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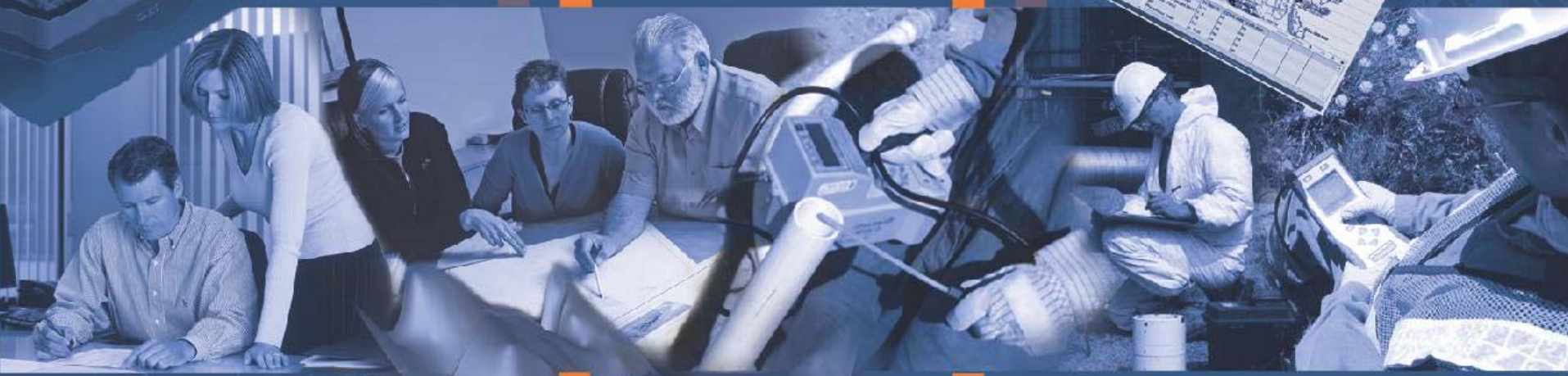

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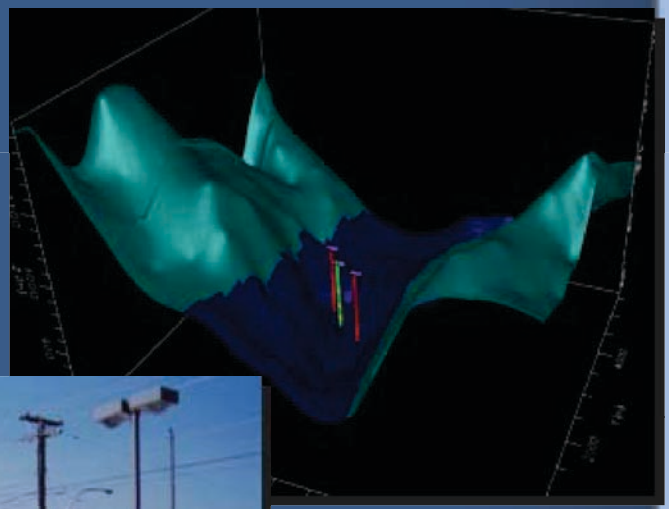
Characterization & Assessment of LNAPL Mobility in Fractured Soils

Emma Kirsh, B.Sc., P.Geol & Douglas Sweeney, M.Sc, P.Eng.

SEACOR Environmental Inc.



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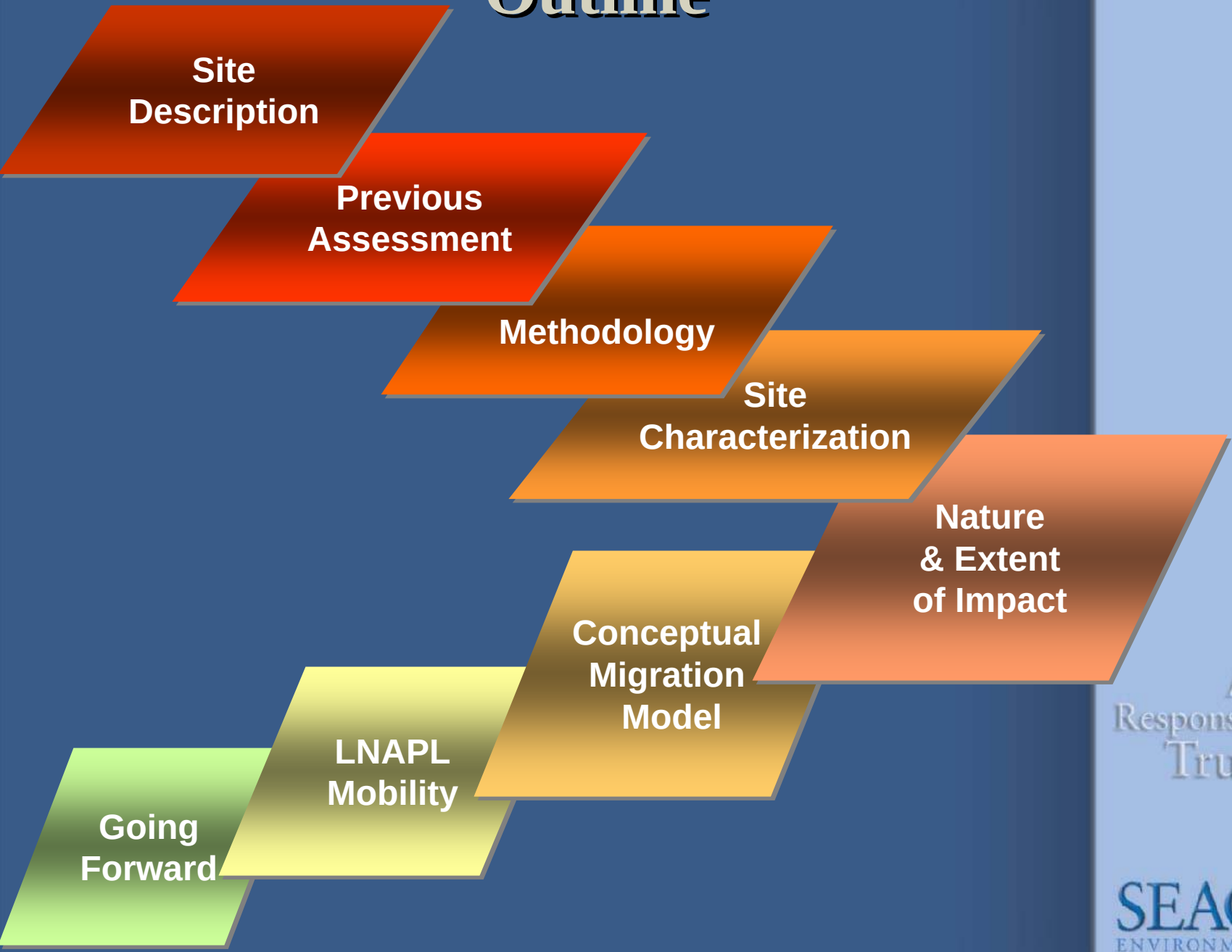
Outline



