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Developing Long-Term Monitoring Strategies for Radiological Contamination Through Modeling & Machine Learning

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Presentation to Federal Remediation Technology Roundtable

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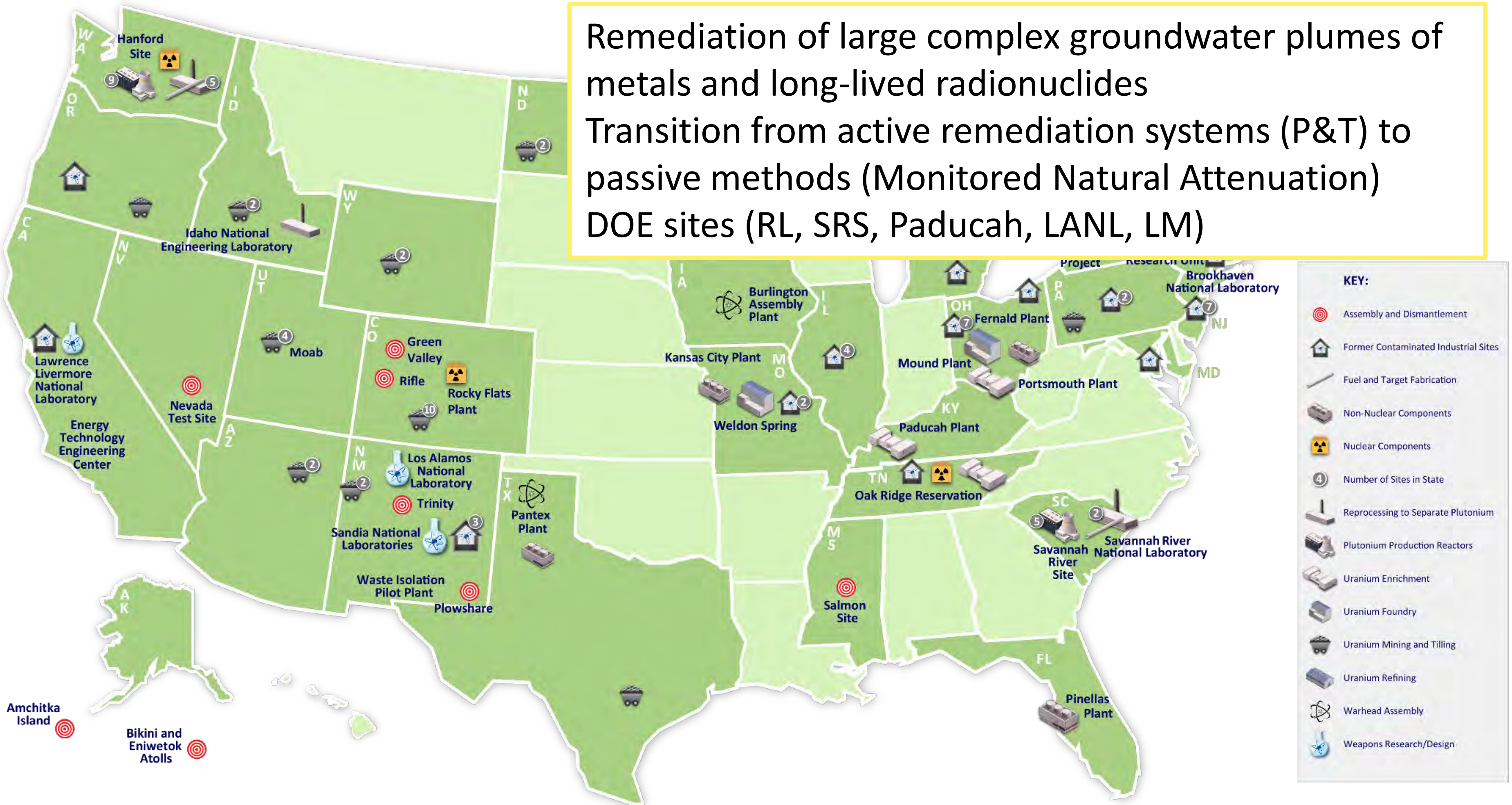
FLUOR • NEWPORT NEWS NUCLEAR • HONEYWELL

The DOE - EM Challenge

- Remediation of large complex groundwater plumes of metals and long-lived radionuclides
- Transition from active remediation systems (P&T) to passive methods (Monitored Natural Attenuation)
- DOE sites (RL, SRS, Paducah, LANL, LM)



107 major sites (1995) → 16 sites (2016)

Need for a New Approach

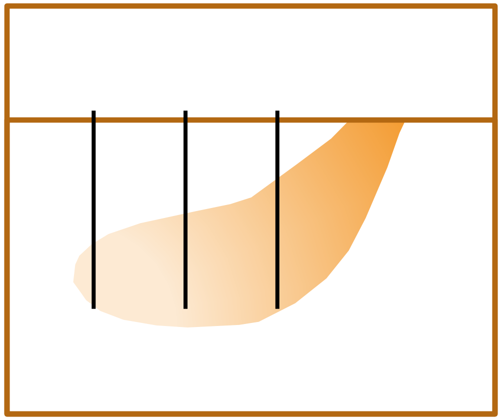
Current LTM approaches developed for monitoring active remediation sites

- **Pump-and-treat, excavation, etc.**
  - Contaminant removed from subsurface until no future hazard is possible
  - LTM to make sure sufficient mass removed or destroyed

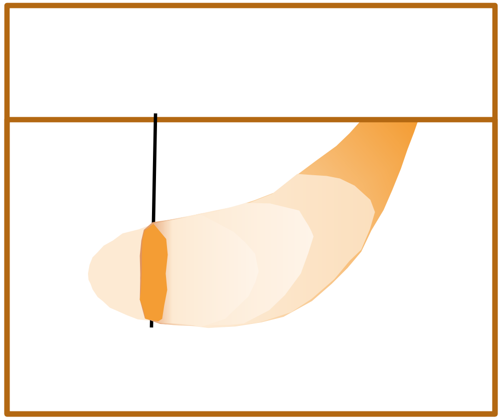
Current LTM approaches not efficient for sites at which attenuation-based remedies deployed

- **Measurements are not predictive of future remedy failure**
- **Consist of expensive measurements that provide minimal information**
  - Contaminant concentrations will be at or below MCLs until conditions change
- **New approach needed**

Pump-and Treat



Attenuation-Based



New Paradigm:
Long-Term Monitoring as a Separate Monitoring Stage

New Long-Term Monitoring Paradigm

Characterization	Remedy Effectiveness	Long-Term
• Define nature & extent of contamination • Develop conceptual model	• Evaluate whether remedy is working • Refine conceptual model to include remedy	• Monitor for systemic changes that potentially mobilize attenuated contaminants
• Measure contaminant concentrations at numerous point locations guided by plume architecture	• Optimize characterization well network and add wells focused on treatment system • Measure contaminant concentrations	• Monitor boundary conditions • Monitor master variables • Use spatially integrative measures of system • Emphasize monitoring in Zones of Vulnerability

Remedy Installation →

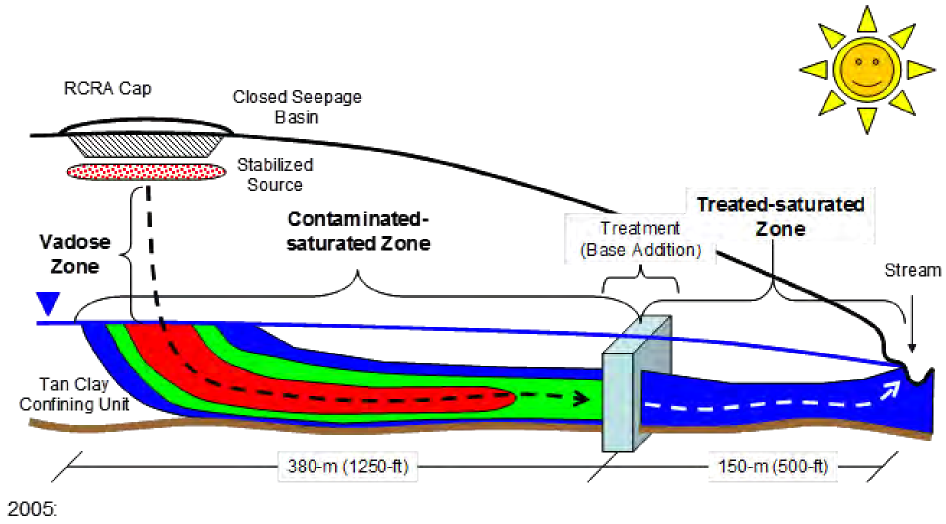
Final Stages of Active Remediation →

Virtual Testbed

How do you test a new paradigm
for remediation and long term monitoring?

