Stability**
  - ***Evaluate plume contours over time***
    - *"One method of evaluating plume status is to plot plume concentrations from four or more events on the same figure."*

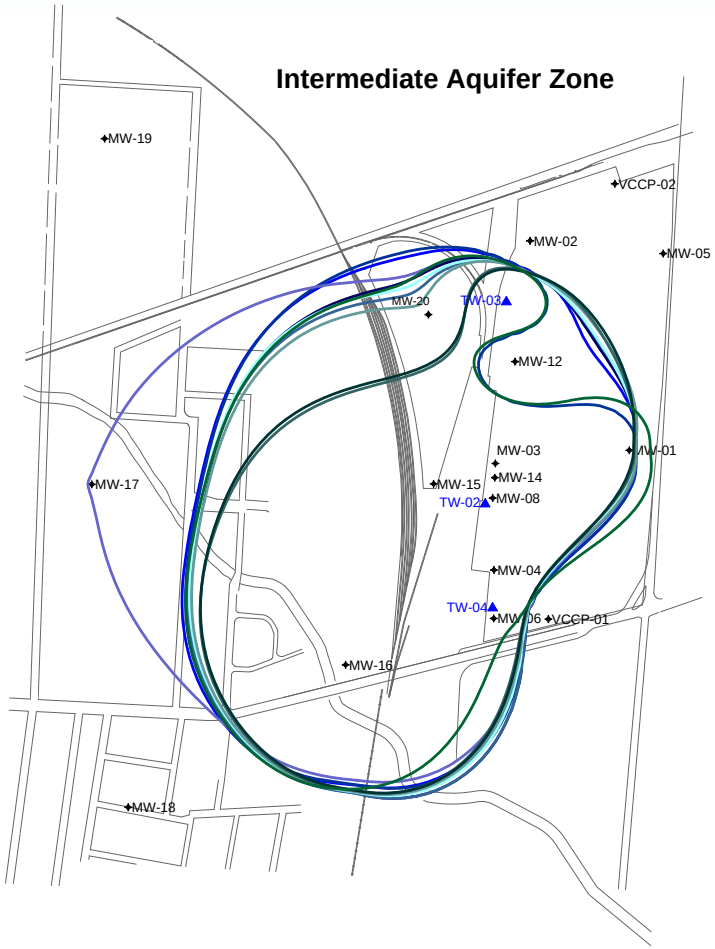
      **- Washington Guidance on Remediation by Natural Attenuation**

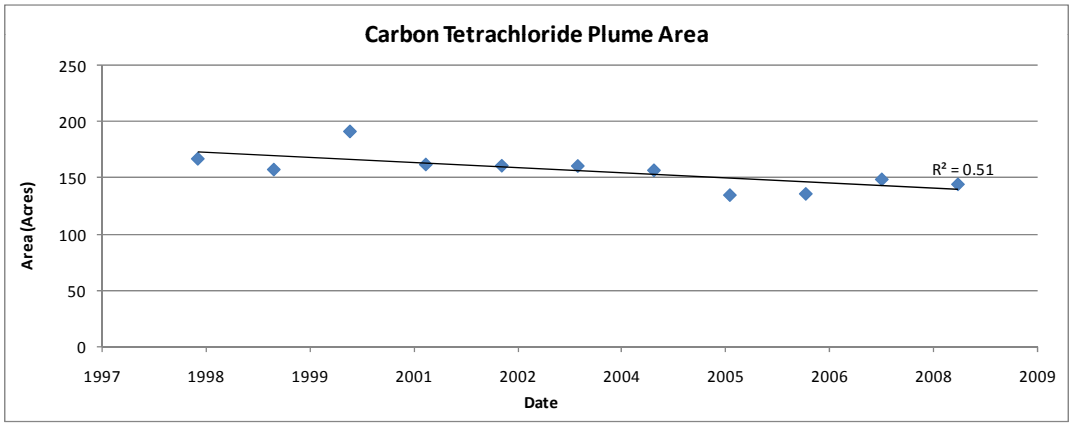
# Plume Stability - Existing Methods



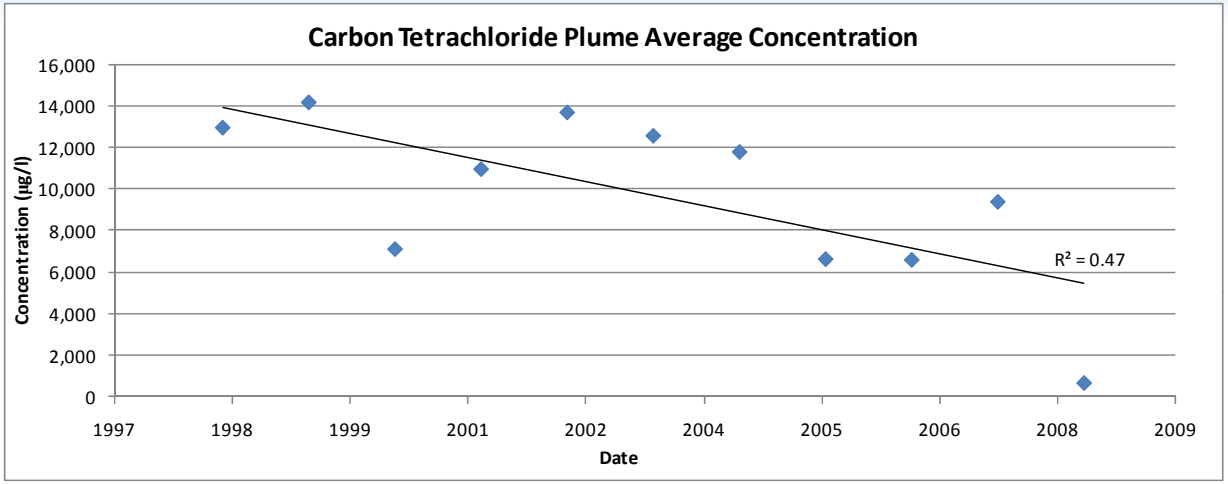

**From State of Washington Guidance on Remediation of Petroleum-Contaminated Ground Water By Natural Attenuation (Publication No. 05-09-091 [*Version 1.0]*)**

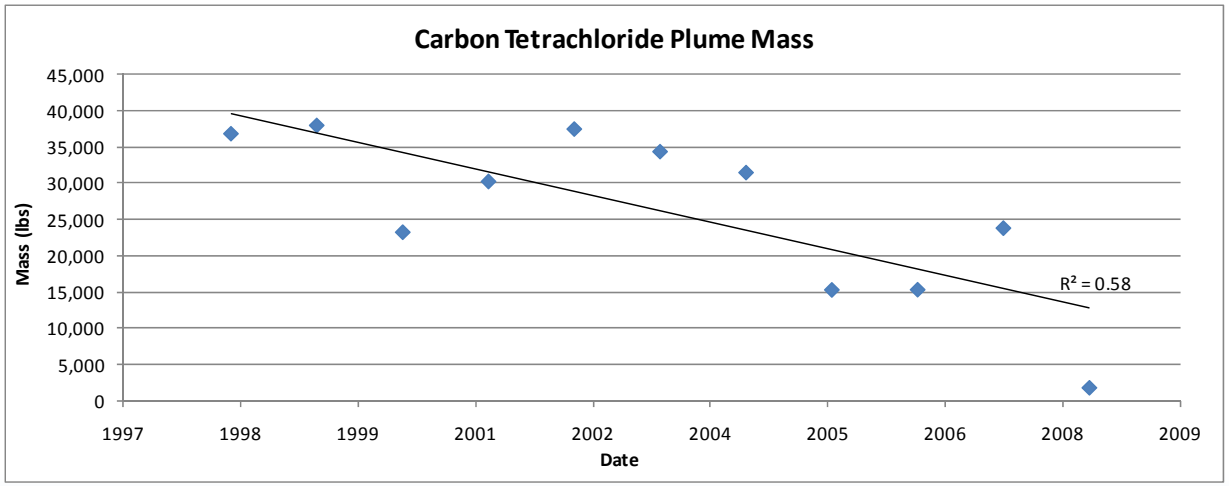
# Plume Stability - Existing Methods



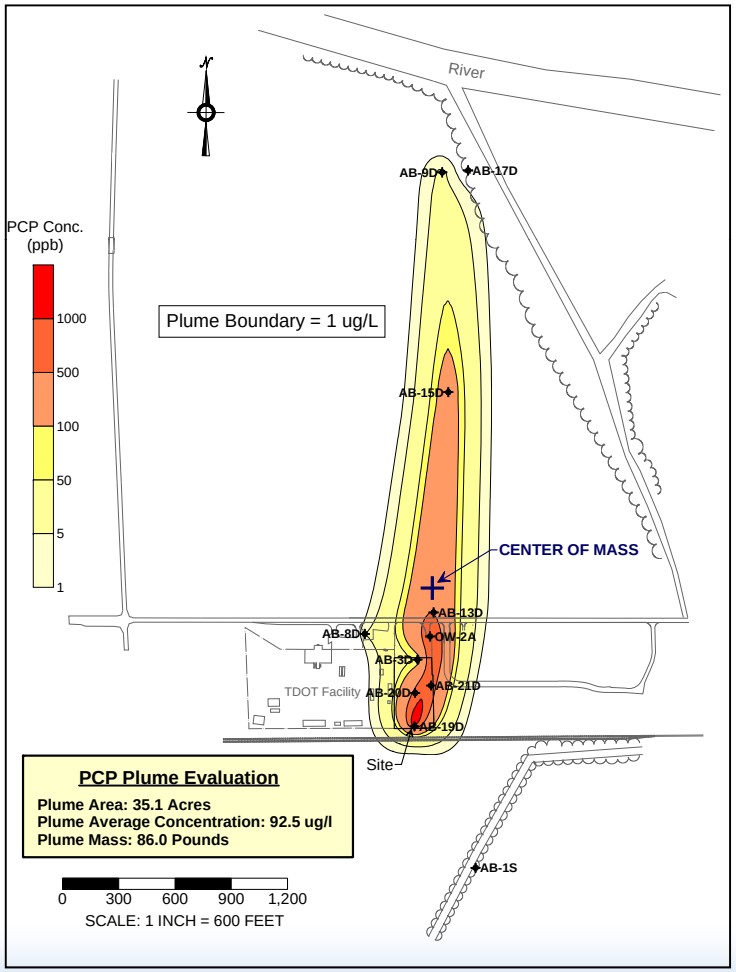
# Plume Stability - Existing Methods



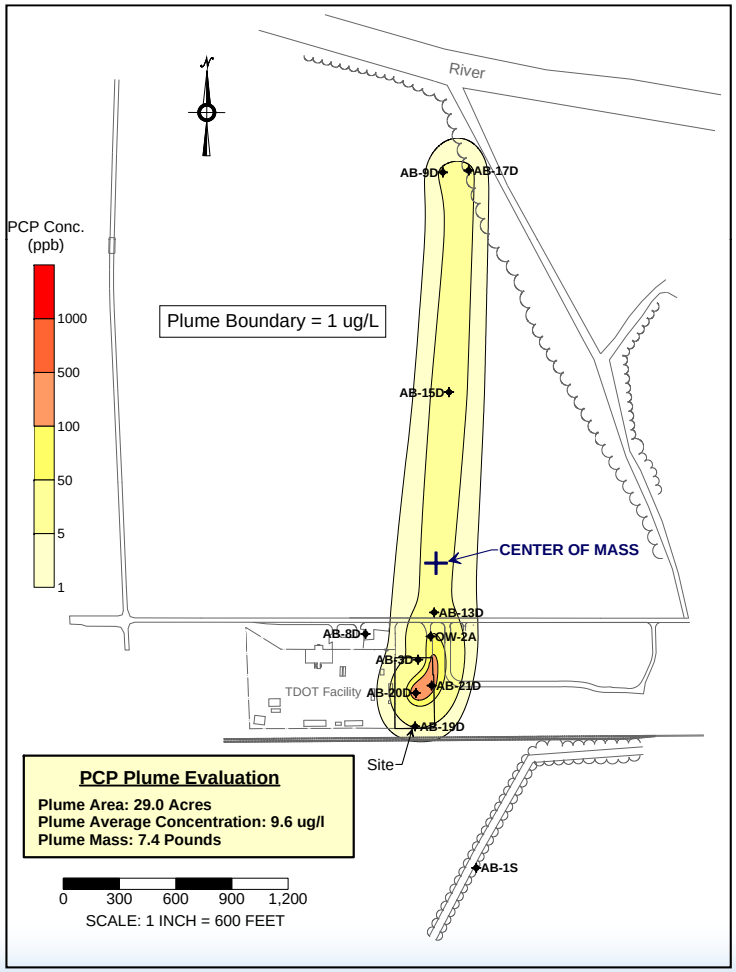



# Plume Stability - Existing Methods

## 1993 PCP Plume

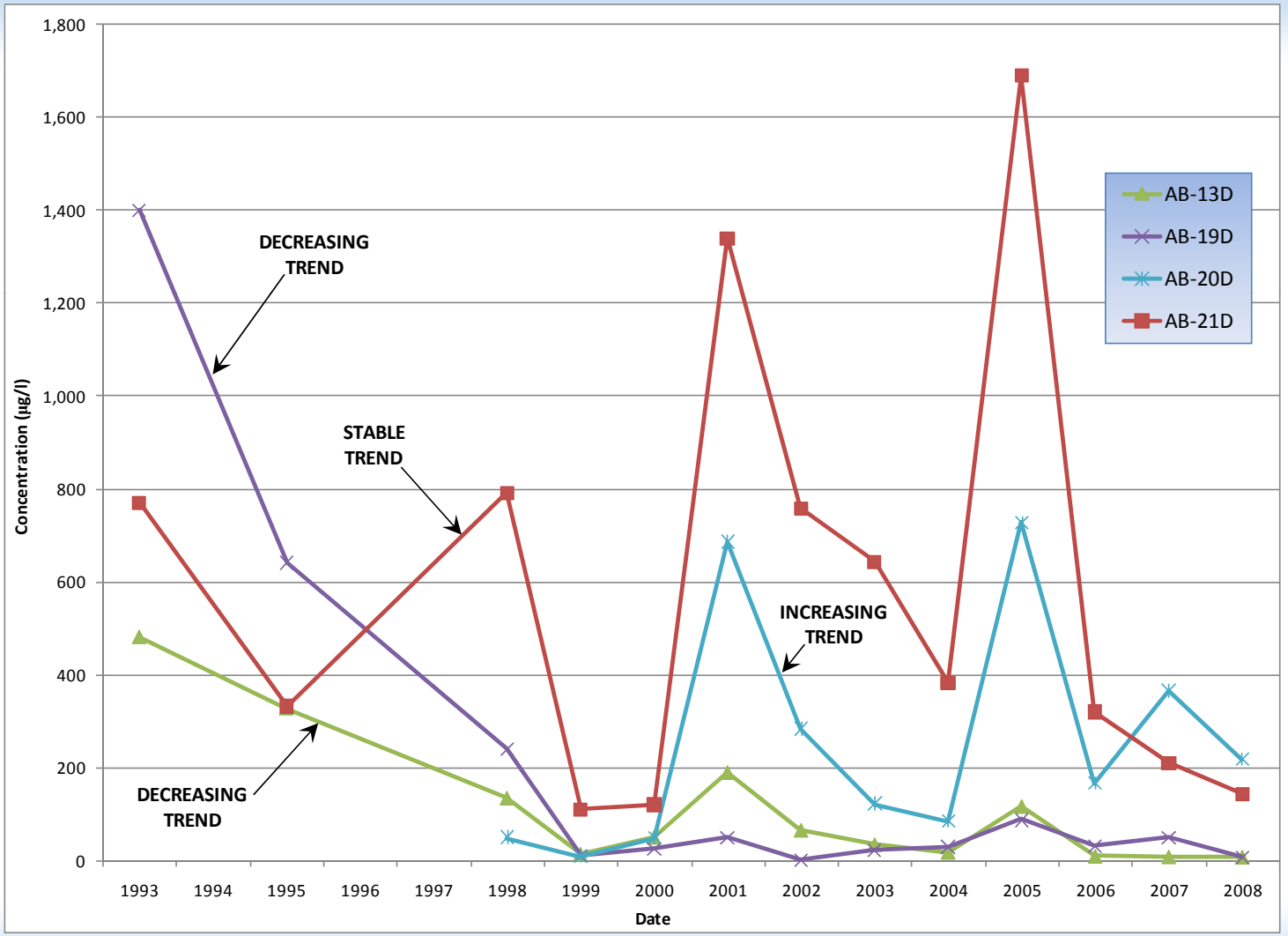



## 2008 PCP Plume

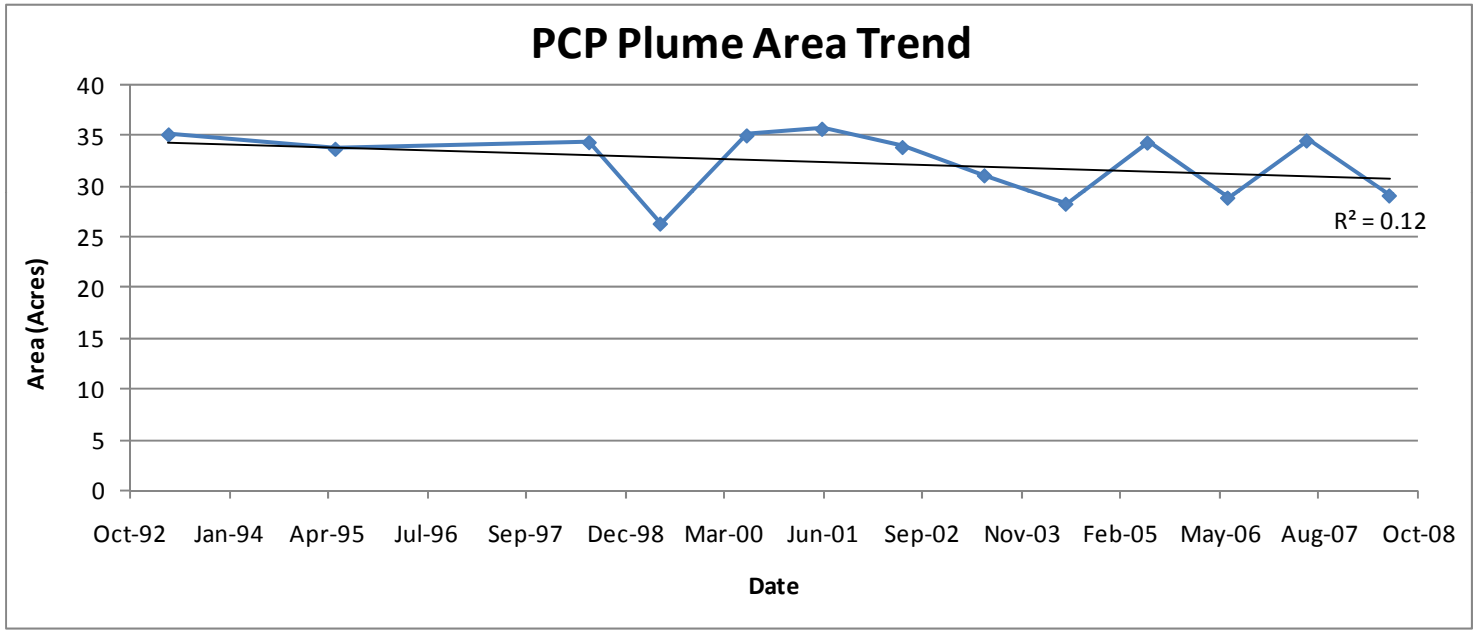


# Plume Stability - Existing Methods

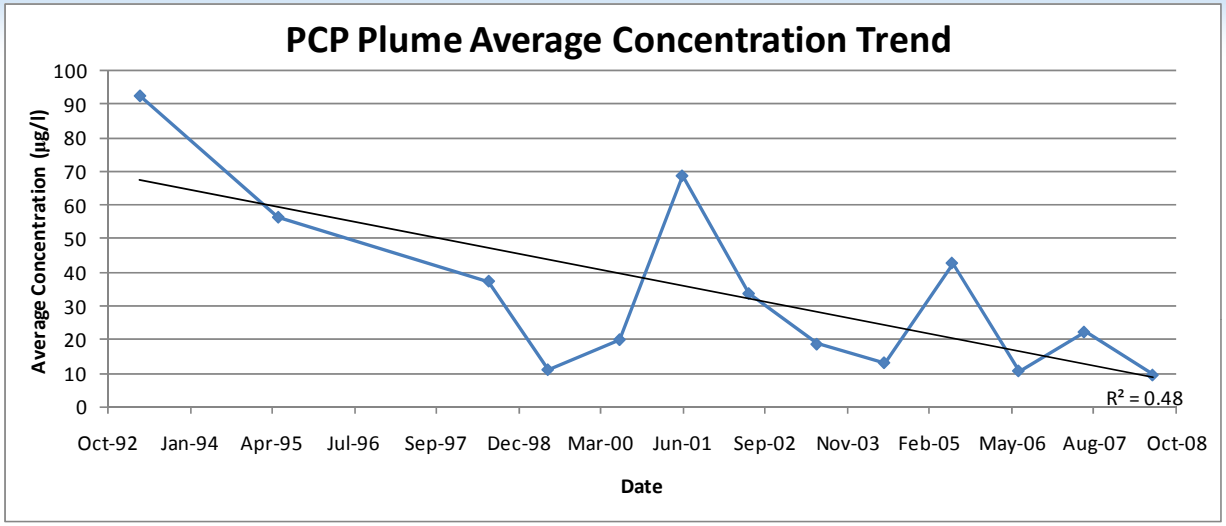
- PCP Plume
- 11 Wells

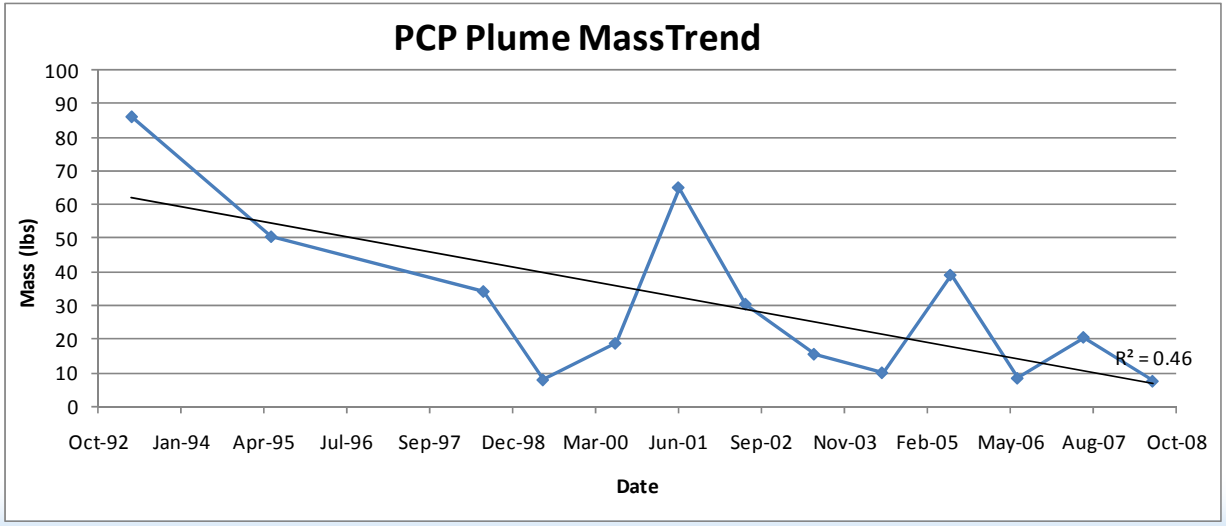


# Plume Stability - Existing Methods



# Plume Stability - Existing Methods



# Plume Stability - Existing Methods

- **Wisconsin DNR Closure Protocol Study – April 2009**
  - ***"Given concerns regarding single-well analysis…to estimate a contaminant reduction rate, consideration should be given to more robust analytical approaches. One approach is the spatial integration of observed concentrations over the groundwater sampling network to estimate total dissolved plume mass at various points in time."***

# Ricker Plume Stability Analysis Method

- **Effective method to evaluate trends in plume characteristics using visual and statistical methods.**
  - ***Area***
  - ***Average concentration***
  - ***Mass***
  - ***Location of plume center of mass***
  - ***Mass Flux***

- **Efficiently assimilates large volume of historical data into concise and meaningful analysis**

# Ricker Plume Stability Analysis Method

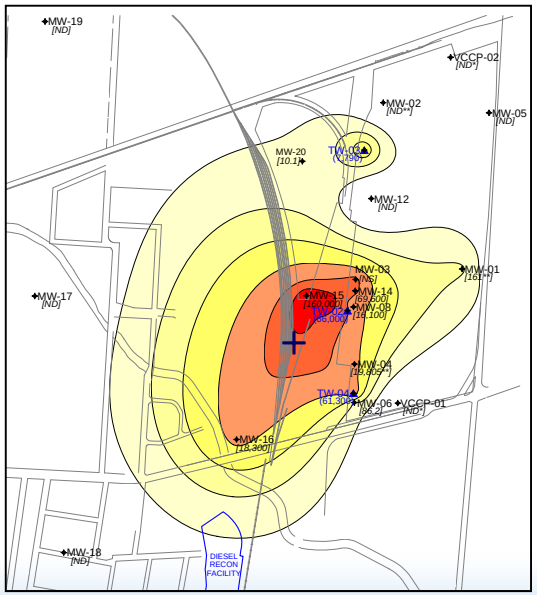
- **Excellent groundwater management tool**
  - ***Termination of remediation systems where low risk is demonstrated***
  - ***Basis for MNA***
  - ***Monitor progress of remediation system***

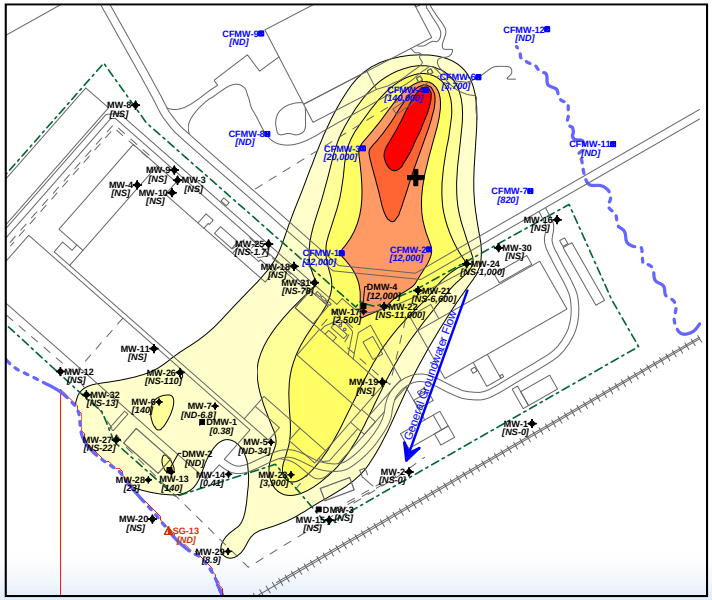
- **Ricker Method Highlighted by USEPA Region IV**
  - ***RCRA Showcase Pilot***
    - http://www.epa.gov/correctiveaction/showcase/rcra_pdf/r4_velsi.pdf

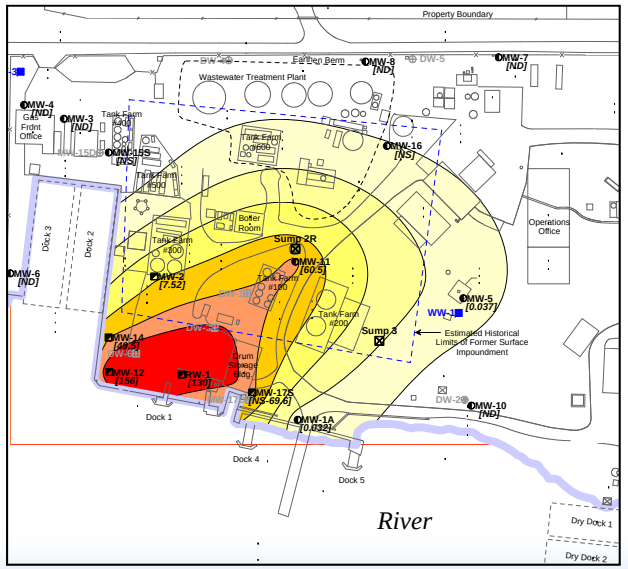
- **Methodology published in *Groundwater Monitoring & Remediation* 28, no. 4/ Fall 2008/pages 85–94**

# Ricker Plume Stability Analysis Method

- **Methodology**
  - ***Selection of indicator compound(s)***
  - ***Develop concentration isopleth maps***
    - *Each indicator compound*
    - *Each aquifer level (shallow, deep, etc.)*
    - *Plume boundary defined by MCL or site-specific level*



# Ricker Plume Stability Analysis Method

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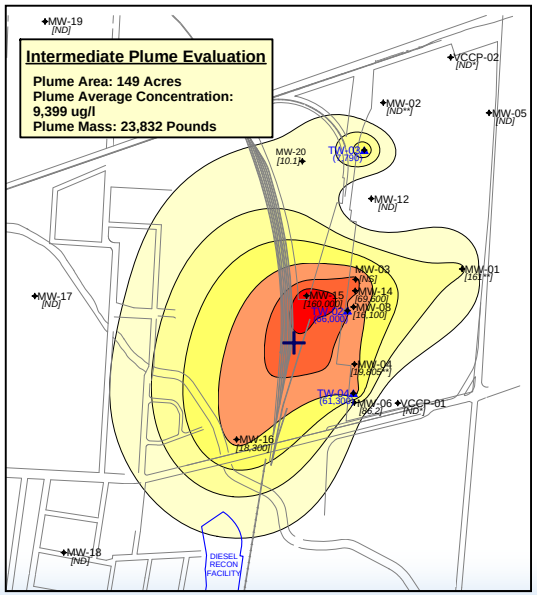
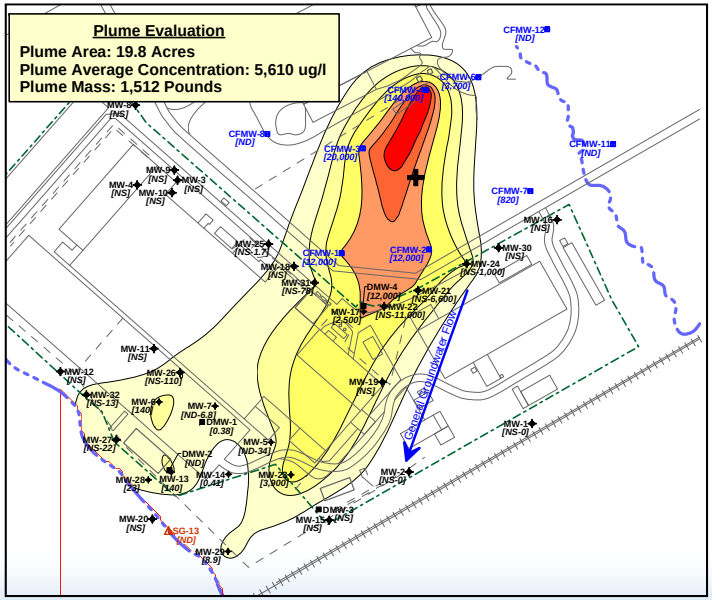
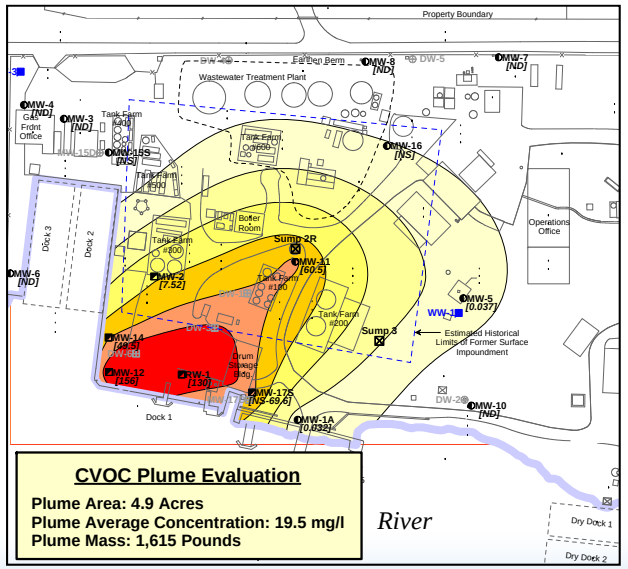
- **Methodology**
  - ***Calculate plume stability characteristics***
    - *Area*
    - *Average concentration*
    - *Mass*
    - *Center of mass*

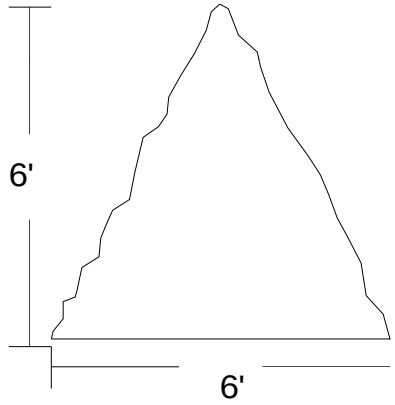


# Ricker Plume Stability Analysis Method

- **Example analogy calculation:**
  - ***Calculate planar area and average height of a conical shaped pile of soil.***

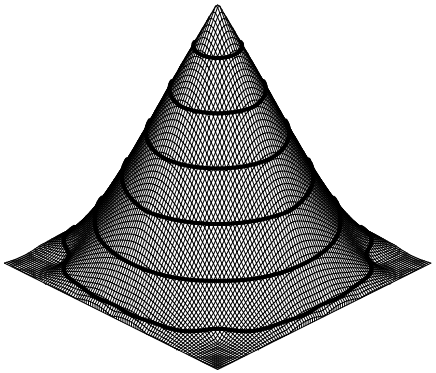



- Planar area; $A = \pi(r)^2 = \pi(3)^2 = 9\pi$ ft$^2$
- Volume; $V = 1/3 * \pi(r)^2 * h = 1/3 * \pi(3)^2 * 6 = 18\pi$ ft$^3$
- Average height (i.e., level) = V/A = 2 feet

# Ricker Plume Stability Analysis Method

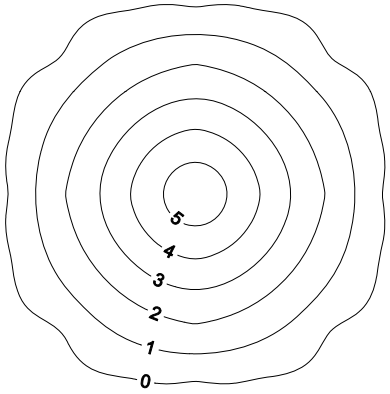
- **Same analogy calculation using Surfer:**

Grid representation of soil pile



Calculated volume of grid = 56.55 $ft^3$

Plan view contour map of soil pile




Calculated Planar Area = 28.27 $ft^2$

Average Height = 56.55 $ft^3$ / 28.27 $ft^2$ = 2.0 ft.

