

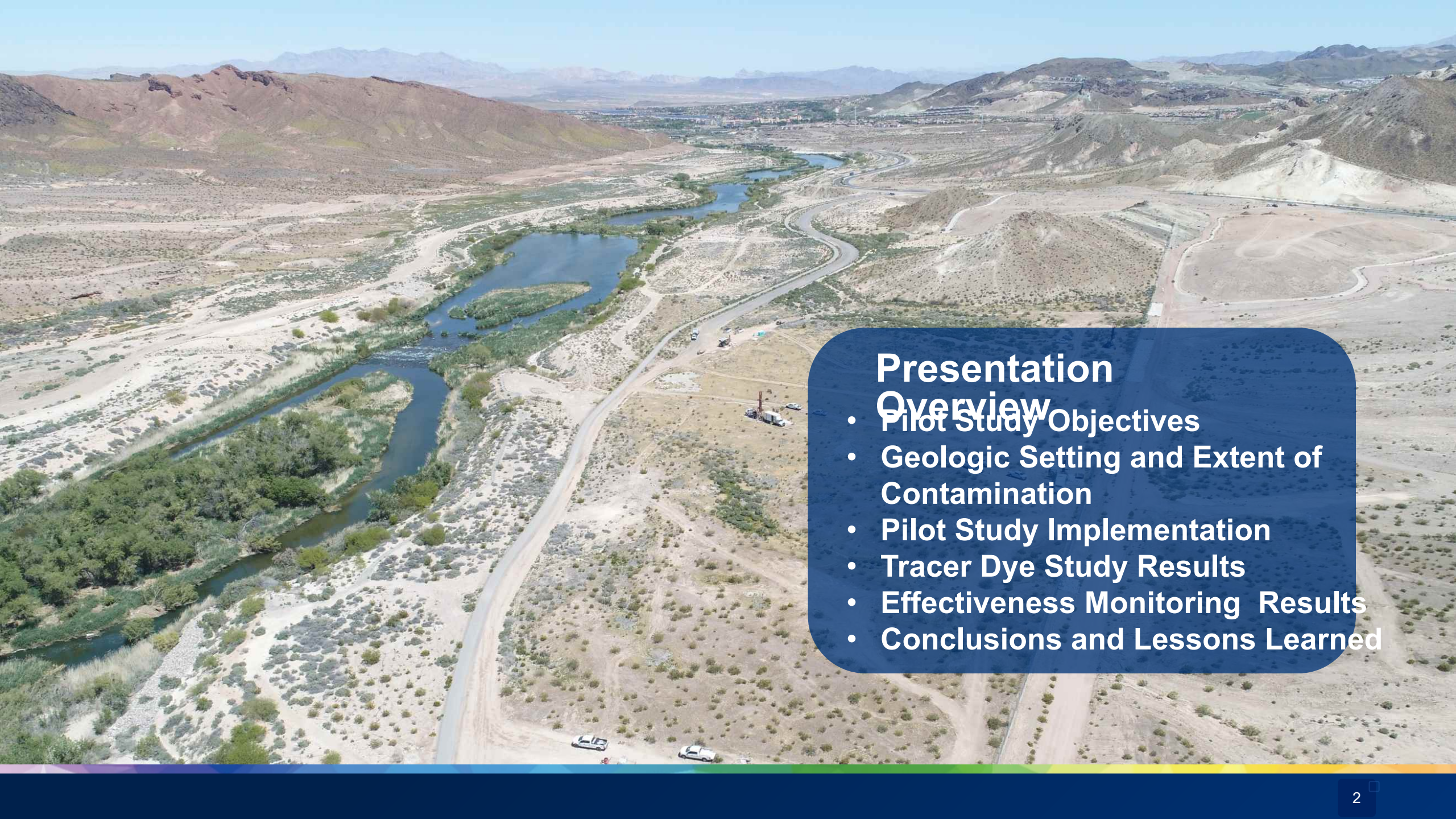


# In Situ Bioremediation of Perchlorate in a Highly Heterogeneous Geologic Setting

Dana Grady, P.E., and Ronnie Britto, P.E.,  
Ph.D.

(Tetra Tech, Tennessee, USA)

