Successful in situ biostimulation: An analysis of six case studies of impacted sites in Saskatchewan

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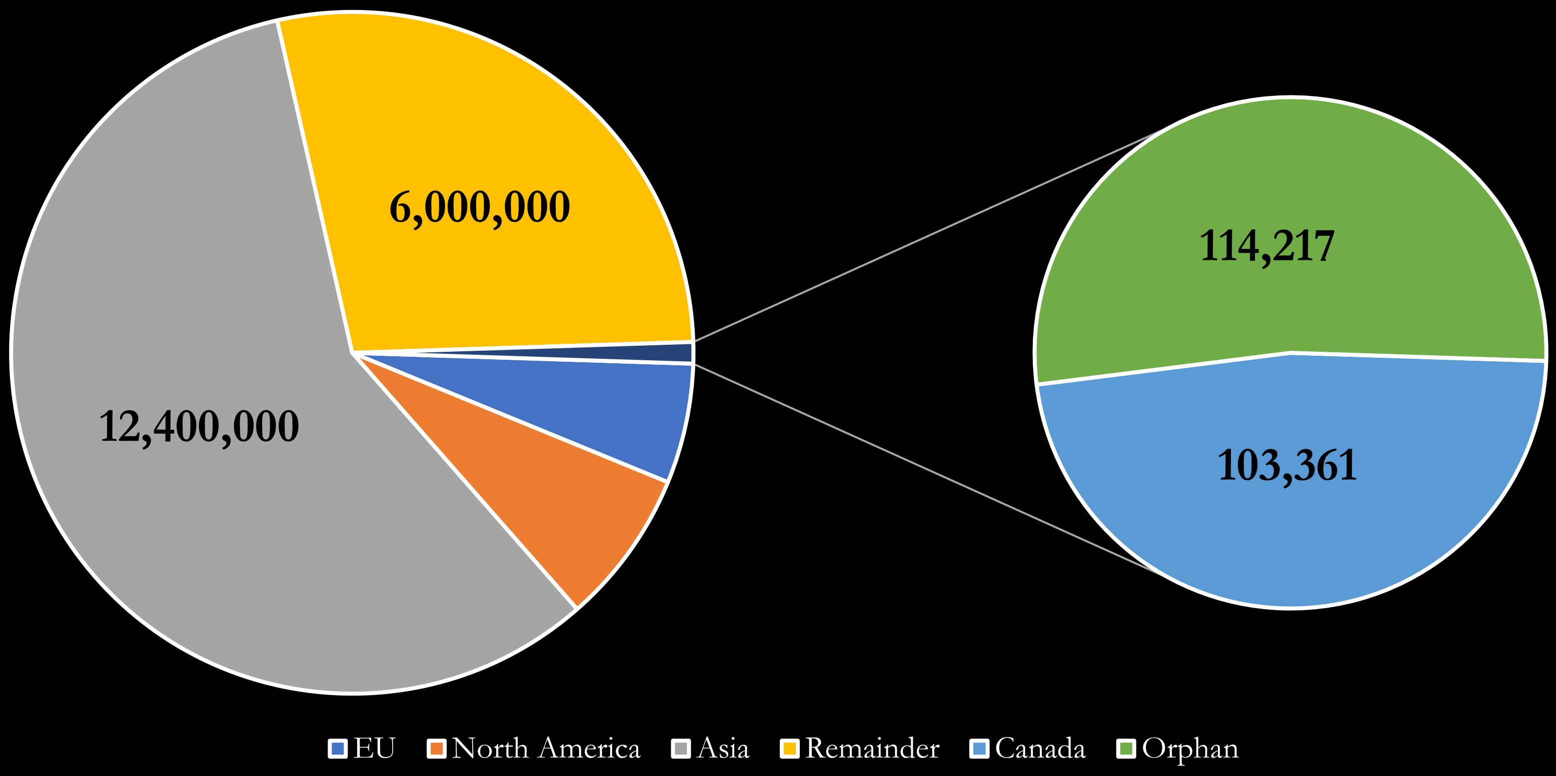
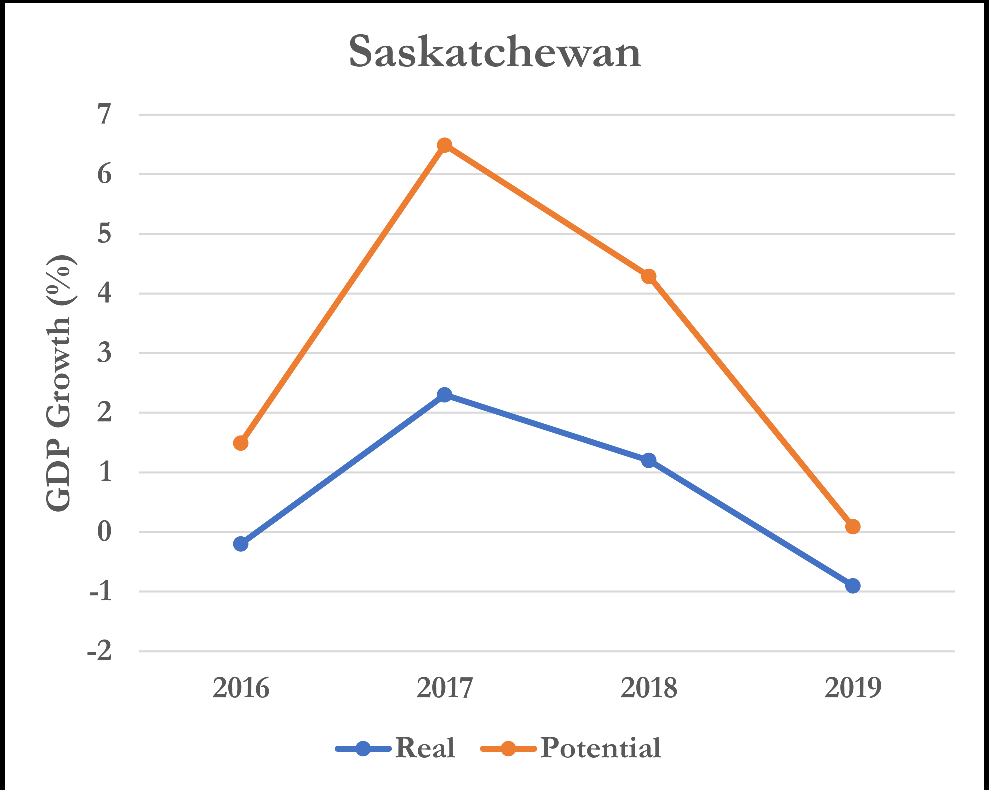
HOW MANY CONTAMINATED SITES ARE THERE?

~ 21 Million Contaminated Sites Worldwide



Social Benefits of Bioremediation
Economic Growth

- Contaminated sites reduce GDP due to stranded assets, capital flight, and reduced redevelopment.
- On going costs
  - Globally $0.2 - $ 1.1 trillion USD /yr
  - EU specific $6 billion € /yr
  - 0.0014 to 1.89% of GDP depending on jurisdiction.



Social Benefits of Bioremediation
Reduced Mortality

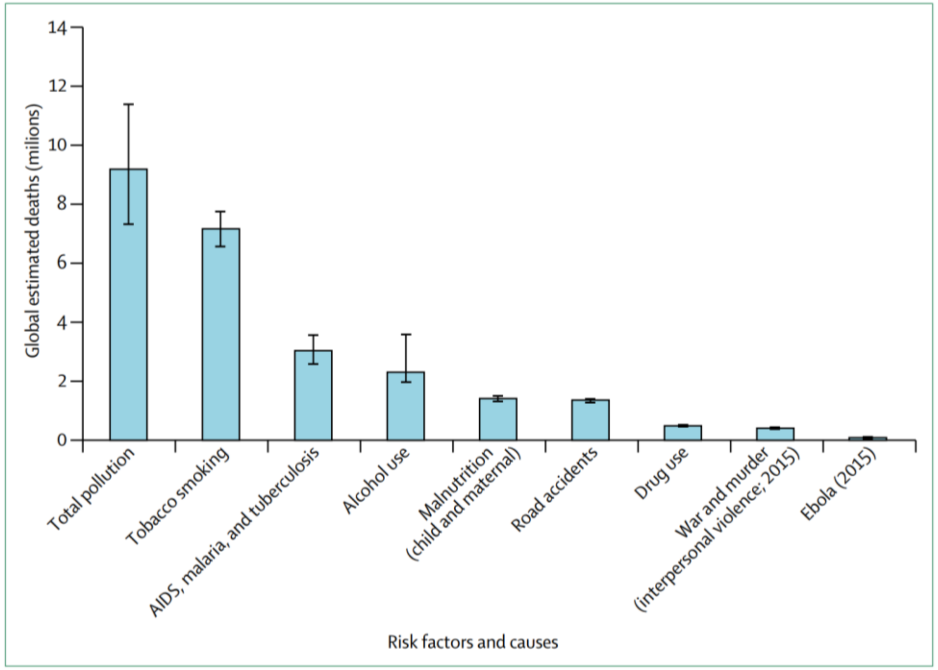


Figure 5: **Global estimated deaths by major risk factor and cause, 2015**

Elkins and Zenghelis 2021. Sustainability Science.

- 9 million deaths from pollution.
- ~2 million from contaminated soil and water
  - ~0.6 million from soil alone.
- Majority of deaths due to artisanal mining, biocides and chemical manufacturing.

