Pump and Treat Groundwater Remedy Optimization Using *In Situ* Bioremediation at Naval Base Kitsap, Bangor Site F

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Site F Remedy Optimization Approach

- Developed **simplified groundwater (GW) model** for Site F to simulate pump and treat (P&T) remedy optimization scenarios
- Performed ***in situ* push-pull tests** to quantify RDX retardation factor and transformation rate constant under anaerobic biostimulation conditions
- **Simulated optimization timeframes and cost** using simplified GW model and *in situ* testing results for the following optimization scenarios
  1) No optimization
  2) Expanded P&T
  3) Anaerobic Bioremediation
  4) Combined Aerobic/Anaerobic Bioremediation
  5) Enhanced P&T with Phased Bioremediation
- **Developed conceptual exit strategy** as part of optimization report

Presentation Overview

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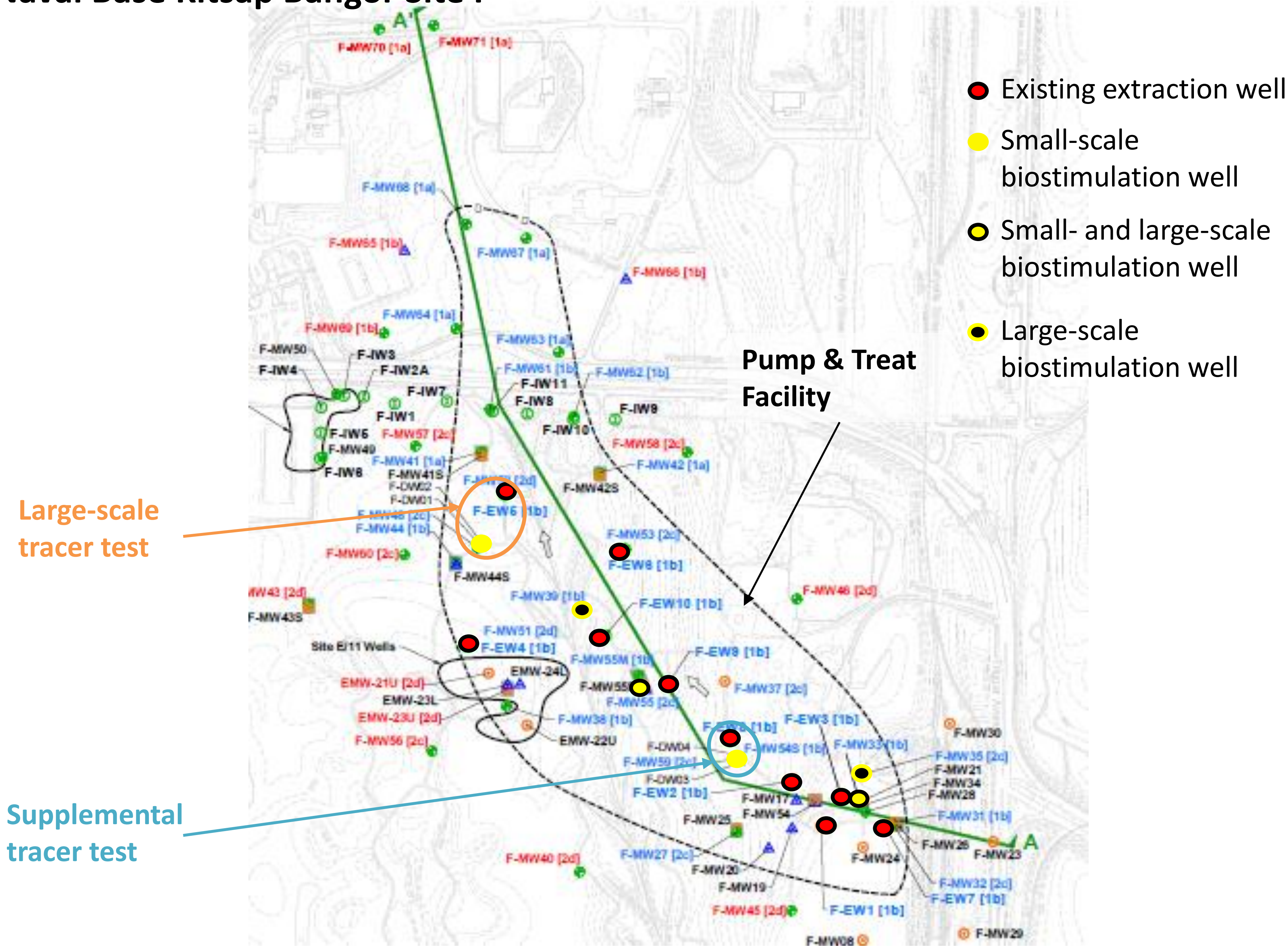
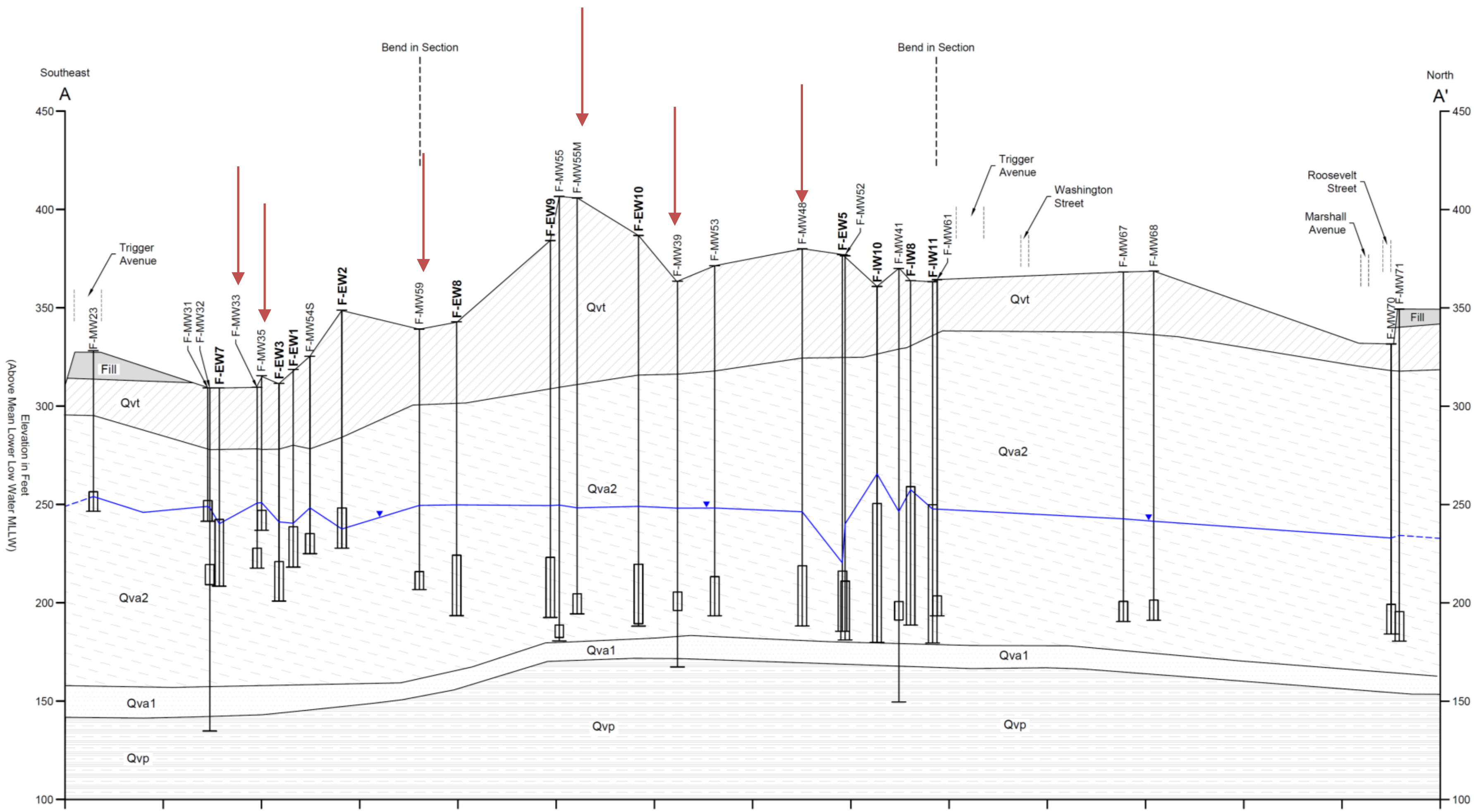
Small- and Large-scale *in situ* anaerobic biostimulation tests