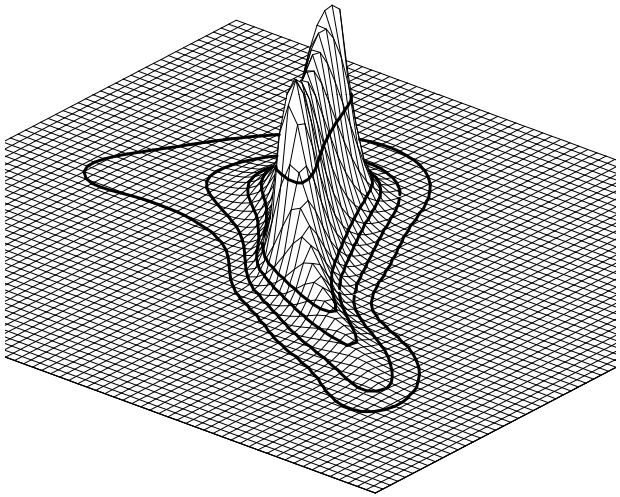
# Ricker Plume Stability Analysis Method

- **Same analogy applied to contaminant isopleth map:**

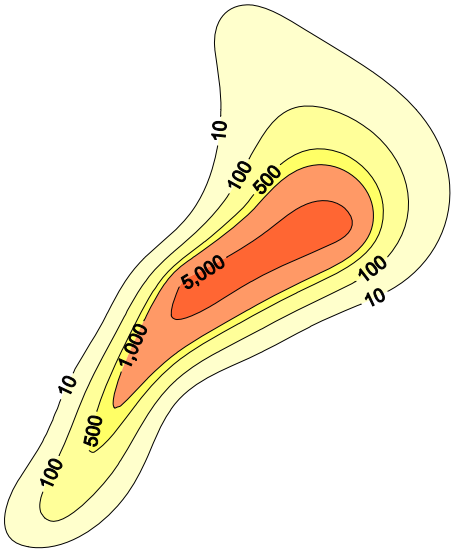
Naphthalene Data for 2005

| Well | X Coord. | Y Coord. | 2005 |
|---|---|---|---|
| DB-15 | 499256 | 99655 | NS |
| DB-18 | 499191 | 99566 | 9,400 |
| DB-21 | 498826 | 99626 | 560 |
| DB-22 | 498610 | 99350 | 7,600 |
| DB-23 | 499213 | 99031 | NS |
| DB-24 | 498686 | 98830 | NS |
| DB-25 | 498127 | 98508 | 190 |
| DB-26 | 497934 | 98867 | ND |
| DB-27 | 498152 | 99275 | ND |
| DB-28 | 498472 | 99668 | ND |
| DB-29 | 498803 | 100290 | 30 |
| DB-33 | 500120 | 98384 | NS |
| DB-34 | 497931 | 99369 | NS |
| DB-35 | 497720 | 98054 | ND |
| DB-36 | 497540 | 97495 | ND |
| DB-37 | 497586 | 98191 | ND |
| DB-38 | 497815 | 98017 | ND |
| DB-39 | 498279 | 98192 | ND |
| DB-40 | 498540 | 98304 | ND |
| DB-41 | 497382 | 97282 | ND |
| DB-42 | 496942 | 98579 | ND |
| DB-43 | 496756 | 97206 | ND |
| DB-44 | 498022 | 100539 | ND |

Grid representation of contaminant plume



Plan view contour map of contaminant plume




Calculated volume of grid = 1.35 x $10^9$ $ft^2$•µg/l

Calculated Planar Area = 1,269,220 $ft^2$

Average Height (Concentration) = 1.35 x $10^9$ $ft^2$•µg/l / 1,269,220 $ft^2$ = 1,062 µg/l

# Ricker Plume Stability Analysis Method

- **Calculation of Plume Center of Mass**
  - ***Grid File Containing 40,000 Nodes***

| Node | X | Y | Z |
|---|---|---|---|
| 1 | 498046 | 98387 | 10.422 |
| 2 | 498065 | 98387 | 10.770 |
| 3 | 498084 | 98387 | 10.740 |
| ↓ | ↓ | ↓ | ↓ |
| 40,000 | 500530 | 100713 | 0.003 |

  - ***Centroid of Grid = Moment around Grid Origin (i.e., concentration weighted average coordinate)***
    - *Center of Mass X Coordinate* = $\frac{\sum_{n=1}^{40,000} X * Z}{\sum_{n=1}^{40,000} Z}$
    - *Center of Mass Y Coordinate* = $\frac{\sum_{n=1}^{40,000} Y * Z}{\sum_{n=1}^{40,000} Z}$

# Ricker Plume Stability Analysis Method

- **Center of Mass Calculated Using Spreadsheet**

| Node | X | Y | Z | XZ | YZ |
|---|---|---|---|---|---|
| 1 | 498046 | 98387 | 10.422 | 5190766 | 1025413 |
| 2 | 498065 | 98387 | 10.770 | 5364014 | 1059597 |
| 3 | 498084 | 98387 | 10.740 | 5349547 | 1056699 |
| ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| 40,000 | 500530 | 100713 | 0.003 | 1574 | 317 |
| | Totals | | 4.07E+06 | 2.03E+12 | 4.05E+11 |

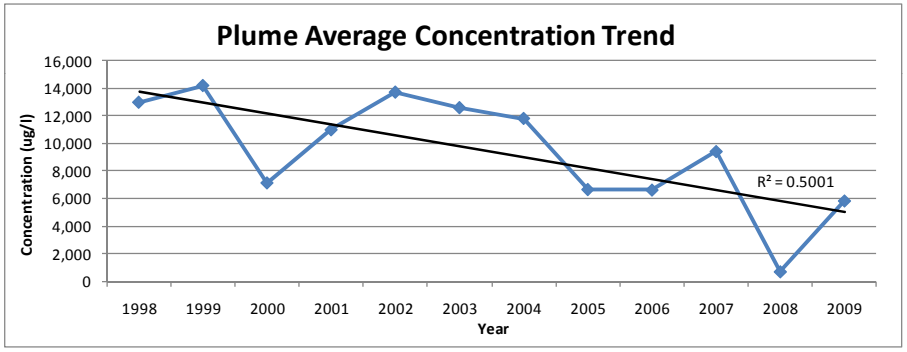
$$\text{Center of Mass X Coordinate} = \frac{\sum_{n=1}^{40,000} X * Z}{\sum_{n=1}^{40,000} Z} = \frac{2.03\text{E}+12}{4.07\text{E}+06} = 498867$$

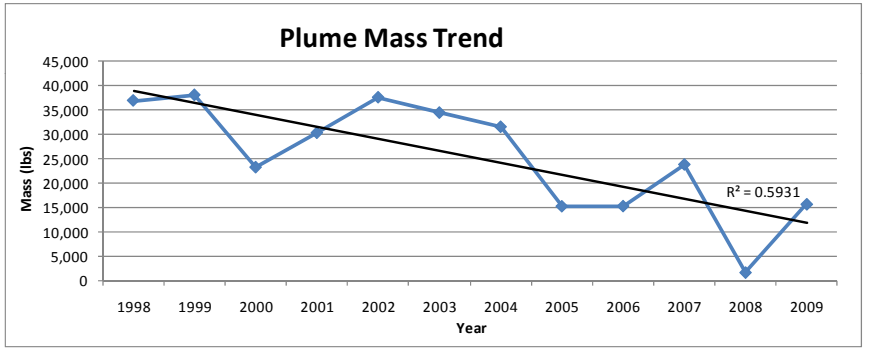
$$\text{Center of Mass Y Coordinate} = \frac{\sum_{n=1}^{40,000} Y * Z}{\sum_{n=1}^{40,000} Z} = \frac{4.05\text{E}+11}{4.07\text{E}+06} = 99429$$

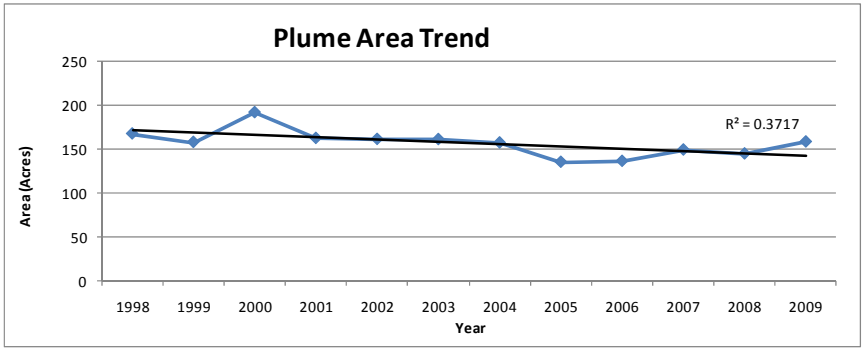
# Ricker Plume Stability Analysis Method

## Methodology

- ***Evaluate temporal trends in plume characteristics using statistical methods***




**Mann-Kendall Trend Analysis Summary**

| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Plume Area | 12 | -34 | 98.8% | 0.10 | Decreasing Trend |
| Plume Average Concentration | 12 | -40 | 99.6% | 0.43 | Decreasing Trend |
| Plume Mass | 12 | -38 | 99.4% | 0.44 | Decreasing Trend |

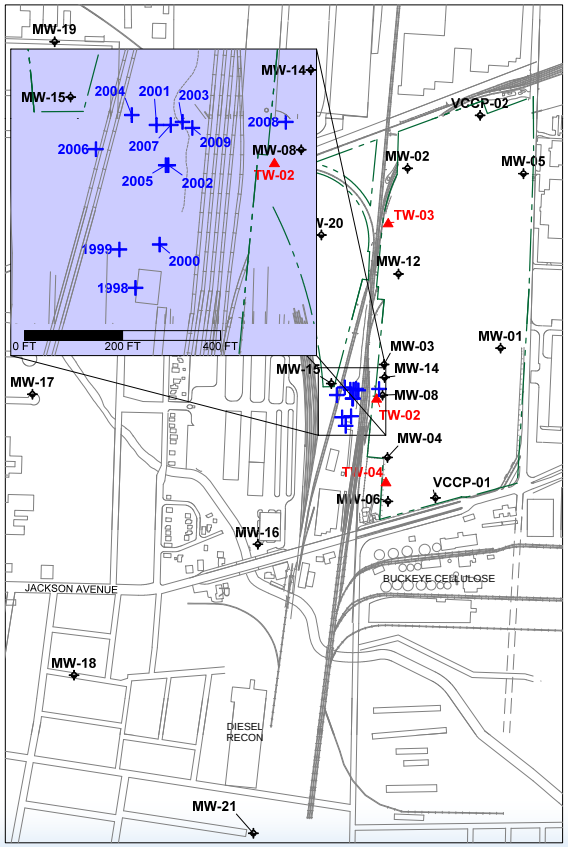
**Linear Regression Trend Analysis Summary**

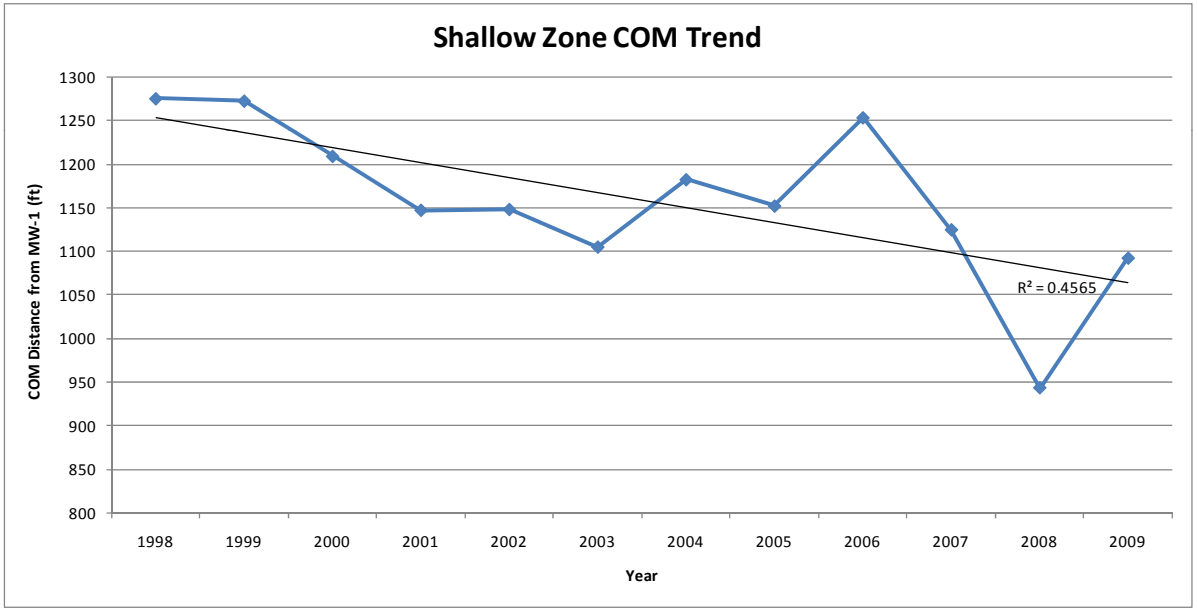
| Parameter | # of samples, n | Slope ($yr^{-1}$) | $R^2$ | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|---|
| Plume Area | 12 | -2.56 | 0.37 | 96.5% | 0.10 | Decreasing Trend |
| Plume Average Concentration | 12 | -452 | 0.43 | 97.9% | 0.43 | Decreasing Trend |
| Plume Mass | 12 | -3,211 | 0.56 | 99.5% | 0.44 | Decreasing Trend |

# Ricker Plume Stability Analysis Method

## Methodology

- ***Evaluate temporal trends in plume characteristics using statistical methods***




**Mann-Kendall Trend Analysis**

n = 12
S Statistic = -36
Confidence Factor = 99.2%
Coeff. of Variation = 0.08
Conclusion: Decreasing Trend

**Linear Regression Trend Analysis**

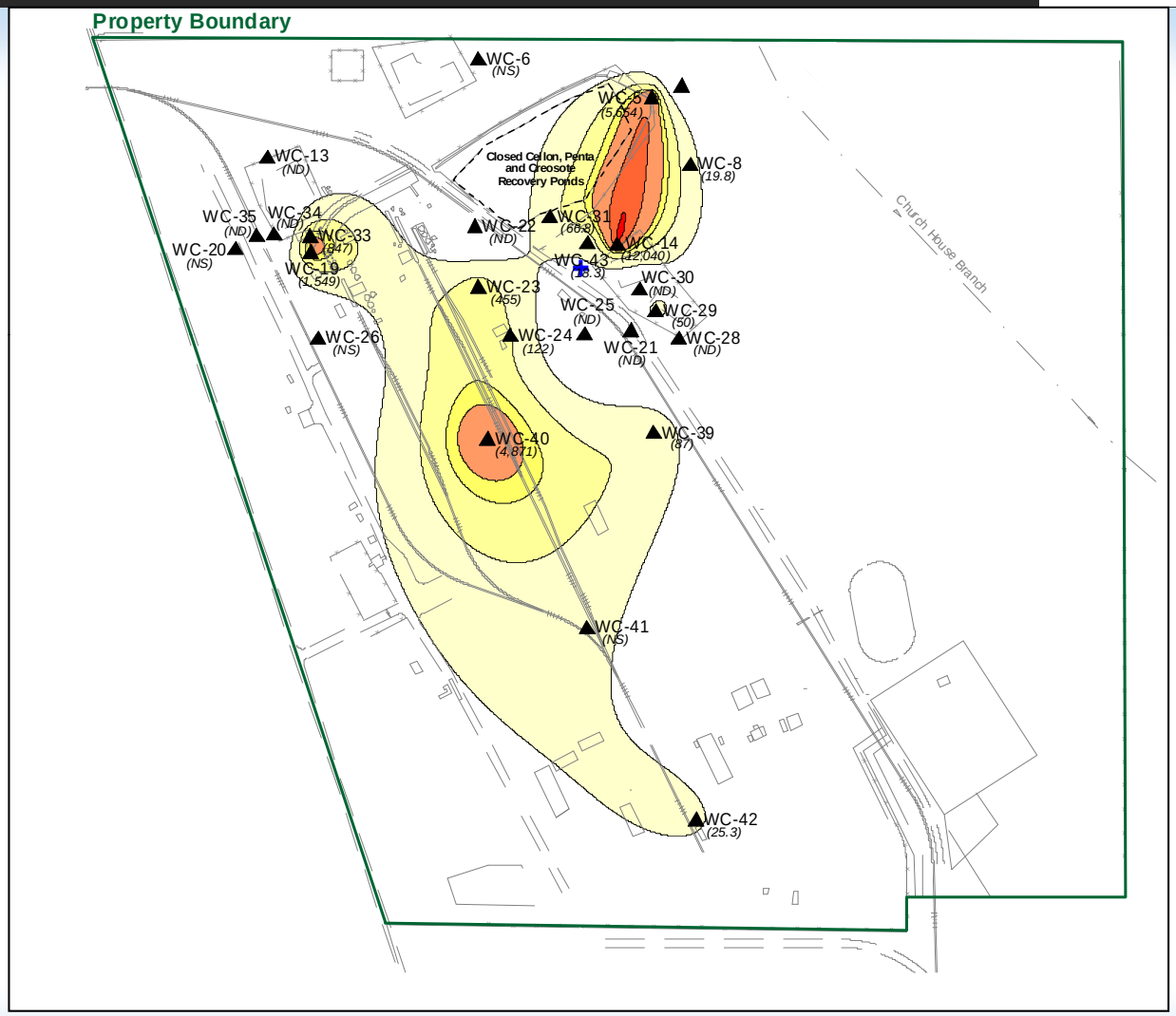
n = 12
Slope = -17.3
$R^2$ = 0.46
Confidence Factor = 98.4%
Coeff. of Variation = 0.08
Conclusion: Decreasing Trend

# Plume Stability Analysis - Example Site 1

- Wood Treating Site in South Mississippi
- Naphthalene Plume
- GW P&T system Operation Through 2002
- Plume Stability Analysis was Basis for Termination of P&T System

