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Characterization and Remediation of Diesel in a Fractured Rock Aquifer with a Nutrient-Flushing System

Presentation by David Thomson and Stefan Humphries

Authors and Collaborators

- Presenting Authors
  - Stefan Humphries and David Thomson
- WorleyParsons Komex
  - M. Brown, J. Armstrong, B. Reiter
- University of Calgary
  - K. McLeish [Ph.D.]
  - Dr. J. Foght
- Environment Canada
  - P. Bacchus

Outline

- SITE BACKGROUND and CONCEPTUAL MODEL
- PHYSICAL HYDROGEOLOGY
- GEOCHEMICAL AND MICROBIOLOGICAL EVIDENCE OF NATURAL ATTENUATION
- NUTRIENT-AMENDED REMEDIATION SYSTEM

Site History

- 1982 – diesel invert mud used to drill gas well; well kicked mud across lease and adjacent land
- 1996 - diesel impact to groundwater, drilling sump excavated
- 1996-2007 – extensive site characterization, remedial pilot tests

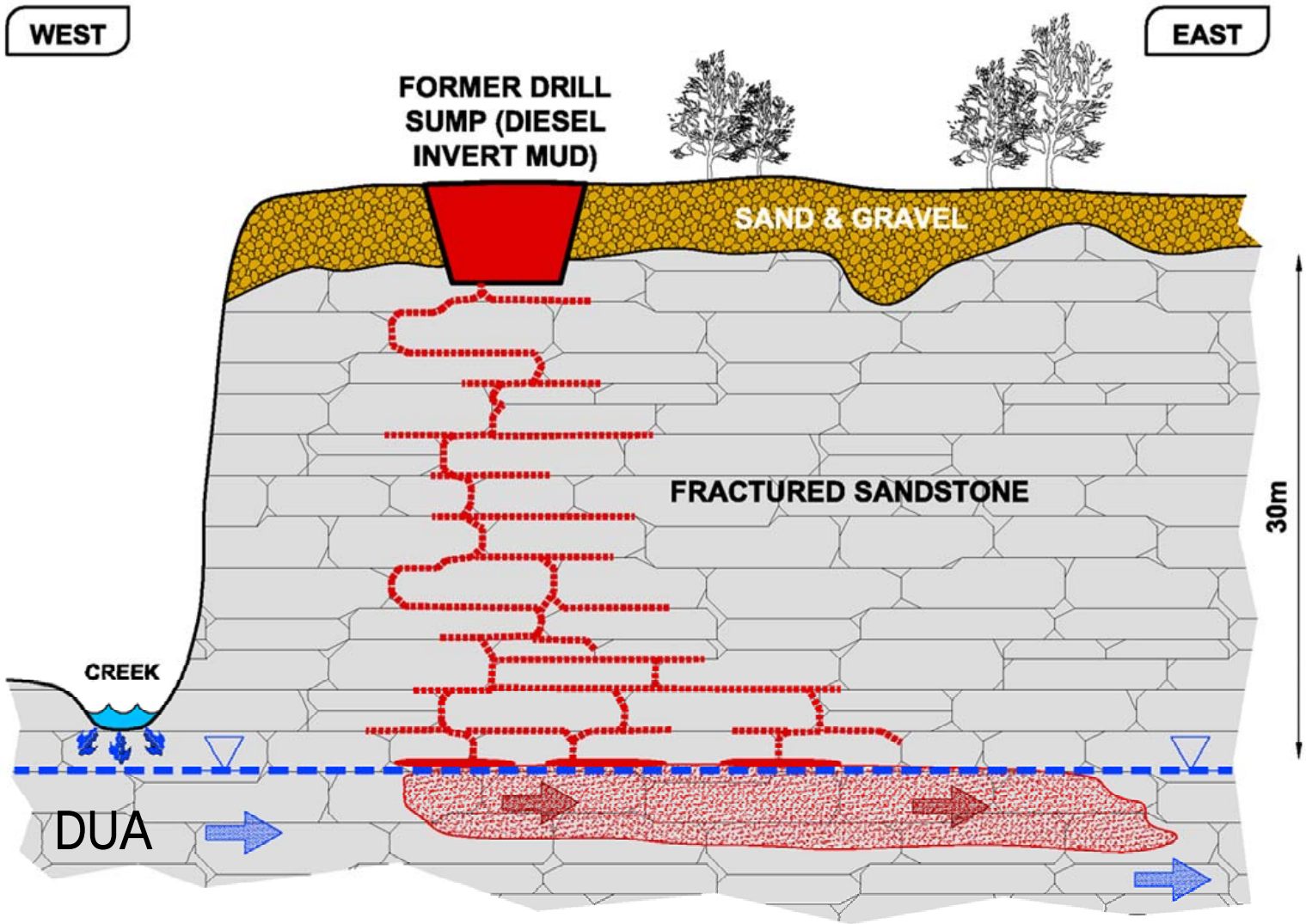
Contaminant characterization

- Contaminant characterization
  - Residual hydrocarbons from the former drill sump
  - Free product and dissolved-phase impacts
  - Typically TEH C_{11} to C_{27}
  - PHC F2 ($C_{>10}$ to C_{16})
  - Negligible salts or metals signature

Site Hydrogeology

- Surficial geology:
  - Thin sand/gravel outwash or till unit (0-3 m)
- Bedrock:
  - Cretaceous fractured sandstone
- Upper Groundwater Bearing Zone (UGBZ)
  - 30 mbgs, within fractured sandstone unit
- Complex Groundwater flow
  - Gradient to NE, fracture control mainly to SE
- Dissolved-phase plume stable [approx. 300 m long]
- Strong indication of ongoing Natural Attenuation

Conceptual Hydrogeology



Importance and Relevance

- Domestic Use Aquifer (DUA) impacted
- Multiple landowners with wells
- Difficult hydrogeological conditions

Characterization Techniques

- Monitoring of 60+ piezometers
  - Annual groundwater monitoring for routine and MNA parameters
  - Dissolved gas sampling
  - Passive Skimmers for product
- Characterization
  - Pilot-scale grid of 12 open boreholes
  - Aquifer pumping test
  - Straddle packer tests
  - Bromide tracer
  - 4 angled coreholes
  - Pilot testing
  - Geophysics
  - Core fracture mapping

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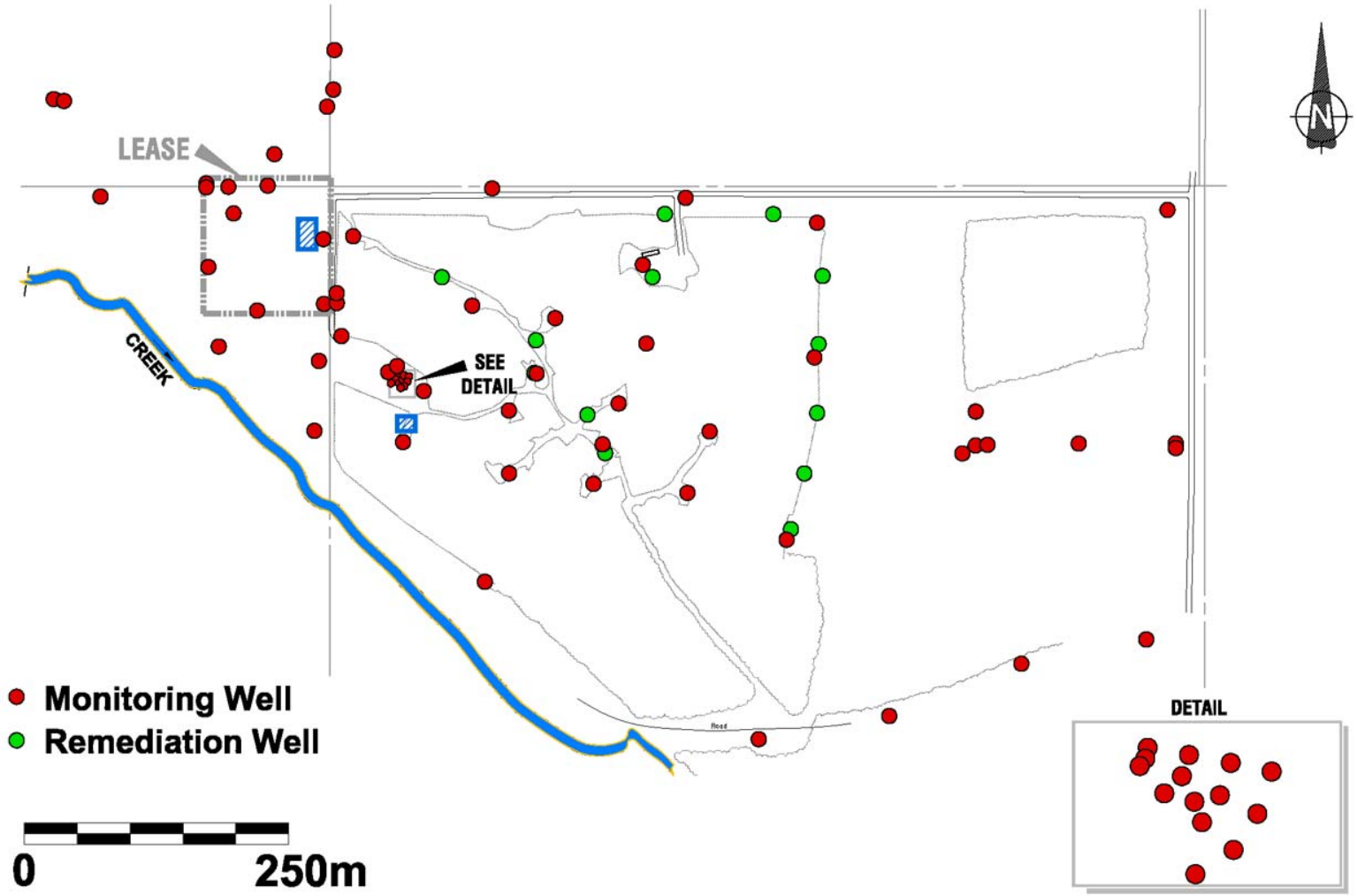
Site Plan