June 5, 2024

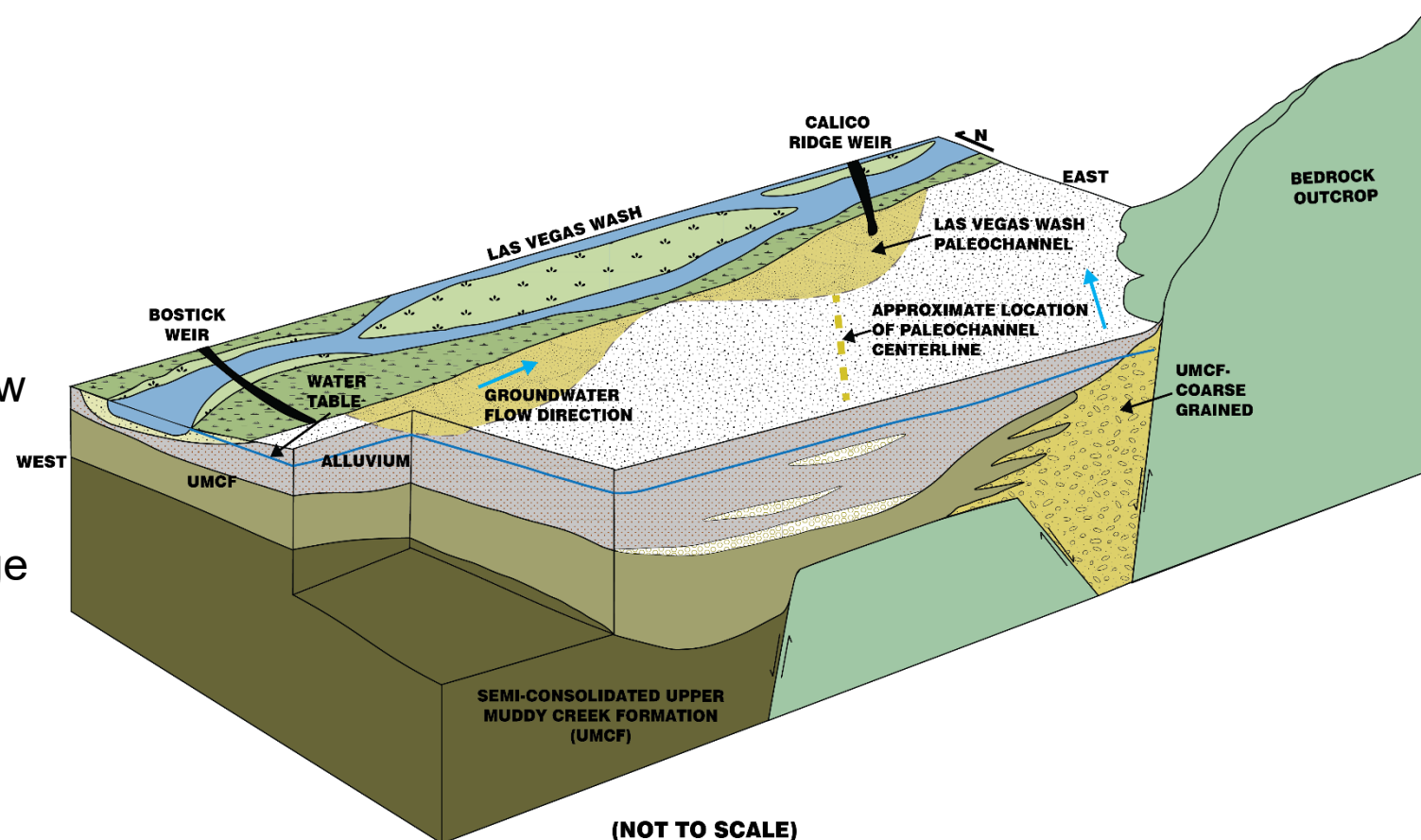


## Presentation Overview

- Pilot Study Objectives
- Geologic Setting and Extent of Contamination
- Pilot Study Implementation
- Tracer Dye Study Results
- Effectiveness Monitoring Results
- Conclusions and Lessons Learned

# Pilot Study Objectives

- Evaluate effectiveness and implementability of in-situ bioremediation (ISB) to reduce perchlorate in groundwater in complex study area:
  - Significant geological heterogeneity
  - Large and deep alluvial paleochannels
  - Secondary porosity associated with a complex fault zone
  - Large saturated thickness of contaminated alluvium and underlying low permeability formation