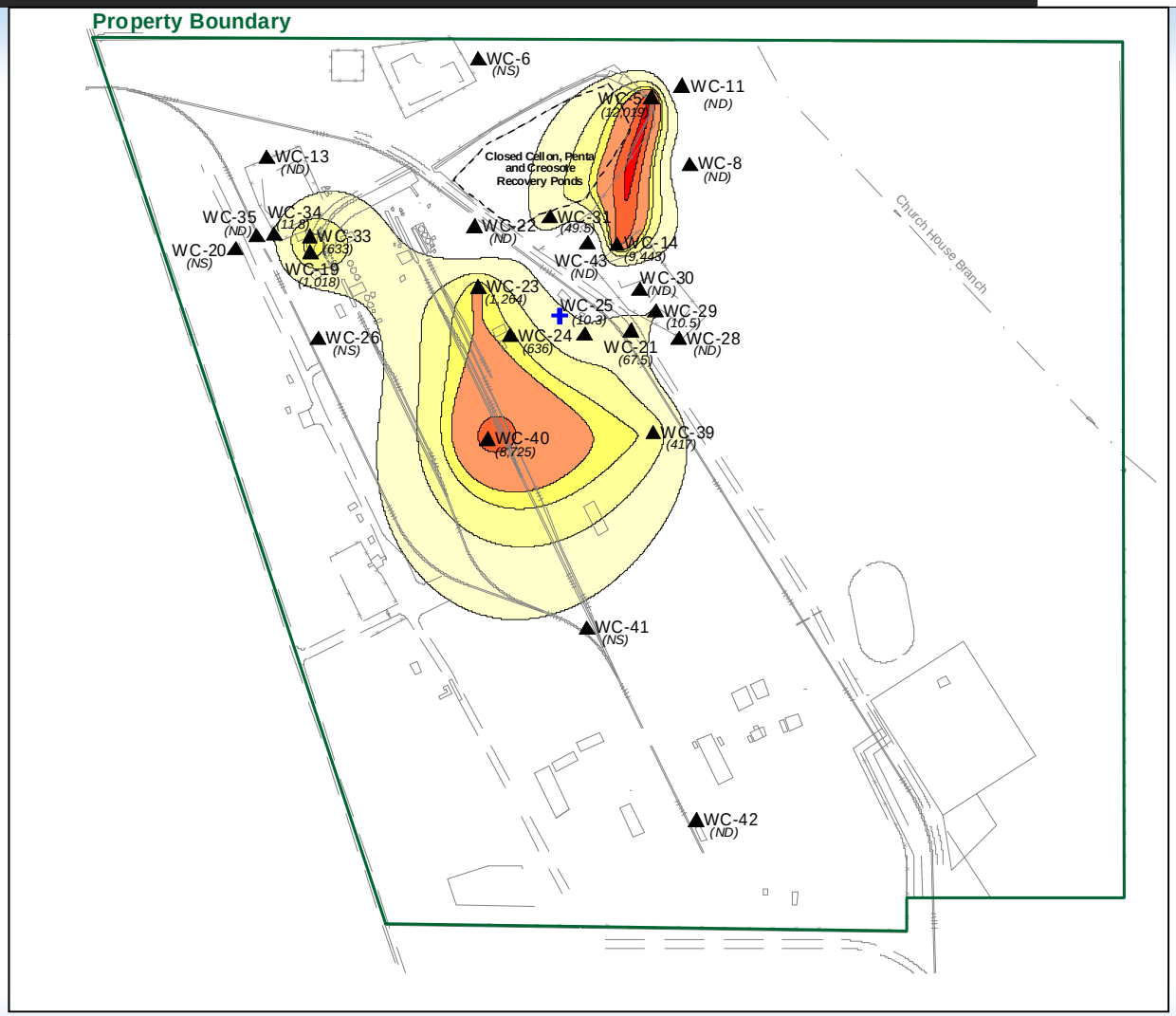
# Naphthalene Time Series

1991



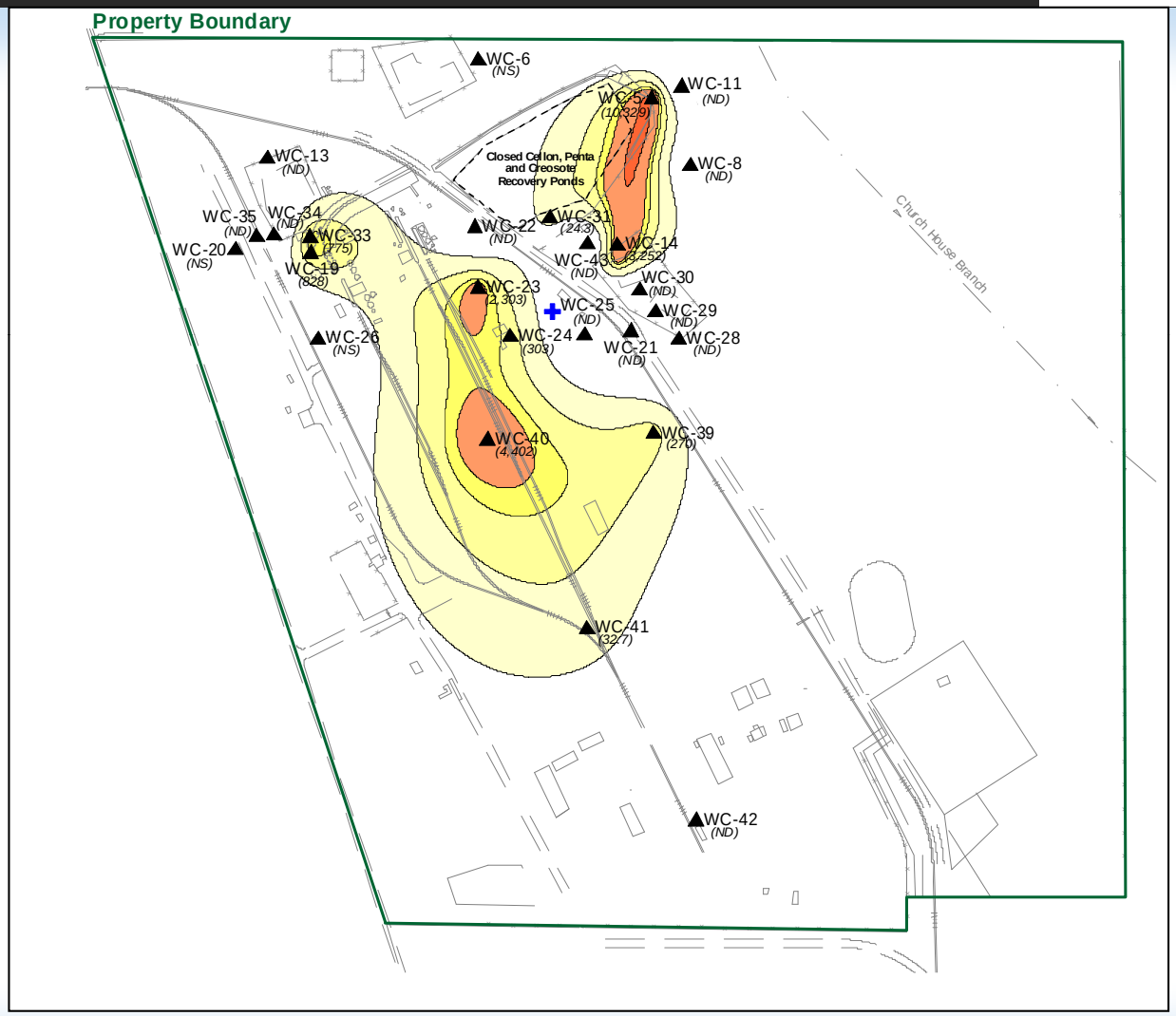
# Naphthalene Time Series

1992



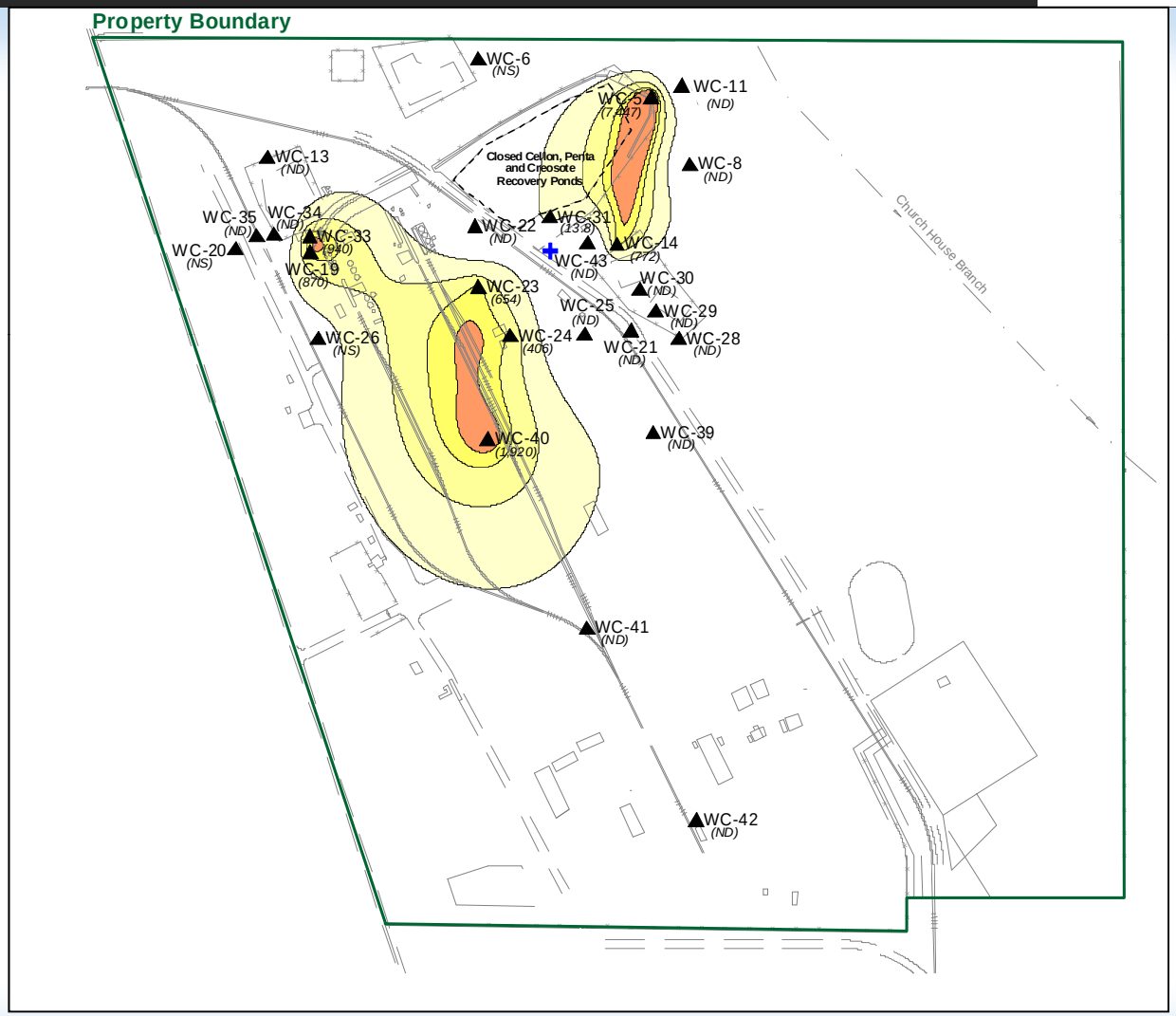
# Naphthalene Time Series

1993



# Naphthalene Time Series

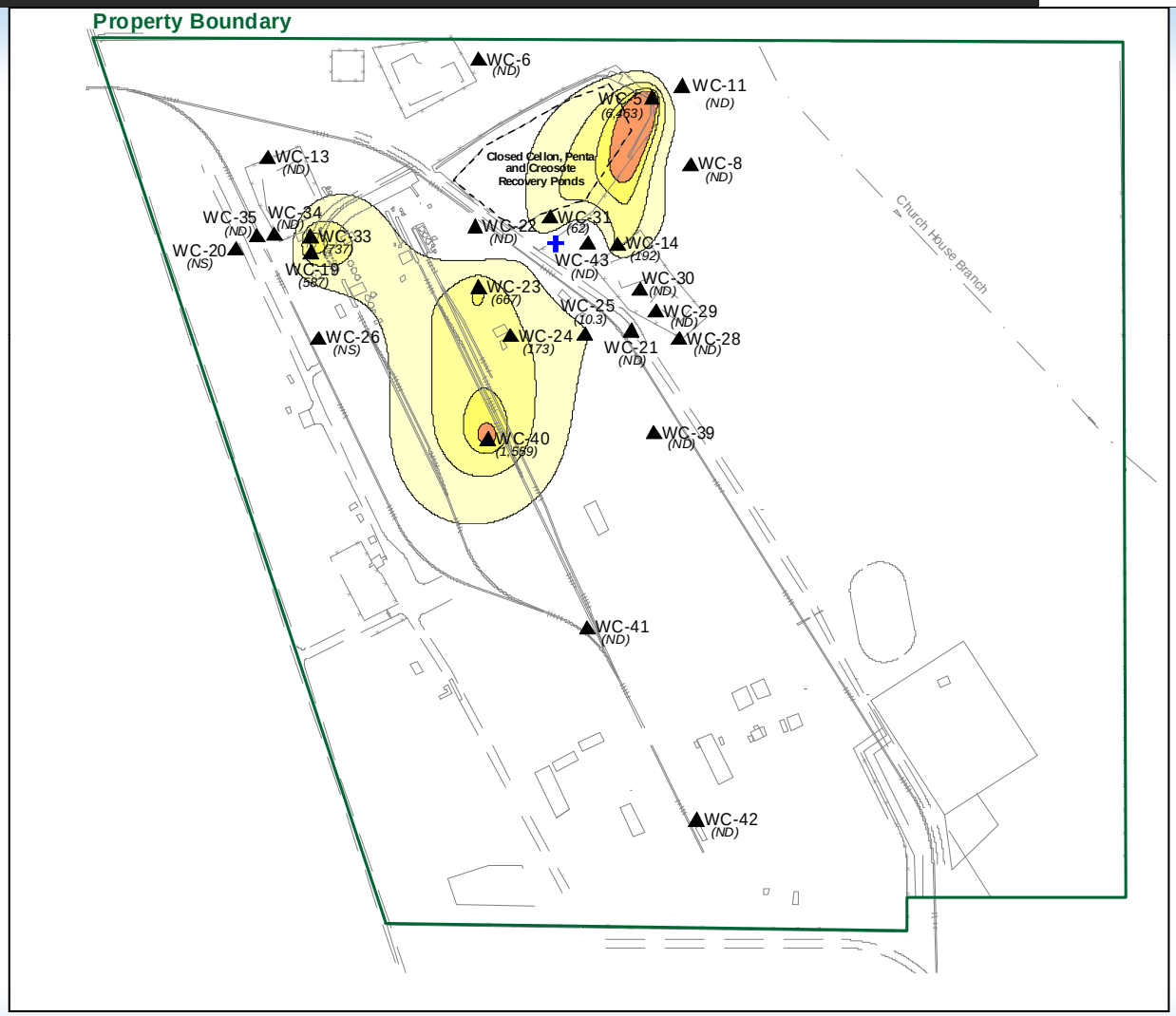
1994



# Naphthalene Time Series

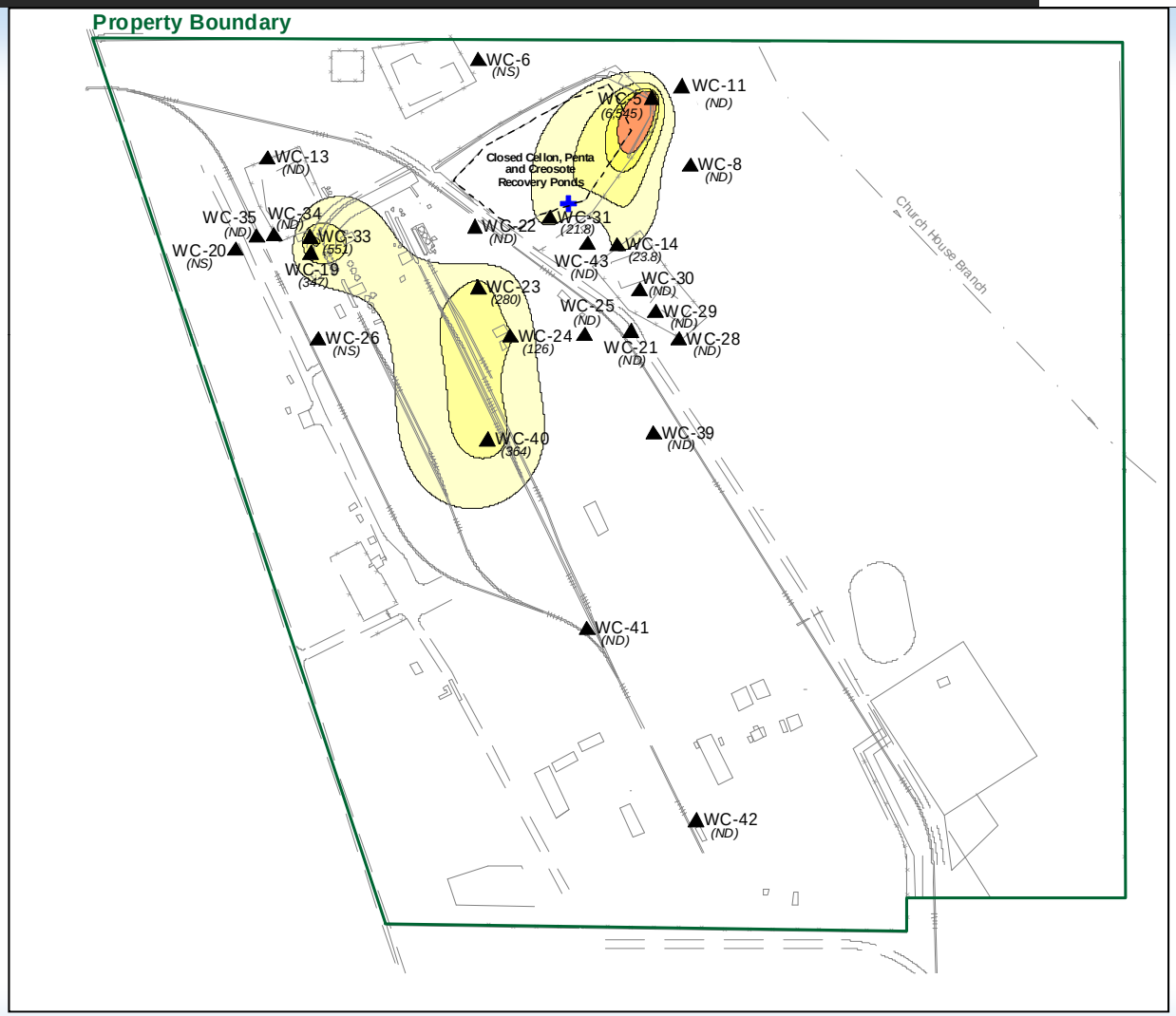
PREMIER ENVIRONMENTAL SERVICES, INC

1995



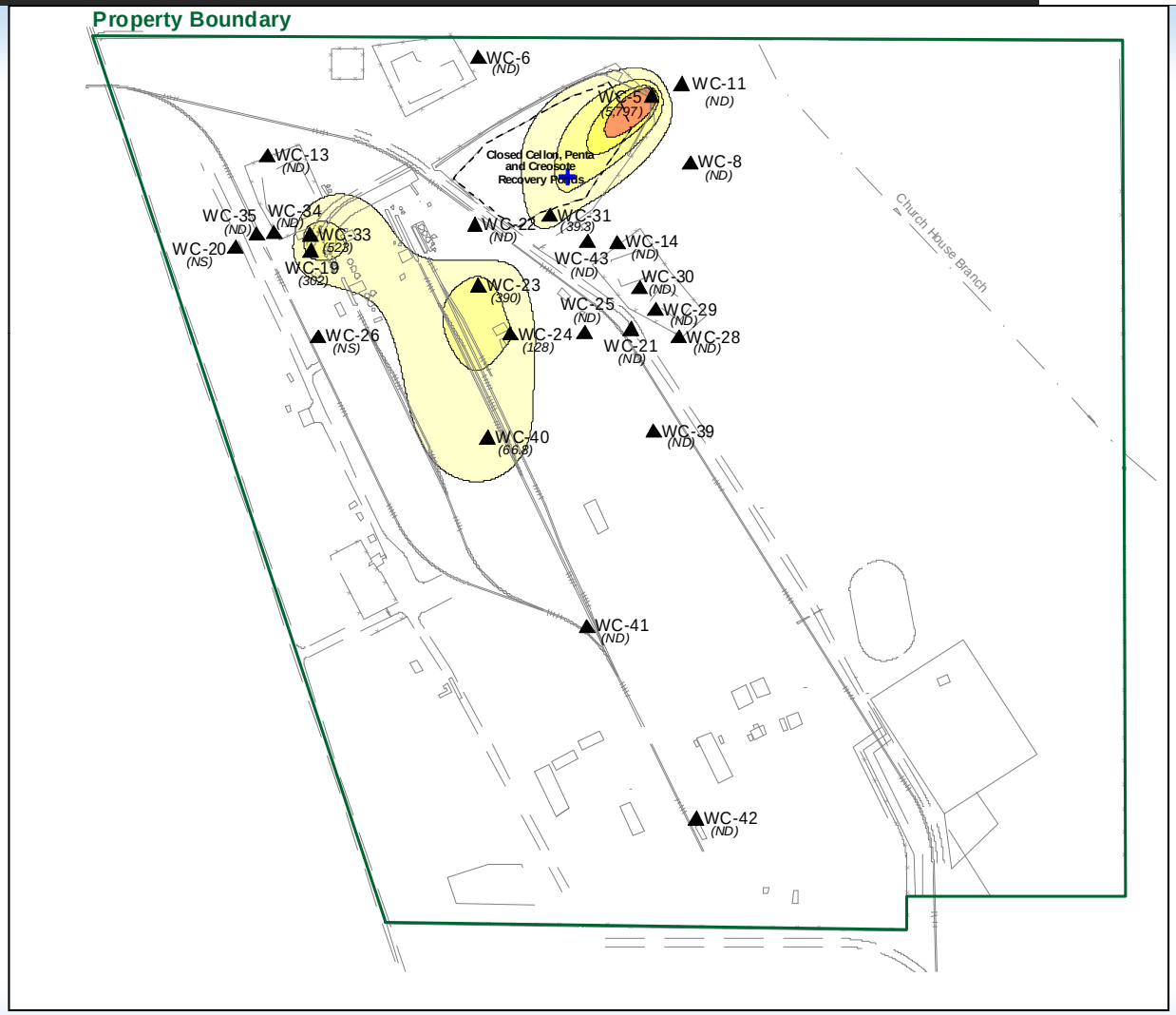
# Naphthalene Time Series

1996



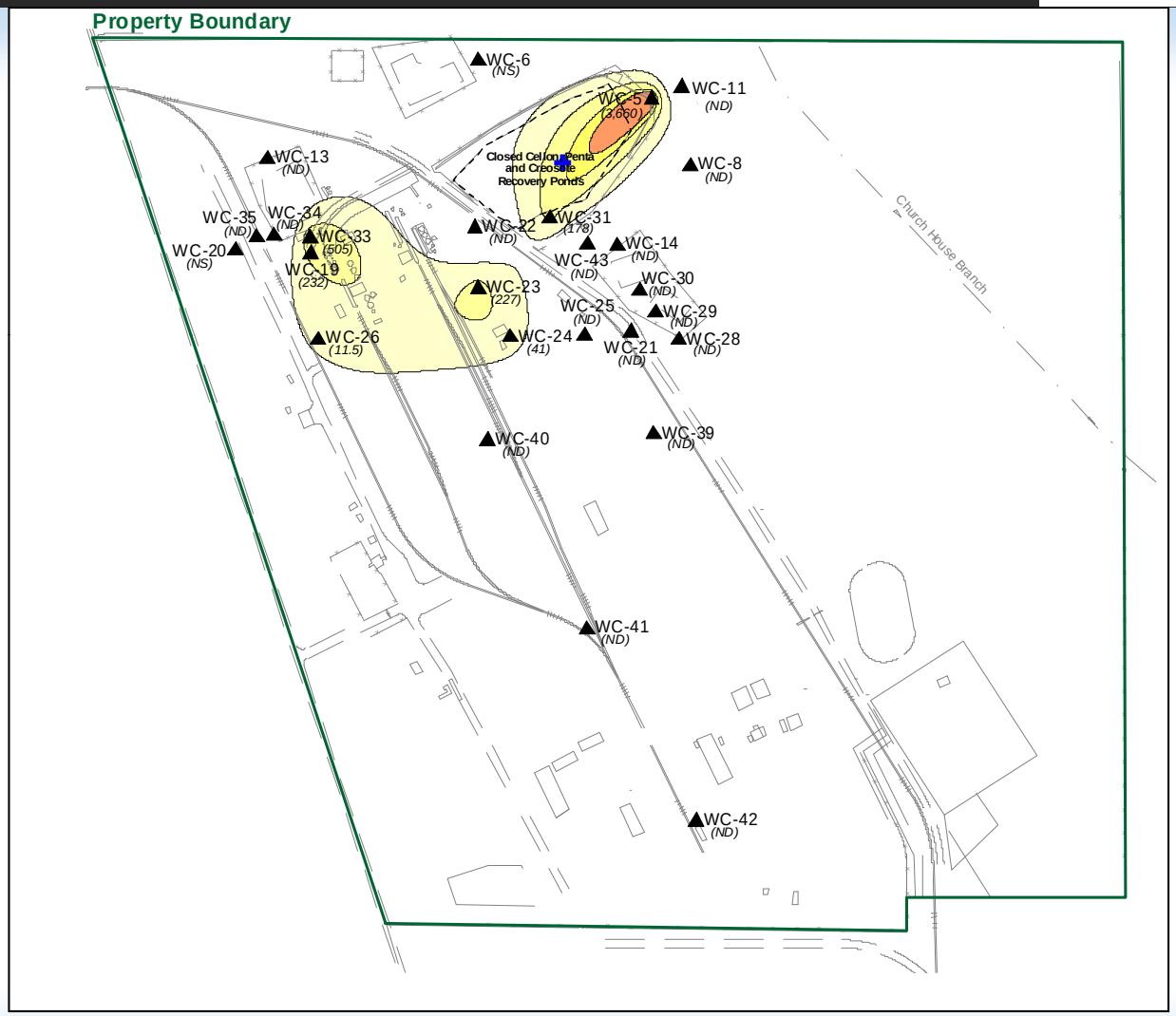
# Naphthalene Time Series

1997



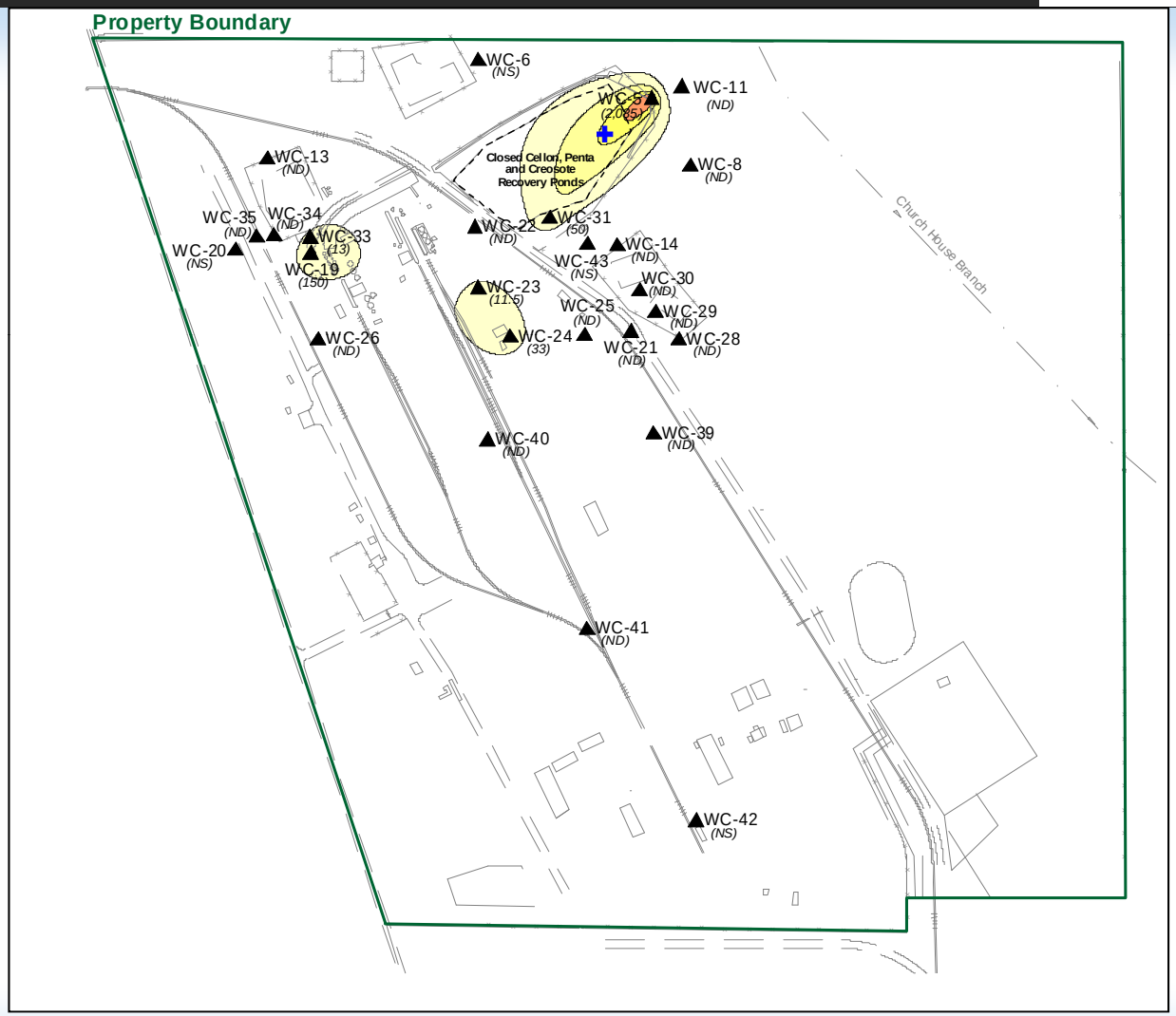
# Naphthalene Time Series

1998



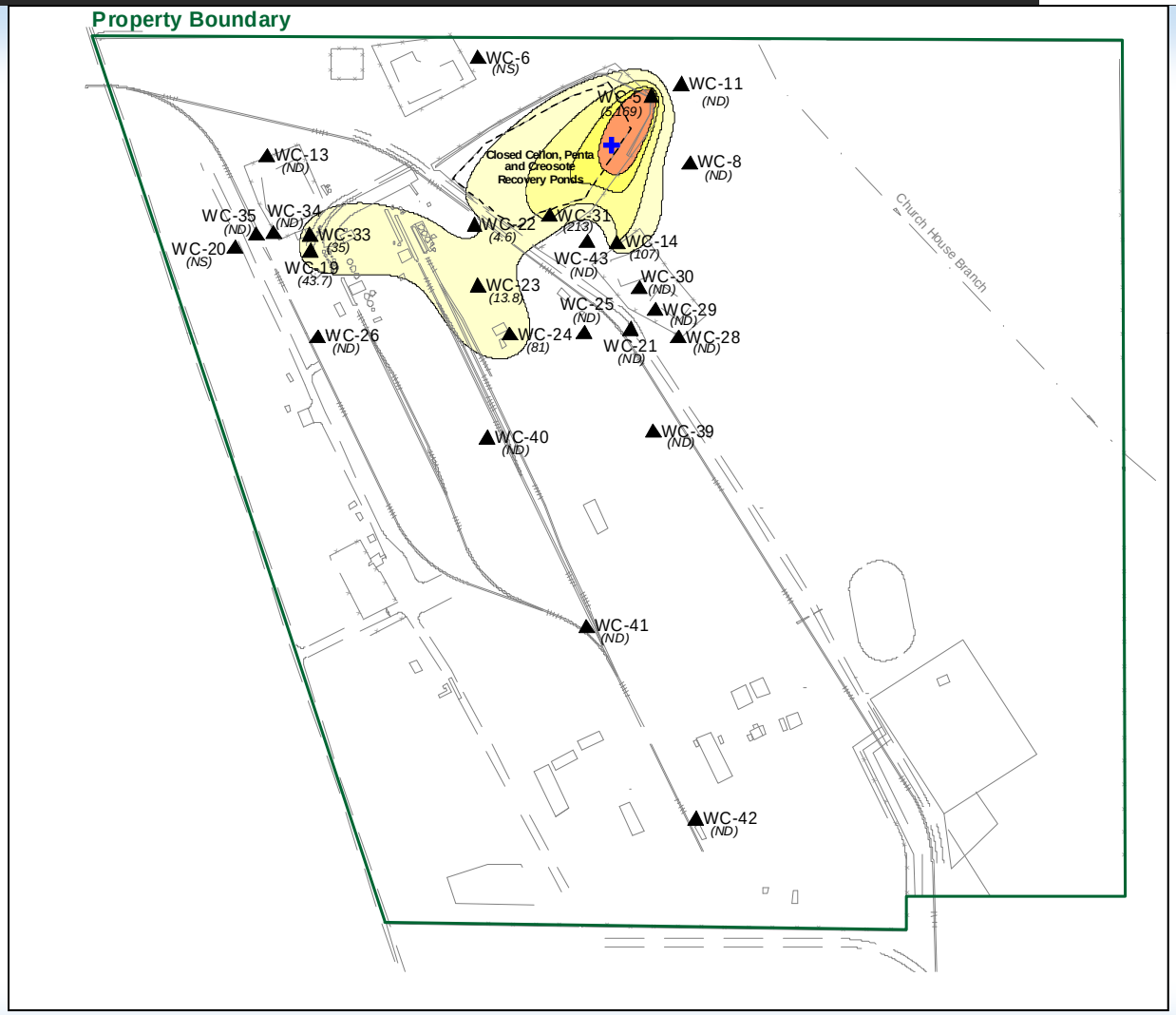
# Naphthalene Time Series

1999



# Naphthalene Time Series

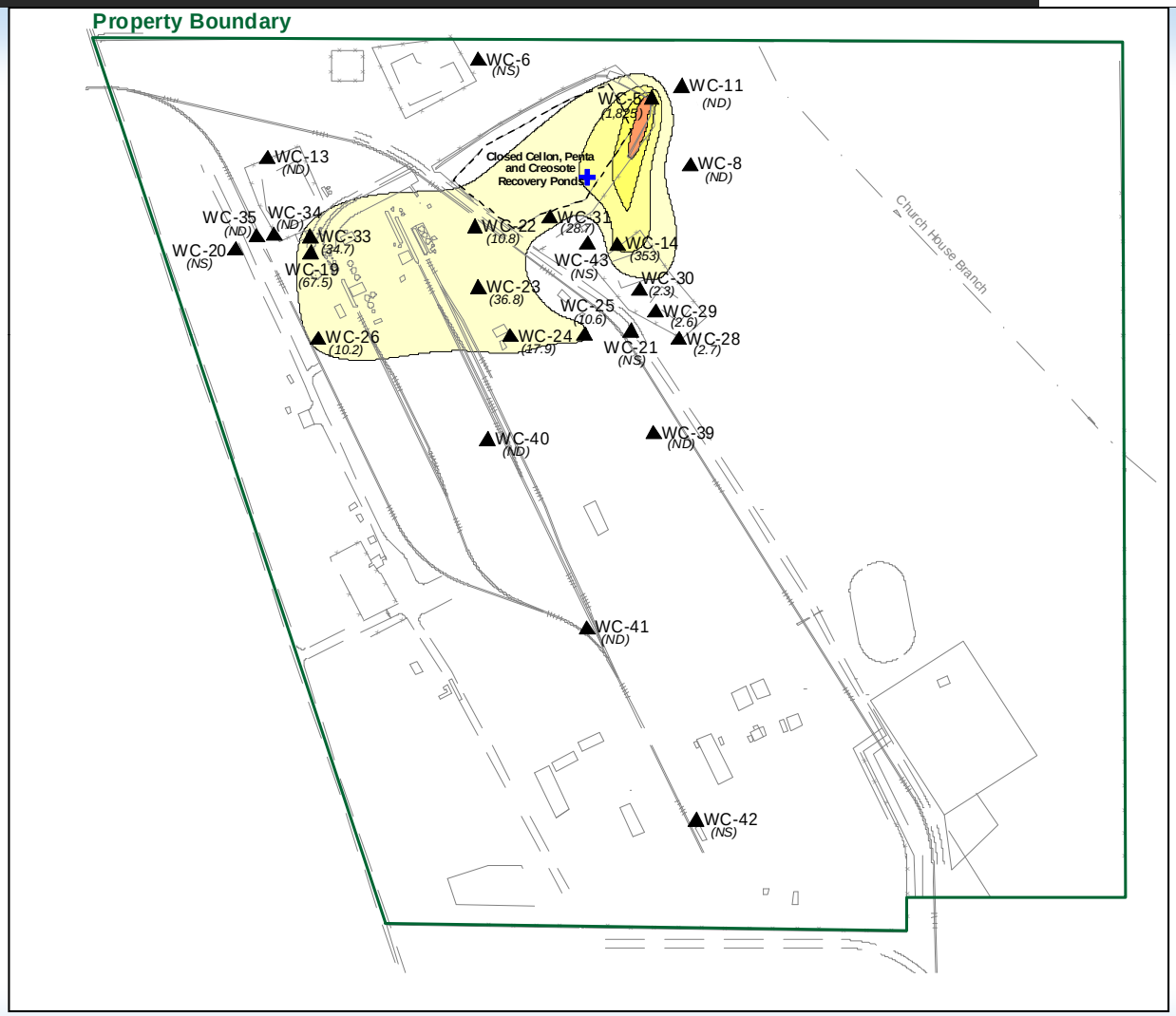
2000



# Naphthalene Time Series

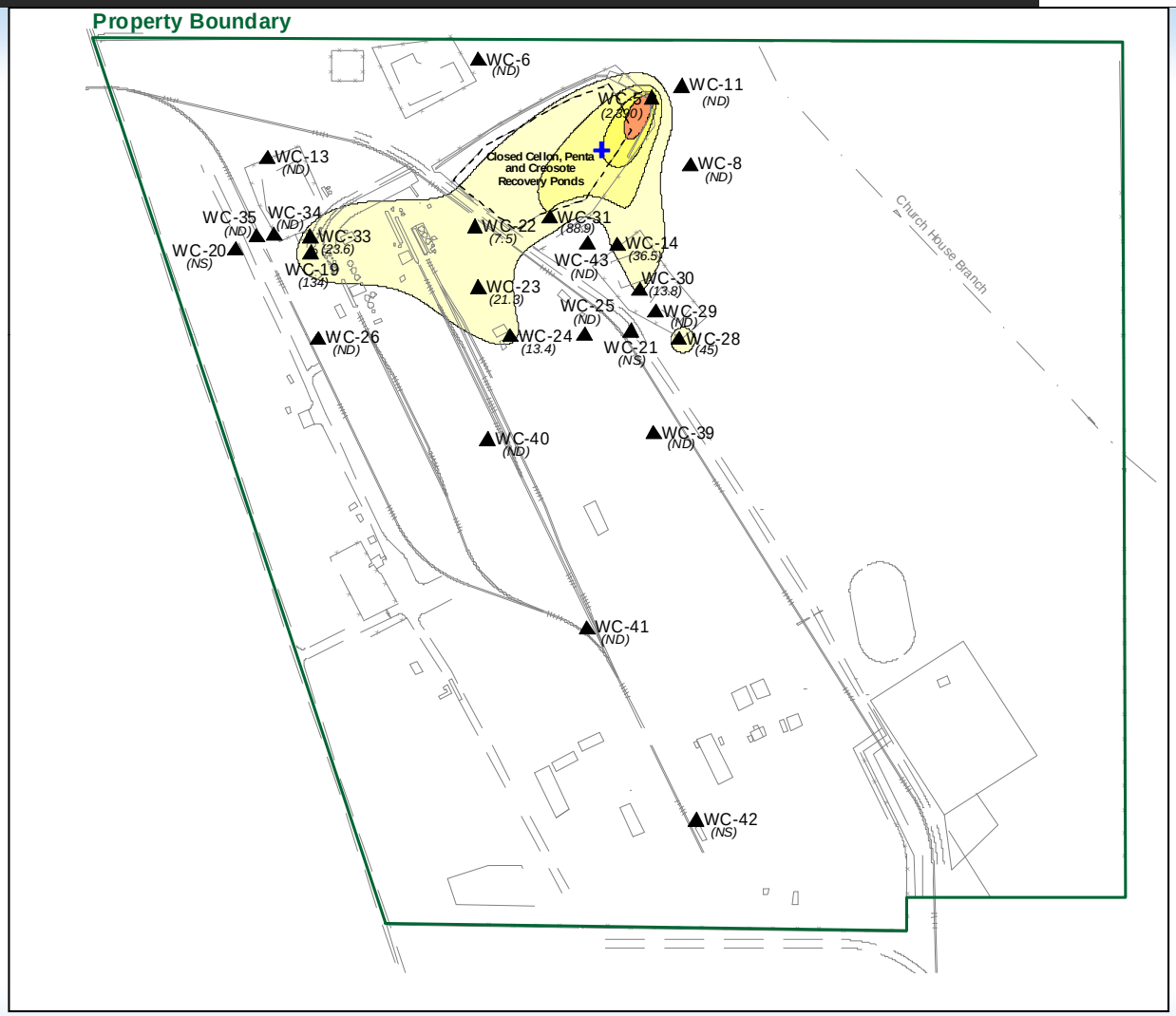
PREMIER ENVIRONMENTAL SERVICES, INC

## 2001



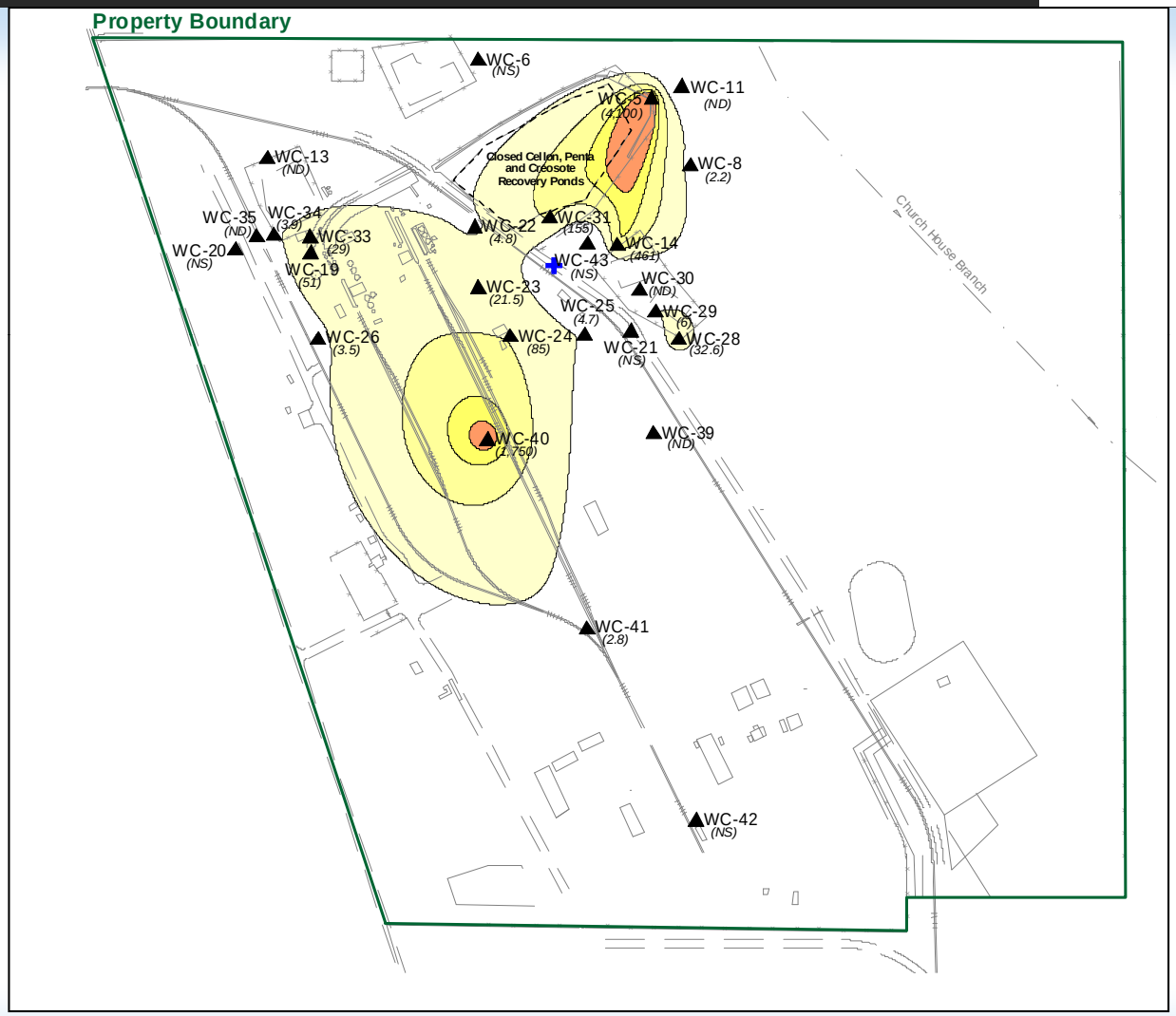
# Naphthalene Time Series

2002



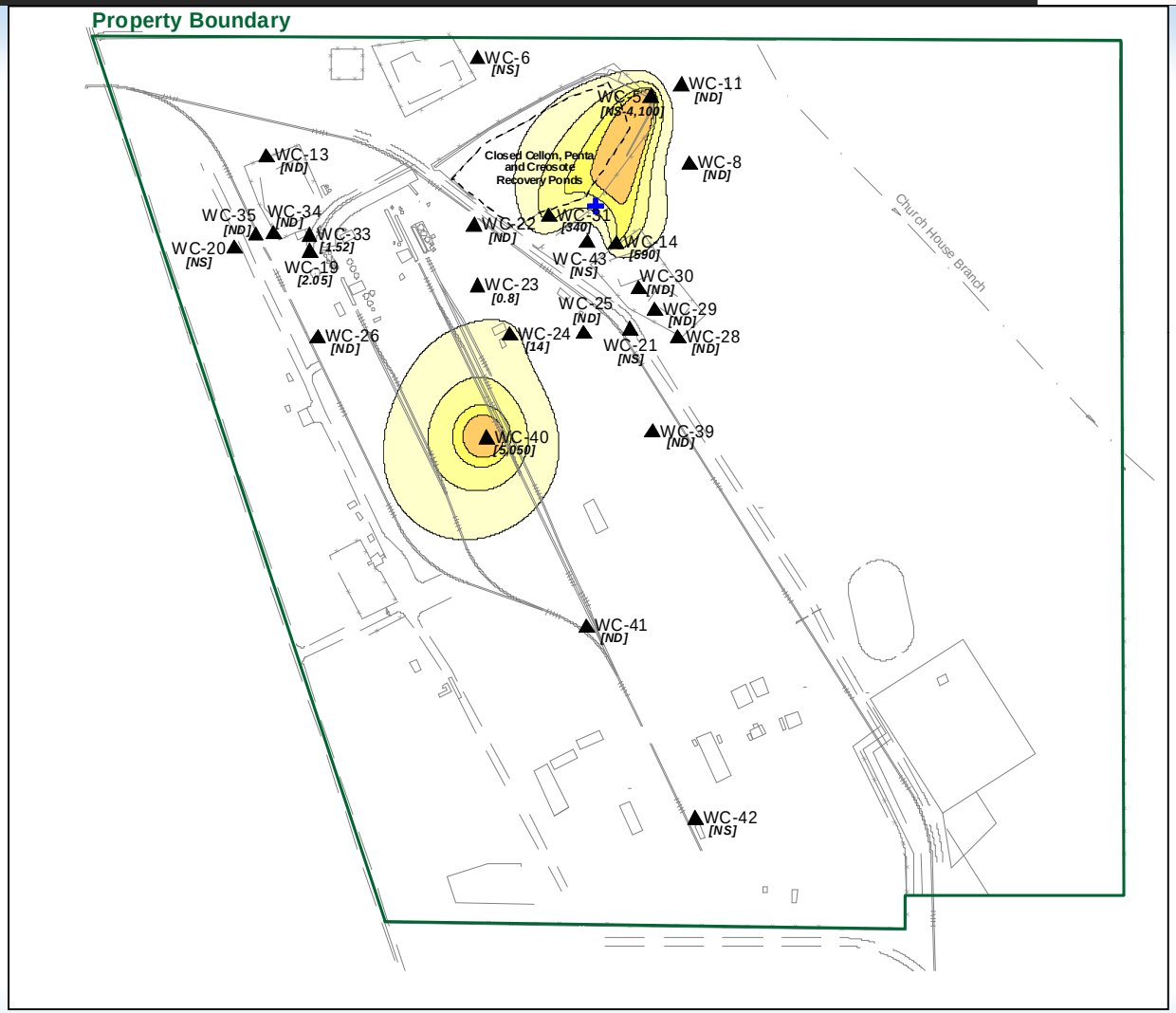
# Naphthalene Time Series

2003



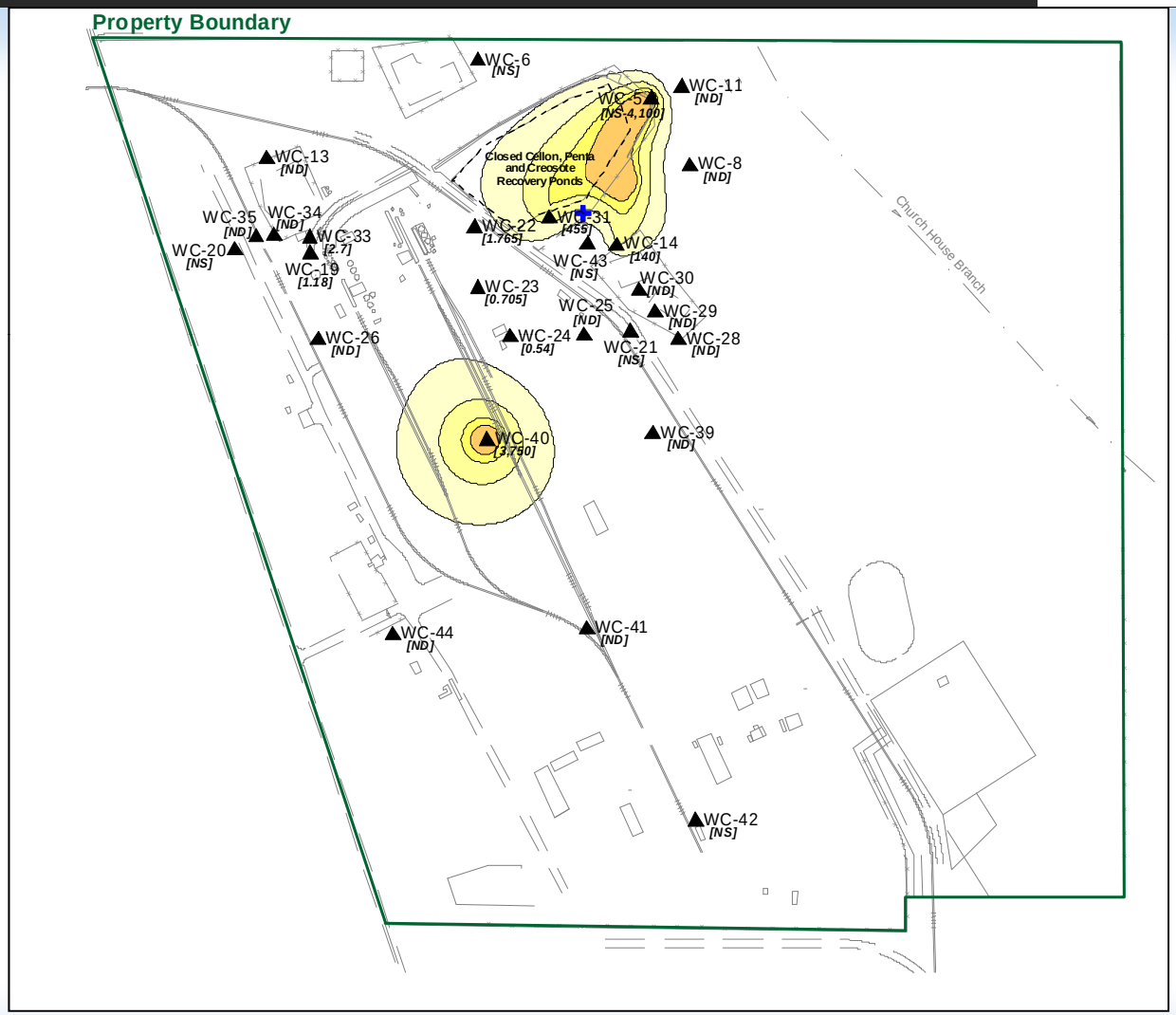
# Naphthalene Time Series

2004



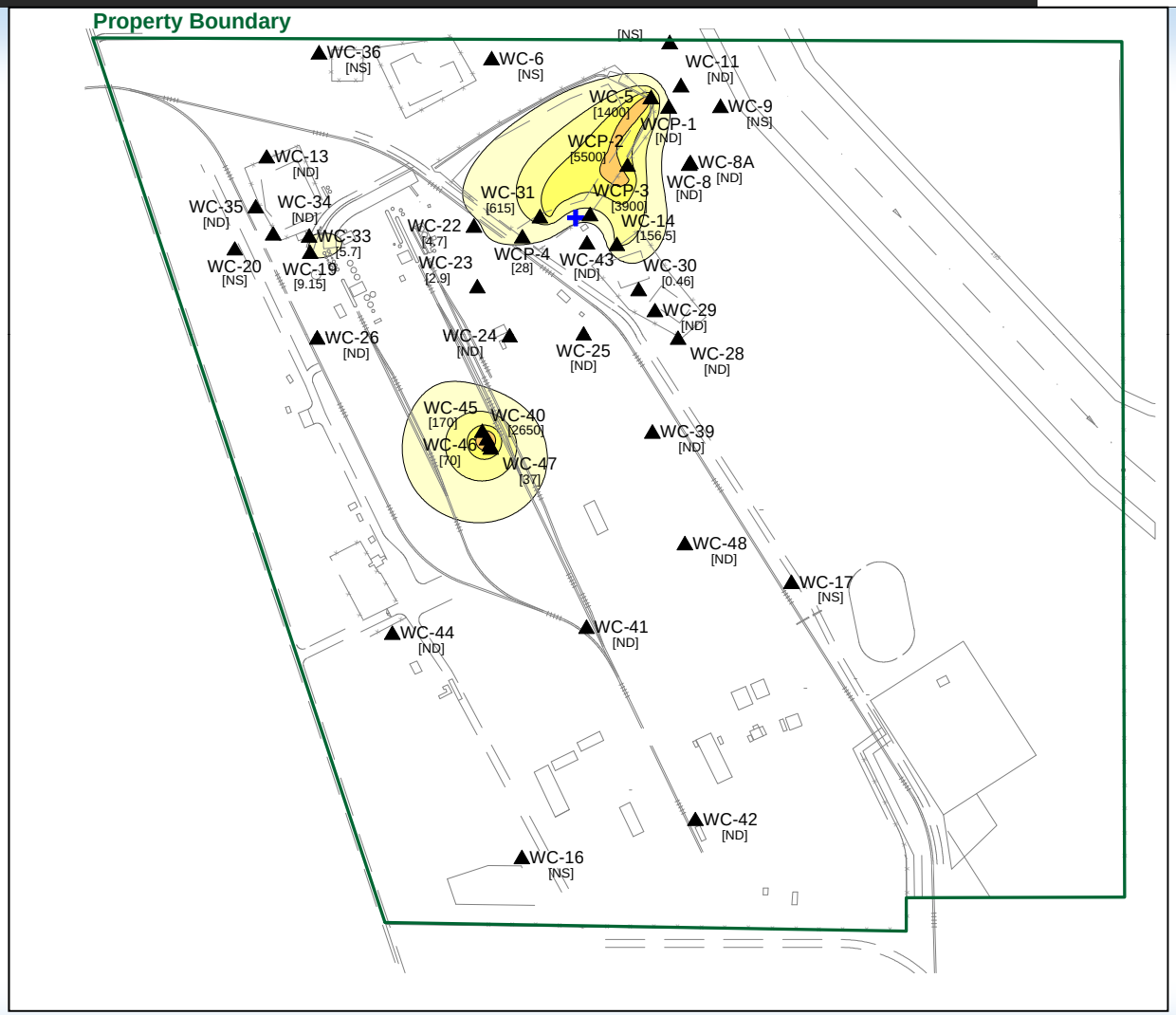
# Naphthalene Time Series

2005



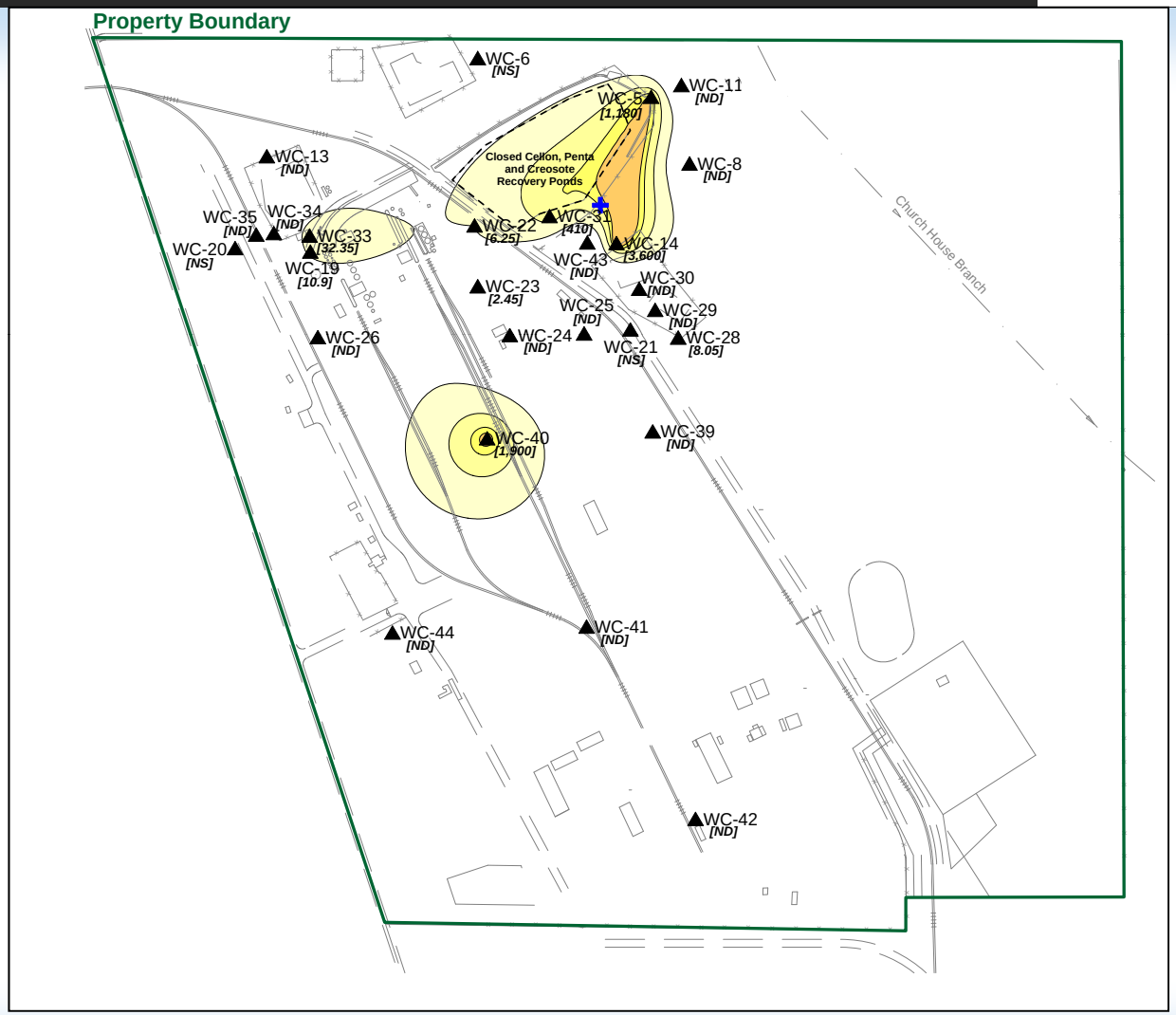
# Naphthalene Time Series

2006



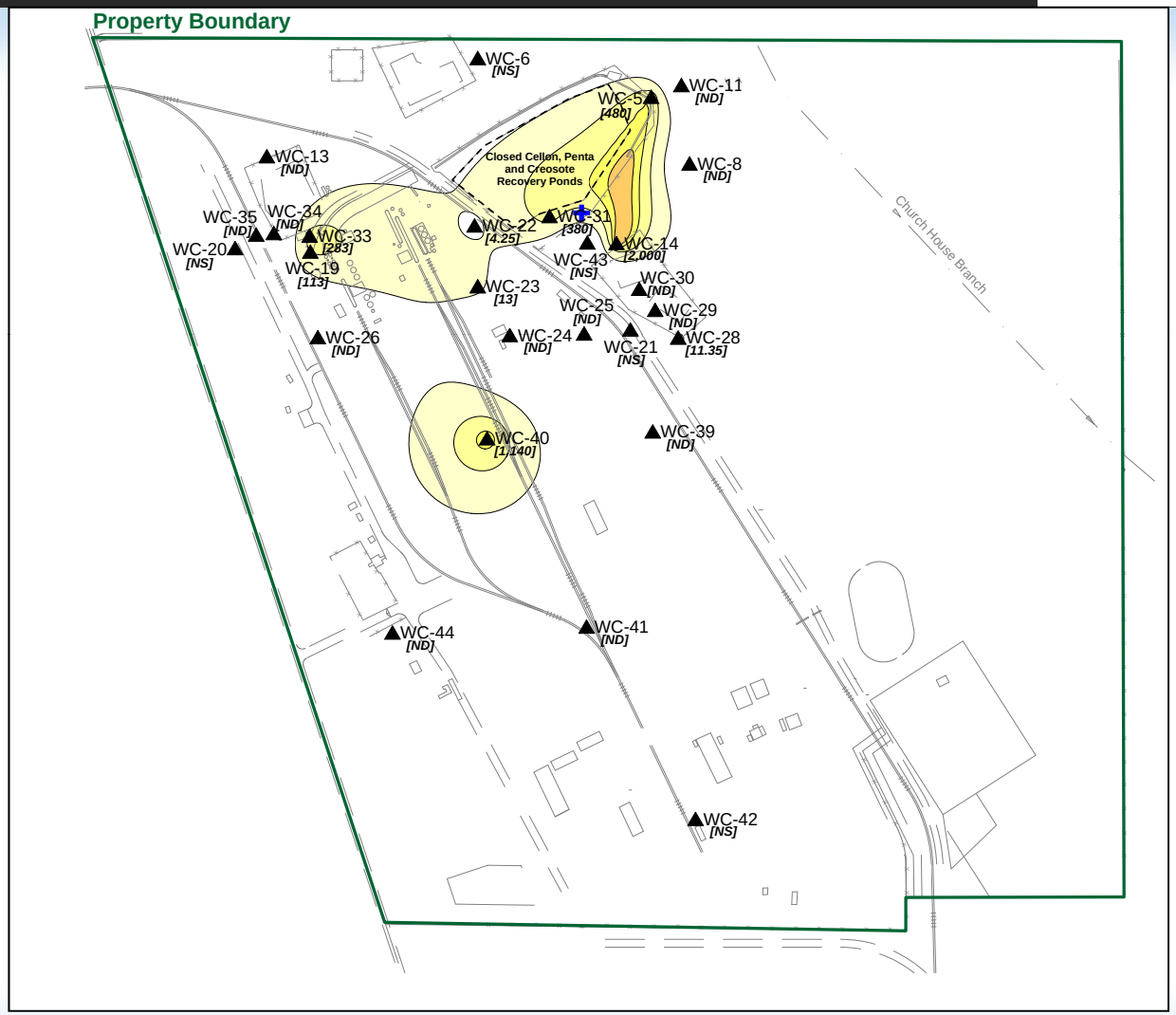
# Naphthalene Time Series

2007



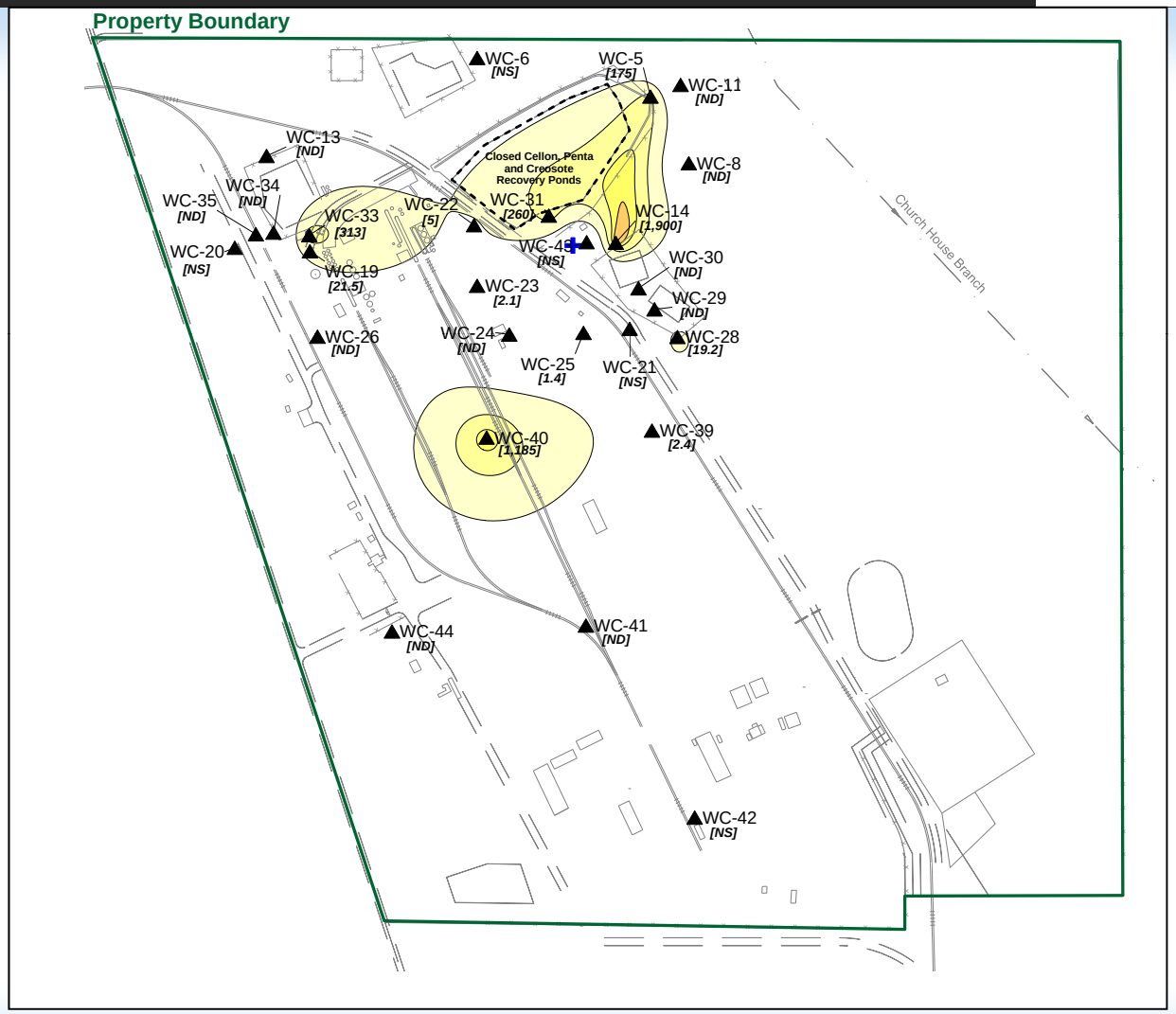
# Naphthalene Time Series

2008



# Naphthalene Time Series

2009

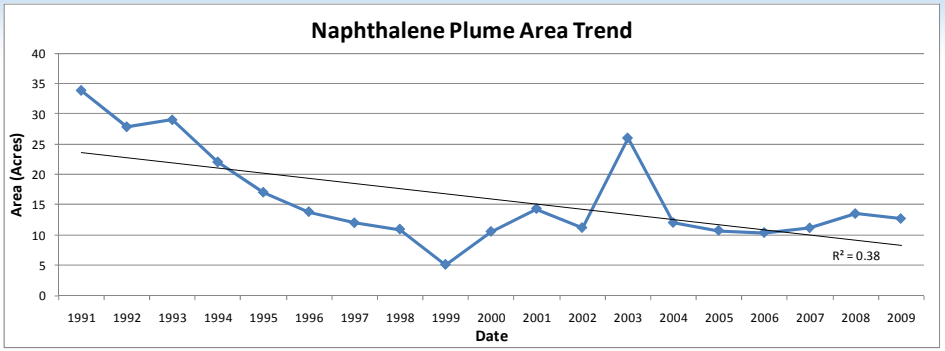


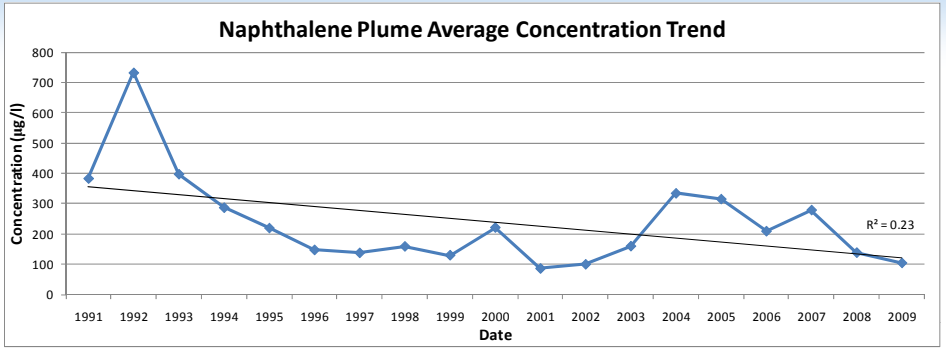
# Summary Naphthalene Plume Characteristics

