U.S. DOE's National Risk Assessment Partnership

Assessing Carbon Storage Risk to Support Decision Making Amidst Uncertainty

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Solutions for Today | Options for Tomorrow

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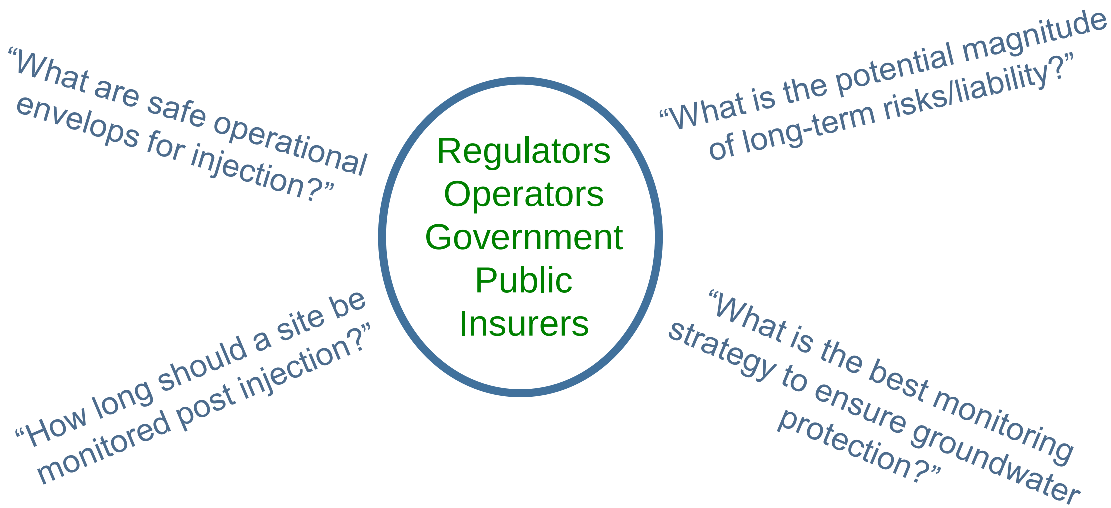
Assessing and managing risks is key for geologic CO_2 storage

Multiple stakeholders with different interests



Confidence in geologic CO_2 storage technology can be increased by using Science (-Based Predictions) to inform decisions related to safe site operations & management

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

BERKELEY LAB

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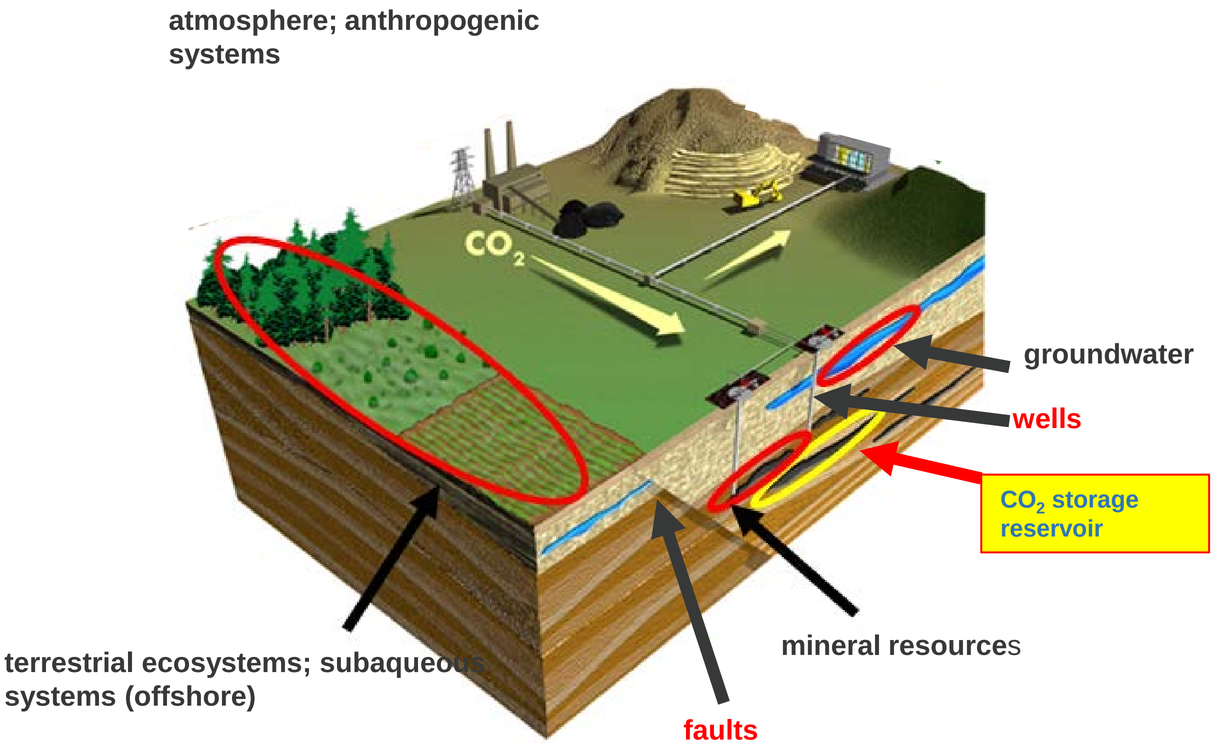
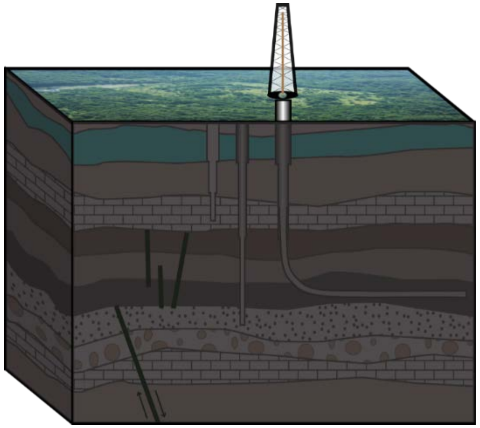
Pacific Northwest NATIONAL LABORATORY