Large-scale tracer test

Next steps: aerobic bioaugmentation pilot (summer 2017)

Naval Base Kitsap Bangor Site F





Fill - Fill Material

Qvt - Vashon Till

Qva1 - Vashon Advance Outwash 1

Qva 2 - Vashon Advance Outwash 2

Qvp - Vashon Proglacial Deposits (Lawton Clay)

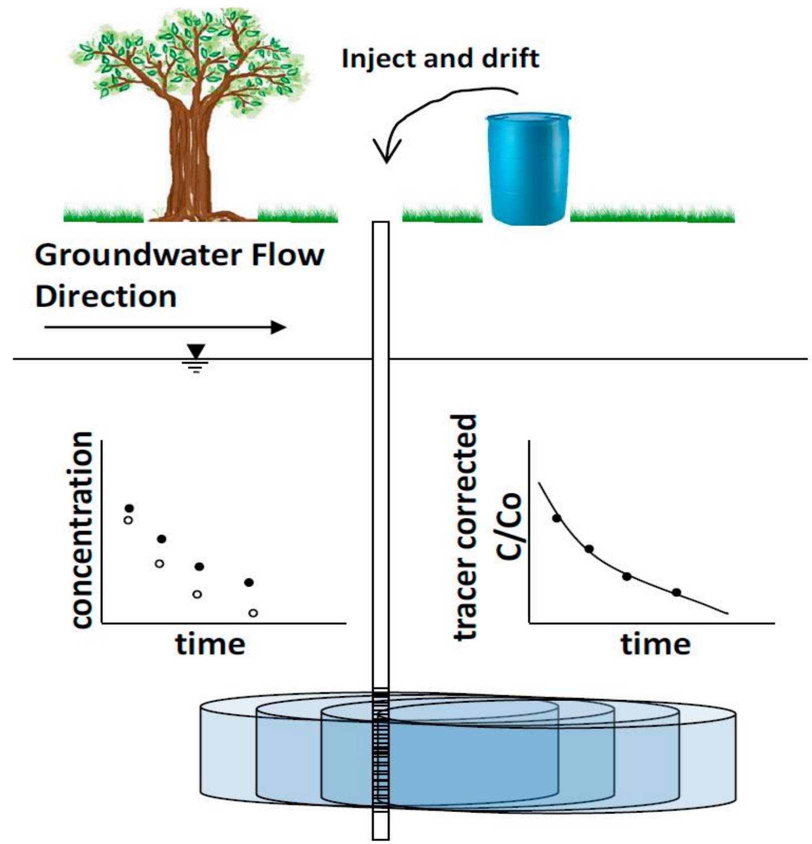
In Situ Bioremediation Testing in Site F Wells

