Innovative Visualization Method For Demonstrating Natural And Enhanced Attenuation

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Porewater Solutions

SMART Remediation
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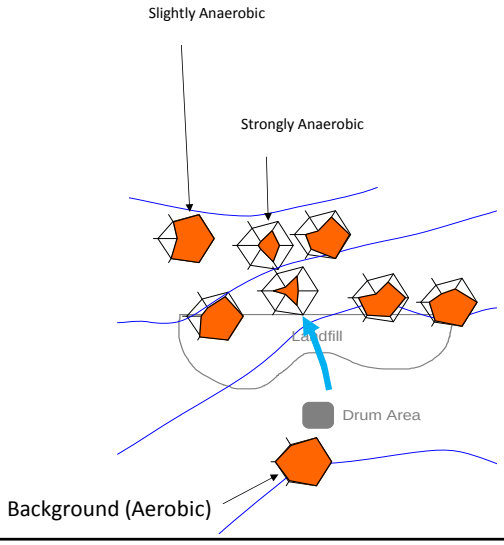
Visualizing Biodegradation Zones

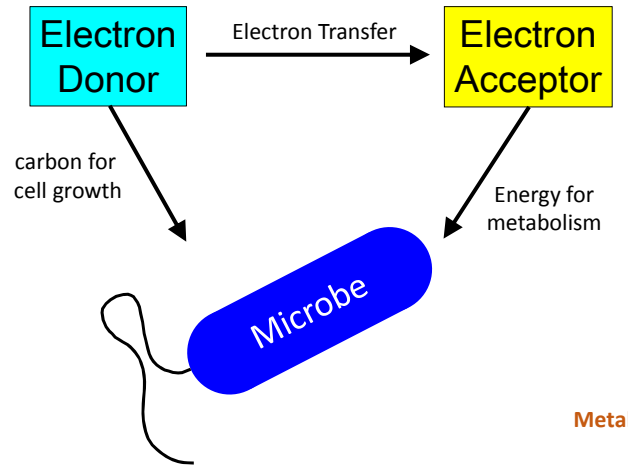
By Grant R. Carey, Ph.D.

Porewater Solutions
Expertise • Experience • Innovation



1

Biogeochemical Processes



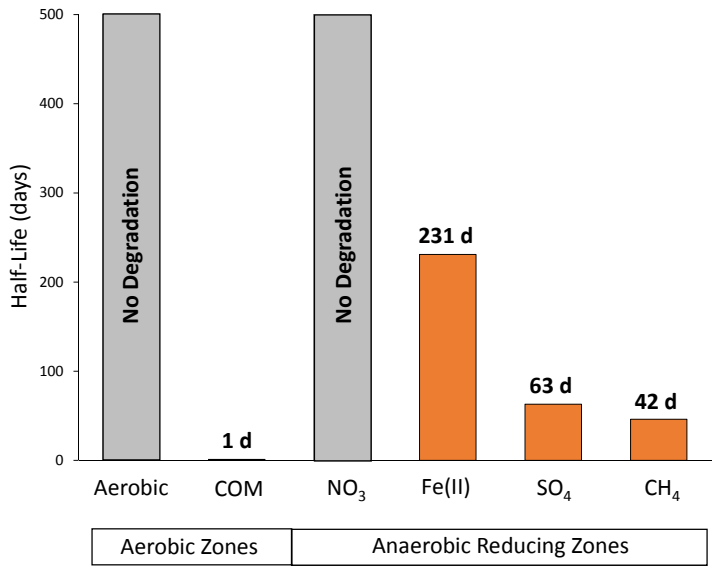
Inorganic Electron Acceptors:

- O_2
- NO_3
- $Mn_{(s)} \rightarrow Mn^{2+}$
- $Fe_{(s)} \rightarrow Fe^{2+}$
- SO_4
- $CO_2 \rightarrow CH_4$

Metabolic Byproducts

2

TCE Degradation by Redox Zone



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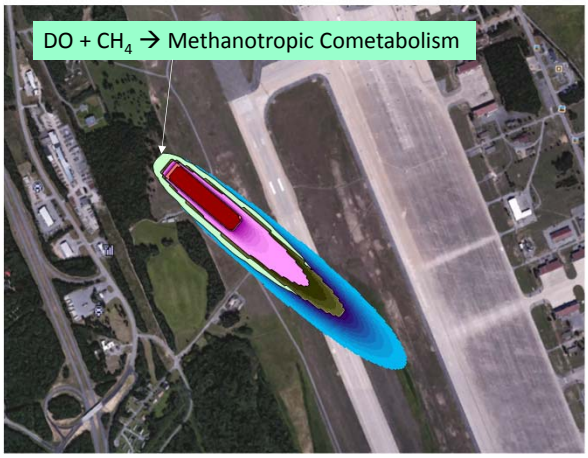
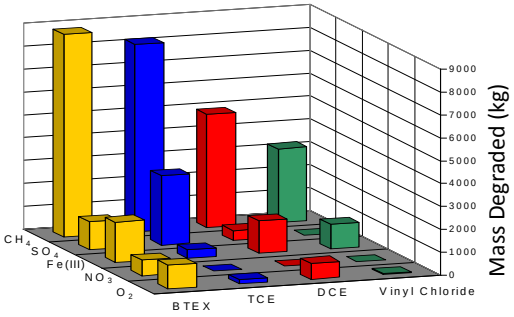
Redox Zone Mass Balance at Plattsburgh Air Force Base