Social Benefits of Bioremediation
Reduced Disability

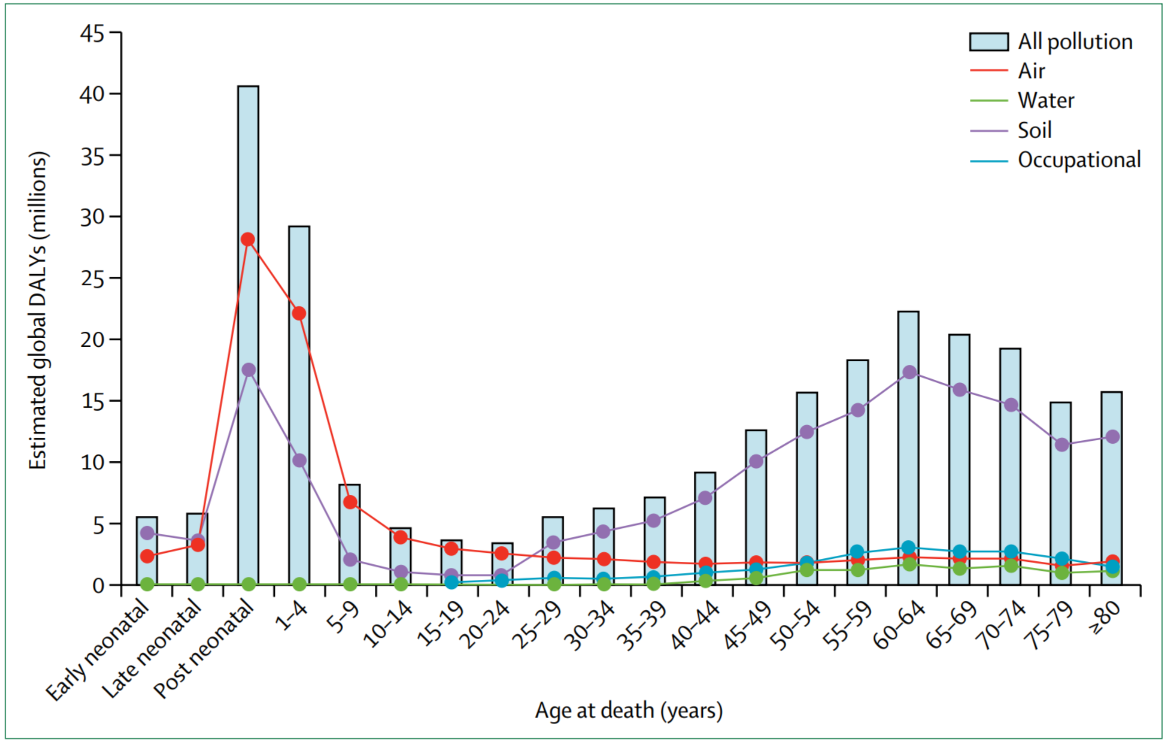


Figure 11: **Estimated global DALYs by pollution risk factor and age at death, 2015**
GBD Study, 2016.[42] DALYs=disability-adjusted life-years.

Above 25 years of age, soil is the leading cause of life years lost to disability

Bioremediation is a Cost-Effective Solution

Technology		Average	Upper Range	Cost per m^3
Ex-Situ		$816,900	$1,429,575	$204 to 357
In-Situ				
Physical	Multi-Phase Extraction	$ 900,000	$ 1,500,000	$225 to 375
Chemical	Chemical Oxidation	$ 431,600	$ 755,300	$108 to 189
Biological	Stimulated Depletion	$ 210,000	$ 420,000	$52 to 105

Western Canada

11,214 sites

$10.4 Billion Ex-Situ

$2.6 Billion In Situ

- Costs estimated assuming a 5-year closure time for an average site size of 4,567 m^3.
- Ex-Situ will close a site in 1 year.
- Physical methods typically do not close sites but recover freely available product.
- 11,214 sites estimated in Western Canada exclude orphan wells.
- 34,143 sites Canada wide.

Environmental Benefits of In Situ Bioremediation compared to Ex Situ Disposal

Soil

Ex Situ

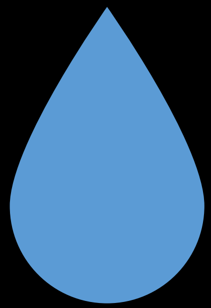
$1.3\ m^3$

In Situ

$0\ m^3$

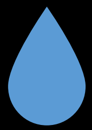
Water

Ex Situ



$1.77\ m^3$

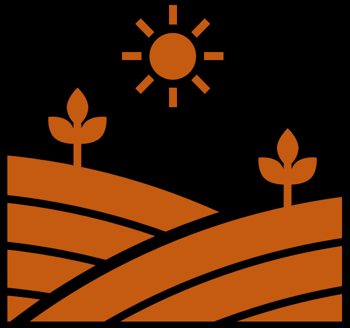
In Situ



$0.053\ m^3$

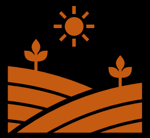
Climate

Ex Situ



8250 kg CO_2-eq

In Situ



0.13 kg CO_2-eq

FACT: It takes 100 years to make 1 cm^3 & 100 million years to make a m^3

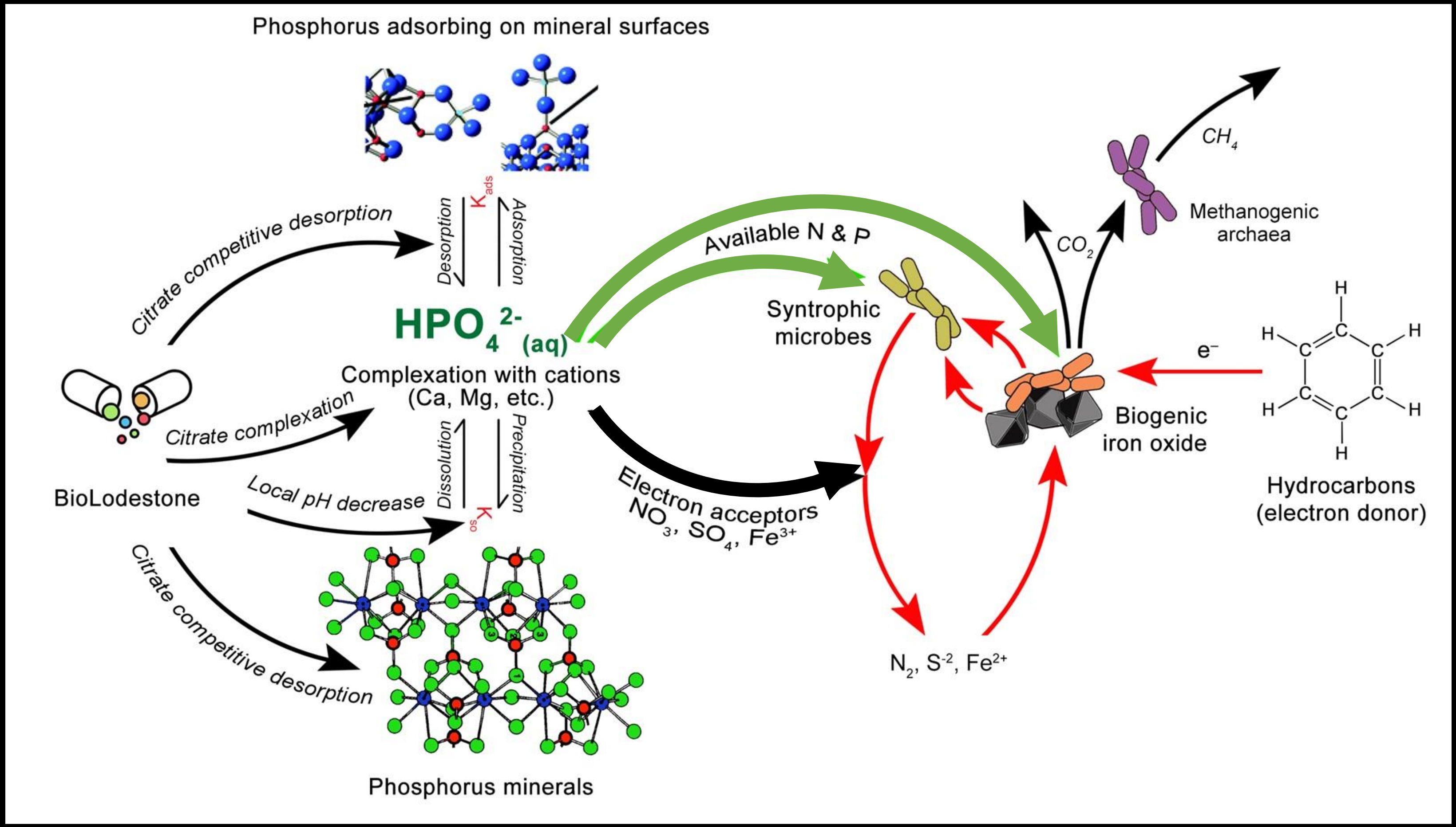
Hydrocarbon remediation in Western Canadian sites

- Challenging due to:
  - Groundwater table fluctuations changes availability of electron acceptors
  - Low hydraulic conductivity and fractured flow
  - Inter-site variability of soil mineralogy, hydrology, biology, sources of hydrocarbons

- Our approach:
  - A biostimulation solution that is a mixture of nutrients and electron acceptors
  - Use fractured flow paths to our advantage