- *In situ* push-pull tests (PPTs) involve injecting a mixture of conservative (e.g. Br-) and reactive (e.g. RDX) tracers to quantify contaminant fate and transport characteristics and degradation rates

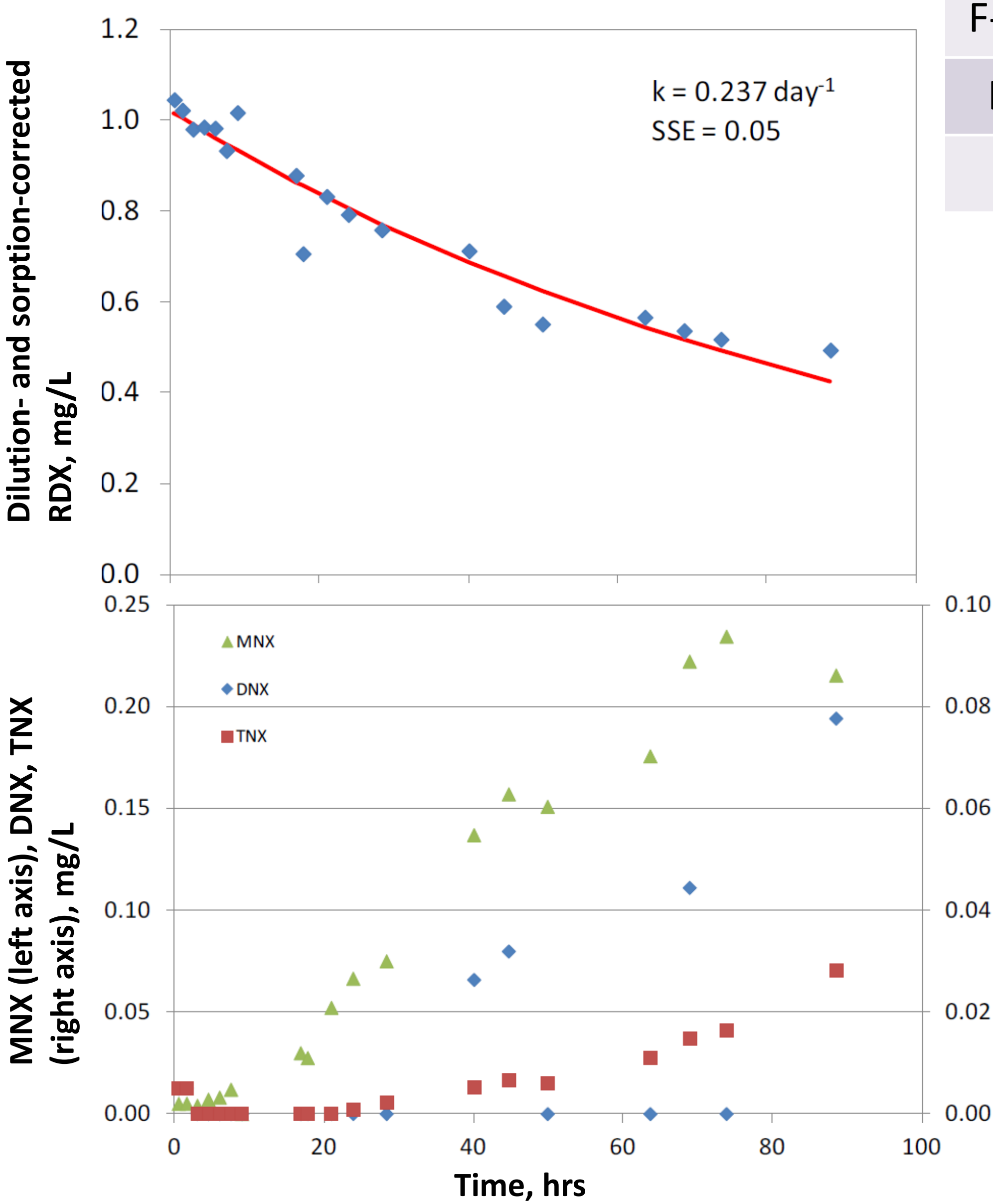
- Typical testing sequence
  1) Retardation Factor Tests
  2) Carbon substrate "feedings"
  3) Push-Pull Tests

- At Site F, a series of small (150 gal) and large (1,500 gal) *in situ* PPTs were performed to measure RDX degradation rates following anaerobic biostimulation

