A Practical Method to Assess Groundwater Remediation System Resiliency: Groundwater Plume Stability is your Indicator Light

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“The ultimate goal of remediation is to protect human health and the environment”

- From ITRC Green and Sustainable Remediation: A Practical Framework Guidance Document (November 2011)

EPA United States Environmental Protection Agency

Office of Solid Waste and Emergency Response (5102G)

May 2011

Introduction to Green Remediation

Office of Superfund Remediation and Technology Innovation

Quick Reference Fact Sheet

Core Elements of Green Remediation

- *Reducing total energy use and increasing the percentage of energy from renewable resources*
- *Reducing air pollutants and greenhouse gas emissions*
- *Reducing water use and negative impacts on water resources*
- *Improving materials management and waste reduction efforts, and*
- *Protecting ecosystem services during site cleanup*

Remediation

↓

Green Remediation/Sustainable Remediation

↓

Resilient Remediation

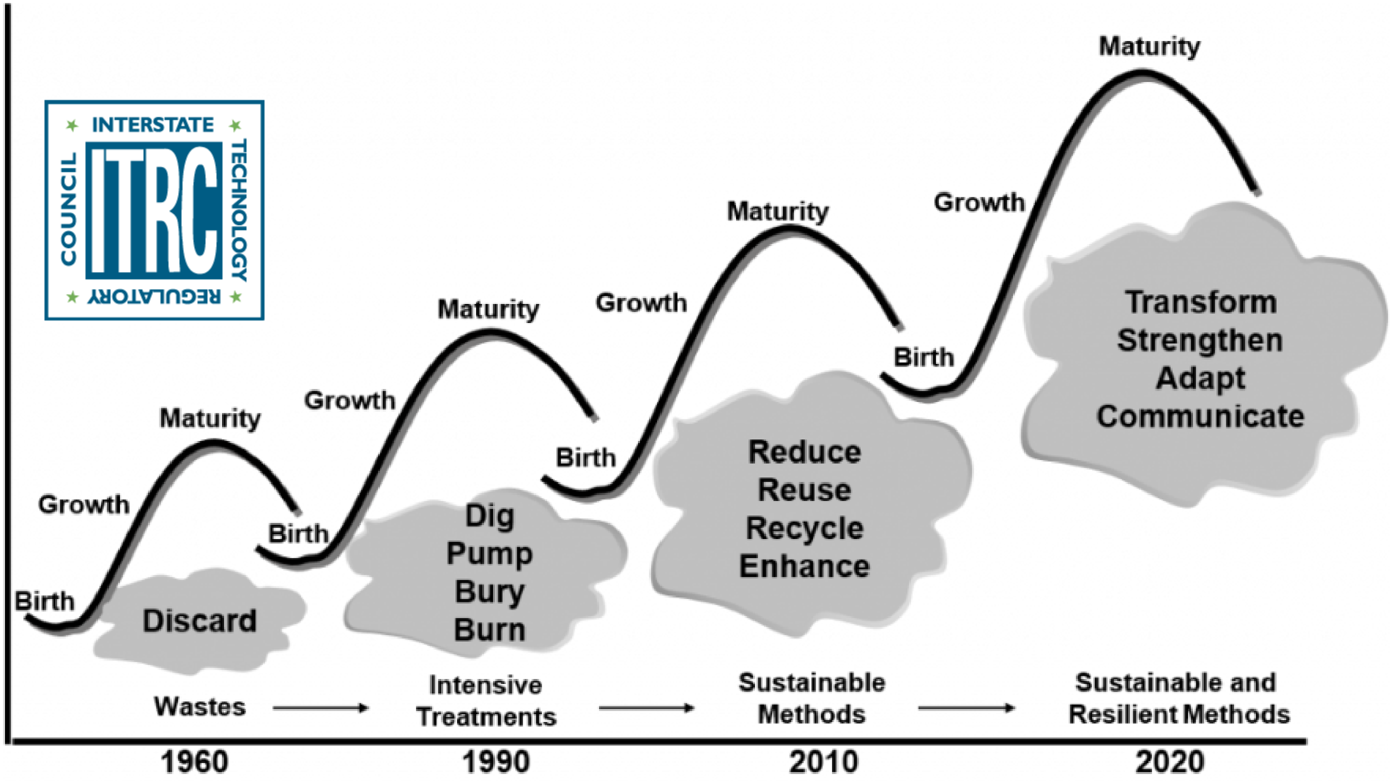


Figure 2-1. Evolution of environmental remediation to SRR.

Source: Adapted from Ellis and Hadley (2009) [2].

Remediation

↓

Green Remediation/Sustainable Remediation

↓

Resilient Remediation

https://srr-1.itrcweb.org/

“Resilience is the capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption”

USEPA. 2020. “Sustainable and Healthy Communities. Strategic Research Action Plan 2019-2022.” EPA 601-K-20-004. Washington, D.C.: United States Environmental Protection Agency, Office of Research and Development. https://www.epa.gov/research/sustainable-and-healthy-communities-strategic-research-action-plan-2019-2022.

Resilient Remediation = "an optimized solution to cleaning up and reusing hazardous waste sites that limits environmental impacts, maximizes social and economic benefits, and creates resilience against the increasing threat of extreme weather events, sea-level rise, and wildfires."

https://srr-1.itrcweb.org/introduction/

If I ask you the question:

Is your groundwater remediation system climate resilient?

How would you answer?

An excellent way to assess whether your remediation system is resilient is to monitor groundwater plume stability over time.

One of the best ways to monitor plume stability is through an empirical, whole-plume analysis (not well-by-well, not modeling).

Ground Water Monitoring&Remediation

A Practical Method to Evaluate Ground Water Contaminant Plume Stability

by Joseph A. Ricker

Abstract

Evaluating plume stability is important for the evaluation of natural attenuation of dissolved chemicals in ground water. When characterizing ground water contaminant plumes, there are numerous methods for evaluating concentration data. Typically, the data are tabulated and ground water concentrations presented on a site figure. Contaminant concentration isopleth maps are typically developed to evaluate temporal changes in the plume boundaries, and plume stability is often assessed by conducting trend analyses for individual monitoring wells. However, it is becoming more important to understand and effectively communicate the nature of the entire plume in terms of its stability (i.e., is the plume growing, shrinking, or stable?). This article presents a method for evaluating plume stability using innovative techniques to calculate and assess historical trends in various plume characteristics, including area, average concentration, contaminant mass, and center of mass. Contaminant distribution isopleths are developed for several sampling events, and the characteristics mentioned previously are calculated for each event using numerical methods and engineering principles. A statistical trend analysis is then performed on the calculated values to assess the plume stability. The methodology presented here has been used at various contaminated sites to effectively evaluate the stability of contaminant plumes comprising tetrachloroethene, carbon tetrachloride, pentachlorophenol, creosote, naphthalene, benzene, and chlordane. Although other methods for assessing contaminant plume stability exist, this method has been shown to be efficient, reliable, and applicable to any site with an established monitoring well network and multiple years of analytical data.

Introduction

Evaluating plume stability is important for the evaluation of natural attenuation of dissolved chemicals in ground water. U.S. EPA (1998) states that the primary line of evidence in evaluating natural attenuation is historical ground water chemistry data that demonstrate a clear and meaningful trend of decreasing contaminant mass and/or concentration over time at appropriate monitoring or sampling points. When characterizing ground water contaminant plumes, there are numerous methods for evaluating concentration data.