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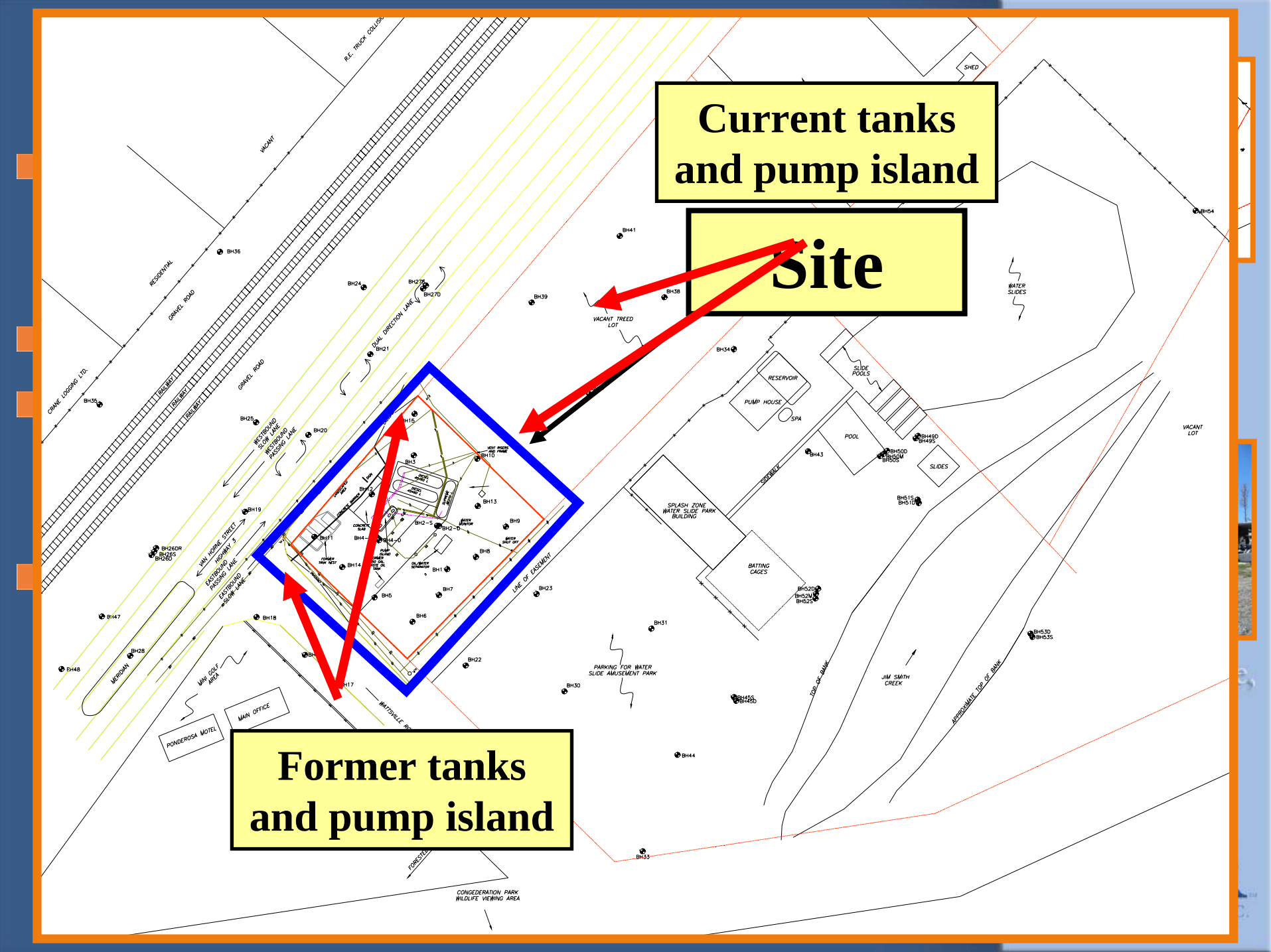
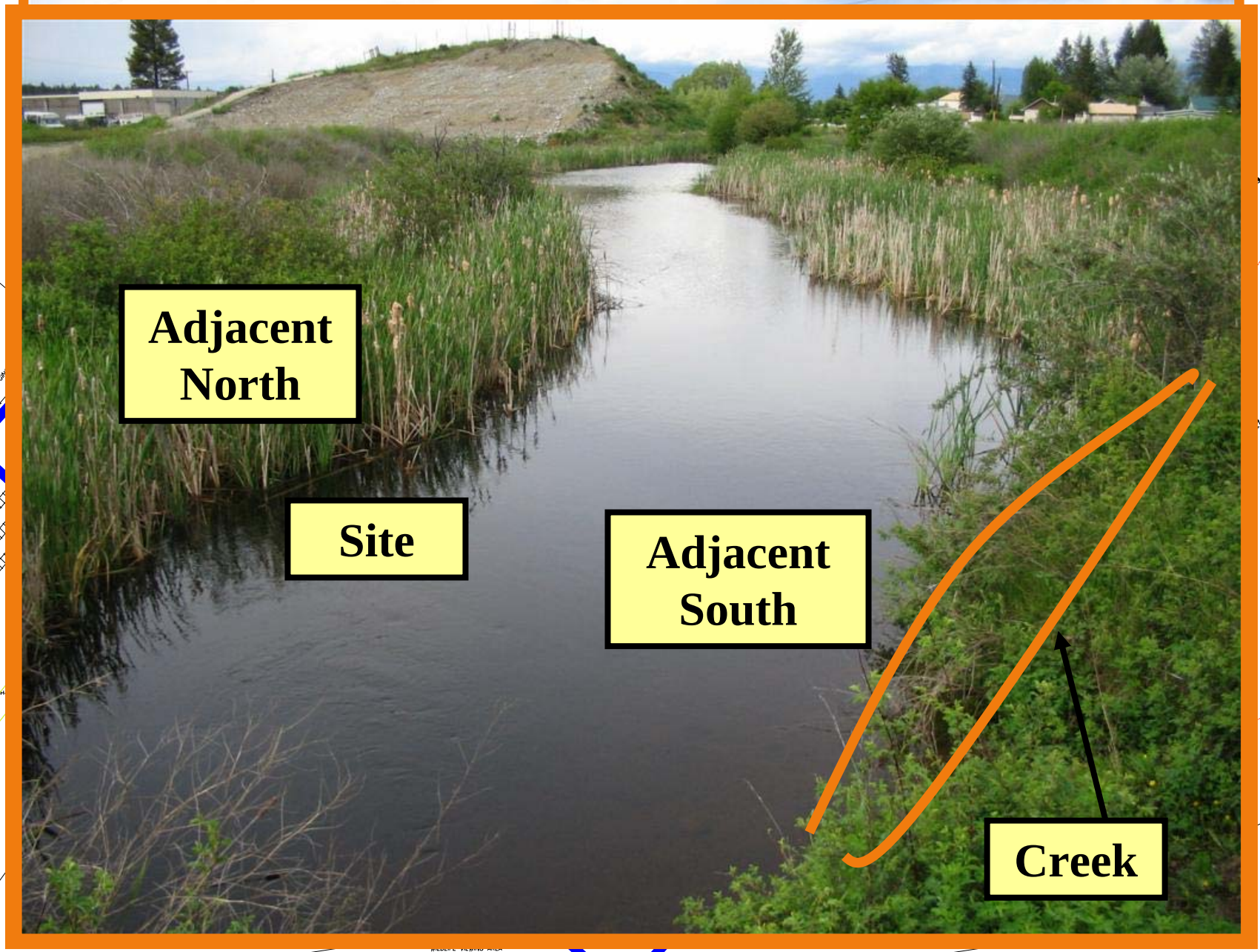