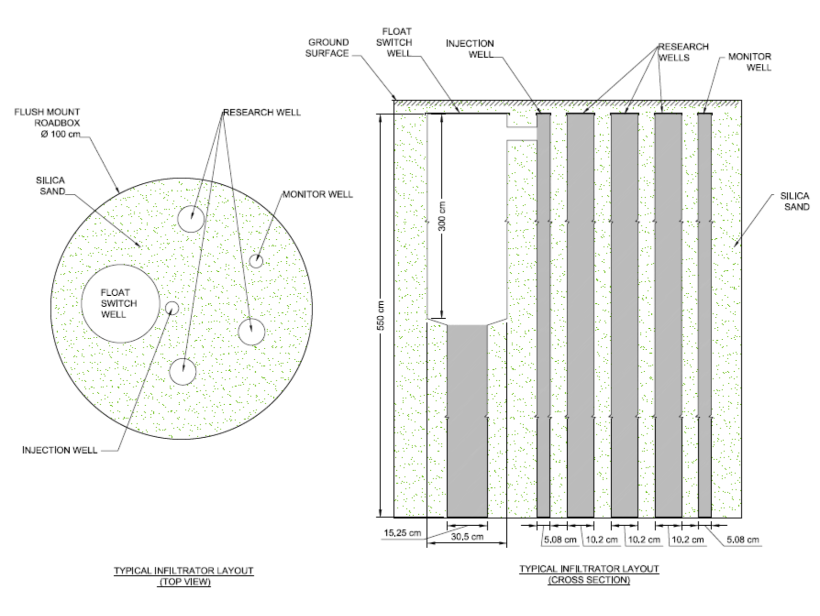
In situ biostimulation

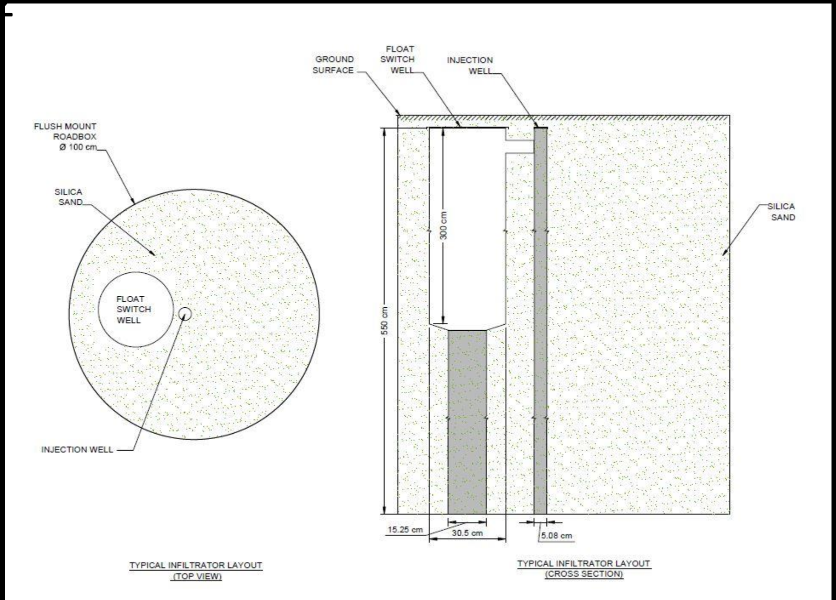
- The foundation of our remediation technology is to stimulate naturally occurring bacteria to degrade hydrocarbons.
- Naturally occurring microorganisms need nutrients and terminal electron acceptors such as O_2, NO_3^-, SO_4^{2}, Mn^{2+}, and Fe^{2+} to degrade hydrocarbons.
- Adding a diverse biostimulation solution with multiple electron acceptors reduces eutrophication and stimulates a diverse community of degraders.
- **Our solution is ideally suited to Western Canadian sites with a fluctuating capillary zone.**

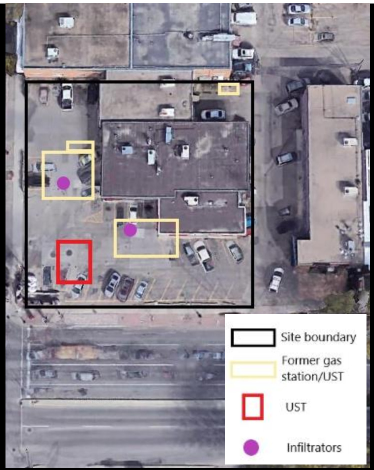


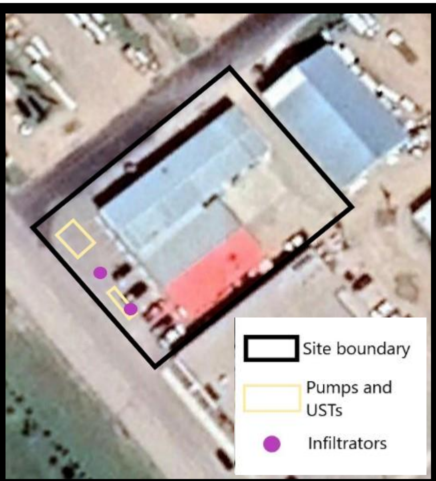
Two injection designs: **Injectors/Infiltrators** and Drive-point networks

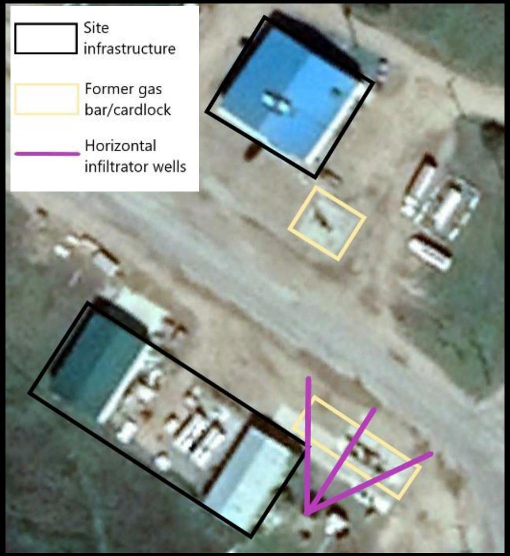
Design intended for source impacted areas such as a former pump island or storage tank area.





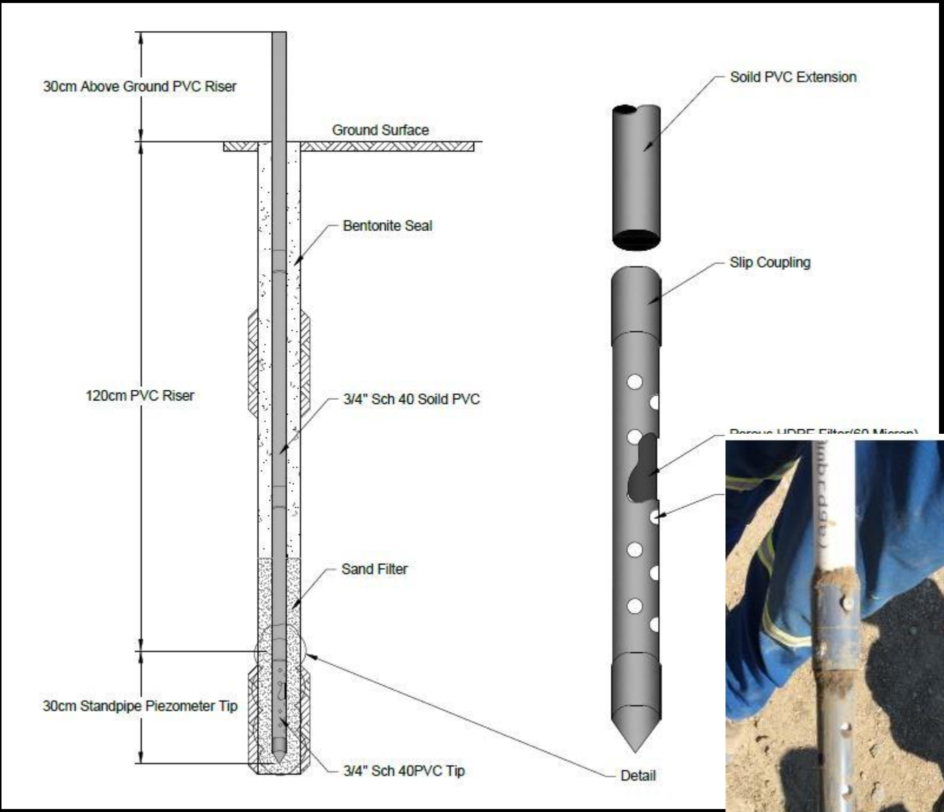


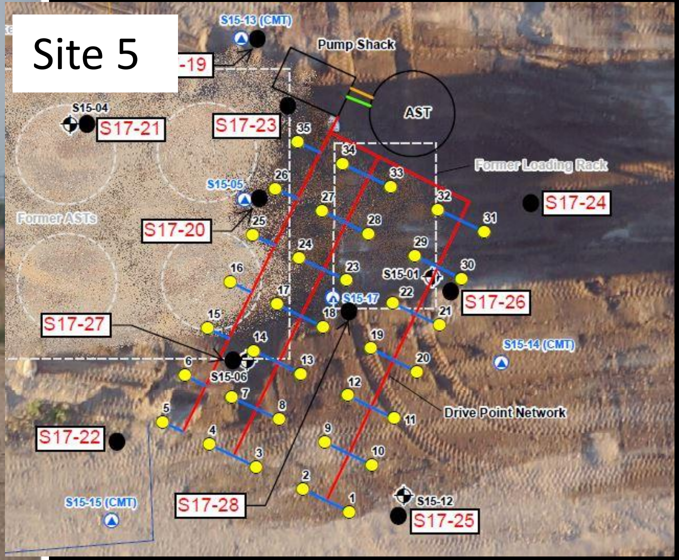




Two injection designs: Injectors/Infiltrators and **Drive-point networks**

Design intended for locations where there was a higher potential for a surficial release over a wider area.