In situ Push-Pull Test Schematic



Small-Scale Test Results



Well	R factor$_{RDX}$	Substrate	k_{RDX}, d^{-1}
F-MW33	4.9	Corn S.	0.237
F-MW55M	8.0	Corn S.	0.173
F-MW59	3.1	EtOH	0.072
F-DW01	7.5	EtOH	0.072

- **RDX transformation via anaerobic reduction pathway occurred during all small-scale tests**
- Biostimulation with 24 mM corn syrup yielded faster RDX removal rates than biostimulation with 50-100 mM EtOH
- Not confirmed during small volume, short duration tests:
  1) Ability to achieve 0.8 µg/L RDX cleanup level
  2) Transient nature of nitroso-RDX derivatives

Large-Scale Bioremediation Testing

- Increase test volume 10x to 1,500 gal
- Extend test duration from 4 to 21 days
- Use average site-specific RDX retardation factor of 5.9±2.3 from initial small-scale tests
- Perform biostimulation with 24 mM fructose only; no EtOH

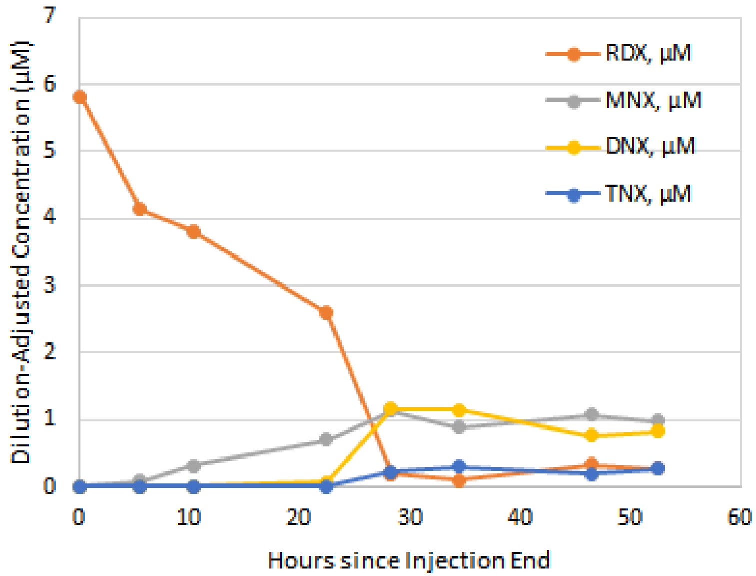
geochemical indicators measured in groundwater prior to each "feeding"

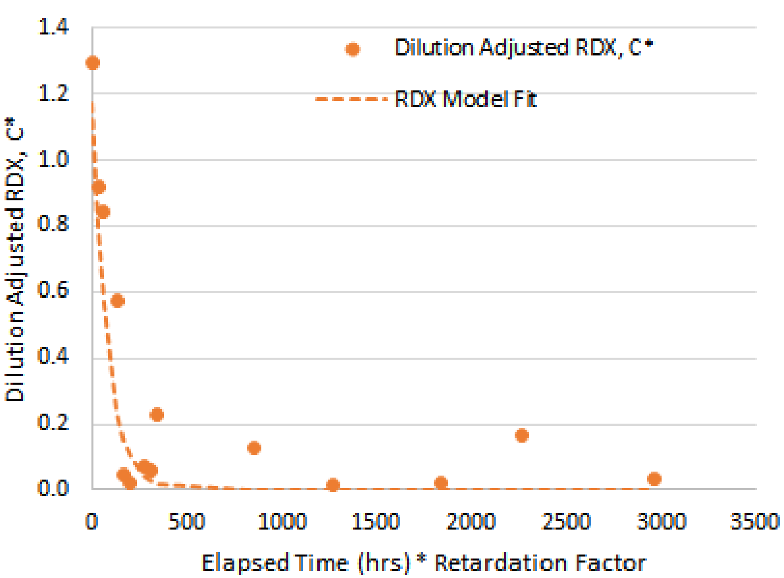
	Wells featured in 2016 biostimulation tests							
	MW35							
Date	3-Jun	17-Jun	1-Jul	15-Jul	29-Jul*	12-Aug*	26-Aug	7-Sep
O_2, ppm	-	2.8	2.2	0.7	0.6	0.7	0.8	0.9
ORP, mV	-	215	-124	-236	-282	-87	-81	-81
Fe(II), mg/L	-	0	2.5	6	5.5	5	5	7
pH	-	6.3	5.9	5.5	5.2	5.6	5.8	5.6
	MW39							
Date	3-Jun	17-Jun	1-Jul	15-Jul	29-Jul*	12-Aug*	26-Aug	7-Sep
O_2, ppm	-	1.5	0.0	0.0	0.0	0.3	0.5	0.1
ORP, mV	-	-264	-468	-479	-485	-139	-111	-274
Fe(II), mg/L	-	3	5	3.5	4.5	7	6	4.5
pH	-	6.3	5.2	4.9	5.2	6.1	6.4	5.7