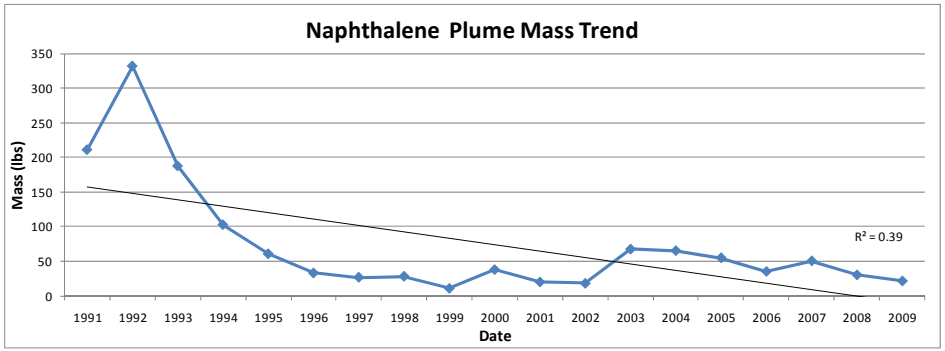
**Summary of Plume Stability Characteristics**

| Date | Area (Acres) | Average Conc. (μg/l) | Mass (lbs) |
|---|---|---|---|
| 1991 | 33.8 | 383 | 211 |
| 1992 | 27.8 | 733 | 332 |
| 1993 | 29.0 | 398 | 188 |
| 1994 | 22.0 | 287 | 103 |
| 1995 | 17.0 | 219 | 60.7 |
| 1996 | 13.8 | 147 | 33.0 |
| 1997 | 11.9 | 137 | 26.7 |
| 1998 | 10.9 | 159 | 28.2 |
| 1999 | 5.1 | 130 | 10.7 |
| 2000 | 10.5 | 221 | 37.9 |
| 2001 | 14.3 | 85.6 | 19.9 |
| 2002 | 11.1 | 99.4 | 18.0 |
| 2003 | 25.9 | 159 | 67.4 |
| 2004 | 12.0 | 334 | 65.3 |
| 2005 | 10.7 | 315 | 54.9 |
| 2006 | 10.3 | 209 | 35.2 |
| 2007 | 11.1 | 279 | 50.5 |
| 2008 | 13.5 | 138 | 30.3 |

# Naphthalene Plume Stability Trends



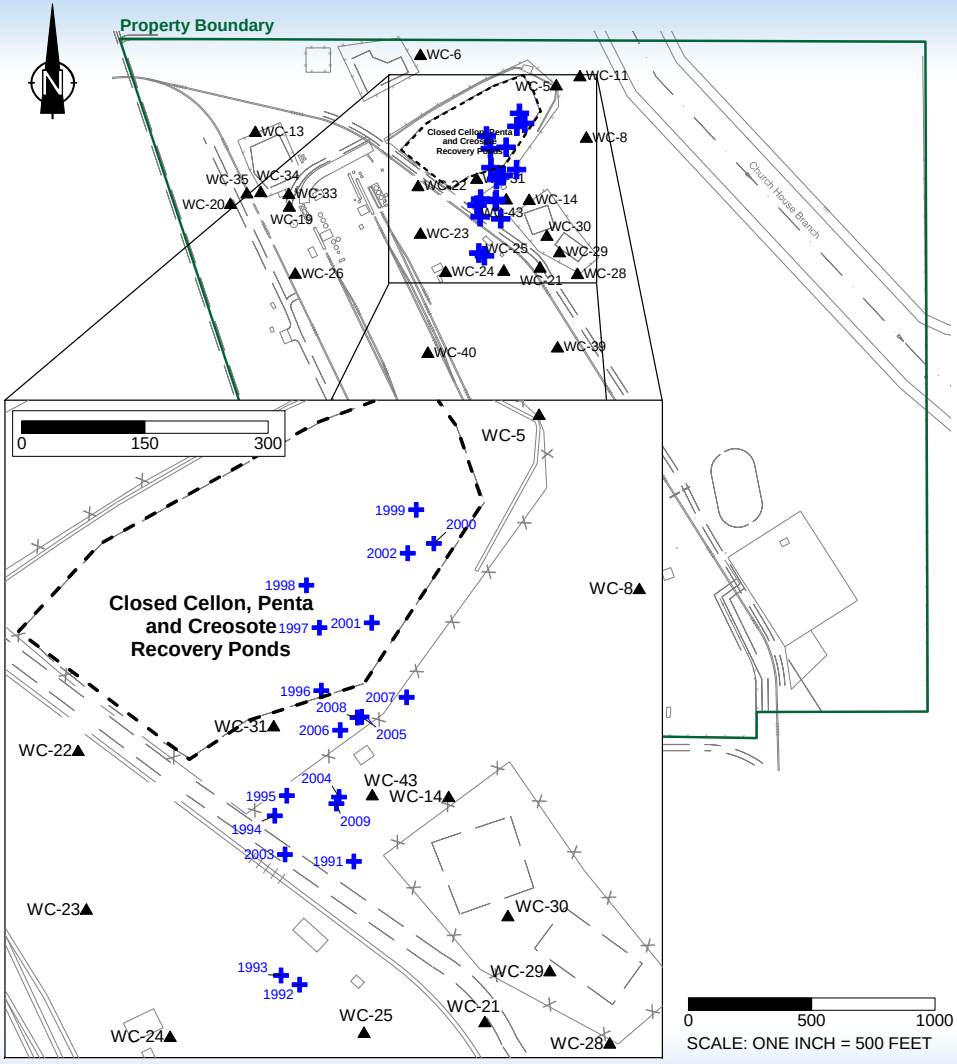



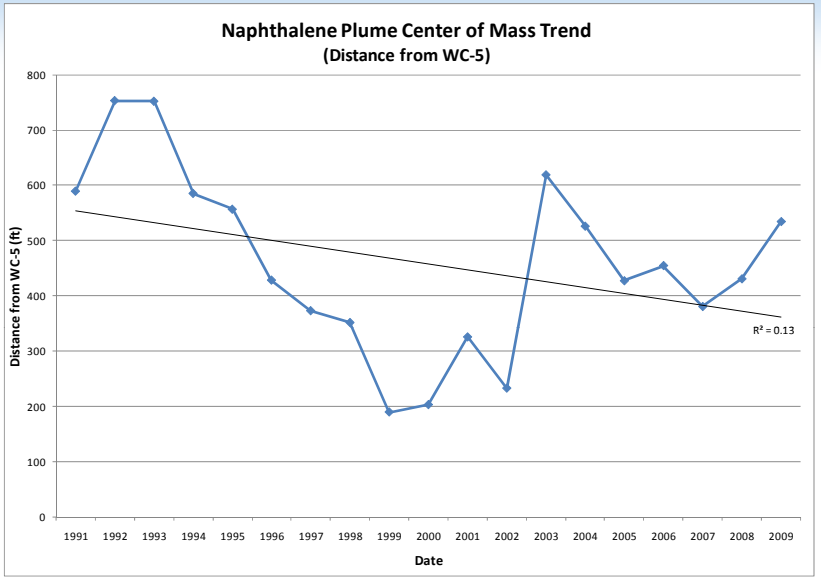




## Mann-Kendall Trend Analysis Summary

| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Naphthalene Plume Area | 19 | -75 | 99.5% | 0.49 | Decreasing Trend |
| Naphthalene Plume Avg. Conc. | 19 | -49 | 95.3% | 0.64 | Decreasing Trend |
| Naphthalene Plume Mass | 19 | -61 | 98.2% | 1.13 | Decreasing Trend |

# Naphthalene Plume Center of Mass Trend




## Mann-Kendall Trend Analysis

**n = 19**

**S Statistic = -43**

**Confidence Factor = 92.9%**

**Coeff. of Variation = 0.36**

**Conclusion: Decreasing Trend**

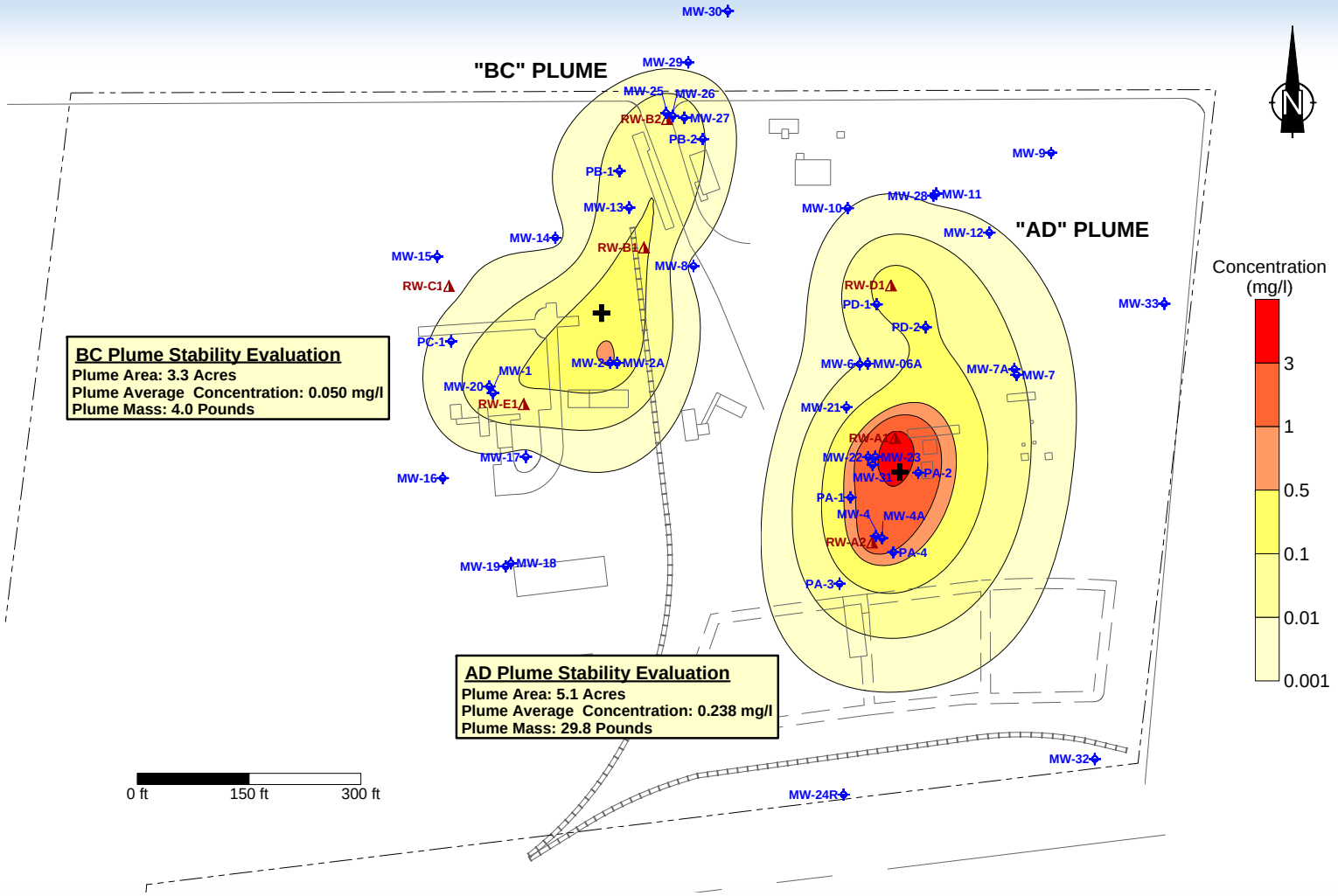
# Plume Stability Analysis - Example Site 2