✓Use historical monitoring data from a waste site with a long history and documented changes to boundary conditions

✓Develop a virtual test bed using 3D reactive flow and transport model

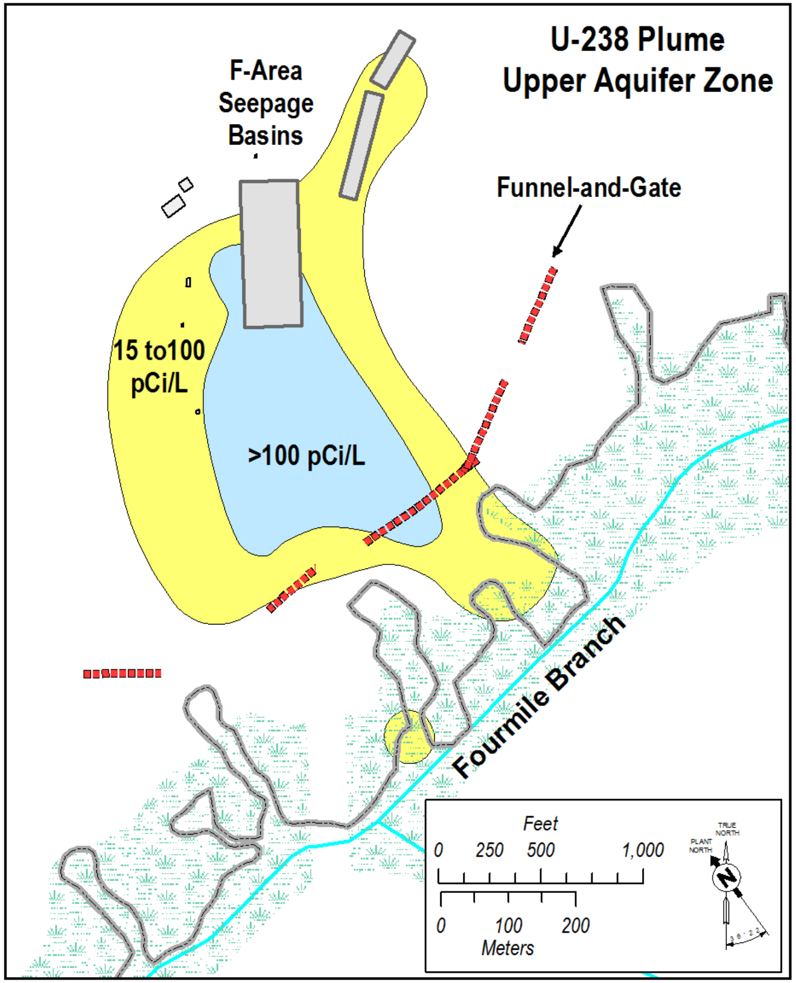


F-Area Seepage Basins

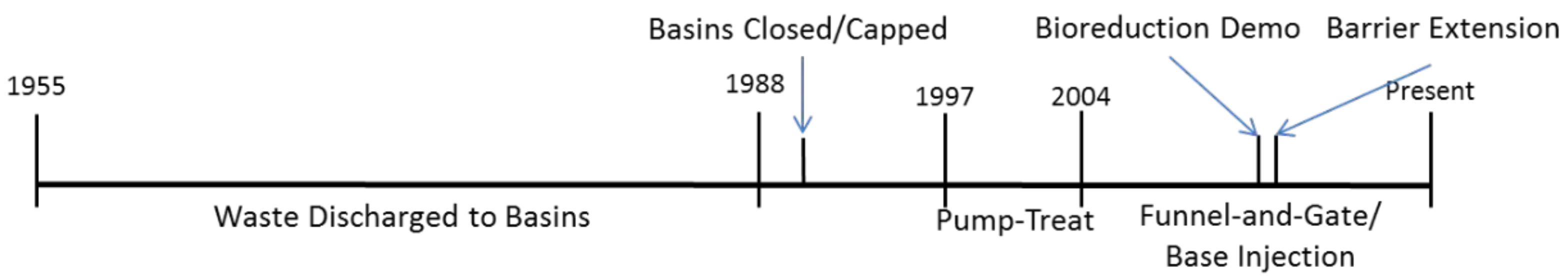
Groundwater plume resulted from 30 years of discharge of low activity wastewater from an industrial nuclear facility. Major contaminants of concern are uranium, tritium, strontium-90 and iodine-129.

Contaminated groundwater crops out at surface in wetlands and Fourmile Branch

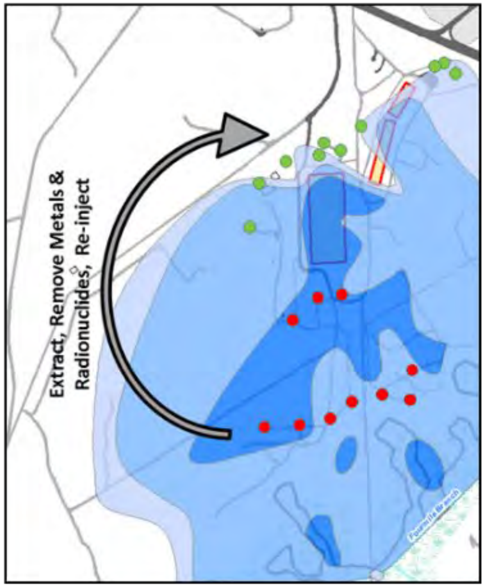
Remediation has focused on limiting migration of contaminants and reducing concentrations in surface water



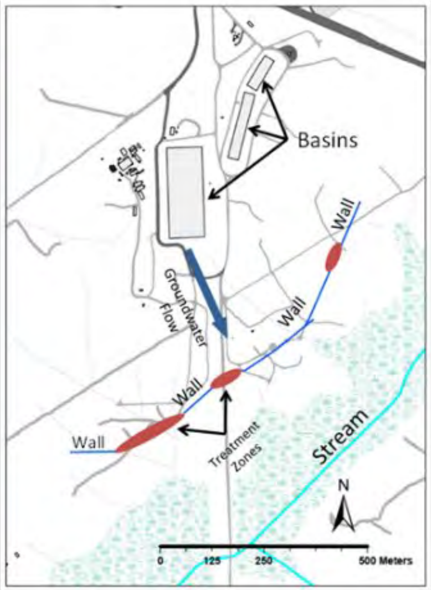
Remediation History



Basin Operation



Pump/Treat/Re-inject



Funnel-Gate/Base Injection

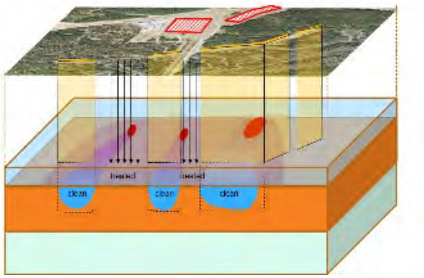
Comprehensive Attenuation-Based Remedy

Basin Capping/Closure

- Contaminants remain in basin soils
- Prevents infiltration that would drive contaminants deeper

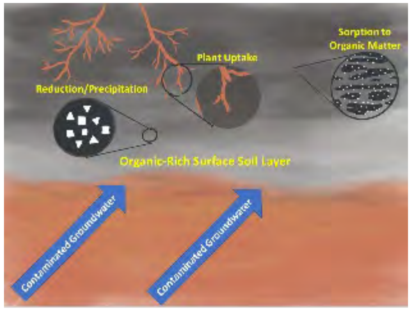
Subsurface Barrier w/Treatment Zones

- U and Sr-90 attenuated by raising pH
- I-129 attenuated by precipitation of AgI