	Wells featured in 2014 and 2016 biostimulation tests							
	MW33							
Date	3-Jun	17-Jun	1-Jul	15-Jul	29-Jul	12-Aug*	26-Aug	7-Sep
O_2, ppm	-	0.1	0.3	0.5	0.1	0.3	0.3	0.2
ORP, mV	-	-203	-41	-43	-447	-110	-66	-116
Fe(II), mg/L	-	0.5	2	1.5	5.5	4.5	5	5
pH	-	6.7	6.5	6.4	5.6	6.2	6.3	6.0
	MW55M							
Date	3-Jun	17-Jun	1-Jul	15-Jul	29-Jul*	12-Aug*	26-Aug	7-Sep
O_2, ppm	-	0.0	0.1	0.0	0.1	0.4	0.1	0.1
ORP, mV	-	-474	-434	-422	-399	-74	-93	-244
Fe(II), mg/L	-	4.5	4	3.5	5	4.5	7	5.5
pH	-	5.3	5.3	4.8	4.6	5.0	6.1	5.2

*No Feedings

Large-Scale Test Results





Site F Wells	k_{RDX}, d^{-1}	Measured at test end, µg/L			
		RDX	MNX	DNX	TNX
33	0.290±0.013	2	1U	1U	1U
35	0.230±0.0036	1U	4	1U	4
55M	*0.056±0.00013*	*1U*	*1U*	*18*	*12*
39	0.480±0.19	1U	3	6	18

- RDX transformation via anaerobic reduction pathway occurred during all large-scale tests; k_{RDX} averaged 0.27 day^{-1}
- RDX mostly non-detect by the end of the tests
- Intermediates MNX, DNX, TNX non-detect or present in low concentrations by end of test
- Low temperature may have had a minor impact on reaction rates (3°C vs 13°C):

$$k_{T_1} = k_{T_2}\theta^{(T_1 - T_2)}$$

Predicted k (@ 13°C) = 0.32 day^{-1}

Anaerobic Biostimulation Results Summary

- Rate coefficients obtained using corn syrup/fructose during small- and large-scale tests were consistent and confirm anaerobic biostimulation efficacy in Site F groundwater
- Aquifer acidification –different results for F-MW55M
- Temperature effects
- Groundwater model simulation results (not shown) indicated phased "enhanced P&T then bioremediation within smaller plume footprint" has potential to significantly expedite groundwater cleanup compared to current P&T remedy and could be a top performer in future feasibility study

Bioaugmentation for *Aerobic* Remediation of RDX-Contaminated Groundwater

ESTCP

Performers: U.S. Army Corps of Engineers, Seattle District; CB&I Federal Services; U.S. Army Engineer Research & Development Center; Oregon State U.

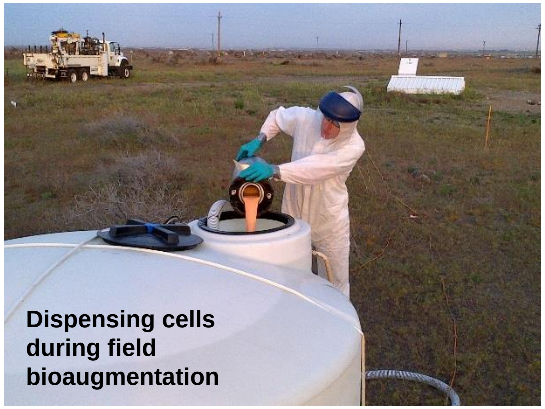
Technology Focus
- *Bioaugmentation with aerobic RDX-degrading bacteria as novel approach for remediation large, aerobic RDX groundwater plumes. Projects completed include ER-201207, NESDI #499.*

Demonstration Sites
- ***Umatilla** Chemical Depot (UMCD), Umatilla, Oregon; **NBK Bangor Site F***

Demonstration Objectives
- *Select optimal aerobic RDX-degrading bacteria; achieve RDX-removal rate and extent similar to anaerobic biostimulation approach with significantly less growth substrate and cost, while preserving groundwater quality.*

Results
- *Bioaugmentation with aerobe Gordonia sp. KTR9 promoted rapid RDX removal at rates similar to anaerobic biostimulation with an order of magnitude less growth substrate required (ER201207, NESDI #499). Inclusion of facultative anaerobe Ps. Strain I-C, which degrades RDX via anaerobic pathway, may enhance bioaugmentation performance in heterogeneous aquifers where pockets of anaerobic conditions can develop (NESDI #499).*


Large-scale cell production; laboratory column testing of bioaugmentation (right)


Dispensing cells during field bioaugmentation

Michalsen, M. M.; Crocker, F.H.; Indest, K.J.; Jung, C.M.; Hatzinger, P.B.; Fuller, M.E.; Istok, J.D. Evaluation of biostimulation and bioaugmentation to stimulate RDX degradation in an aerobic groundwater aquifer. ***Environmental Science & Technology***, 2016. 50 (14): p. 7625-7632. July 2016.