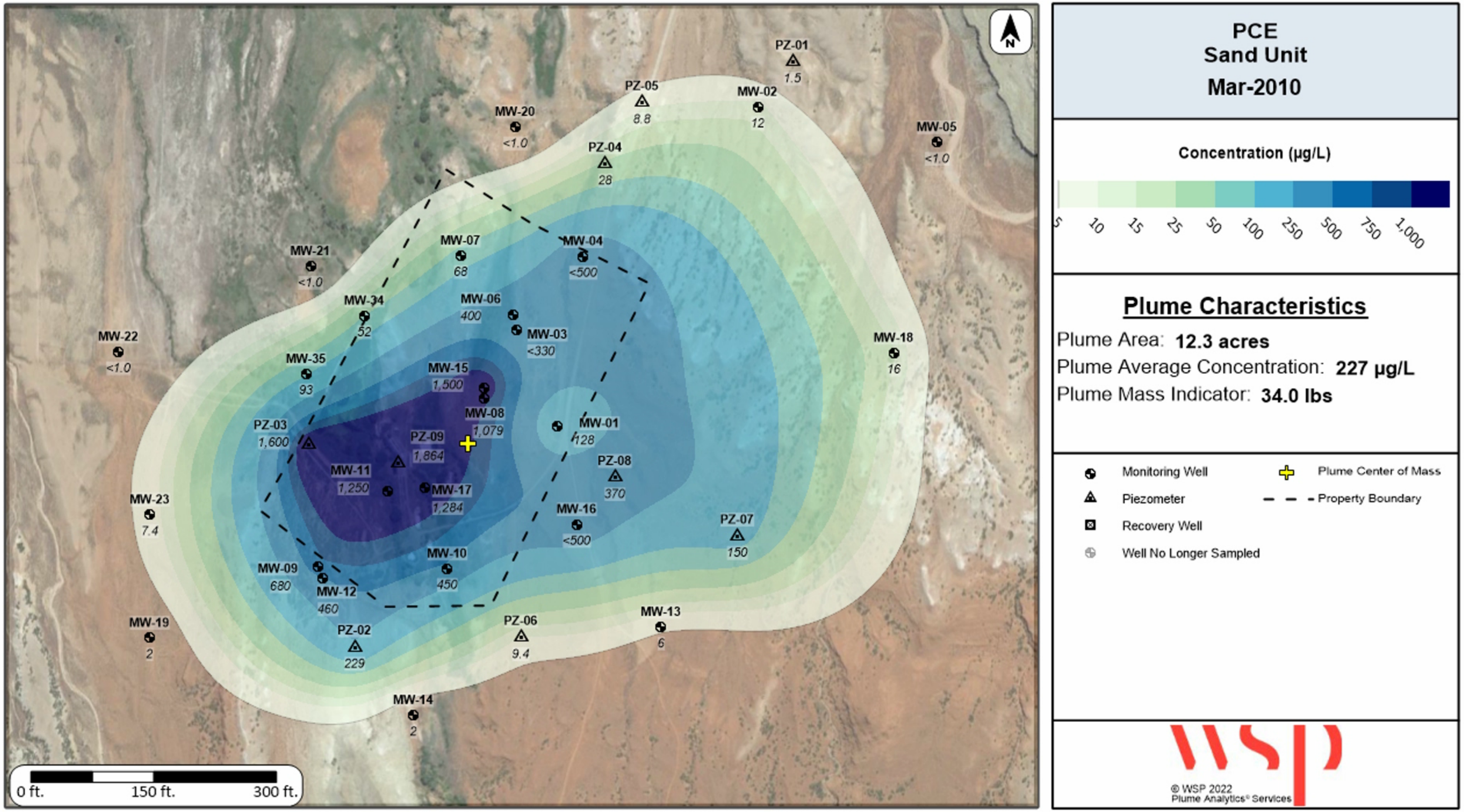
Wiedemeier et al. (2000) discussed common approaches for evaluating plume stability using both graphical and statistical techniques. Graphical methods include the following: (1) the preparation of contaminant concentration isopleth maps; (2) plotting concentration data vs. time for individual monitoring wells; and (3) plotting concentration data vs. distance downgradient for several monitoring wells. Common statistical methods for evaluation of temporal and spatial trends include regression analysis (U.S. EPA 2006), the Mann-Whitney *U*-test (Mann and Whitney 1947), and the Mann-Kendall test (U.S. EPA 2006; Gilbert 1987).

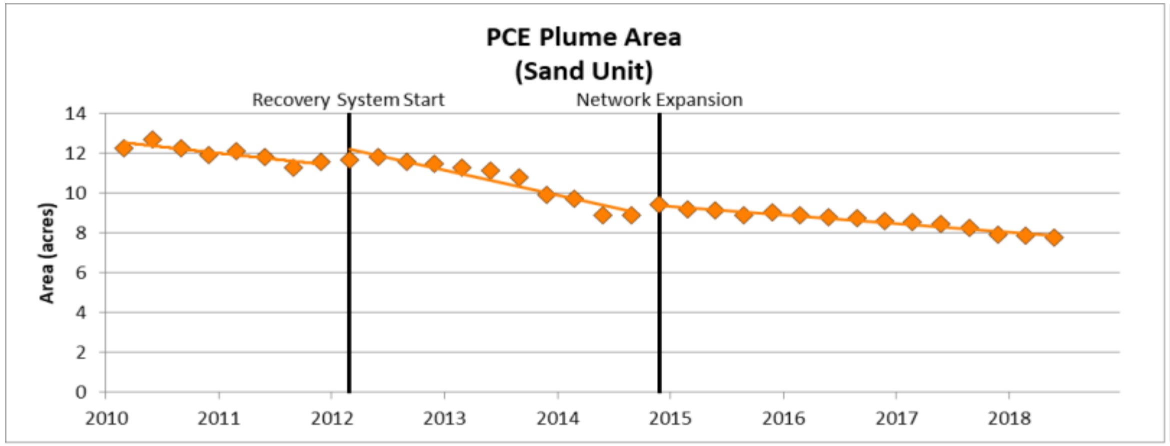
Graphical plume stability analysis by comparing isopleth maps over time can provide compelling visual evidence for natural attenuation. However, a comparison of apparent plume size over time does not always provide a complete analysis. Consider, for example, the case of a plume that discharges to a surface water body, or a plume geometry that is persistent over time. In this case, the plume area would remain relatively unchanged, whereas the overall plume average concentration and mass may be decreasing. The change in plume mass would not be necessarily reflected in the visual analysis of isopleth maps. However, a quantitative analysis of changes in overall plume concentration and mass would provide a better understanding of the plume stability.

A common approach for evaluating plume stability is the use of statistical analysis techniques for single-well data. However, chemical concentration trends at individual monitoring wells may show different trends. For example, at a given site, there may be wells exhibiting decreasing

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

Ricker Method® Plume Stability Analysis Example

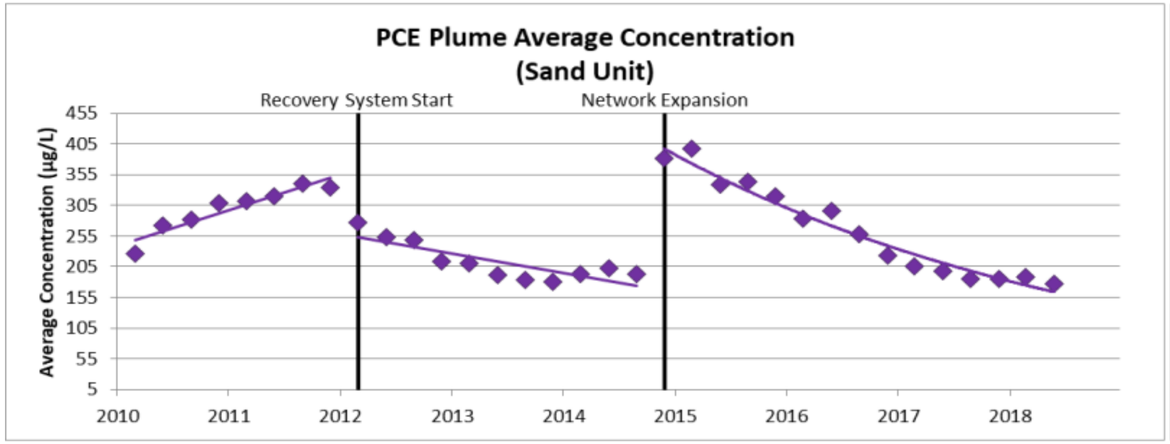

PCE
Sand Unit
Mar-2010
Concentration (µg/L)
5 10 15 25 50 100 250 500 750 1,000
Plume Characteristics
Plume Area: 12.3 acres
Plume Average Concentration: 227 µg/L
Plume Mass Indicator: 34.0 lbs
Monitoring Well
Piezometer
Recovery Well
Well No Longer Sampled
Plume Center of Mass
Property Boundary
© WSP 2022
Plume Analytics® Services
PZ-01 1.5
PZ-05 8.8
MW-02 12
MW-20 <1.0
MW-05 <1.0
PZ-04 28
MW-07 68
MW-04 <500
MW-21 <1.0
MW-34 52
MW-06 400
MW-03 <330
MW-22 <1.0
MW-35 93
MW-15 1,500
MW-18 16
MW-08 1,079
MW-01 128
PZ-03 1,600
PZ-09 1,864
PZ-08 370
MW-11 1,250
MW-17 1,284
MW-23 7.4
MW-16 <500
PZ-07 150
MW-10 450
MW-09 680
MW-12 460
PZ-06 9.4
MW-13 6
MW-19 2
PZ-02 229
MW-14 2
0 ft. 150 ft. 300 ft.
N