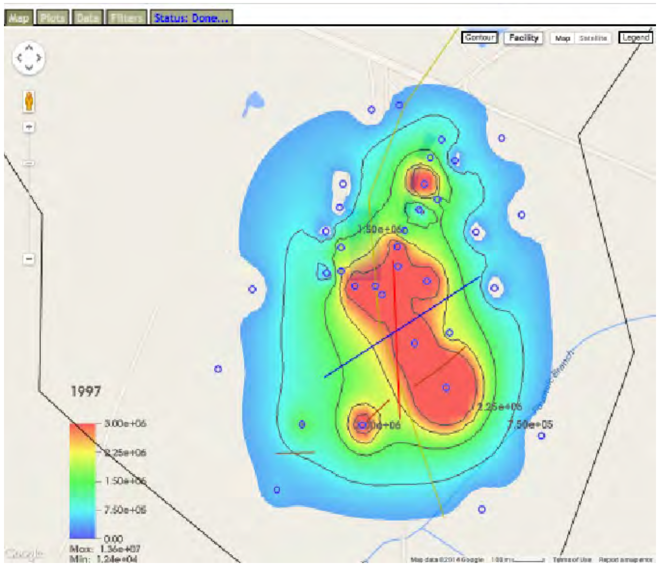
Wetlands

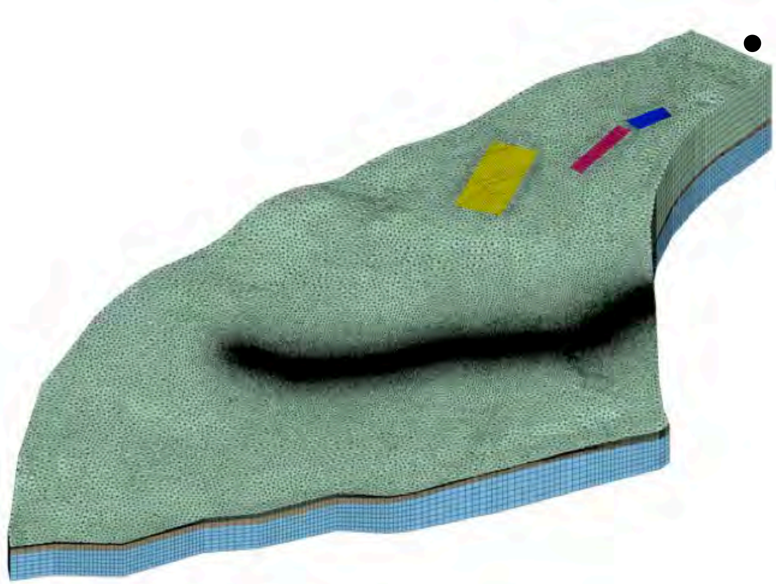
- Contaminants attenuated by processes in organic-rich soils
- Sorption to organic matter, plant uptake, reduction/precipitation for some contaminants



F-Area Virtual Testbed

- Field Test Bed
  - Historical datasets
    → Advanced statistical analysis
  - Data mining
  - Machine learning



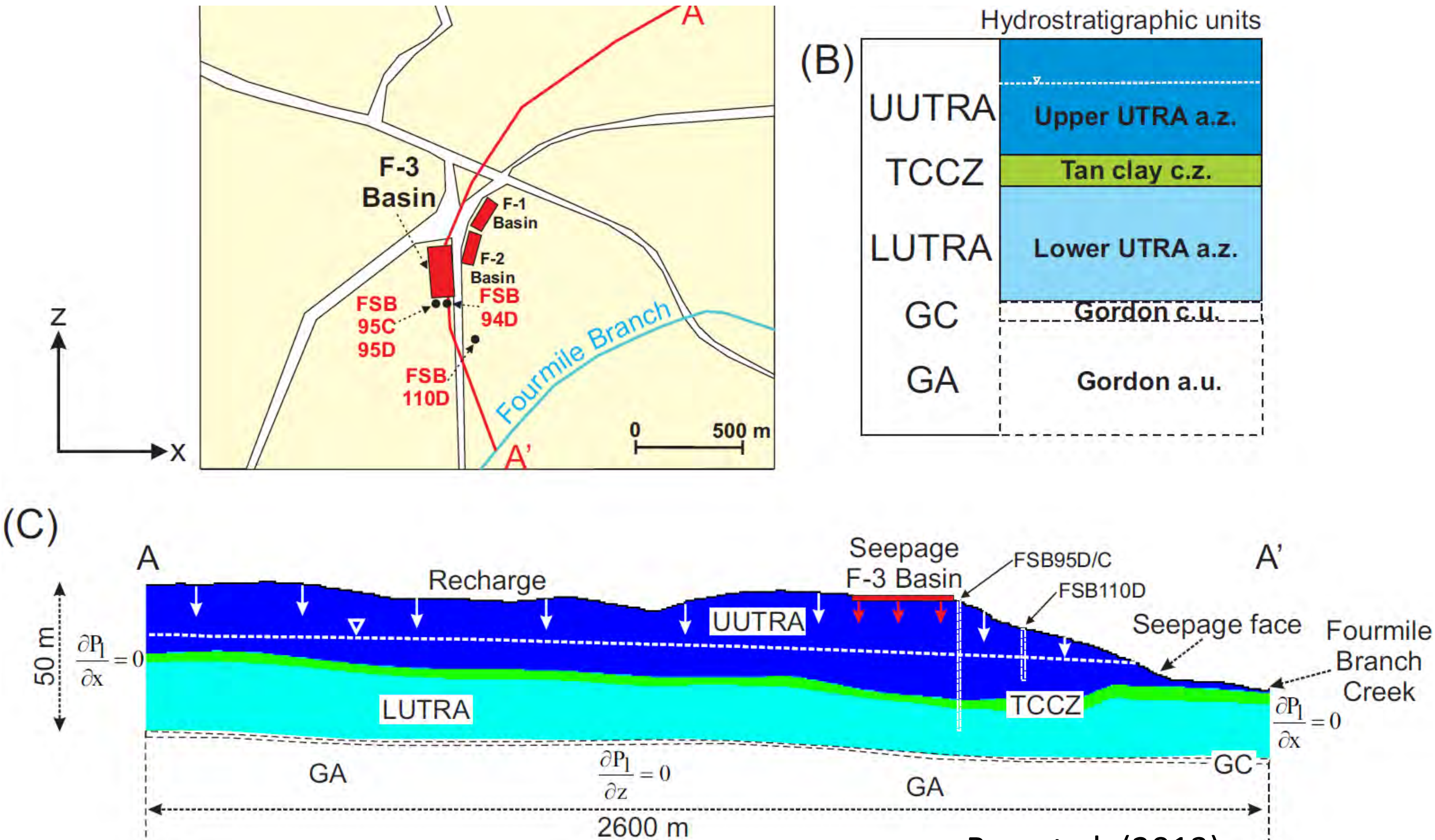


- **Virtual Test Bed**
  - 3D reactive transport simulations
  - Super computers

→ System understanding, long-term predictions, testing different methods

We put science to work.™

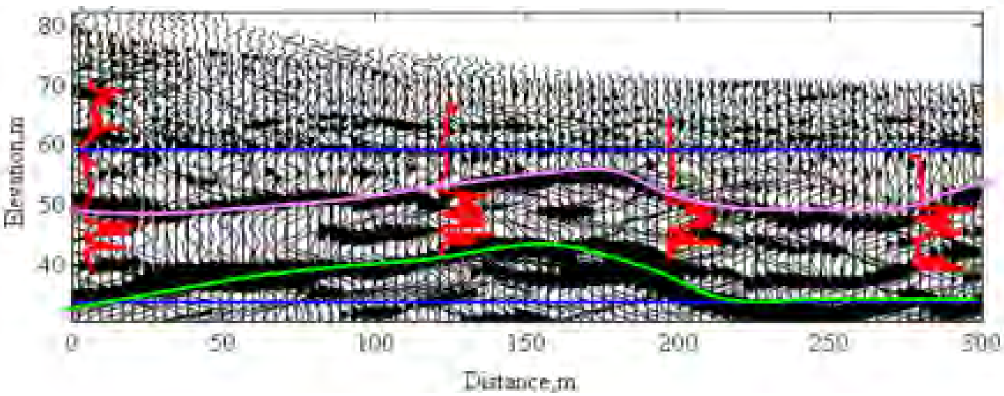
Flow/Transport Model

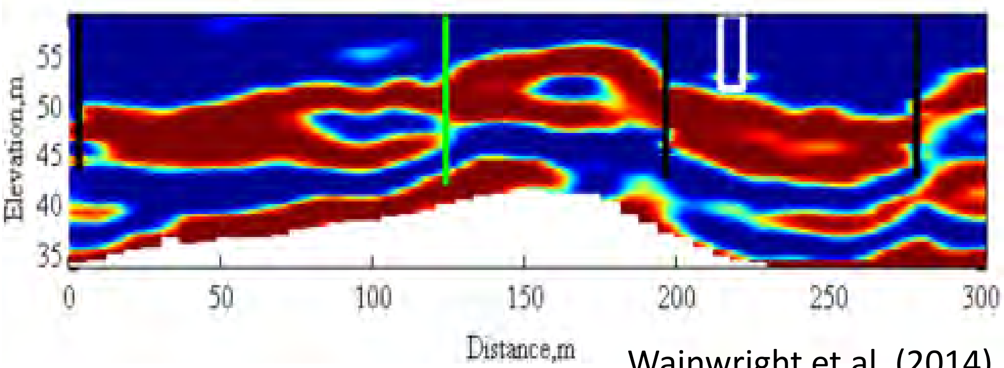


Bea et al. (2013)