Current tanks and pump island
Site
Former tanks and pump island
VACANT
RESIDENTIAL
GRAVEL ROAD
RAILWAY
TRAILWAY
CRANE LOGGING LTD.
DUAL DIRECTION LANE
WESTBOUND SLOW LANE
WESTBOUND PASSING LANE
VAN HORNE STREET
HIGHWAY 3
EASTBOUND PASSING LANE
EASTBOUND SLOW LANE
VACANT TREED LOT
RESERVOIR
PUMP HOUSE
SPA
SLIDE POOLS
WATER SLIDES
POOL
SLIDES
SHED
VACANT LOT
SPLASH ZONE WATER SLIDE PARK BUILDING
BATTING CAGES
PARKING FOR WATER SLIDE AMUSEMENT PARK
LINE OF EASEMENT
TOP OF BANK
JIM SMITH CREEK
APPROXIMATE TOP OF BANK
MERIDIAN
MINI GOLF AREA
MAIN OFFICE
PONDEROSA MOTEL
WATSHVILLE RD
FORESTED
CONGEDERATION PARK WILDLIFE VIEWING AREA


Adjacent North
Site
Adjacent South
Creek

Environmental Assessments

- Stage 1 and 2 Preliminary Site Investigations in 2000 and additional since
- Total of 76 monitor wells on site and off site surrounding properties
- On site & NW off site soil - BTEX, VPH > standards
- SE off site soil B, VPH > standards
- Groundwater – BTEX, VH_W, VPH, EPH_w, $LEPH_w$ > standards

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Investigation Methodology

- Objectives
  - Detailed site characterization of soil and groundwater
  - Develop LNAPL mobility assessment based on site characterization analysis
  - Eventually develop remedial options based on site characterization analysis and LNAPL mobility assessment

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Investigation Methodology

- E
  - te
  - s
  - p
  - fl
- C
  - m
  - e
- In
  -
  -

Investigation Methodology

Test Pit Location	Depth (m)	% Fines - % Sand - % Gravel	Atterberg Limits	Dry Bulk Density (ρb) (kg/m3)	Water Content (%)	Porosity (-)
TP102	2.5 - 2.6	100 - 0 - 0	---	---		
TP102	2.8 - 3.3	89 - 11 - 0	---	---		
TP102	3.5 - 3.6	97 - 1 - 2	---	---		
TP101 - East side	2.0 - 2.5	100 - 0 - 0		1536	23.5	0.43
TP101 - East side	3.0 - 3.5	99 - 1 -0	CL - Low plasticity clay	1397	31.1	0.48
TP101 - West side	3.0 - 3.5	100 - 0 - 0	---	1343	32.7	0.50
TP101 - West side	4.0 - 4.2	96 - 2 - 2	---	1468	28.0	0.46
TP102 - South side	3.0 - 3.2	100 - 0 - 0	---	1279	37.4	0.53
TP102 - South side	4.0 - 4.2	100 - 0 - 0	---	1569	23.5	0.42
Geometric Means				1428	28.9	0.47

Additional Constants:	Value:	Units:

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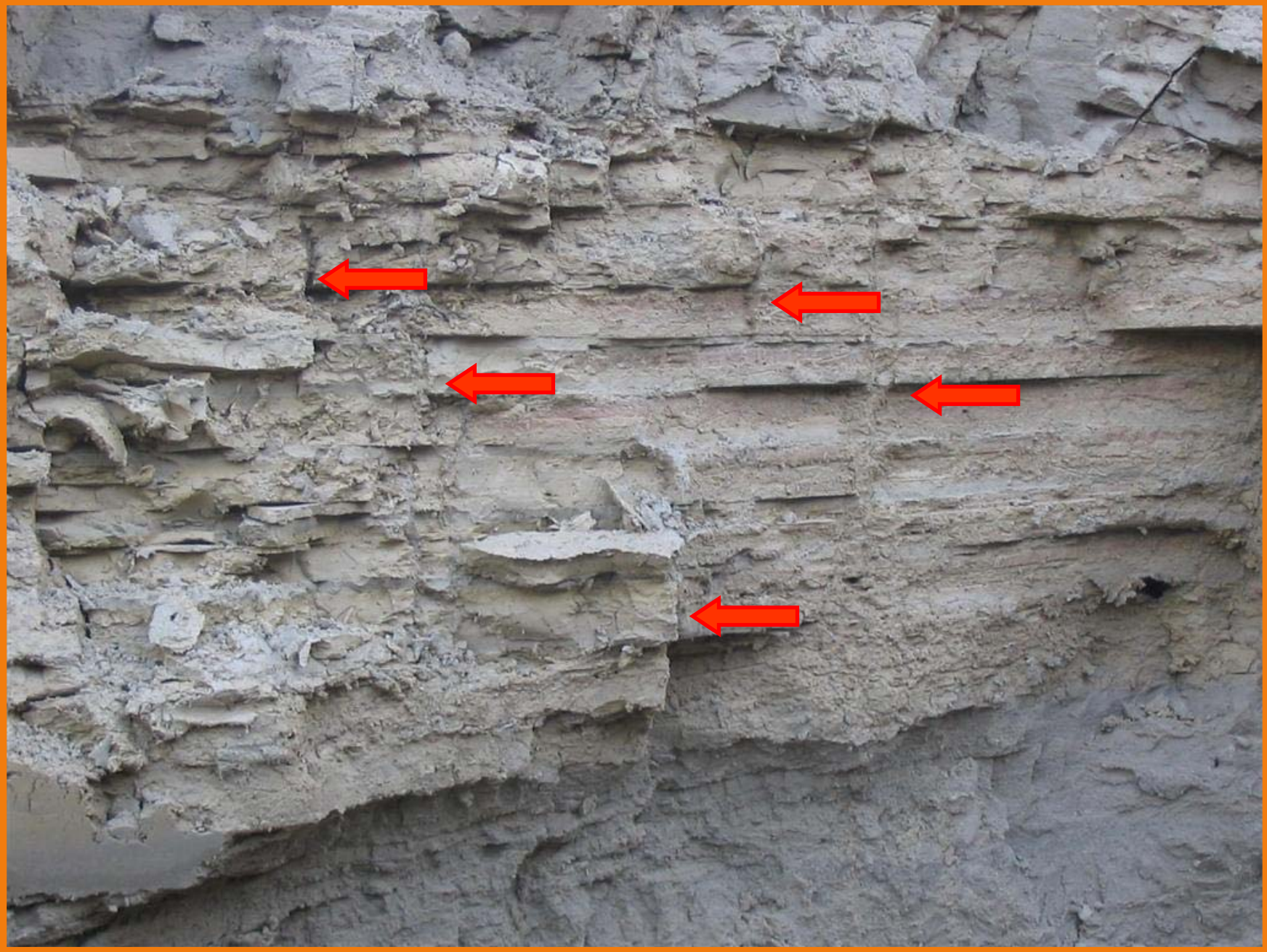
Site Characterization