Modeled using In-Situ Remediation (ISR-MT3DMS)

Modeled Mass Balance by Redox Zone (t = 40 years)



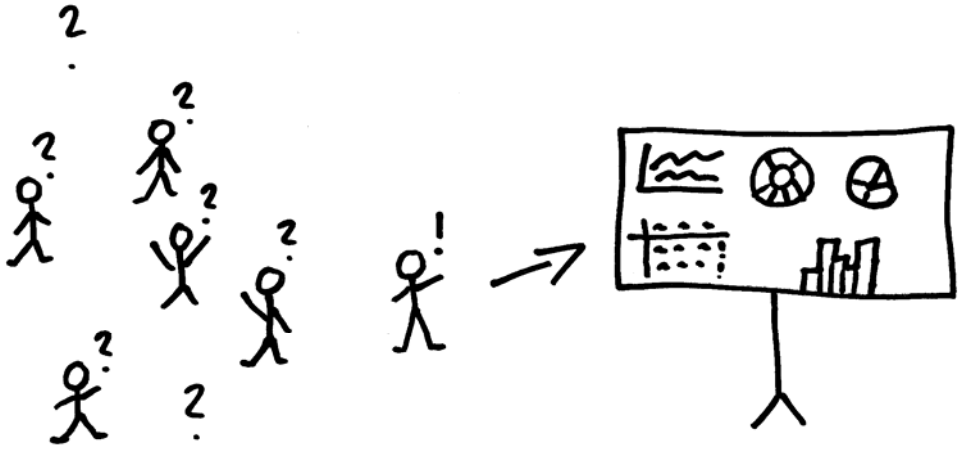
	CH_4	SO_4	Fe/Mn	NO_3	O_2
PCE					
TCE					
cis-DCE					
Vinyl Chloride					

Oxidation (rapid, NO Daughters)
Reductive Dechlorination (moderate, Daughters, need ED)
Reductive Dechlorination (slow, Daughters, need ED)
Cometabolism (rapid if substrate present, NO Daughters)

4

Main Challenge with MNA and EISB

How do we communicate results??



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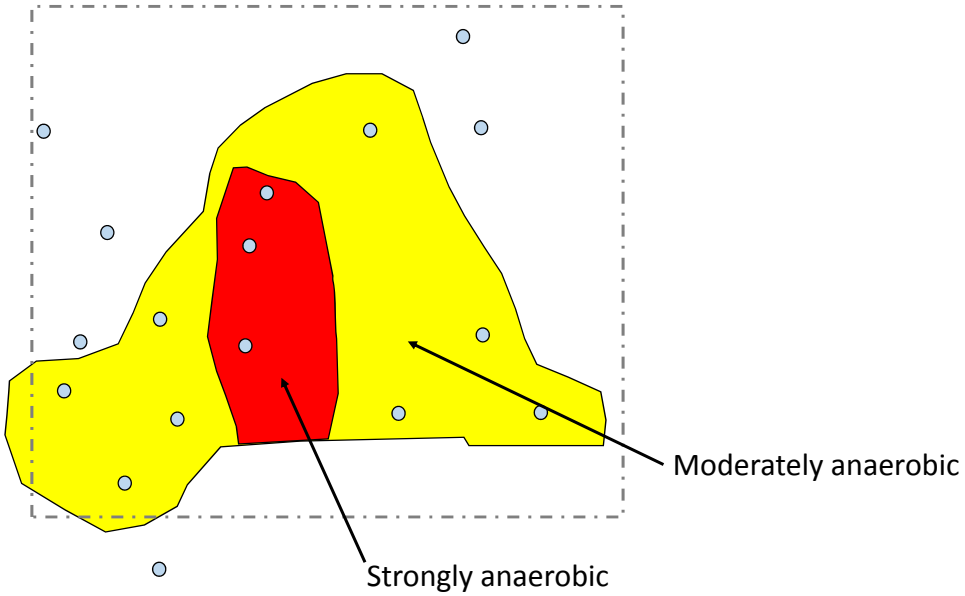
Example of Redox Zone Delineation