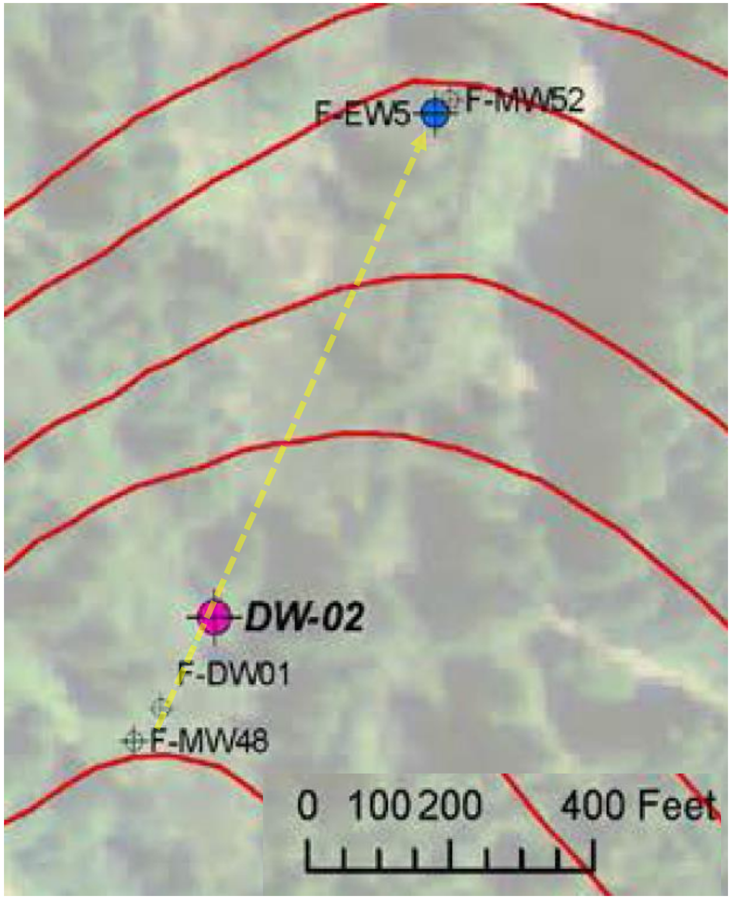
Crocker, F.; Indest, K.; Jung, C.; Hancock, D.; Fuller, M; Hatzinger, P.; Vainberg, S.; Istok, J.; Wilson, E.; Michalsen, M. Evaluation of microbial transport during aerobic bioaugmentation of an RDX-contaminated aquifer. **Biodegradation**, 2015. 26(6): p. 443-451.

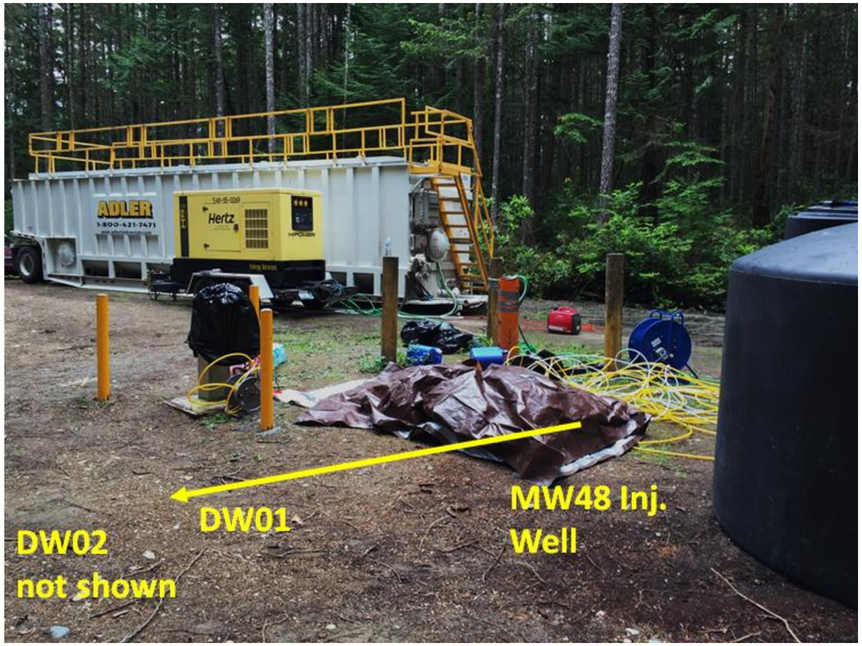
Fuller, M., Hatzinger, P., Condee, C., Andaya, C., Vainberg, S., Michalsen, M., Crocker, F., Indest, K., Jung, C., Hancock, D., Istok, J. Laboratory Evaluation of Bioaugmentation for Aerobic Treatment of RDX in Groundwater. ***Biodegradation***. 26 (1), 77-89, February 2015.