- Stratigraphy – thin horizontal bedded clayey silt with occasional sand laminations between silt beds
- Soil oxidized to maximum testpit depth
- Variable clay content – maximum % at 2.0-3.5 m, then decreasing with depth
- Atterberg limits – CL – low plastic clay and even though clay content does not approach 50% even small clay content strong governing factor for key soil properties



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Site Characterization

- Hydrogeological parameters from ongoing monitoring events
- Horizontal flow in 2 main directions
  - Southeast from site towards creek and northwest towards road-some site mounding component and utilities/infrastructure control on movement
- Vertical flow – variable downward depending on season/proximity to creek, 0-0.6 m/m, average 0.01 m/m

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TABLE 5: SUMMARY OF HYDRAULIC CONDUCTIVITY TESTING				
Monitor Well	Screen Interval (mbgs)	Soil Type	Hydraulic Conductivity (m/s)	Intrinsic Permeability (m^2)
BH26S	5.5 - 6.4	Silt	1.1E-07	1.8E-14
BH26DR	8.2 - 9.1	Silt	2.6E-08	4.2E-15
BH27S	4.6 - 5.5	Sand	6.7E-07	1.1E-13
BH27D	7.3 - 8.2	Sand	2.5E-07	4.0E-14
BH32S	3.4 - 4.3	Silt	1.4E-06	2.2E-13
BH32D	6.1 - 7.0	Silt	3.6E-09	5.8E-16
BH50S	1.5 - 2.4	Silt	3.2E-07	5.1E-14
BH50D	7.3 - 7.9	Silt	2.0E-07	3.2E-14
BH52S	3.4 - 4.3	Silt	1.2E-05	1.9E-12
BH52M	6.1 - 7.0	Sand	1.1E-06	1.8E-13
BH52D	8.8 - 9.4	Sand	5.2E-07	8.3E-14
BH53D	6.1 - 6.9	Silt	4.9E-07	7.8E-14
Geometric mean for wells in upper 6 m of soil			8.3E-07	1.3E-13
Geometric mean for wells in soil below 6 m depth			1.4E-07	2.3E-14

10^{-7} m/s

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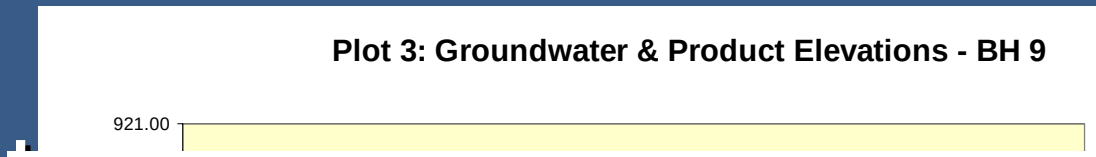
Site Characterization

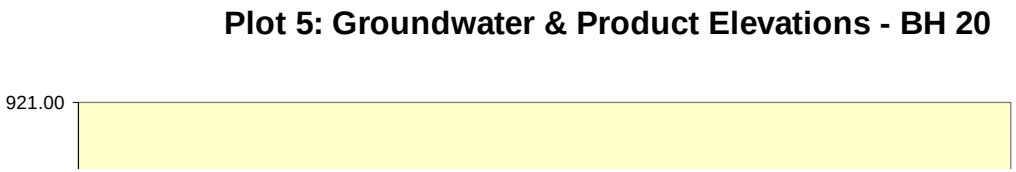
- **MATRIX POROSITY**
  - [illegible] for matrix

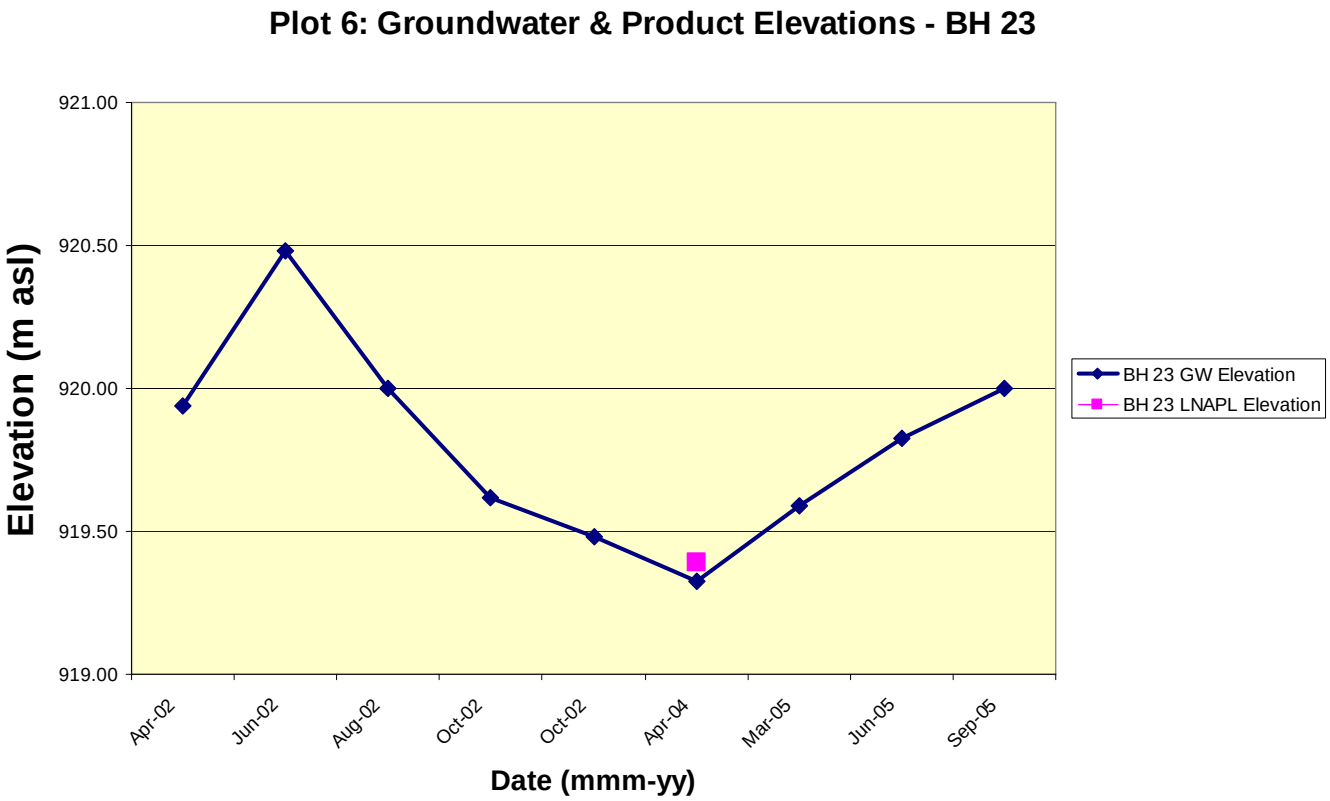
TABLE 6: SUMMARY OF FRACTURE APERTURES & POROSITIES					
Fracture Flow System	Fracture Spacing	Average Fracture Spacing (1/m)	Mean Hydraulic Conductivity (m/s)	Aperature Width (m)	Fracture Porosity (%)
Horizontal Fracture Flow	min	9	8.E-07	3.0E-05	0.03
	max	17	8.E-07	2.5E-05	0.04
	average	14	8.E-07	2.6E-05	0.04
Cubic Fracture Flow	min	9	8.E-07	3.8E-05	0.1
	max	31	8.E-07	2.5E-05	0.2
	average	15	8.E-07	3.2E-05	0.1