Saskatchewan Case Studies

- Six impacted sites across Central and Southern Saskatchewan
- In situ biostimulation technology implemented for 1-5 years
- Sites had historical (>10 years) hydrocarbon impacts due to former pump islands, underground storage tanks, multi tank storage facilities on site
- Sites ranged between fine- and coarse-grained soils, depths of hydrocarbon impacts (1-7.5 meters), and depth of groundwater (1-4 meters)

Four key indicators of robust technology and design

- Groundwater nutrient monitoring
  - Are we pumping in too many nutrients to change natural groundwater concentrations?
- Monitoring delineation wells
  - Are we moving the contaminant plume?
- Soil electrical conductivity
- Soil contaminant concentrations
  - Has the variance (i.e., spread of contaminant concentration values) changed?

Four key indicators of robust technology and design:

Groundwater nutrients

Possible concern:

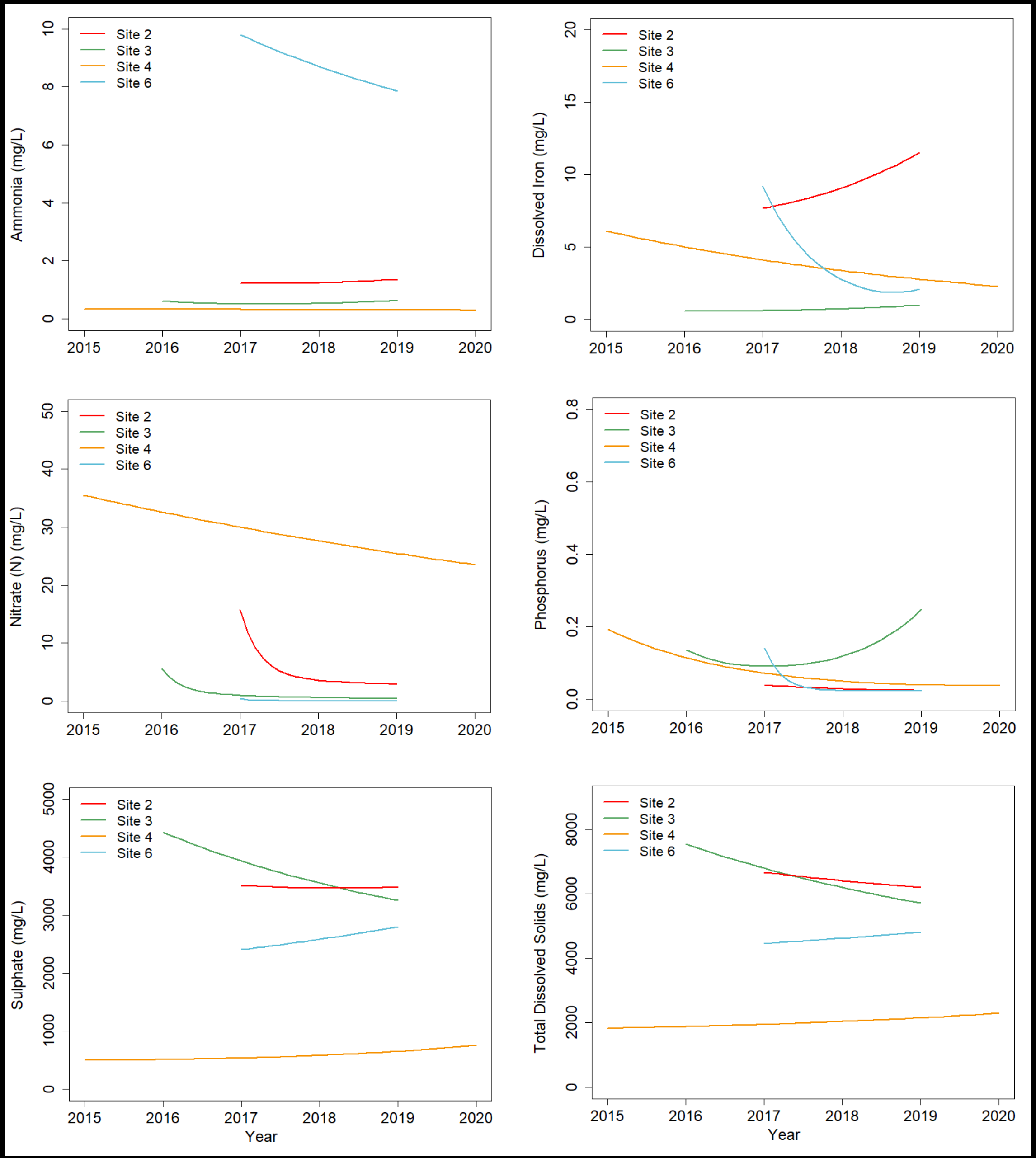
- Is our system pumping in high levels of nutrients that are increasing groundwater nutrient concentrations above guidelines?

Our approach:

- Amendment solution nutrients are injected at concentrations within the range of nutrients found on site.
- Dilution occurs once the solution enters the groundwater.

Have we been successful?

- **Yes!**
- We found no significant increases of amendment solution nutrients over the course of remediation at four core sites.

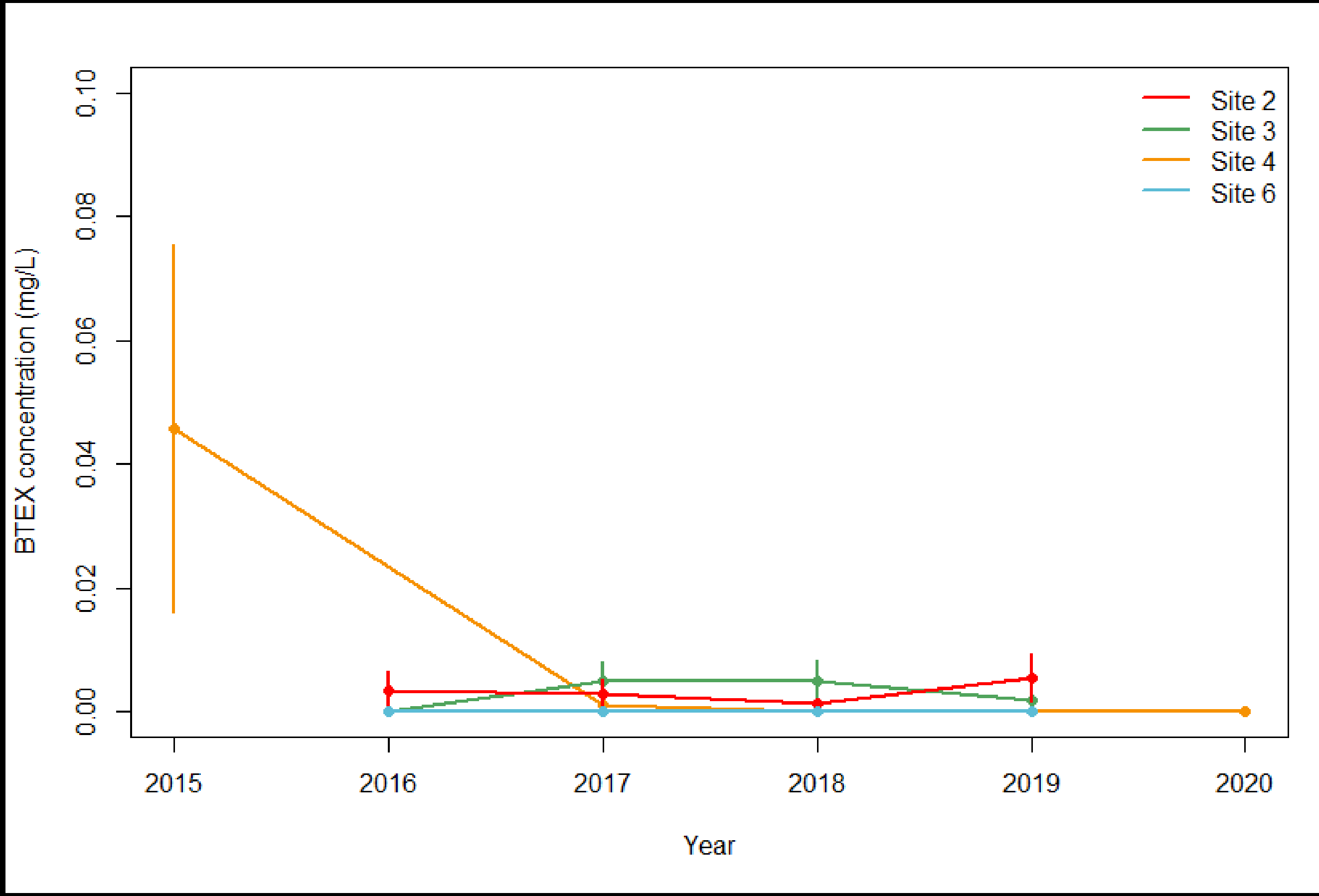


Four key indicators of robust technology and design: **Delineation wells**

Possible concern:
- Is our system increasing mobility of LNAPL?

Our approach:
- Technology is employed when the LNAPL plume is relatively stable or residual state.
- We inject the amendment solution at a slow rate (32 ml/min).

Have we been successful?
- **Yes!**
- No increase in LNAPL or dissolved BTEX concentrations observed over time in delineation wells.