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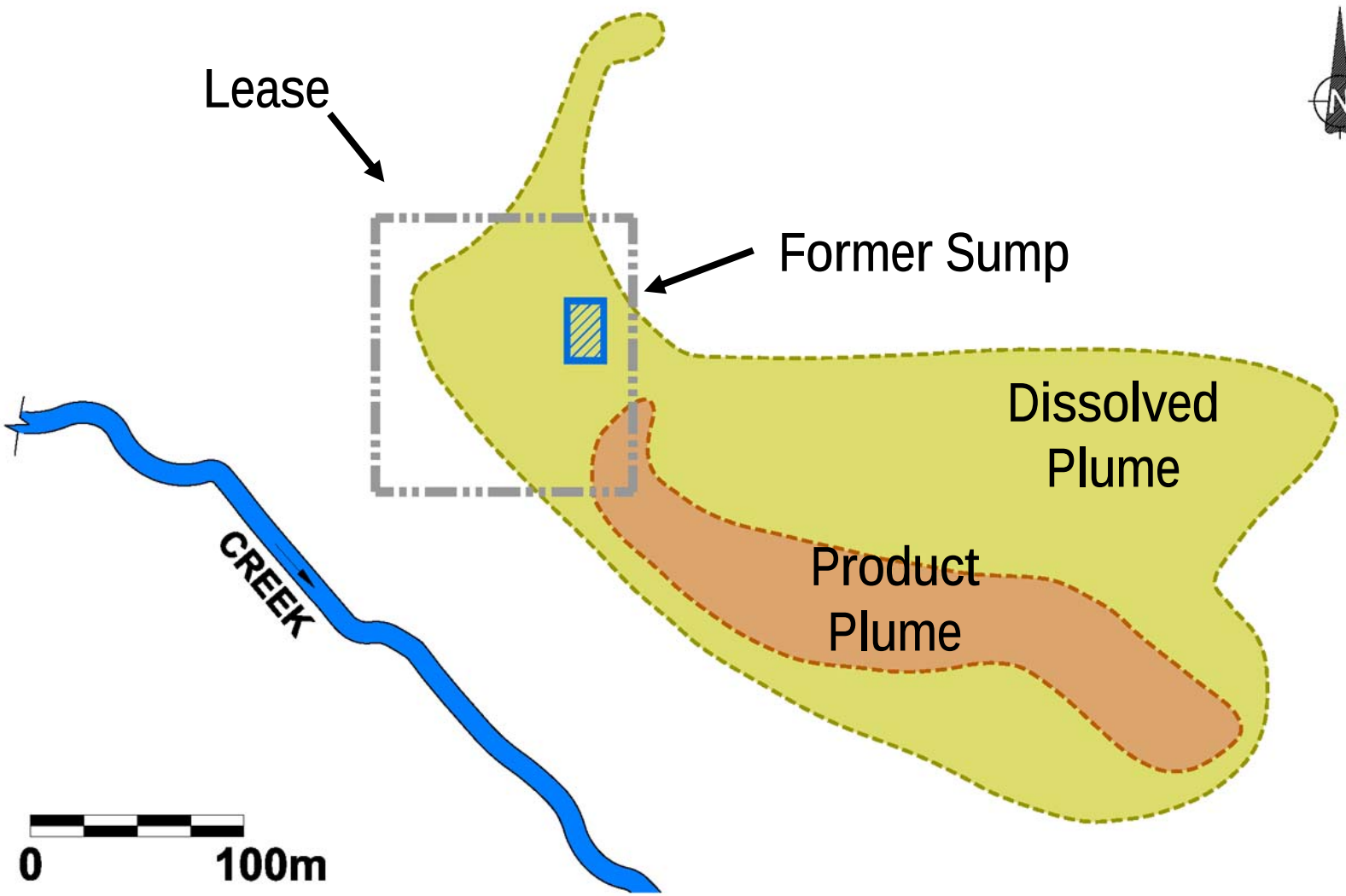
NAPL versus Dissolved-Phase



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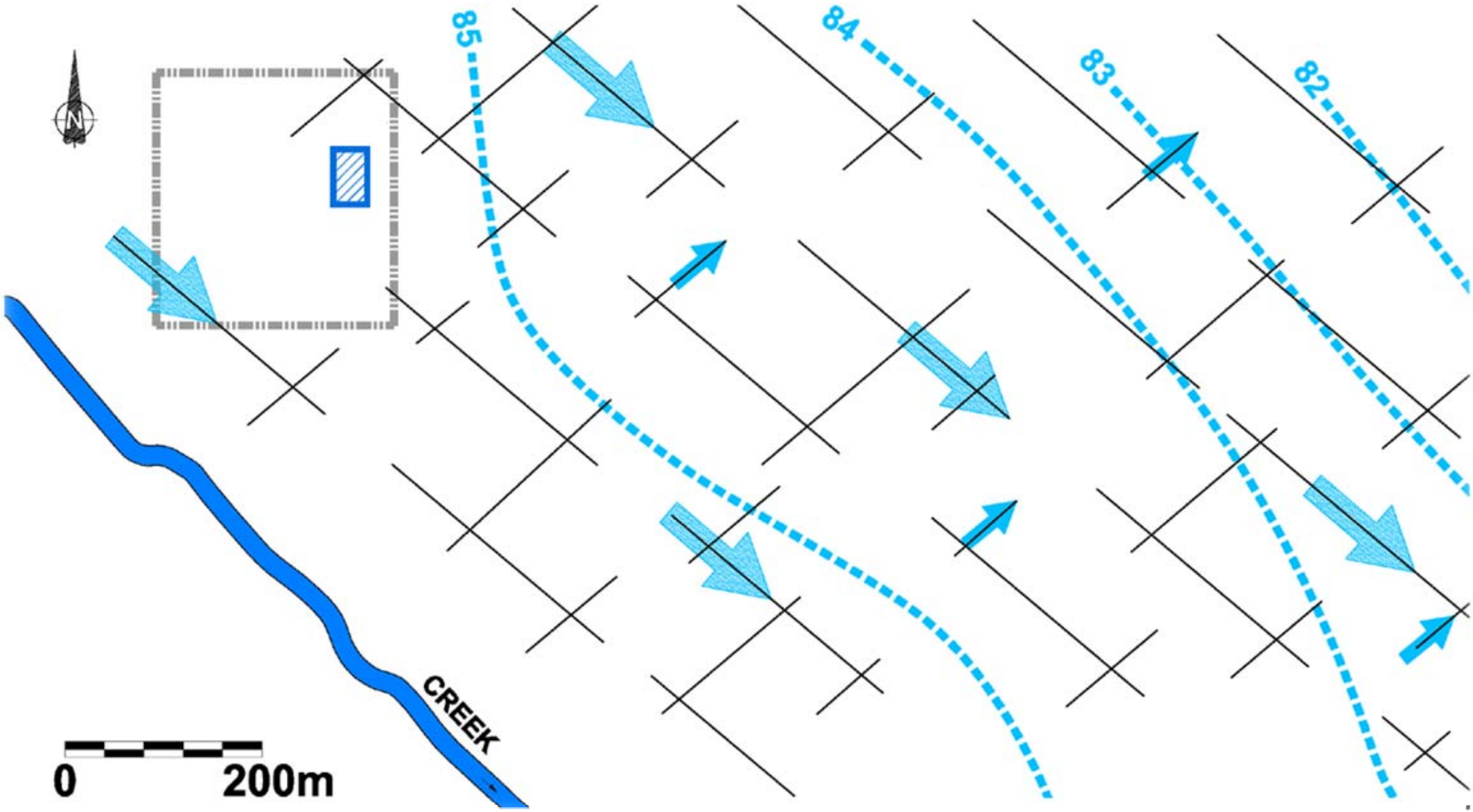
Fracture Control – Transport Mainly to Southeast



Background

- Fracture-controlled system with offset plume axes
- Dissolved-phase and product-phase plumes are spatially and temporally stable
- Strong evidence of natural attenuation
  - Geochemical indicators
  - Stable plume

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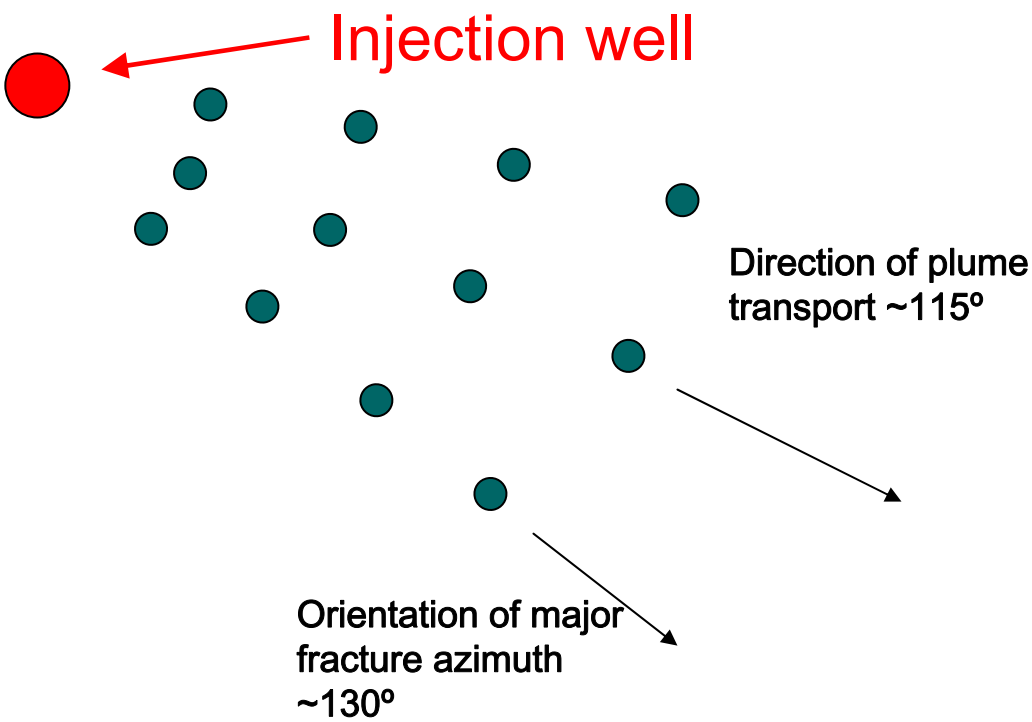
Characterization for Remediation

- Pilot-scale grid of 12 open boreholes to investigate complex flow system

- Detailed physical characterization via:
  - Aquifer pumping test
  - Bromide tracer
  - Straddle packer tests
  - Core fracture mapping