- SVOC Site with two identified plumes
- Site Underwent Chemical Oxidation

# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

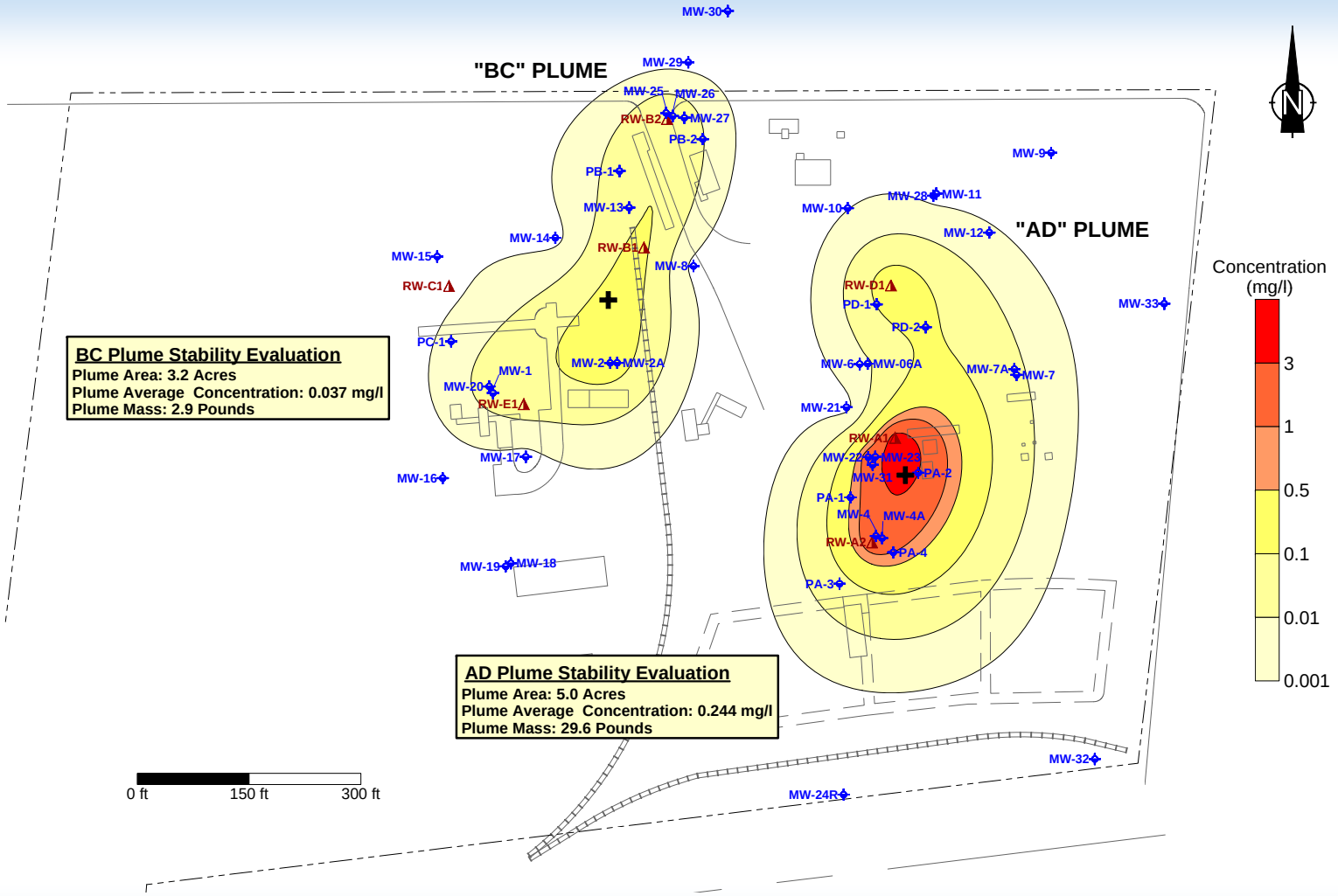
## 1995



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

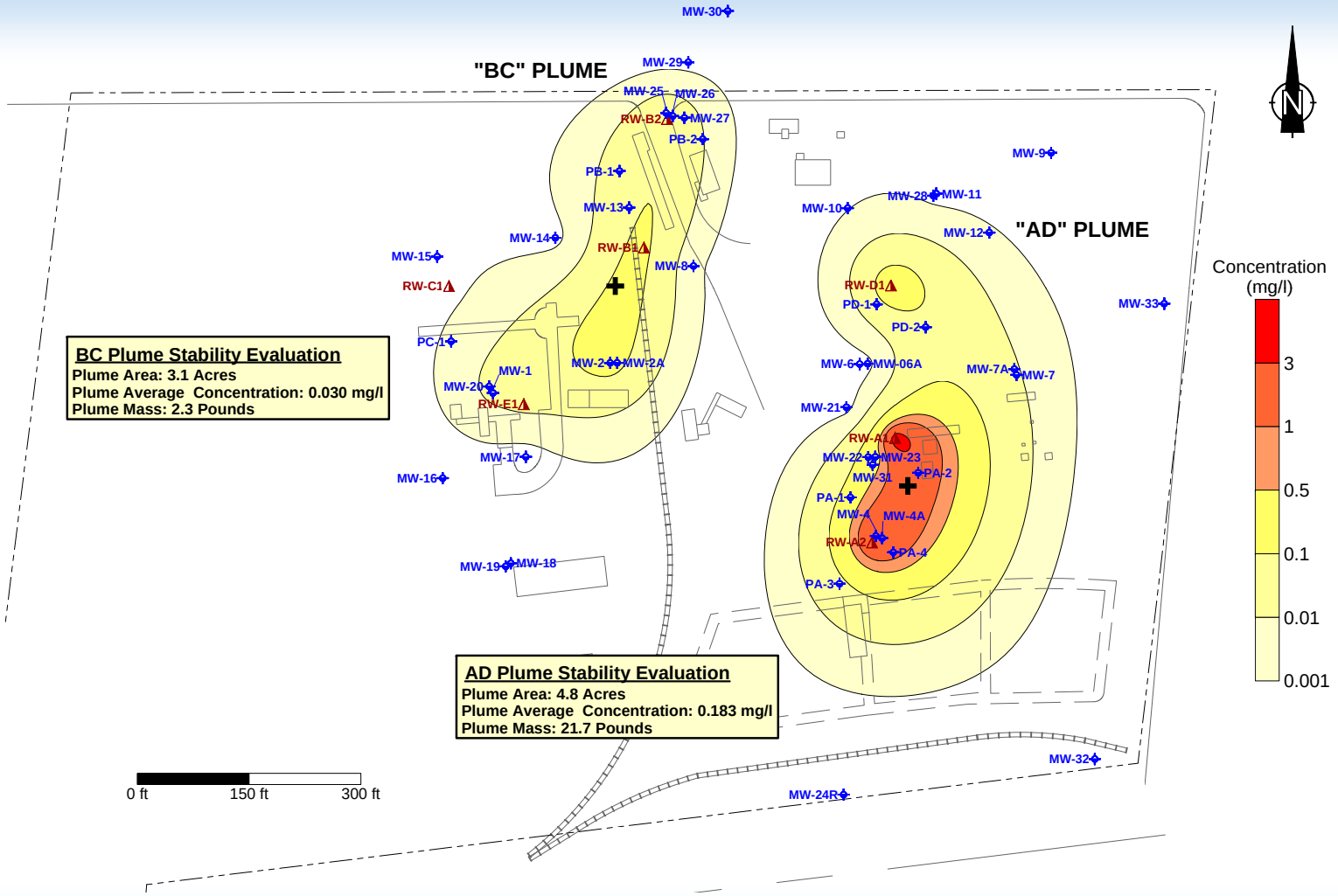
## 1996



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

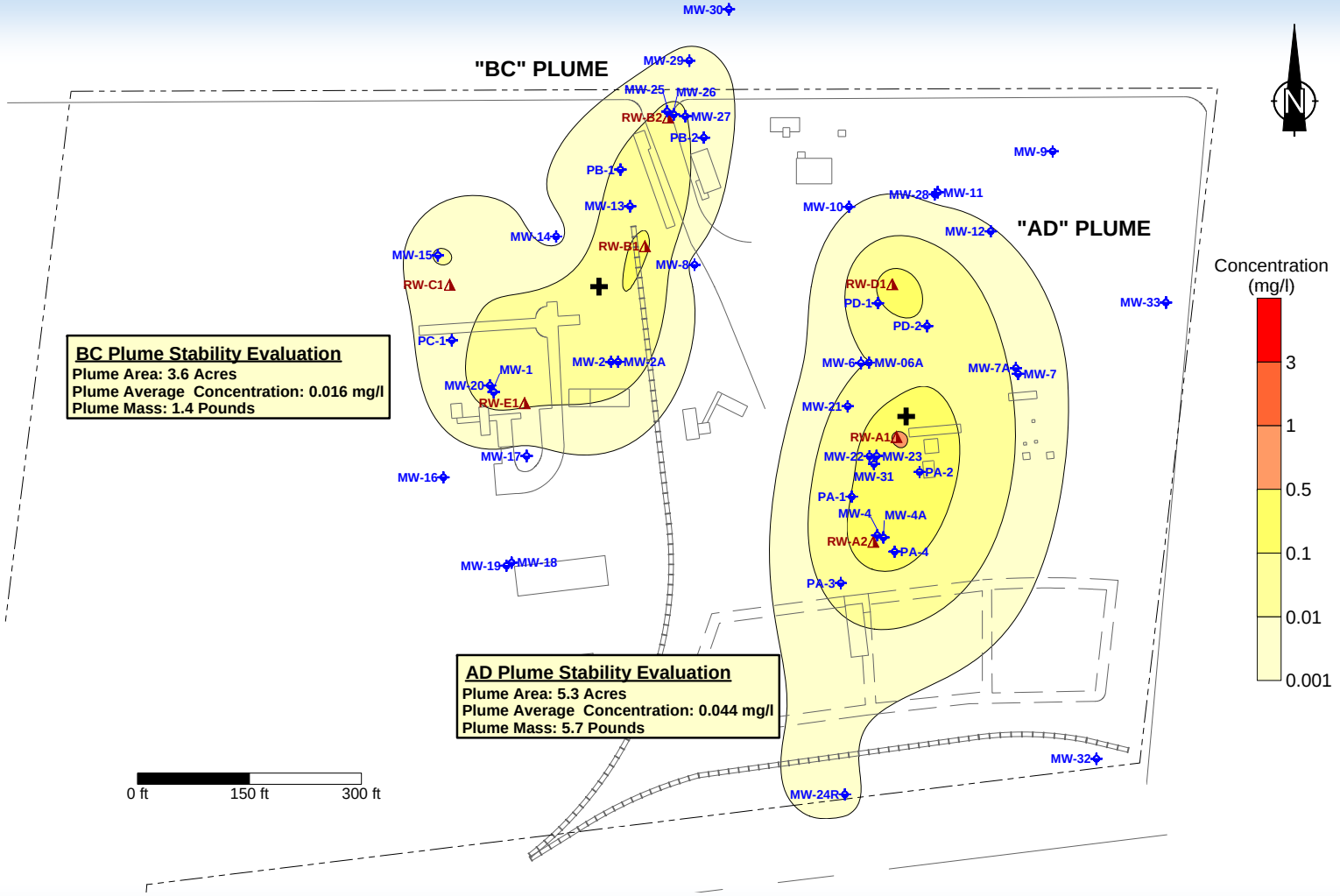
## 1997



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

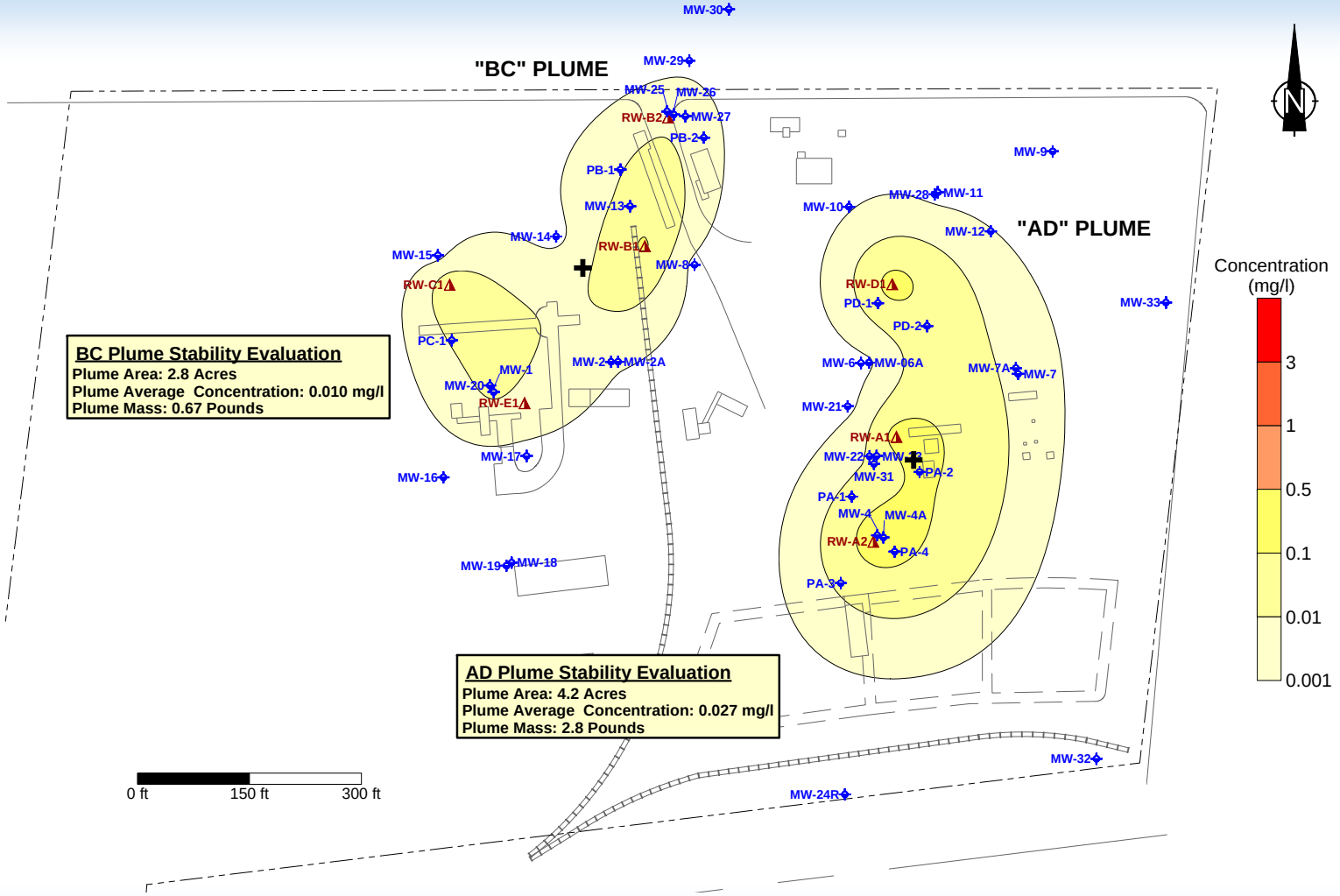
## 1998



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

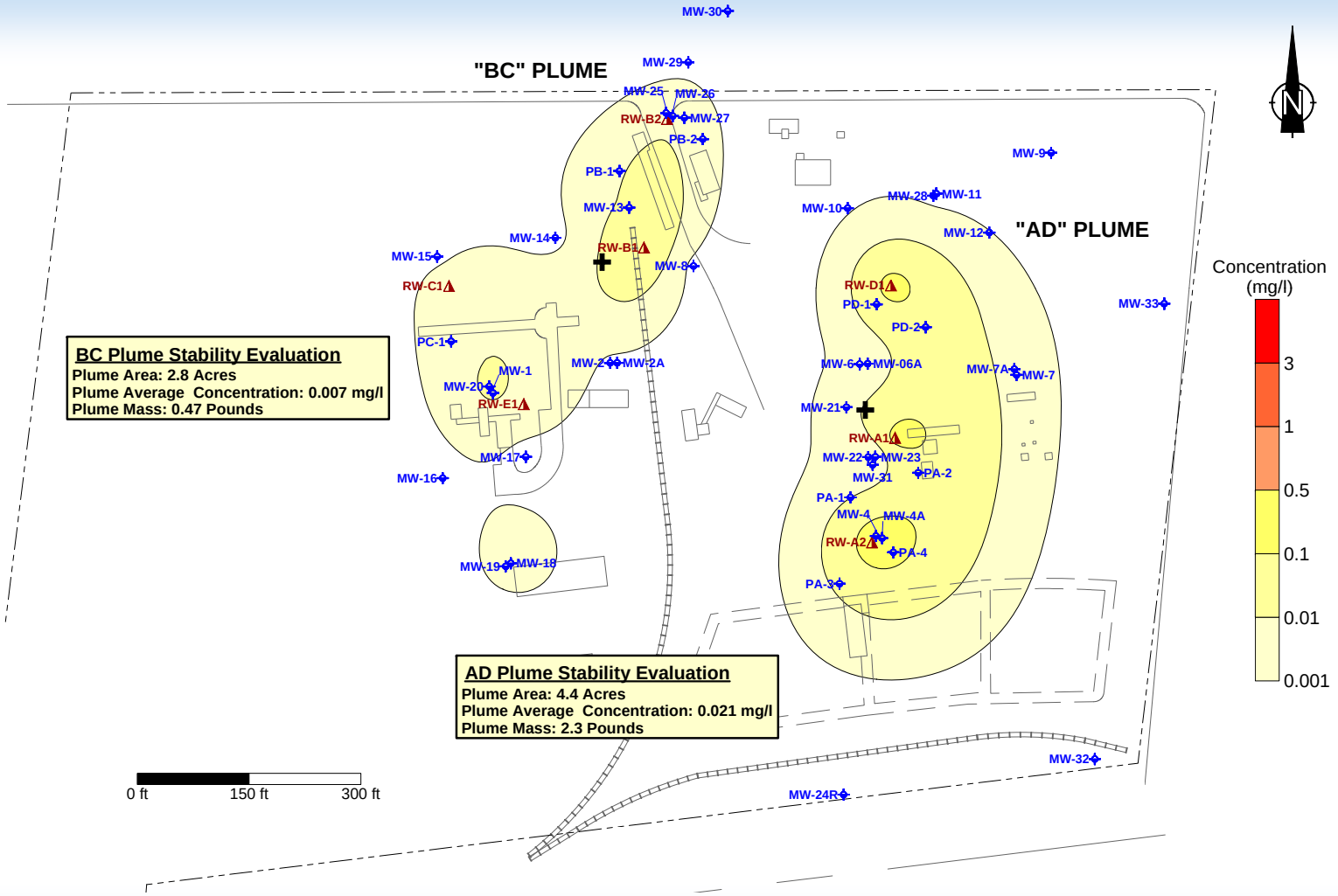
## 1999



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

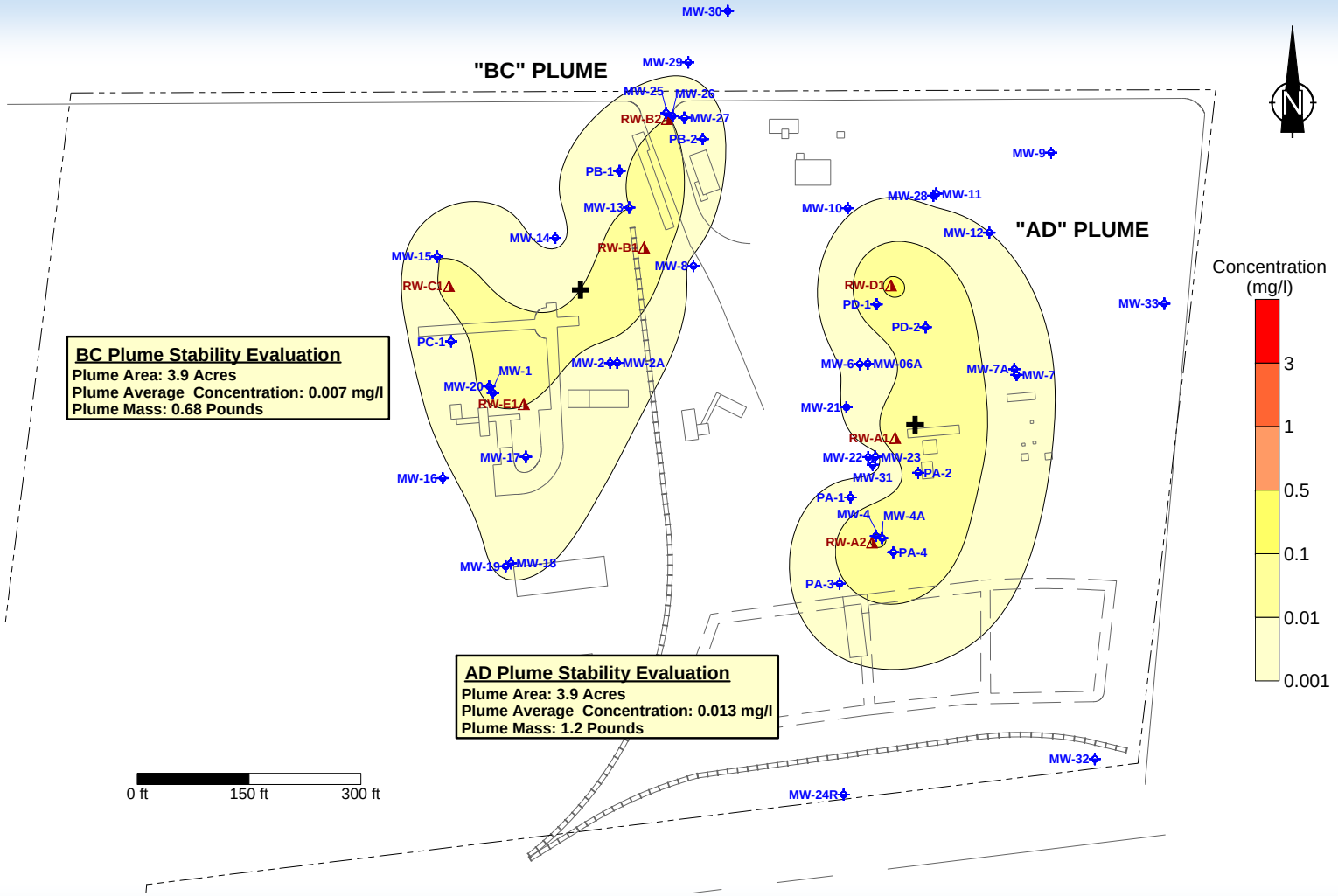
## 2000



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

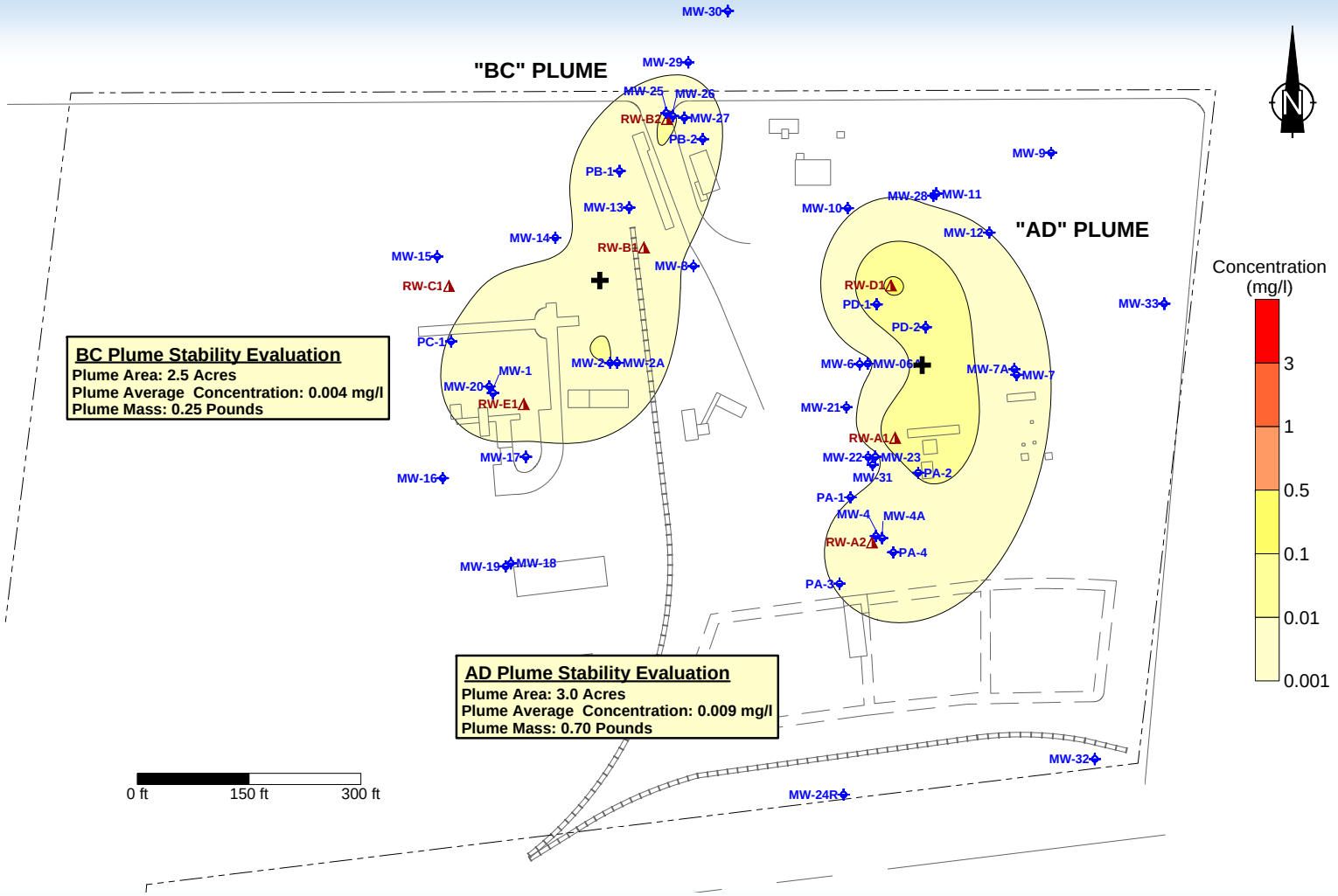
## 2001



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

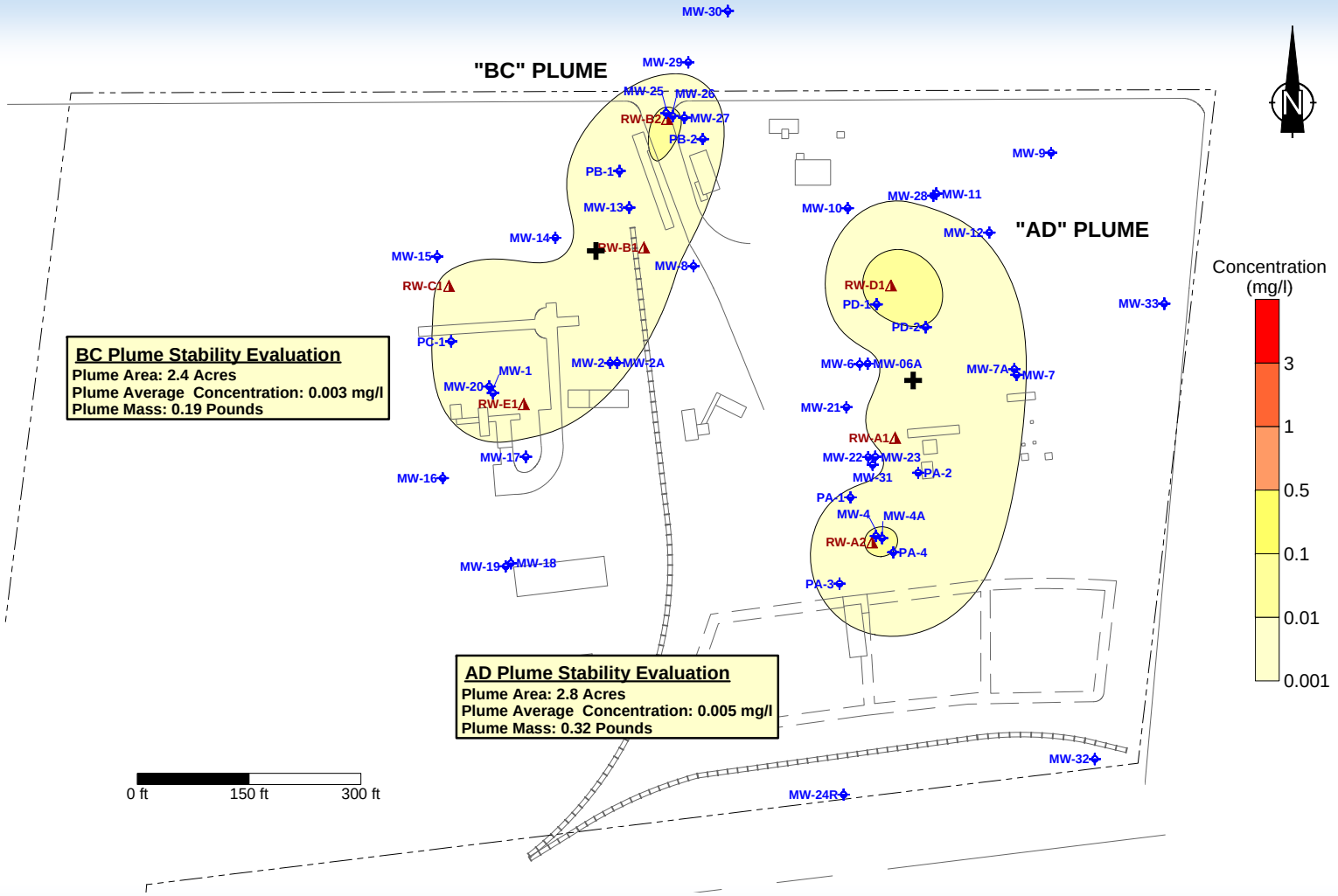
## 2002



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

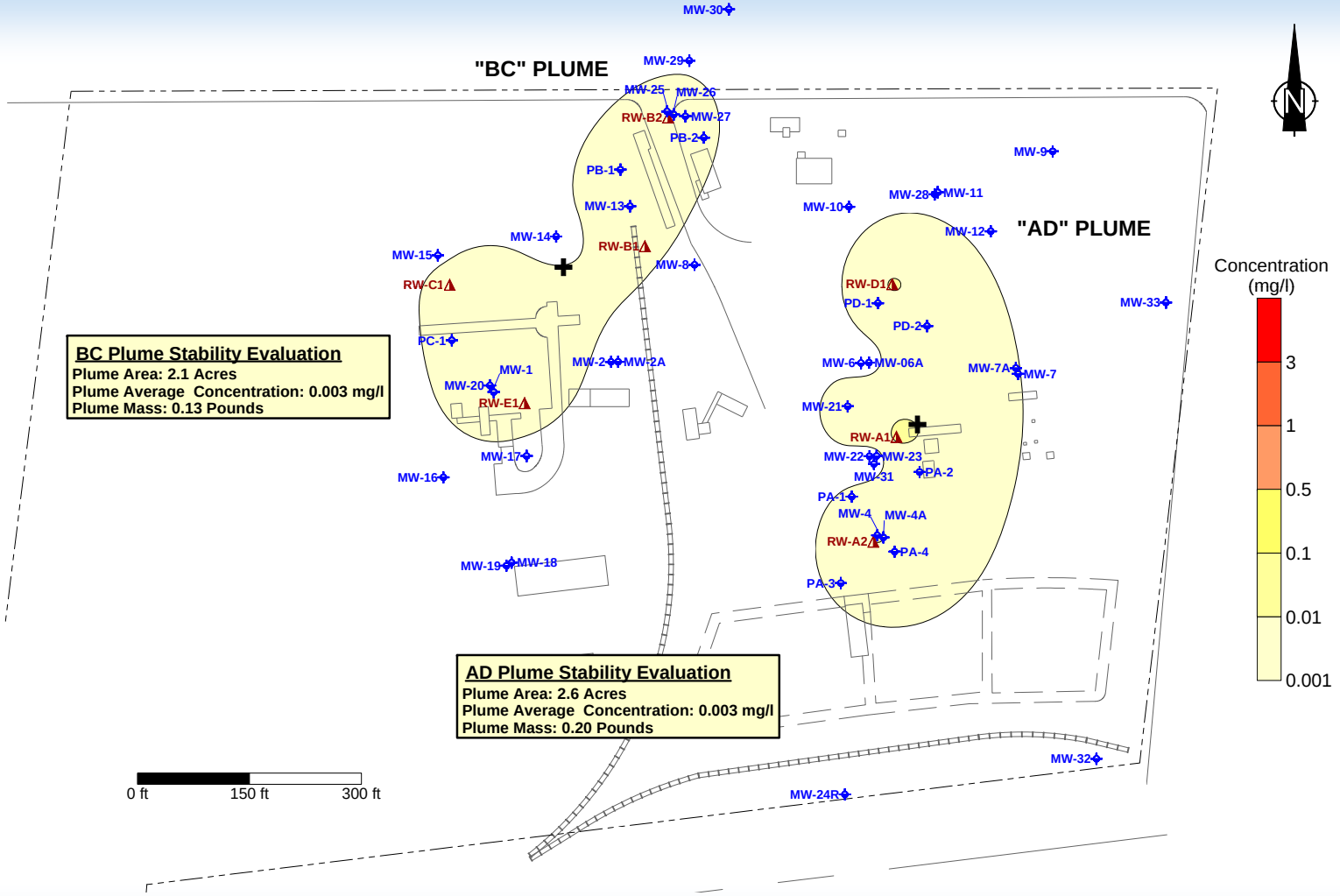
## 2003



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

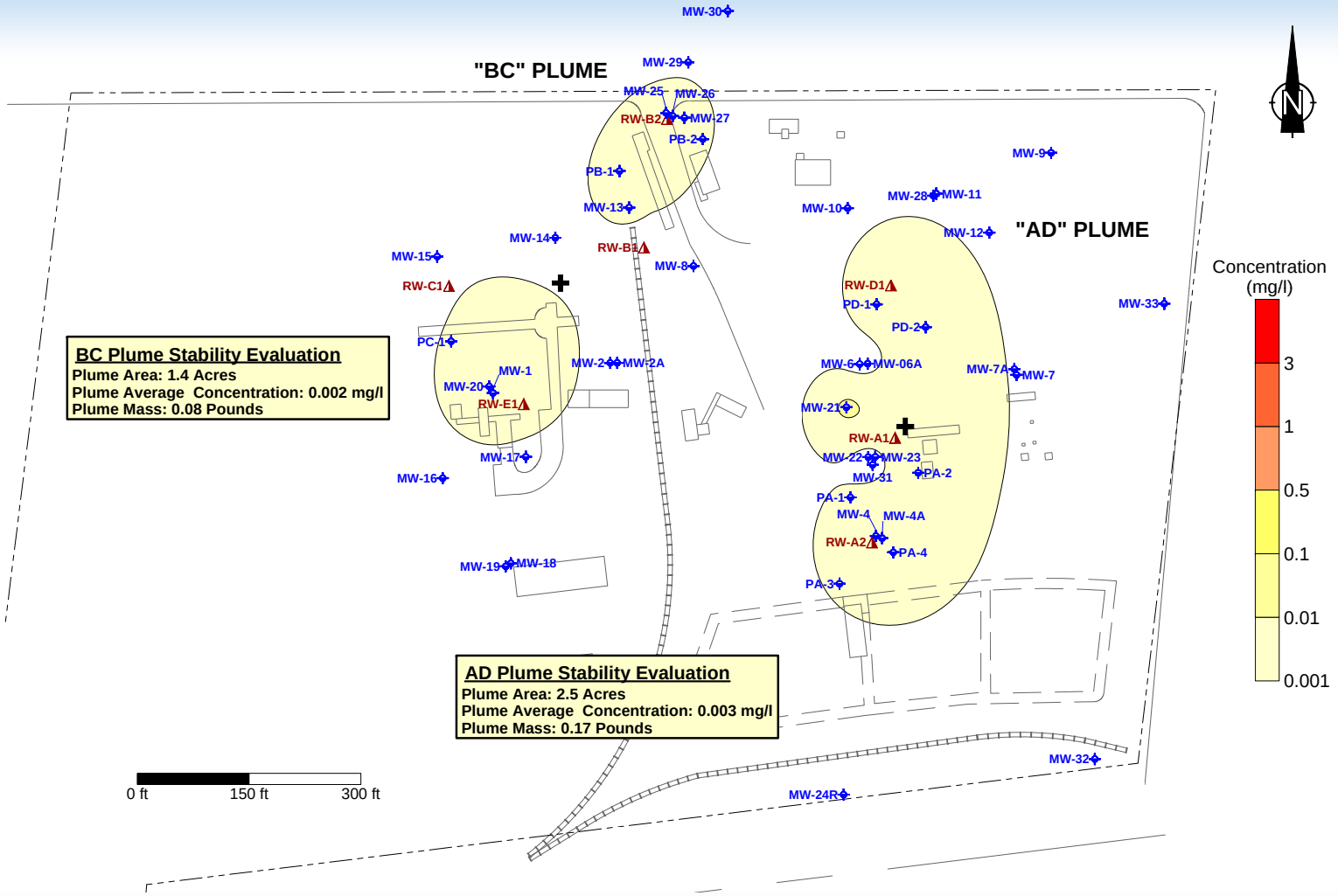
## 2004



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

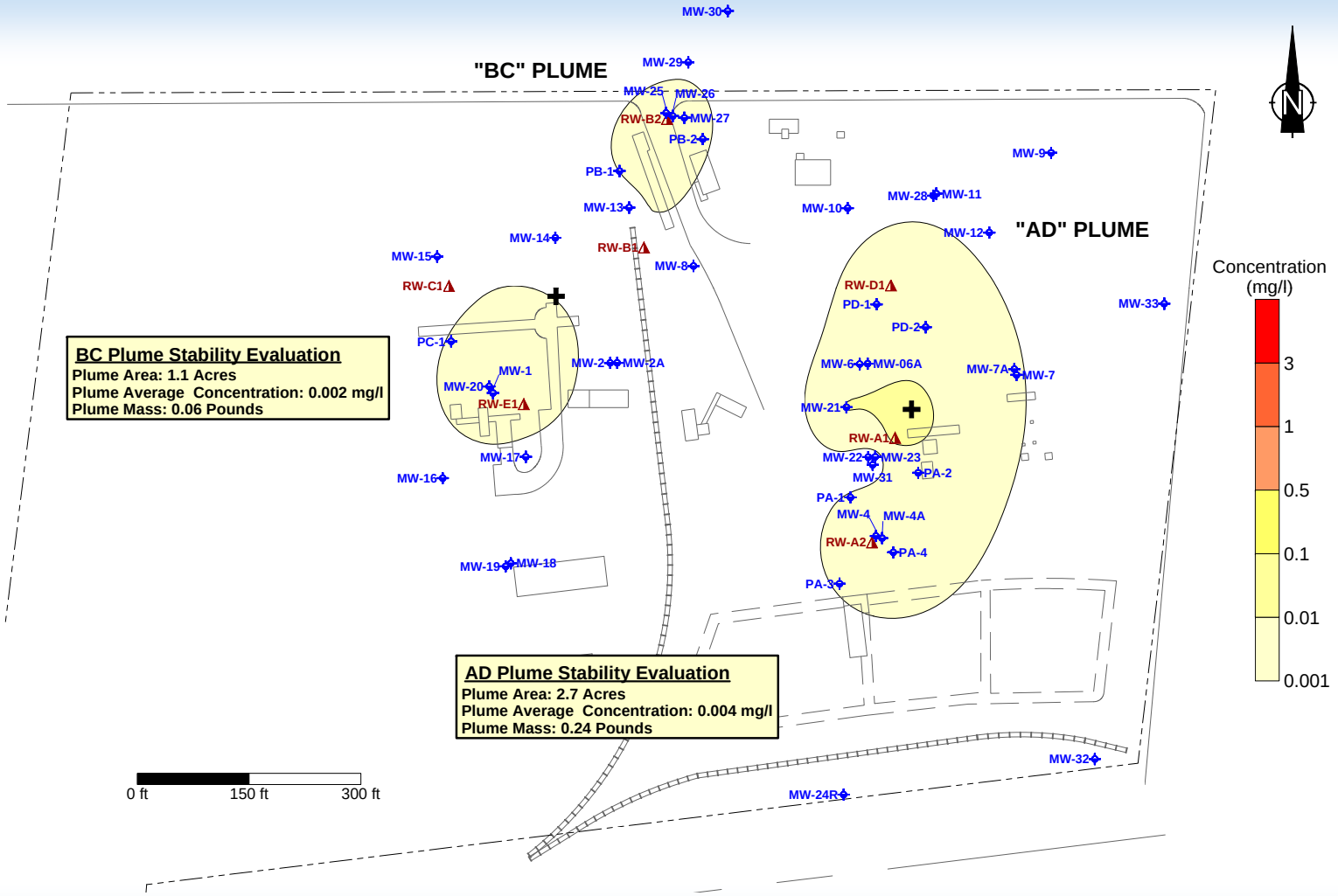
## 2005



# Example Site 2 Plume Stability Analysis

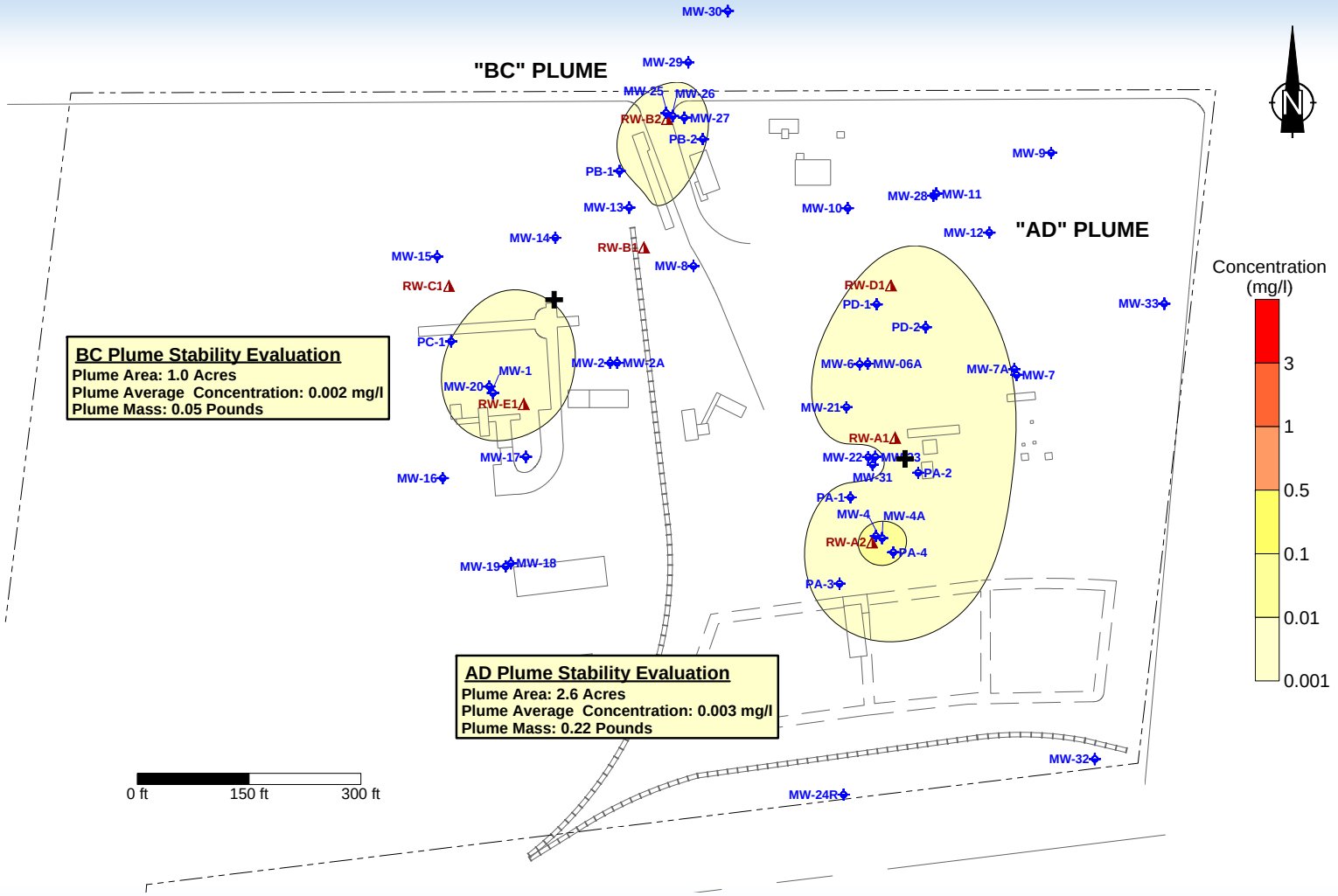
PREMIER ENVIRONMENTAL SERVICES, INC

## 2006



# Example Site 2 Plume Stability Analysis

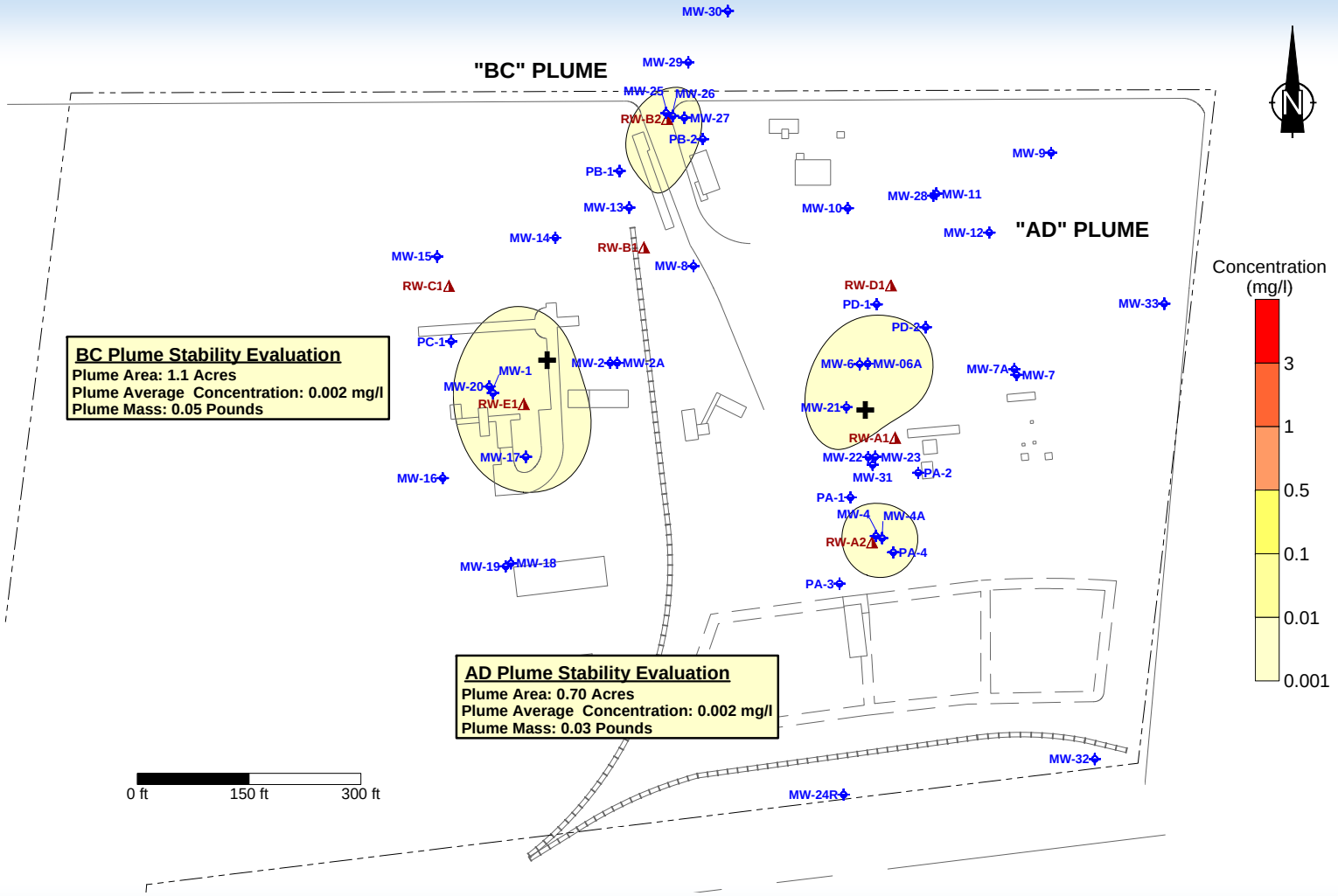
2007



# Example Site 2 Plume Stability Analysis

PREMIER ENVIRONMENTAL SERVICES, INC

## 2008



# Example Site 2 Plume Stability Analysis

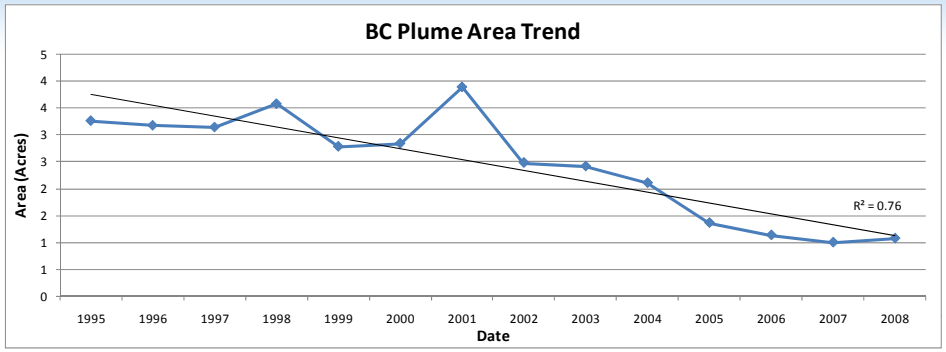
**Summary of BC Plume Stability Characteristics**

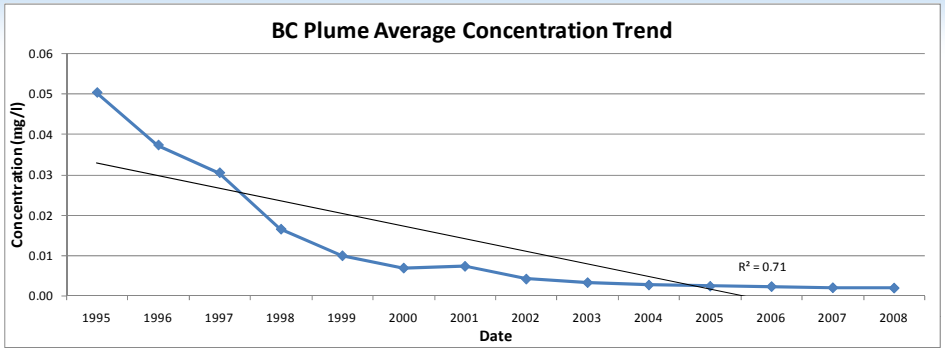
| Date | Area (Acres) | Average Conc. (mg/l) | Mass (lbs) |
|---|---|---|---|
| 1995 | 3.3 | 0.050 | 4.0 |
| 1996 | 3.2 | 0.037 | 2.9 |
| 1997 | 3.1 | 0.030 | 2.3 |
| 1998 | 3.6 | 0.016 | 1.4 |
| 1999 | 2.8 | 0.010 | 0.67 |
| 2000 | 2.8 | 0.007 | 0.47 |
| 2001 | 3.9 | 0.007 | 0.68 |
| 2002 | 2.5 | 0.004 | 0.25 |
| 2003 | 2.4 | 0.003 | 0.19 |
| 2004 | 2.1 | 0.003 | 0.13 |
| 2005 | 1.4 | 0.002 | 0.08 |
| 2006 | 1.1 | 0.002 | 0.06 |
| 2007 | 1.0 | 0.002 | 0.05 |
| 2008 | 1.1 | 0.002 | 0.05 |

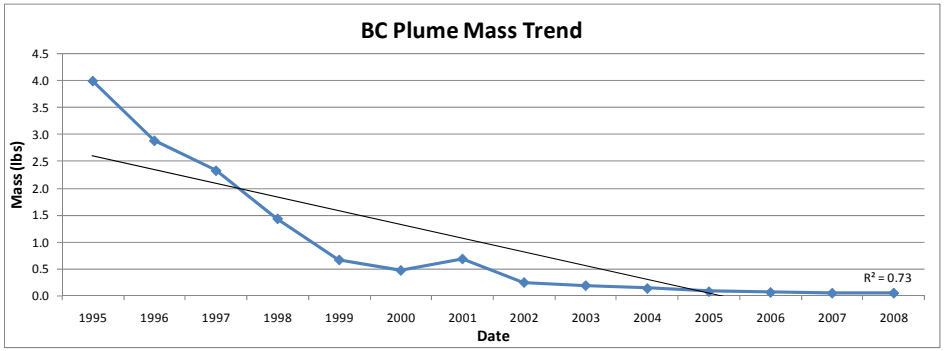
**Summary of AD Plume Stability Characteristics**

| Date | Area (Acres) | Average Conc. (mg/l) | Mass (lbs) |
|---|---|---|---|
| 1995 | 5.1 | 0.238 | 29.8 |
| 1996 | 5.0 | 0.244 | 29.6 |
| 1997 | 4.8 | 0.183 | 21.7 |
| 1998 | 5.3 | 0.044 | 5.7 |
| 1999 | 4.2 | 0.027 | 2.81 |
| 2000 | 4.4 | 0.021 | 2.29 |
| 2001 | 3.9 | 0.013 | 1.19 |
| 2002 | 3.0 | 0.009 | 0.70 |
| 2003 | 2.8 | 0.005 | 0.32 |
| 2004 | 2.6 | 0.003 | 0.20 |
| 2005 | 2.5 | 0.003 | 0.17 |
| 2006 | 2.7 | 0.004 | 0.24 |
| 2007 | 2.6 | 0.003 | 0.22 |
| 2008 | 0.70 | 0.002 | 0.03 |

# Example Site 2 Plume Stability Analysis – BC Plume



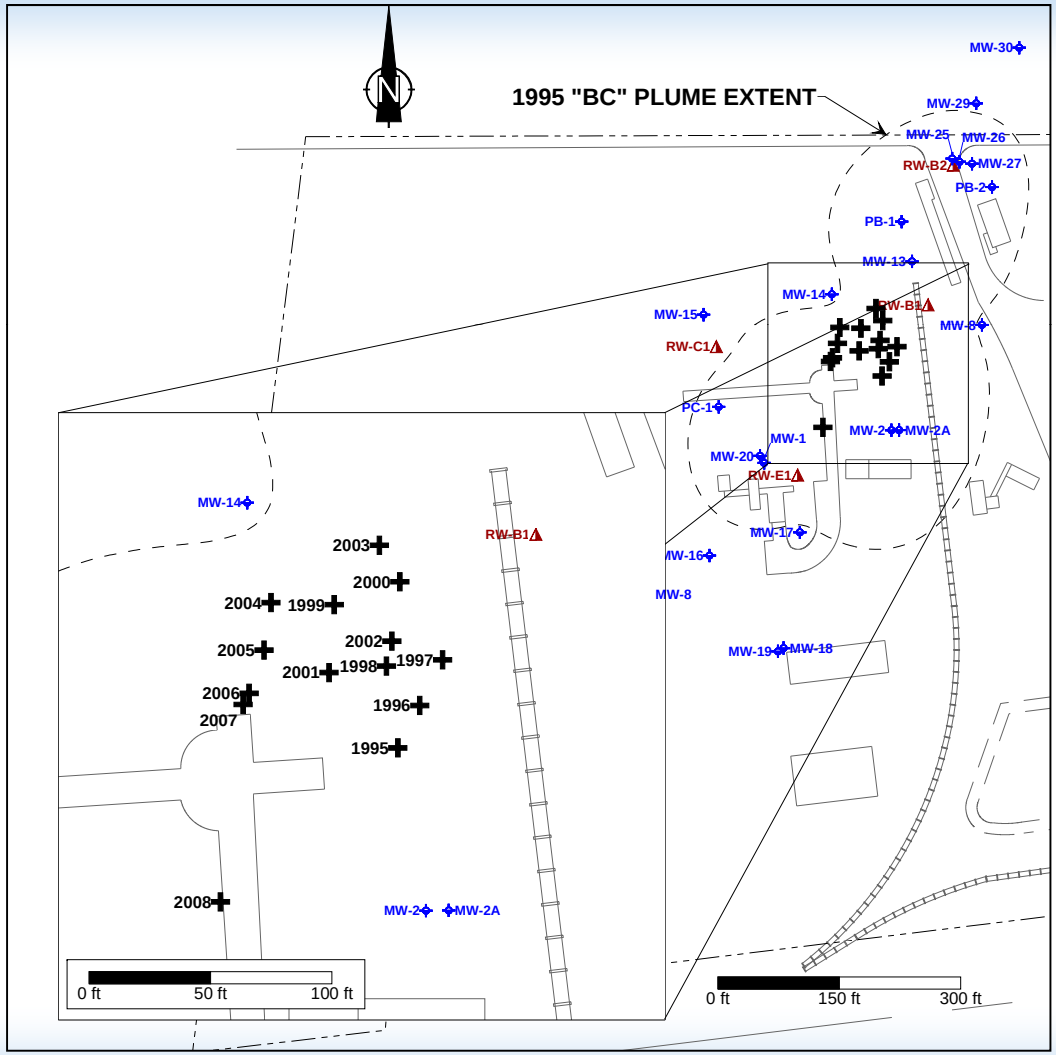



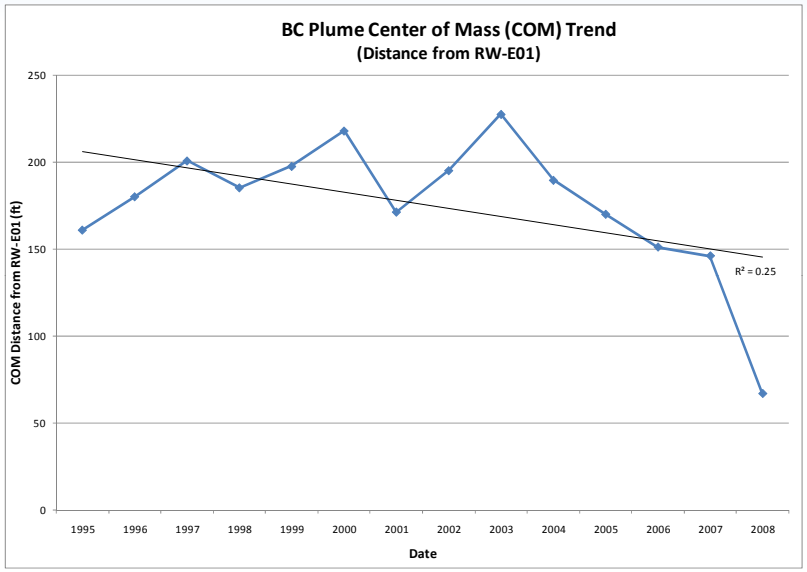




## Mann-Kendall Trend Analysis Summary

| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| BC Plume Area | 14 | -69 | 100.0% | 0.40 | Decreasing Trend |
| BC Plume Avg. Conc. | 14 | -89 | 100.0% | 1.23 | Decreasing Trend |
| BC Plume Mass | 14 | -85 | 100.0% | 1.32 | Decreasing Trend |

# Example Site 2 Plume Stability Analysis – BC Plume




**Mann-Kendall Trend Analysis**

n = 14

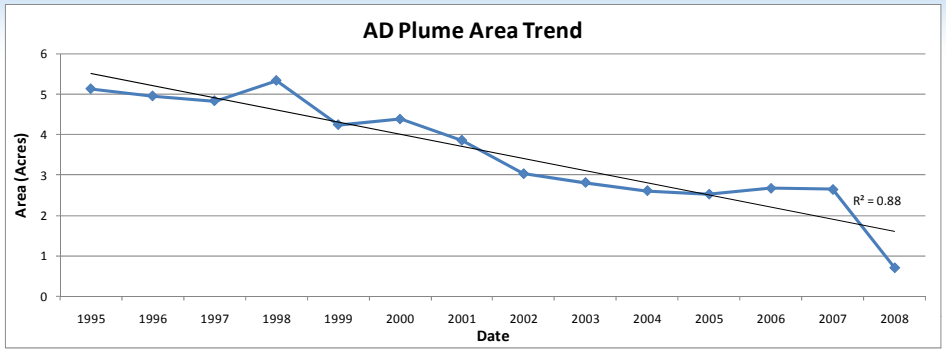
S Statistic = -29

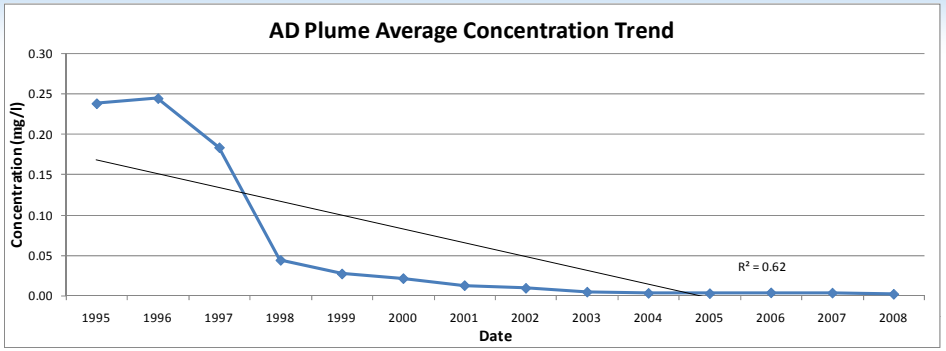
Confidence Factor = 93.7%

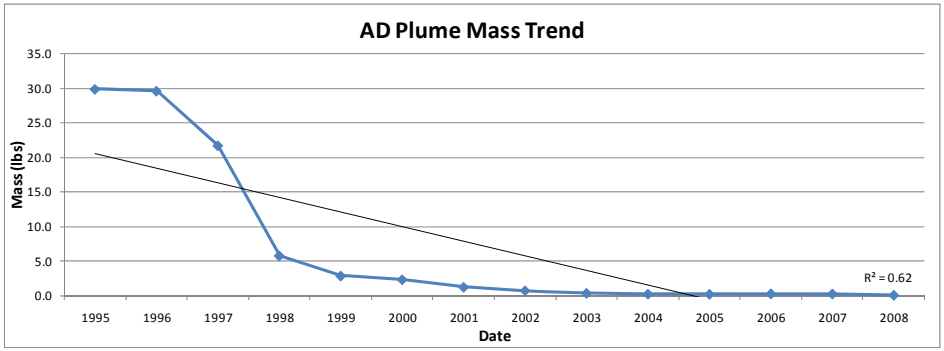
Coeff. of Variation = 0.22

Conclusion: Decreasing Trend

# Example Site 2 Plume Stability Analysis – AD Plume



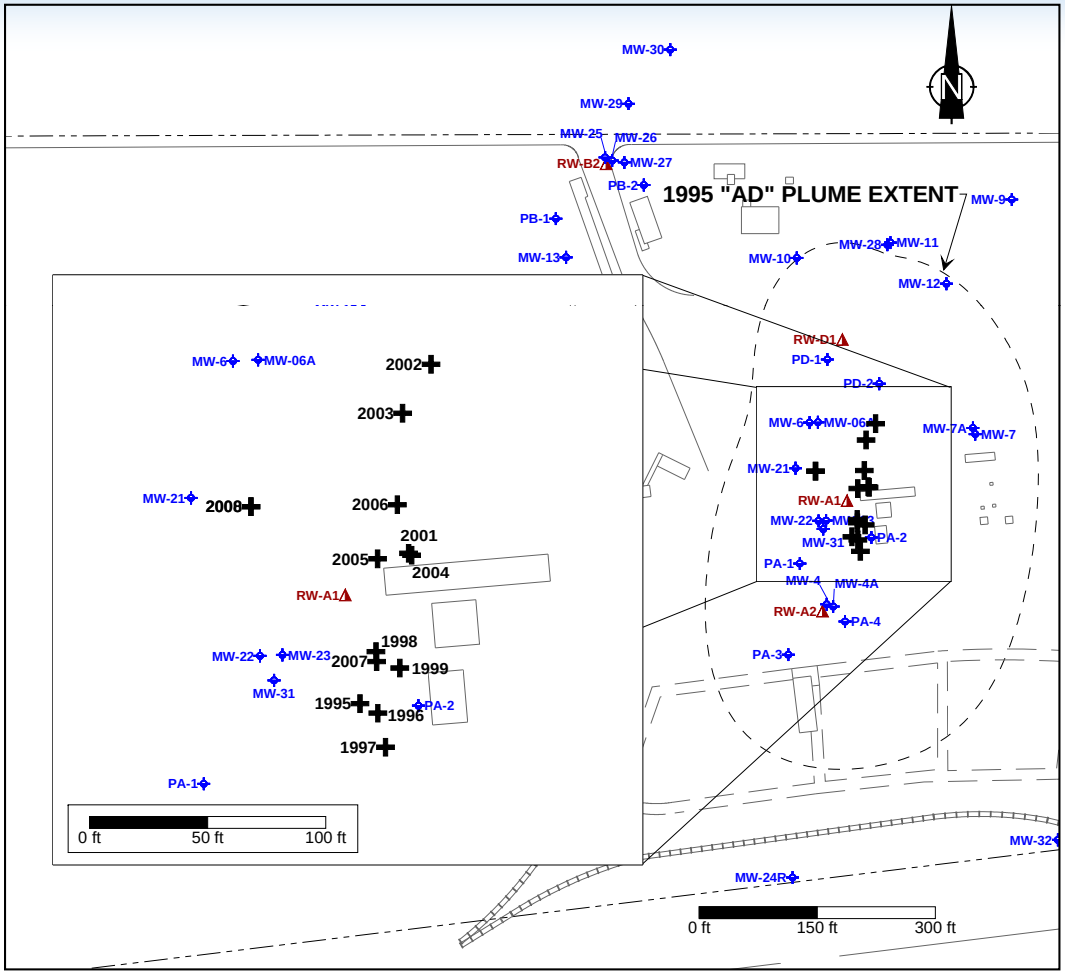



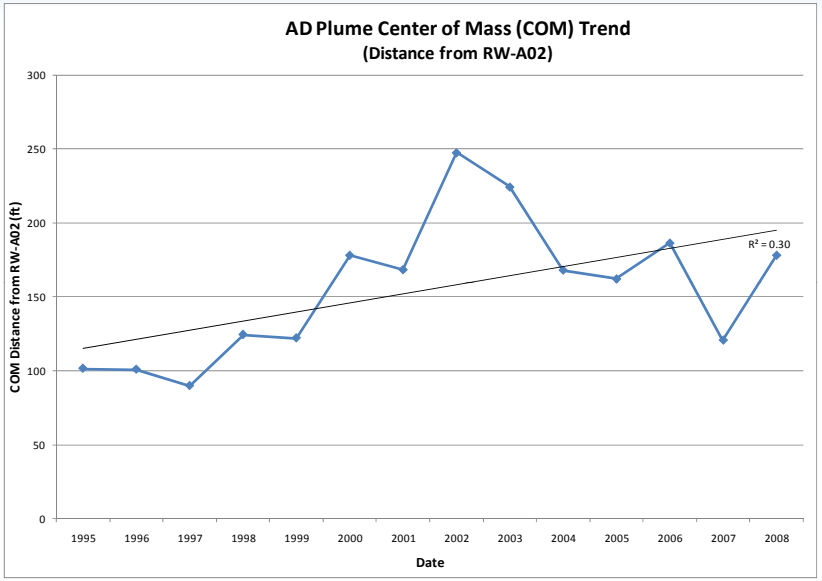




## Mann-Kendall Trend Analysis Summary

| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| AD Plume Area | 14 | -75 | 100.0% | 0.37 | Decreasing Trend |
| AD Plume Avg. Conc. | 14 | -81 | 100.0% | 1.59 | Decreasing Trend |
| AD Plume Mass | 14 | -83 | 100.0% | 1.65 | Decreasing Trend |