Mar-2010 to Dec-2011
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: 99% Confidence

Mar-2012 to Sep-2014
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence

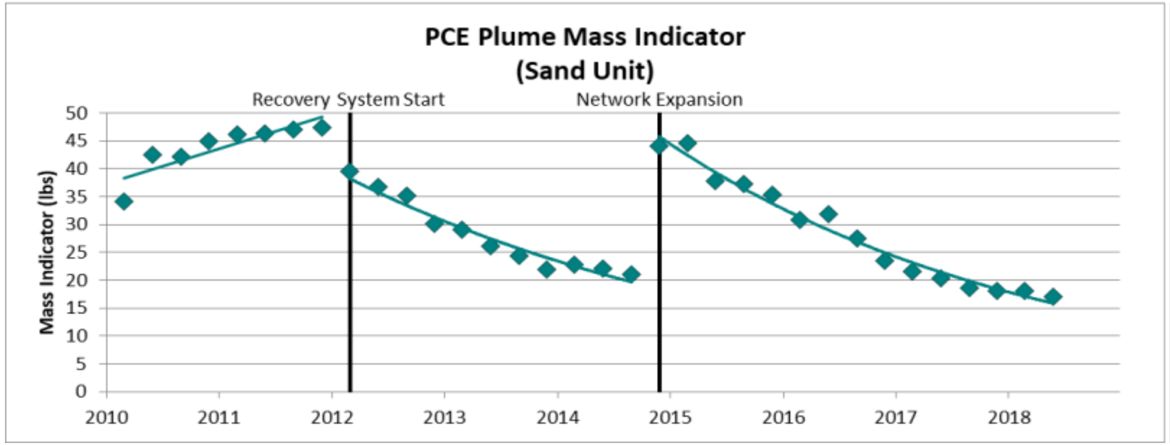
Dec-2014 to Jun-2018
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence



Mar-2010 to Dec-2011
Increasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence

Mar-2012 to Sep-2014
Decreasing Trend
Mann-Kendall: 99% Confidence
Regression: >99% Confidence

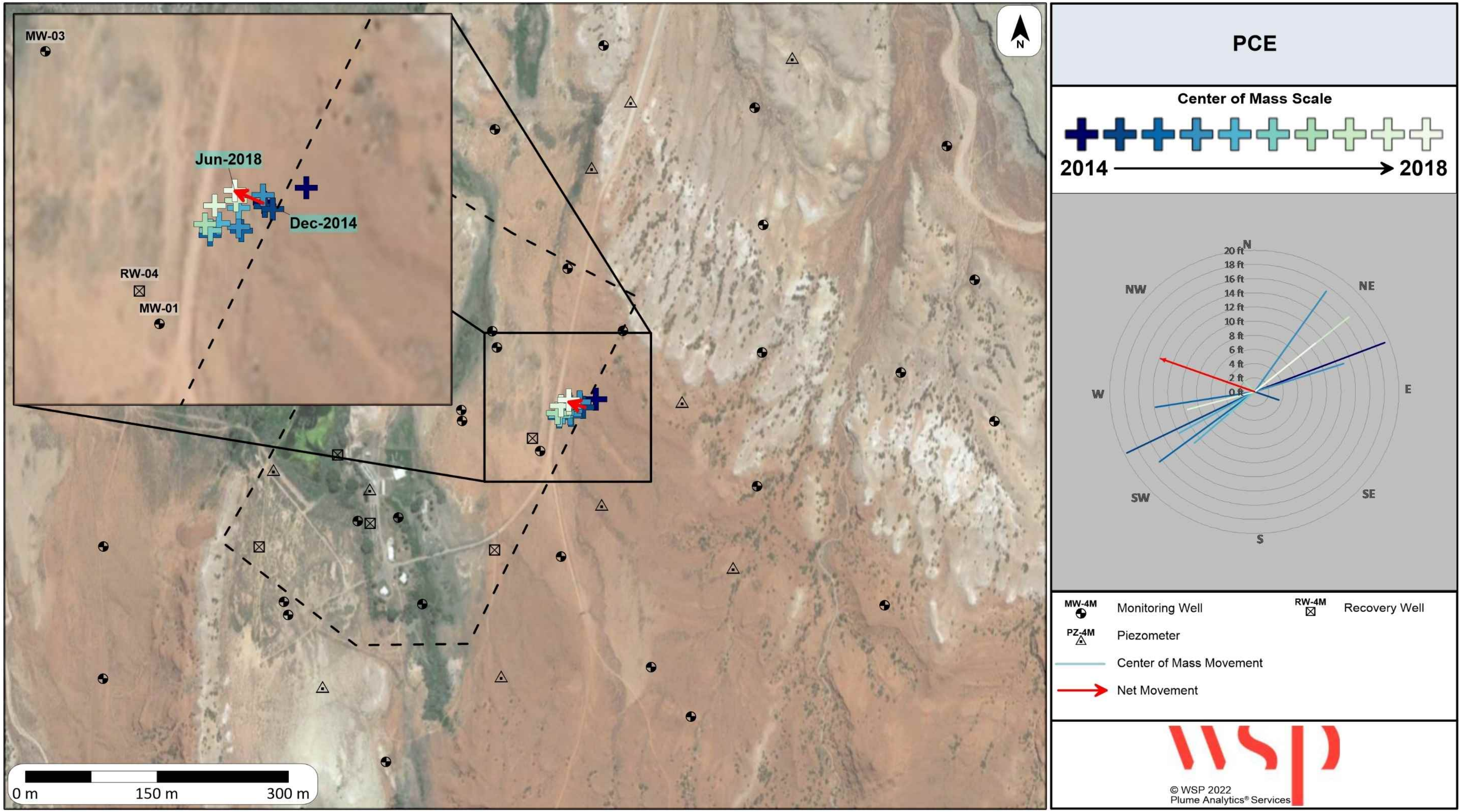
Dec-2014 to Jun-2018
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence



Mar-2010 to Dec-2011
Increasing Trend
Mann-Kendall: >99% Confidence
Regression: 99% Confidence