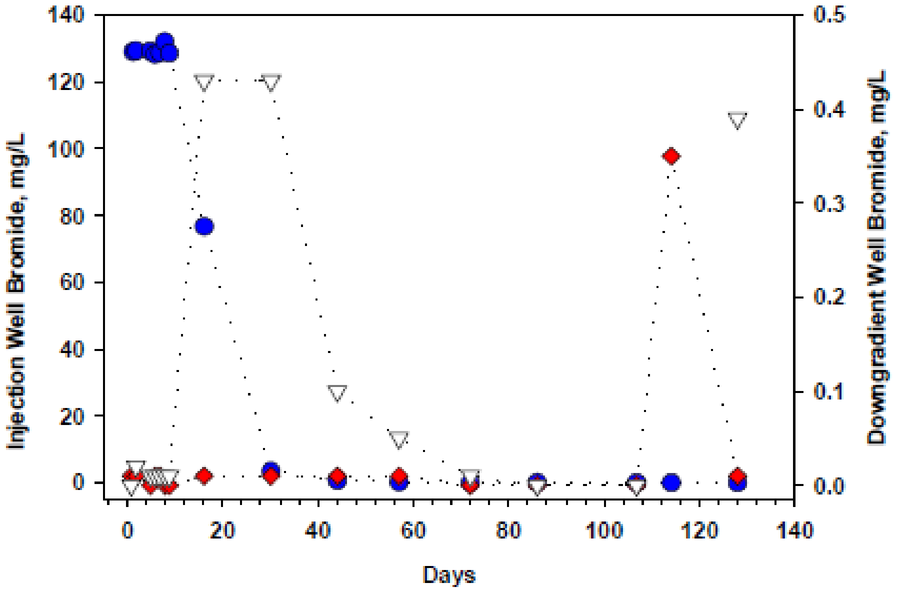
Fuller ME, Hatzinger PB, Condee CW, Andaya C, Reses R, Michalsen MM, Crocker FH, Indest KJ, Jung CM, Blakeney GA, Istok JD, Hammett SA. RDX degradation in bioaugmented model aquifer columns under aerobic and low oxygen conditions. ***Applied Microbiology and Biotechnology*** (in press).

Large-scale Tracer Test at Site F

- Large-scale tracer test goals
  - Confirm groundwater seepage velocity
  - Verify hydraulic connectivity between wells