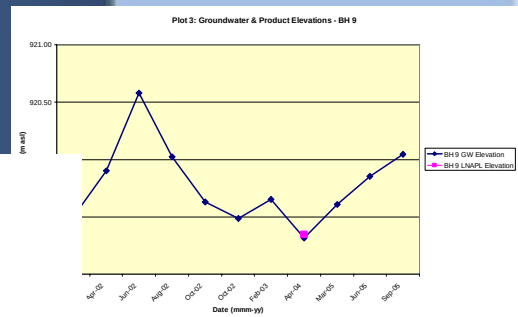
system
  - equation modification for flow system dominated by horizontal bedding or cubic fractures
  - mean K and field fracture spacing
  - Horizontal system – 0.03-0.04%
  - Cubic system – 0.1-0.2%

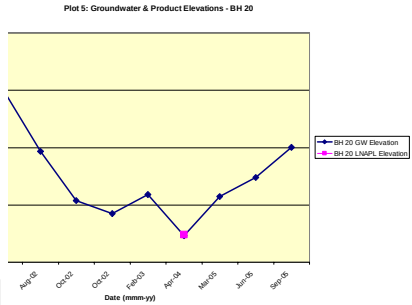
Nature & Extent of

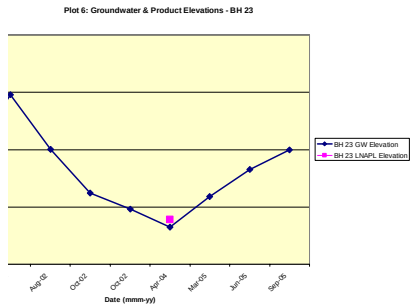












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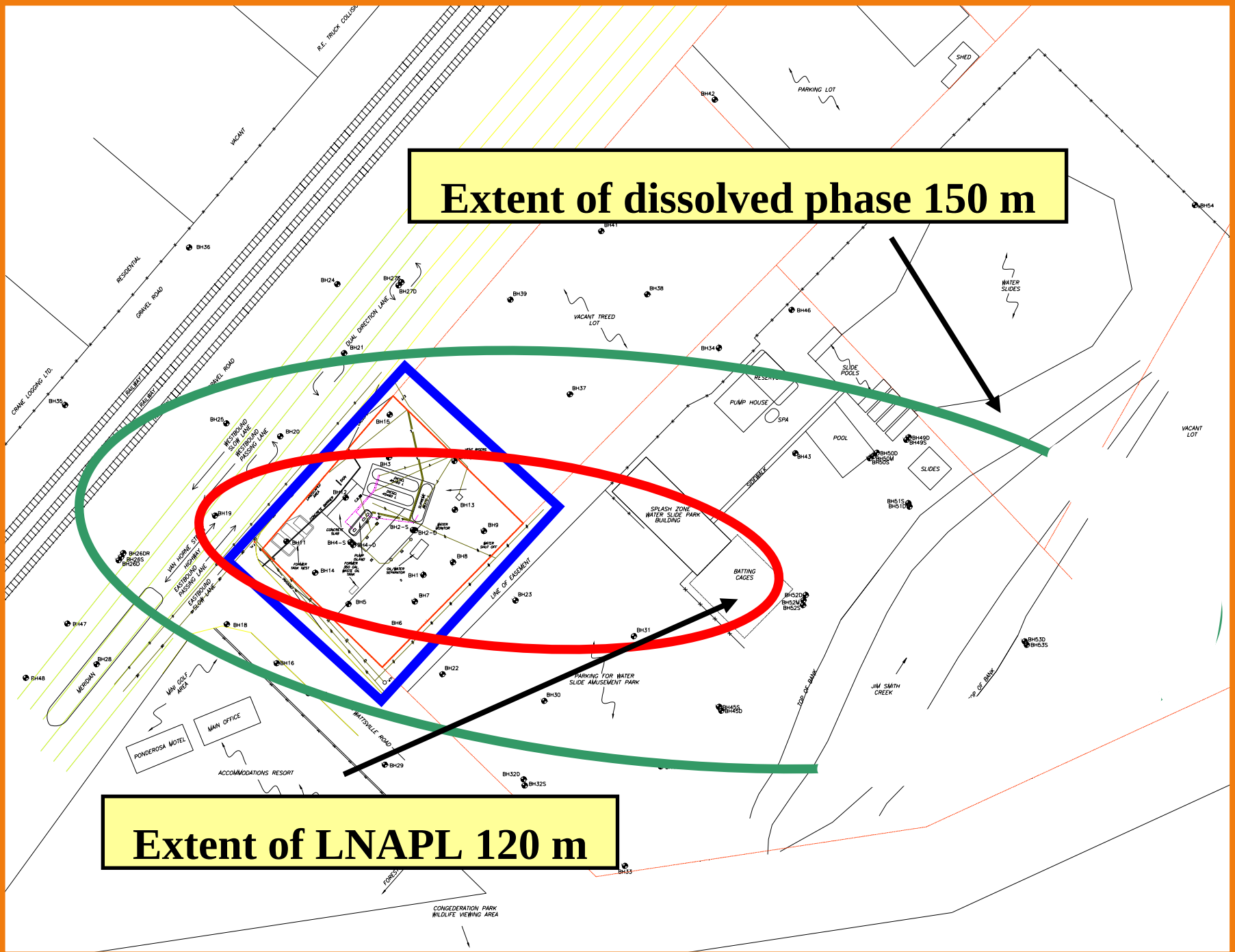
Nature & Extent of Hydrocarbon Impacts

- Residual phase – 186 soil hydrocarbon analyses
- TOTAL PETROLEUM HYDROCARBONS
- 89 % soil TPH < 100 mg/kg (165)
- 21 % soil TPH ~ 122-2225 mg/kg (21)
- Oil saturations – Maximum 0.8 %, majority <0.2 %
- Fracture flow porosity ≈ Volumetric oil content (0.02-0.4 %)

Nature & Extent of

TABLE 10: SUMMARY OF GROUNDWATER CHEMISTRY RESULTS WITH DISSOLVED TPH > 40,000 ug/L					
Sample ID	Date	VHw	LEPHw	HEPHw	TPH
BH 2D	25-Aug-00	36000	17900	1000	54900
BH 2D	24-Oct-00	44000	5000	<1000	49000
BH 3	24-Oct-00	51000	4700	<1000	55700
BH 7	26-Jan-01	43000	3500	<1000	46500
BH 8	26-Jan-01	46000	3600	<1000	49600
BH 9	26-Jan-01	46000	2000	<1000	48000
BH 12	26-Jan-01	4300			129100
BH 14	26-Jan-01	5400			60000
BH 15	26-Jan-01	4900			51100
BH 23	3-Mar-05	2870			49300
BH 23	3-Mar-05	29100	19300	<1000	48400
BH 50D	6-Aug-02	421000	39400	1000	461400
BH 50M	23-Jul-02	289000	19200	<1000	308200
BH 50M	6-Aug-02	7060000	7200	<1000	7067200
BH 52M	23-Jul-02	114000	10000	<1000	124000
BH 52M	6-Aug-02	239000	22300	1000	262300
BH 52S	23-Jul-02	286000	18500	<1000	304500
BH 52S	6-Aug-02	110000	19200	<1000	129200
BH 72	30-Apr-04	41000	6380	<1000	47380