# Example Site 2 Plume Stability Analysis – AD Plume




**Mann-Kendall Trend Analysis**

n = 14

S Statistic = 32

Confidence Factor = 95.5%

Coeff. of Variation = 0.30

Conclusion: Increasing Trend

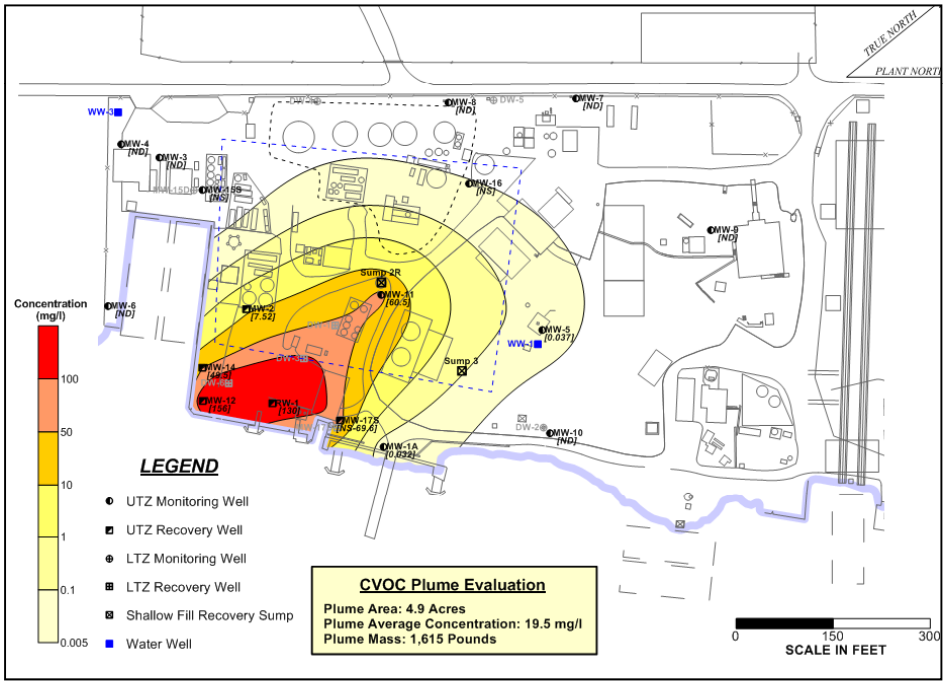
# Plume Stability Analysis - Example Site 3

- Active marine services facility along major shipping channel
- Historical disposal activities resulted in BTEX and chlorinated VOC plumes
- Active pump & treat system

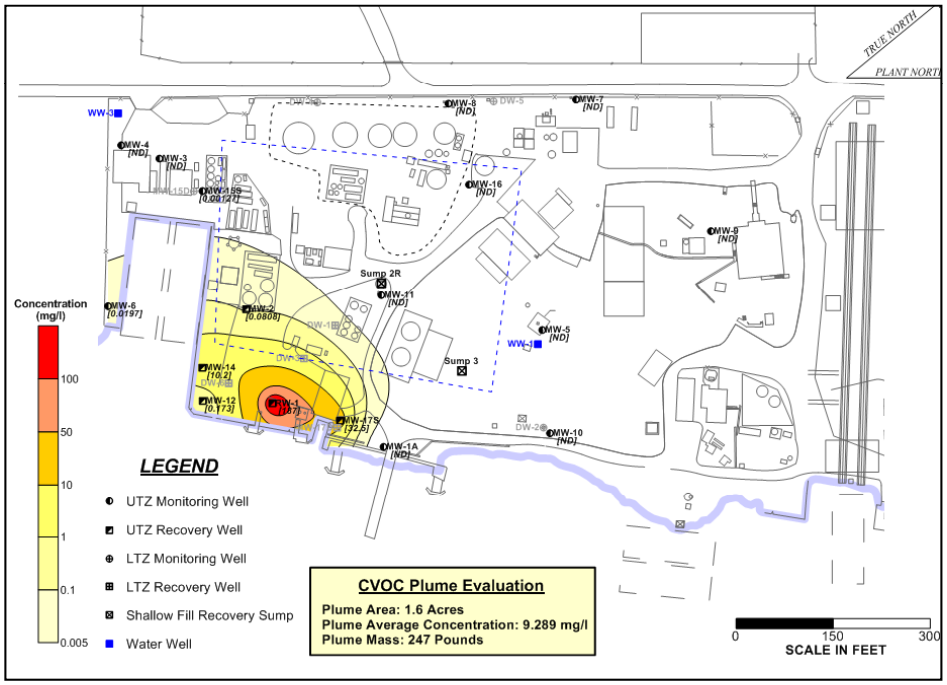
# Plume Stability Analysis - Example Site 3

PREMIER ENVIRONMENTAL SERVICES, INC

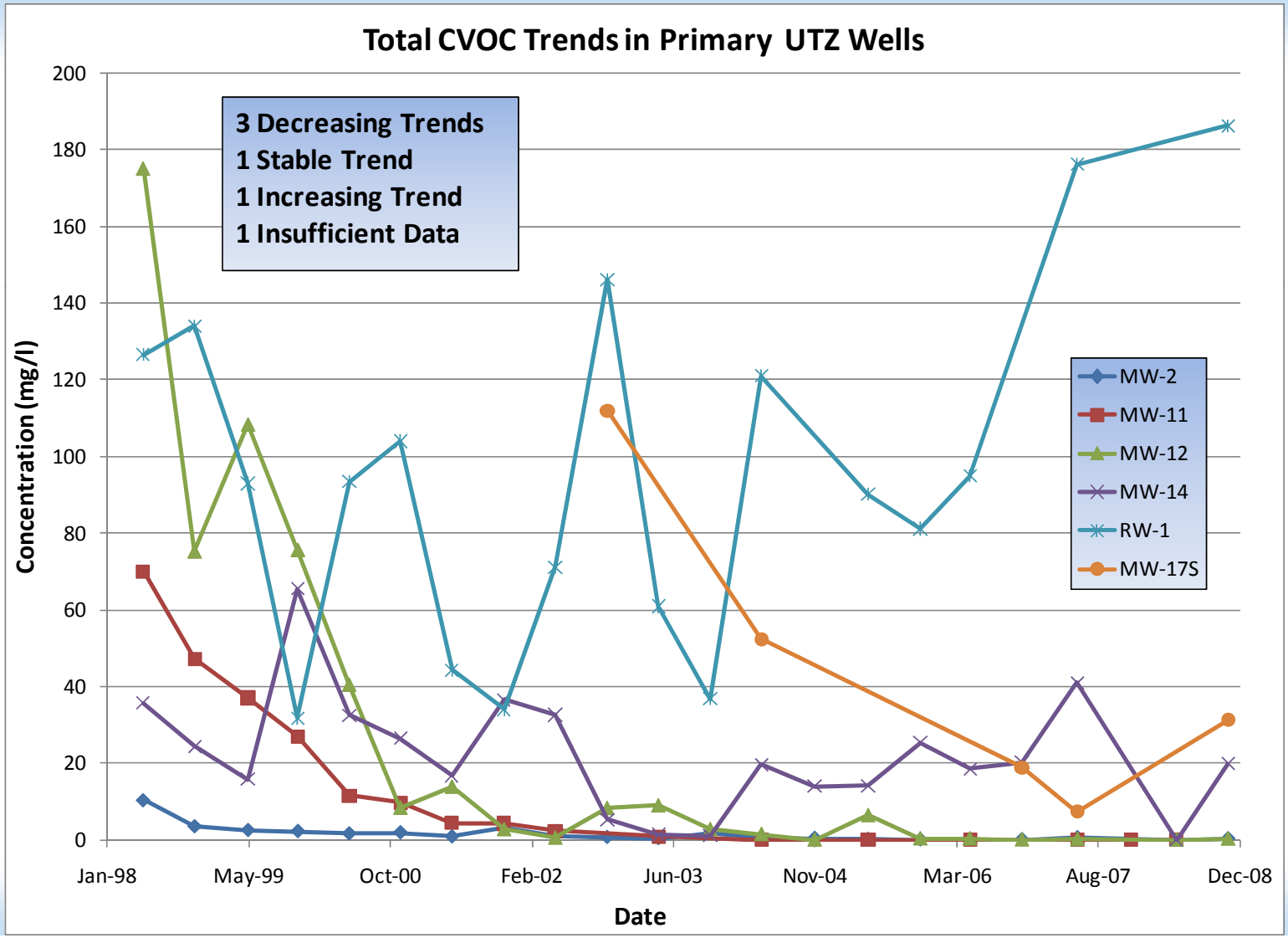
## 1998 CVOC Plume




## 2008 CVOC Plume



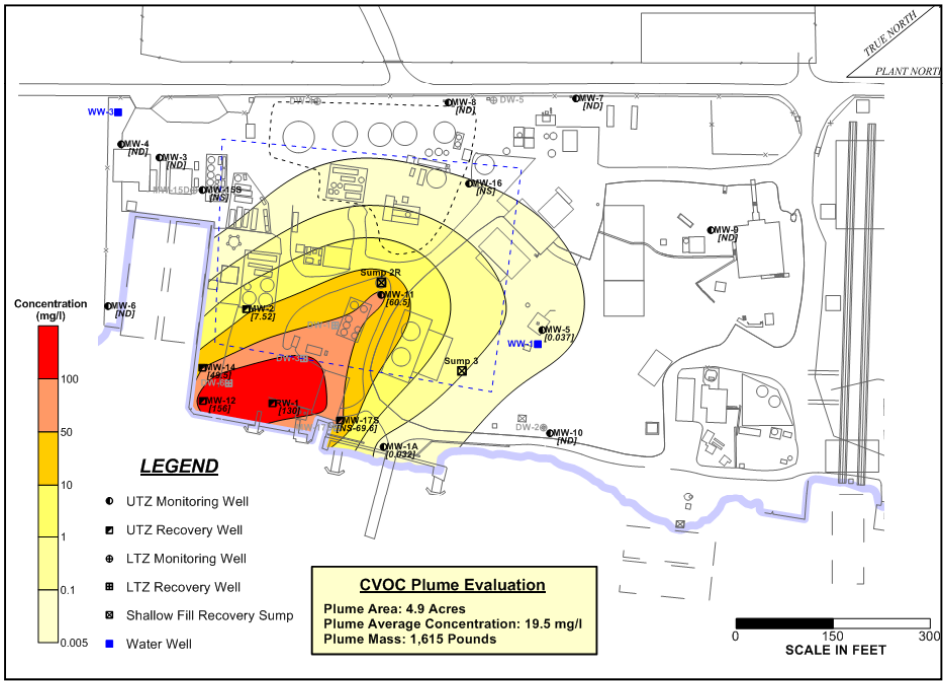
# Plume Stability Analysis - Example Site 3



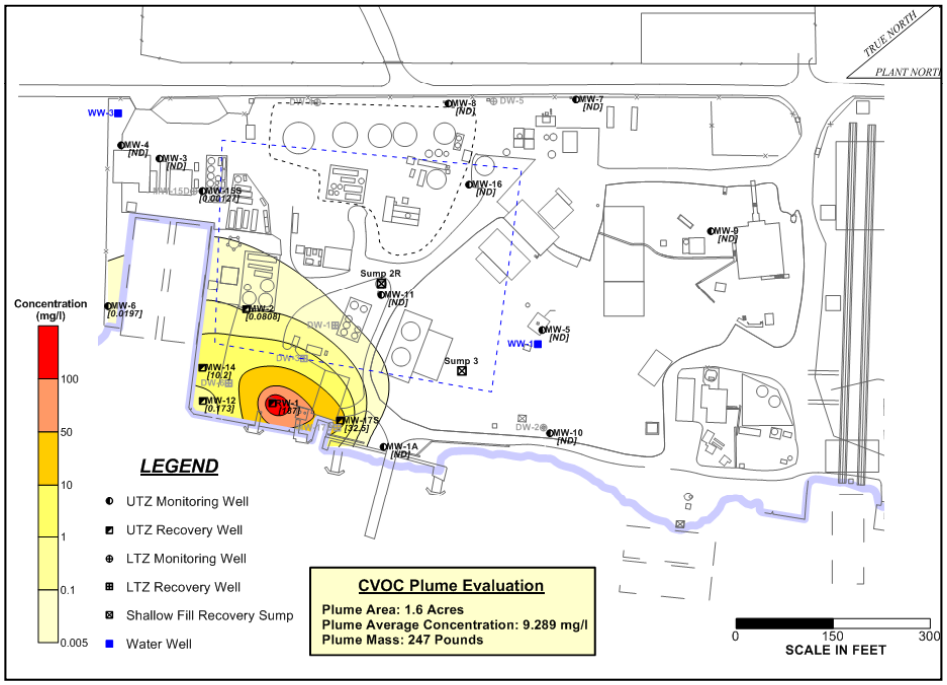
# Plume Stability Analysis - Example Site 3

PREMIER ENVIRONMENTAL SERVICES, INC

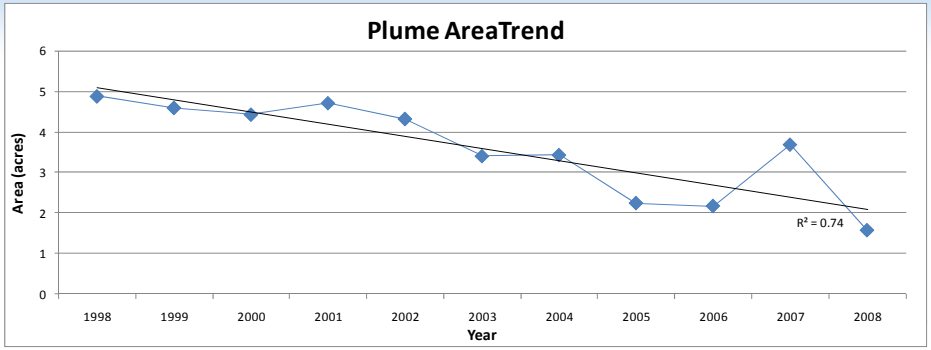
## 1998 CVOC Plume

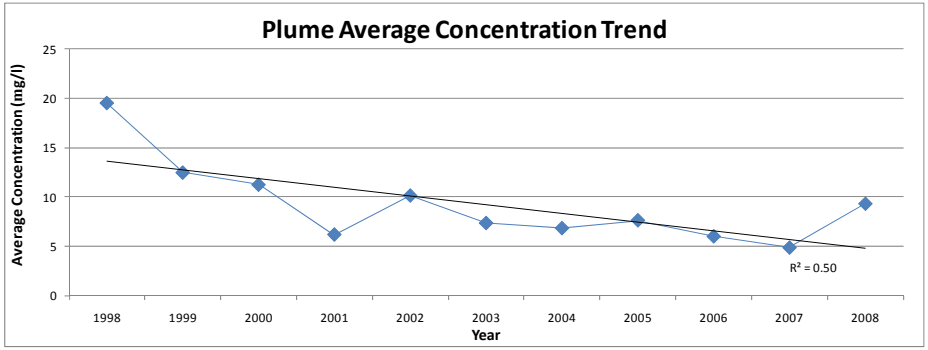


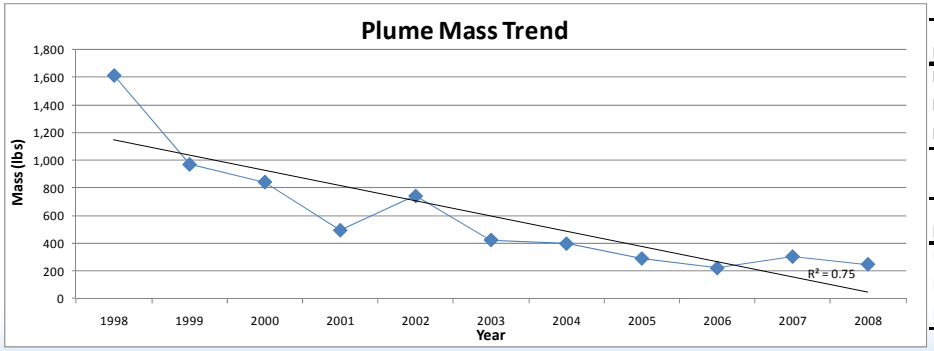

## 2008 CVOC Plume



# Plume Stability Analysis - Example Site 3




## Summary of Plume Stability Characteristics

| Date | Area (Acres) | Average Conc. (mg/l) | Mass (lbs) |
|---|---|---|---|
| 1998 | 4.9 | 19.500 | 1,615 |
| 1999 | 4.6 | 12.449 | 971 |
| 2000 | 4.4 | 11.221 | 844 |
| 2001 | 4.7 | 6.172 | 494 |
| 2002 | 4.3 | 10.119 | 742 |
| 2003 | 3.4 | 7.333 | 423 |
| 2004 | 3.4 | 6.823 | 397 |
| 2005 | 2.2 | 7.615 | 290 |
| 2006 | 2.2 | 5.984 | 220 |
| 2007 | 3.7 | 4.845 | 303 |
| 2008 | 1.6 | 9.289 | 247 |

## Mann-Kendall Trend Analysis Summary

| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Plume Area | 11 | -41 | 99.9% | 0.32 | Decreasing Trend |
| Plume Average Concentration | 11 | -31 | 99.0% | 0.45 | Decreasing Trend |
| Plume Mass | 11 | -47 | 100.0% | 0.71 | Decreasing Trend |

## Linear Regression Trend Analysis Summary

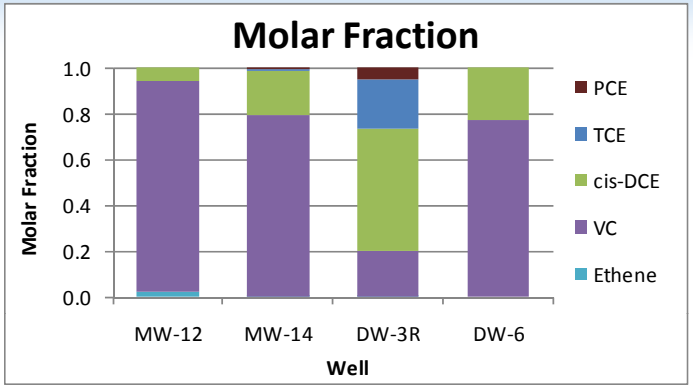
| Parameter | # of samples, n | Slope ($yr^{-1}$) | $R^2$ | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|---|
| Plume Area | 11 | -0.30 | 0.74 | 99.9% | 0.32 | Decreasing Trend |
| Plume Average Concentration | 11 | -0.887 | 0.50 | 98.6% | 0.45 | Decreasing Trend |
| Plume Mass | 11 | -110 | 0.75 | 99.9% | 0.71 | Decreasing Trend |

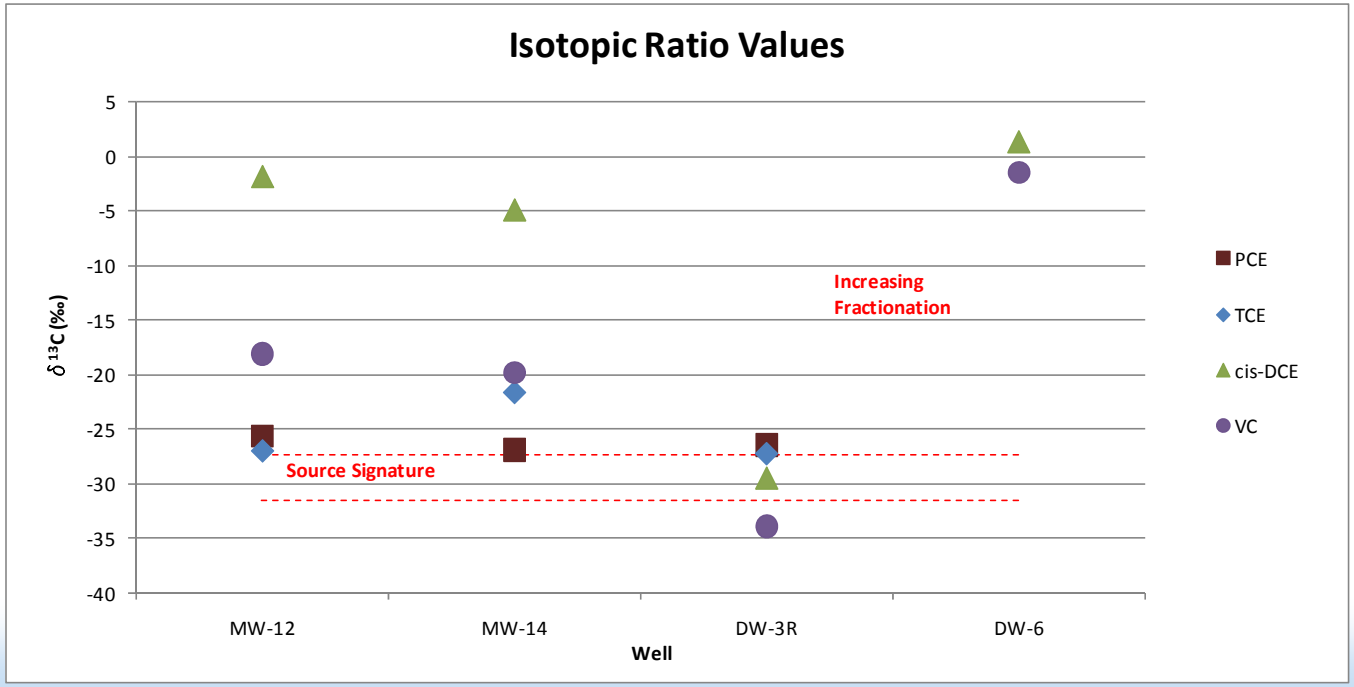
# Plume Stability Analysis - Example Site 3

- **Plume stability data can be combined with other site data to explain mechanisms for observed reductions in plume concentration and mass**
  - ***Geochemical data isopleth maps***
  - ***Forensic analyses (e.g. compound specific isotope analysis, CSIA)***
  - ***Molar ratio plots for parent/daughter complexes***

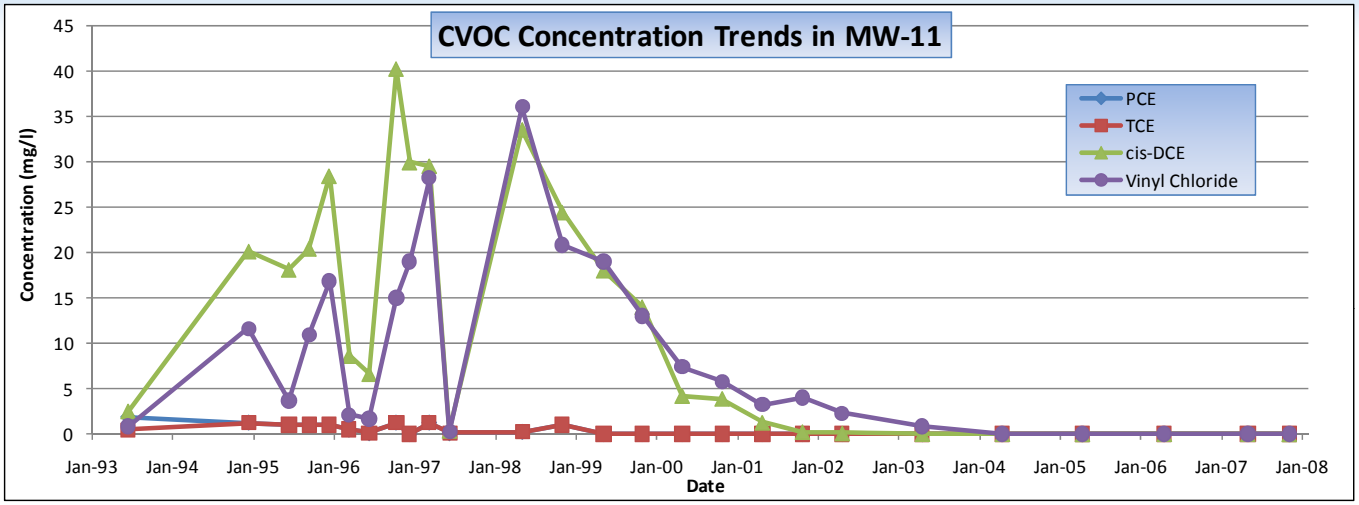
# Plume Stability Analysis - Example Site 3

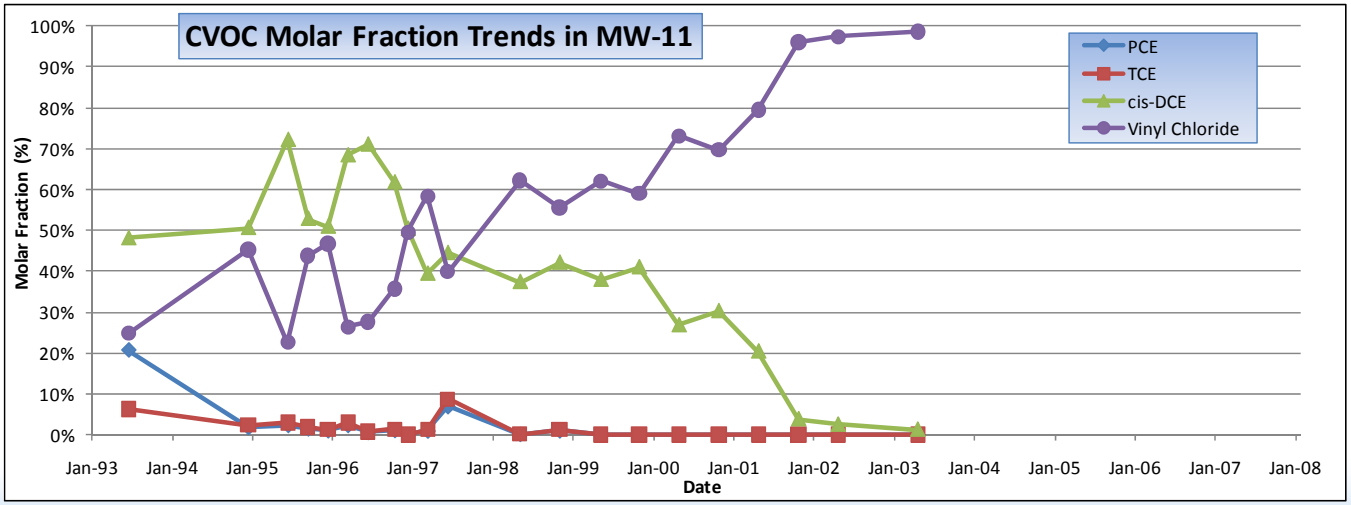
| Well | Stable Carbon Isotope Ratio, $\delta^{13}C$ (‰) | | | |
|---|---|---|---|---|
| | PCE | TCE | cis-1,2-DCE | Vinyl Chloride |
| UTZ Wells | | | | |
| MW-12 | -25.65 | -26.96 | -1.90 | -18.10 |
| MW-14 | -26.91 | -21.64 | -4.96 | -19.80 |
| LTZ Wells | | | | |
| DW-3 | -26.43 | -27.21 | -29.54 | -33.89 |
| DW-6 | ND | ND | 1.29 | -1.48 |



# Plume Stability Analysis - Example Site 3



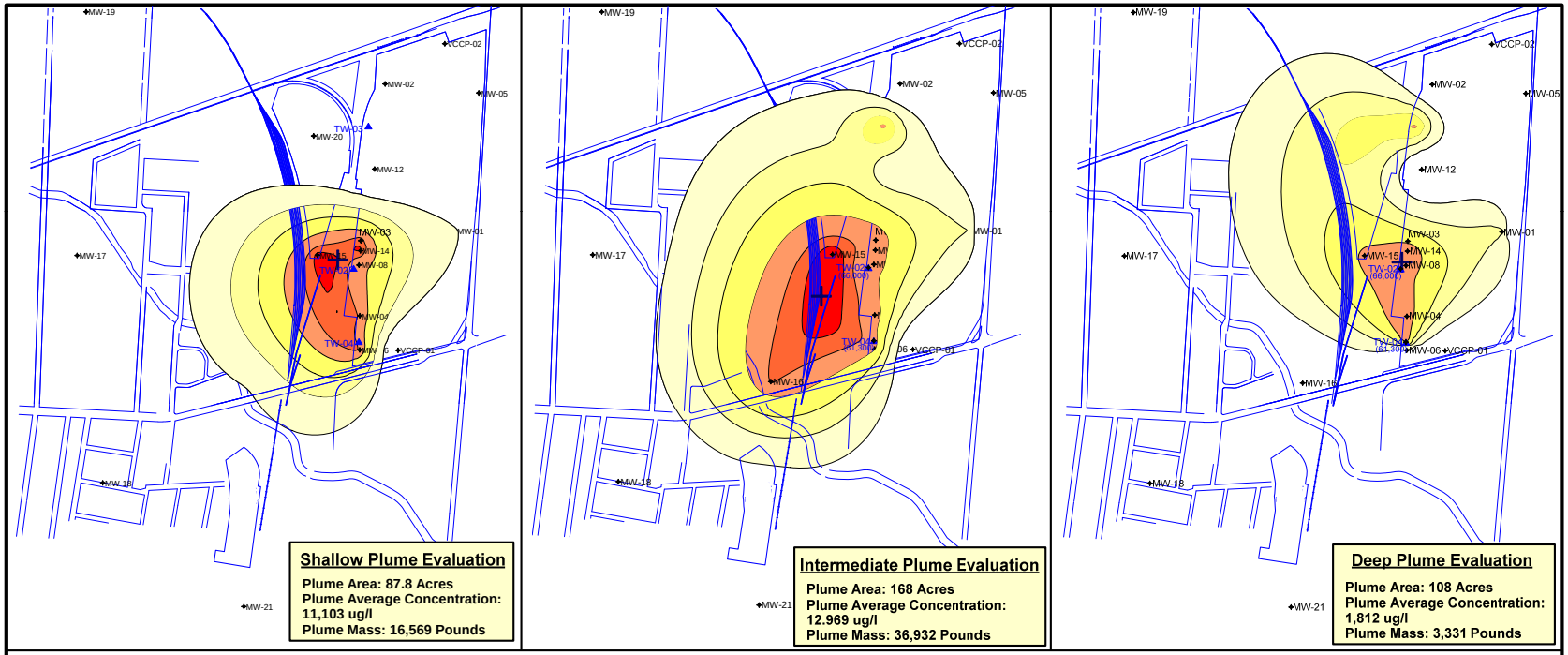
# Plume Stability Analysis - Example Site 4

- Chemical manufacturing plant
- Site impacted by VOCs, SVOCs, pesticides
- Pump & treat system operating since 1998
- 75 foot thick sand & gravel semi-confined aquifer
- Well clusters contain shallow, intermediate, and deep wells

# Plume Stability Analysis - Example Site 4

PREMIER ENVIRONMENTAL SERVICES, INC

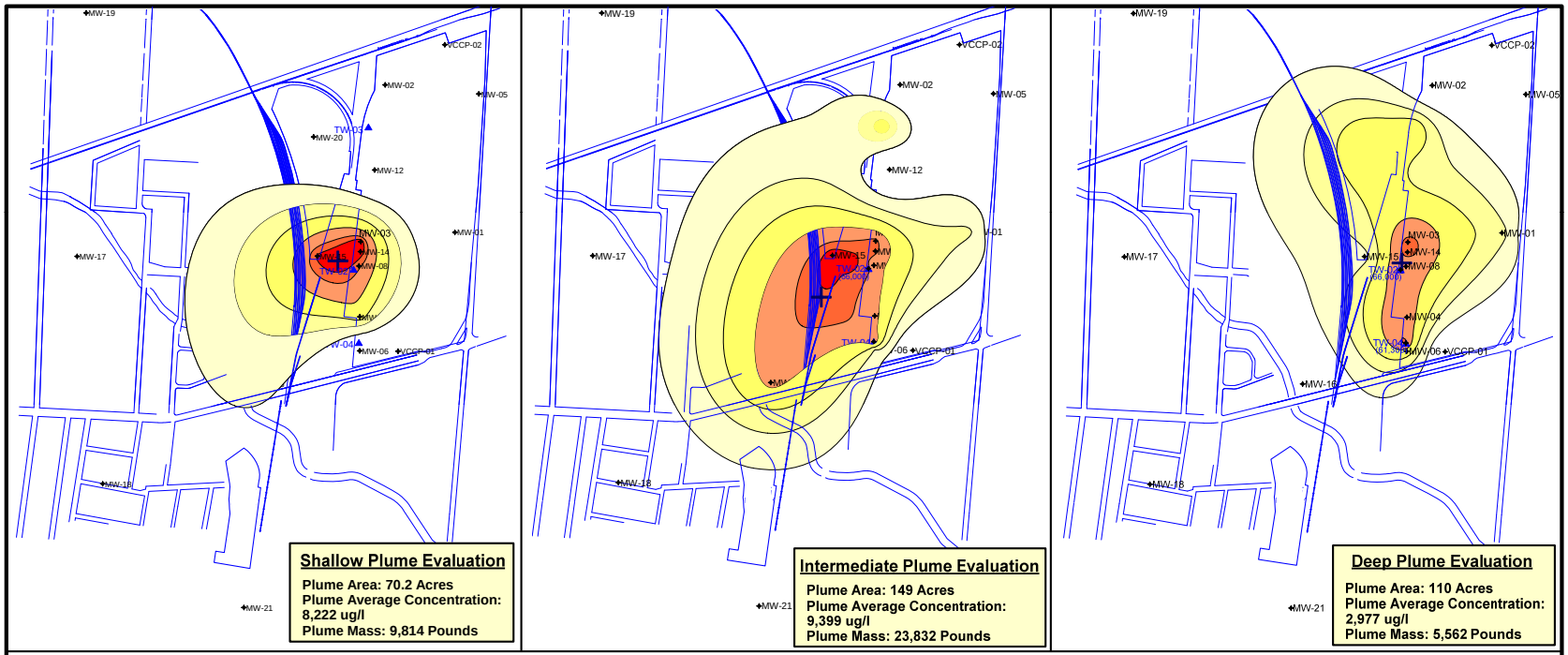
- Plume stability analysis for carbon tetrachloride



# Plume Stability Analysis - Example Site 4

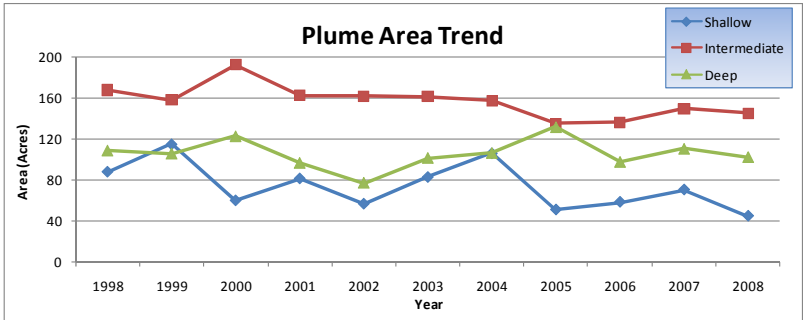
PREMIER ENVIRONMENTAL SERVICES, INC

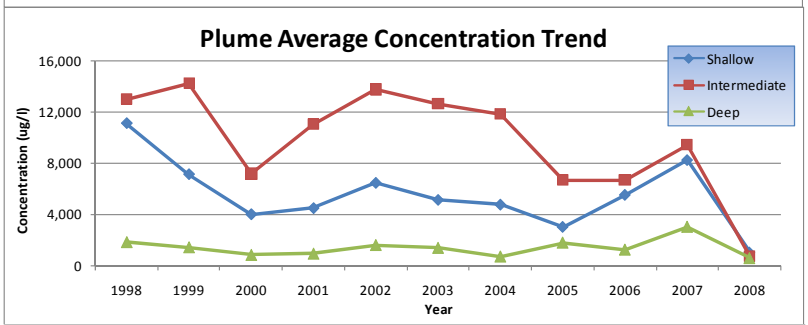
- Plume stability analysis for carbon tetrachloride

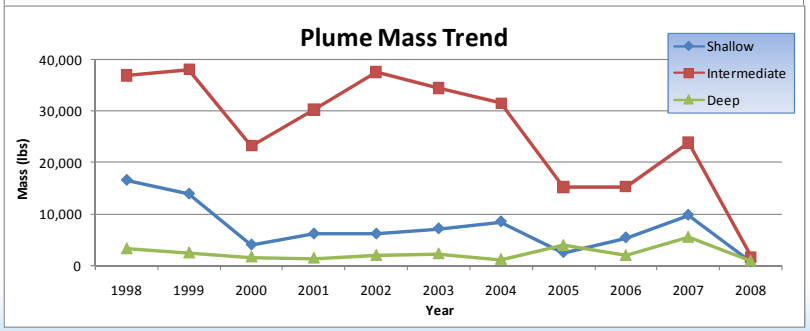


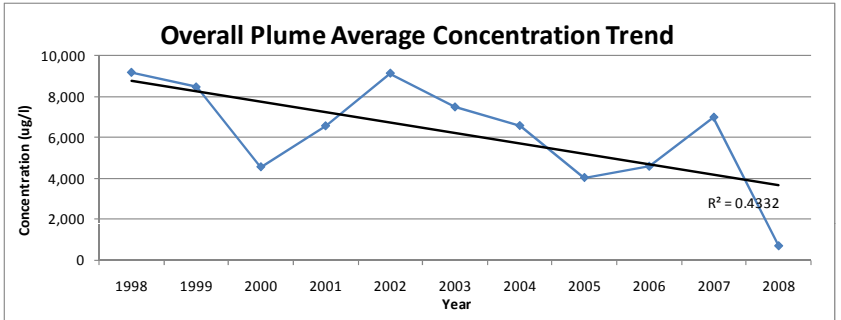
# Plume Stability Analysis - Example Site 4

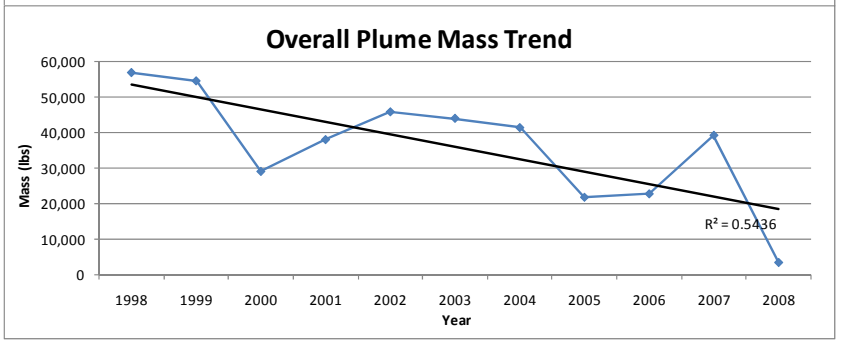
## Plume stability analysis for carbon tetrachloride



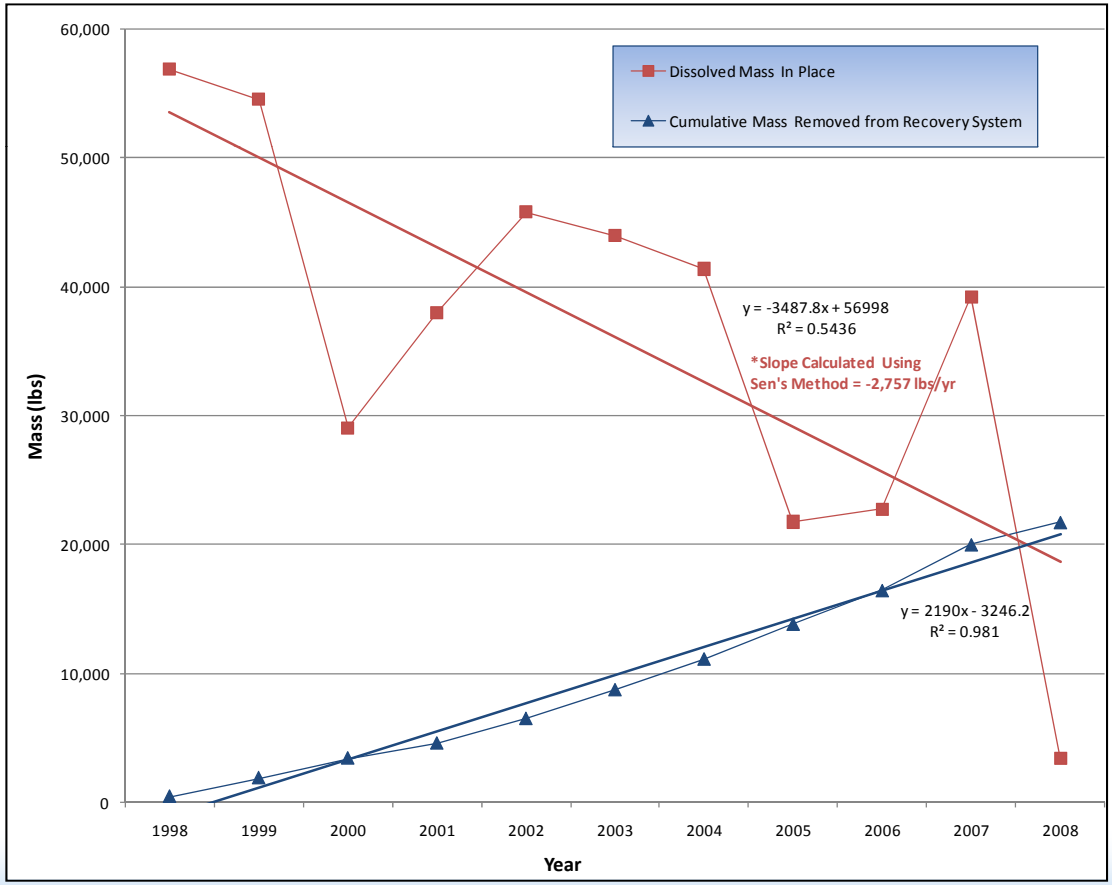




### Trend Analysis Summary

| Parameter | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|
| Shallow Plume Area | -23 | 95.7% | 0.31 | Decreasing Trend |
| Intermediate Plume Area | -35 | 99.6% | 0.10 | Decreasing Trend |
| Deep Plume Area | 1 | 50.0% | 0.13 | Stable Trend |
| Overall Plume Average Concentration | -25 | 96.9% | 0.41 | Decreasing Trend |
| Overall Plume Mass | -31 | 99.0% | 0.43 | Decreasing Trend |