  - Located immediately upgradient of a surface water body at a primary discharge point for a major hydrographic basin



## Upper Muddy Creek Formation

### Alluvium



- Highly heterogenous
- Silty sand to sandy gravel with lenses of silt and clay due to paleochannels
- Water table ~30 ft bgs
- Extends to a depth of 120 ft bgs near surface water

### UMCf



- Underlies alluvium (erosional contact)
- Silt and clay to silty fine-grained sand
- Locally faulted

### UMCf-cg



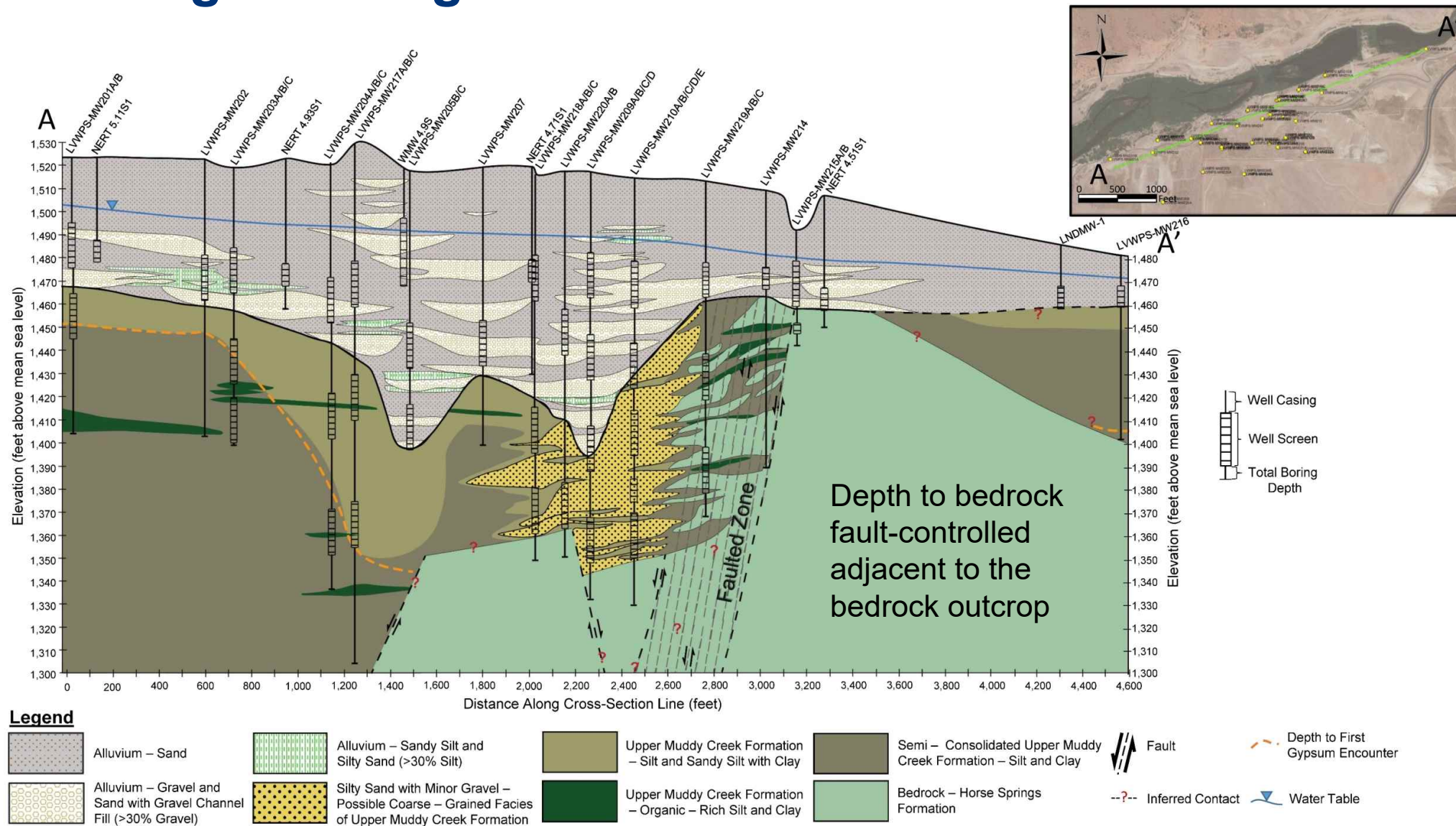
- Coarse grained facies
- Increasing clayey sands with up to 15% gravel
- Interbedded with UMCf adjacent to fault zone