>70,000 µg/L


Extent of dissolved phase 150 m
Extent of LNAPL 120 m
R.E. TRUCK COLLISION
VACANT
RESIDENTIAL
GRAVEL ROAD
RAILWAY
TRAILWAY
CRANE LOGGING LTD.
BH36
BH35
BH24
BH27S
BH27D
BH21
DUAL DIRECTION LANE
BH25
BH20
WESTBOUND SLOW LANE
WESTBOUND PASSING LANE
BH19
VAN HORNE ST
EASTBOUND PASSING LANE
EASTBOUND SLOW LANE
BH26DR
BH26S
BH26D
BH47
BH48
BH28
MERIDIAN
BH18
BH16
MINI GOLF AREA
PONDEROSA MOTEL
MAIN OFFICE
ACCOMMODATIONS RESORT
WATSHVILLE ROAD
BH29
FOREST
CONGEDERATION PARK WILDLIFE VIEWING AREA
BH15
BH3
BH13
BH12
BH9
BH2-S
BH2-D
BH4-S
BH4-D
BH11
BH14
BH8
BH1
BH5
BH7
BH6
LINE OF EASEMENT
BH23
BH22
BH30
BH31
PARKING FOR WATER SLIDE AMUSEMENT PARK
BH42
SHED
PARKING LOT
BH41
BH39
BH38
VACANT TREED LOT
BH37
BH34
BH46
RESERVE
PUMP HOUSE
SPA
SLIDE POOLS
WATER SLIDES
BH54
POOL
BH43
BH49D
BH49S
BH50D
BH50M
BH50S
SLIDES
SIDEWALK
SPLASH ZONE WATER SLIDE PARK BUILDING
BH51S
BH51D
VACANT LOT
BATTING CAGES
BH52D
BH52M
BH52S
BH53D
BH53S
TOP OF BANK
JIM SMITH CREEK
BH45S
BH45D
BH32D
BH32S
BH33

Conceptual Migration Model

TABLE 11: SUMMARY OF GROUNDWATER TRAVEL TIME CALCULATIONS						
LNAPL Migration Model	Hydraulic Conductivity (m/s)	Migration Model Effective Porosity -	Gradient (m/m)	Average Linear Groundwater Velocity (m/yr)	Travel Time (years)	Travel Distance (m)
Matrix Flow	8E-07	0.3	0.003	0.25	50	13
Cubic Fracture Flow	8E-07	0.002	0.003	38	50	1892
Horizontal Fracture Flow	8E-07	0.0004	0.003	189	50	9461
Cubic Fracture Flow	8E-07	0.002	0.003	38	3	121
Horizontal Fracture Flow	8E-07	0.0004	0.003	189	0.6	120

minimal mixing occurring

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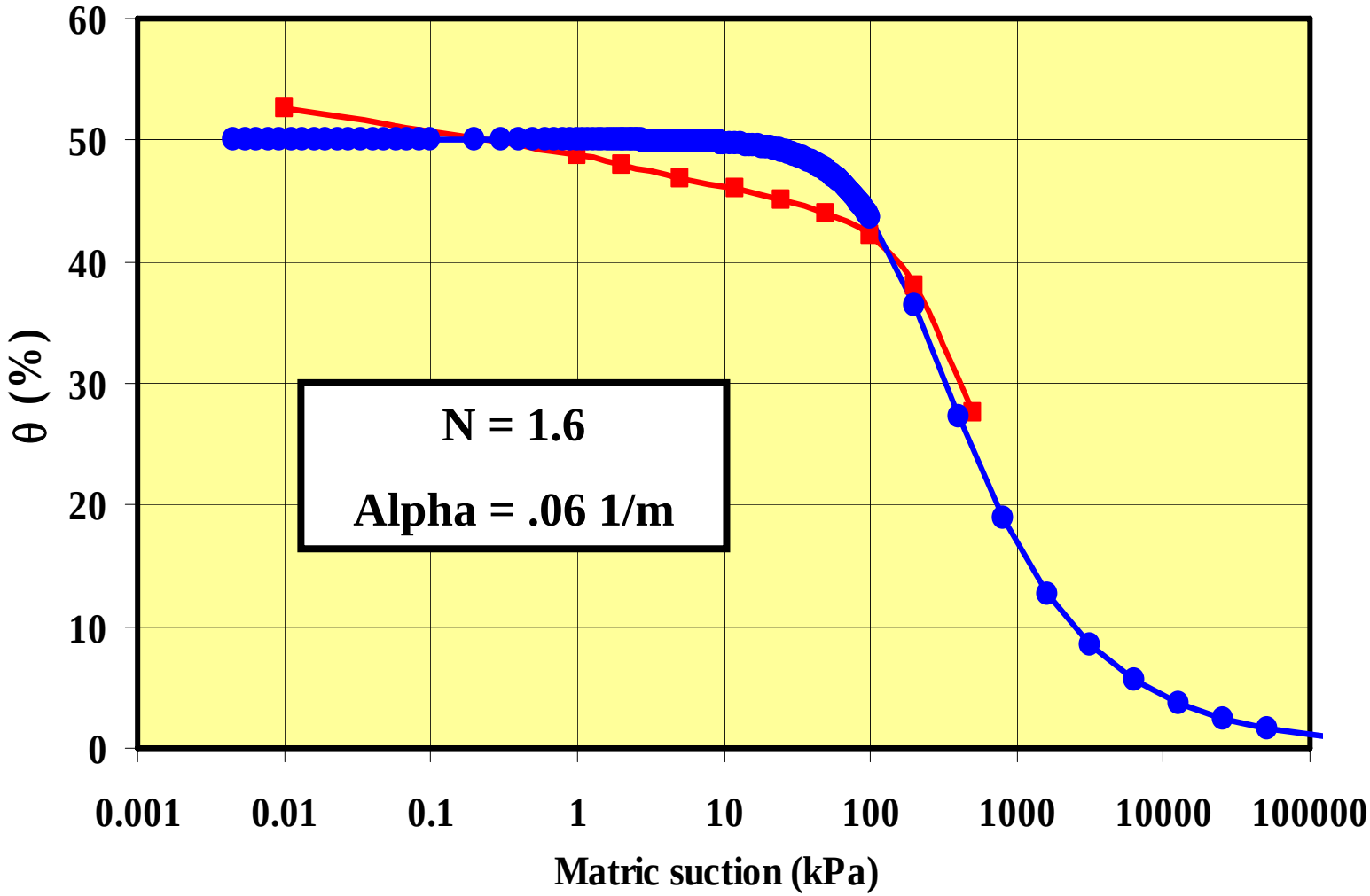
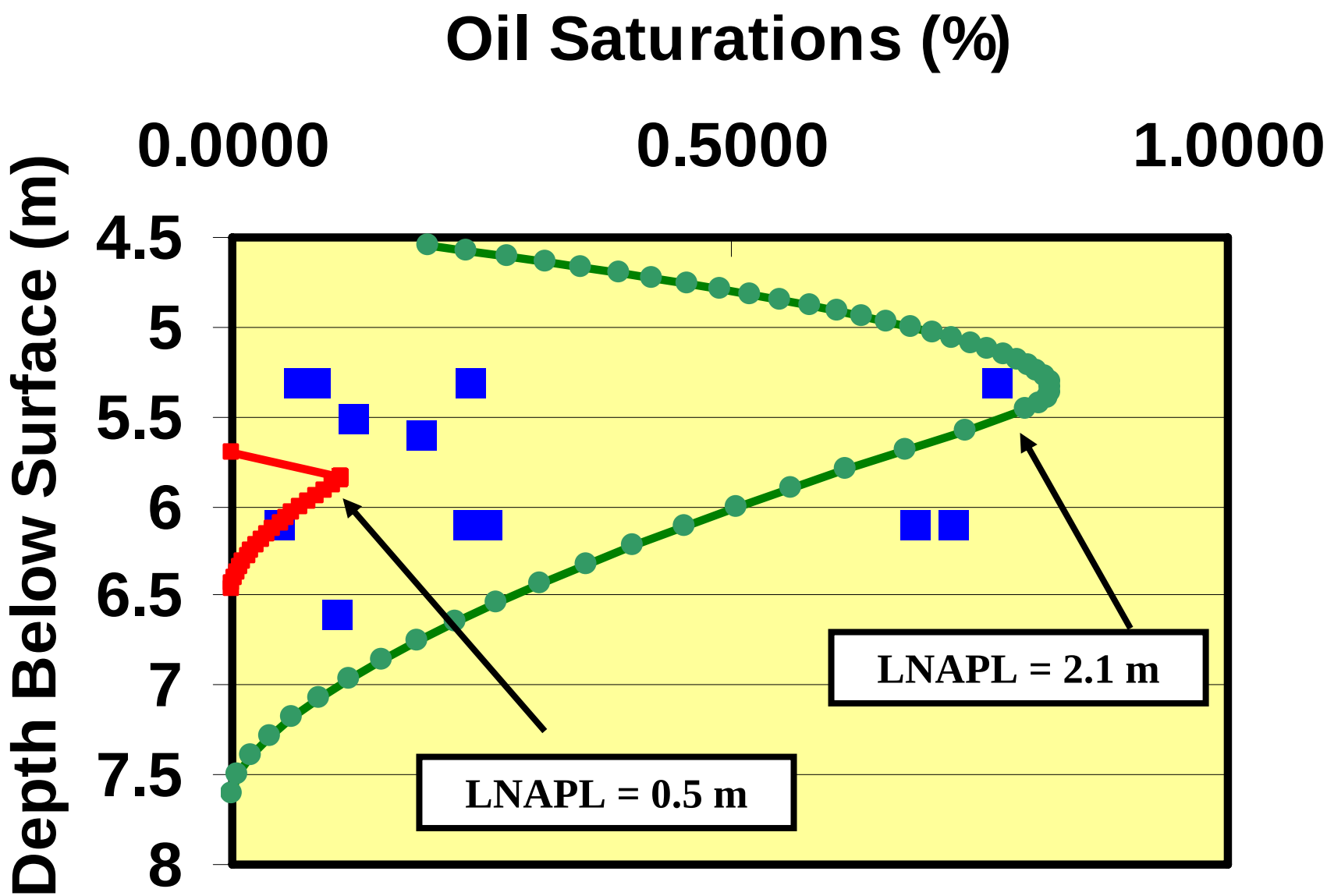
Soil-Water Characteristic Curve for Clayey Silt Matrix



