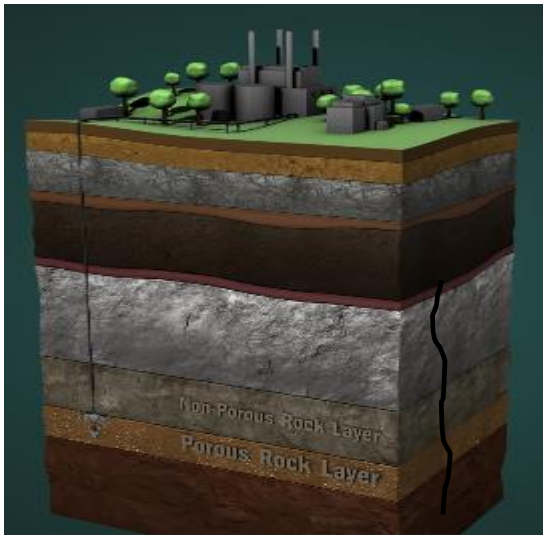
National Risk Assessment Partnership (NRAP)

Objective: Building tools and improving the science base to address key questions related to environmental impacts from potential release of CO_2 or brine from the storage reservoir, and potential ground-motion impacts due to injection of CO_2

Technical Team

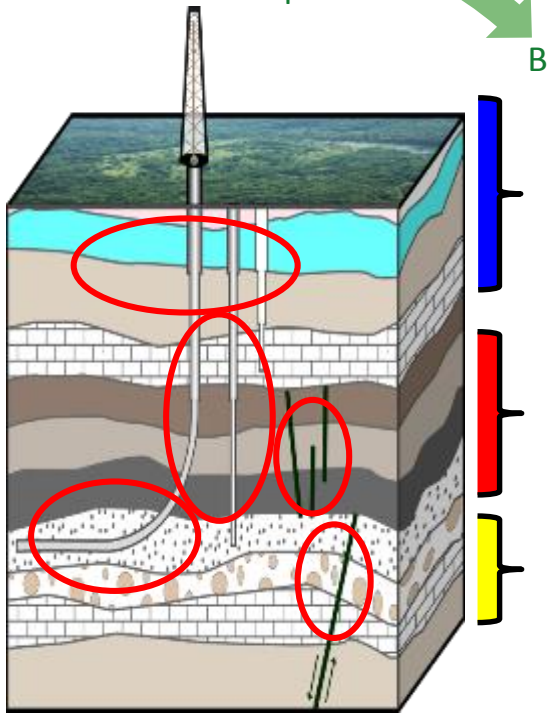


Stakeholder Group

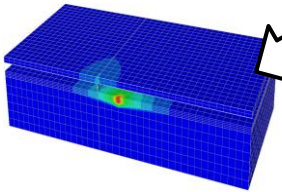
Wade, LLC

NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.

A. Divide system into discrete components



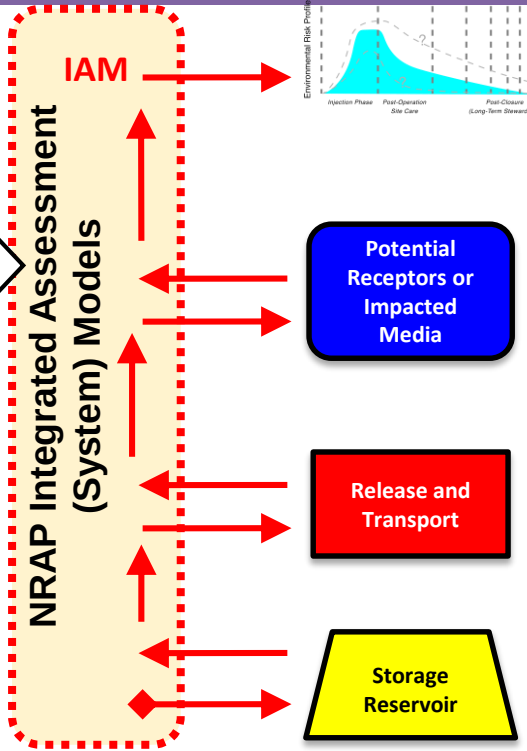
B. Develop detailed component models that are validated against lab/field data



Energy Data Exchange (EDX)

C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

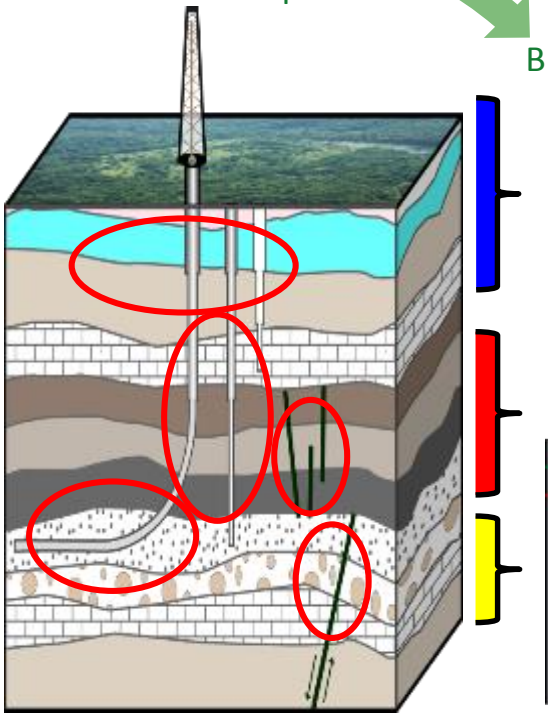
D. Link ROMs via integrated assessment models (IAMs) to predict system performance



E. Exercise whole system model to explore risk performance

NRAP developed detailed component models where needed and used existing high fidelity physics-based model when available.

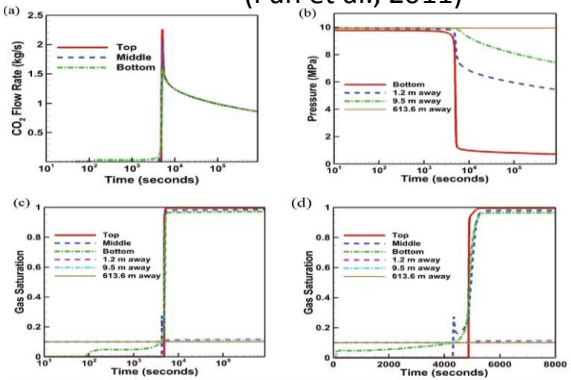
A. Divide system into discrete components



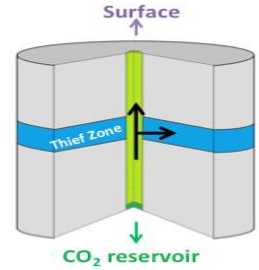
B. Develop detailed component models that are validated against lab/field data

Open Wellbore

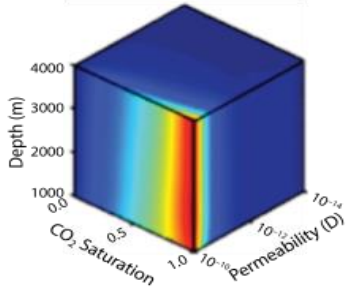
(Pan et al., 2011)



Cemented Wellbore with Thief Zone

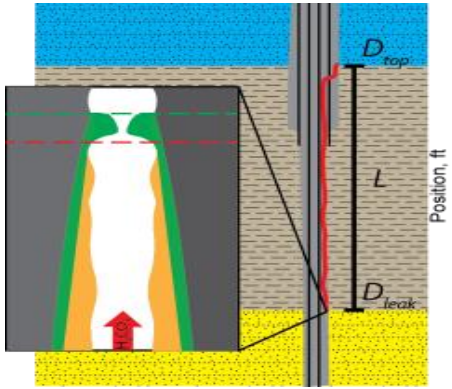


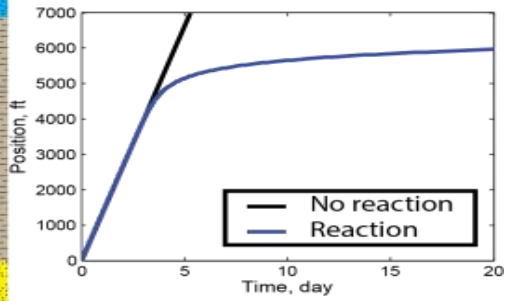
CO$_2$ Flow Rate



(Jordan et al., 2015; Harp, et al., 2016)

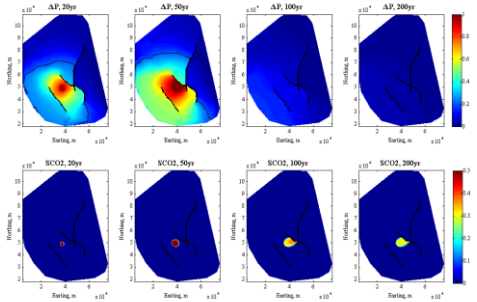
Brine leakage through Fractured Cement



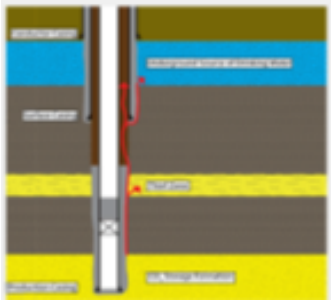


(Huerta, et al., 2016)

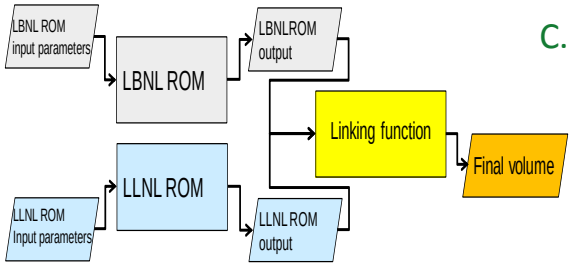
Many scientific and technical advances were needed to develop appropriate reduced-order models.



Investigated most critical reservoir and seal parameters for risk



Identified necessary conditions for coupling system components



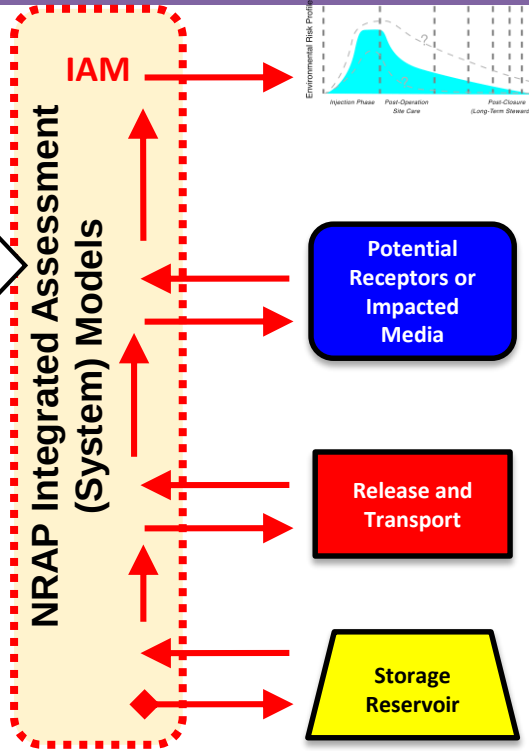
Studied the decoupling of hydrology and geochemistry in GW models

C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

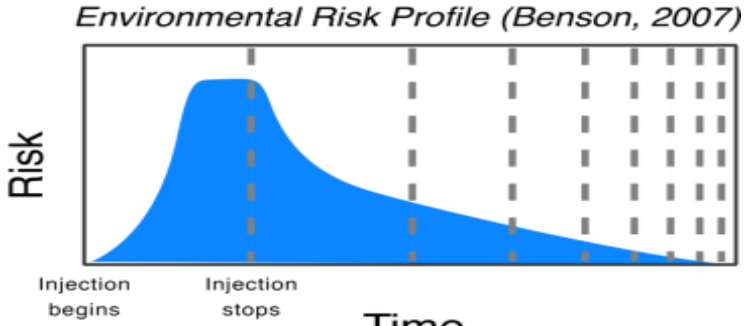
D. Link ROMs via integrated assessment models (IAMs) to predict system performance

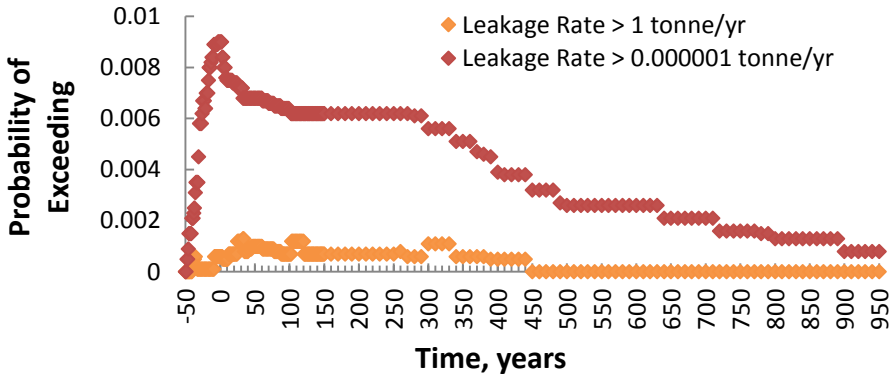
Energy Data Exchange (EDX)

Data



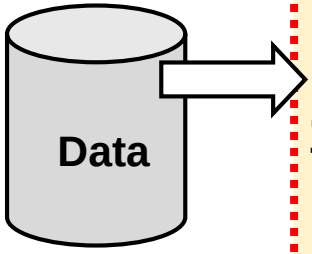
NRAP's Integrated Assessment Model simulates carbon storage system behavior, probing uncertainty in the system.