### Semi-Consolidated

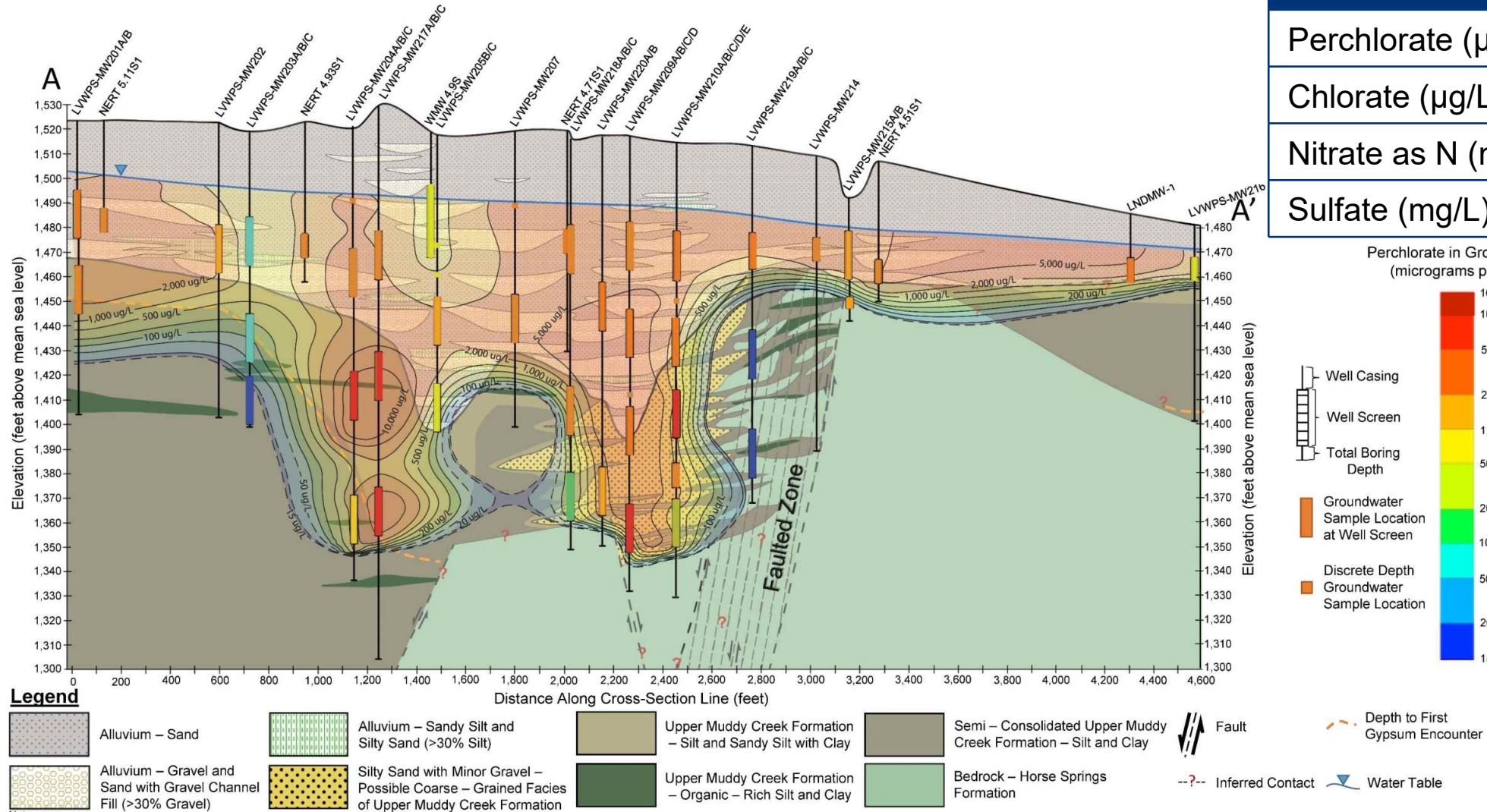


- At depth, UMCf cemented with abundant gypsum

# Geologic Setting

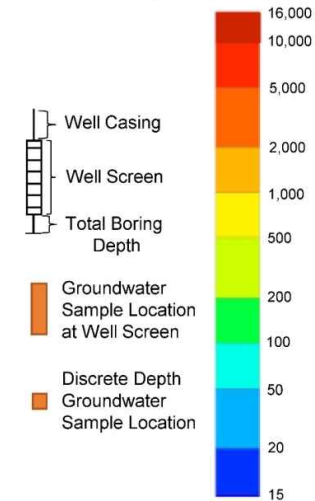


# Extent of Contamination



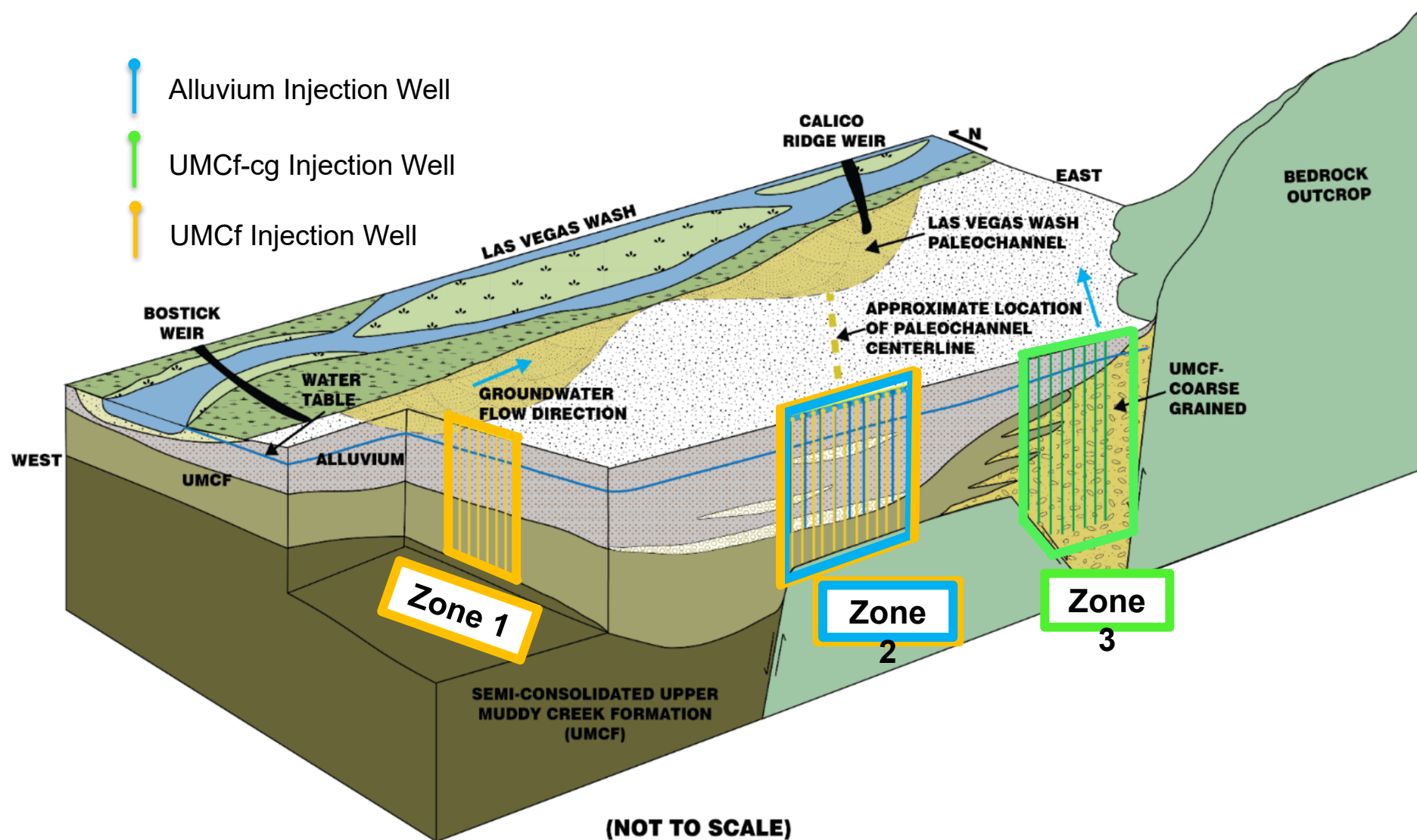
| Constituent         | Concentration  |
|---------------------|----------------|
| Perchlorate (µg/L)  | <0.50 – 16,000 |
| Chlorate (µg/L)     | <10 – 24,000   |
| Nitrate as N (mg/L) | <0.11 – 23     |
| Sulfate (mg/L)      | 640 – 14,000   |

Perchlorate in Groundwater  
(micrograms per liter)