Pilot-scale Test Area

- 12 closely spaced boreholes [4 cored]
- Oriented along major fracture azimuth



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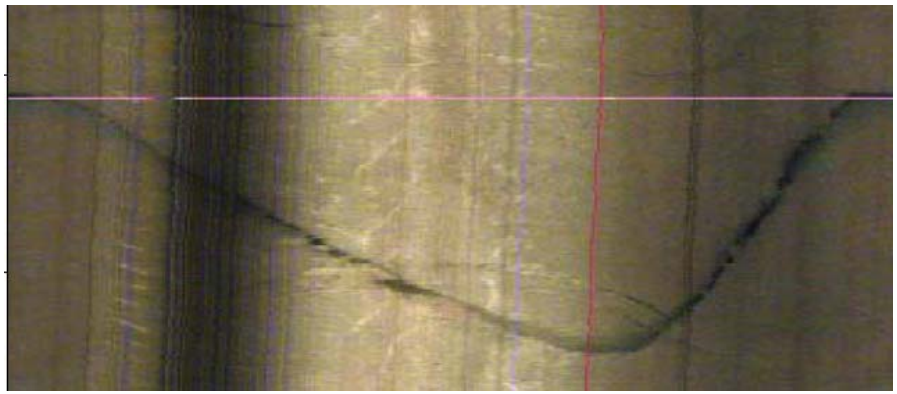
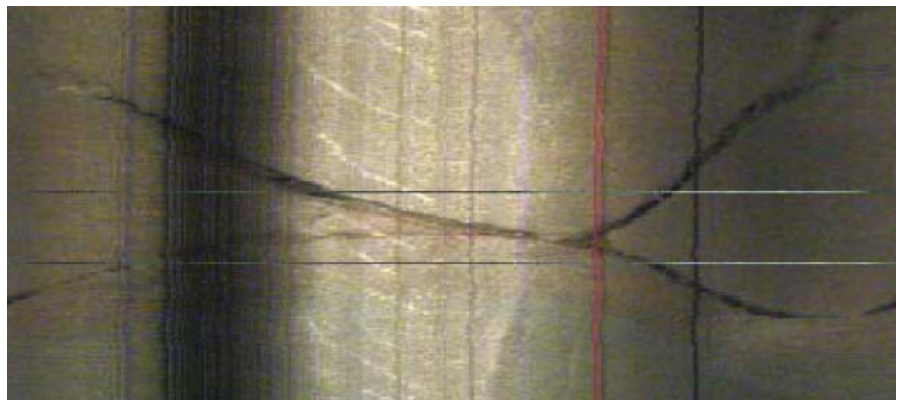
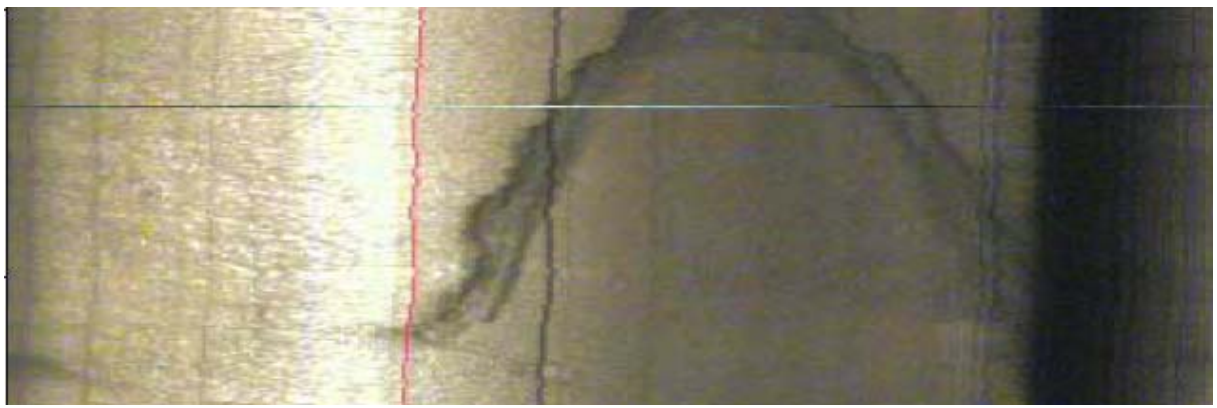
Bedrock Coring – Fracture and Oxidation Halo

Optical Televiewer Images





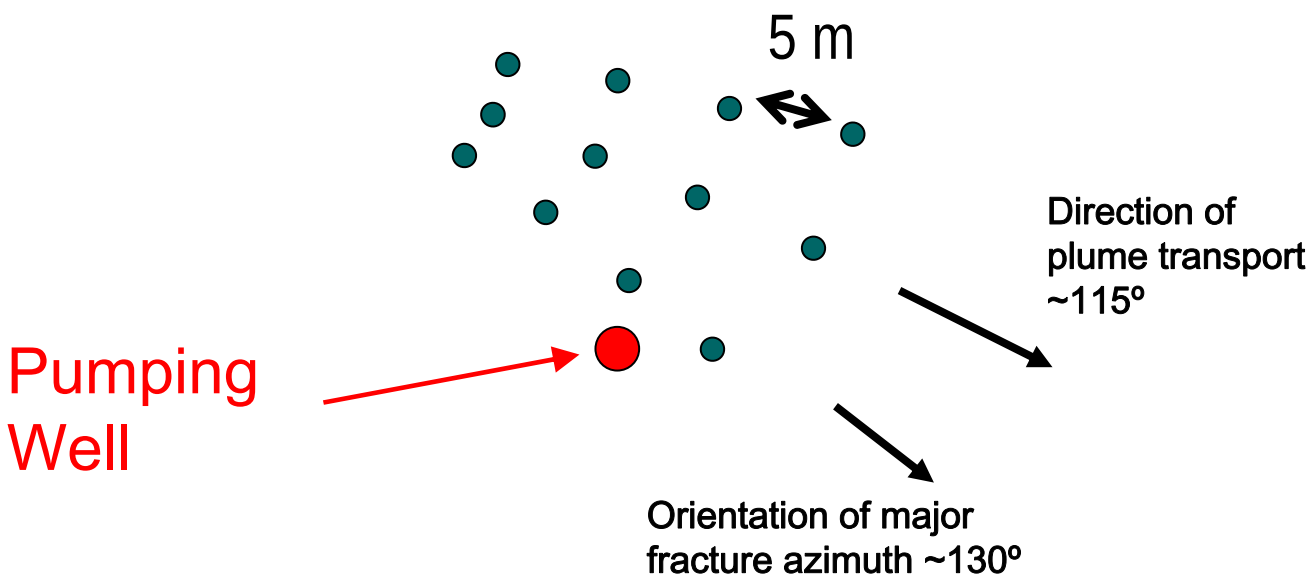


Fracture characterization

- High-angle jointing [>60 degrees]
  - Orientation approximately 130 degrees
- Sub-horizontal bedding planes [<30 degrees]
- Matrix Permeability
  - Permeability, porosity, grain density, pore throat radius
  - No differences between grey and brown sandstone
- Permeability is orders of magnitude less than bulk rock

Pumping Test

- 48 hour pumping test at 5 gpm [18.9 lpm]
- Max. 12 cm drawdown in pilot-scale test area versus 2.5 m drawdown in PW
- Transmissivity estimates 7 to 30 m^2/day

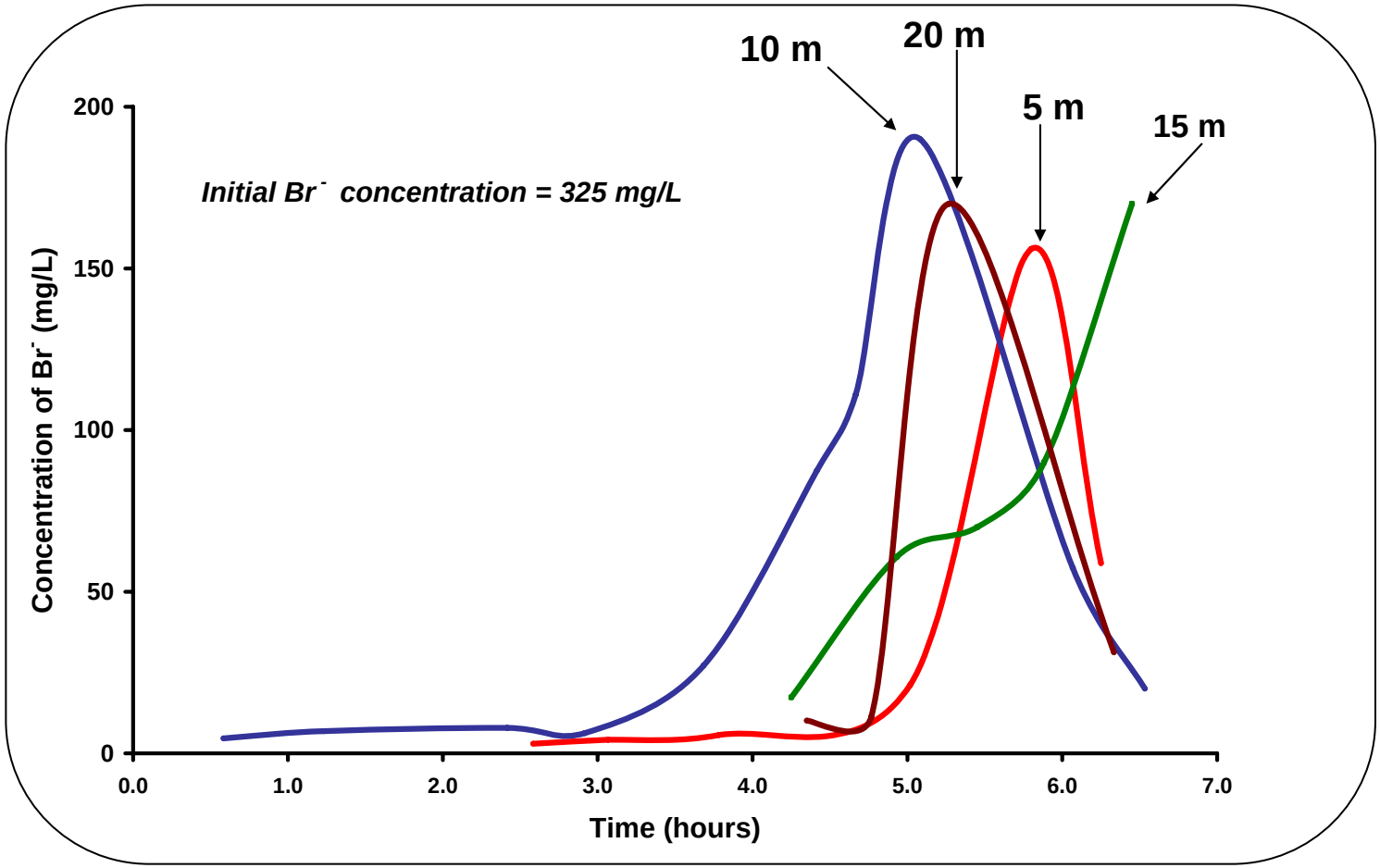


Bromide Tracer Test

- Experimental setup
  - Injection solution of 900L of formation water containing 325 mg/L bromide
  - Tracer injection at 1 gpm
  - Injection lasted approx. 90 minutes

Bromide Tracer Test

- Define solute transport & fracture interconnection



Results: 2004 Tracer Test

- Fastest bromide travel time approx 5 hours [for one 10m and one 20m borehole]
- Apparent tracer velocity 50 m/day
- Good results – let's add nutrient next year