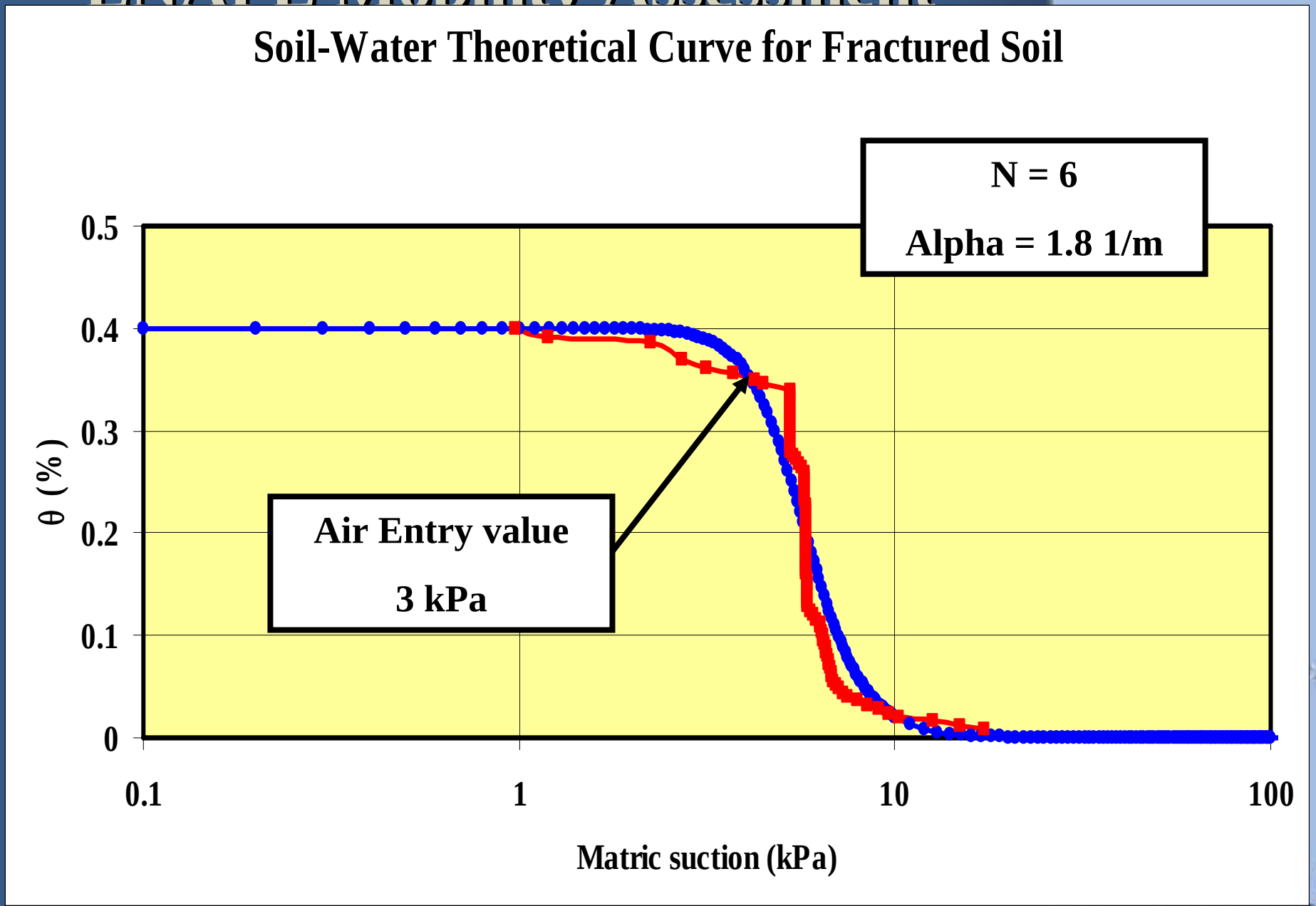

Oil Saturations (%)
0.0000
0.5000
1.0000
Depth Below Surface (m)
4.5
5
5.5
6
6.5
7
7.5
8
LNAPL = 2.1 m
LNAPL = 0.5 m