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Redox Radial Diagrams

Section 2.1

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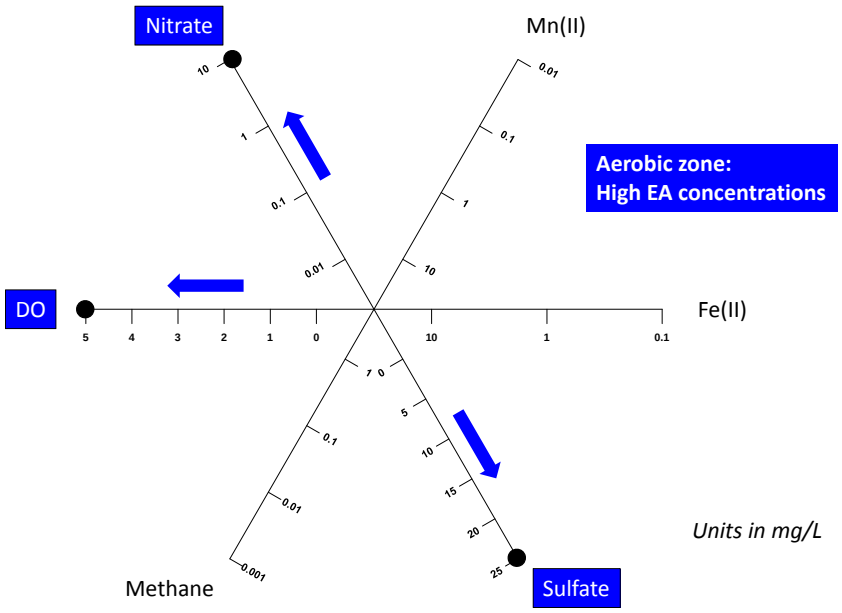
Redox Diagram: Electron Acceptors (EA)



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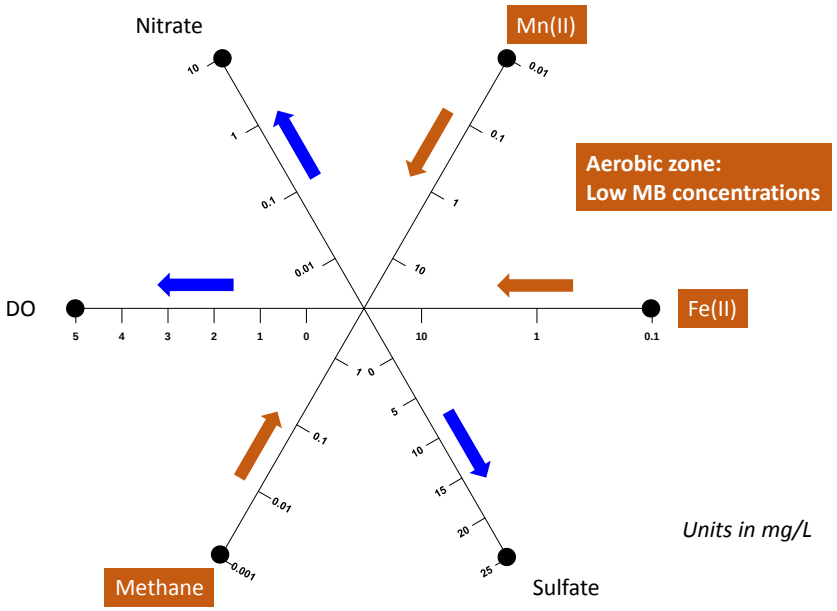
Redox Diagram: Metabolic By-Products (MB)



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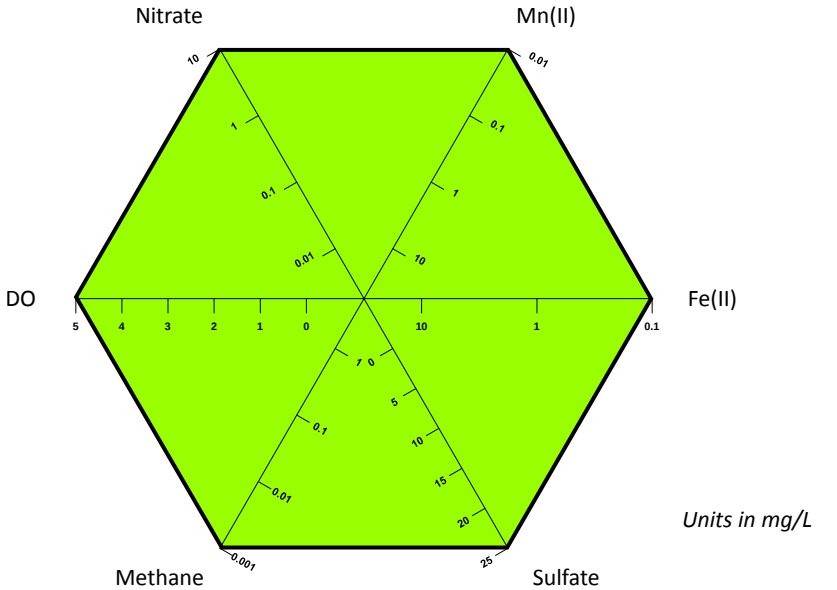
Redox Diagram: Aerobic (Background)