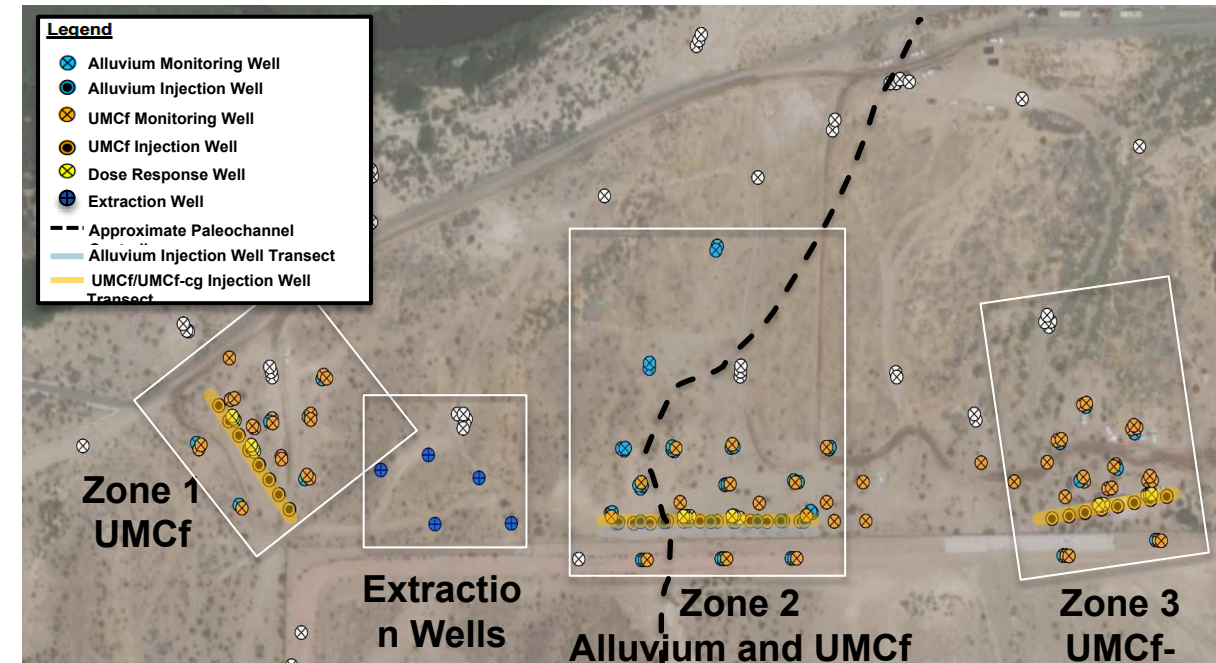
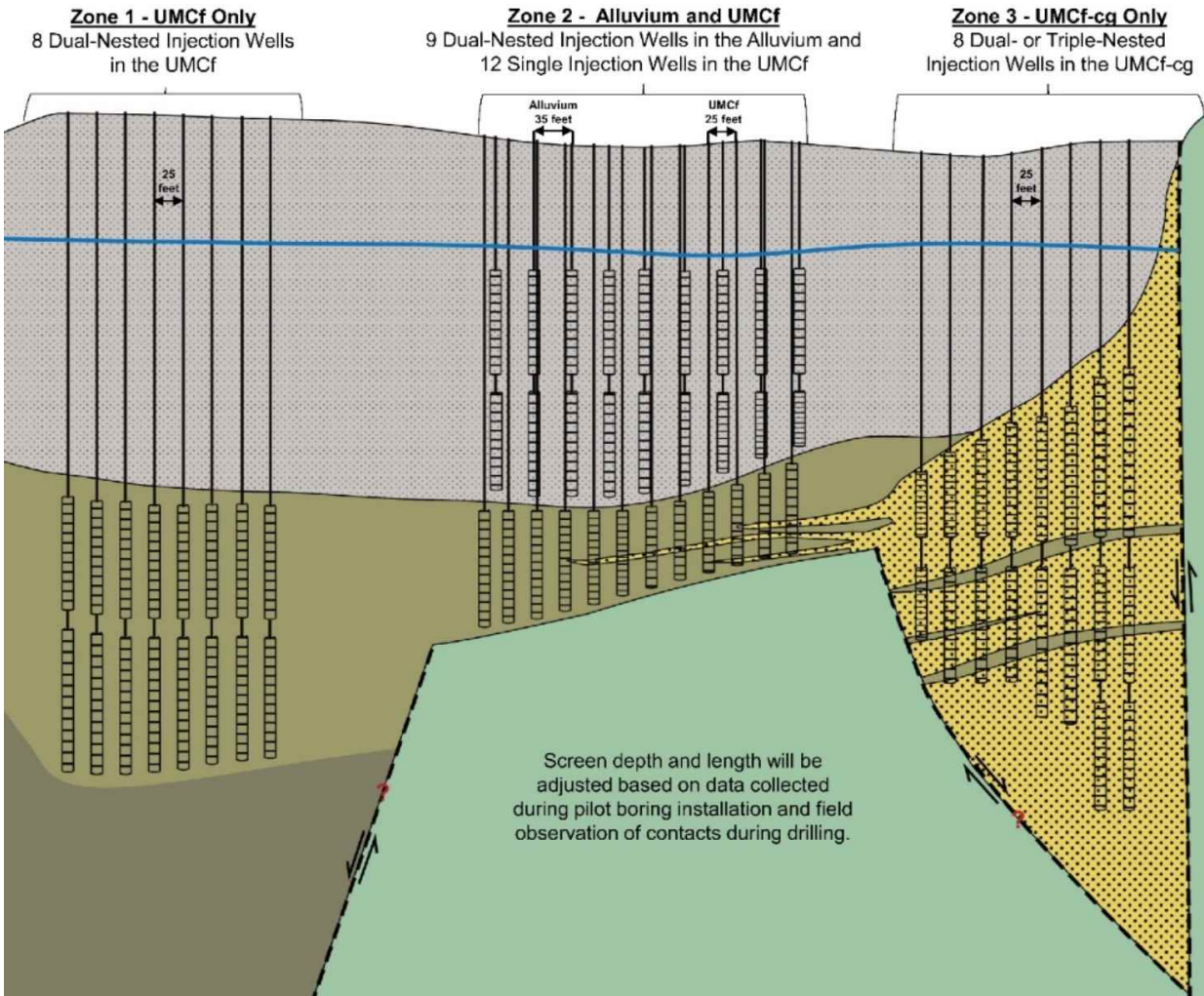


# Pilot Study Implementation

- Targeted 3 isolated zones to evaluate ISB in various lithologies
- Installation of Well Network (254 wells)
- Three Injection Events of Carbon Substrate Solution
- Tracer Dye Study
- Effectiveness Monitoring