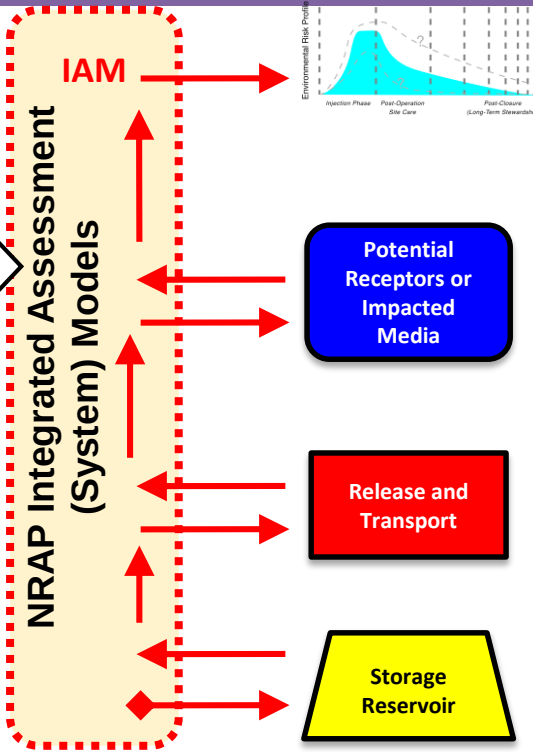




Monte-Carlo simulation allows robust, time-dependent uncertainty quantification

Energy Data Exchange (EDX)





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NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.

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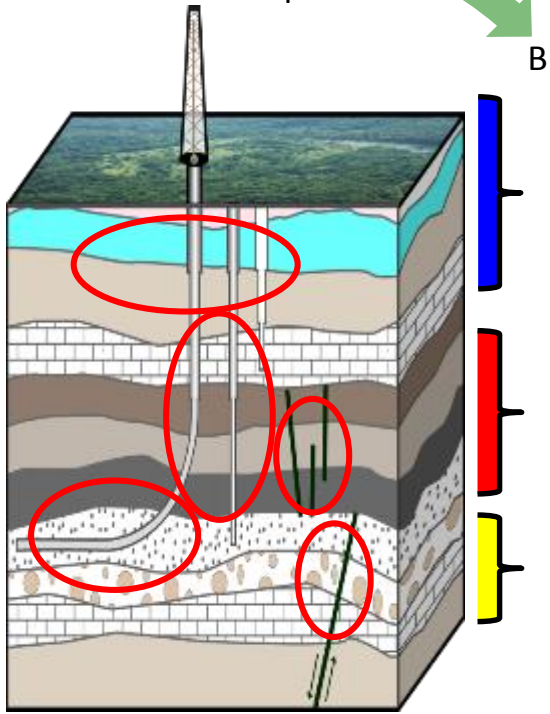

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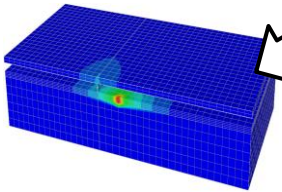

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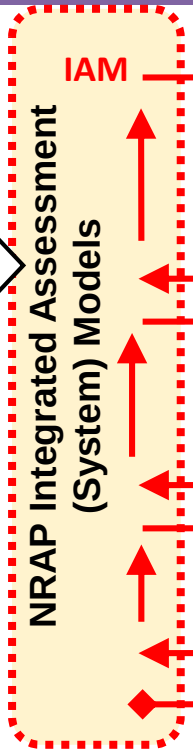
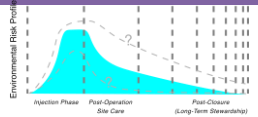
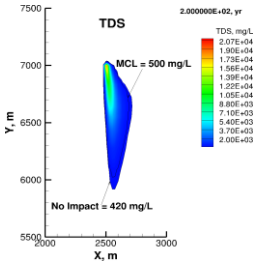


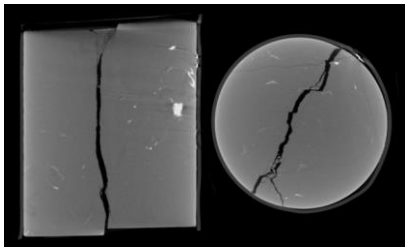


E. Exercise whole system model to explore risk performance

NRAP Phase I Accomplishments

- **Pioneered the movement into quantitative risk assessment, uncertainty quantification, and reduced order modeling for carbon storage**
- **Developed insights into key technical issues**
  - Reservoir behavior
  - Wellbore-risk relationships
  - Geochemical impacts to fracture flow
  - Groundwater impact assessments
  - Induced Seismicity risk
- **Key findings published**
  - IJGGC Virtual Special Issue
  - Other journal publications
  - TRS Report Series
- **Ten NRAP tools available to others for testing and use**





NRAP Tool	Recorded Webinar Link	
	SLIDES	VIDEO
Integrated Assessment ModelCarbon Storage (NRAP-IAM-CS)		
Natural Seal ROM (NSealR)		
Reservoir Evaluation and Visualization (REV) Tool		
Wellbore Leakage Analysis Tool (WLAT)		
Aquifer Impact Model (AIM)		
Design for Risk Evaluation and Monitoring (DREAM)		
Short Term Seismic Forecasting (STSF)		
NRAP-IAM-CS and RROM-Gen Webinar		

Final release, https://edx.netl.doe.gov/nrap

NRAP CO_2 Storage Risk Assessment Toolset

***Tool Beta Testing Link**: www.edx.netl.doe.gov/nrap*

Multiple Source Leakage ROM

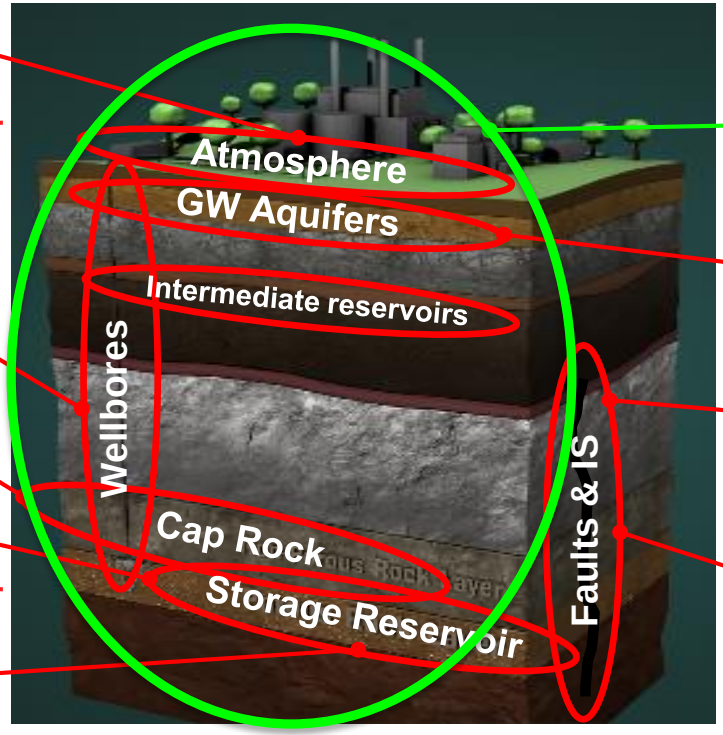
Designs for Risk Evaluation and Management

Wellbore Leakage Analysis Tool

Natural Seal ROM

Reservoir Evaluation and Visualization

Reservoir ROM Generator



NRAP Integrated Assessment Model for Carbon Storage

Aquifer Impact Model

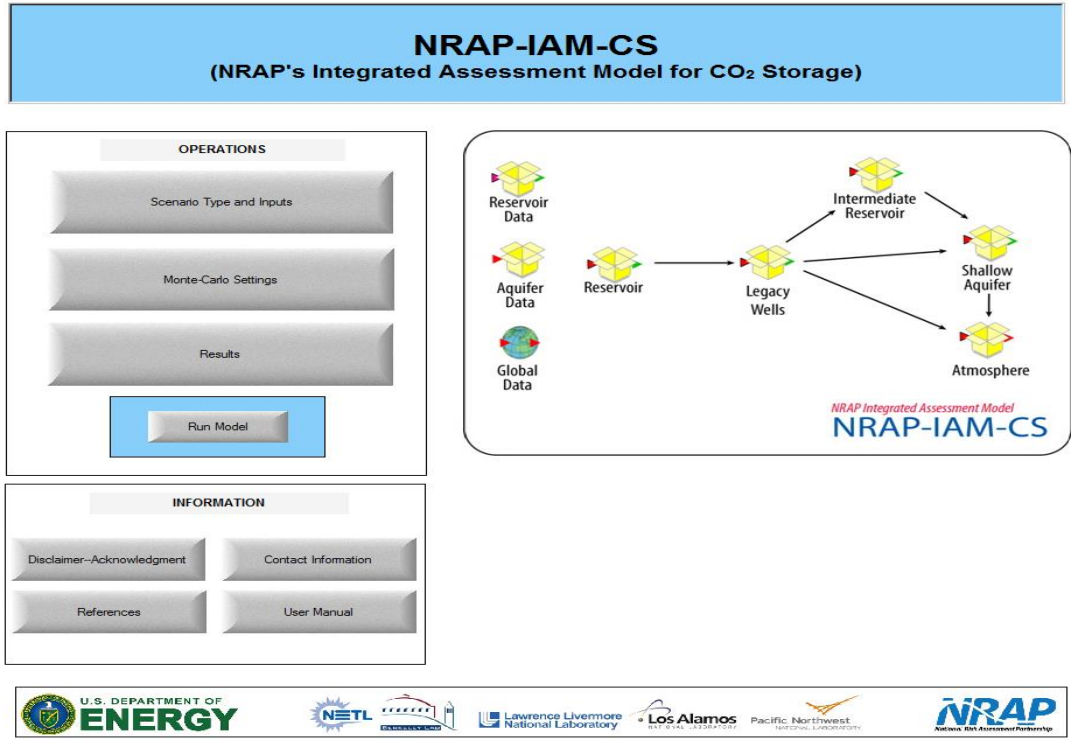
Short Term Seismic Forecasting

Ground Motion Prediction application for potential Induced Seismicity

NRAP's Integrated Assessment Model for Carbon Storage
NRAP-IAM-CS

- Simulates long-term, full-system behavior (reservoir to aquifer/atmosphere)
- Results can be used to:
  - Compute risk profiles (time-dependent probability of leakage and GW impact)
  - Quantitatively estimate storage permanence amidst system uncertainty
  - Identify key drivers of risk in context of uncertainty