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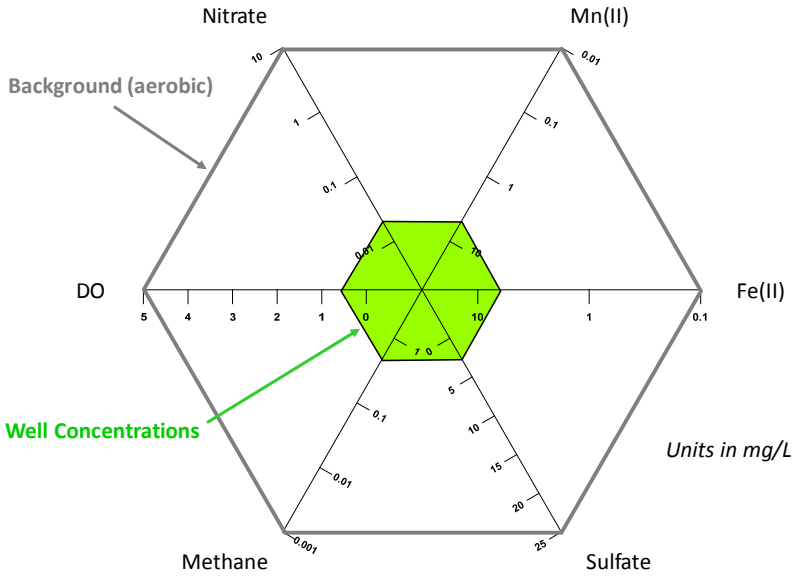
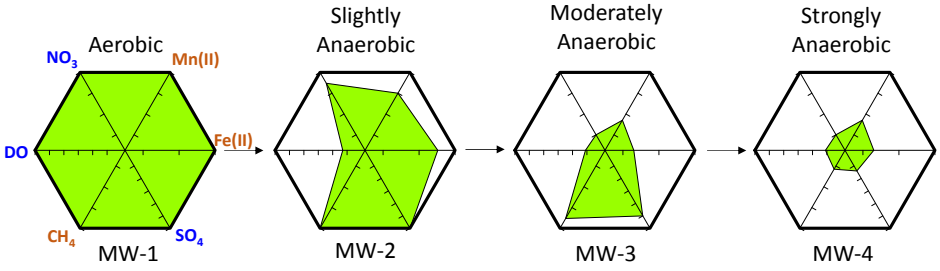
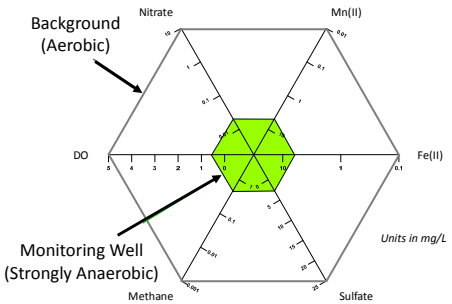
Redox Diagram: Strongly Anaerobic at Well

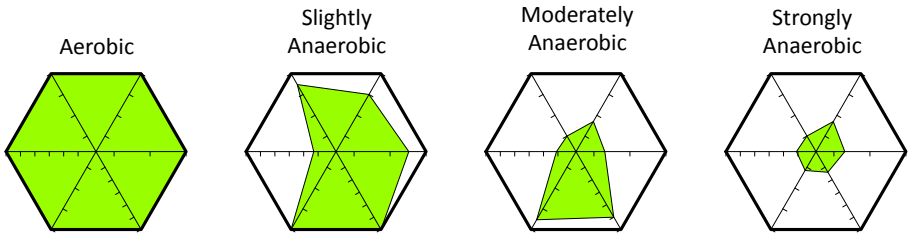


Redox Zone Transition





Redox Zone Transition



Radial diagrams are ideal for plotting relationships between redox indicators at each monitoring well.