Mar-2012 to Sep-2014
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence

Dec-2014 to Jun-2018
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence


MW-03
Jun-2018
Dec-2014
RW-04
MW-01
N
0 m
150 m
300 m
PCE
Center of Mass Scale
2014
2018
N
NE
E
SE
S
SW
W
NW
20 ft
18 ft
16 ft
14 ft
12 ft
10 ft
8 ft
6 ft
4 ft
2 ft
0 ft
MW-4M
Monitoring Well
RW-4M
Recovery Well
PZ-4M
Piezometer
Center of Mass Movement
Net Movement
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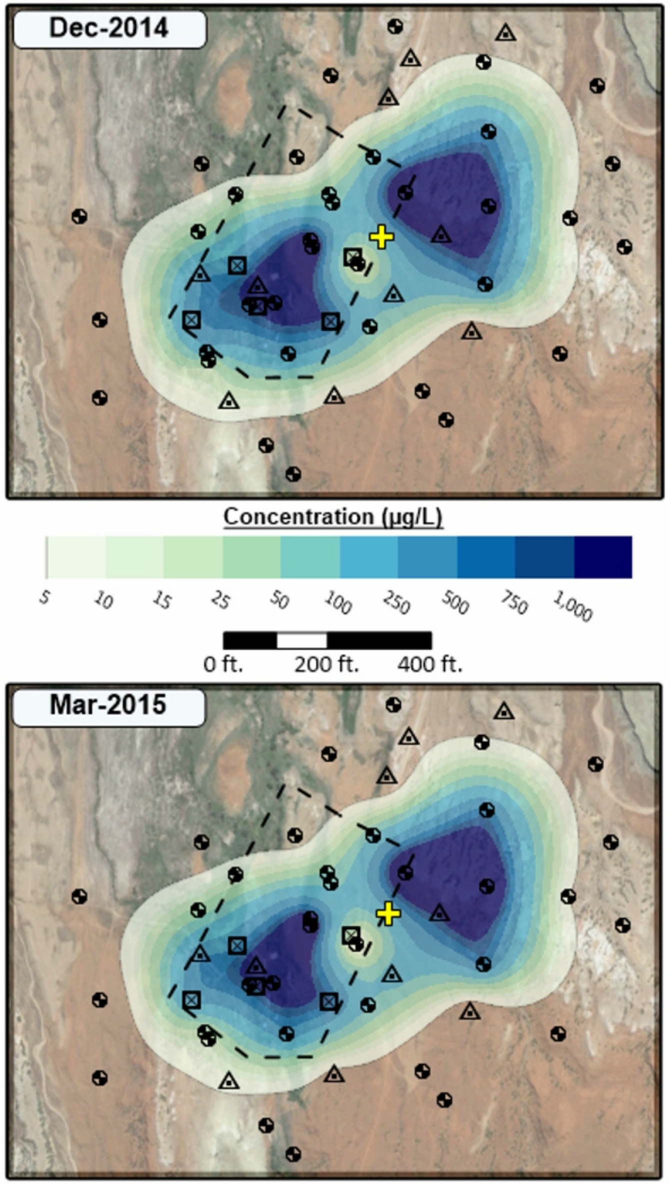
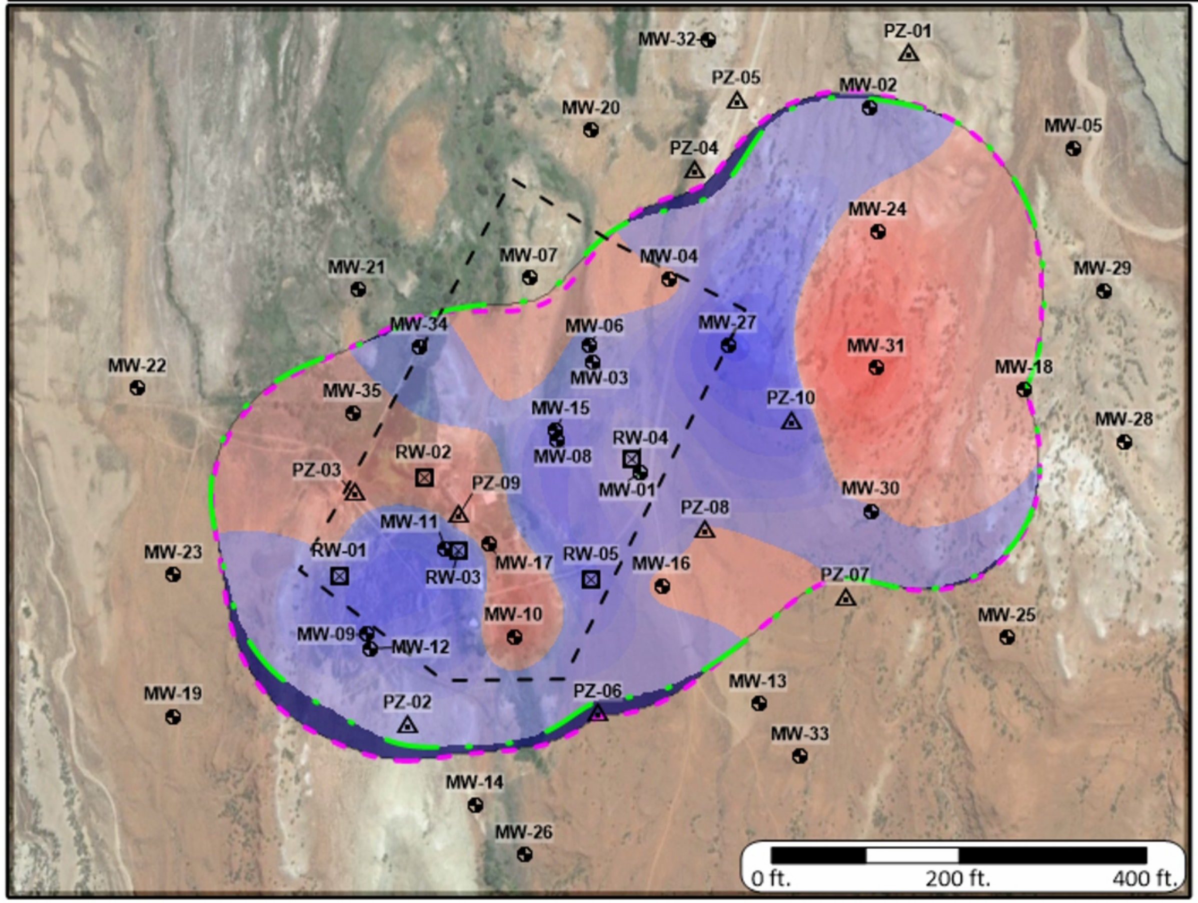


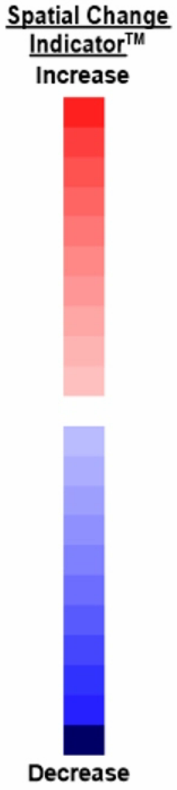
PCE Sand Unit — Spatial Changes Dec-2014 vs Mar-2015

Plume Characteristics

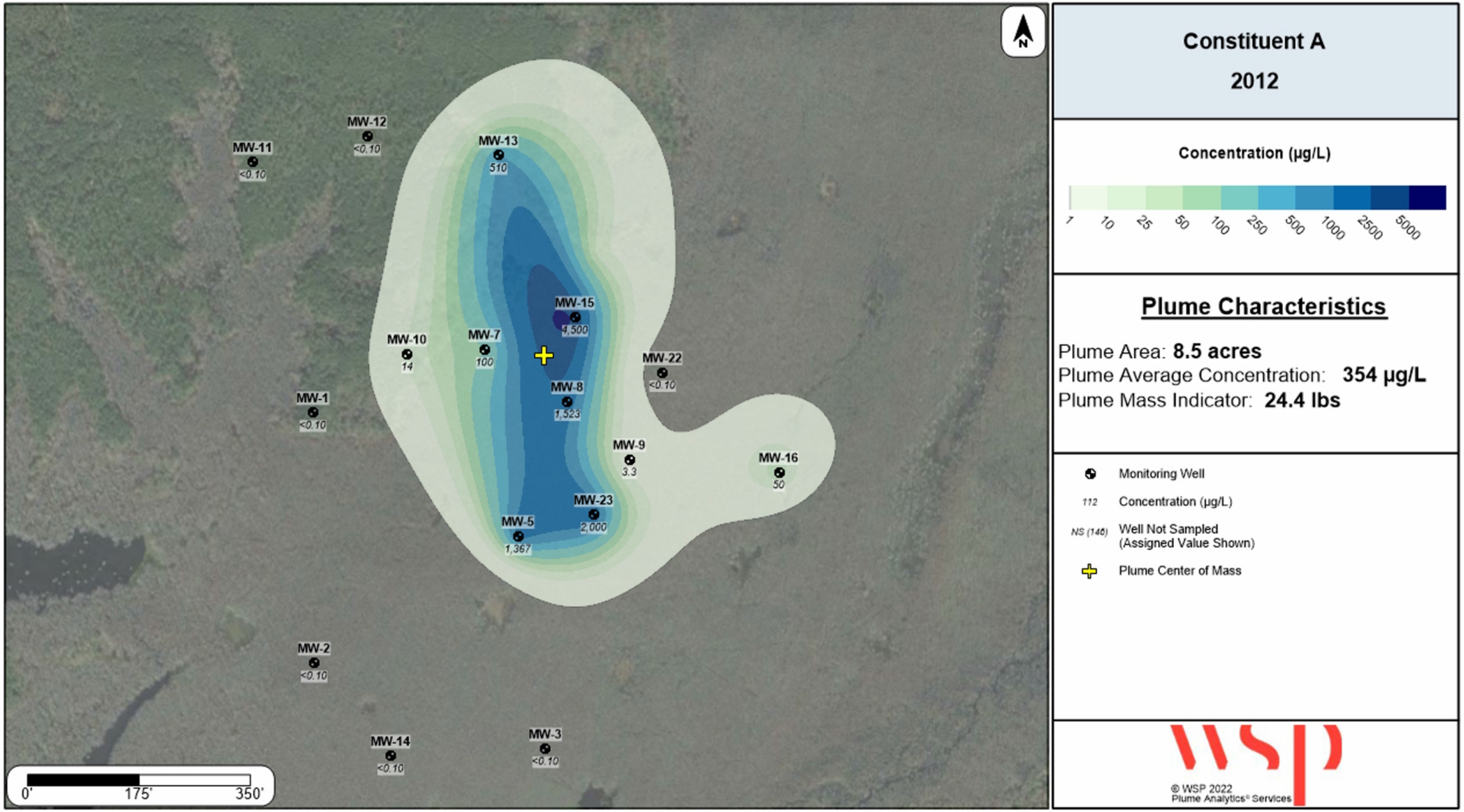
Area: **3% Decrease**
Average Concentration: **4% Increase**
Mass Indicator: **1% Increase**
Mass Increase: **3.61 lbs Increase**
Mass Decrease: **3.16 lbs Decrease**