2005 tracer/nutrient injection

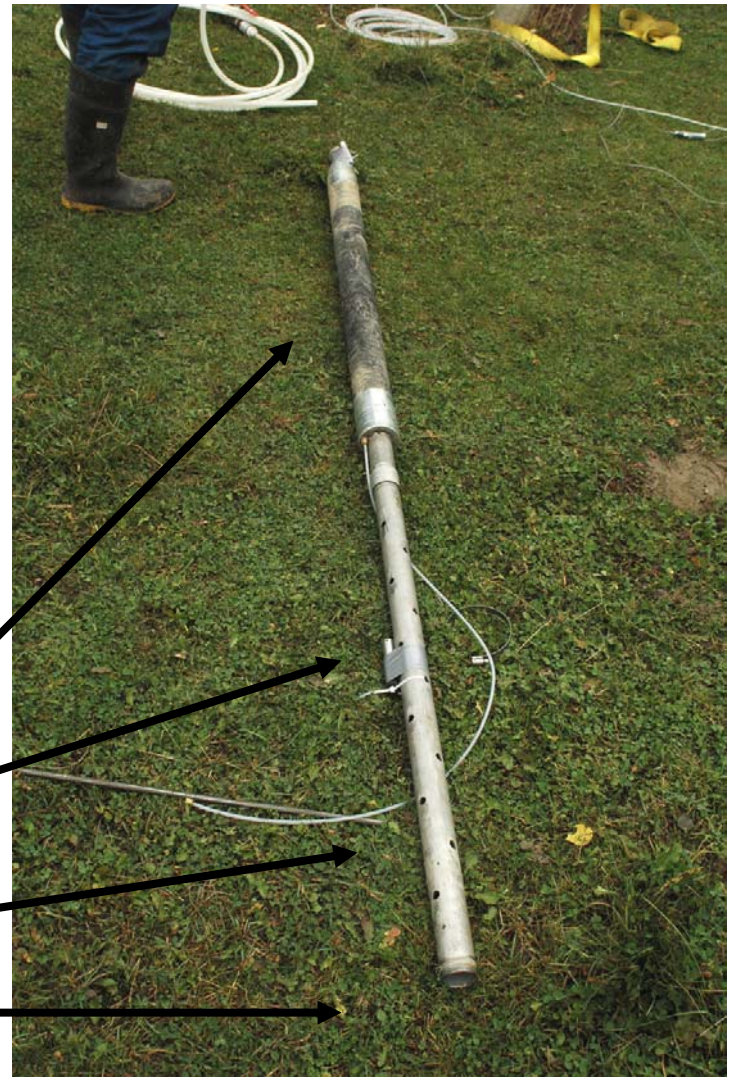
- Result: We couldn't find the tracer

- Why?
  - Excess precipitation in 2005 led to several metres increase in groundwater elevation
  - Likely that new flowpaths were accessed with higher water table
  - Variable hydraulic conductivity with depth

- Conduct packer tests to determine variability in hydraulic conductivity with depth

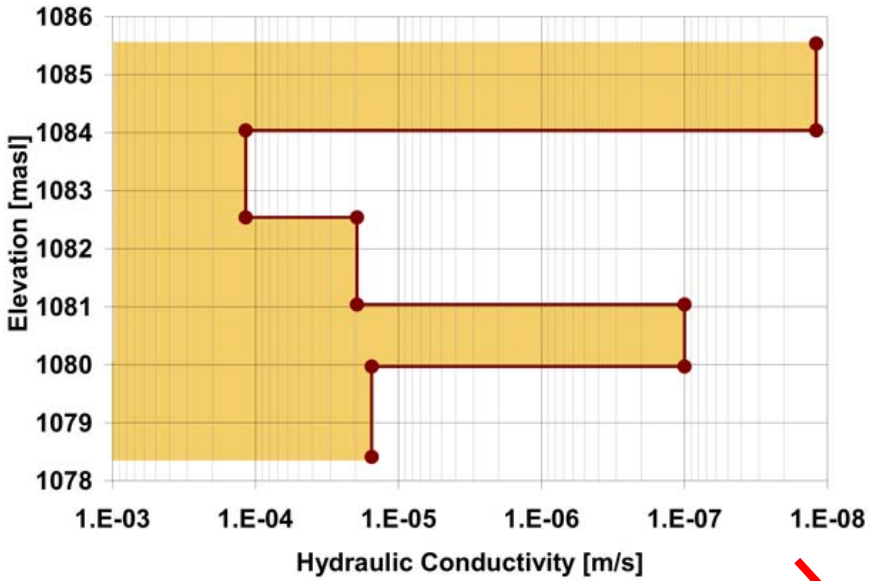
Straddle Packer Tests

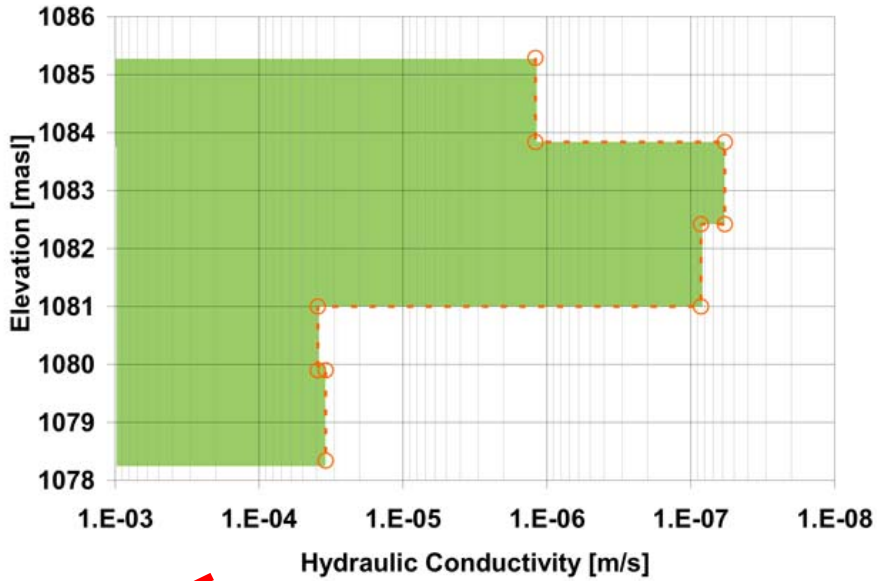
- Experimental setup
  - One 1.5m screen with two ~1m packers
  - Pressure transducers inside screen and above/below packers
  - Constant-head and falling-head tests on 6 open boreholes

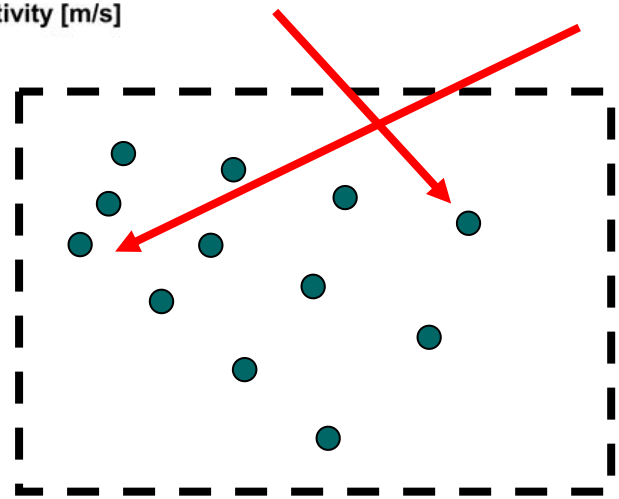


Straddle Packer Tests

Straddle Packer Results







Straddle Packer Results

- More than 4 orders of magnitude change in hydraulic conductivity over small vertical intervals
- Upper portion of saturated interval generally more conductive
- No definitive correlation with fracture mapping results

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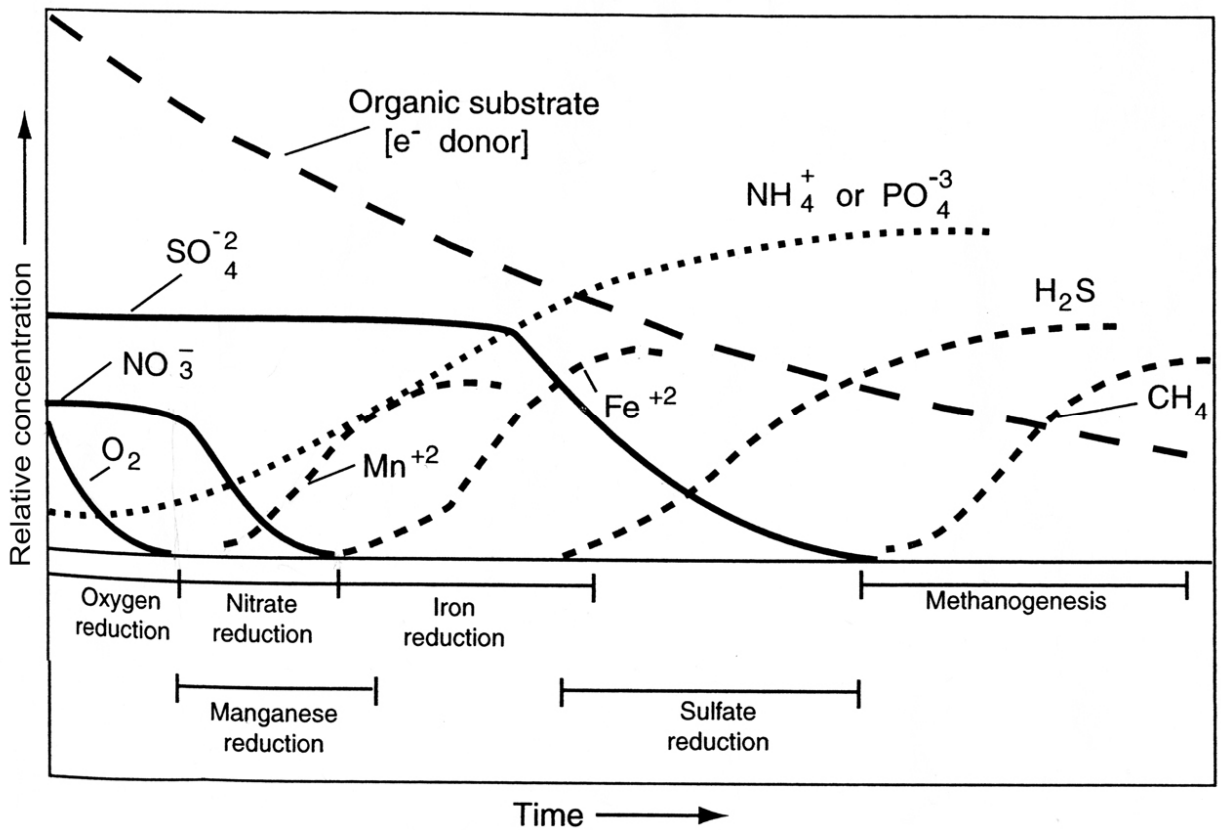
Natural Attenuation Indicators

- Aerobic Biodegradation: Oxygen = electron acceptor
- Anaerobic Biodegradation: Absence of oxygen
  - Redox Sequence: $NO_3^- \rightarrow Mn^{4+} \rightarrow Fe^{3+} \rightarrow SO_4^{2-} \rightarrow CO_2$



Mitsch and Gosselink (2000)