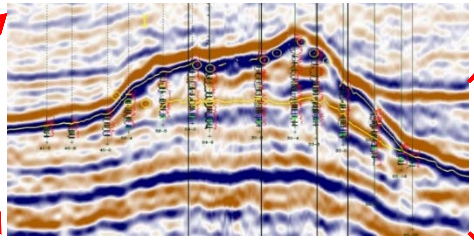
Geologic CO_2 storage sites are complex



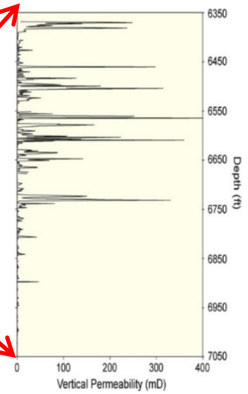
Assessing long-term risks requires predictions that take into account key aspects of geologic CO_2 storage sites

Geologic CO_2 storage sites have uncertainties





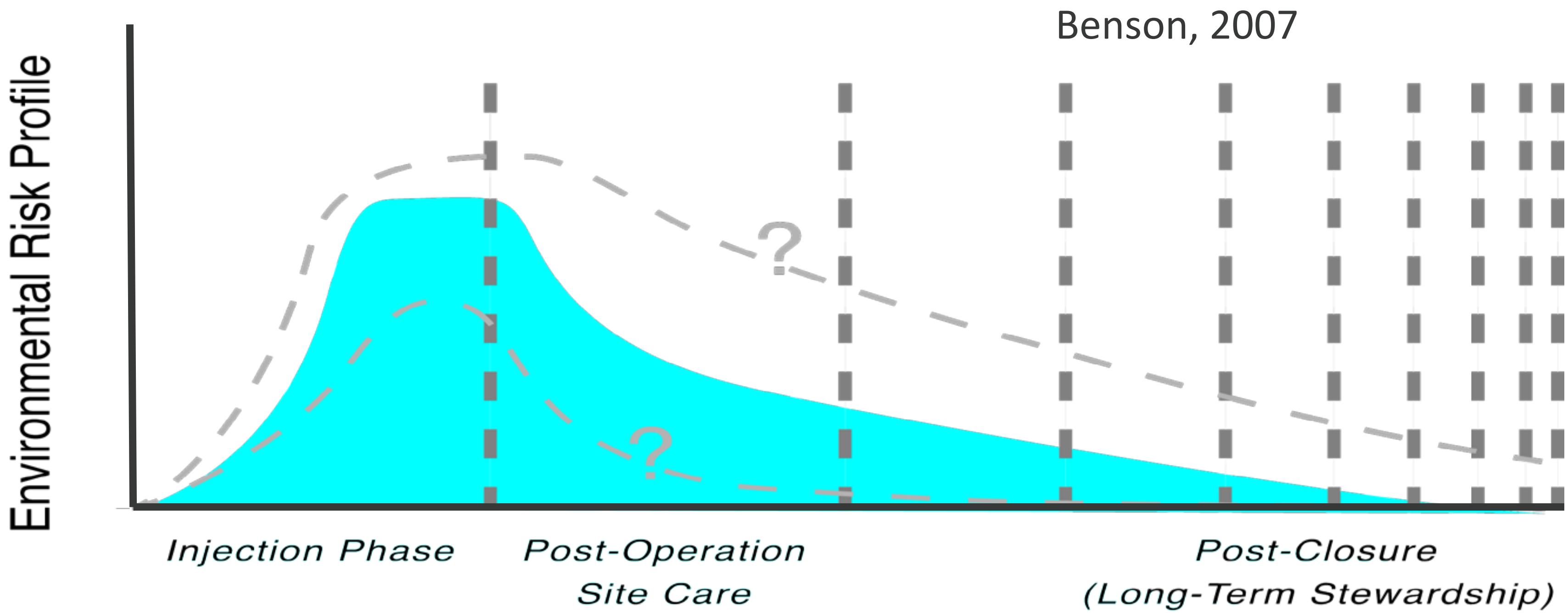
Seismic data from reservoir zone in operating oil field



Core data from same reservoir