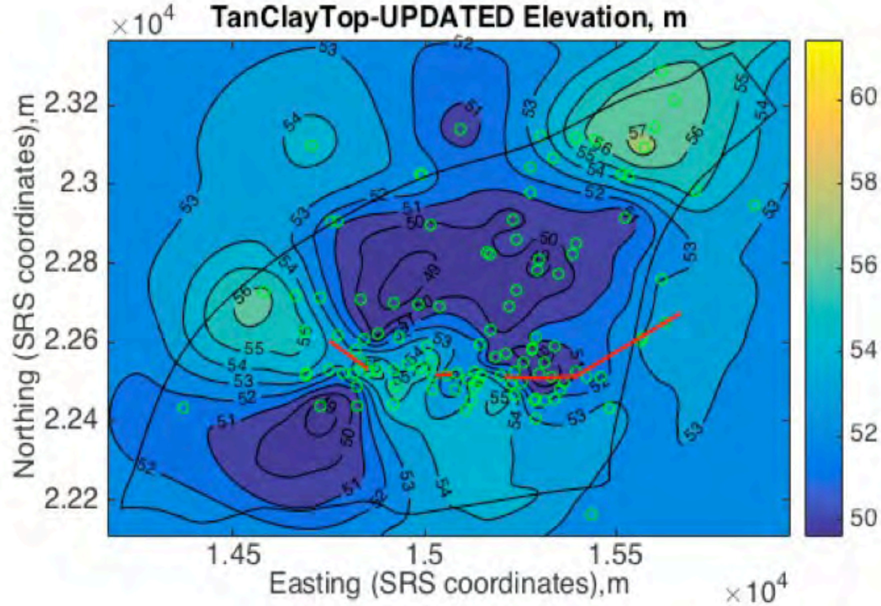
Seismic Layers

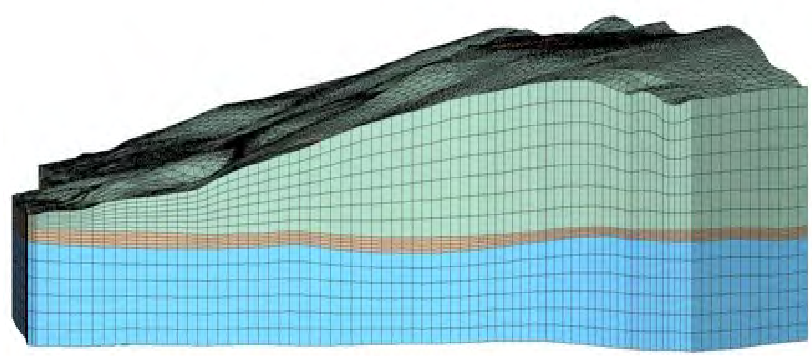
Surface Seismic Method



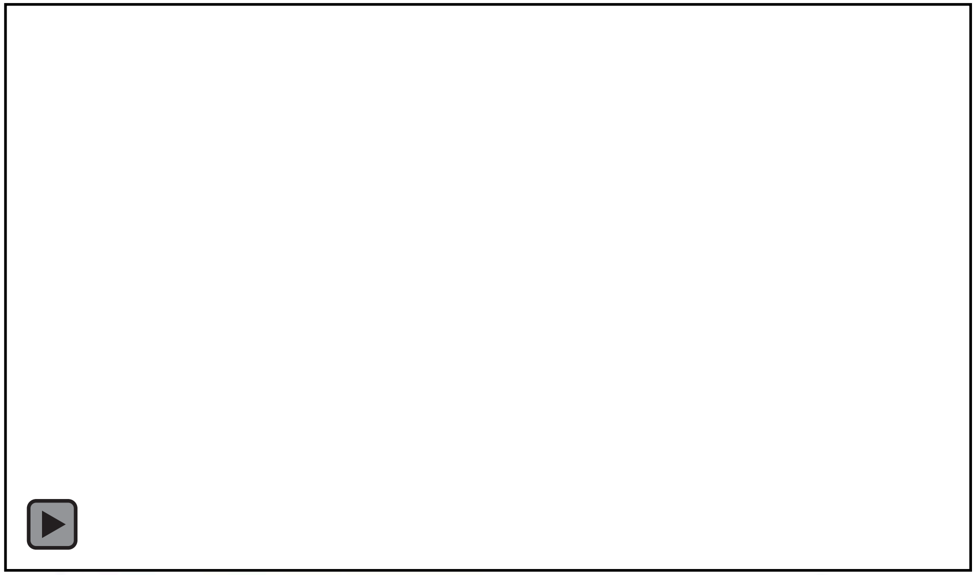


Wainwright et al. (2014)

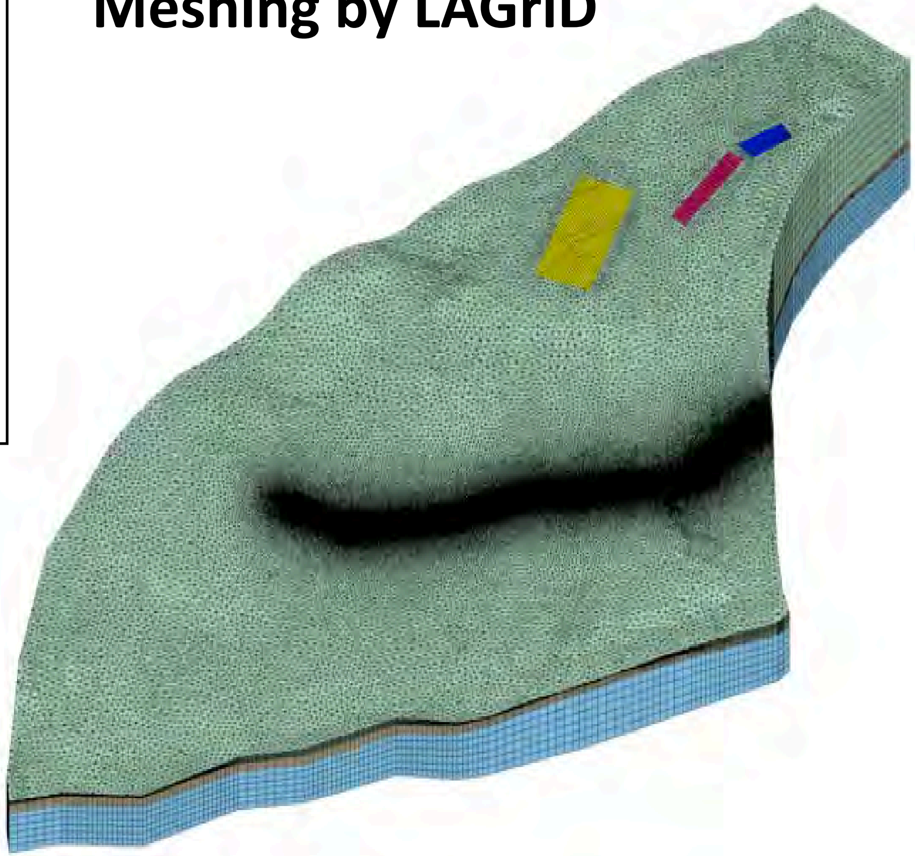


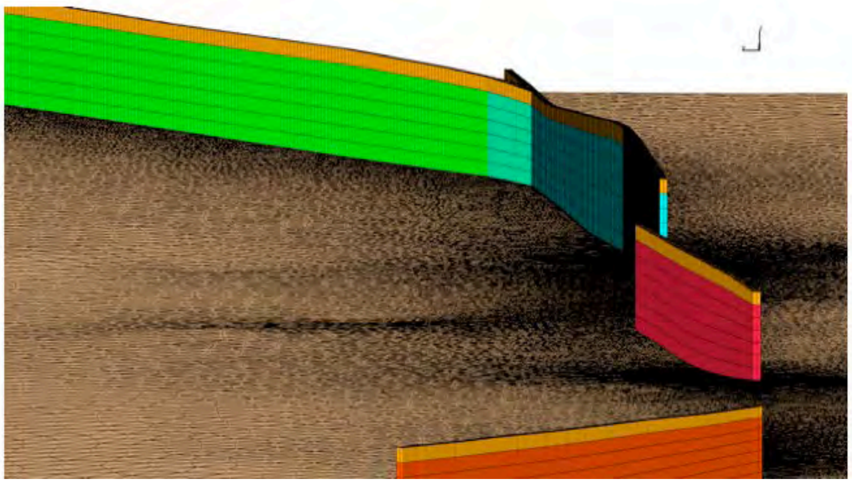


3D Mesh for Artificial Barriers



Meshing by LAGriD





Geochemistry Development

- Complex geochemistry
  - pH Dependent
  - Aqueous complexation
  - Surface complexation
  - Mineral dissolution/precipitation
  - Cation exchange
  - Decay