LNAPL Mobility Assessment

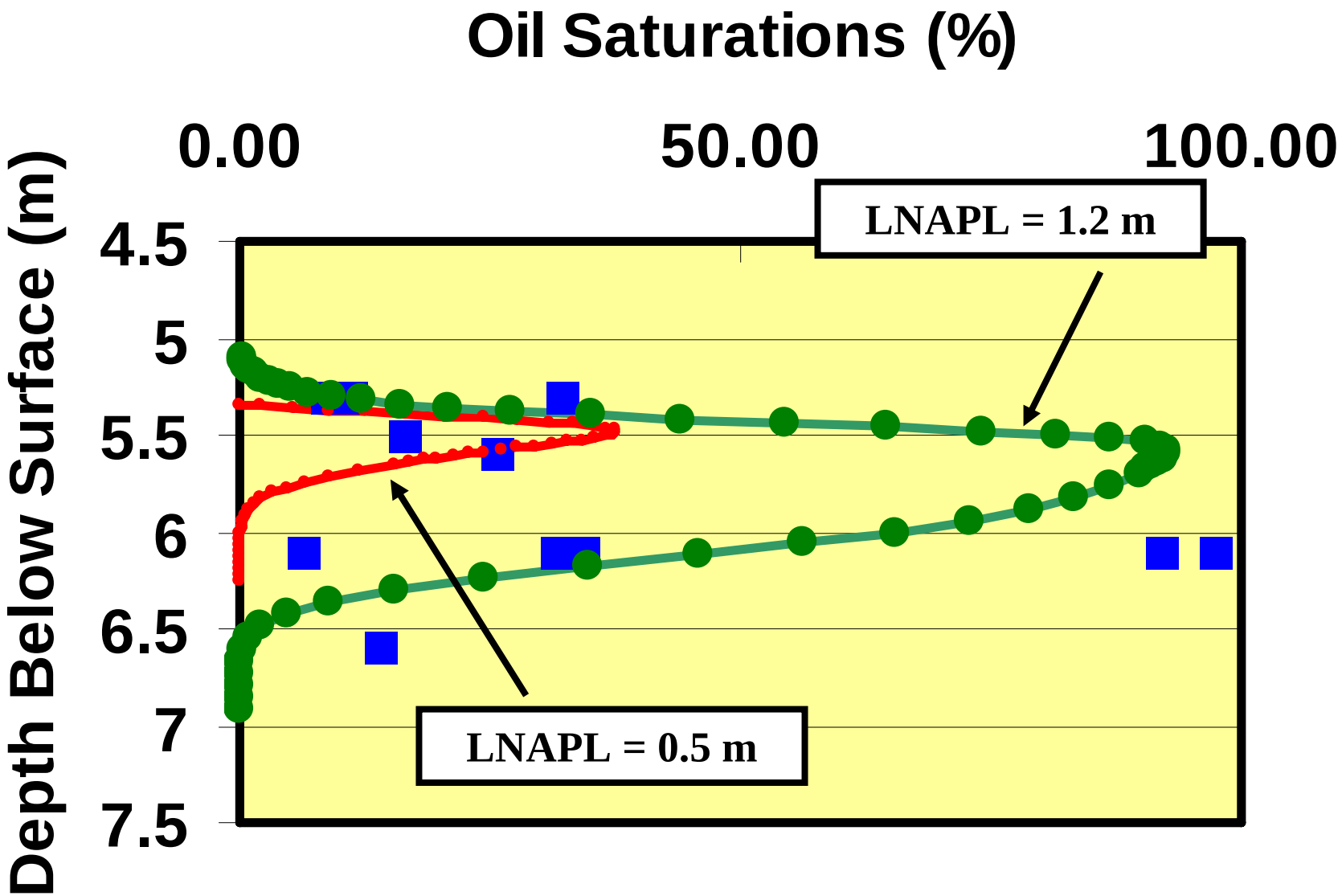
Fluid Retention in Fractured Soil

- Dr. Mendoza (1992) derived constitutive relationships for fluid flow and migration in fractured geologic media
- Based on physical principles
  - Invasion percolation theory
  - Inlet accessibility & fluid trapping criteria
- Developed a numerical model with a log normal fracture aperture distribution and a log aperture variance of 1
- Results apply for any fractured soil retention curve with known geometric mean aperture
- Critical assumption of aperture log normal distribution

LNAPL Mobility Assessment



LNAPL Mobility Assessment



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LNAPL Mobility Assessment

- LNAPL behavior/observations
- Dissolved plume stability
- Theoretical Mobility Assessment using API Tools

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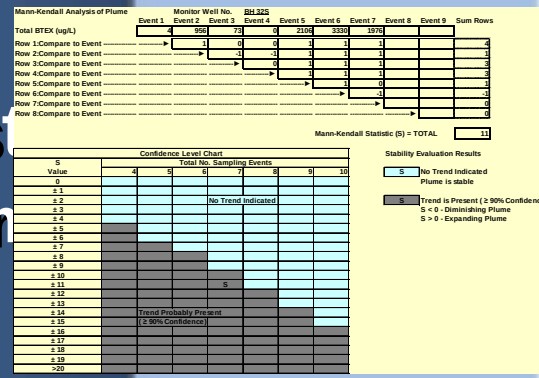
LNAPL Mobility Assessment

- 7 monitor well locations single observation – no new wells with LNAPL down gradient
- Mann-Kendall statistical trend test
  - 36 wells on and off site with minimum sampling events for analysis
  - Shallow, mid-level and deep wells
- Stability results:
  - 13 diminishing plume trend (on & off)
  - 22 stable plume trend (on & off)
  - 1 expanding plume trend (off)
- Supporting LNAPL plume stability



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LNAPL Mobility Assessment

Macro Scale Mobility

- API modeling with developed moisture retention curve, fracture porosity and gasoline properties
- V LNAPL ≈ 5×10^{-4} m/day
- V ASTM de minimus ≈ 9×10^{-4} m/day

Micro Scale Mobility

- Local displacement head – based on air entry value (≈ 0.3 m) and LNAPL properties (Brooks - Corey)
- H calculated ≈ 0.65 m
- H site maximum observed ≈ 0.5 m

Macro/micro scale suggest LNAPL no longer mobile

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Going Forward

- Now established network allowing key monitoring points for trend observation – plume center of mass evaluation
- Future implications of low water table and LNAPL drainage - extended drawdown/pump tests
- Coring and UV light fluorescence for field LNAPL saturation verification
- Risk Assessment and Remediation

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QUESTIONS?

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