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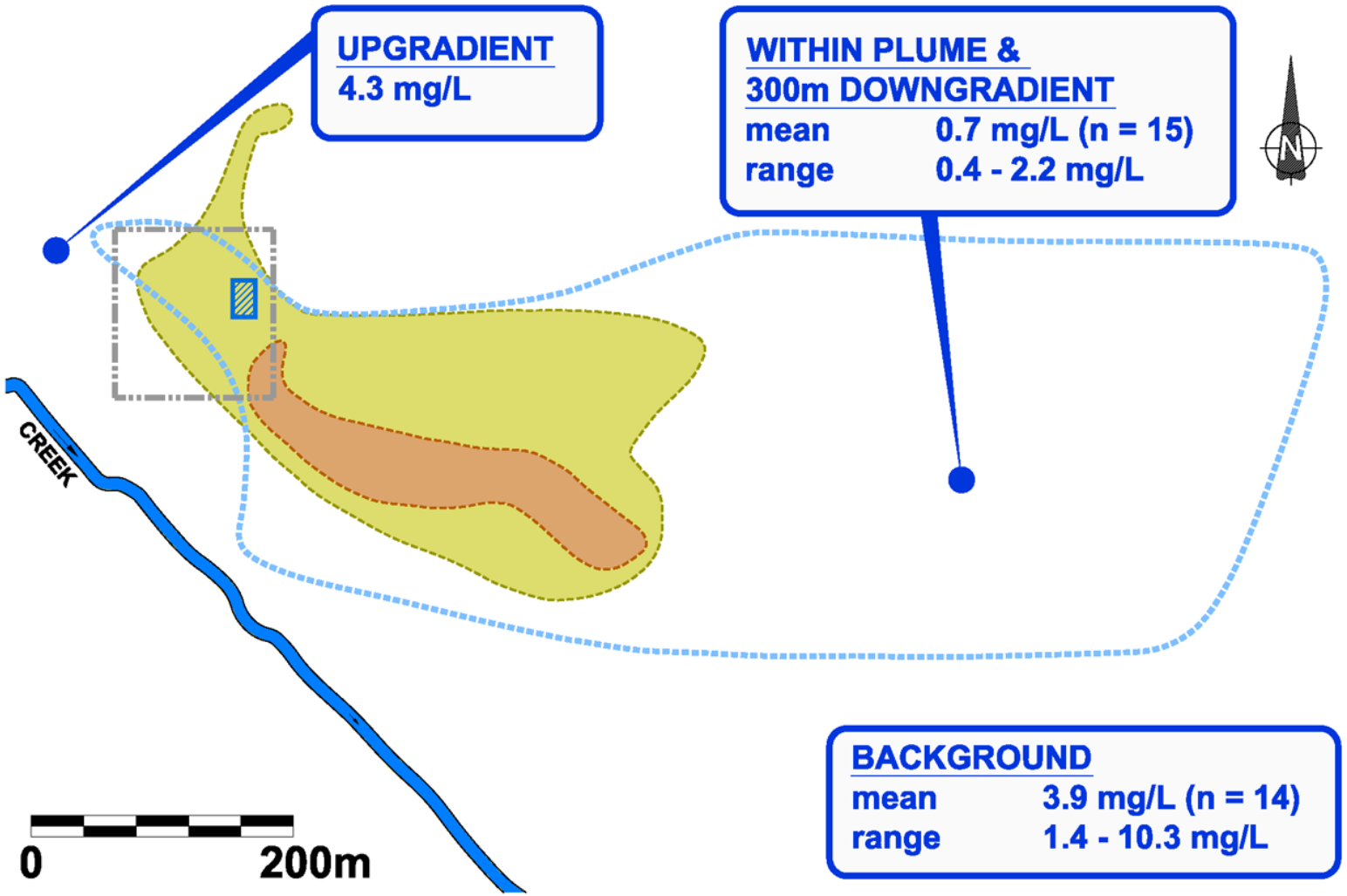
Zone of Depleted Dissolved Oxygen



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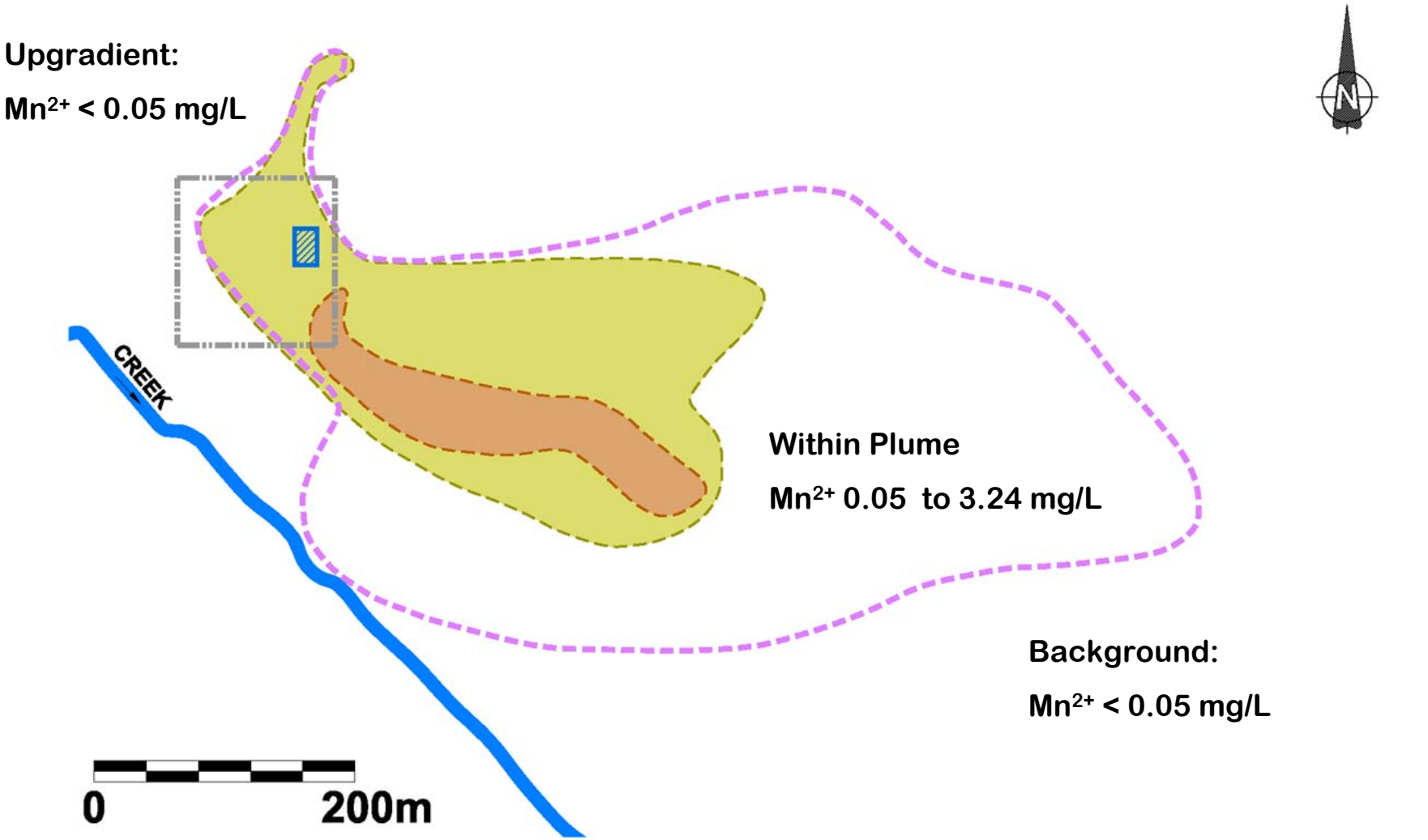
Zone of Enriched Manganese



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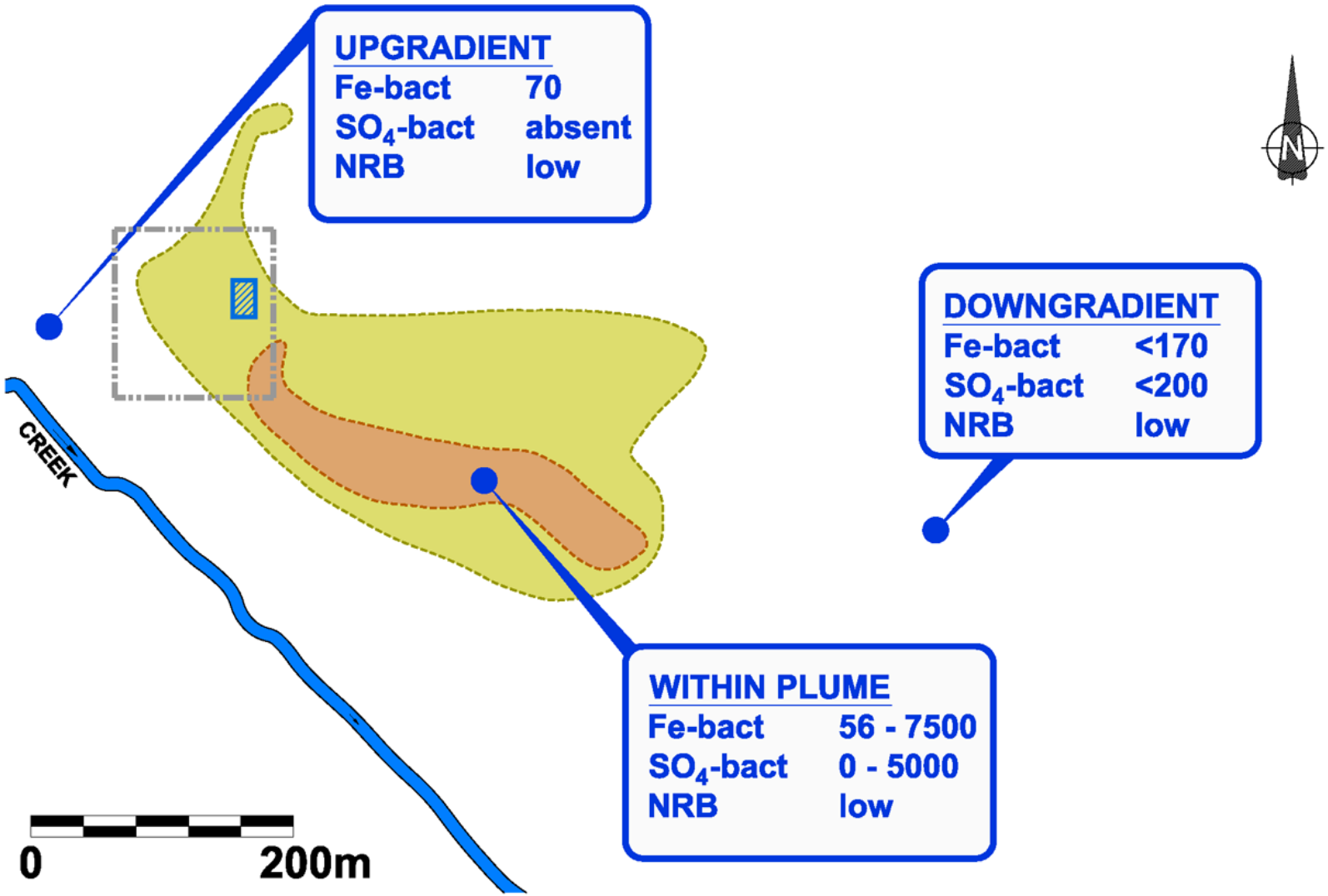
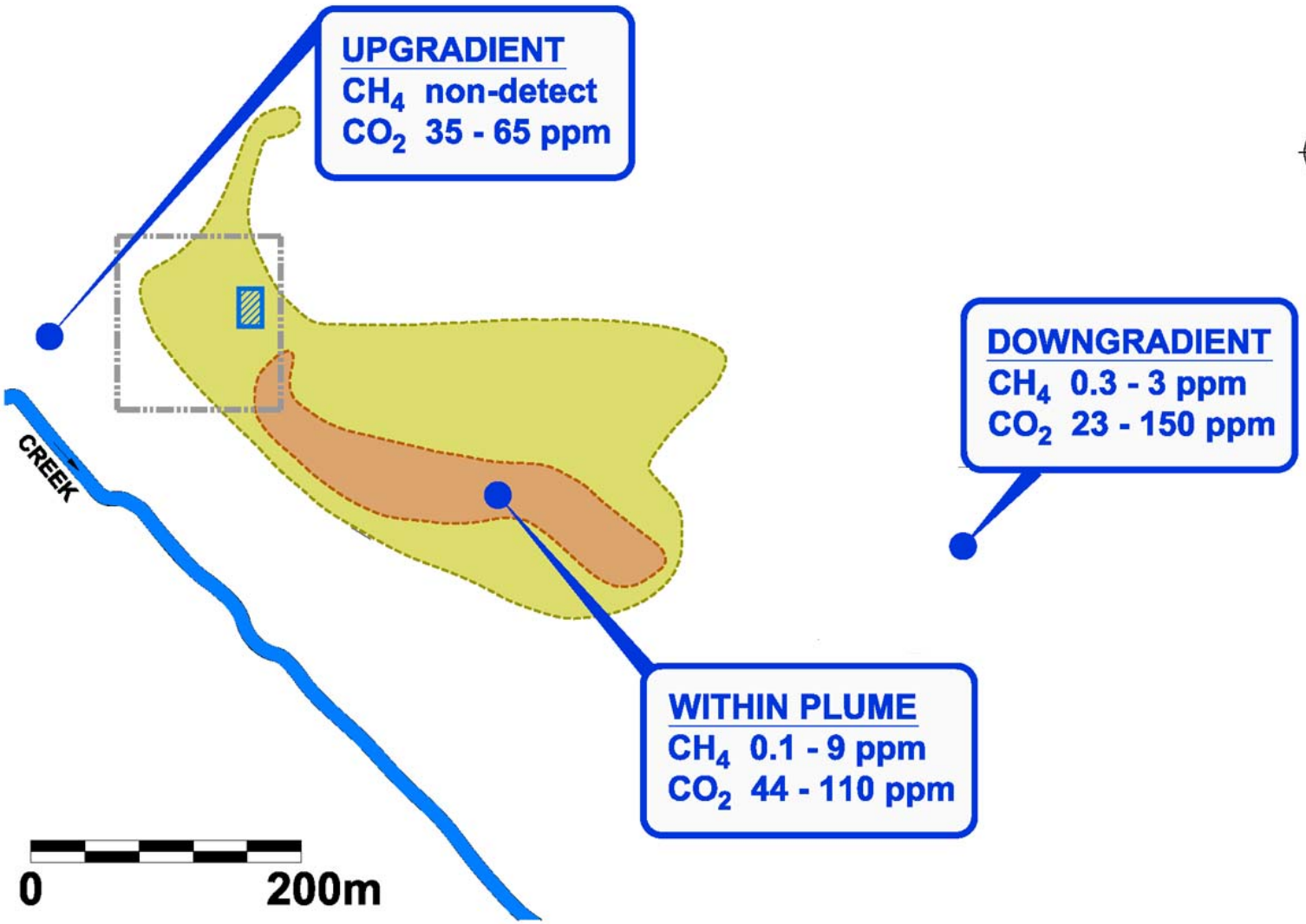
Monitoring Results: Bacterial Populations