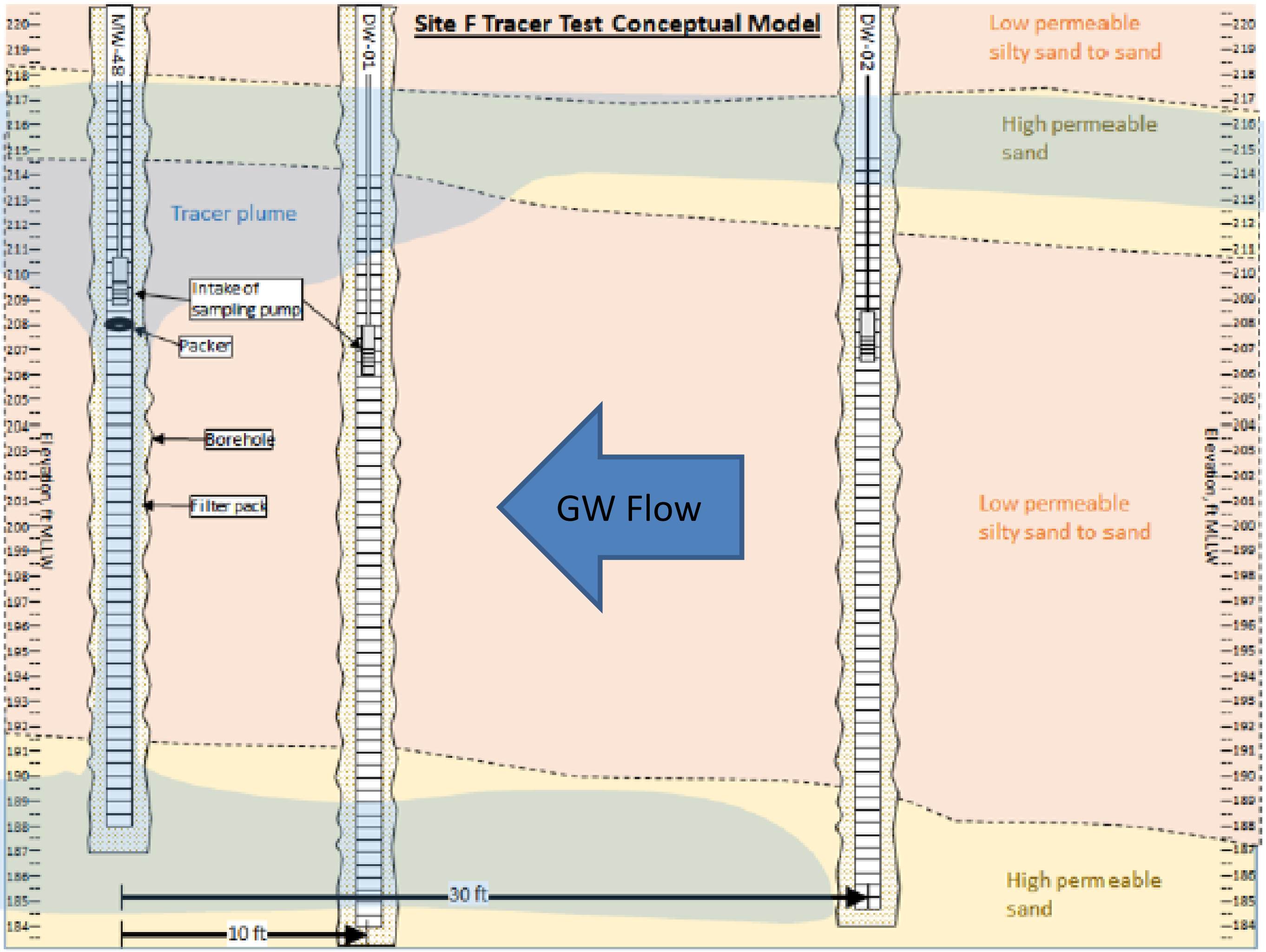




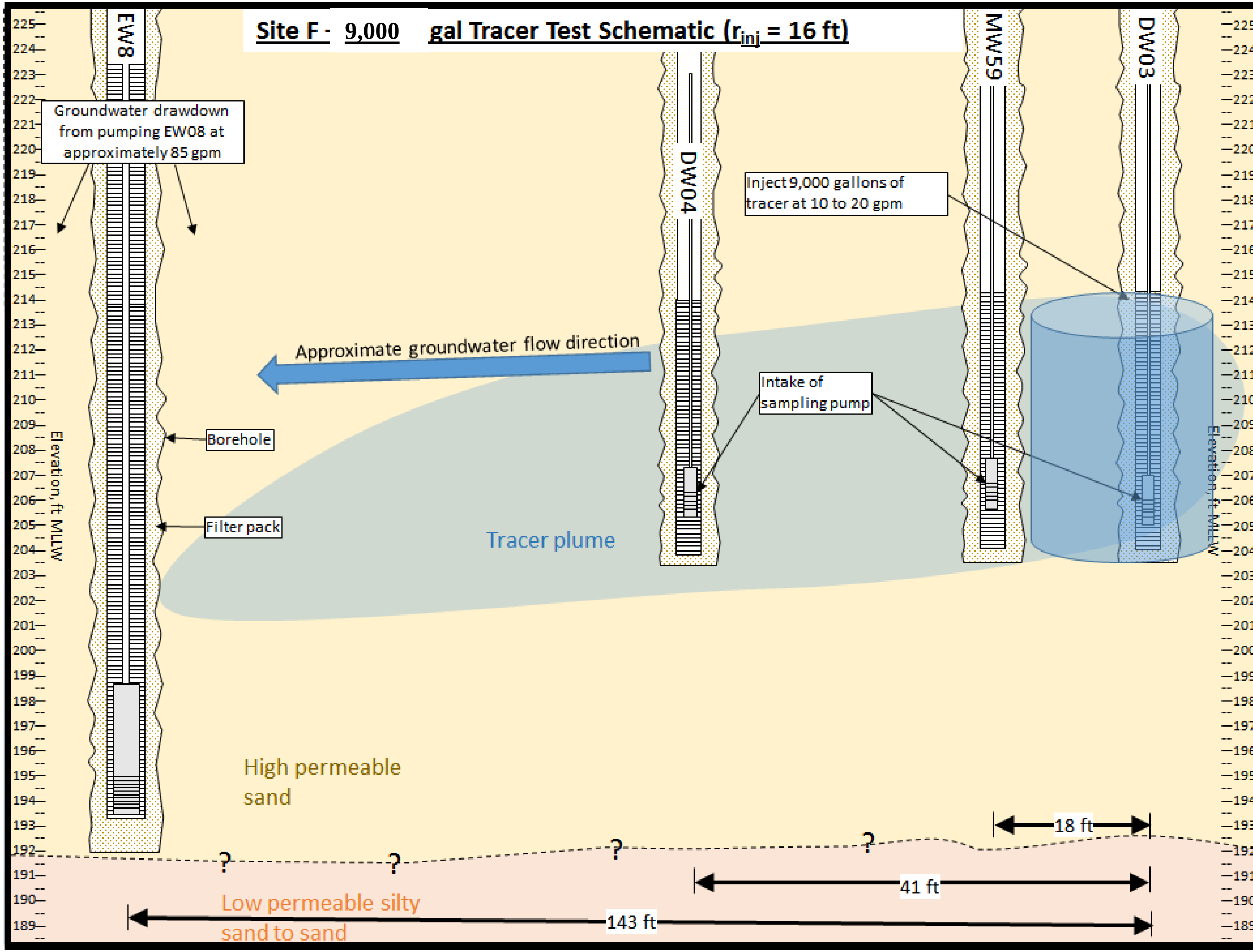


Forced-gradient Tracer Test

- Large-scale Tracer Test Results
  - Less than 1% of tracer observed at downgradient monitoring wells
  - Temporal analysis of response curves suggest a 20.3 day travel time from F-MW48 to F-DW01 (10 feet away); apparent seepage velocity ~ 0.5 ft/day



Supplemental Tracer Test



Take Home Messages and Next Steps

- Anaerobic biostimulation demonstrated to rapidly degrade RDX; can achieve 0.8 µg/L cleanup level; nitroso-RDX derivatives formed are transient in nature
- Aerobic Bioaugmentation Pilot Test, Summer 2017
  - Precursor laboratory column study using repacked Site F aquifer materials
  - ~18,000 gallons injection in F-DW03 with tracer and bioaugmentation cells (*Gordonia* sp. KTR9 and *Ps.* Strain I-C) planned for August 2017
  - Monitor *xplA and xenB* gene copies and viable cell counts in injection and downgradient wells
- Simulate optimized groundwater (GW) remedy scenarios using site-specific groundwater model and key field pilot results
  - Formation response to large-volume injections; verified GW flow directions and seepage velocities
  - Anaerobic biostimulation RDX removal kinetics
  - Aerobic bioaugmentation cell transport and RDX removal kinetics

Questions?