NRAP POC: Rajesh Pawar (LANL)

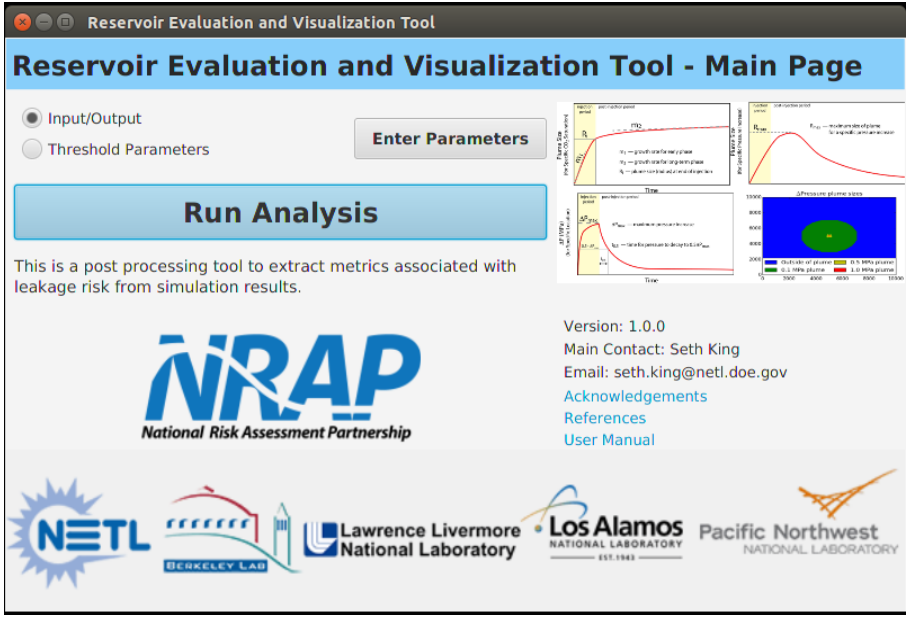


Reservoir Evaluation & Visualization (REV) Tool and Reservoir ROM Generator (RROMGEN)

Reservoir Evaluation and Visualization (REV) Tool - Generates pressure and CO_2 plumes sizes over time

- Suitable for Area of Review (AoR) determination
- Visualizes reservoir behavior probabilistically

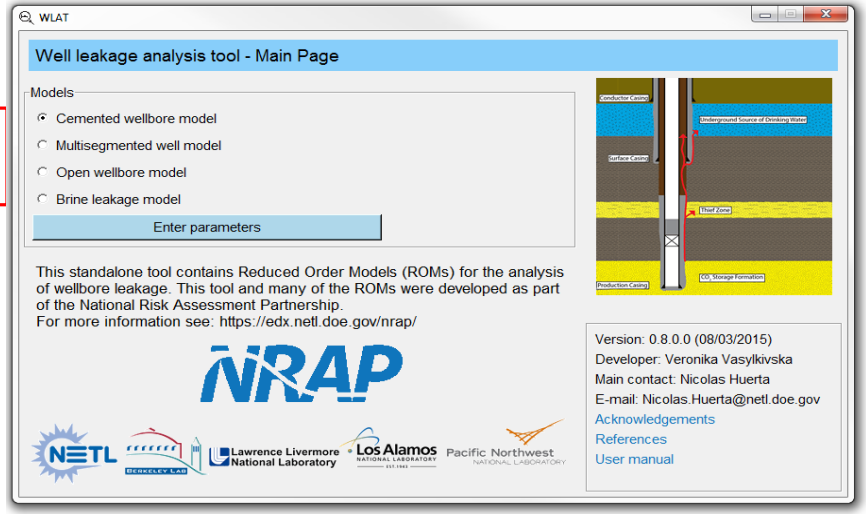
Reservoir ROM Generator (RROMGEN) – Converts reservoir simulation results into reduced order models (ROMs) for input to NRAP-IAM-CS

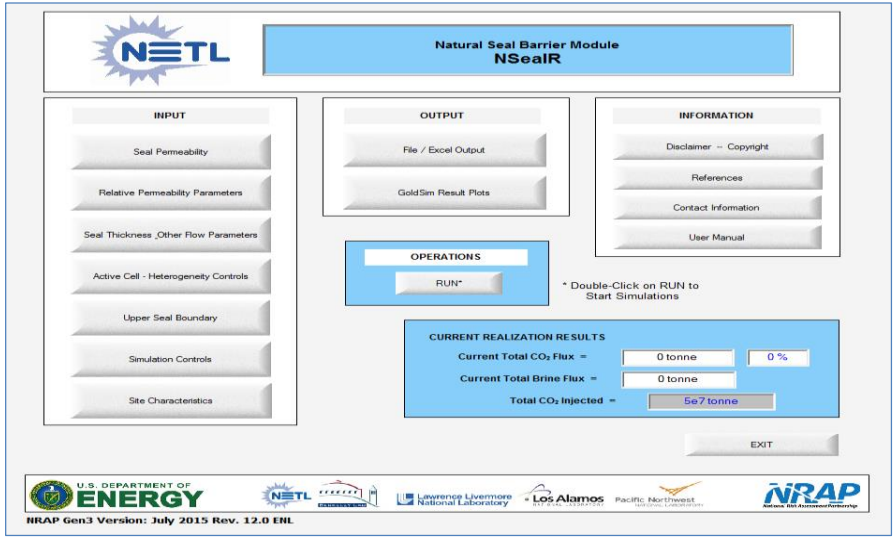


Well- and seal-related tools addresses vertical migration for a variety of possible scenarios.

Wellbore Leakage Analysis Tool (WLAT) – Evaluates leakage potential primarily for existing wells

- Explores leakage response as a function of well disposition
- Evaluates the implications of permeable overburden zones





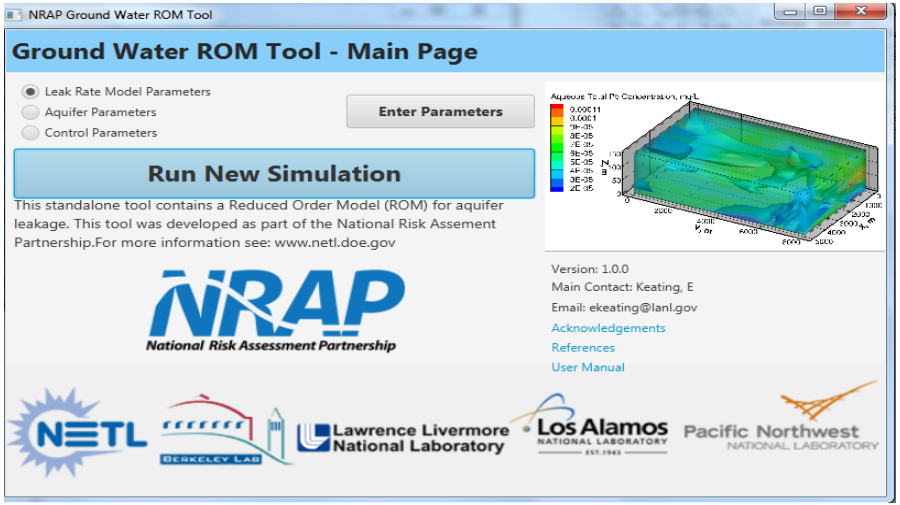
Natural Seal ROM (NSealR) - Estimates flux through a fractured or perforated seal

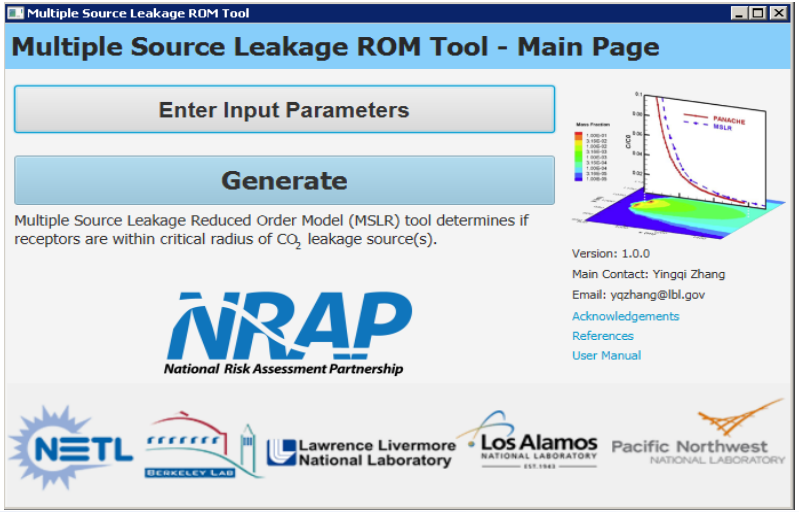
- Accounts for storage outside of primary target zone

Aquifer Impact Model (AIM) and Multiple Source Leakage ROM (MSLR) address potential receptors.

Aquifer Impact Model (AIM) - Estimation aquifer volume impacted by a leak (for pH, TDS, select metals and organics)

- Distinguishes between CO_2 and brine leaks
- Used to determine impact of threshold criteria.





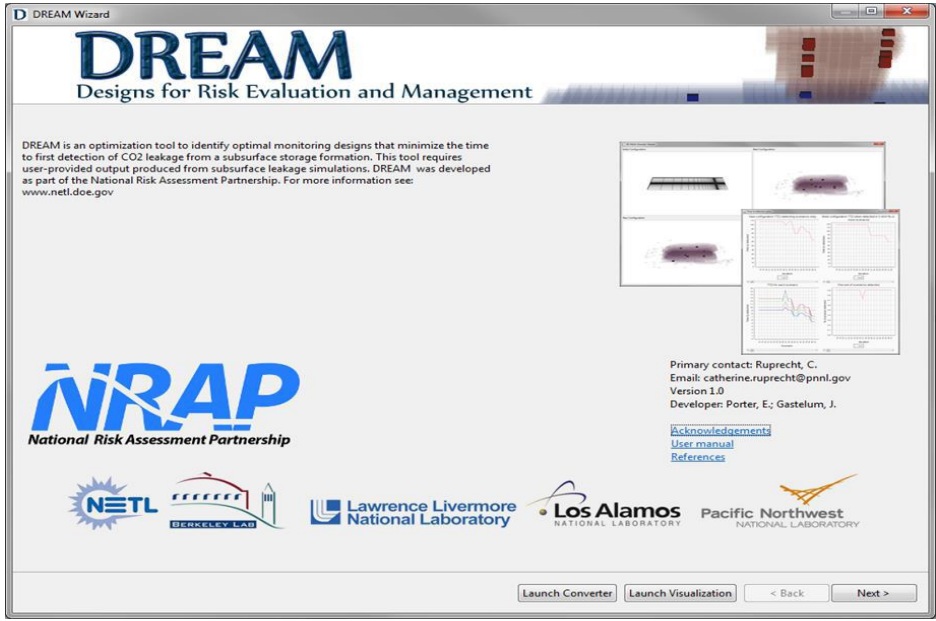
Multiple Source Leakage ROM (MSLR) – Characterizes atmospheric dispersion of leaked CO_2

- Determines probability that the monitors are able to detect CO_2 in the atmosphere based on their location.