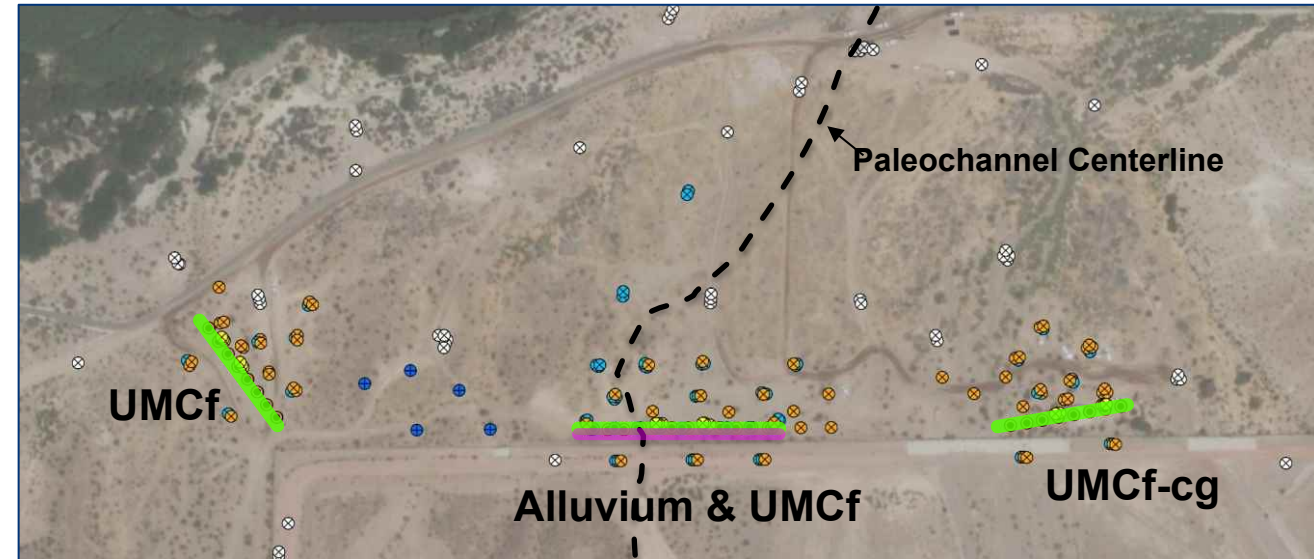
# Pilot Study Implementation – Well Network



- 64 injection wells (single, dual-nested, and triple-cg nested)
- 167 Upgradient, cross-gradient, and downgradient monitoring wells
- 18 dose response wells (dye study monitoring)
- 5 extraction wells

# Pilot Study Implementation – Injections and Dye Study

| Injection Program      | Alluvium                                                                      | UMCf/UMCf-cg                 |
|------------------------|-------------------------------------------------------------------------------|------------------------------|
| Injectate Solution     | Emulsified vegetable oil, glycerin, phosphate solution, sodium sulfite, water |                              |
| Tracer Dye             | Rhodamine WT                                                                  | Fluorescein                  |
| Frequency              | Three Events<br>4-5 months apart                                              | Two events<br>8 months apart |
| Injection Rate         | 15-30 gpm                                                                     | Up to 5 gpm                  |
| Injection Well Spacing | 35 feet                                                                       | 25 feet                      |



# Pilot Study Implementation – Effectiveness Monitoring

## Monitoring Program

- Duration of 18 months
- Charcoal and water samples collected for dye analysis during the first 6 months
- Monthly surface water sampling
- Periodic aquifer testing for pre- and post-injection hydraulic conductivities

| Groundwater Sampling Program         | Alluvium                                                                                                                                             | UMCf/UMCf-cg                  |
|--------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| Sample Frequency                     | Biweekly then Monthly                                                                                                                                | <b>Monthly then Bimonthly</b> |
| Well Network                         | 50 to 850 feet downgradient                                                                                                                          | 25 to 150 feet downgradient   |
| Key Parameters (All Wells)           | Perchlorate, chlorate, nitrate, total organic carbon, and sulfate                                                                                    |                               |
| Additional Parameters (Select Wells) | Metals, total dissolved solids, alkalinity, volatile fatty acids, methane, microbial parameters (phospholipid fatty acids and perchlorate reductase) |                               |

# Tracer Dye Study Results

- Confirmed horizontal and vertical distribution at targeted radius of influence (ROI) (17.5 feet for alluvium; 12.5 feet for the UMCf)
- Shortest travel time to surface water (~850 feet downgradient) was 15 days in alluvium (57 ft/day)
- Fluorescein injected into UMCf appeared in alluvial wells, suggesting upflux into overlying alluvium
- Rhodamine injected into alluvium was detected in UMCf, suggesting some downflux into UMCf

| Lithology | Effective Porosity (percent) | Hydraulic Conductivity (feet/day) | Groundwater Flow Velocity (feet/day) |
|-----------|------------------------------|-----------------------------------|--------------------------------------|
| Alluvium  | 6                            | 100                               | 1 to 13                              |
| UMCf      | 1 to 2                       | 0.5                               | <0.1 to 0.3                          |
| UMCf-cg   | 1 to 3                       | 2                                 | 0.2 to 2                             |

## Notes:

1. Alluvium Groundwater Velocity ~ 90 ft/day near surface water
2. UMCf Groundwater Velocity of ~ 2 ft/day in faulted portion

# Tracer Dye Study Results - Alluvium



# Tracer Dye Study Results - UMCf

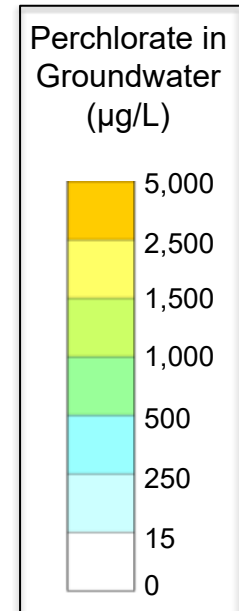
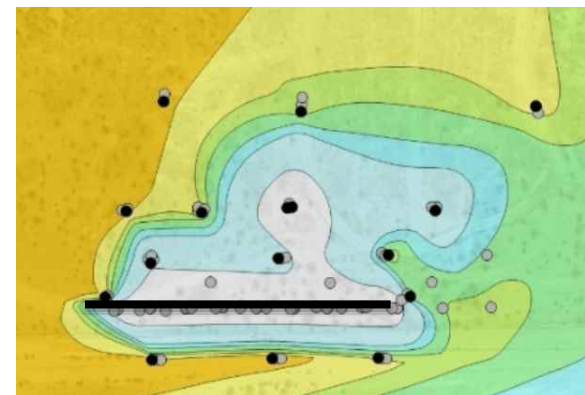
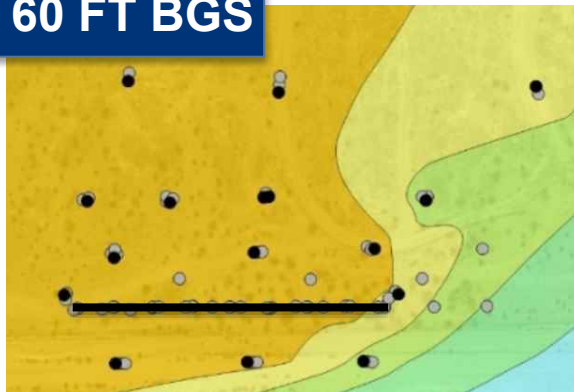