- Monitoring Well
- Piezometer
- Recovery Well
- Well No Longer Sampled
- Dec-2014 Plume Boundary
- Mar-2015 Plume Boundary
- Plume Center of Mass
- Property Boundary

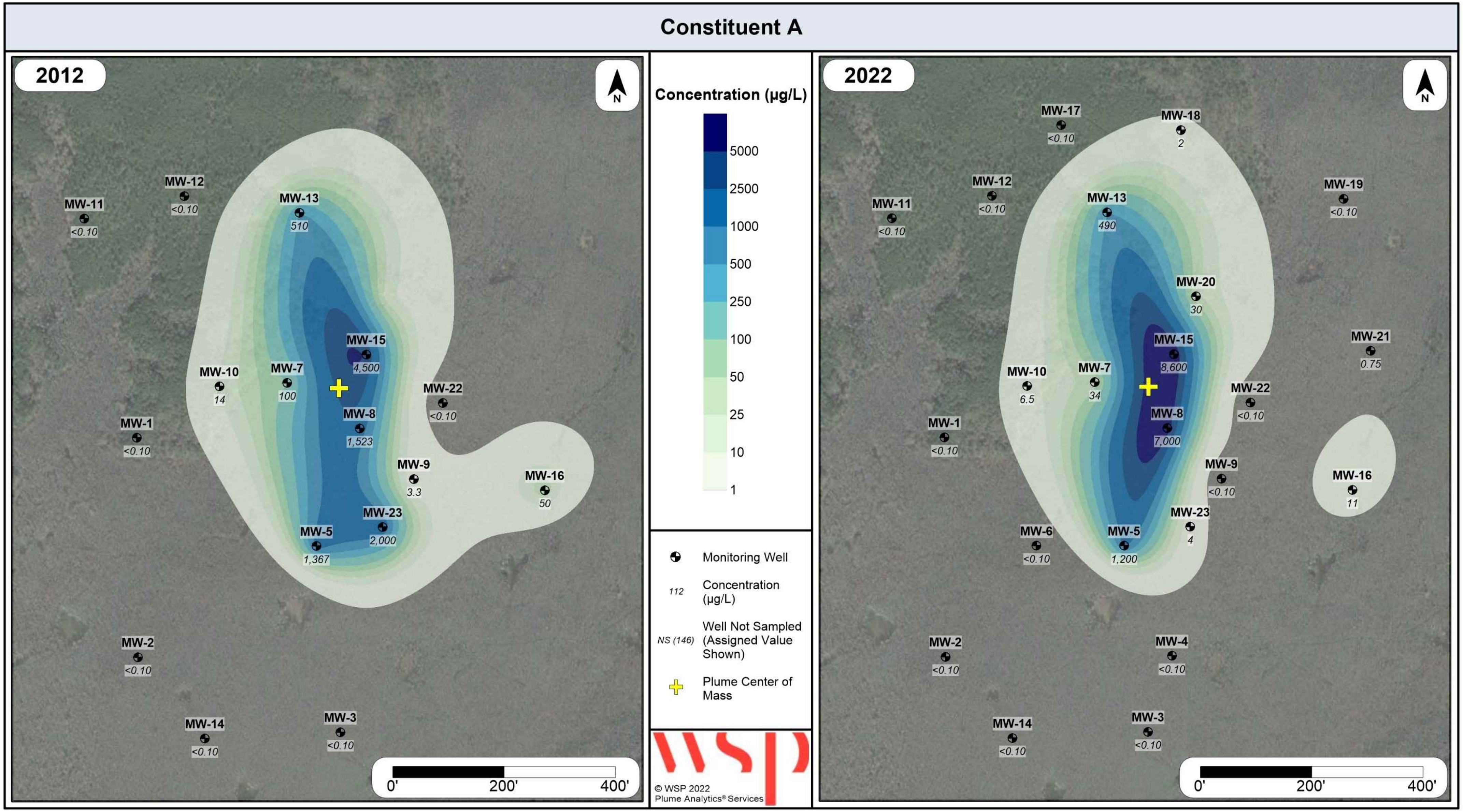


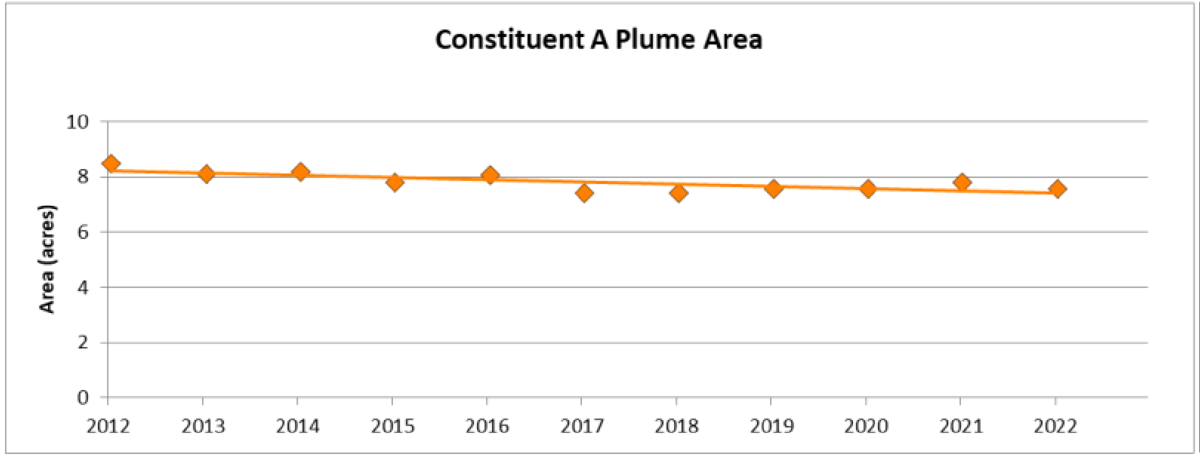


The Benefits of a Whole-plume Plume Stability Analysis over a Well-by-Well or “Footprint” Analysis