Four key indicators of robust technology and design:

Soil electrical conductivity

Possible concern:

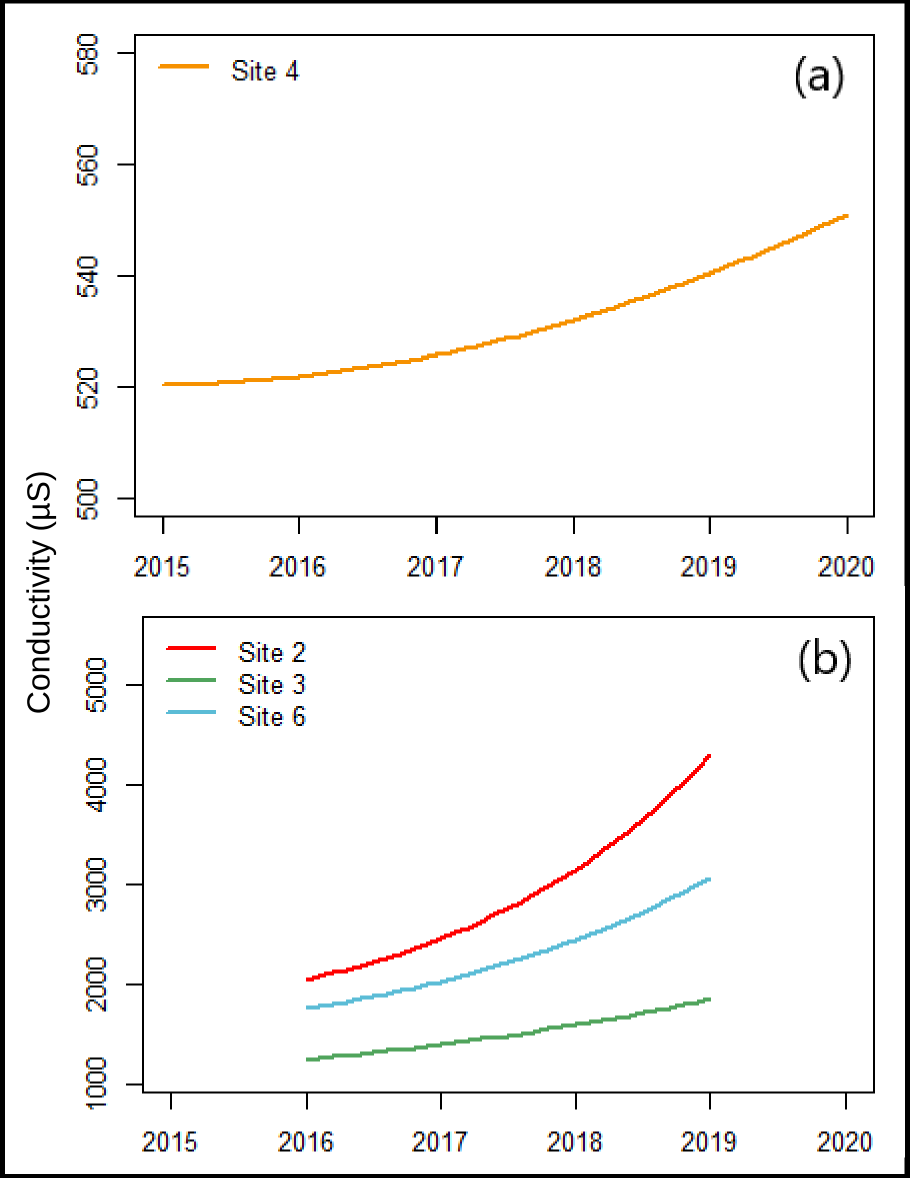
- Adsorbed in the soil?

Our approach:

- Slow injection rate of amendment solution should allow for nutrients to follow fractured flow and be made available to microbes throughout the impacted area.

Have we been successful?

- **Yes!**
- Electrical conductivity increased (from 6 – 109%, dependent on the site) after 4-5 years of remediation.



Four key indicators of robust technology and design:
Soil contaminant concentrations

Possible concern:

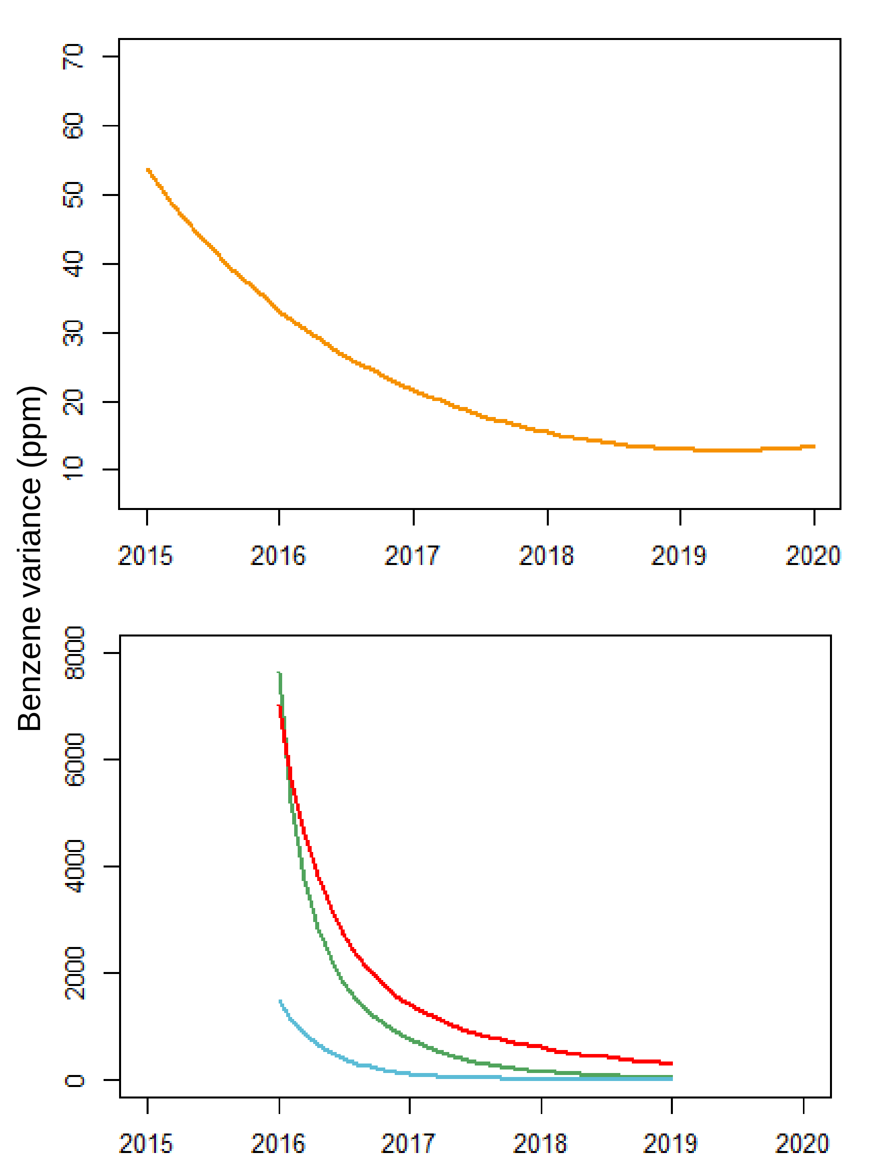
- High concentrations of soil contaminants?

Our approach:

- Slow injection rate of amendment solution should allow for nutrients to follow fractured flow and be made available to microbes throughout the impacted area.

Have we been successful?

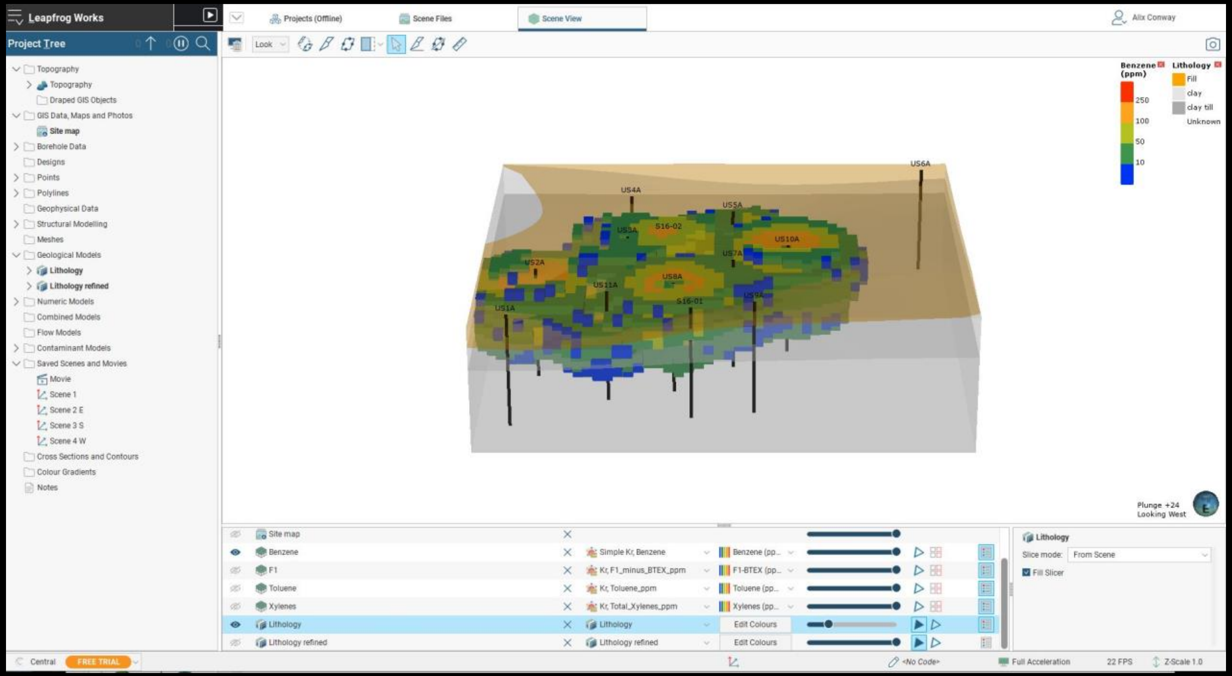
- **Yes!**
- Sharp reductions in soil benzene concentration variance, which reflects the spread of the data, is a strong indicator that hotspots have been reduced.