Dissolved Gases



Lines of Evidence (EPA): Natural Attenuation

- Historical Geochemical Database Showing Plume Stabilization

- Contaminant and Geochemical Analytical Data Showing Biodegradation
  - High to very high levels of Fe, Mn, and low levels of NO_3 within the plume

- Microbiological Laboratory Data
  - High counts of Fe- and SO_4-reducing bacteria within the plume and at the periphery
  - ↑ microbiological activity within plume

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Remediation limitations

- Traditional hydrocarbon recovery methods limited by:
  - Depth of impacts
  - Complex fractured media
  - Discontinuous distribution of hydrocarbons
  - Low volatility of contaminant

Enhanced Biodegradation

- Natural biodegradation confirmed in field

- Laboratory bench-scale biodegradation experiments
  - Nutrient amendment experiments at University of Alberta
  - Cross, Biggar et al. (J. Env. Eng. manuscript)

Lab Scale Microcosms

- Anaerobic TEH (C_{11} to C_{27}) Degradation

Microcosm	Temperature (deg C)	Estimated Half-Life (yrs)
No amendment	**10**	**3.8**
Sulphate amended	**10**	**3.2**
Nitrate amended	**10**	**1.9**
Nutrient mix amended	**10**	**1.2**

Nutrient Amendment Proposal

Parameter	Target (mg/L)	Drinking Water Guideline (mg/L)
Nitrate (NO3 as N)	**8**	**10**
Sulphate (SO4)	**200**	**500**
Phosphate (PO4 as P)	**3**	**- -**
Ammonium (NH4)	**10**	**- -**
Potassium (K)	**30**	**- -**
Chloride (Cl)	**20**	**250**

Permission from AENV

- Several conditions related to input values to DUA
- Hydraulic controls to ensure no uncontrolled migration (*i.e.,* forced gradient best)

Tracer & pilot testing

- Confirm flowpaths & velocity by conservative tracer
- Ensure quality control of nutrient solution

  (*i.e.,* impurities in commercial fertilizers)

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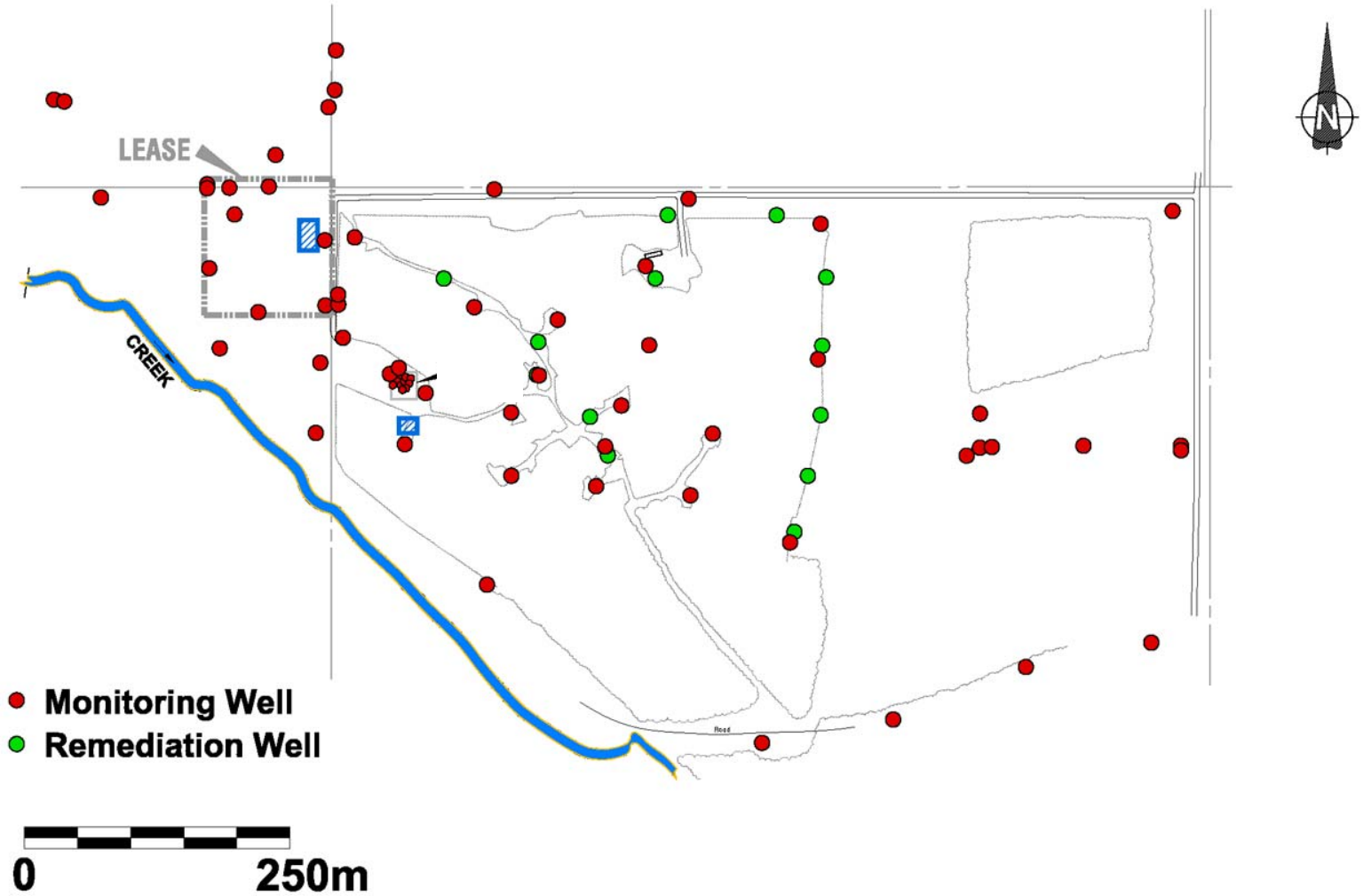
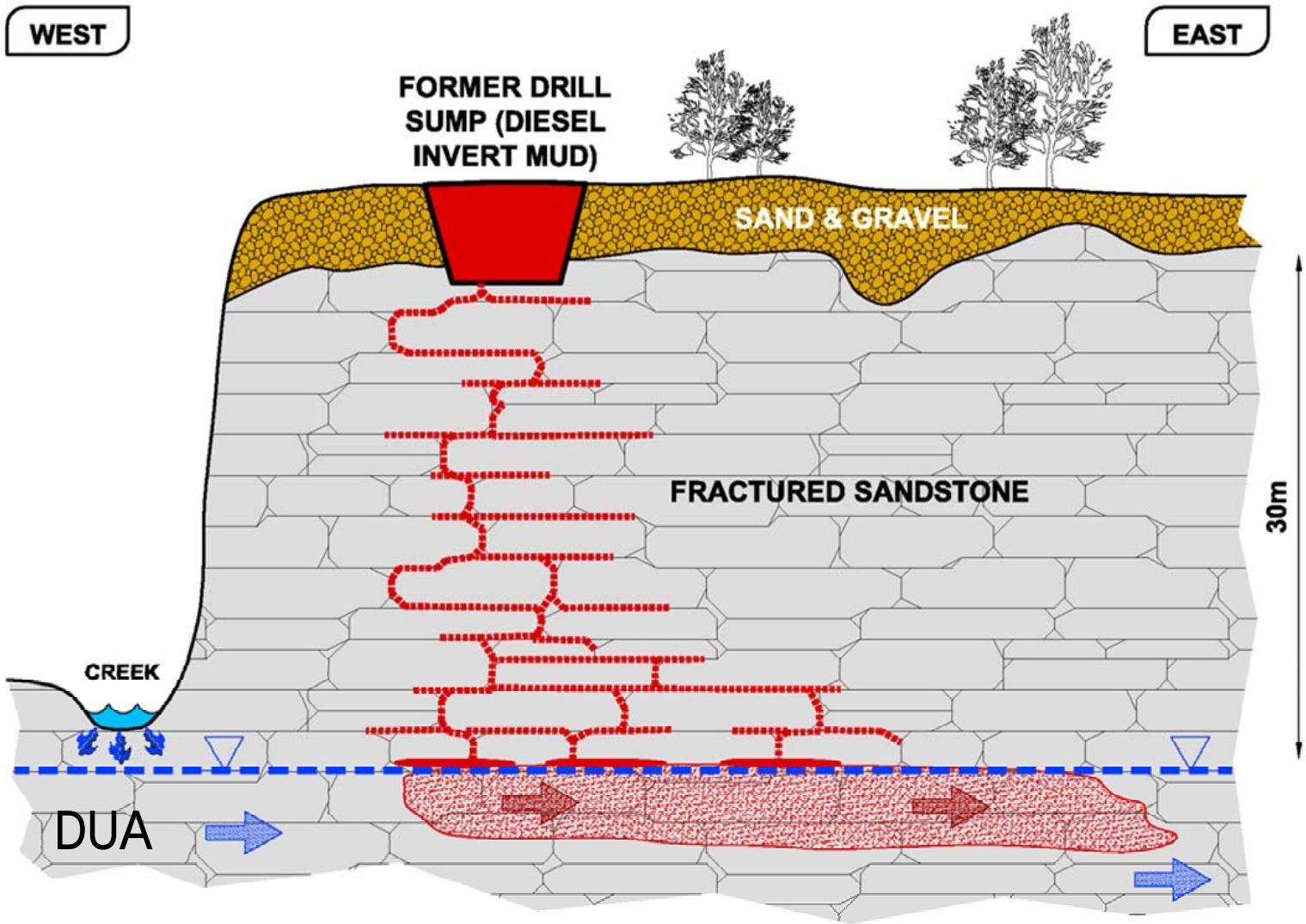
Site Plan