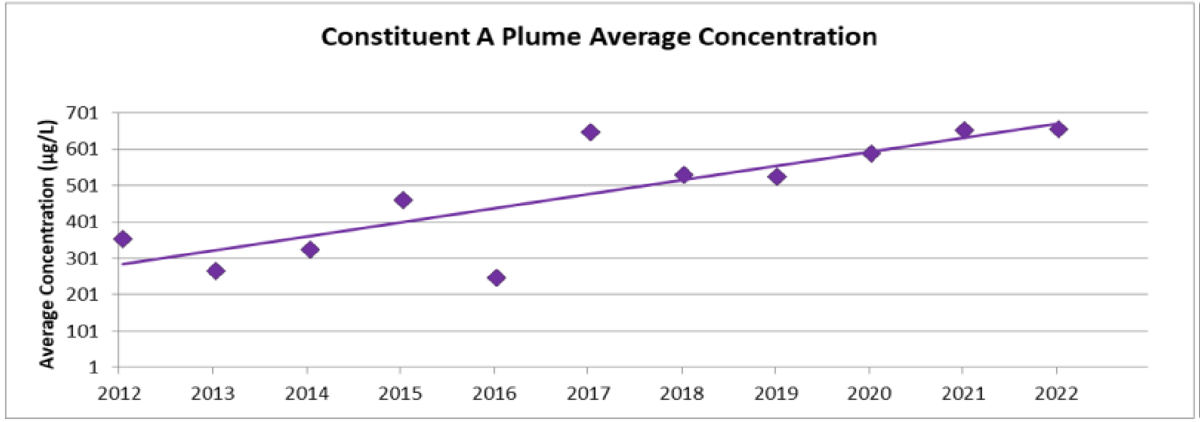


MW-11
<0.10
MW-12
<0.10
MW-13
510
MW-15
4,500
MW-10
14
MW-7
100
MW-22
<0.10
MW-1
<0.10
MW-8
1,523
MW-9
3.3
MW-16
50
MW-23
2,000
MW-5
1,367
MW-2
<0.10
MW-14
<0.10
MW-3
<0.10
0'
175'
350'
N
Constituent A
2012
Concentration (µg/L)
1
10
25
50
100
250
500
1000
2500
5000
Plume Characteristics
Plume Area: 8.5 acres
Plume Average Concentration: 354 µg/L
Plume Mass Indicator: 24.4 lbs
Monitoring Well
112 Concentration (µg/L)
NS (146) Well Not Sampled (Assigned Value Shown)
Plume Center of Mass
© WSP 2022
Plume Analytics® Services

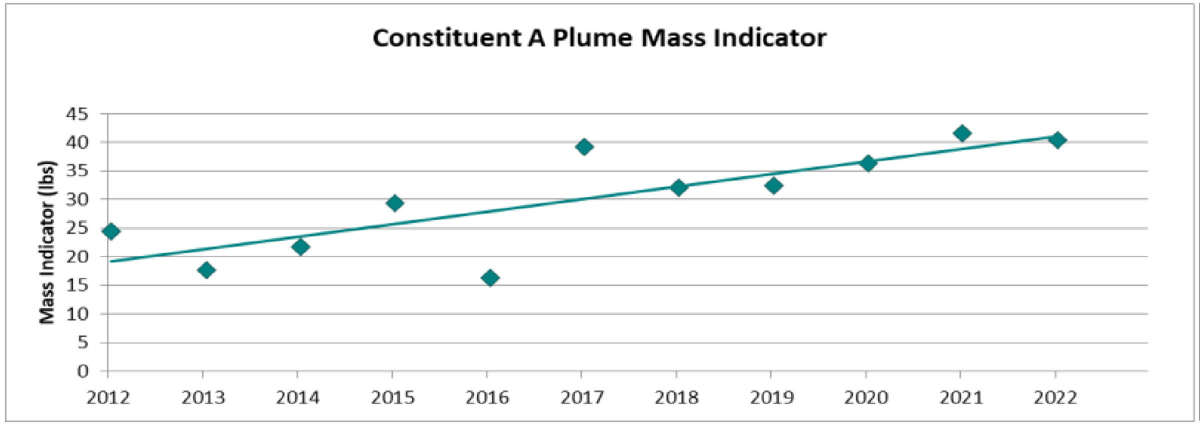

Constituent A
2012
N
MW-11
<0.10
MW-12
<0.10
MW-13
510
MW-15
4,500
MW-10
14
MW-7
100
MW-22
<0.10
MW-1
<0.10
MW-8
1,523
MW-9
3.3
MW-16
50
MW-23
2,000
MW-5
1,367
MW-2
<0.10
MW-14
<0.10
MW-3
<0.10
0'
200'
400'
Concentration (µg/L)
5000
2500
1000
500
250
100
50
25
10
1
Monitoring Well
112
Concentration (µg/L)
NS (146)
Well Not Sampled (Assigned Value Shown)
Plume Center of Mass
© WSP 2022
Plume Analytics® Services
2022
N
MW-17
<0.10
MW-18
2
MW-12
<0.10
MW-19
<0.10
MW-11
<0.10
MW-13
490
MW-20
30
MW-21
0.75
MW-15
8,600
MW-10
6.5
MW-7
34
MW-22
<0.10
MW-1
<0.10
MW-8
7,000
MW-9
<0.10
MW-16
11
MW-23
4
MW-6
<0.10
MW-5
1,200
MW-2
<0.10
MW-4
<0.10
MW-14
<0.10
MW-3
<0.10
0'
200'
400'



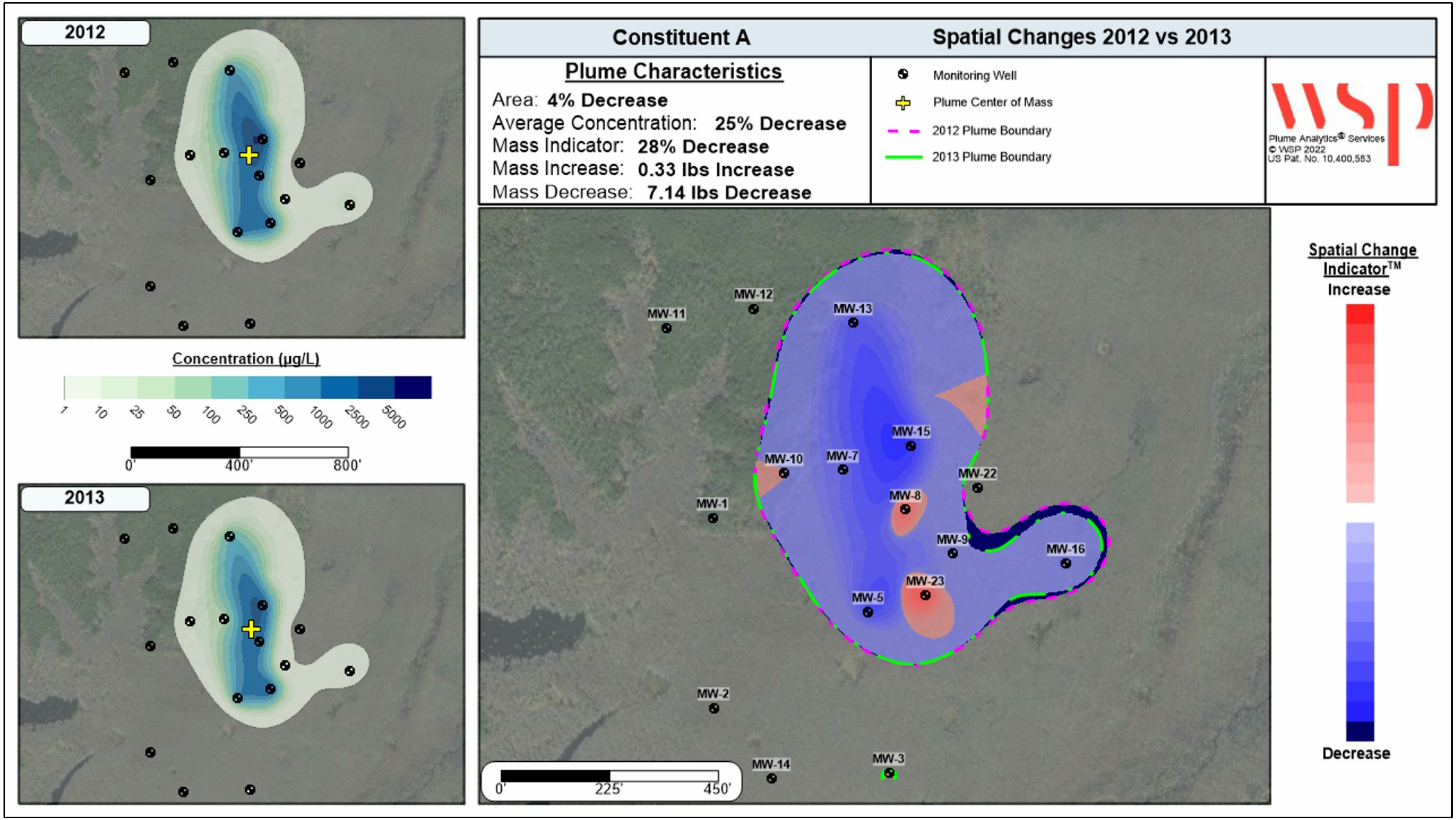
Jan-2012 to Jan-2022
Decreasing Trend
Mann-Kendall: 99% Confidence
Regression: 99% Confidence