Quantifying remediation success

Soil analyses comparing pre- and post-remediation:

- Site-wide mean PHC concentrations
- PHC volume (LeapFrog Works)

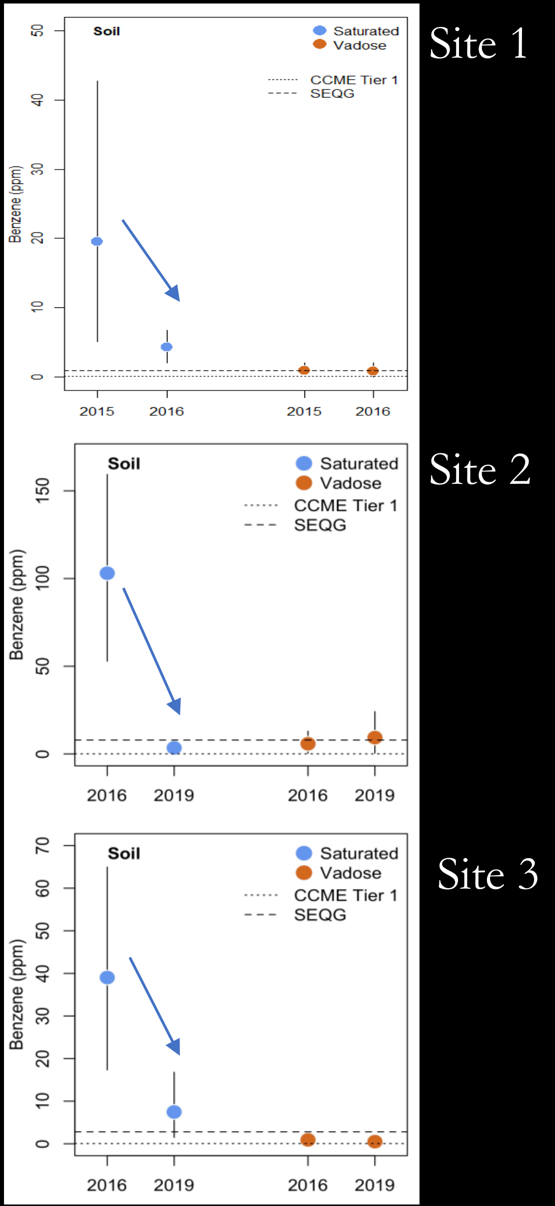


Groundwater analyses comparing pre- and post-remediation:

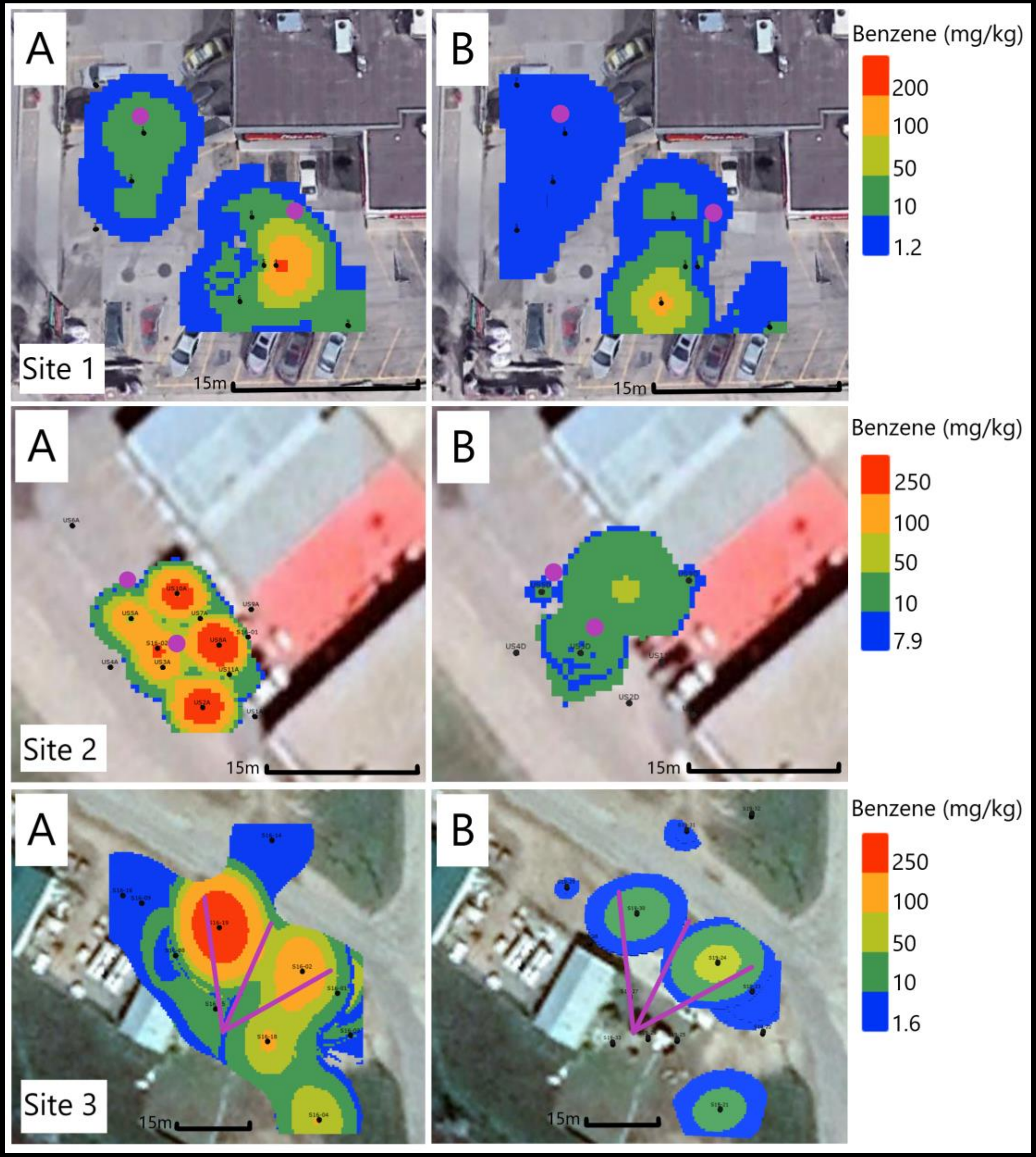
- Site-wide mean PHC concentrations

Quantifying soil remediation success

Site-wide mean



Areal extent and concentration



Volume and concentration

PHC volume (m³)			PHC maximum concentration (mg/kg)	
Pre-treatment	Post-treatment	Annual reduction	Pre-treatment	Post-treatment
74.5	44.3	**40.4%**	258.6	128.5

PHC volume (m³)			PHC maximum concentration (mg/kg)	
Pre-treatment	Post-treatment	Annual reduction	Pre-treatment	Post-treatment
261.8	31		2.9	123.9