# Effectiveness Monitoring Results – Alluvium

## PRE-INJECTION

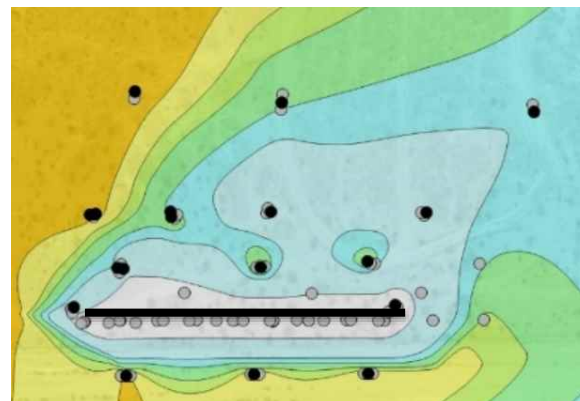
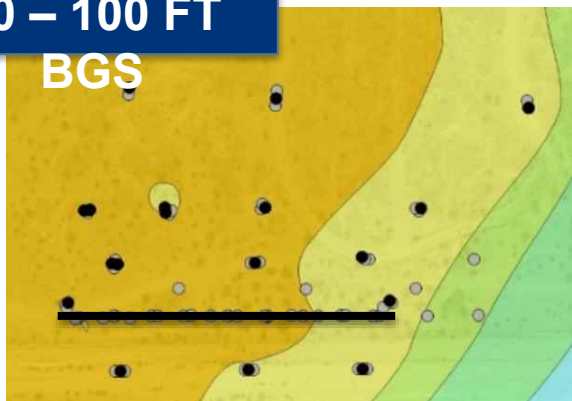
## POST-INJECTION

**35 – 60 FT BGS**



  
100 FEET

**60 – 100 FT BGS**



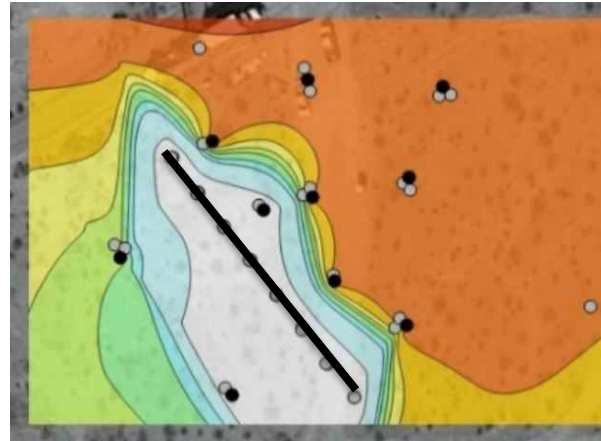
- Perchlorate concentrations in groundwater from cross-gradient ROI wells decreased 80 to 99%
- Strong reductions (97%) observed 200-250 feet downgradient
- Reductions in perchlorate concentrations in both shallow and deep alluvium, but varied based on groundwater velocity

# Effectiveness Monitoring Results – UMCf

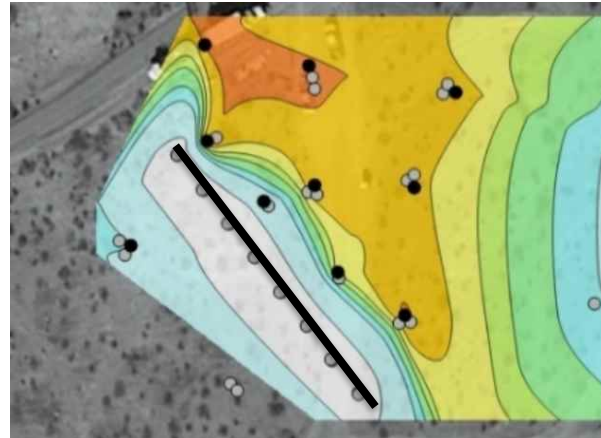
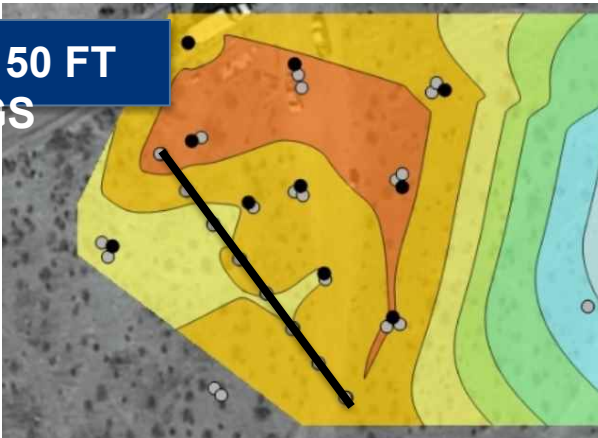
## PRE-INJECTION