Jan-2012 to Jan-2022
Increasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence



Jan-2012 to Jan-2022
Increasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence



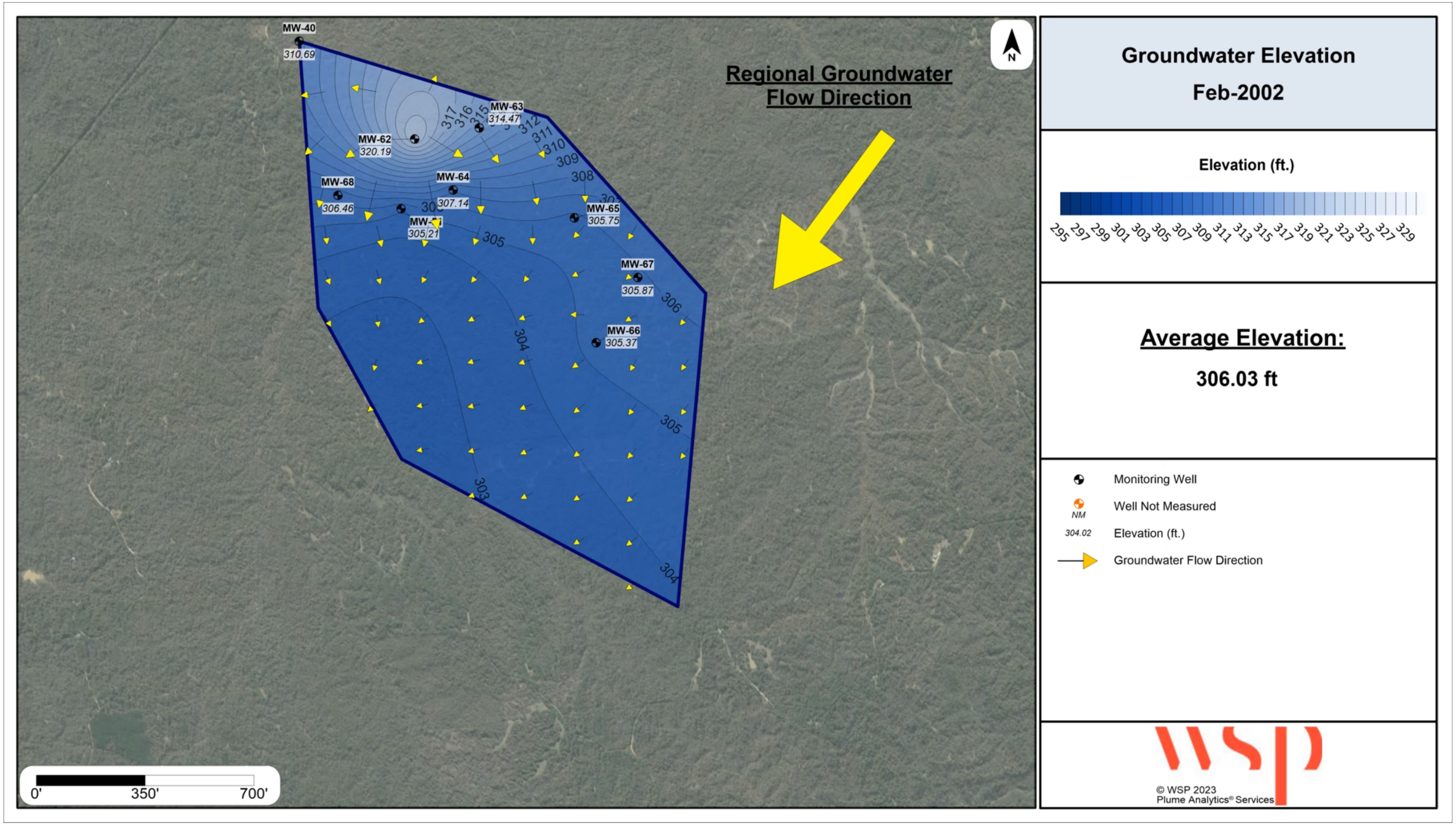
2012
2013
Concentration (µg/L)
1
10
25
50
100
250
500
1000
2500
5000
0'
400'
800'
Constituent A
Spatial Changes 2012 vs 2013
Plume Characteristics
Area: 4% Decrease
Average Concentration: 25% Decrease
Mass Indicator: 28% Decrease
Mass Increase: 0.33 lbs Increase
Mass Decrease: 7.14 lbs Decrease
Monitoring Well
Plume Center of Mass
2012 Plume Boundary
2013 Plume Boundary
Plume Analytics® Services
© WSP 2022
US Pat. No. 10,400,583
MW-11
MW-12
MW-13
MW-15
MW-10
MW-7
MW-22
MW-1
MW-8
MW-9
MW-16
MW-23
MW-5
MW-2
MW-14
MW-3
0'
225'
450'
Spatial Change Indicator™
Increase
Decrease

Plume stability analyses allow us to evaluate changes in the groundwater plume due to climatic factors (i.e. resiliency)

Are my stable or declining trends starting to shift due to climatic impacts?

You likely won't pick this up through predictive modeling

Shift in Groundwater Flow Direction due to Rising Groundwater Elevations



MW-40
310.69
MW-63
314.47
MW-62
320.19
MW-64
307.14
MW-68
306.46
MW-65
305.75
305.21
MW-67
305.87
MW-66
305.37
Regional Groundwater Flow Direction
0'
350'
700'
Groundwater Elevation
Feb-2002
Elevation (ft.)
295 297 299 301 303 305 307 309 311 313 315 317 319 321 323 325 327 329
Average Elevation:
306.03 ft
Monitoring Well
Well Not Measured
NM
304.02
Elevation (ft.)
Groundwater Flow Direction
© WSP 2023
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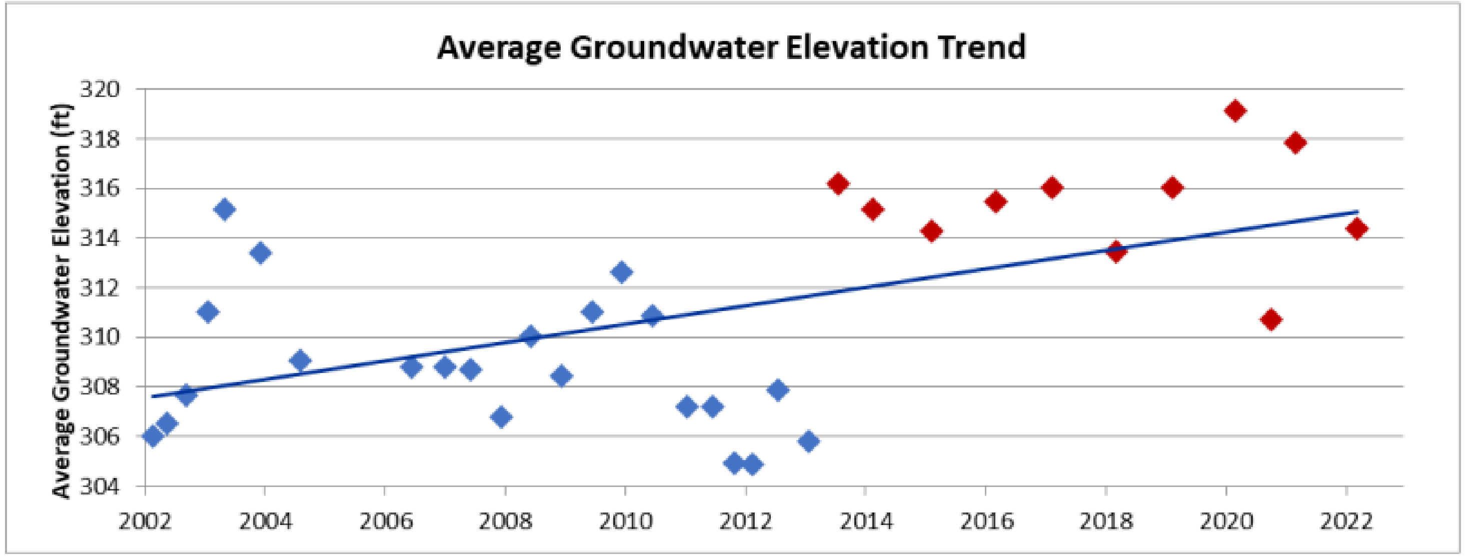
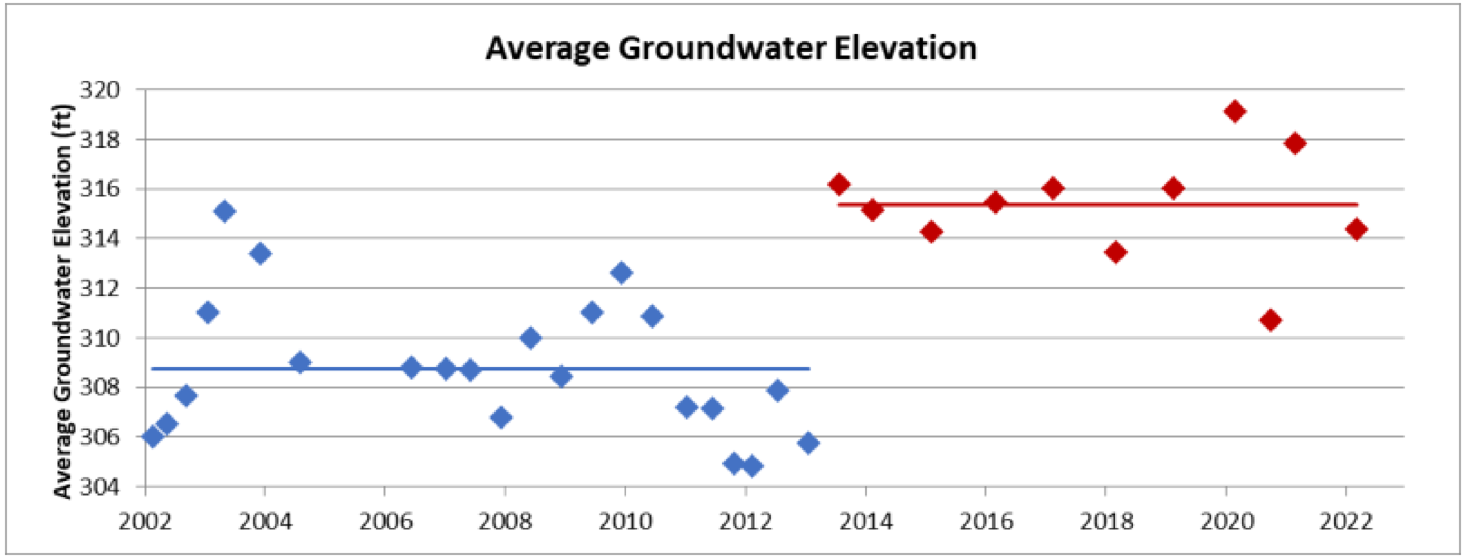