# Plume Stability Analysis - Example Site 4

- **Summary of Carbon Tetrachloride Mass Removed vs. Mass In Place Reduction**




Rate of Mass Removal = 2,190 lbs/yr

Rate of Mass-in-Place Reduction = 3,488 lbs/yr (linear regression)

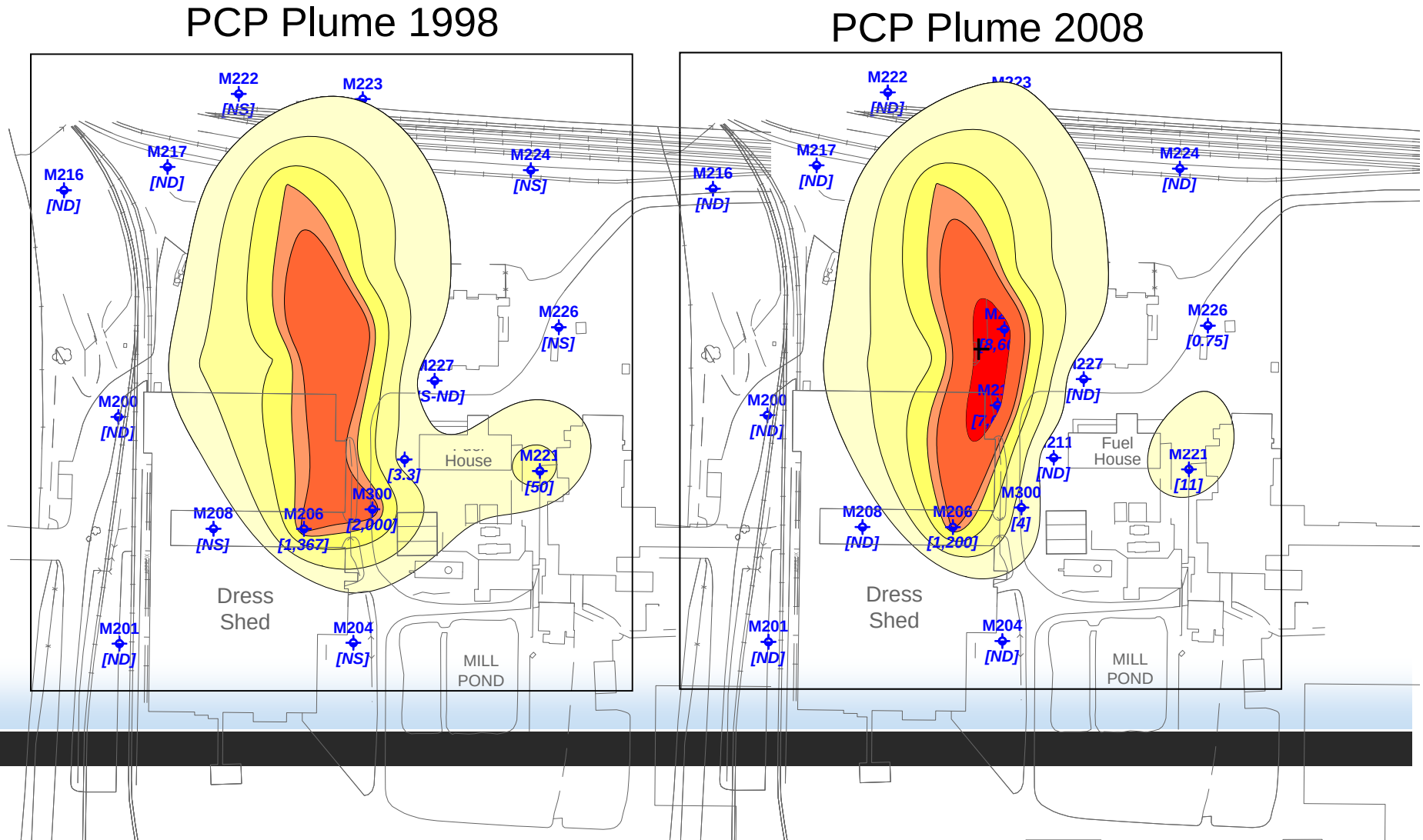
Rate of Mass-in-Place Reduction = 2,757 lbs/yr (Sen's method)

# Plume Stability Analysis - Example Site 5

- Former Wood Treating Site
- Site impacted by pentachlorophenol (PCP)
- Pump & treat system operated from 1999-2006, no active treatment since 2006
- Plume stability analysis used to evaluate remedial system effectiveness and for placement of additional recovery wells

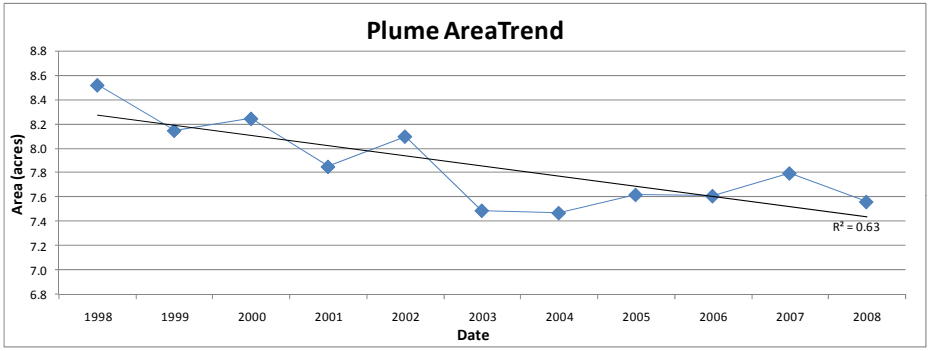
# Plume Stability Analysis - Example Site 5

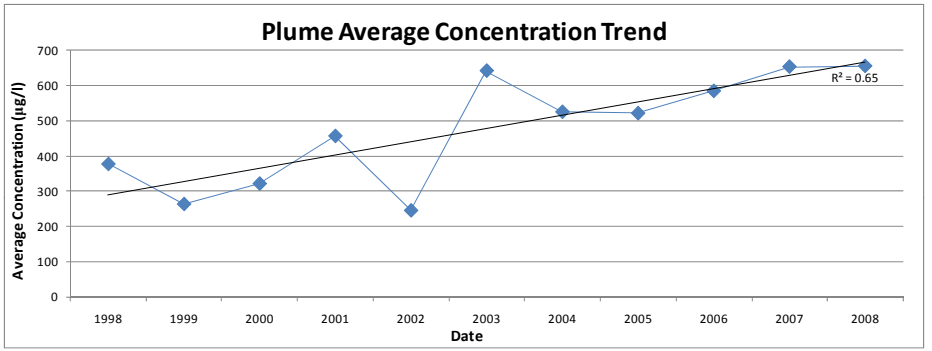
- **Example Site 4 Plume Stability Analysis**

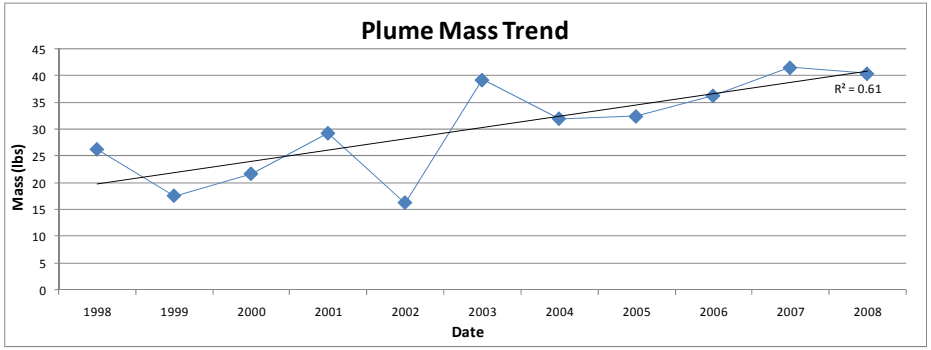


# Plume Stability Analysis - Example Site 5

## Example Site 4 Plume Stability Analysis



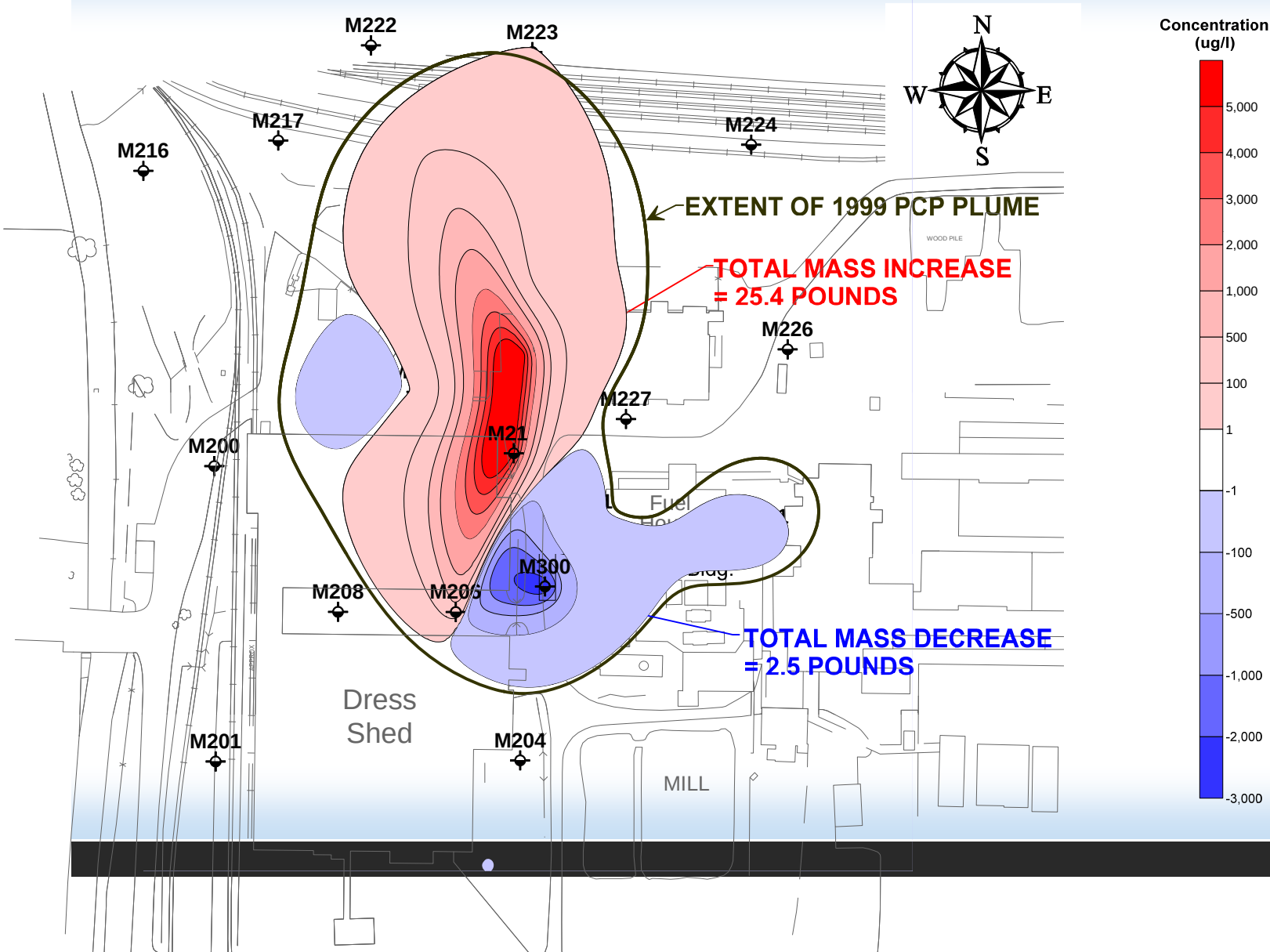




### Mann-Kendall Trend Analysis Summary

| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Plume Area | 11 | -31 | 99.0% | 0.04 | Decreasing Trend |
| Plume Average Concentration | 11 | 35 | 99.6% | 0.32 | Increasing Trend |
| Plume Mass | 11 | 35 | 99.6% | 0.30 | Increasing Trend |

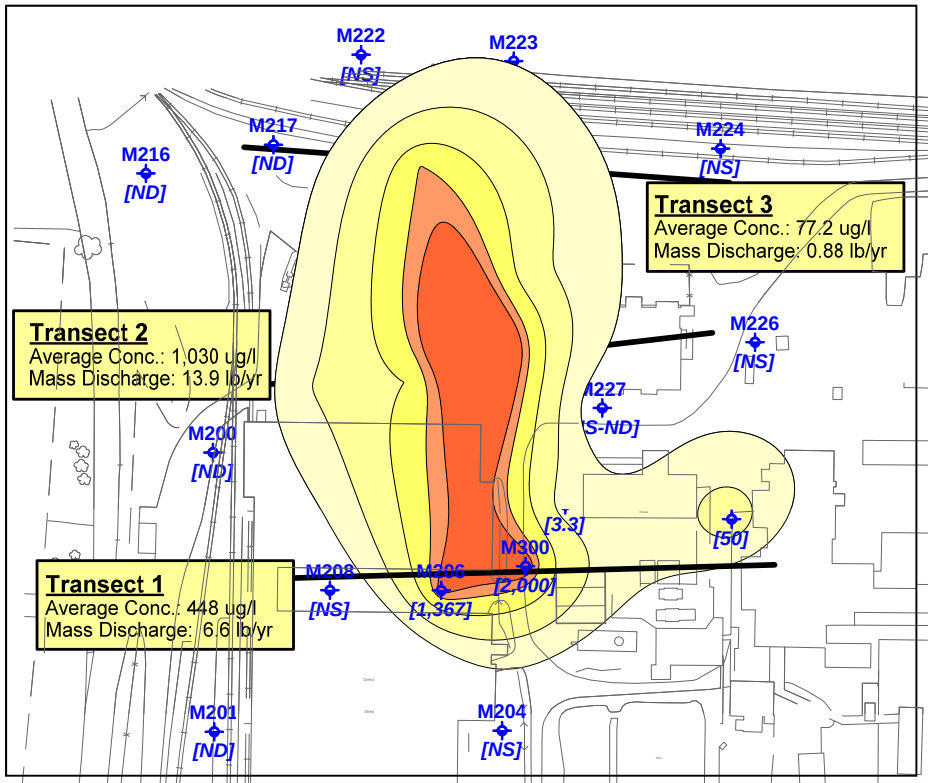
# Plume Stability Analysis - Example Site 5



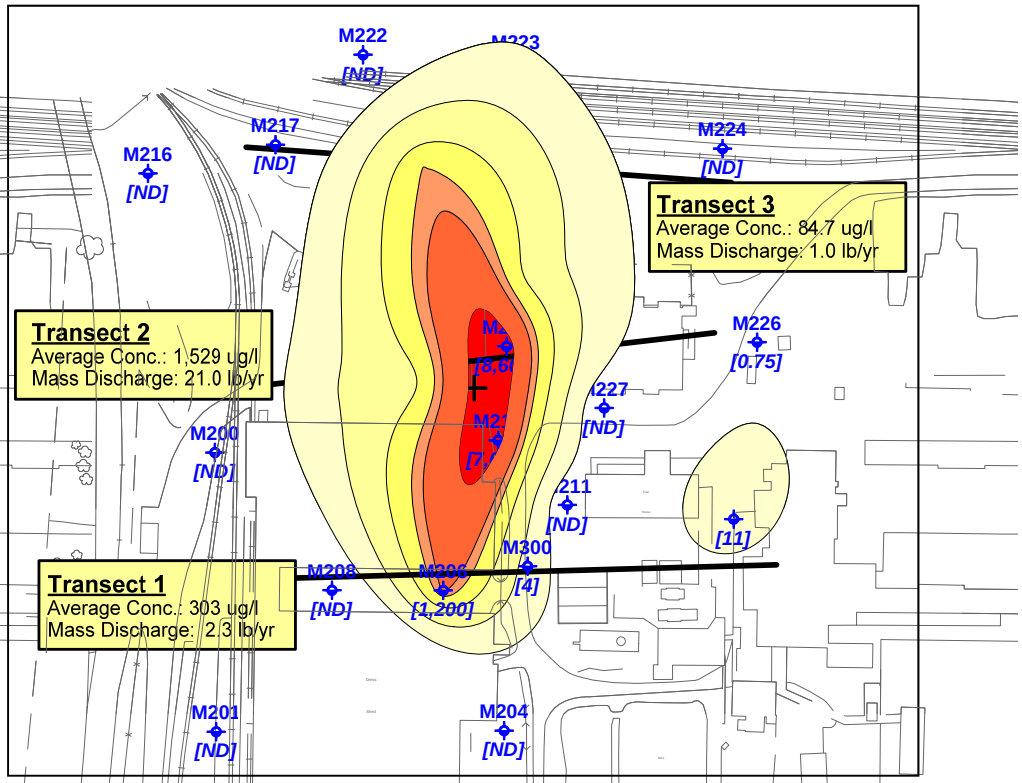
# Plume Stability Analysis - Example Site 5

## Example Site 4 Plume Mass Flux Analysis

PCP Plume 1998

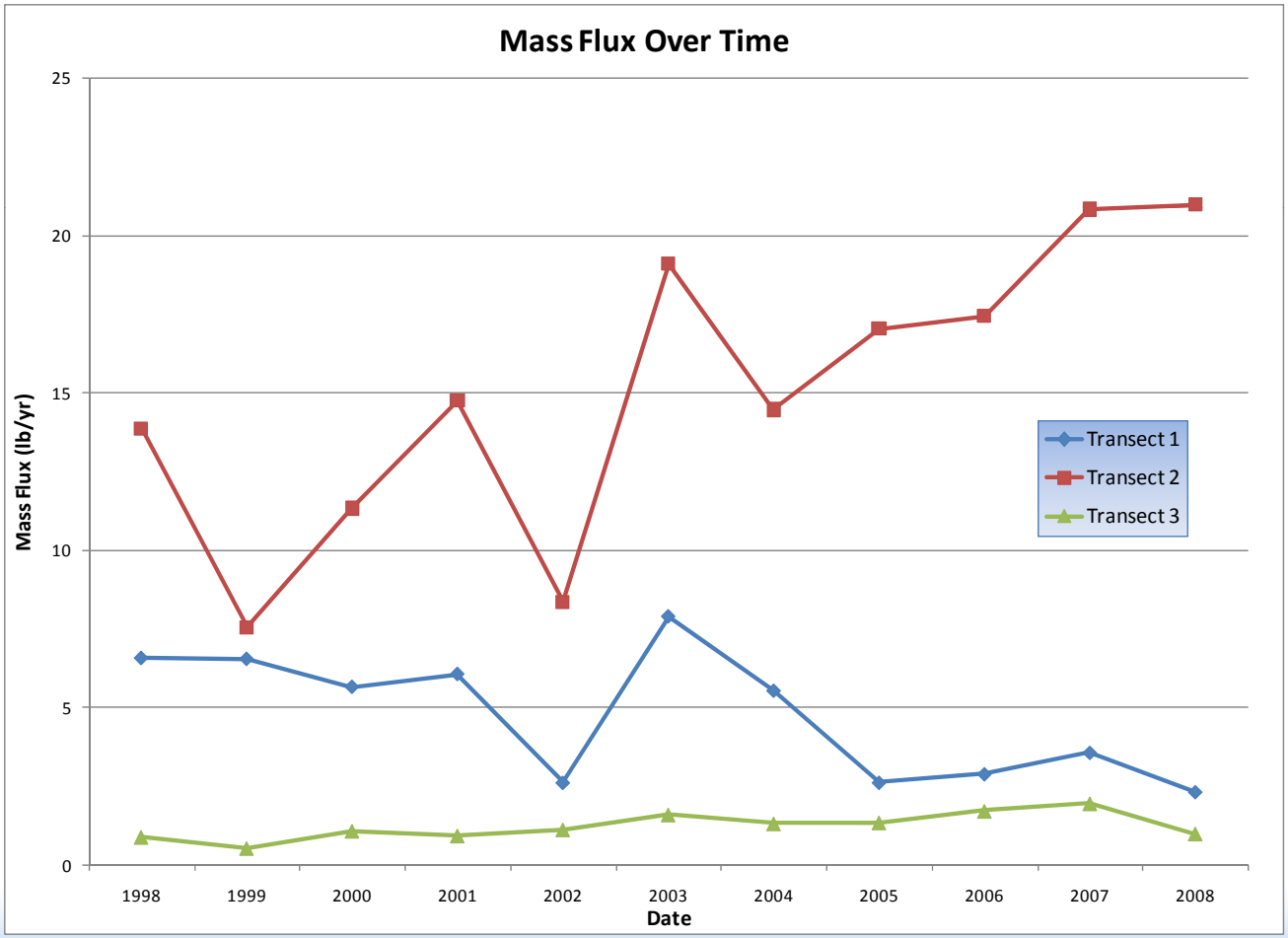



PCP Plume 2008



# Plume Stability Analysis - Example Site 5

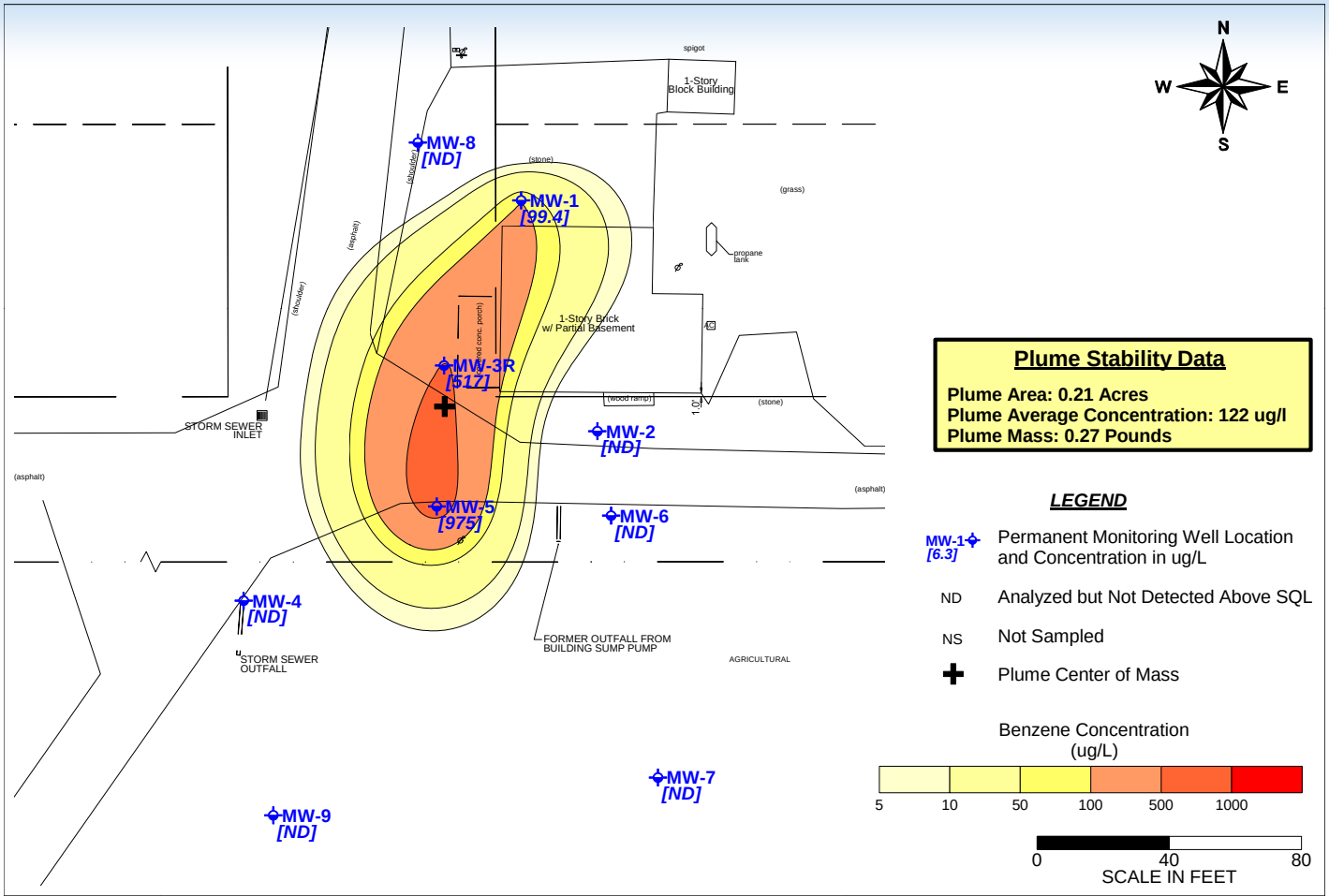
## Example Site 4 Plume Mass Flux Analysis



# Plume Stability Analysis - Example Site 6

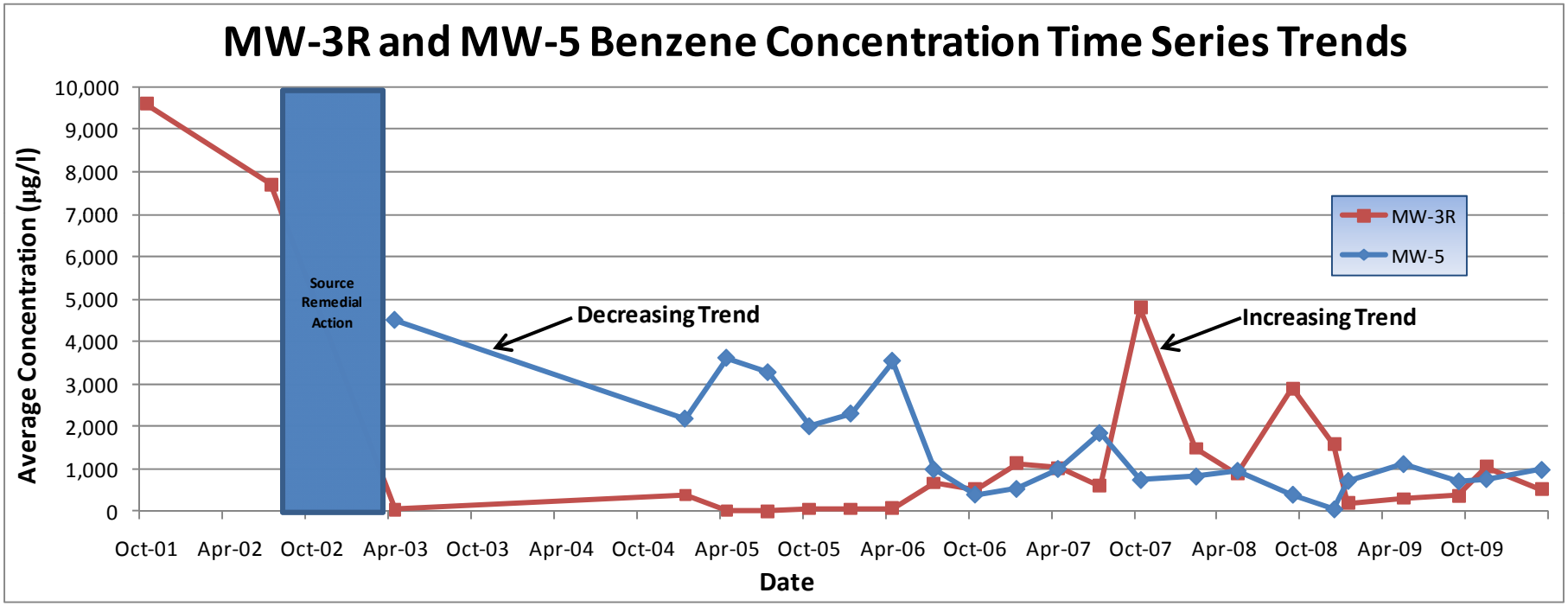
- Former service station
- Site impacted by benzene and MTBE
- Source area excavated in 2002

# Plume Stability Analysis - Example Site 6




| | | | |
|---|---|---|---|
| PROJECT NUMBER | DATE: 4/13/10 | BENZENE PLUME STABILITY ANALYSIS - MARCH 2010 | Premier Environmental Services, Inc.<br>55 South State Avenue, Suite 382<br>Indianapolis, Indiana 46201<br>317-472-6259 |
| | DWN. BY: JAR | | |
| | CHKD. BY: JDH | | |
| | SCALE: 1" = 40' | | |

# Plume Stability Analysis - Example Site 6



# Plume Stability Analysis - Example Site 6

PREMIER ENVIRONMENTAL SERVICES, INC

**Summary of Plume Stability Characteristics**

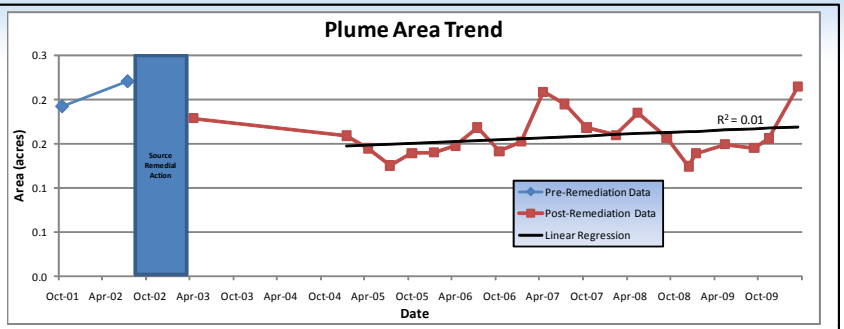
| Date | Area (Acres) | Average Conc. (µg/l) | Mass (lbs) |
|---|---|---|---|
| Oct-01 | 0.19 | 789 | 1.55 |
| Jul-02 | 0.22 | 668 | 1.50 |
| Apr-03 | 0.18 | 152 | 0.28 |
| Jan-05 | 0.16 | 172 | 0.28 |
| Apr-05 | 0.14 | 132 | 0.19 |
| Jul-05 | 0.13 | 112 | 0.14 |
| Oct-05 | 0.14 | 115 | 0.16 |
| Jan-06 | 0.14 | 123 | 0.18 |
| Apr-06 | 0.15 | 164 | 0.25 |
| Jul-06 | 0.17 | 137 | 0.23 |
| Oct-06 | 0.14 | 92 | 0.13 |
| Jan-07 | 0.15 | 141 | 0.22 |
| Apr-07 | 0.21 | 153 | 0.32 |
| Jul-07 | 0.19 | 160 | 0.32 |
| Oct-07 | 0.17 | 321 | 0.55 |
| Feb-08 | 0.16 | 184 | 0.30 |
| May-08 | 0.18 | 144 | 0.27 |
| Sep-08 | 0.16 | 209 | 0.33 |
| Dec-08 | 0.12 | 103 | 0.13 |
| Jan-09 | 0.14 | 83.6 | 0.12 |
| May-09 | 0.15 | 117 | 0.18 |
| Sep-09 | 0.15 | 101 | 0.15 |
| Nov-09 | 0.16 | 154 | 0.25 |
| Mar-10 | 0.21 | 122 | 0.27 |

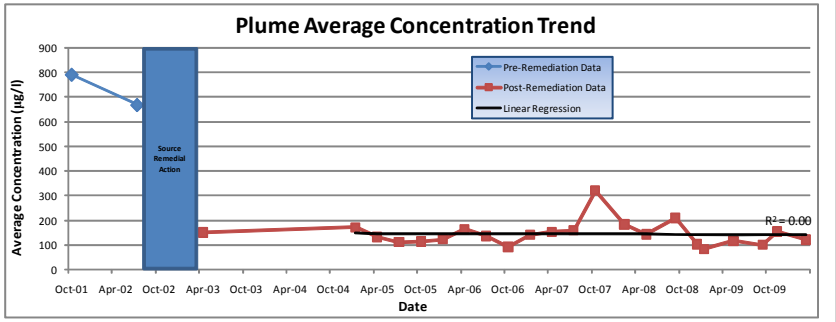
**Mann-Kendall Trend Analysis Summary (Post-Remediation Data since Jan-05)**

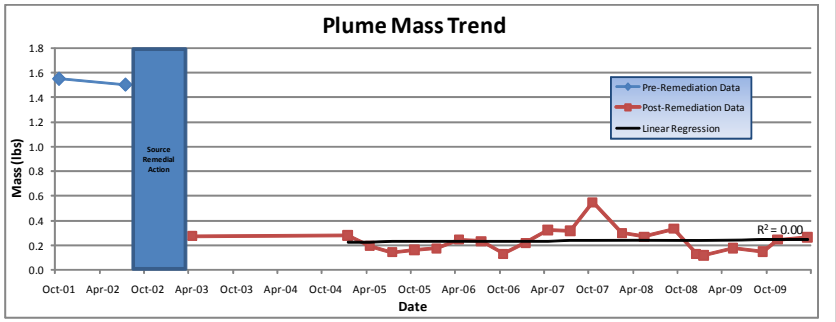
| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Benzene Plume Area | 21 | 34 | 84.0% | 0.17 | Stable/No Trend |
| Benzene Plume Average Concentration | 21 | -6 | 56.0% | 0.35 | Stable/No Trend |
| Benzene Plume Mass | 21 | 8 | 58.4% | 0.42 | Stable/No Trend |

**Linear Regression Trend Analysis Summary (Post-Remediation Data since Jan-05)**

| Parameter | # of samples, n | Slope ($yr^{-1}$) | $R^2$ | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|---|
| Benzene Plume Area | 21 | 0.00 | 0.07 | 75.9% | 0.17 | Stable/No Trend |
| Benzene Plume Average Concentration | 21 | -1.05 | 0.00 | 11.2% | 0.35 | Stable/No Trend |
| Benzene Plume Mass | 21 | 0.00 | 0.00 | 20.9% | 0.42 | Stable/No Trend |



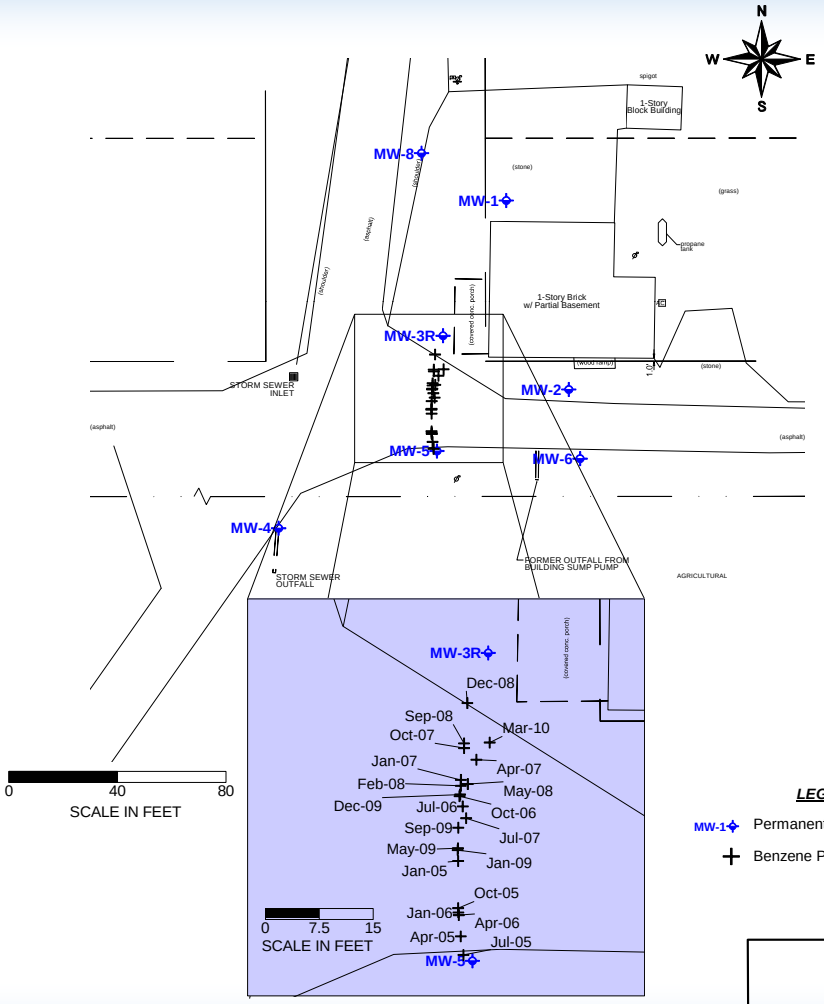



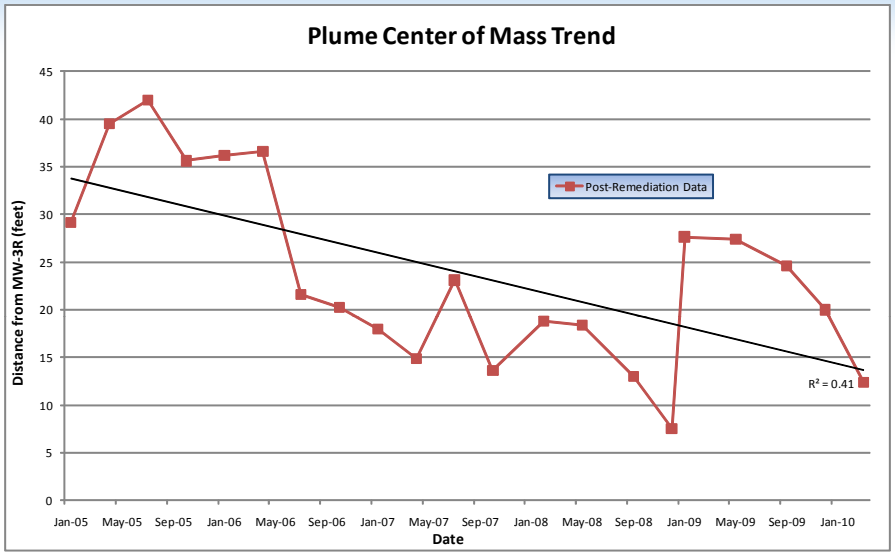

PREMIER ENVIRONMENTAL SERVICES, INC

BENZENE PLUME STABILITY ANALYSIS SUMMARY

DESIGNED: JAR | CHECKED: JDH | DATE: APRIL 13, 2010 | FIGURE NO. 1
DRAWN: JAR | FILE NAME: | SCALE: NONE

# Plume Stability Analysis - Example Site 6




**Mann-Kendall Trend Analysis**

n = 21
S Statistic = -96
Confidence Factor = 99.8%
Coeff. of Variation = 0.41
Conclusion: Decreasing Trend

**Linear Regression Trend Analysis**

n = 21
Slope = -3.91
$R^2$ = 0.41
Confidence Factor = 99.8%
Coeff. of Variation = 0.41
Conclusion: Decreasing Trend