Prototype DREAM monitoring optimization tool. (Design for Risk Evaluation and Management)

Design for Risk Evaluation and Management (DREAM) -Selects monitoring design that is optimized for minimum time to detection

- Can incorporate budget and operational constraints
- Uses a set of subsurface simulation realizations

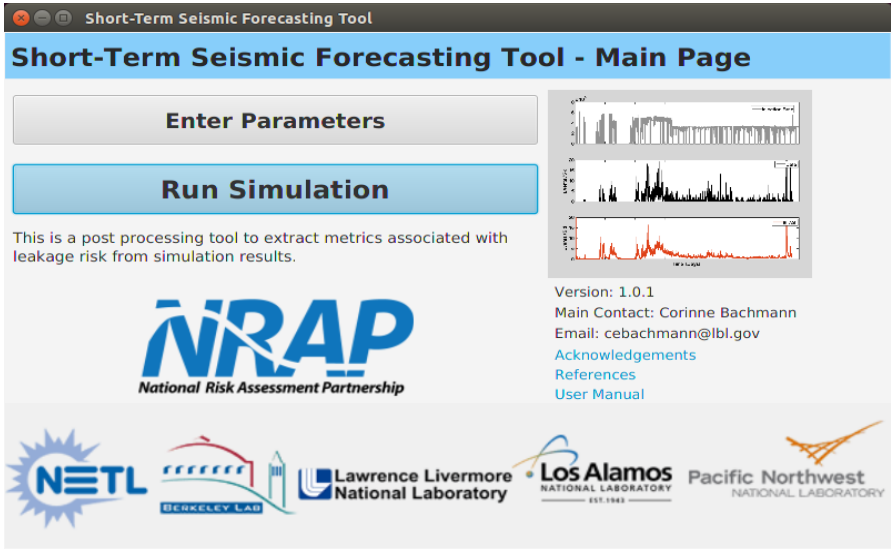


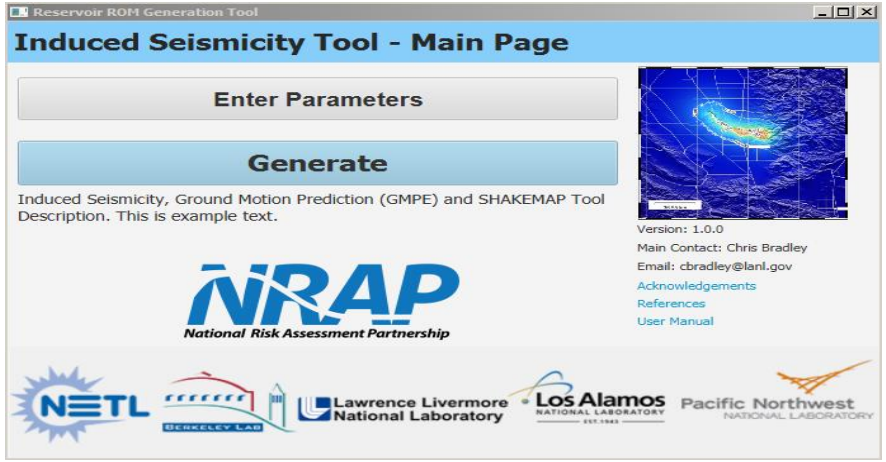
NRAP POC: Catherine Yonkofski (PNNL)O

Two other tools can help prepare for and manage the risk of induced seismicity.

Short Term Seismic Forecasting (STSF) - Forecasts seismic event frequency during injection, over hours/days

- Potential to complement stoplight approach for induced seismicity planning and permitting





Ground Motion Prediction application for potential Induced Seismicity (GMPIS) - Predicts ground motion response from potential induced earthquakes

- Based on global dataset, usable when site-specific data is sparse

NRAP Phase II is beginning this FY.

- Focus is on Risk Management and Uncertainty Reduction
- Looking for opportunities to benchmark models/tools
- Major Tasks for Phase II:
  - Containment Risk
  - Induced Seismicity and probabilistic hazard/risk
  - Strategic Monitoring
  - Field Validation, Demonstration
  - Key Insights around Risk Management

Thank you!

Interested to learn more about or beta test the NRAP tools?
Visit: www.edx.netl.doe.gov/nrap

Contact information:

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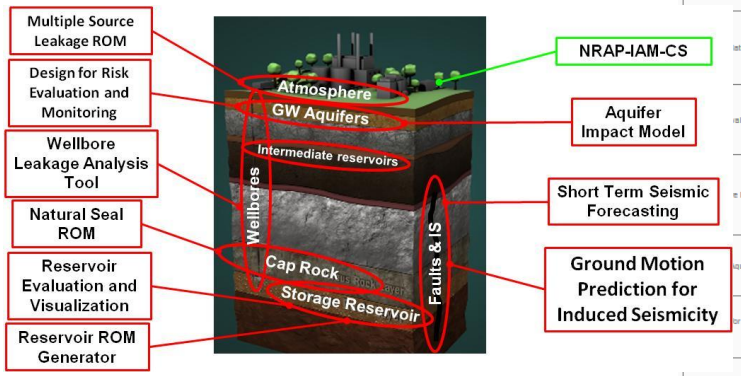
(304) 285-4688



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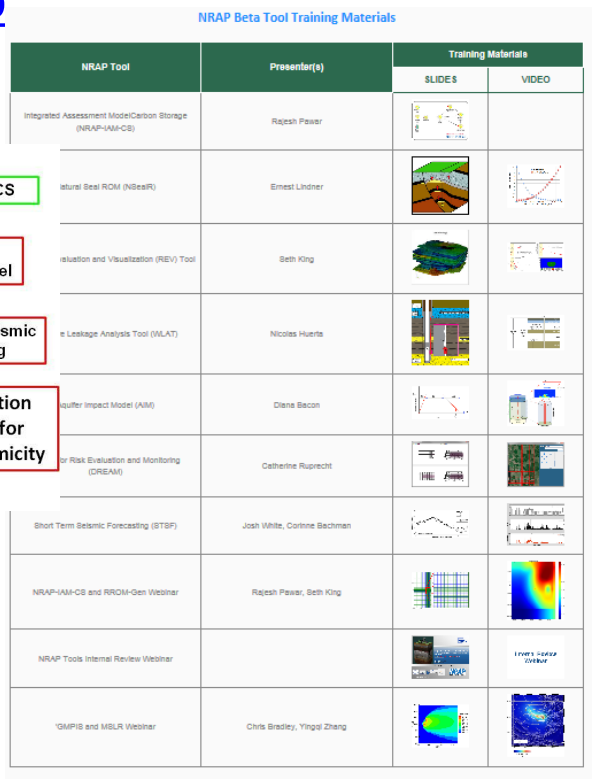
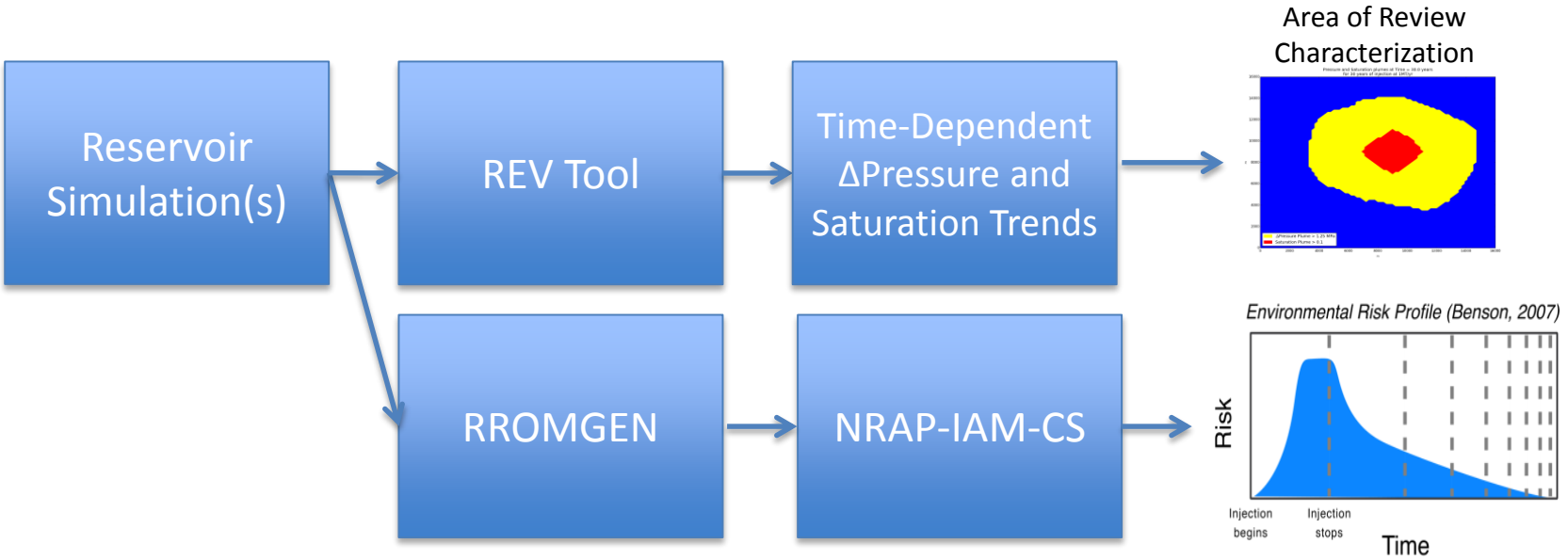


National Risk Assessment Partnership

Workflow Example

Reservoir Simulation to Risk Profile and Reservoir Simulation to AoR Characterization



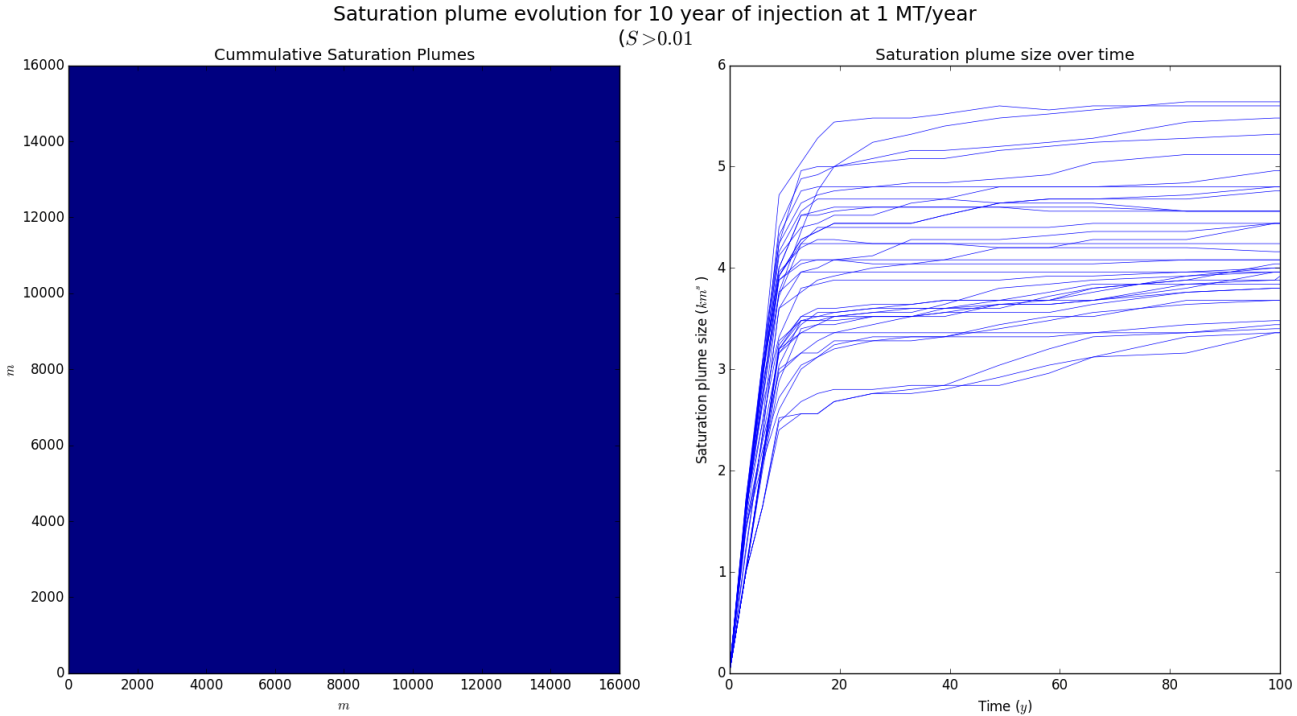
Example Scenario: Candidate Injection Site in Continental U.S.