Location	DO (mg/L)	Nitrate (mg/L)	Mn(II) (mg/L)	Fe(II) (mg/L)	Sulfate (mg/L)	Methane (mg/L)
Aerobic	5	10	<0.01	<0.1	25	<0.001
Slightly Anaerobic	0.3	3	0.1	0.3	25	<0.001
Moderately Anaerobic	0.1	<0.01	2	5	18	0.01
Strongly Anaerobic	0.1	<0.01	2	5	2	0.7

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VOC Radial Diagrams

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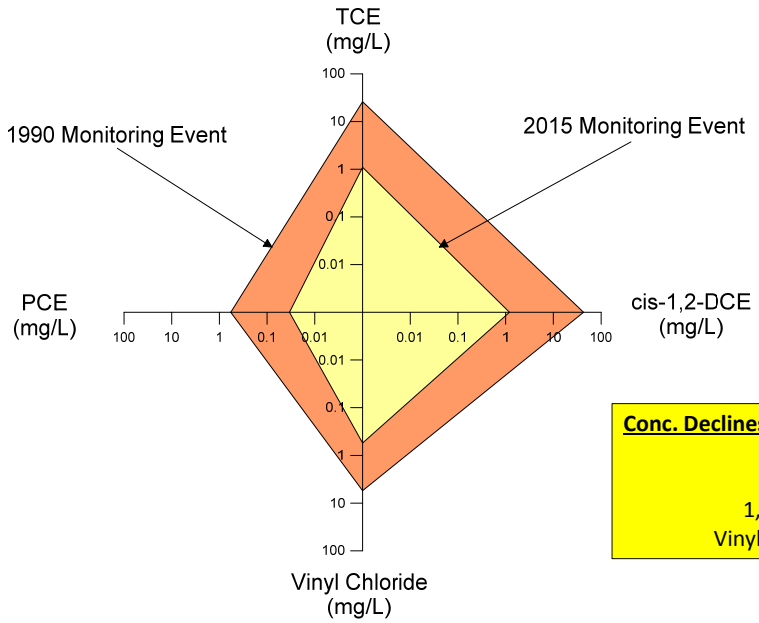
VOC Radial Diagram: Source Depletion



Conc. Declines at Well (1990 to 2015)
PCE: 10x
TCE: 30x
1,2-DCE: 30x
Vinyl Chloride: 10x

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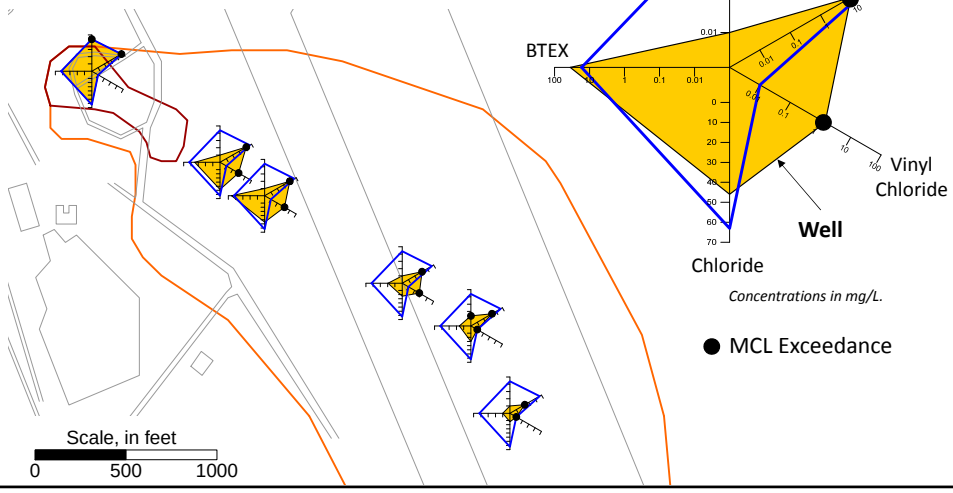
Plattsburgh Air Force Base: Plume Attenuation

Carey et al. (2003)