## POST-INJECTION

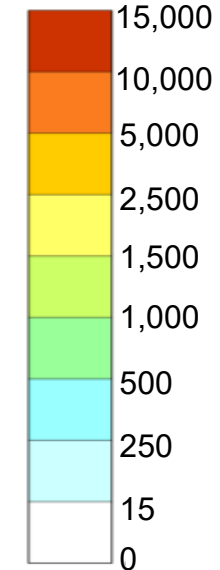
90 – 120 FT BGS



120 – 150 FT BGS



Perchlorate in  
Groundwater  
( $\mu\text{g/L}$ )



50 FEET

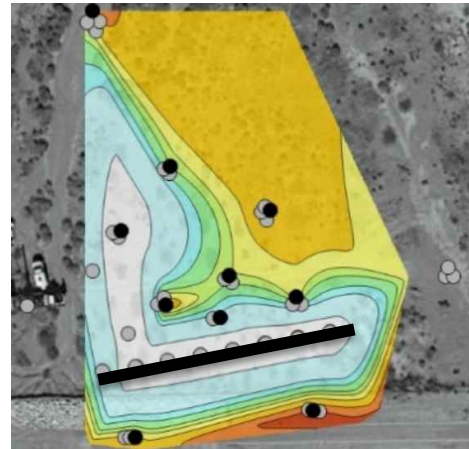
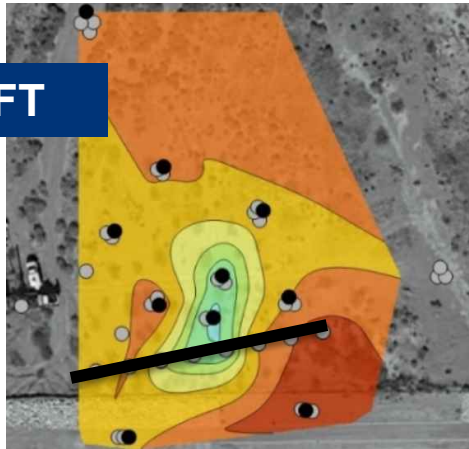
- Upgradient perchlorate concentrations reduced >99% (low effective porosity)
- Reductions generally observed within 25 feet downgradient in UMCf
- Treatment (>99% reduction) observed in alluvium wells 100 to 150 feet downgradient

# Effectiveness Monitoring Results – UMCf-cg

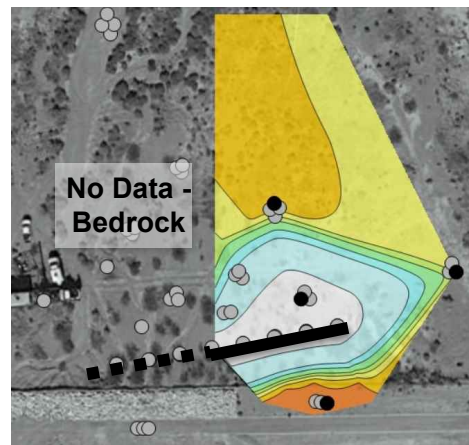
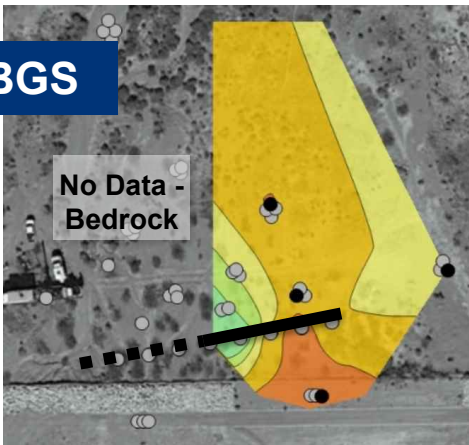
## PRE-INJECTION

## POST-INJECTION

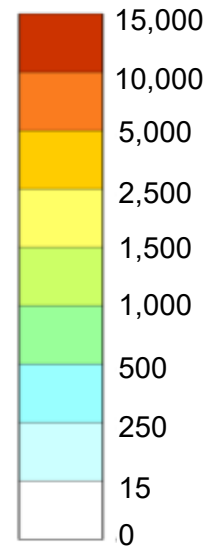
110-150 FT



>150 FT BGS



Perchlorate in  
Groundwater  
( $\mu\text{g/L}$ )



50 FEET

- Reductions in perchlorate concentrations observed in UMCf-cg farther downgradient than in UMCf
  - 99% reductions 150 feet downgradient
  - Up to 60% reductions in groundwater from wells up to 250 feet downgradient
- No change in overlying alluvium or upgradient in the UMCf-cg

# Conclusions and Lessons Learned

- Periodic ISB injections created biologically active zones in all three lithologic units (alluvium, UMCf, and UMCf-cg)
- Denitrification occurred rapidly, followed by perchlorate and chlorate degradation concurrently
- Reductions in perchlorate concentrations observed in both shallow and deep alluvium, but higher reductions observed in intervals with lower groundwater velocities (more residence time)
- Periodic ISB injections gradually increased the overall biodegradation in groundwater over time, creating a more uniform biologically active zone over time
- ISB in UMCf-cg was more effective than ISB in UMCf due to difference in lithology:
  - UMCf – Pronounced preferential flow pathways and upward vertical gradient resulted in upflux into overlying alluvium downgradient of injection well transect
  - UMCf-cg – Coarser material and higher groundwater flow resulted in improved injectate distribution
  - More perchlorate mass destroyed in UMCf-cg than UMCf

# Conclusions and Lessons Learned

- Dual treatment in both alluvium and UMCf (Zone 2) resulted in more mass being treated over time and/or improved use of carbon substrate in both alluvium and UMCf
- Nested injection wells (dual- and triple-nested) in large saturated intervals successfully distributed the injectate vertically and resulted in cost savings of 30-40% compared to clustered single injection wells
- Nested injection wells could allow application of injectate at targeted depth intervals and/or lithologic units at varied frequencies/doses
- Injection wells within the alluvium, UMCf and UMCf-cg maintained injectability over three injection events (minimal pressure increases and/or reduced injection rates)