Infiltration Gallery

Infiltration



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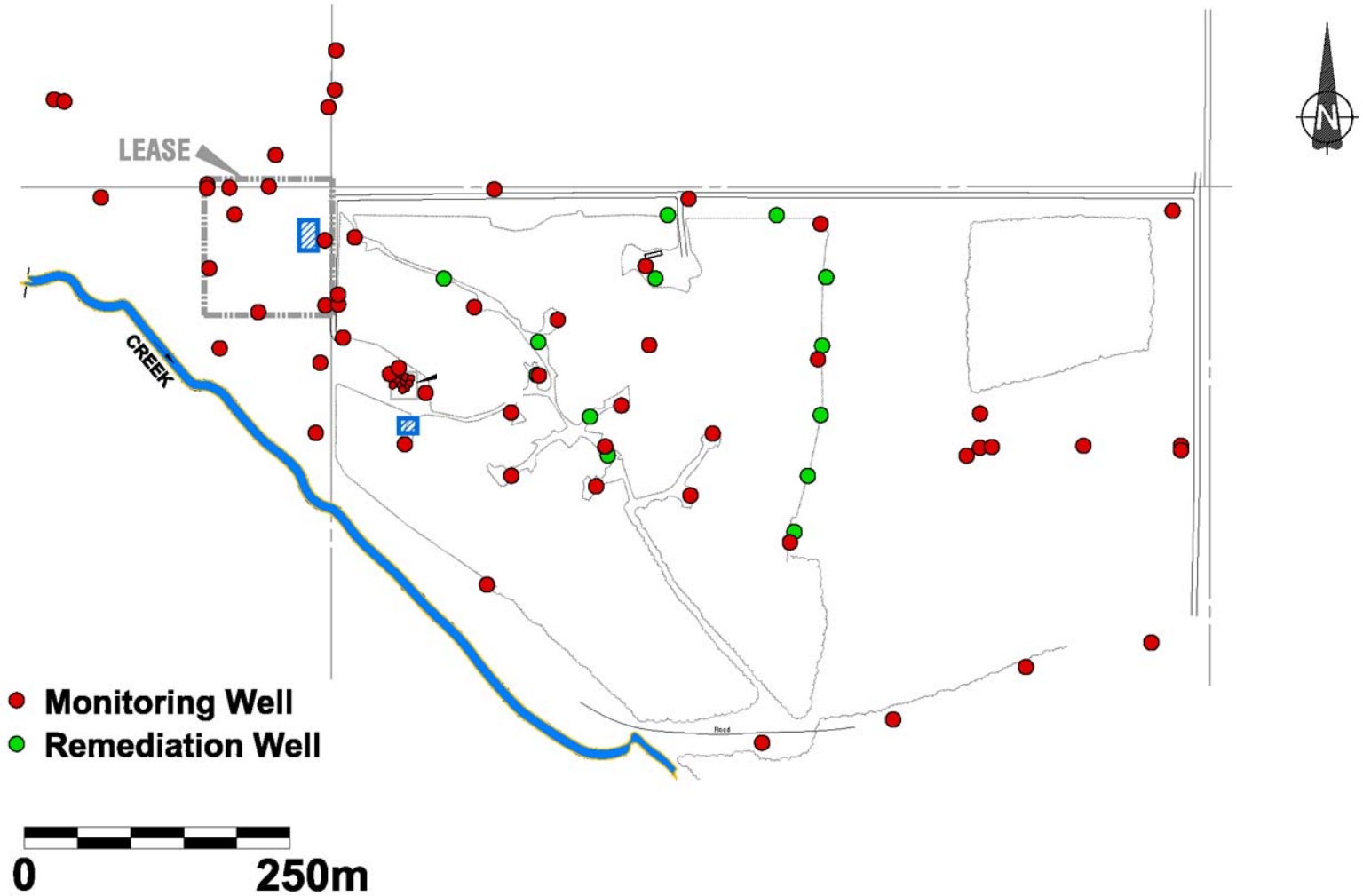