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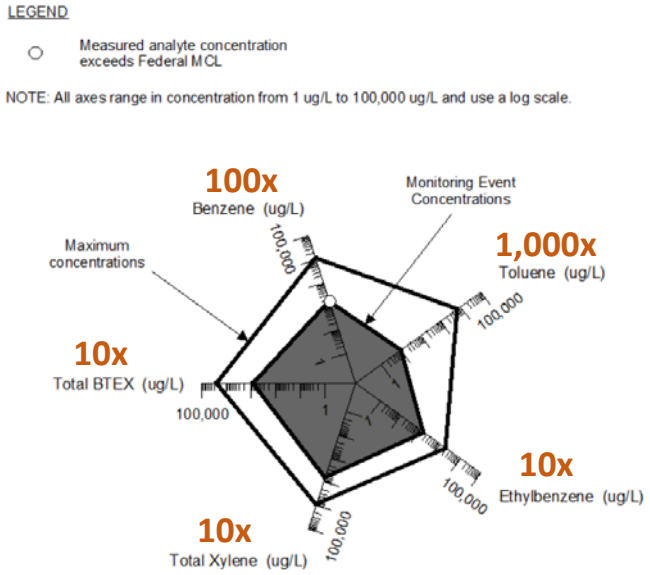
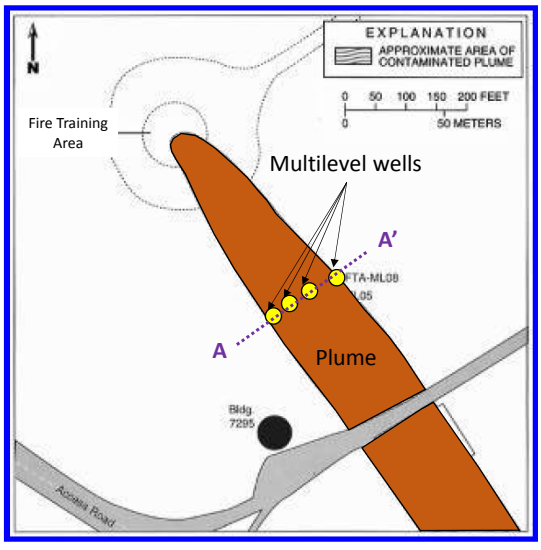
Hill Air Force Base: Plume Attenuation

Carey et al. (1999)



Wurtsmith Air Force Base, Michigan



Redox Indicators

- 20 wells
- 5 indicators

→ 100 data points

ES&T, 1996, 30: 3565-3569

Comparison of E_h and H_2 Measurements for Delineating Redox Processes in a Contaminated Aquifer

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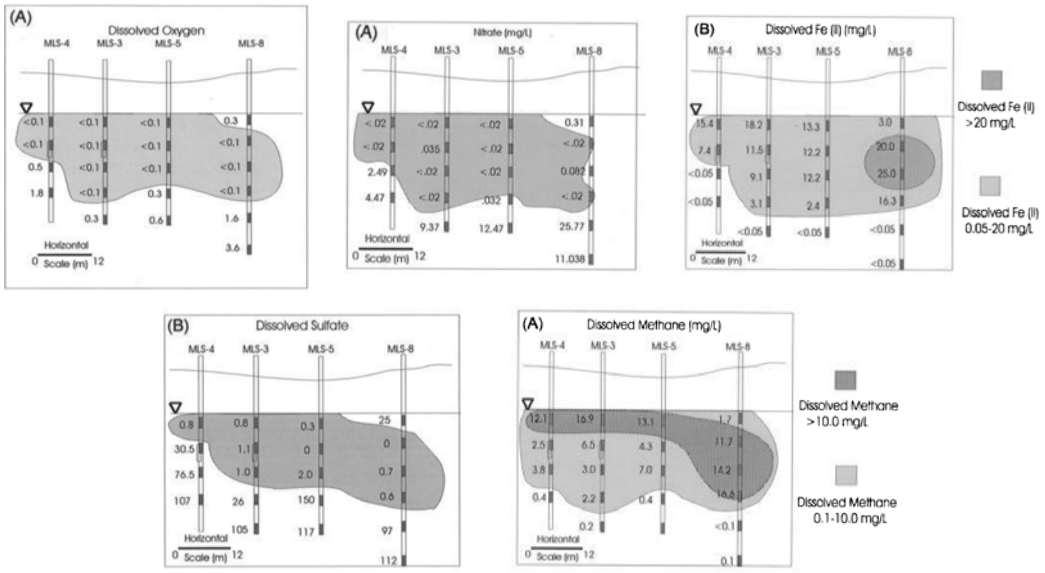
Presentation Method #1 – The TABLE

Well	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (mg/L)
MLS-3A	<0.1	<0.02	18.2	0.8	16.9
MLS-3B	<0.1	0.035	11.5	1.1	6.5
MLS-3C	<0.1	<0.02	9.1	1	3
MLS-3D	<0.1	<0.02	3.1	26	2.2
MLS-3E	0.3	9.37	<0.05	105	0.2
MLS-4A	<0.1	<0.02	15.4	0.8	12.1
MLS-4B	<0.1	<0.02	7.4	30.5	2.5
MLS-4C	0.5	2.49	<0.05	76.5	3.8
MLS-4D	1.8	4.47	<0.05	107	0.4
MLS-5A	<0.1	<0.02	13.3	0.3	13.1
MLS-5B	<0.1	<0.02	12.2	<0.5	4.3
MLS-5C	<0.1	<0.02	12.2	2	7
MLS-5D	0.3	0.032	2.4	150	0.4
MLS-5E	0.6	12.47	<0.05	117	<0.1
MLS-8A	0.3	0.31	3	25	1.7
MLS-8B	0.3	<0.02	20	<0.5	11.7
MLS-8C	0.3	0.082	25	0.7	14.2
MLS-8D	0.3	<0.02	16.3	0.6	16.6
MLS-8E	1.6	25.77	<0.05	97	<0.1
MLS-8F	3.6	11.038	<0.05	112	0.1