Surface complexation, cation exchange

Reaction	$\log_{10}$ K (25° C)
[(1)] Equilibrium Surface Complexation	
$(>SO)UO_2^+ \leftrightarrow >SOH - H^+ + UO_2^{2+}$	-0.44
[(2)] Cation Exchange	K (25 C)
$NaX \leftrightarrow Na^+ + X^-$	1.0
$CaX_2 \leftrightarrow Ca^{2+} + 2X^-$	0.316
$AlX_3 \leftrightarrow Al^{3+} + 3X^-$	1.71
$HX \leftrightarrow H^+ + X^-$	0.025

Mineral dissolution/precipitation

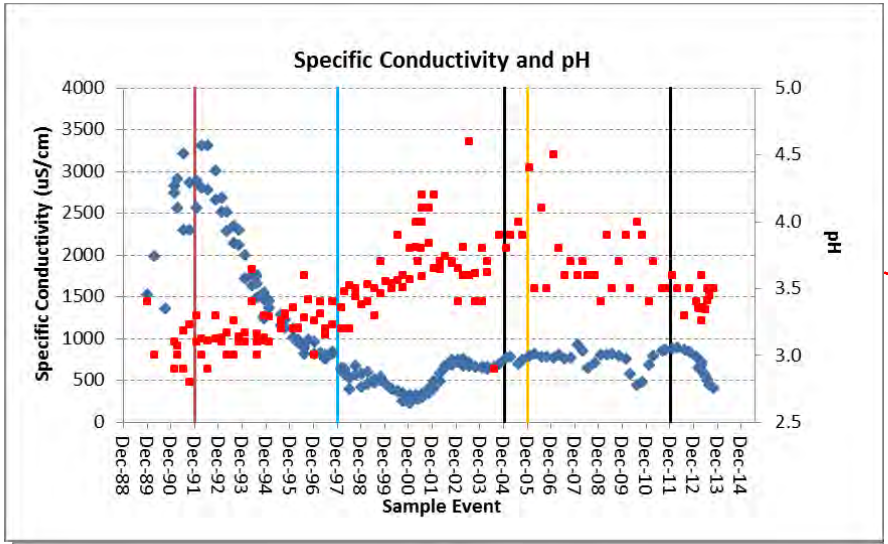
Reaction	$\log_{10}$ K (25° C)	Ref.
$Quartz \leftrightarrow SiO_2(aq)$	-3.7501	(1)
$Kaolinite \leftrightarrow 2Al^{+3} + 2SiO_2(aq) + 5H_2O - 6H^+$	7.57	(2)
$Goethite \leftrightarrow Fe^{+3} + 2H_2O - 3H^+$	0.1758	
$Schoepite \leftrightarrow UO_2^{+2} + 3H_2O - 2H^+$	4.8443	(1)
$Gibbsite \leftrightarrow Al^{+3} + 3H_2O - 3H^+$	7.738	(3)
$Jurbanite \leftrightarrow Al^{+3} + SO_4^{-2} + 6H_2O - H^+$	-3.8	(4)
$Basaluminite \leftrightarrow 4Al^{+3} + SO_4^{-2} + 15H_2O - 10H^+$	22.251	(4)
$Opal \leftrightarrow SiO_2(aq)$	-3.005	(5)

Aqueous complexation

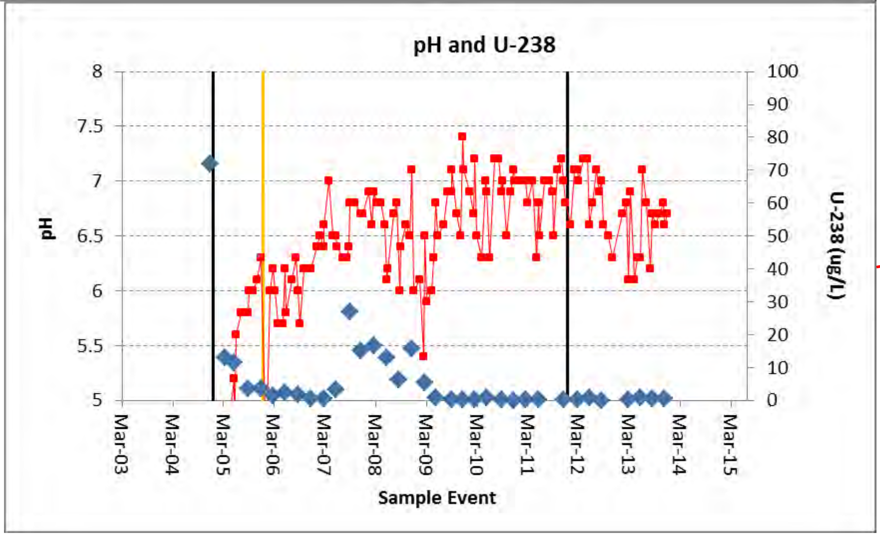
Reaction	$\log_{10}$ K (25° C)
$OH^- \leftrightarrow H_2O - H^+$	13.99
$AlOH^{2+} \leftrightarrow Al^{3+} + H_2O - H^+$	4.96
$Al(OH)_2^+ \leftrightarrow Al^{3+} + 2H_2O - 2H^+$	10.59
$Al(OH)_3(aq) \leftrightarrow Al^{3+} + 3H_2O - 3H^+$	16.16
$Al(OH)_4^- \leftrightarrow Al^{3+} + 4H_2O - 4H^+$	22.88

(and more)