- Multi-layered limestone-dolostone reservoir
- Depth approximately 2,500 meters
- Permeability: 1-210 mD; porosity 5-15%
- Lateral and vertical heterogeneities in the reservoir
- Numerical simulations done using FEHM with16 x 16 km^2 domain
- Simulation time on order of 10 hours per realization

AIM has utility as a site screening tool to compare groundwater quality impacts due to CO2 or brine leaks

- **Two aquifer models:**
  - Unconfined, oxidizing carbonate aquifer (based on Edwards Aquifer)
  - Confined alluvium aquifer (based on High Plains Aquifer)
- **Calculates volume of aquifer beyond threshold concentrations:**
  - pH
  - TDS
  - Trace metals: arsenic, barium, cadmium, lead
  - Organics: benzene, naphthalene, phenol
- **Two threshold values for each volume calculation:**
  - MCL
  - No-impact (background 95th percentile) - (Last, 2013)

Saturation plume (>0.01) evolution over 100 years
1MT injected/yr for 10 years; 90 years post-injection

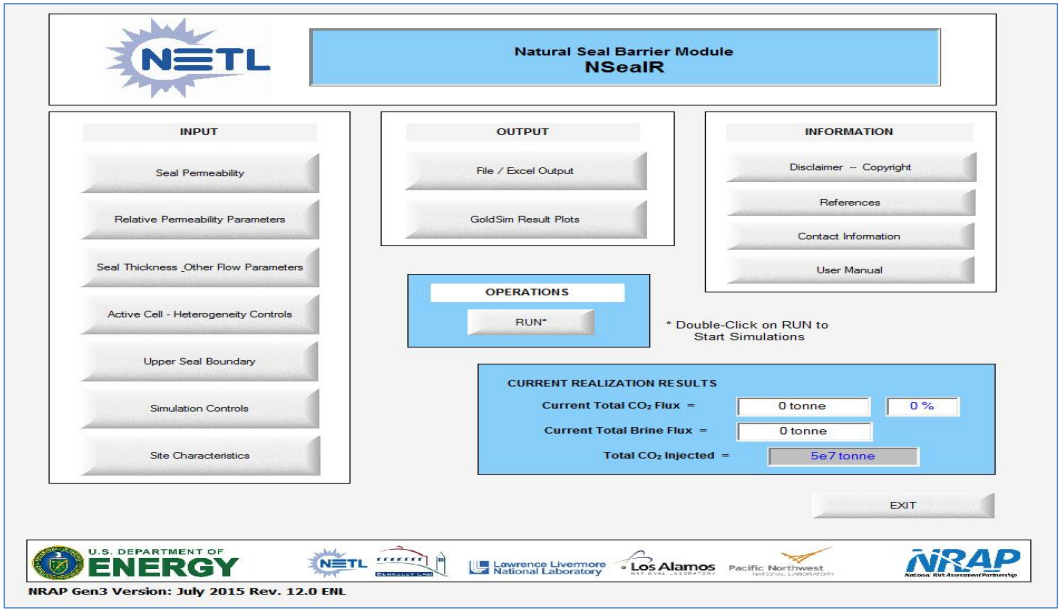


37 equiprobable realizations,

Tool for estimating leakage through fractured seal *(NSealR)*

- Estimates flux through a fractured or perforated seal
- Accounts for storage outside of primary target zone

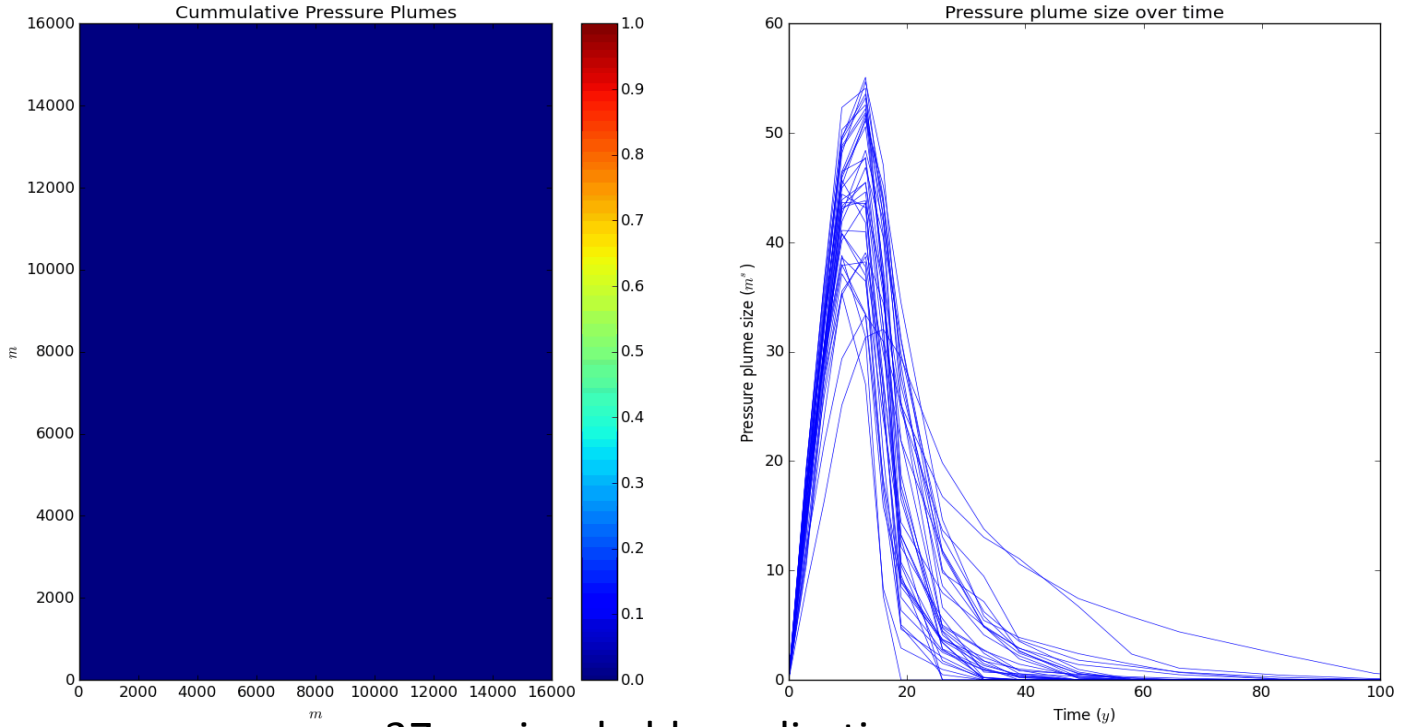
- Uses inputs of pressure and saturation at the reservoir/seal interface
- Computes two-phase (brine and supercritical CO_2) flux and includes fluid thermal/pressure dependence
- Predicts leakage through a Barrier (Seal) Layer
- Allows for various levels of complexity to model barrier response
- Accounts for effective stress dependence of aperture



NRAP POC: Ernest Lindner (NETL, AECOM)

Pressure Increase Area (> 0.628 MPa) evolution over 100 years - 1MT/yr for 10 years, 90 years post-injection

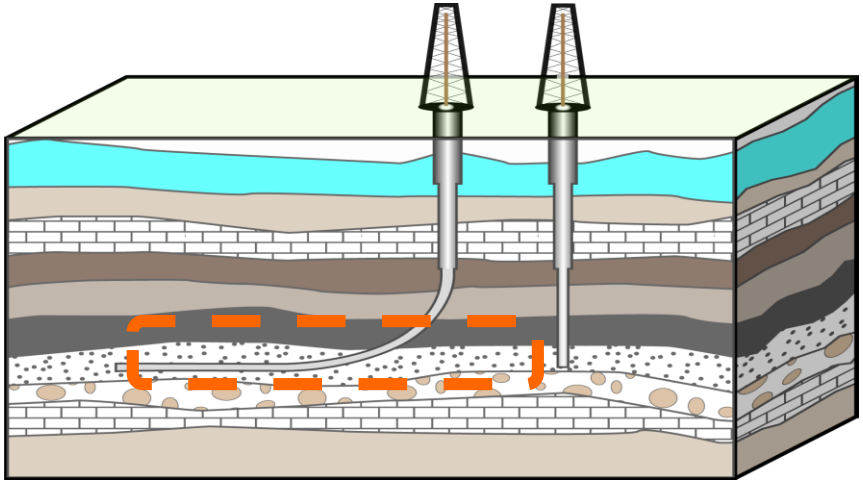
Pressure plume evolution for 10 year of injection at 1 MT/year



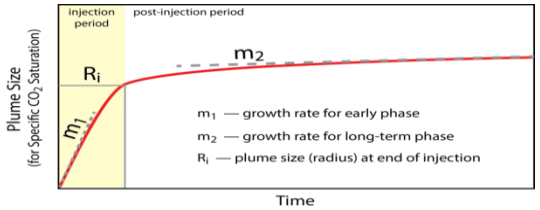
37 equiprobable realizations

NRAP analyzed key risk-based metrics for the reservoir component of the storage system using tools.

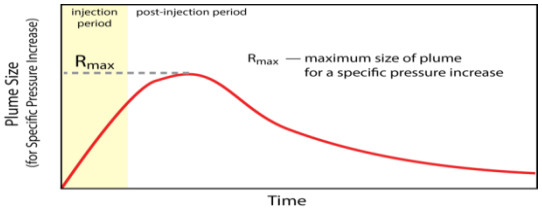
- **Size of CO_2 plume injection**
  - Rate of growth for early phase
  - Rate of growth for long-term phase
  - Plume radius at end of injection
- **Size of pressure plume**
  - Maximum size of plume
  - Various pressure thresholds, relevant to:
    - Brine rise
    - Fault-slip criteria
- **Pressure at a location**
  - Maximum pressure increase



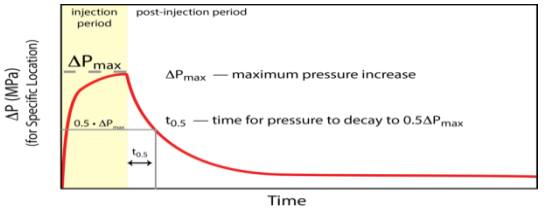
Bromhal et al., 2014



Size of CO_2 Plume



Size of Pressure Plume

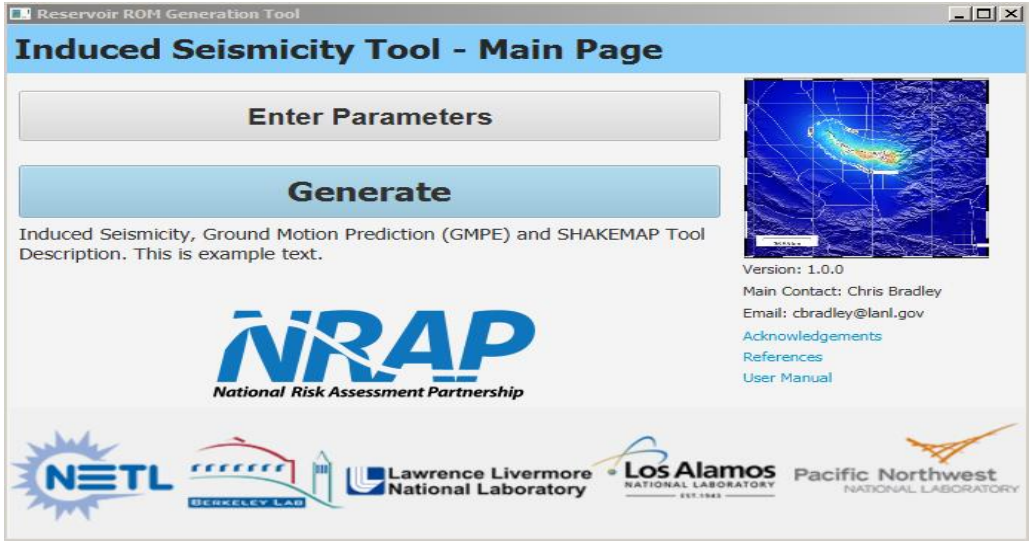


Pressure at at a Location

Ground Motion Prediction application to potential Induced Seismicity (GMPIS)