1.19

Presentation Method #2 – Individual Contour Maps



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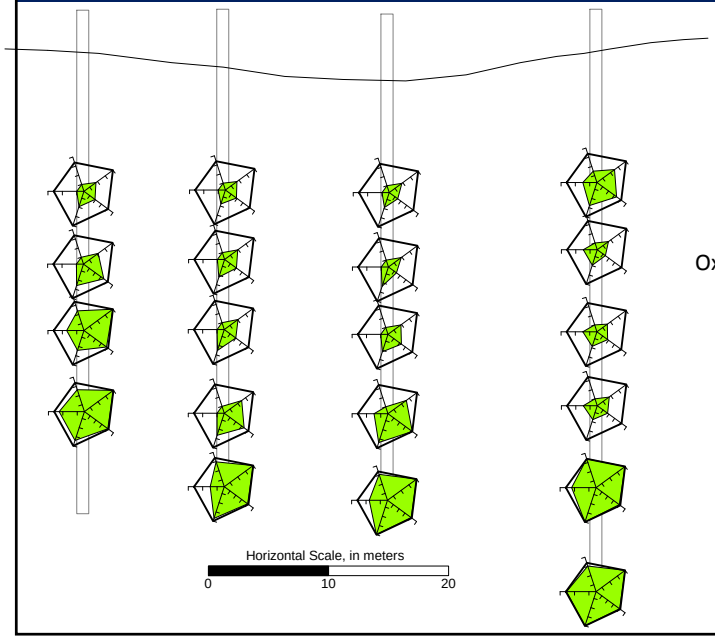
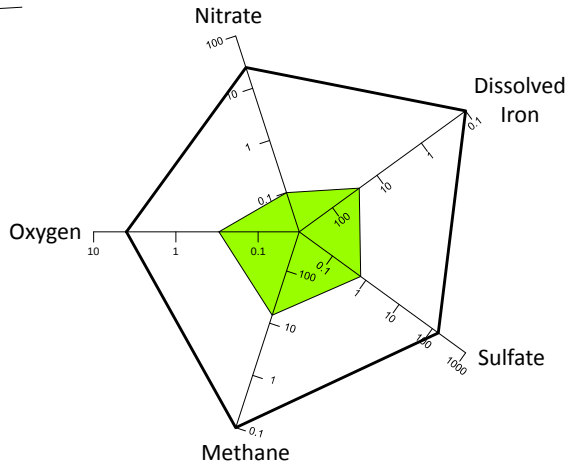
Redox Radial Diagrams





All concentrations in mg/L.

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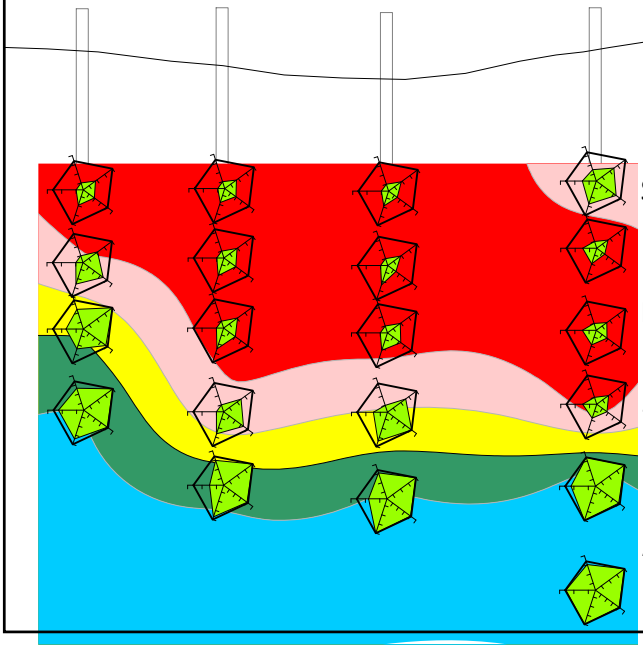
Relative Redox Area Contours