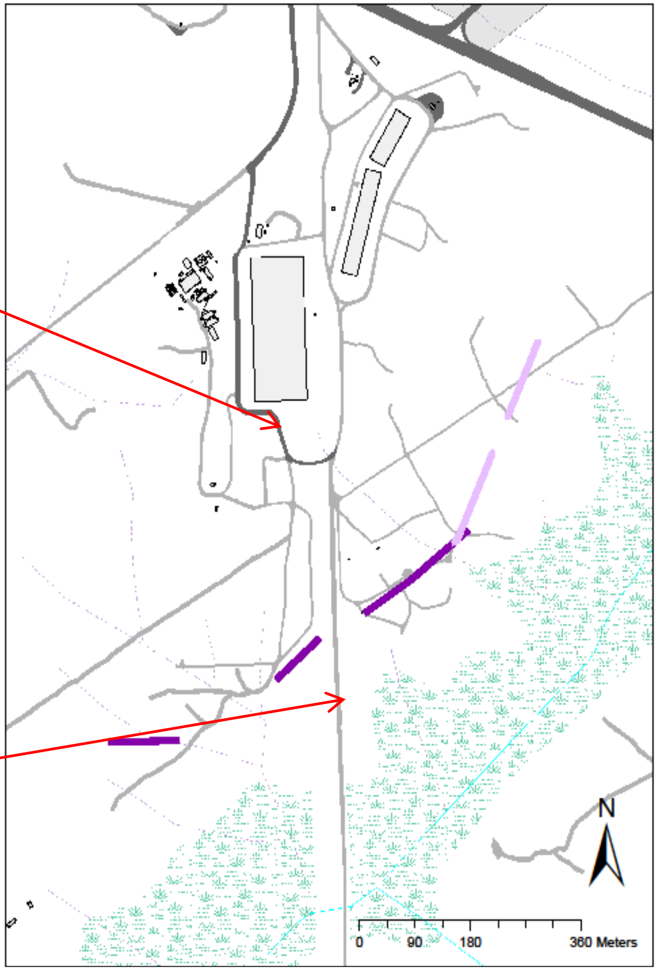
Plume Visualization



Specific Conductivity and pH
Specific Conductivity (uS/cm)
pH
Sample Event



pH and U-238
pH
U-238 (ug/L)
Sample Event



N
0
90
180
360 Meters

Complexities

Lots of “noise” in the measurements

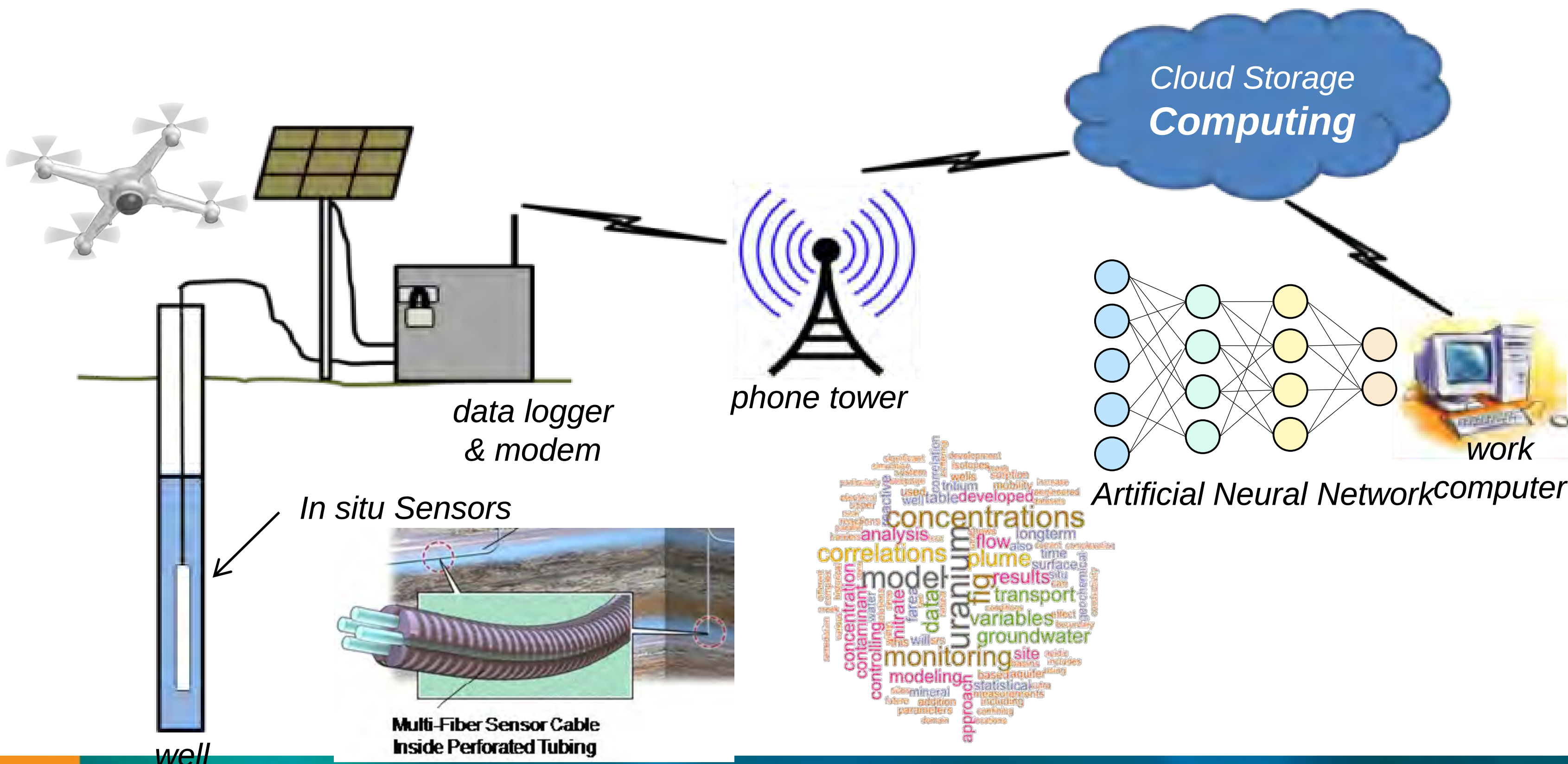
Small water level changes cause significant changes in measurement of stratified plume.

Times scale of change -- Daily, Seasonal, Climatic

What is a significant change? -- Determination of trigger levels.

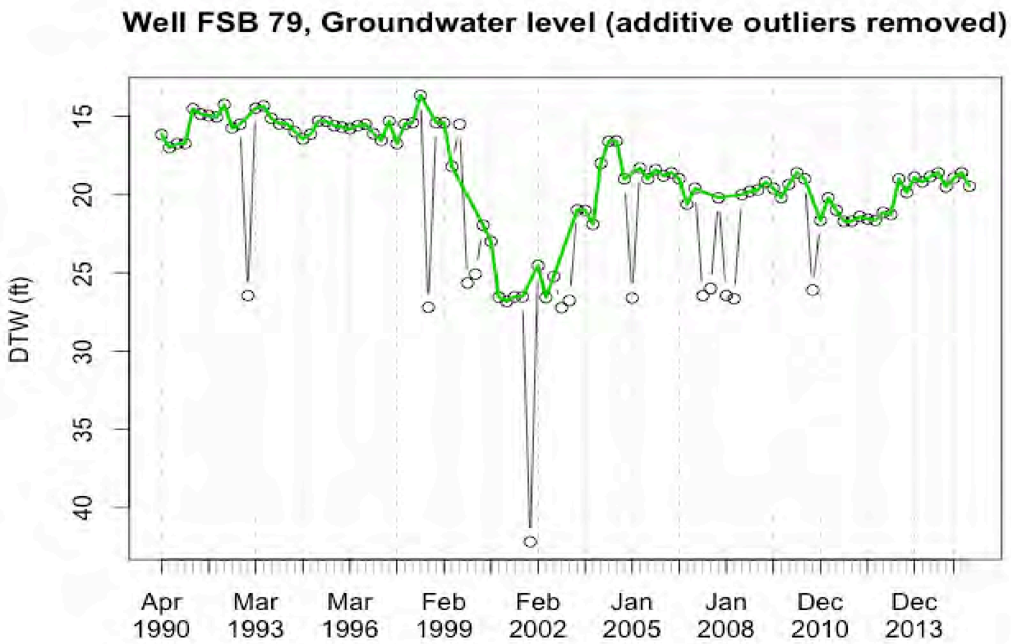
Remote Sensing

New sensing technologies for automated remote continuous monitoring -- In situ sensors, geophysics, fiber optics, UAVs



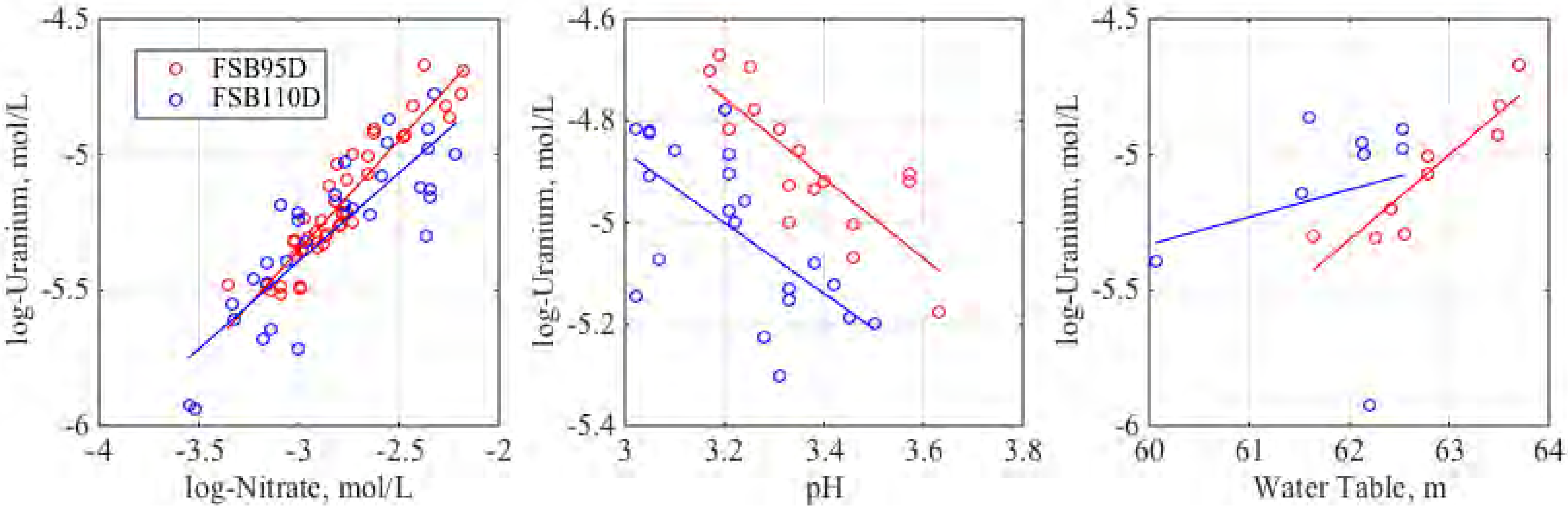
Big Data

Automated QA/QC



- Remove outliers or noise using smoothing
- Gap filling
- Detect significant changes