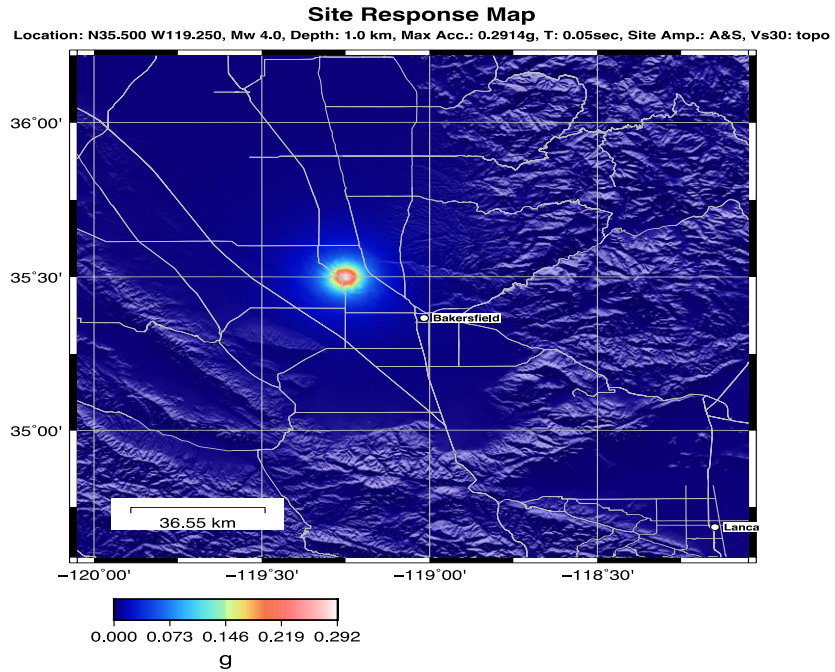
- Ground motion prediction from potential induced earthquakes based on global dataset
- Tectonic scenario earthquakes could provide a valuable planning tool due to potential of injection to stimulate the rate of natural seismicity

- **Two approaches to characterizing ground motion: peak ground acceleration (PGA) and peak ground velocity (PGV)**
- **Database includes induced seismicity (IS) from global active geothermal locations producing nearly 4,000 records**
- **Implements IS empirical ground motion prediction equations (Douglas et al., 2013)**
- **Applicable for cases where little site-specific seismic data are available**
- **Incorporates published models for site-specific amplification corrections (Boore and Atkinson, 2008; Abrahamson and Silva; 2008.**

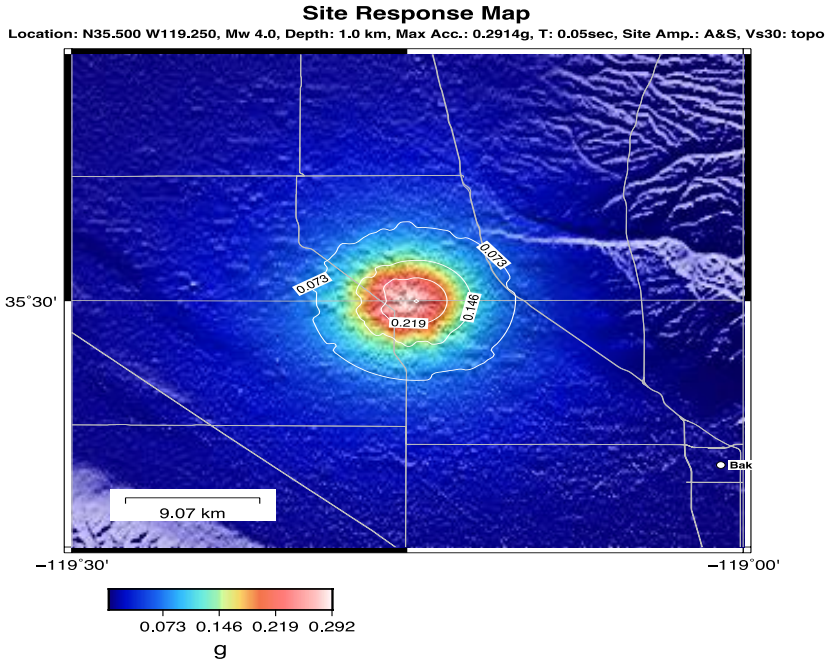


NRAP POC: Chris Bradley (LANL)

Induced Seismic Event: Near the Pond-Poso Fault- median ground motions predicted for a hypothetical Mw 4.0 earthquake



Map of Site response from an induced event In San Joaquin Valley



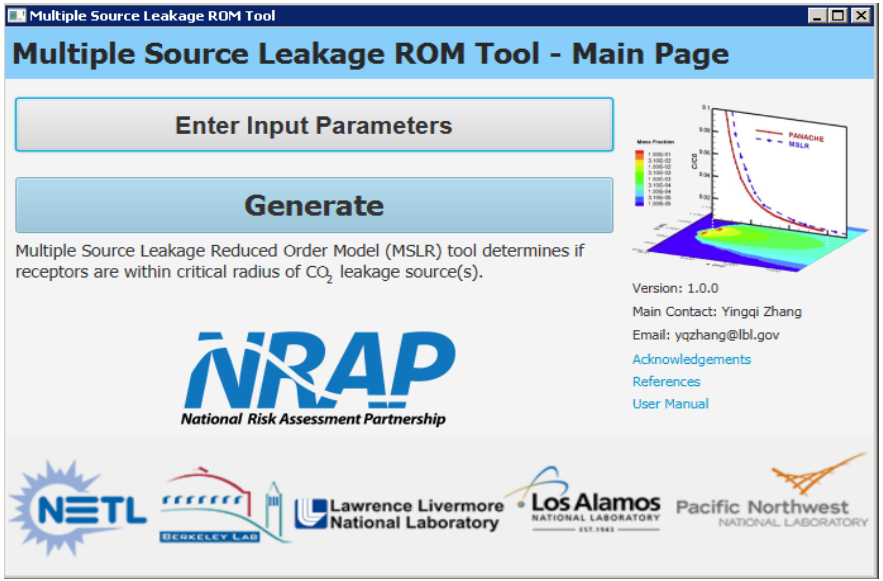
Large Scale Map of Site response showing the detail accelerations in Kimberlina area

NOTE: Hypothetical case for demonstration purposes only

Multiple Source Leakage ROM (MSLR) Tool

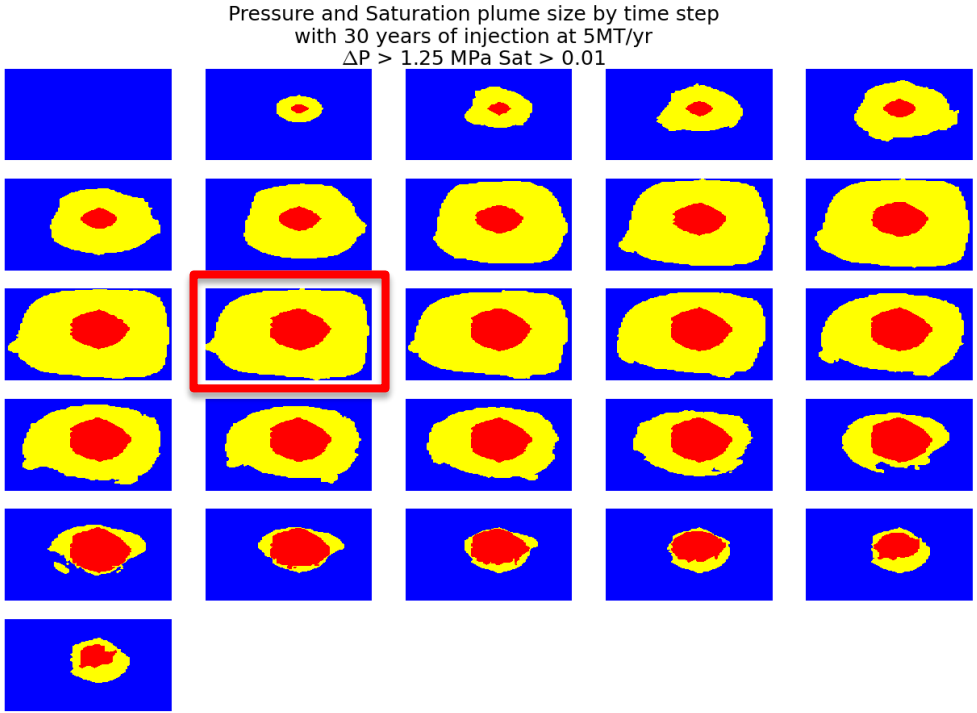
- MSLR handles single- or multiple-source CO_2 leakage using a reduced-order model (ROM).
- Determines the probability that the monitors are located within the extent of plume above a critical concentration.

- **Adapts single-source correlation method (Britter and McQuaid, 2008) to multiple source releases**
- **Predicts plume extent and concentration of dense gases near the ground surface**
- **Focuses on the large volume release events, such as those simulated by the NRAP-IAM-CS open well option**

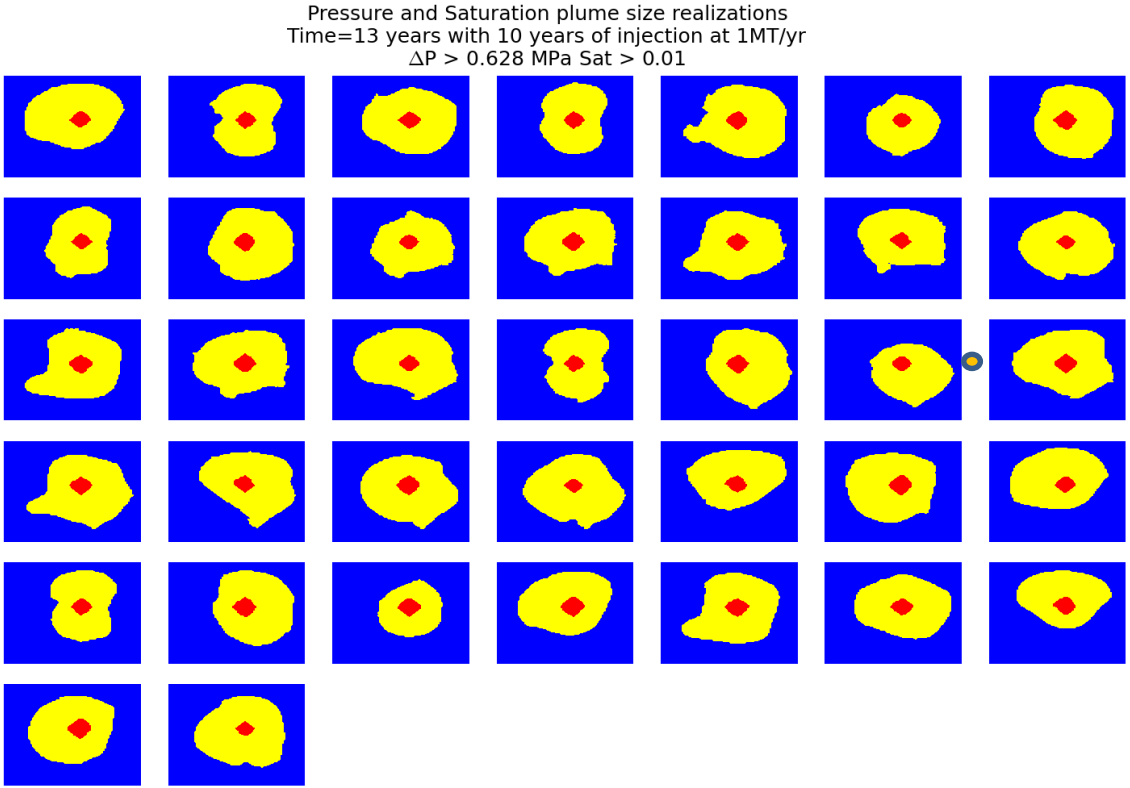


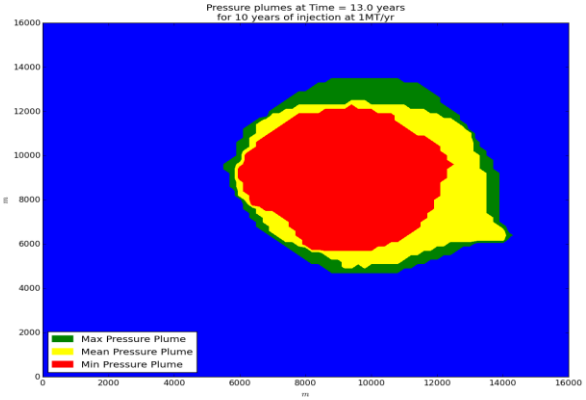
NRAP POC: Yingqi Zhang (LBNL)