Sulfate-reducing

Methanogenic

Sulfate-reducing
Iron-reducing
Nitrate-reducing

Aerobic

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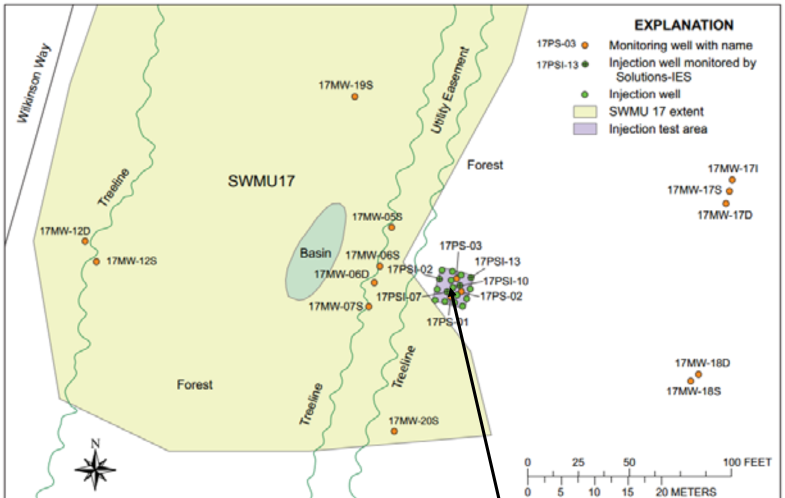
Charleston Naval Weapons Station, South Carolina



USGS, 2009

Emulsified Oil
Pilot Test Area

Redox Indicators

- 7 wells
- 6 redox indicators
- 12 events

➡ 500 data points

Charleston Naval Weapons Station

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
17PSI-07	865	9/25/06	1.81	<0.5	0.620	320	<0.5	2684.9
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1

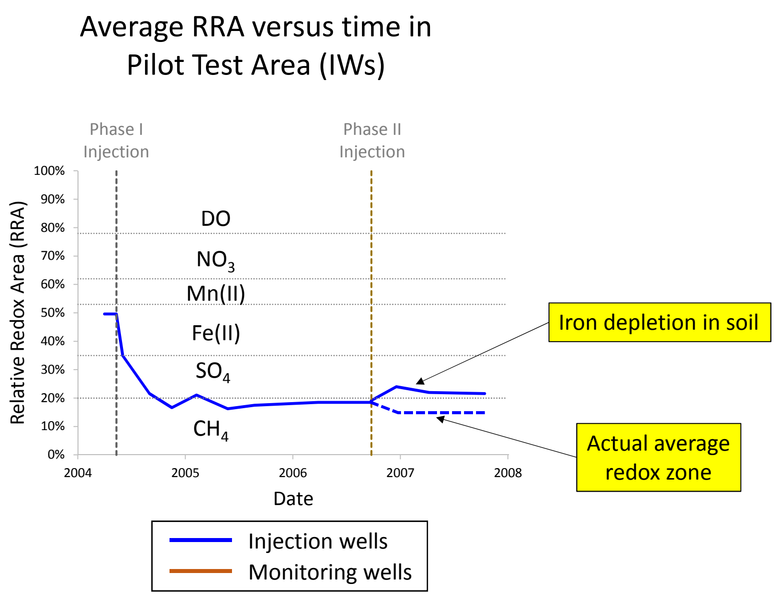
Redox Indicators

- 7 wells
- 6 indicators
- 12 events

➡ 500 data points

Charleston Naval Weapons Station

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
17PSI-07	865	9/25/06	1.81	<0.5	0.620	320	<0.5	2684.9
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1



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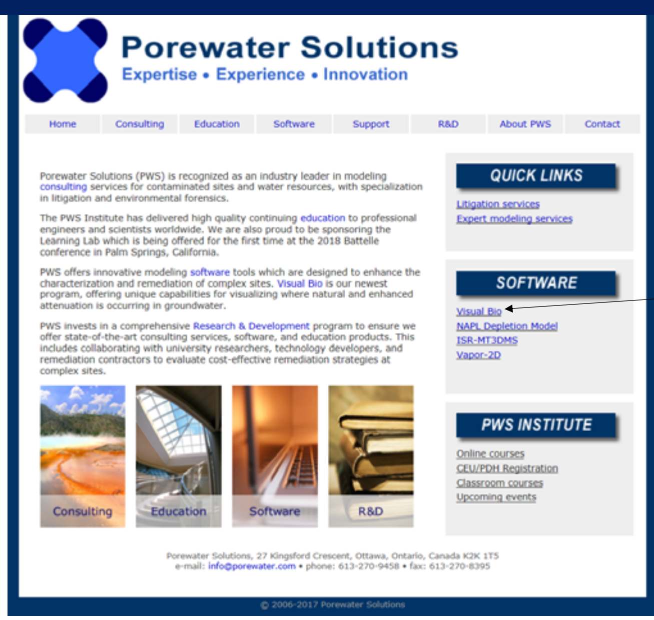

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