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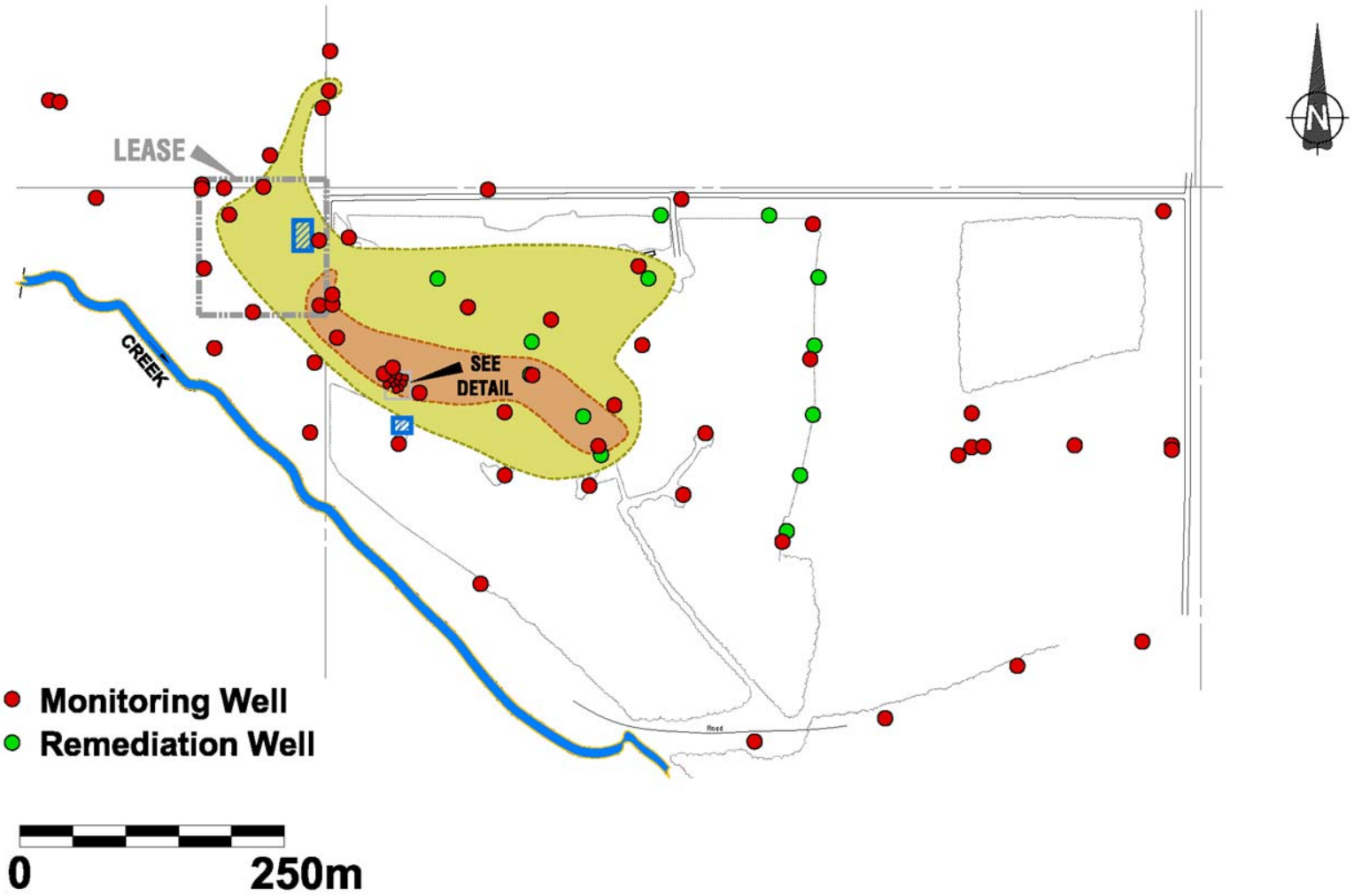
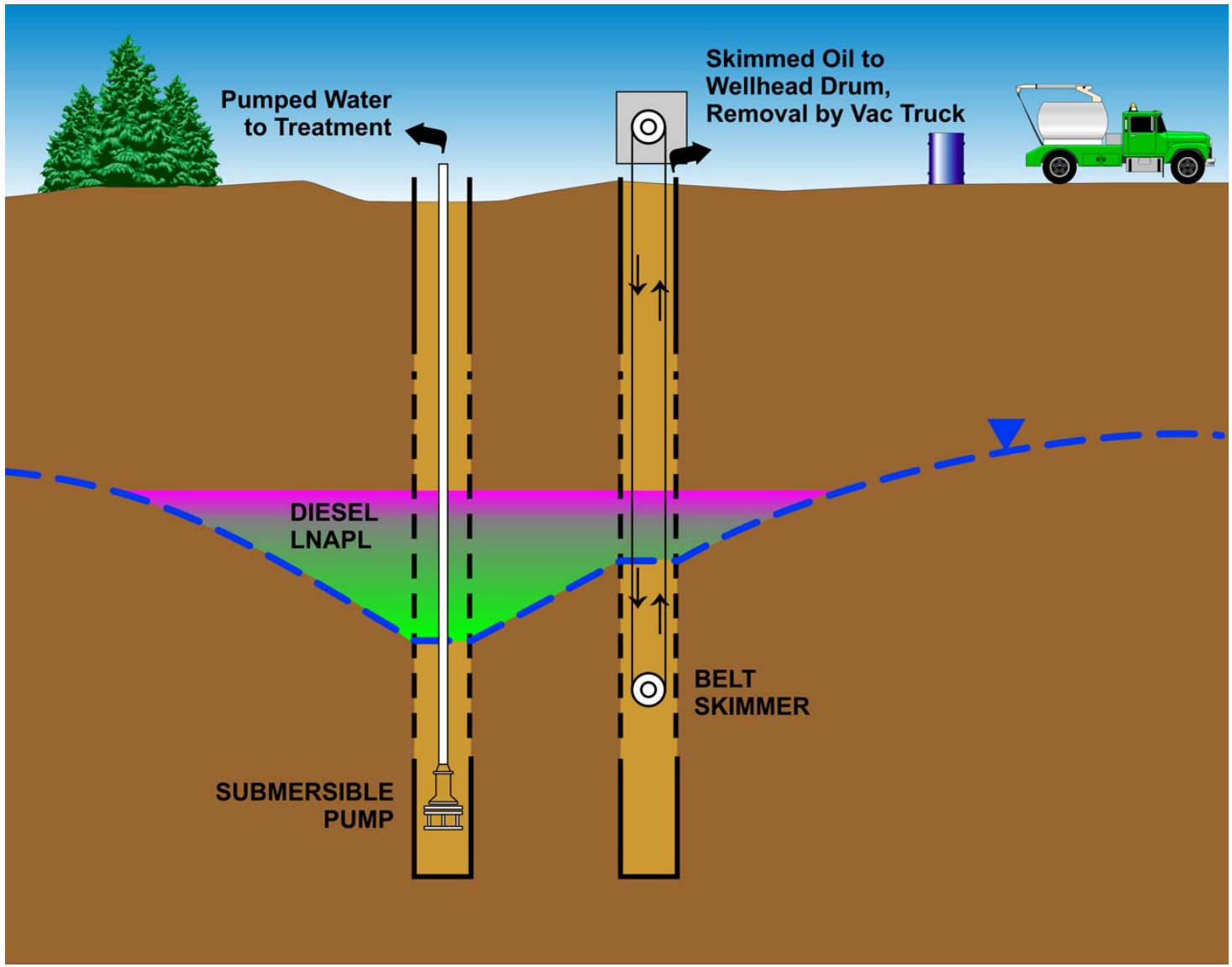
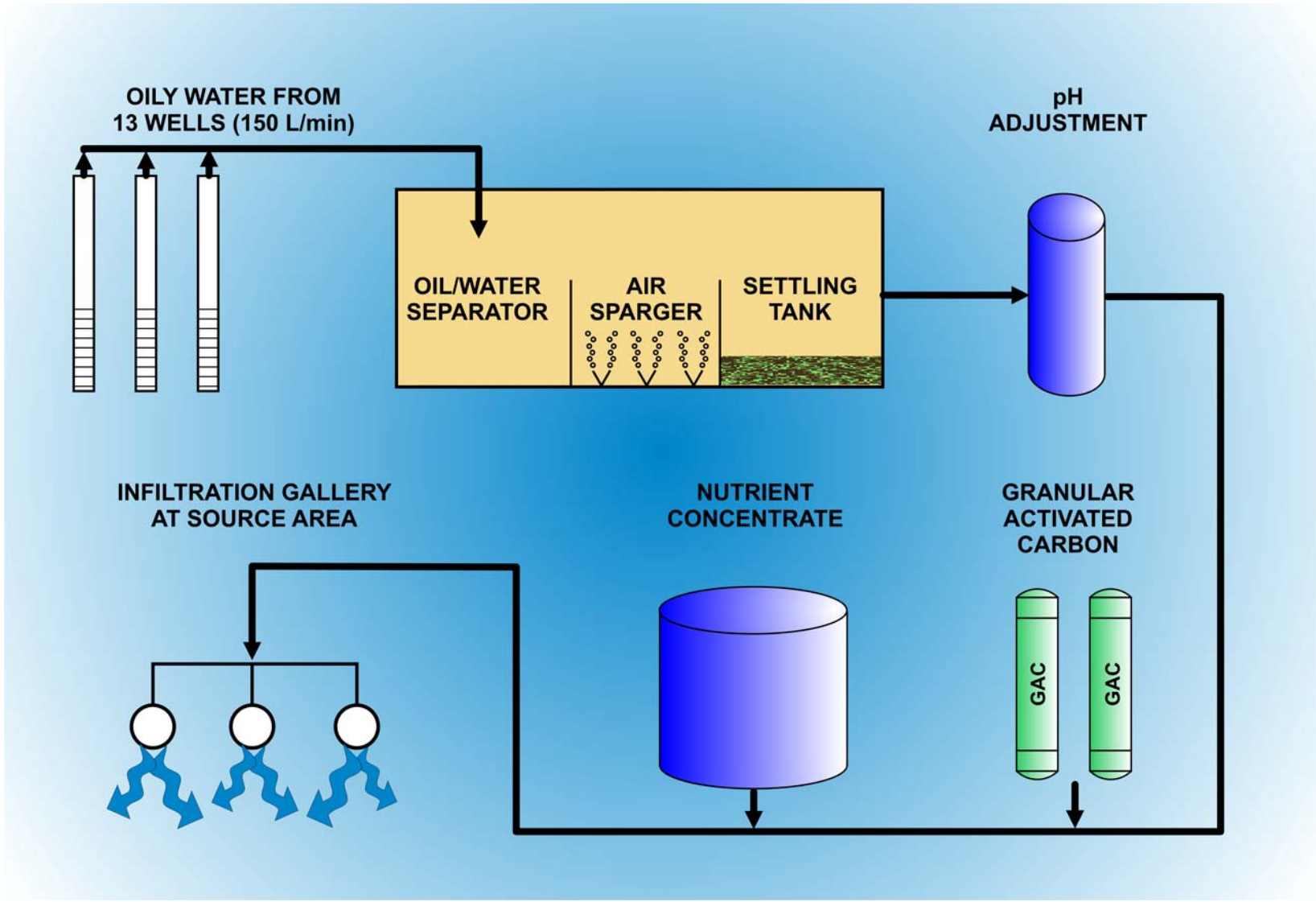


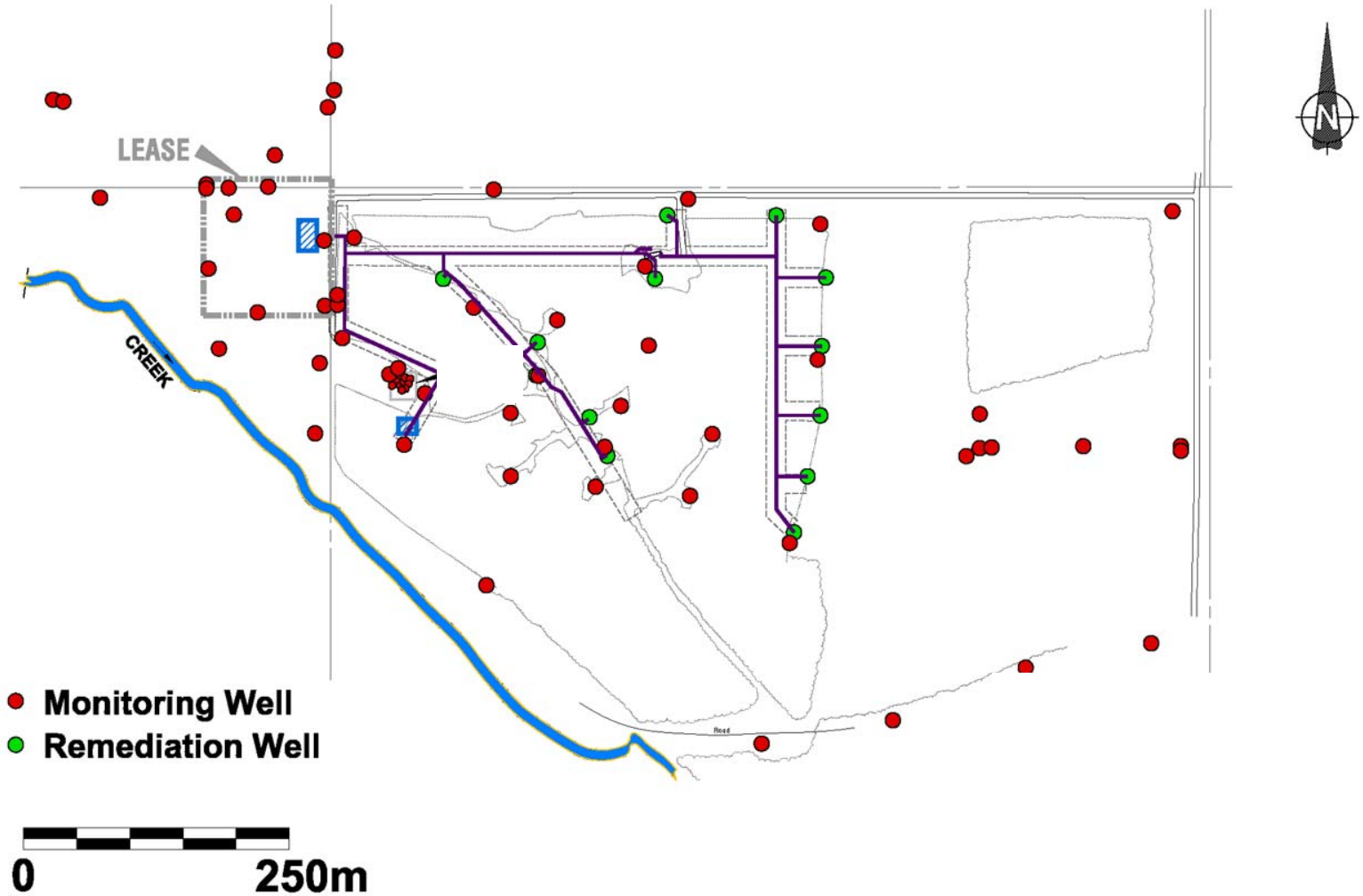
Well Pairs


Pumped Water
to Treatment
Skimmed Oil to
Wellhead Drum,
Removal by Vac Truck
DIESEL
LNAPL
BELT
SKIMMER
SUBMERSIBLE
PUMP

Process Design



Collection Network



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Pictures from the field

Remediation Summary

- Nutrient Amendment works at the lab scale
- Modelled estimate 13 wells & 2 infiltration galleries
  - Outer Perimeter Wells and 2nd infiltration gallery for hydraulic control of plume
  - Inner Well Pairs attempt to limit smearing of free phase plume
- GW Treatment train
  - Remove HC & amend with NO3, SO4, micronutrients, dissolved oxygen
- Forced gradient nutrient circulation for in-situ treatment of dissolved phase HC
  - Concentration gradient will assist with matrix diffusion
- Free product skimming near pumped wells

Conclusions

- Fractured rock sites require extensive characterization (standard & unconventional)
- Detailed hydrogeological model is key
- Difficult conditions (non-volatile hydrocarbons, fractures, domestic use aquifer) require innovation
- Nutrient amendments a promising alternative for in-situ treatment
- Full scale system is currently being constructed

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QUESTIONS?

Dissolved Gases