Pressure and saturation plume size through time with 30 years of injection at 5 MT/yr (ΔP> 1.25 Mpa, Sat > 0.01)



ΔP and saturation plume extend for 37 reservoir simulation realizations (ΔP > 0.628 Mpa, Sat > 0.01)



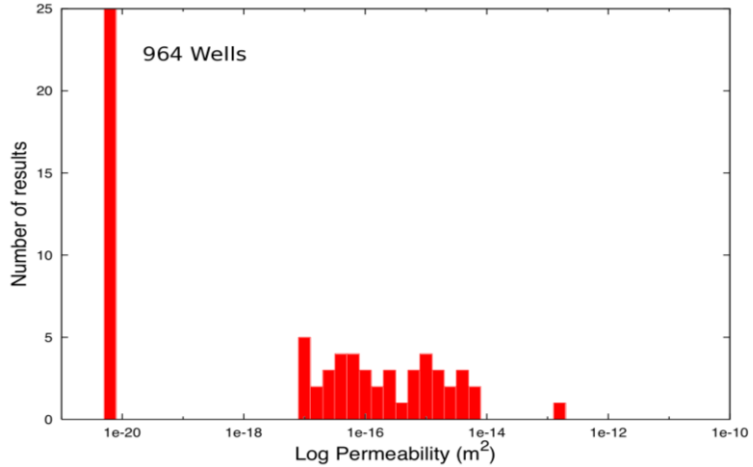


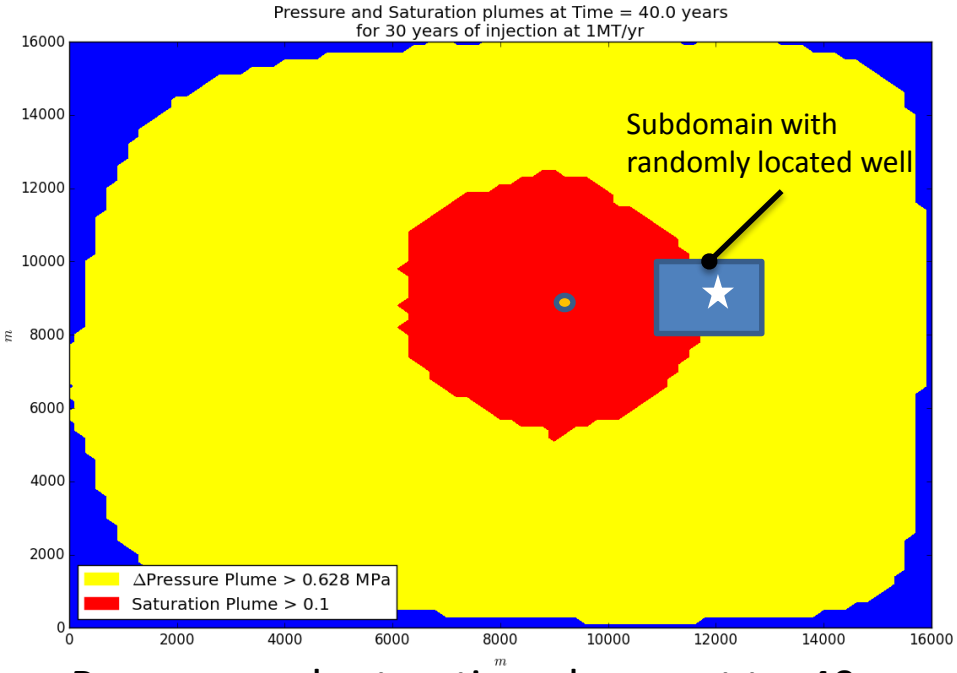
Max, Mean, Min Δ pressure plume at t=13 years scenario: 10 year injection at 1 MT/yr

Example Scenario: Unknown leaky well at candidate injection site in continental U.S.

What happens if we place an uncharacterized well in the storage domain?

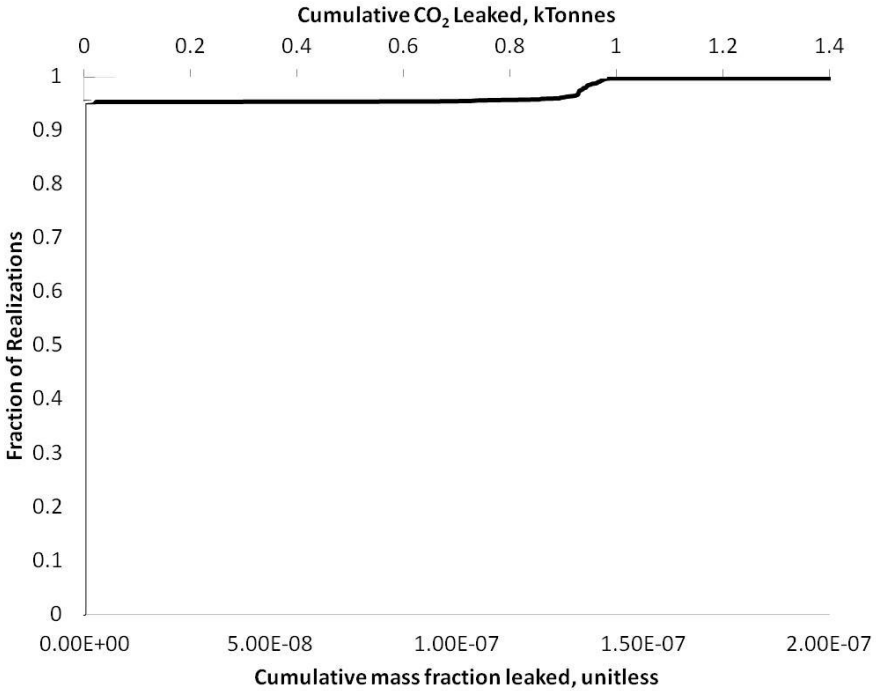
Alberta Basin: 4.6% of wells fail over life history (Carey, 2014)

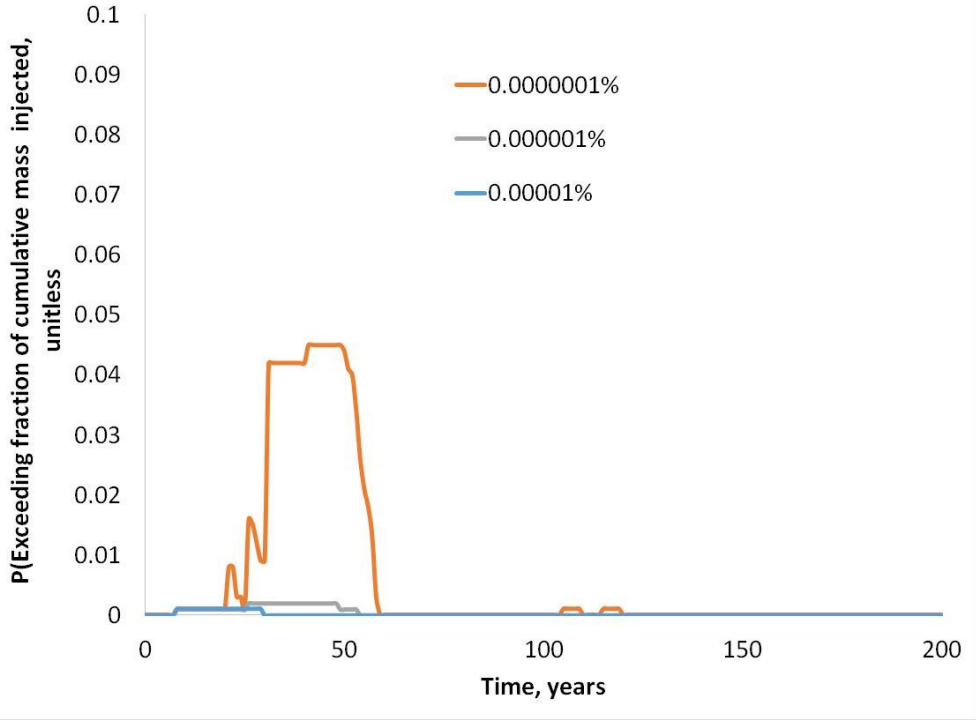




Pressure and saturation plumes at t = 40 years scenario: 30 years of injection at 1 MT/yr

Example Scenario: Atmospheric Leakage
1000 realizations, 300 years site performance

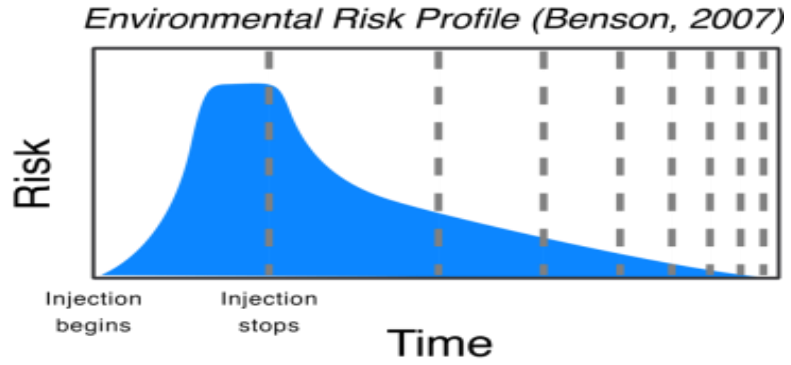


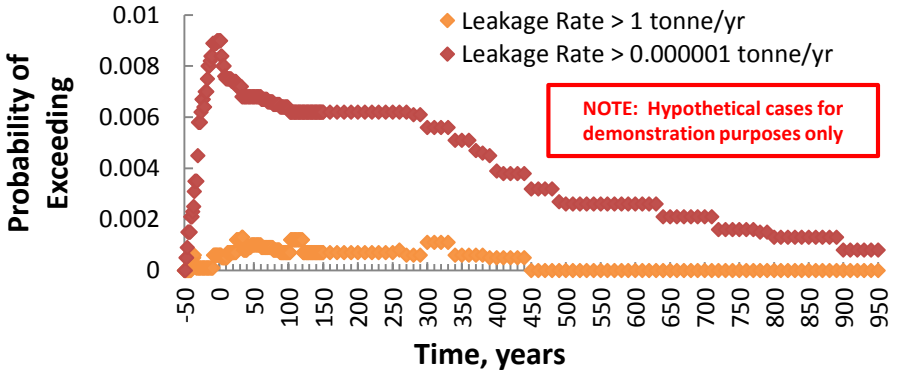


There is no predicted impact volume based on MCL threshold (pH < 6.5 or TDS > 500 ppm)

NRAP's Integrated Assessment Model simulates carbon storage system behavior.