***LEGEND***

MW-1 Permanent Monitoring Well Location

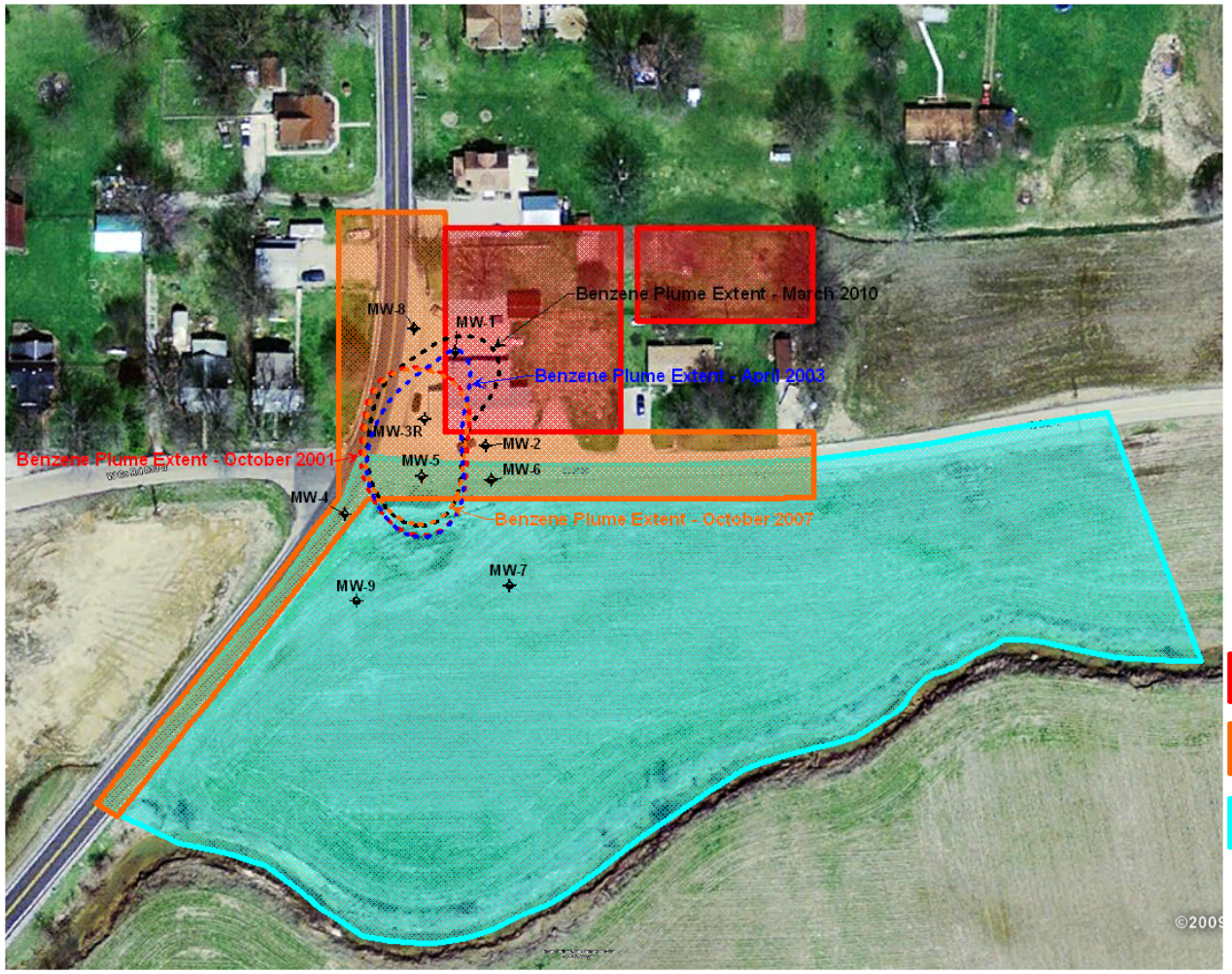
Benzene Plume Center of Mass Location

PREMIER ENVIRONMENTAL SERVICES, INC

BENZENE PLUME CENTER OF MASS ANALYSIS SUMMARY

| DESIGNED: JAR | CHECKED: JDH | DATE: APRIL 13, 2010 | PLUME NO. 3 |
|---|---|---|---|
| DRAWN: JAR | FILE NAME: | SCALE: NONE | |

# Plume Stability Analysis - Example Site 6




N
W
E
S

**LEGEND**

MW-1

0 FT 80 FT 160 FT

| | |
|---|---|
| DATE: | 4/6/10 |
| DWN. BY: | JAR |
| CHKD. BY: | JDH |
| SCALE: | 1" = 80' |

FIGURE 1


Premier Environmental Services, Inc.
55 South State Avenue, Suite 382
Indianapolis, Indiana 46201
317-472-6259

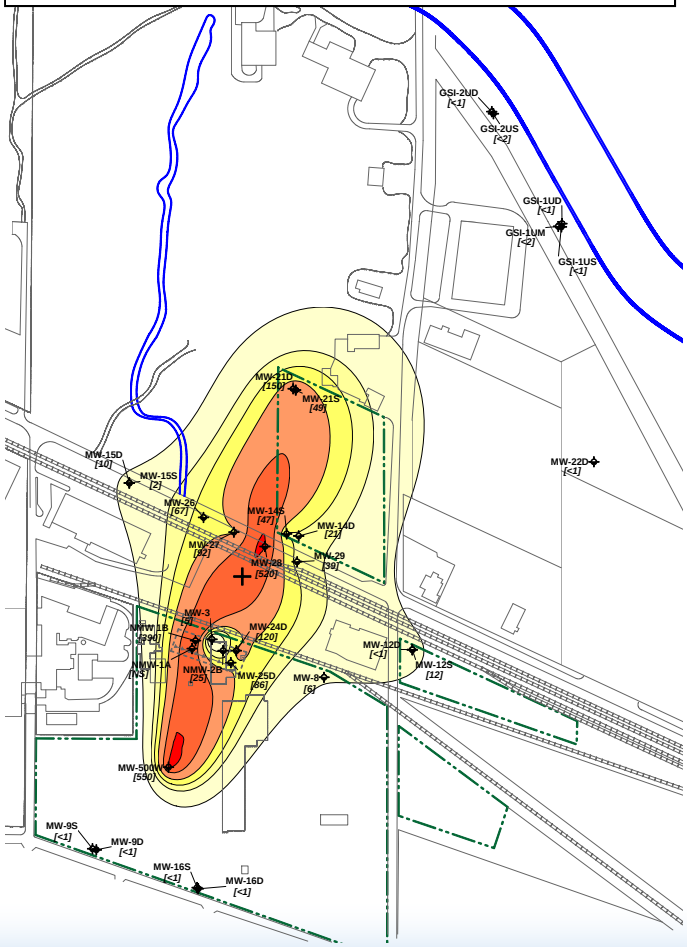
# Plume Stability Analysis - Example Site 7

- Former engine components manufacturing plant from 1930 – 1983
- Site impacted by chlorinated VOCs
- Historic pump and treatment remediation system from 1992 – 2002
- Limited enhanced biodegradation from 2002-2008 (whey injection)
- 34 active monitoring wells

# Plume Stability Analysis - Example Site 7

PREMIER ENVIRONMENTAL SERVICES, INC

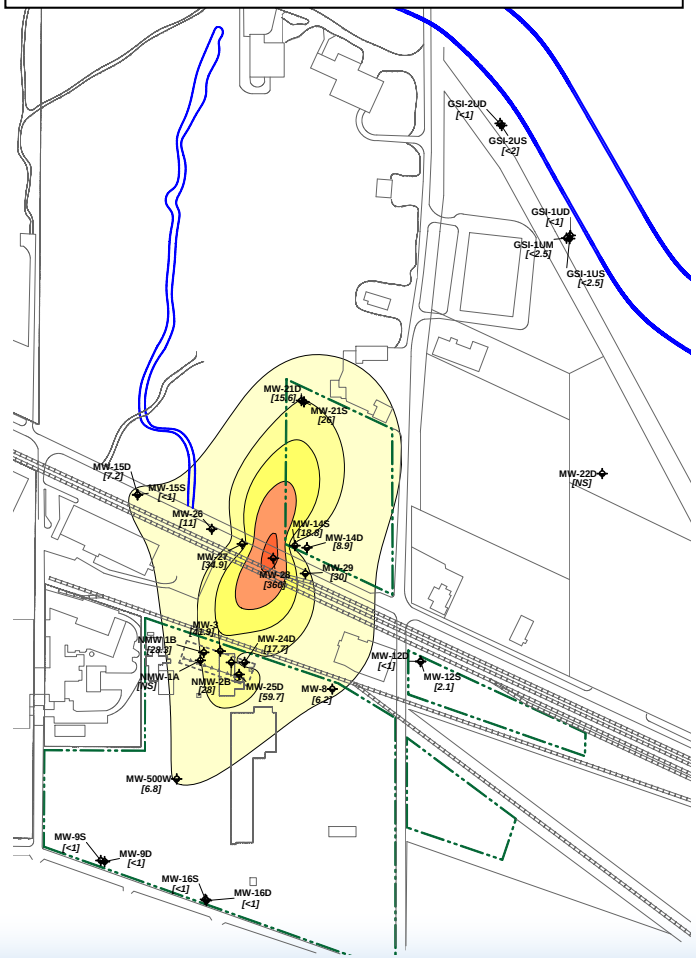
## May 2002 TCE Plume




CONCENTRATION (uG/L)

500
250
100
50
25
5

## April 2010 TCE Plume



# Plume Stability Analysis - Example Site 7

PREMIER ENVIRONMENTAL SERVICES, INC

**Summary of Plume Stability Characteristics**

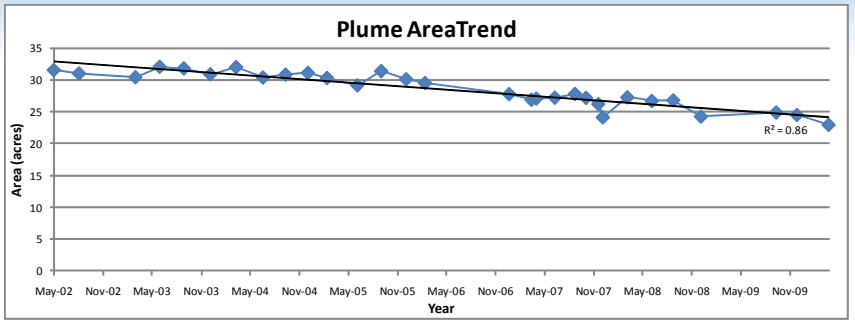
| Date | Area (Acres) | Average Conc. (µg/l) | Mass (lbs) |
|---|---|---|---|
| May-02 | 31.5 | 86.3 | 73.9 |
| Aug-02 | 31.0 | 73.1 | 61.5 |
| Mar-03 | 30.4 | 66.2 | 54.7 |
| Jun-03 | 32.0 | 82.1 | 71.4 |
| Sep-03 | 31.8 | 69.6 | 60.1 |
| Dec-03 | 30.9 | 68.6 | 57.6 |
| Mar-04 | 32.0 | 76.7 | 66.6 |
| Jun-04 | 30.4 | 67.3 | 55.5 |
| Sep-04 | 30.8 | 72.0 | 60.2 |
| Dec-04 | 31.1 | 80.9 | 68.3 |
| Feb-05 | 30.3 | 74.0 | 60.9 |
| Jun-05 | 29.1 | 61.6 | 48.7 |
| Sep-05 | 31.4 | 66.3 | 56.5 |
| Dec-05 | 30.1 | 55.3 | 45.2 |
| Feb-06 | 29.5 | 67.0 | 53.7 |
| Jan-07 | 27.8 | 52.1 | 39.3 |
| Mar-07 | 26.9 | 45.9 | 33.5 |
| Apr-07 | 27.1 | 46.9 | 34.5 |
| Jun-07 | 27.2 | 36.5 | 27.0 |
| Sep-07 | 27.8 | 37.2 | 28.1 |
| Oct-07 | 27.2 | 34.3 | 25.4 |
| Nov-07 | 26.2 | 33.9 | 24.1 |
| Dec-07 | 24.1 | 33.3 | 21.8 |
| Mar-08 | 27.3 | 40.0 | 29.6 |
| Jun-08 | 26.7 | 38.4 | 27.8 |
| Sep-08 | 26.8 | 35.4 | 25.8 |
| Dec-08 | 24.3 | 30.4 | 20.1 |
| Sep-09 | 24.9 | 32.8 | 22.2 |
| Dec-09 | 24.5 | 33.5 | 22.3 |
| Apr-10 | 23.0 | 30.7 | 19.1 |

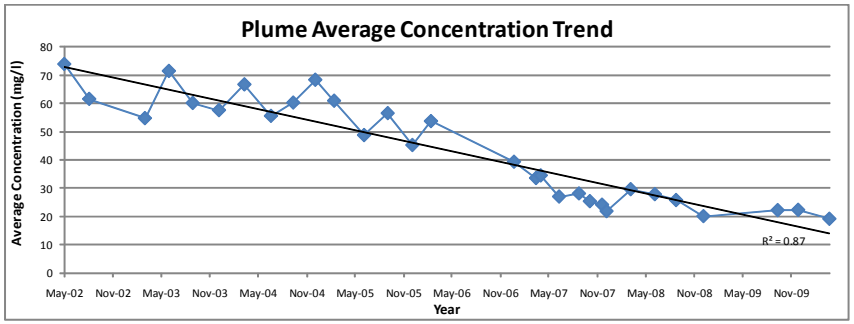
**Mann-Kendall Trend Analysis Summary**

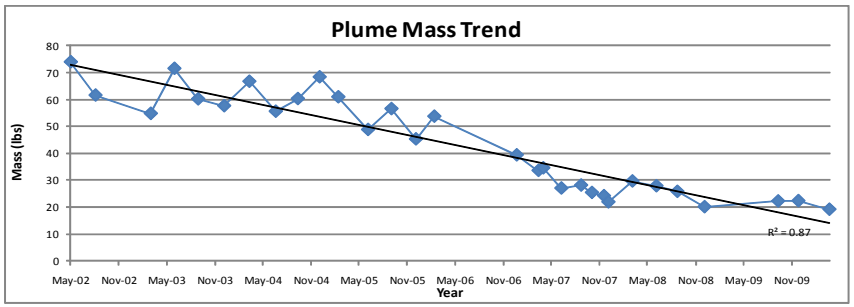
| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| TCE Plume Area | 30 | -327 | 100.0% | 0.09 | Decreasing Trend |
| TCE Plume Average Concentration | 30 | -331 | 100.0% | 0.34 | Decreasing Trend |
| TCE Plume Mass | 30 | -337 | 100.0% | 0.42 | Decreasing Trend |

**Linear Regression Trend Analysis Summary**

| Parameter | # of samples, n | Slope ($yr^{-1}$) | $R^2$ | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|---|
| TCE Plume Area | 30 | -1.10 | 0.86 | 100.0% | 0.09 | Decreasing Trend |
| TCE Plume Average Concentration | 30 | -7.61 | 0.86 | 100.0% | 0.34 | Decreasing Trend |
| TCE Plume Mass | 30 | -7.46 | 0.87 | 100.0% | 0.42 | Decreasing Trend |




PREMIER ENVIRONMENTAL SERVICES, INC

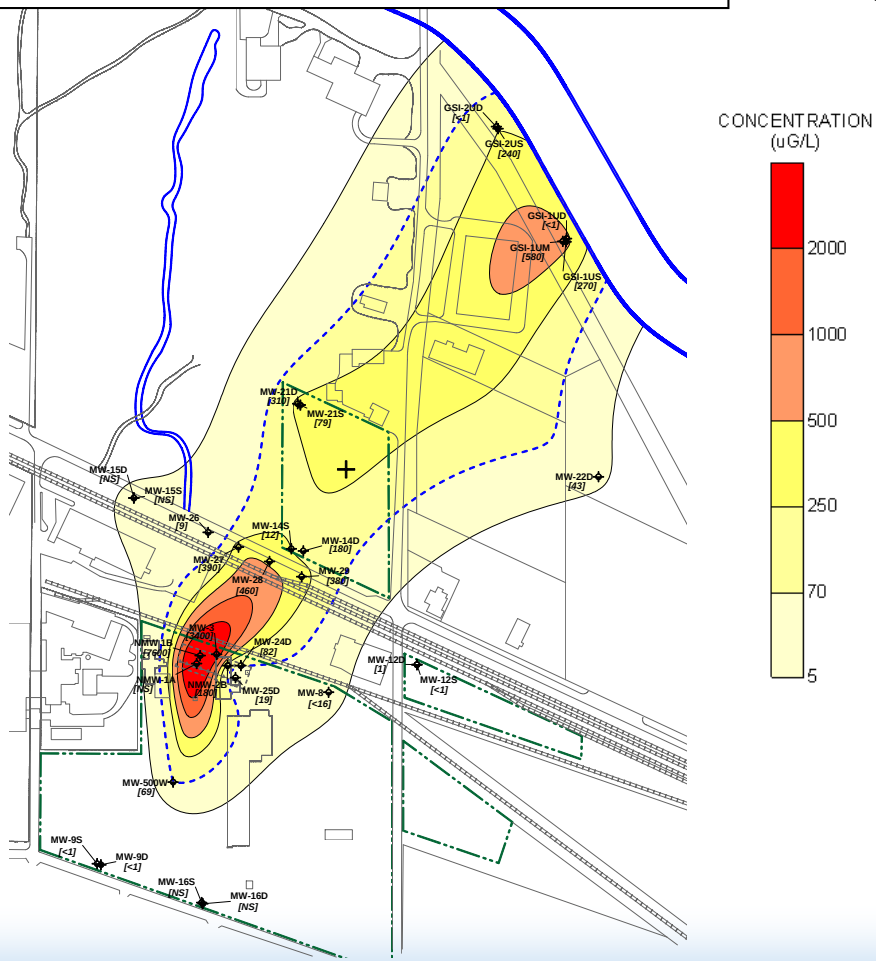
TCE PLUME STABILITY ANALYSIS SUMMARY

| DESIGNED: JAR | CHECKED: JDH | DATE: APRIL 21, 2010 | FIGURE NO. 6 |
|---|---|---|---|
| DRAWN: JAR | FILE NAME: TCE PSA Summary | SCALE: NONE | |

# Plume Stability Analysis - Example Site 7

PREMIER ENVIRONMENTAL SERVICES, INC

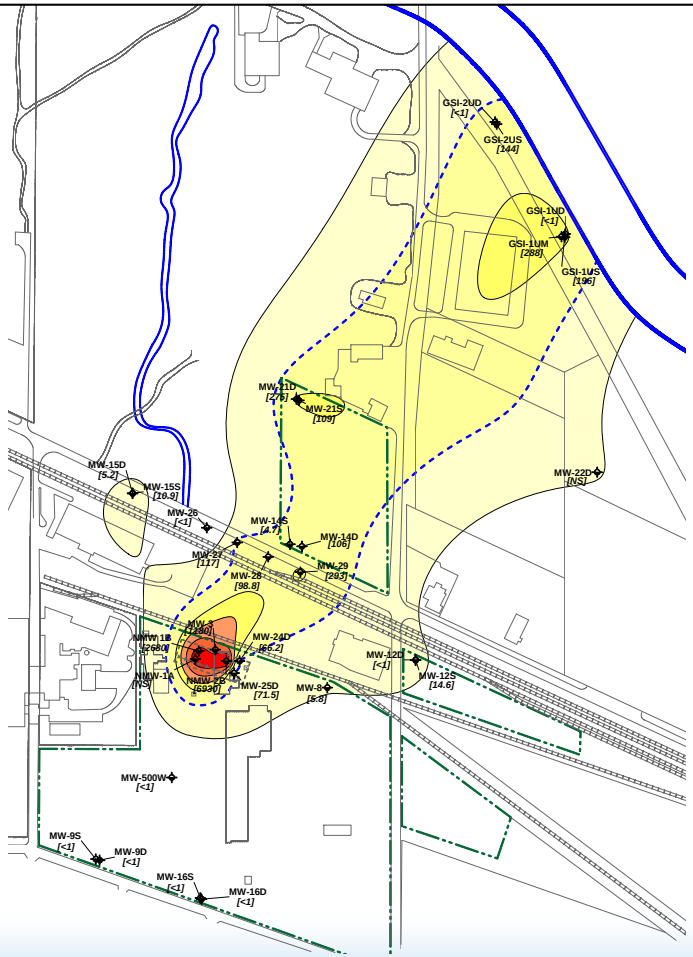
## Sep 2003 cis-DCE Plume







## April 2010 cis-DCE Plume



# Plume Stability Analysis - Example Site 7

PREMIER ENVIRONMENTAL SERVICES, INC

**Summary of Plume Stability Characteristics**

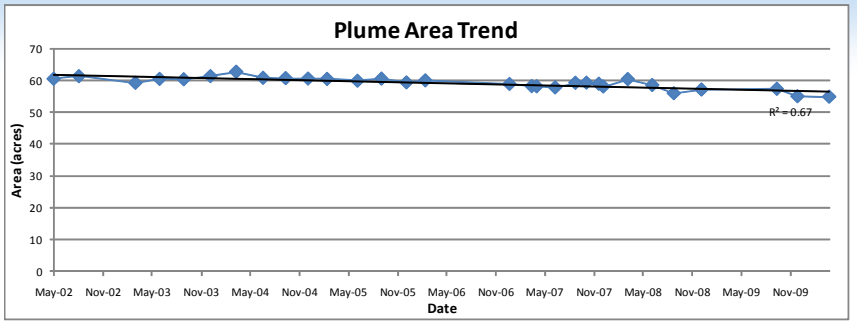
| Date | Area (Acres) | Average Conc. (µg/l) | Mass (lbs) |
|---|---|---|---|
| May-02 | 60.5 | 202 | 332 |
| Aug-02 | 61.3 | 189 | 314 |
| Mar-03 | 59.2 | 166 | 266 |
| Jun-03 | 60.4 | 184 | 302 |
| Sep-03 | 60.3 | 212 | 347 |
| Dec-03 | 61.3 | 179 | 297 |
| Mar-04 | 62.7 | 167 | 284 |
| Jun-04 | 60.7 | 165 | 272 |
| Sep-04 | 60.7 | 173 | 284 |
| Dec-04 | 60.5 | 185 | 304 |
| Feb-05 | 60.4 | 185 | 303 |
| Jun-05 | 59.8 | 146 | 238 |
| Sep-05 | 60.5 | 165 | 271 |
| Dec-05 | 59.3 | 144 | 231 |
| Feb-06 | 60.0 | 143 | 234 |
| Jan-07 | 58.8 | 137 | 218 |
| Mar-07 | 58.1 | 125 | 198 |
| Apr-07 | 58.1 | 122 | 192 |
| Jun-07 | 57.7 | 105 | 165 |
| Sep-07 | 59.2 | 127 | 204 |
| Oct-07 | 59.2 | 131 | 211 |
| Nov-07 | 58.9 | 125 | 199 |
| Dec-07 | 58.0 | 122 | 192 |
| Mar-08 | 60.4 | 131 | 214 |
| Jun-08 | 58.5 | 109 | 172 |
| Sep-08 | 55.9 | 119 | 180 |
| Dec-08 | 57.1 | 103 | 159 |
| Sep-09 | 57.3 | 125 | 194 |
| Dec-09 | 54.9 | 141 | 210 |
| Apr-10 | 54.8 | 112 | 166 |

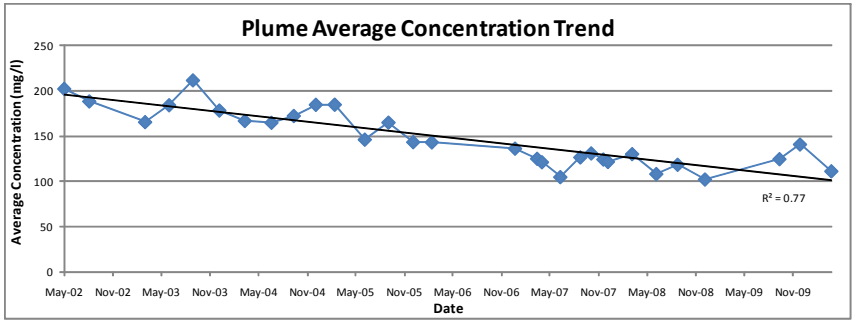
**Mann-Kendall Trend Analysis Summary**

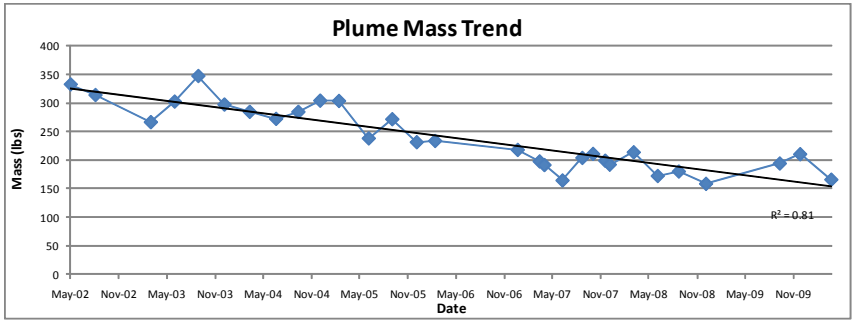
| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Cis 1,2-DCE Plume Area | 30 | -285 | 100.0% | 0.03 | Decreasing Trend |
| Cis 1,2-DCE Plume Average Concentration | 30 | -299 | 100.0% | 0.21 | Decreasing Trend |
| Cis 1,2-DCE Plume Mass | 30 | -305 | 100.0% | 0.23 | Decreasing Trend |

**Linear Regression Trend Analysis Summary**

| Parameter | # of samples, n | Slope ($yr^{-1}$) | $R^2$ | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|---|
| Cis 1,2-DCE Plume Area | 30 | -0.67 | 0.67 | 100.0% | 0.03 | Decreasing Trend |
| Cis 1,2-DCE Plume Average Concentration | 30 | -11.90 | 0.77 | 100.0% | 0.21 | Decreasing Trend |
| Cis 1,2-DCE Plume Mass | 30 | -21.82 | 0.81 | 100.0% | 0.23 | Decreasing Trend |




PREMIER ENVIRONMENTAL SERVICES, INC

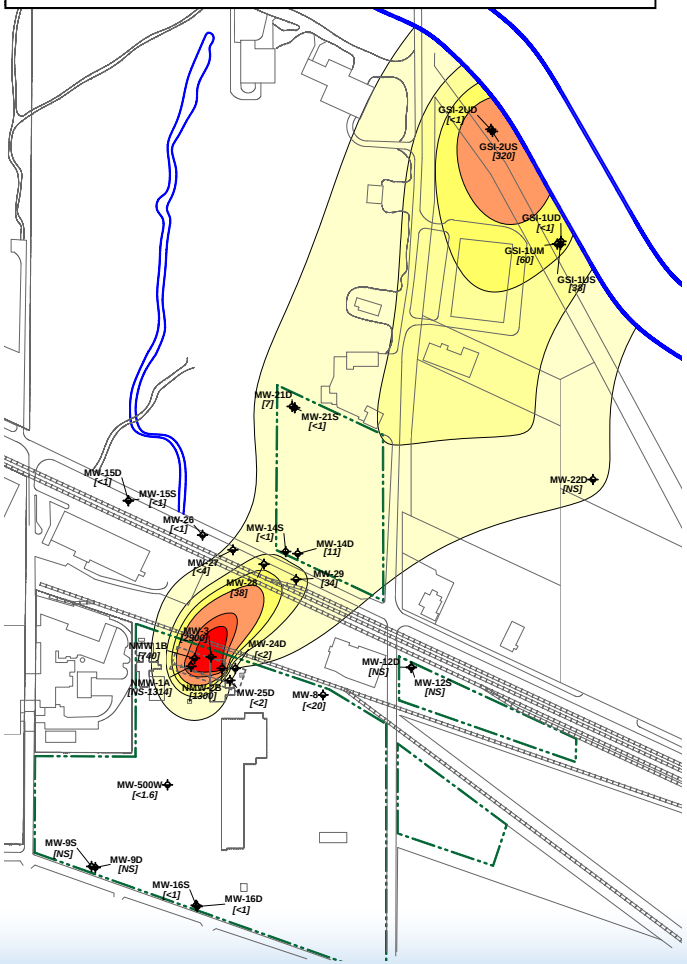
CIS 1,2-DCE PLUME STABILITY ANALYSIS SUMMARY

| DESIGNED: JAR | CHECKED: JDH | DATE: APRIL 21, 2010 | FIGURE NO. 7 |
|---|---|---|---|
| DRAWN: JAR | FILE NAME: DCE PSA Summary | SCALE: NONE | |

# Plume Stability Analysis - Example Site 7

PREMIER ENVIRONMENTAL SERVICES, INC

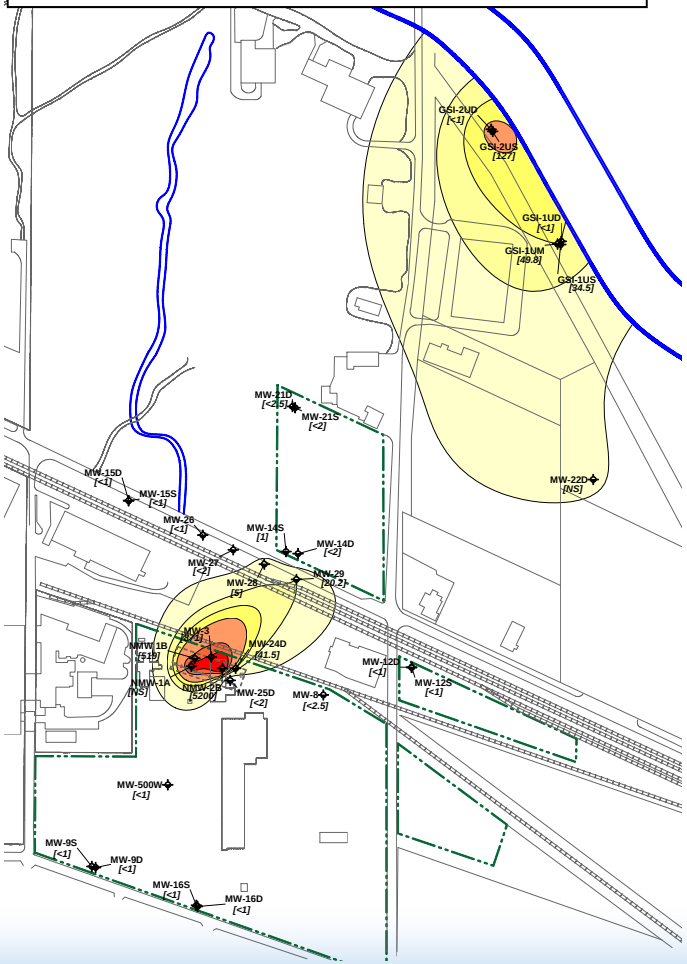
## June 2003 VC Plume




CONCENTRATION (uG/L)

800
400
100
50
20
2

## April 2010 VC Plume



# Plume Stability Analysis - Example Site 7

PREMIER ENVIRONMENTAL SERVICES, INC

**Summary of Plume Stability Characteristics**

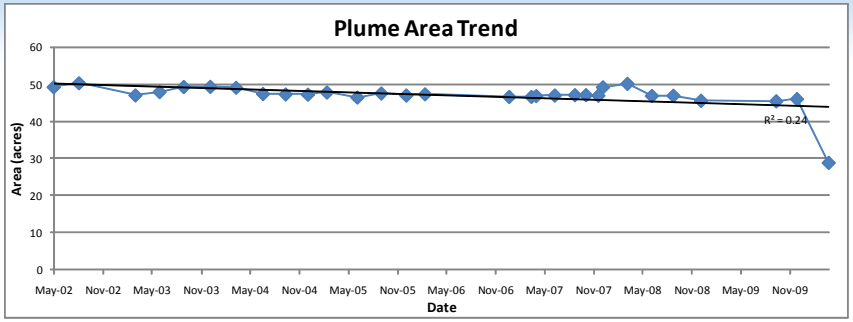
| Date | Area (Acres) | Average Conc. (µg/l) | Mass (lbs) |
|---|---|---|---|
| May-02 | 49.3 | 35.6 | 47.6 |
| Aug-02 | 50.3 | 38.1 | 52.1 |
| Mar-03 | 47.0 | 32.5 | 41.5 |
| Jun-03 | 48.0 | 43.2 | 56.2 |
| Sep-03 | 49.3 | 42.9 | 57.5 |
| Dec-03 | 49.4 | 38.3 | 51.4 |
| Mar-04 | 49.1 | 37.2 | 49.6 |
| Jun-04 | 47.4 | 33.8 | 43.6 |
| Sep-04 | 47.3 | 33.3 | 42.7 |
| Dec-04 | 47.3 | 32.3 | 41.5 |
| Feb-05 | 47.8 | 28.1 | 36.5 |
| Jun-05 | 46.5 | 26.4 | 33.3 |
| Sep-05 | 47.6 | 31.9 | 41.2 |
| Dec-05 | 47.0 | 30.8 | 39.3 |
| Feb-06 | 47.4 | 36.1 | 46.4 |
| Jan-07 | 46.6 | 28.1 | 35.5 |
| Mar-07 | 46.7 | 24.6 | 31.1 |
| Apr-07 | 46.9 | 26.8 | 34.1 |
| Jun-07 | 47.0 | 29.5 | 37.7 |
| Sep-07 | 47.1 | 29.5 | 37.7 |
| Oct-07 | 47.1 | 31.5 | 40.4 |
| Nov-07 | 47.0 | 30.8 | 39.4 |
| Dec-07 | 49.2 | 28.9 | 38.6 |
| Mar-08 | 50.2 | 31.8 | 43.3 |
| Jun-08 | 46.9 | 27.5 | 35.0 |
| Sep-08 | 47.0 | 31.1 | 39.7 |
| Dec-08 | 45.6 | 28.8 | 35.6 |
| Sep-09 | 45.5 | 28.9 | 35.7 |
| Dec-09 | 46.0 | 32.1 | 40.2 |
| Apr-10 | 28.8 | 31.1 | 24.3 |

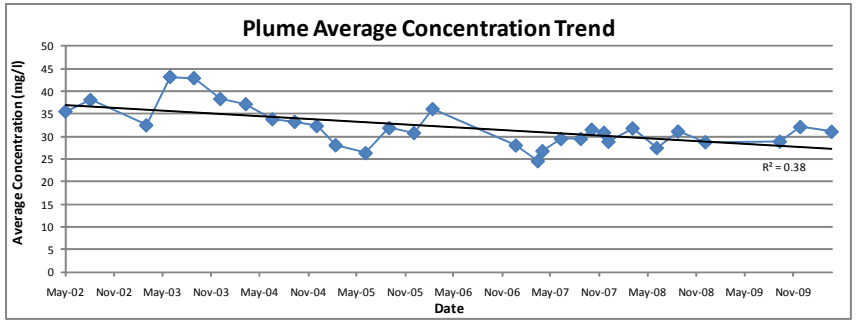
**Mann-Kendall Trend Analysis Summary**

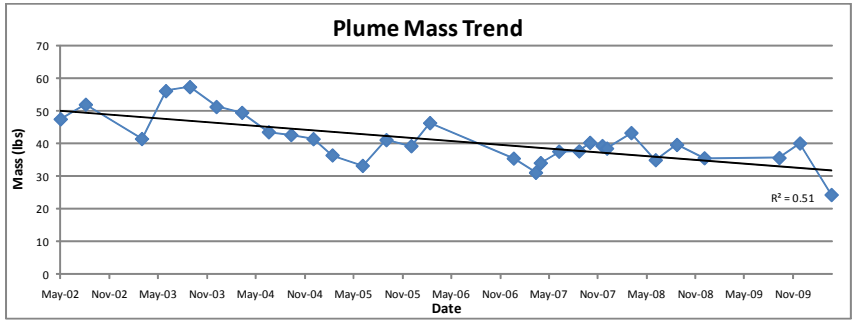
| Parameter | # of samples, n | S Statistic | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|
| Vinyl Chloride Plume Area | 30 | -213 | 100.0% | 0.08 | Decreasing Trend |
| Vinyl Chloride Plume Average Concentration | 30 | -177 | 99.9% | 0.15 | Decreasing Trend |
| Vinyl Chloride Plume Mass | 30 | -201 | 100.0% | 0.18 | Decreasing Trend |

**Linear Regression Trend Analysis Summary**

| Parameter | # of samples, n | Slope ($yr^{-1}$) | $R^2$ | Confidence Factor | Coeff. of Variation | Conclusion |
|---|---|---|---|---|---|---|
| Vinyl Chloride Plume Area | 30 | -0.79 | 0.24 | 99.4% | 0.08 | Decreasing Trend |
| Vinyl Chloride Plume Average Concentration | 30 | -1.32 | 0.41 | 100.0% | 0.15 | Decreasing Trend |
| Vinyl Chloride Plume Mass | 30 | -2.41 | 0.52 | 100.0% | 0.18 | Decreasing Trend |



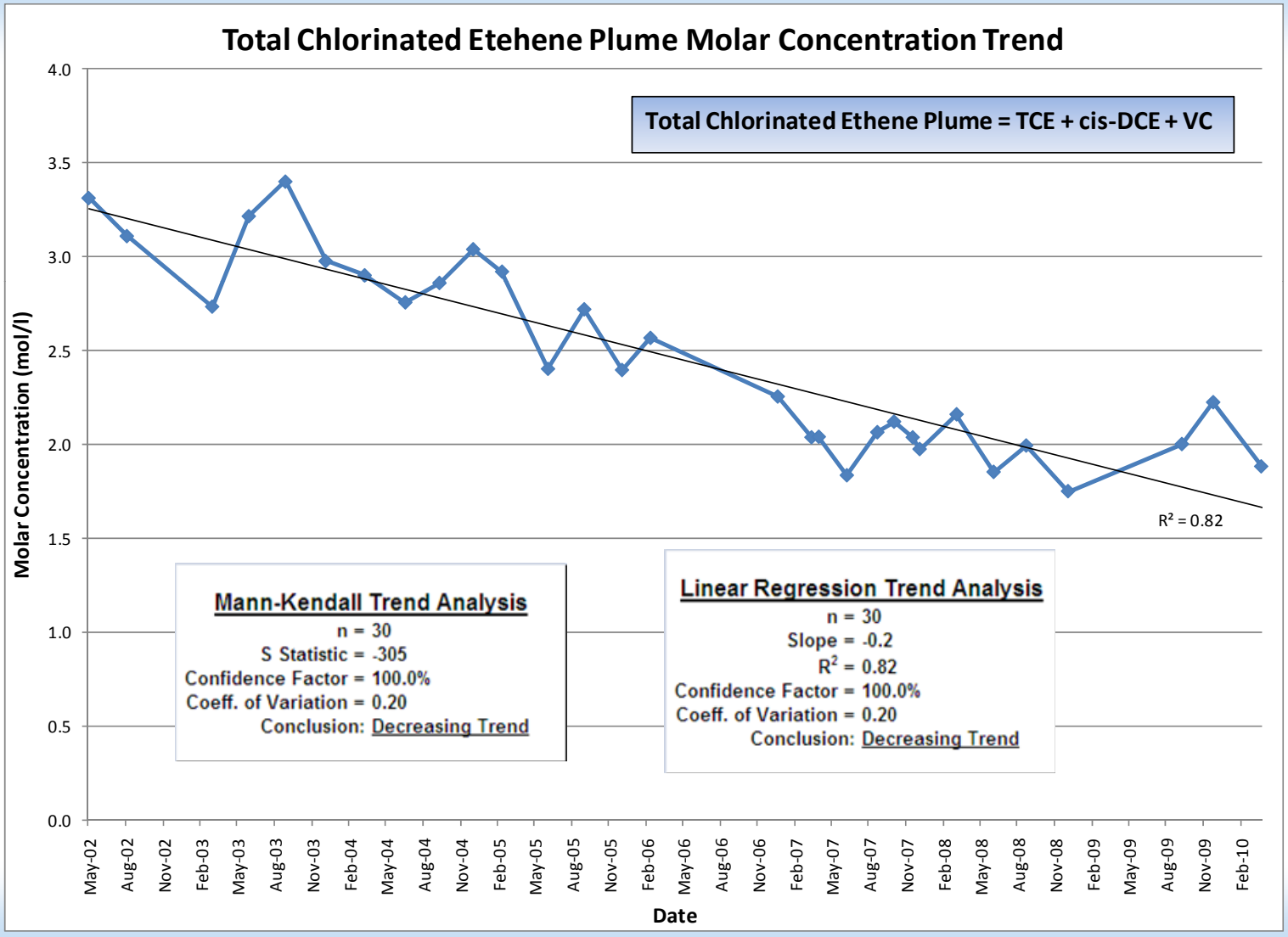




PREMIER ENVIRONMENTAL SERVICES, INC

VINYL CHLORIDE PLUME STABILITY ANALYSIS SUMMARY

| DESIGNED: JAR | CHECKED: JDH | DATE: APRIL 21, 2010 | FIGURE NO. 8 |
|---|---|---|---|
| DRAWN: JAR | FILE NAME: VC PSA Summary | SCALE: NONE | |

# Plume Stability Analysis - Example Site 7



# Ricker Plume Stability Analysis Summary

- Efficiently assimilates large volume of historical data into concise and meaningful analysis
- Makes full use of all data (e.g., non-detect wells)
- Can be used as a basis for termination, reduction, or modification of remediation systems
- Can be used as a basis for closing sites
- Excellent tool for monitoring progress of any remediation system
- Eliminates human bias in plume stability analysis

# Ricker Plume Stability Analysis Summary

- **Limitations**
  - ***May not be applicable to karst or fractured rock***
  - ***Does not account for source mass (e.g., NAPL) or source flux***
  - ***Empirical analysis tool for chemical data, does not model hydrogeology (e.g., flow gradients, reactions, etc.)***

# Close

PREMIER
ENVIRONMENTAL SERVICES, INC

# QUESTIONS?