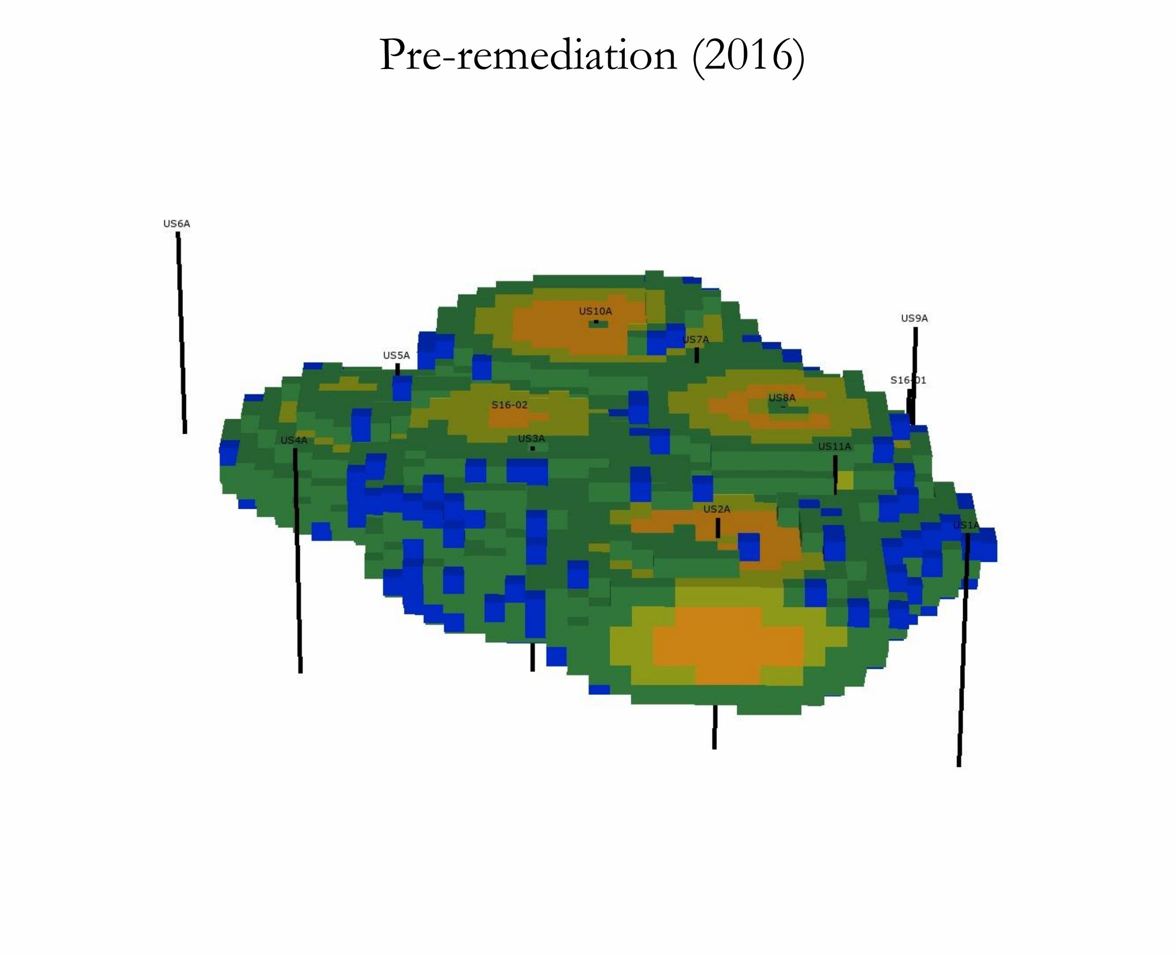
4 years = 88%

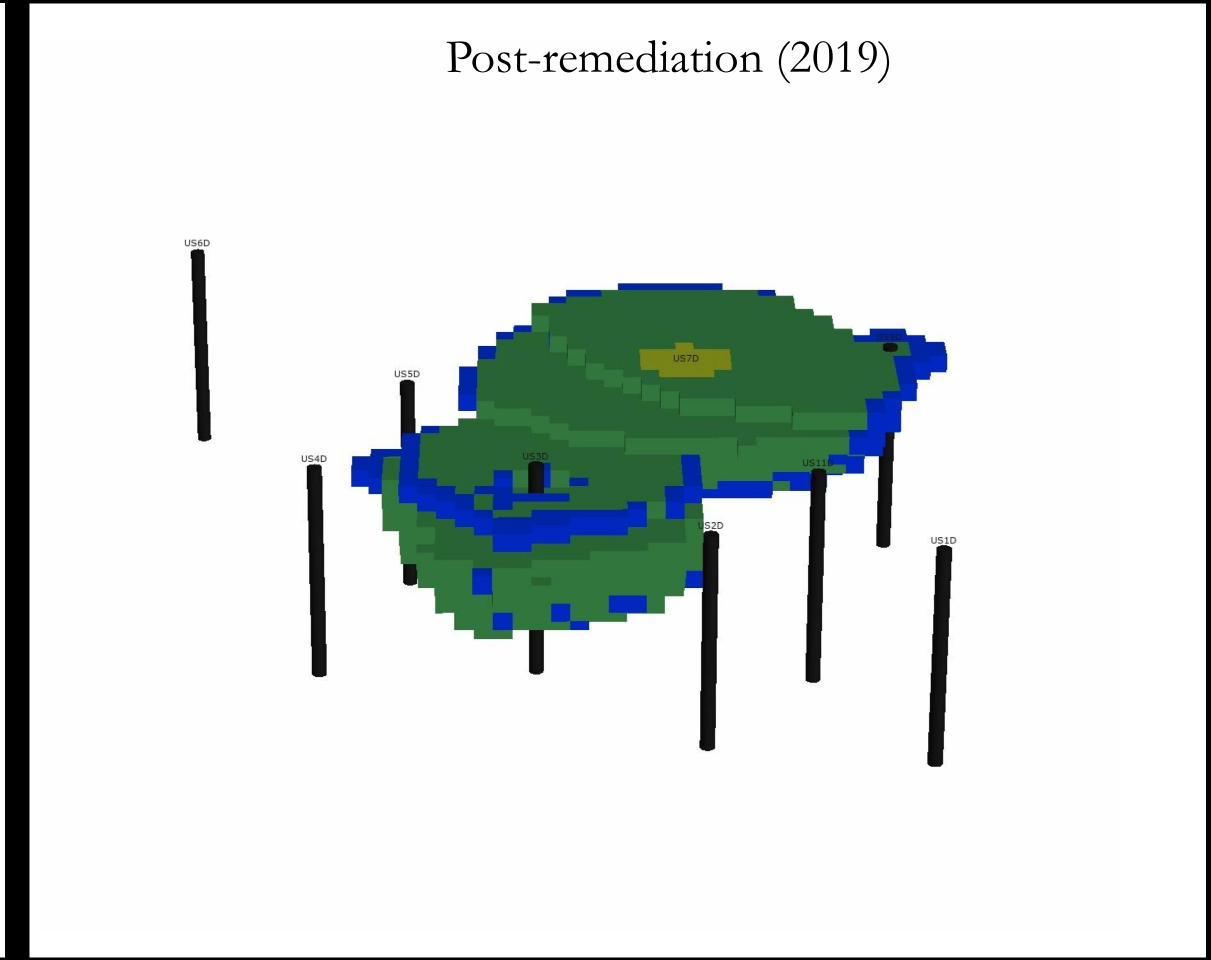
PHC volume (m³)			PHC maximum concentration (mg/kg)	
Pre-treatment	Post-treatment	Annual reduction	Pre-treatment	Post-treatment
988.1	14		.9	106.2

4 years = 86%

Quantifying soil remediation success

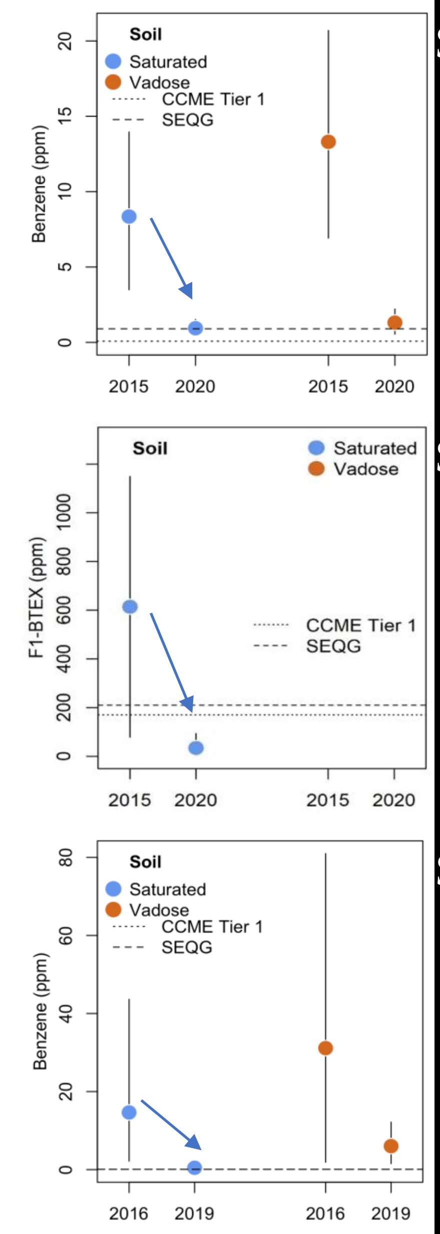
Site 2





Quantifying soil remediation success

Site-wide mean

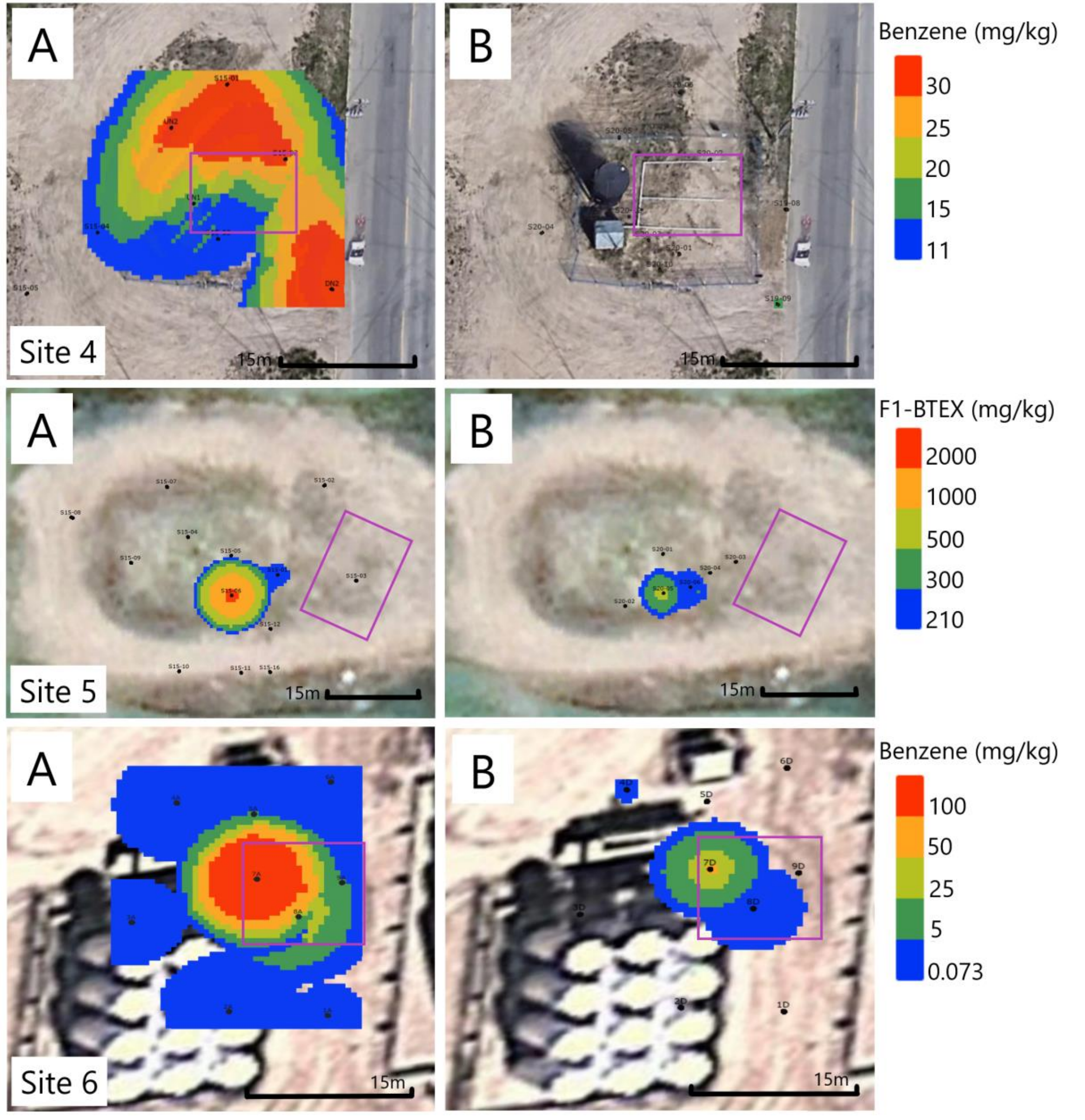


Site 4

Site 5

Site 6

Areal extent and concentration



Volume and concentration

Site 4

PHC volume (m^3)			PHC maximum concentration (mg/kg)	
Pre-treatment	Post-treatment	Annual reduction	Pre-treatment	Post-treatment
77.0	5 years = 99%		4.3	12.8