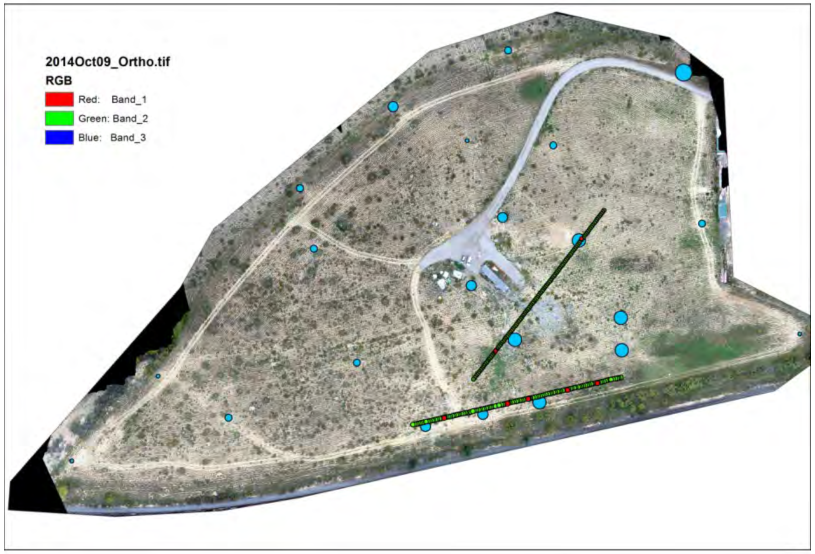
In situ Variables vs. Contaminants

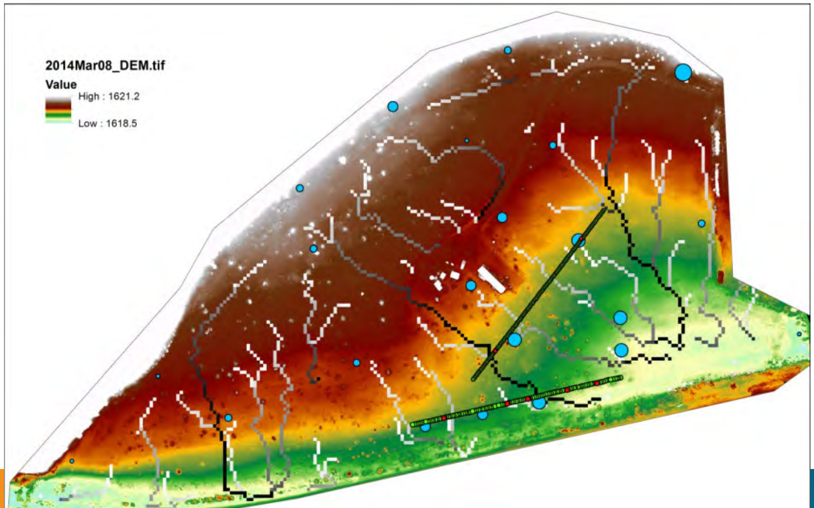


→ Feasibility of In situ Monitoring

Drone-based Sensing Technologies

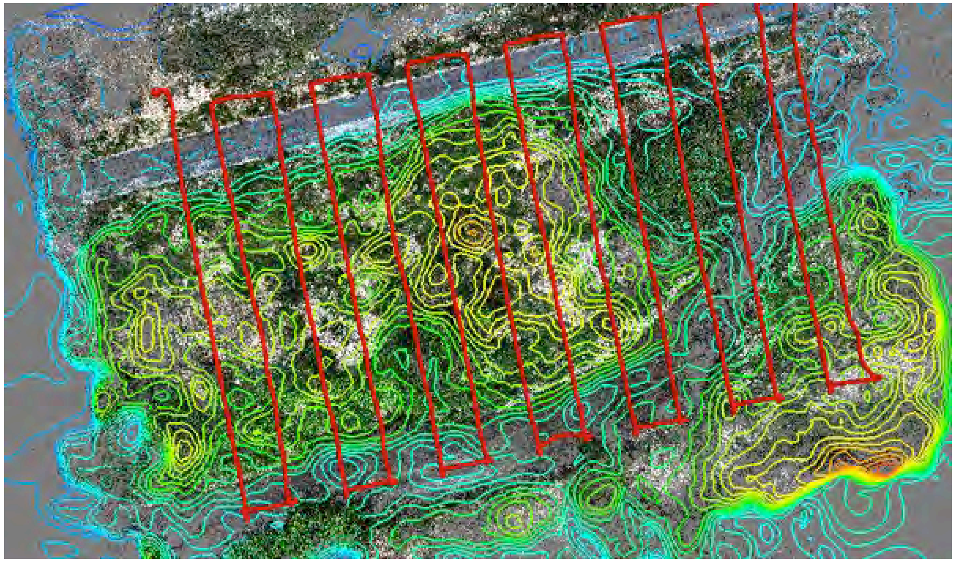
Soil Moisture/Surface Drainage Mapping





Courtesy to Dafflon et al.

Fukushima Gamma Source Mapping



Courtesy to Kai Vetter et al.

- Microtopography
- Surface deformation
- Vegetation dynamics/characteristics
- Surface temperature
- Radioactive contamination

Summary

- Real/Virtual Test Bed at SRS F-Area
  - Data analysis confirmed the feasibility of in situ monitoring
  - ASCEM 3D flow and transport simulations quantified the correlations (spatially and temporally variable) but also the future trajectory
  - UQ/sensitivity analysis: the long-term feasibility of monitoring
- Cost-effective strategies for long-term monitoring of contaminants (incl. Tritium)
  - **In situ sensors, data streaming** and **data analytics** for automated continuous monitoring
  - **Advanced technologies**: geophysics, fiber optics, UAVs
  - **Data Analytics: QA/QC, correlations** between master variables and contaminant concentrations
  - **Integrated approach** (data + modeling) for system understanding/estimation

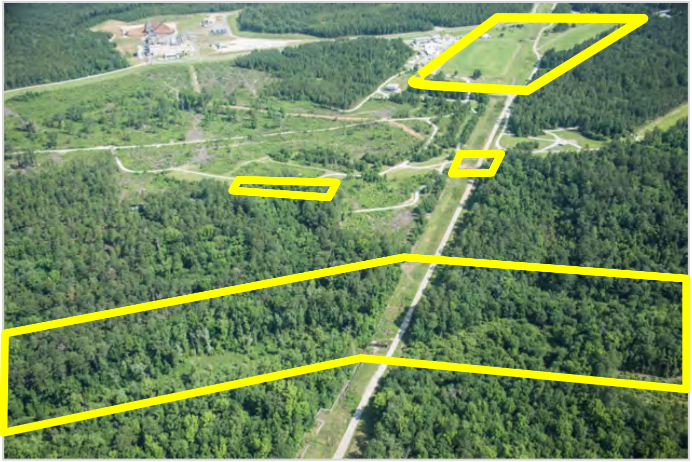
Zones of Vulnerability

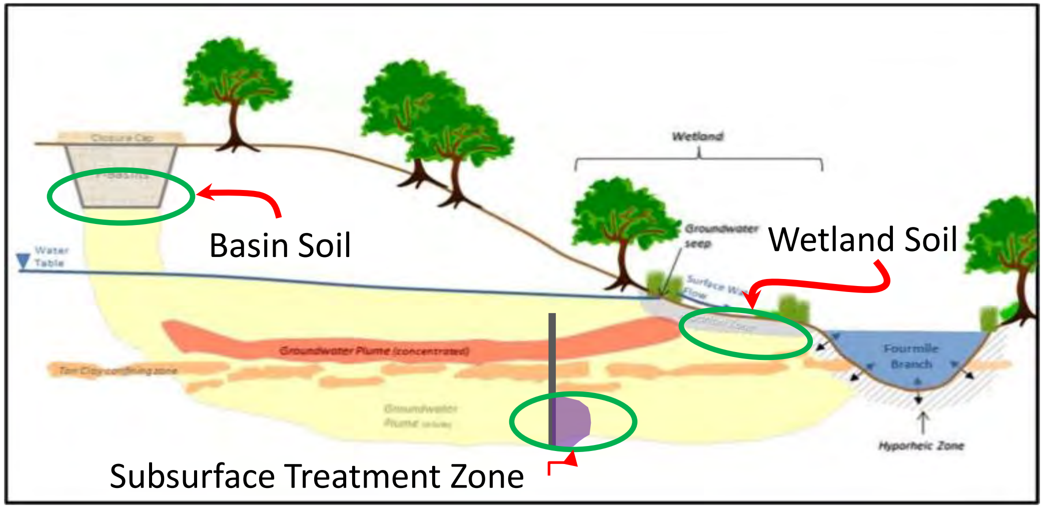
Long-Term Monitoring

- Monitor for systemic changes that potentially mobilize attenuated contaminants

- Emphasize monitoring in Zones of Vulnerability
- Monitor boundary conditions
- Monitor master variables
- Use spatially integrative measures of system