- Integrates ROMs of system components including: storage reservoir, cemented and open wellbores, groundwater aquifer, and atmosphere
- Quantifies flux of CO_2 and brine to overlying receptors (groundwater and atmosphere), and impacts to groundwater aquifers
- Monte-Carlo simulation allows robust, time-dependent uncertainty quantification
- Uses built-in and user-defined models
- Quantitative risk profiles with realistic storage conditions
  - Over 100s to 1000s of years

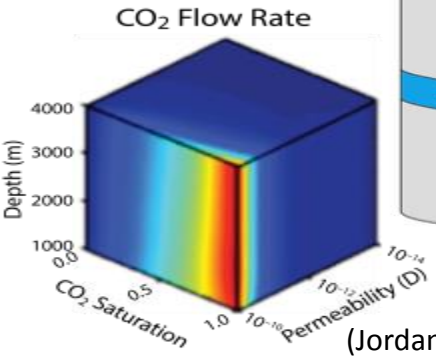


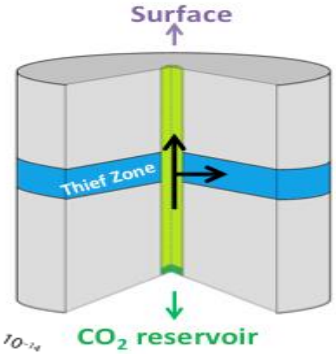


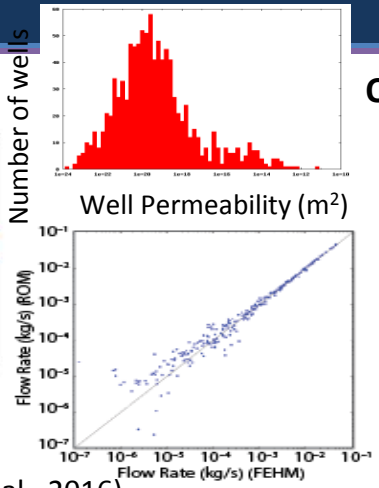
Ref: Bromhal et al, IEAGHG, 2013

Well Leakage Scenarios in WLAT

Cemented Wellbore with Thief Zone



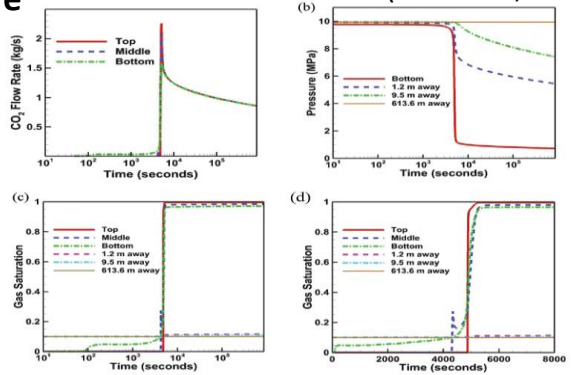




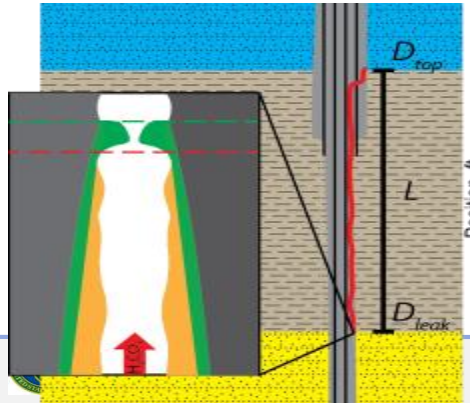
(Jordan et al., 2015; Harp, et al., 2016)

Open Wellbore

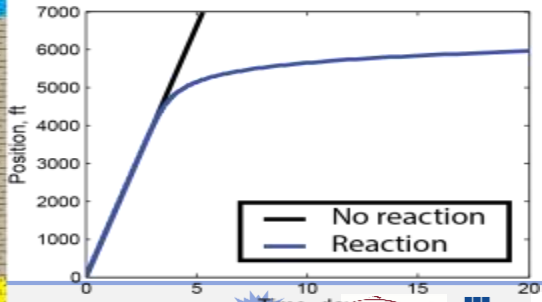
(Pan et al., 2011)



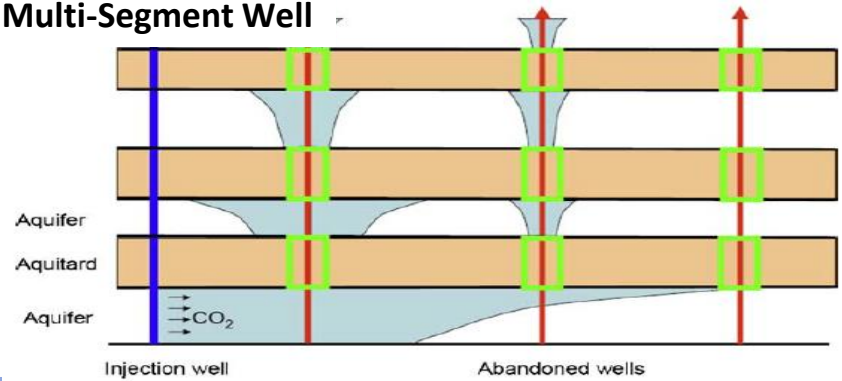
Brine leakage through Fractured Cement



(Huerta, et al., 2016)

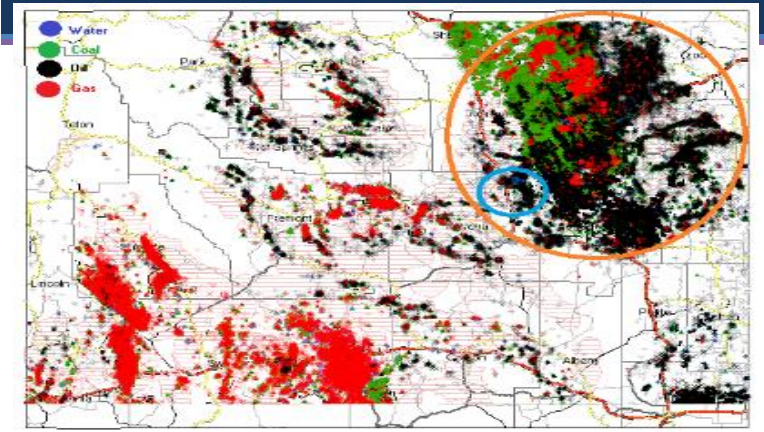


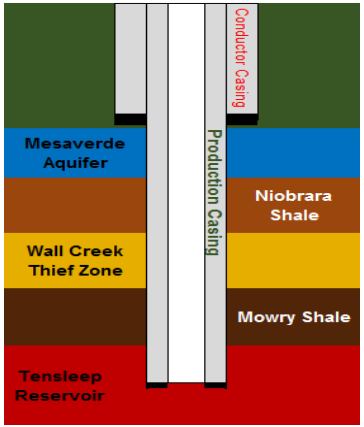
Multi-Segment Well

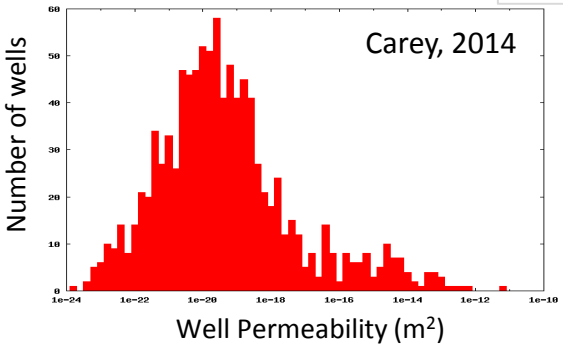


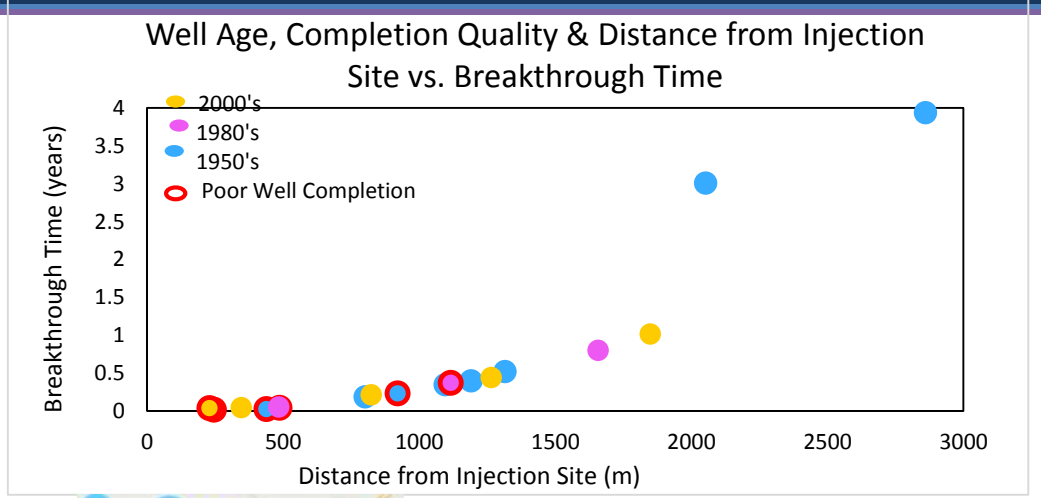
(Nordbotten, et al., 2004)

Rapid exploration of trends in potential well leakage







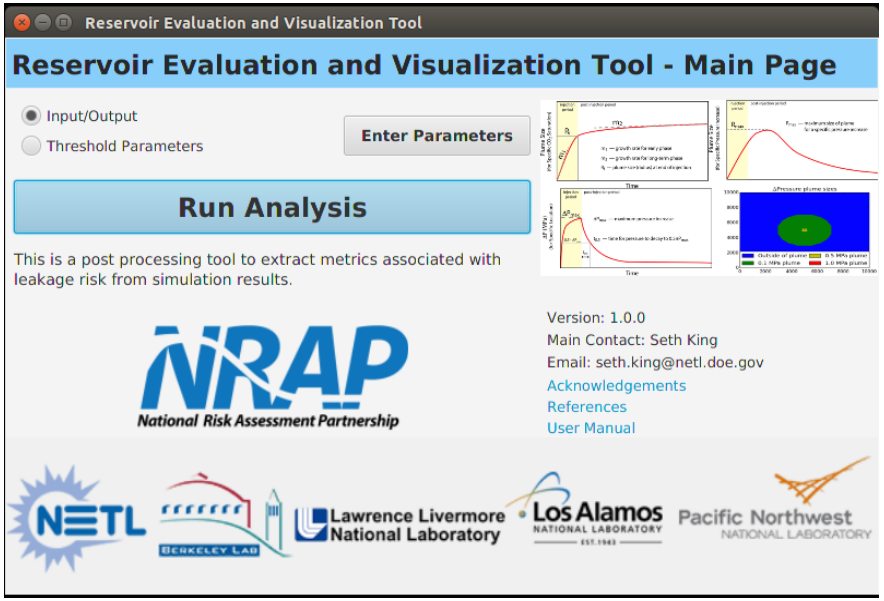


- What is the relative role of individual well parameters?
- Can we use additional data to rank wells and develop monitoring and mitigation strategies?

Reservoir Evaluation & Visualization (REV) Tool and Reservoir ROM Generator (RROMGEN)

- Generates pressure and CO_2 plumes size relationships over time
- Facilitates determination of Area of Review (AoR)
- Visualizes reservoir behavior probabilistically

- Uses pressure and saturation values from reservoir simulation(s) - modular design accommodates different file types
- Outputs plume sizes through time and pressure values in specified grid blocks at each time step.
- Functions for a single realization or accepts multiple simulations and outputs probabilistic values for defined thresholds.



NRAP POC: Seth King (NETL, AECOM)

NRAP Phase I CO_2 Storage Risk Assessment Toolset

Integrated Assessment Model – Carbon Storage (NRAP-IAM-CS) - Simulates long-term full system leakage and containment behavior (reservoir to aquifer/atmosphere)

Reservoir Evaluation and Visualization (REV) Tool - Generates pressure and CO_2 plumes sizes over time

Wellbore Leakage Analysis Tool (WLAT) – Evaluates existing well leakage potential

Natural Seal ROM (NSealR) - Estimates flux through a fractured or perforated seal

Aquifer Impact Model (AIM) - Estimation aquifer volume impacted by a leak (for pH, TDS, select metals and organics)

Design for Risk Evaluation and Management (DREAM) -Selects optimal monitoring design for minimum time to detection

Short Term Seismic Forecasting (STSF) - Forecasts seismic event frequency during injection, over hours/days

Reservoir ROM Generator (RROMGEN) – Converts reservoir simulation results for input to NRAP-IAM-CS

Ground Motion Prediction application for potential Induced Seismicity (GMPIS) - Predicts ground motion response from potential induced earthquakes

Multiple Source Leakage ROM (MSLR) – Characterizes atmospheric dispersion of leaked CO_2