Feb-2002 to Mar-2022
Increasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence

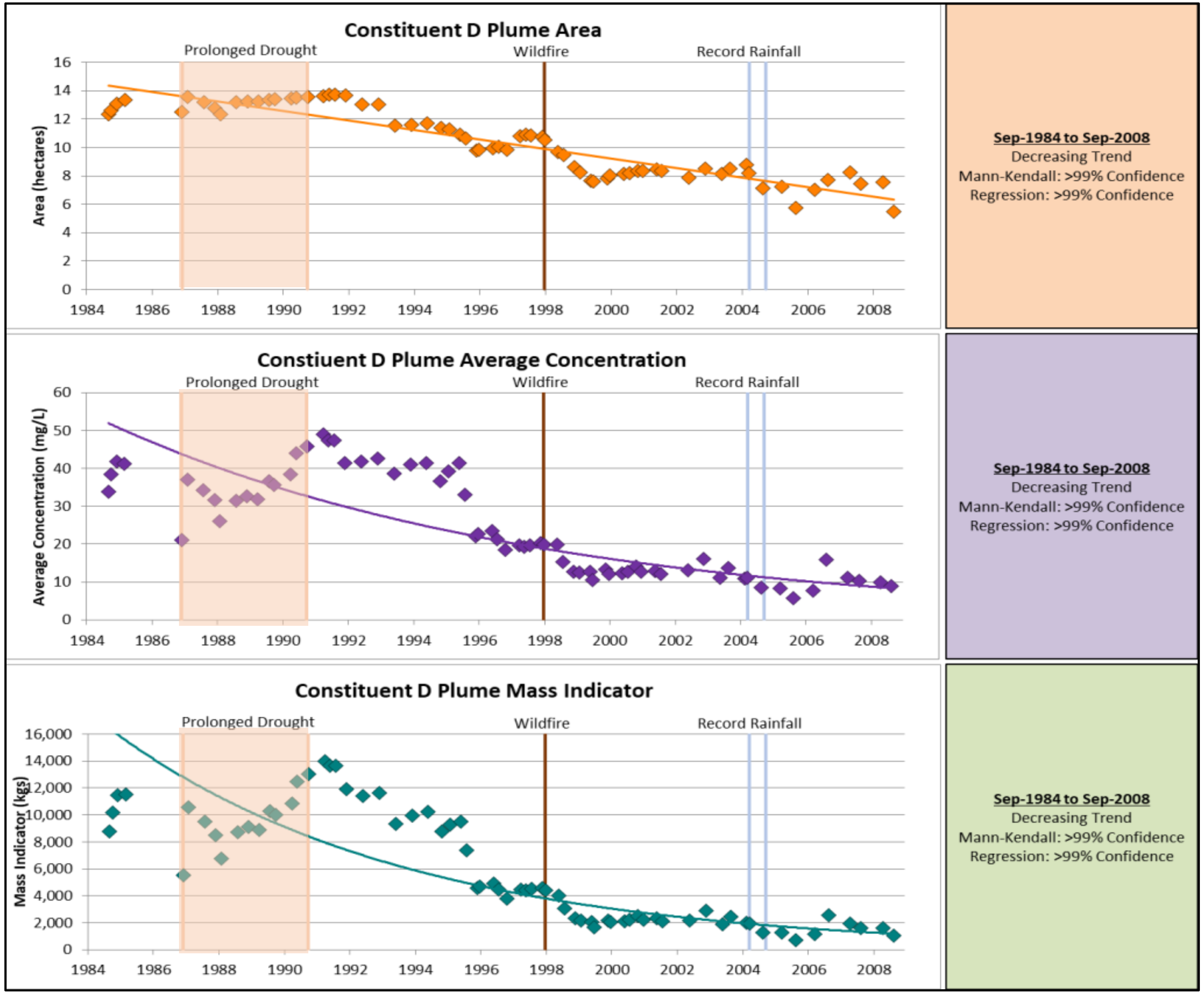


Assessing Groundwater Remediation System Resiliency against Various Climate-related Events - Conceptual

We need to remember that climate change/impacts are not just forward-looking challenges.

We know that climate change/impacts have already happened in the past.

We can look at plume stability to see how historical climate events impacted groundwater plume behavior…which we can then use to anticipate future impacts and assess resiliency.


Constituent D Plume Area
Prolonged Drought
Wildfire
Record Rainfall
Area (hectares)
16
14
12
10
8
6
4
2
0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Sep-1984 to Sep-2008
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence
Constiuent D Plume Average Concentration
Prolonged Drought
Wildfire
Record Rainfall
Average Concentration (mg/L)
60
50
40
30
20
10
0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Sep-1984 to Sep-2008
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence
Constituent D Plume Mass Indicator
Prolonged Drought
Wildfire
Record Rainfall
Mass Indicator (kgs)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Sep-1984 to Sep-2008
Decreasing Trend
Mann-Kendall: >99% Confidence
Regression: >99% Confidence

In Summary:

- *Climate impacts are not just future events, they also occurred in the past. Use the past to assess the future.*
- *A whole-plume stability analysis will provide you insight into past, present and future climate impacts.*
- *A whole-plume stability analysis should be part of your routine OM&M program to assess whether the groundwater remedy continues to be resilient – "Vulnerability Analysis".*
- *Evaluating groundwater plume stability changes over time will alert you as to whether climate change is having a deleterious impact on your groundwater remedy before that realization comes too late.*

Thank You

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