Site 5

PHC volume (m^3)			PHC maximum concentration (mg/kg)	
Pre-treatment	Post-treatment	Annual reduction	Pre-treatment	Post-treatment
762.2	3 years = 90%		16.7	650.0

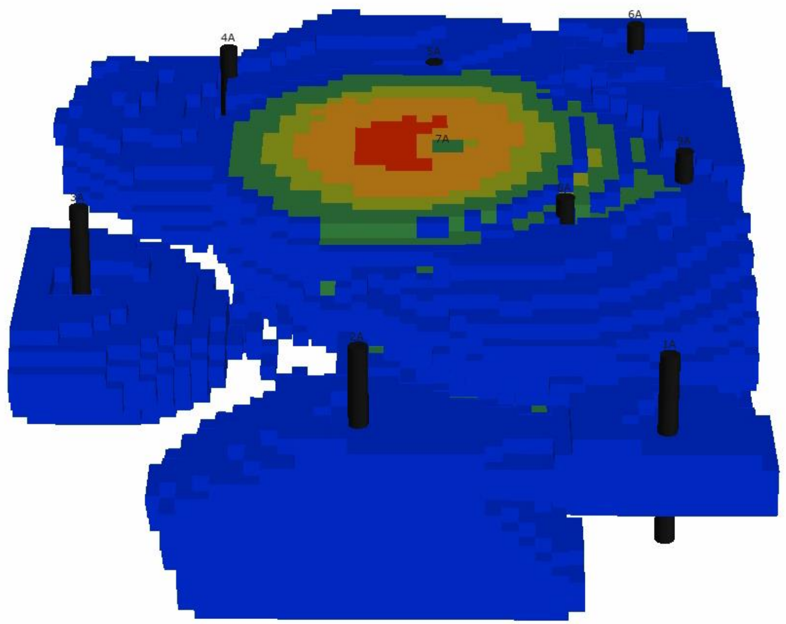
Site 6

PHC volume (m^3)			PHC maximum concentration (mg/kg)	
Pre-treatment	Post-treatment	Annual reduction	Pre-treatment	Post-treatment
432.2	4 years = 97%		709.1	75.9

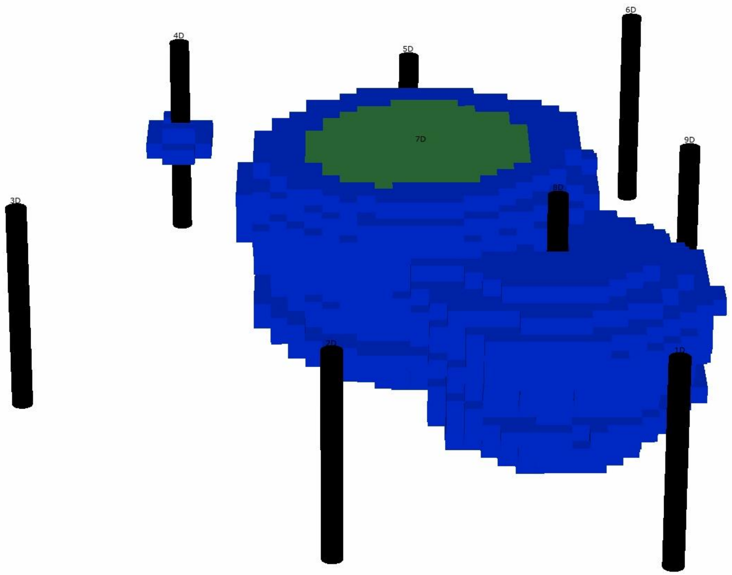
Quantifying soil remediation success

Site 6

Pre-remediation (2016)

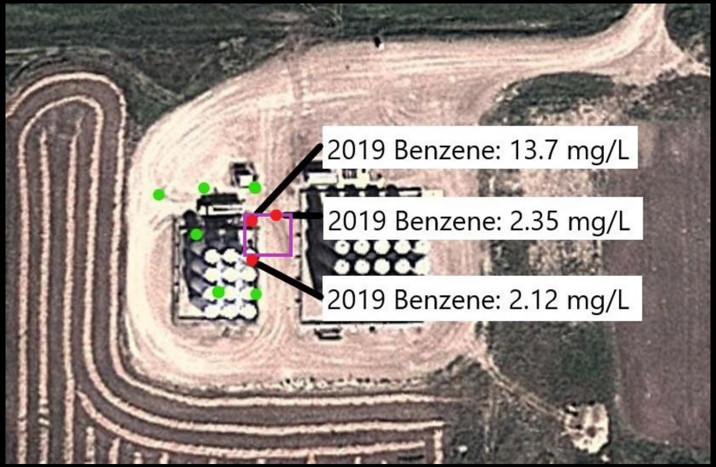


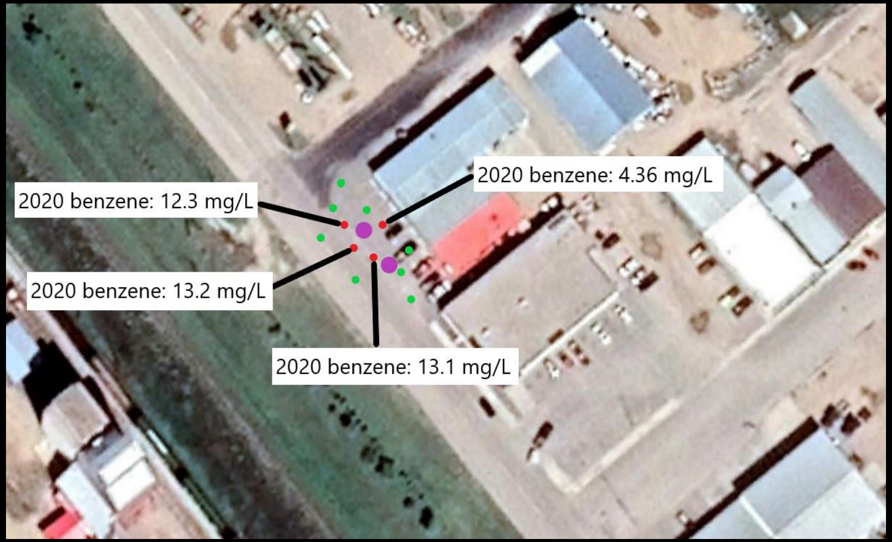
Post-remediation (2019)

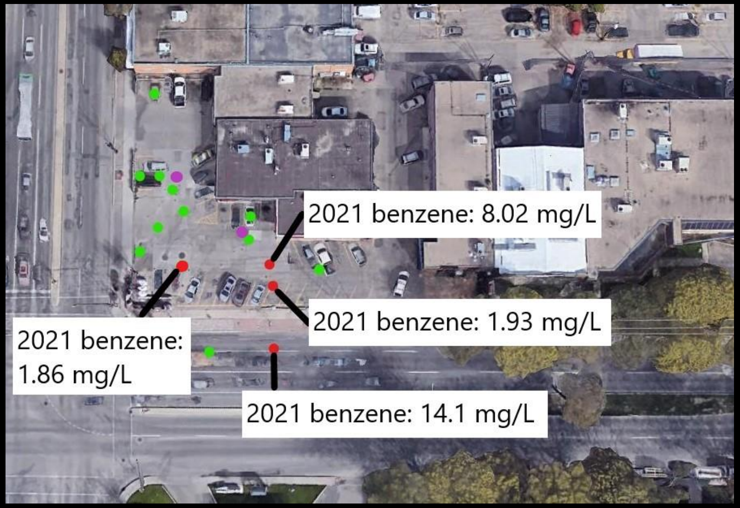


Quantifying groundwater remediation success

Site	Hydrocarbon	Mean (mg/L)		**P-value**	Maximum (mg/L)	
		Pre-treatment	Post-treatment		Pre-treatment	Post-treatment
1	Benzene	12.22	7.50	**0.51**	22.50	14.10
2	Benzene	3.40	5.91	**0.56**	7.98	13.20
3	Benzene	3.75	5.21	**0.59**	38.90	40.00
4	Benzene	6.47	2.03	**0.23**	27.00	6.40
5	F1-BTEX	0.10	<0.10	**NA**	0.34	<0.10
6	Benzene	7.61	3.88	**0.22**	24.76	15.00







Summary

- Successfully reduced hydrocarbon concentrations by > 90% at six sites across Saskatchewan.

- All six case study sites are ready for risk-based site closure supported by a site-specific risk assessment.

- With refinements and optimizations over the past 5 years, our technology has proven robust and is a sustainable and economically feasible remedial solution to manage impacted hydrocarbon sites.

Acknowledgements

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Key References

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