At a contamination site where attenuation-based remedies were used, zones of vulnerability are the locations in the system where contaminants are attenuated and subject to remobilization





Establishing Action Criteria

Action criteria, or "trigger levels", define the window of parameter values, conditions, or rate of change of conditions that require more detailed monitoring

- Manual survey of conditions
- Analysis of samples for contaminant concentrations

Trigger levels established using integrated approach

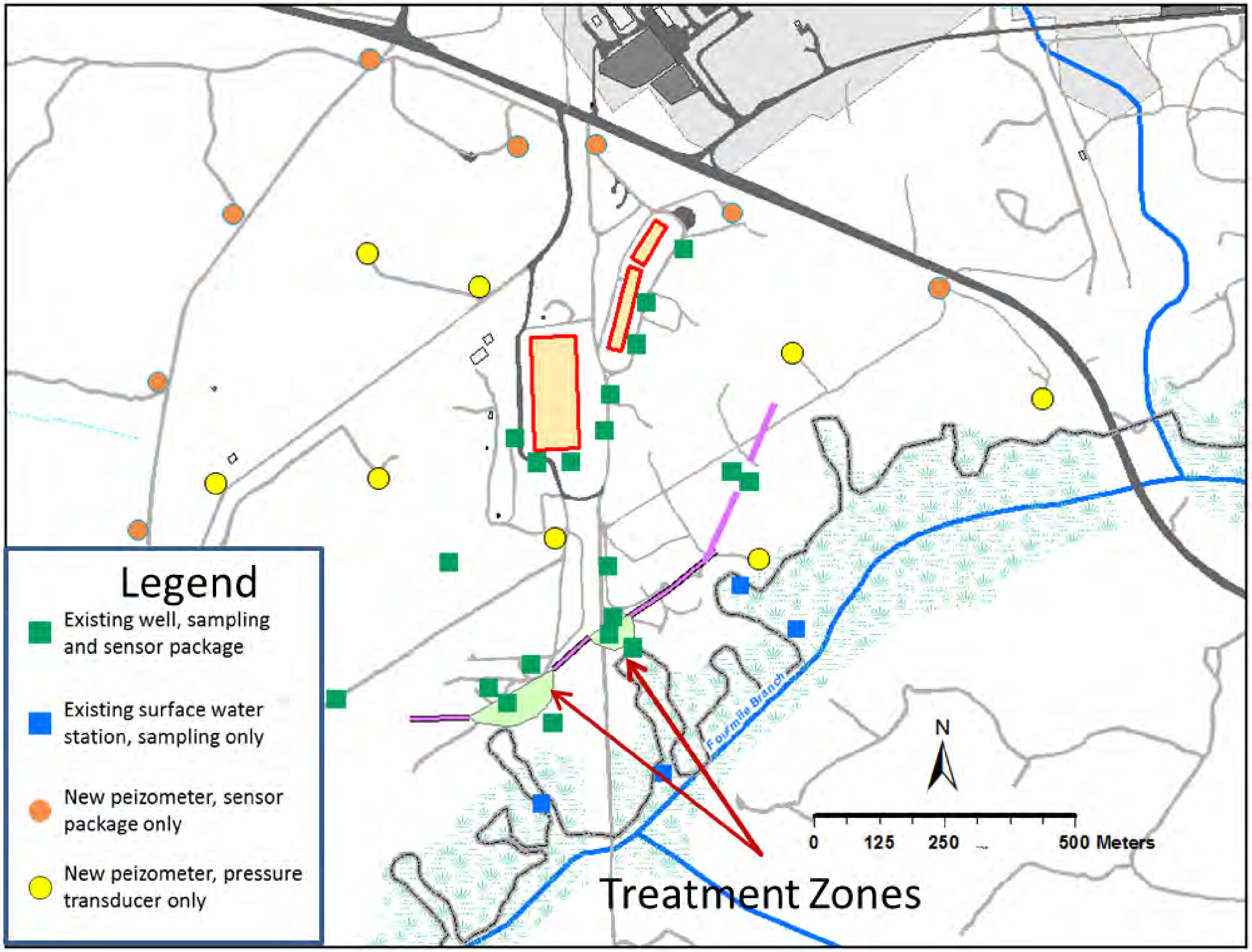
- Geochemical knowledge of contaminant behavior
- Predictive modeling
- Data analytics

Example LTM Plan for F-Area Seepage Basins

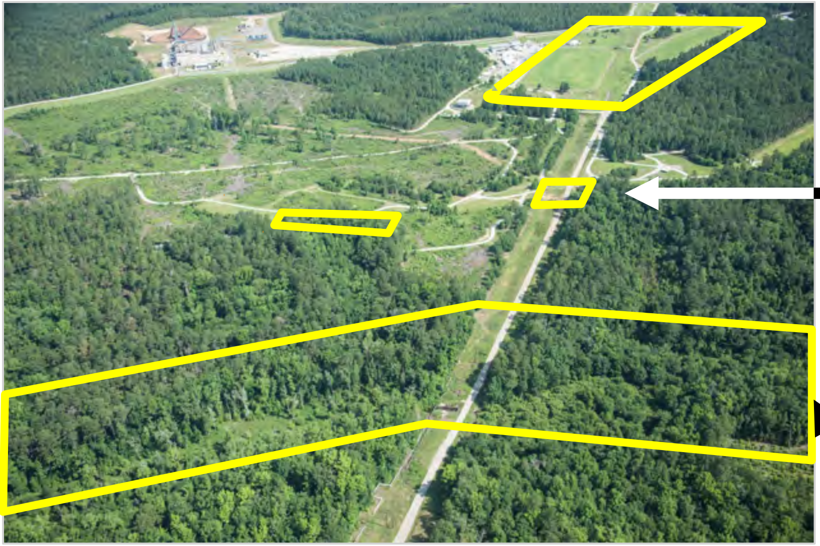
Objective: To detect systemic changes that could lead to mobilization of attenuated contaminants from zones of vulnerability

- **Basin Caps**
  - Primarily spatially integrative tools
  - Downhole sensors in compliance wells to measure water levels and master variable
- **Subsurface Treatment Zones**
  - Primarily downhole sensors to monitor water levels and master variables
- **Wetlands**
  - Combination of spatially integrative tools and sensors in surface water to measure master variables
- **Additional subsurface sensors to measure water levels and master variables in groundwater**
  - Background
  - Upgradient of zones of vulnerability

Potential Network of Point Source Measurements



Potential Use of Integrative Tools



UAV & Satellite Imaging

- Evidence of degradation of cap

Geophysics

- Evidence of increased infiltration through cap

Potentially geophysics to image subsurface treatment zones

UAV & Satellite Imaging

- Seep locations, hot spots, evapotranspiration, topographic changes, vegetation changes, etc.

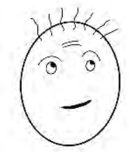
Distributed Fiber Optic Sensors

- Seep locations, moisture content of soils, specific conductance, gamma emissions

Benefits of New Paradigm for Long-Term Monitoring

- Focusing on vulnerabilities using point source and integrative measurements provides more complete picture of conditions at the site
- Monitoring of conditions that can mobilize attenuated contaminants, rather than just contaminants themselves, facilitates proactive decisions
  - *Just measuring contaminant concentrations (a lagging indicator) results in crisis when concentrations increase*
    - Little time to understand why concentrations are increasing and to consider appropriate actions
    - Crisis mode decisions

  - *New paradigm emphasizes measurement of leading indicators that warn of potential problem*
    - Allows ample time to assess situation and consider appropriate actions and make better decisions



- New paradigm is more efficient
  - *Large long-term cost savings for taxpayer*