Decisions related to the behavior of engineered–natural systems must take into account uncertainties

Long term environmental risk profiles have been qualitative



Quantitative approaches are needed by various stakeholders

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

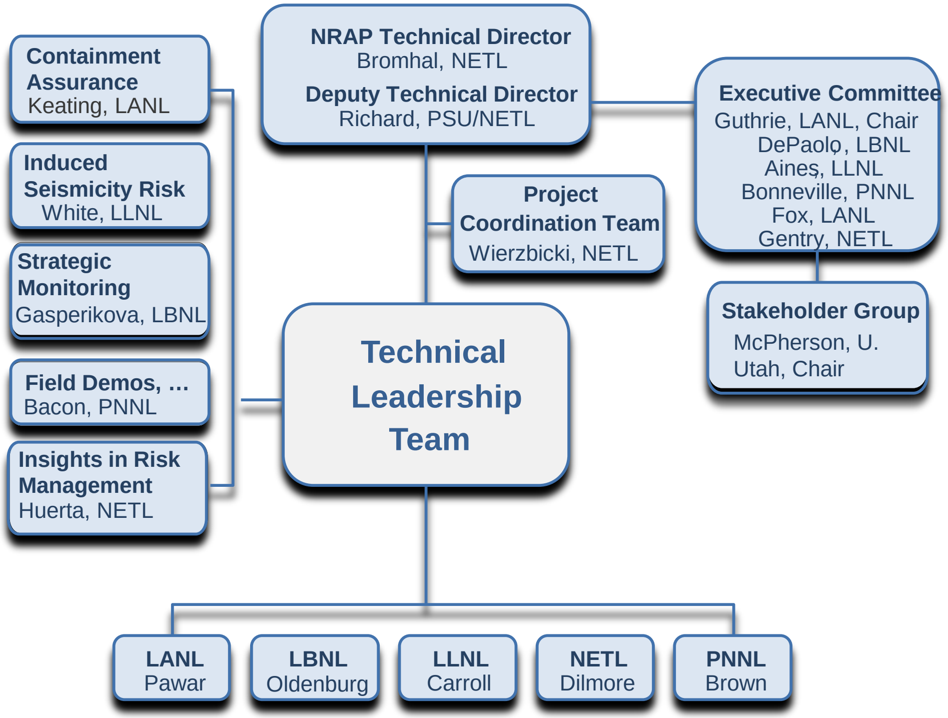
Stakeholder Group

Wade, LLC

NRAP is part of US DOE's Carbon Storage Program

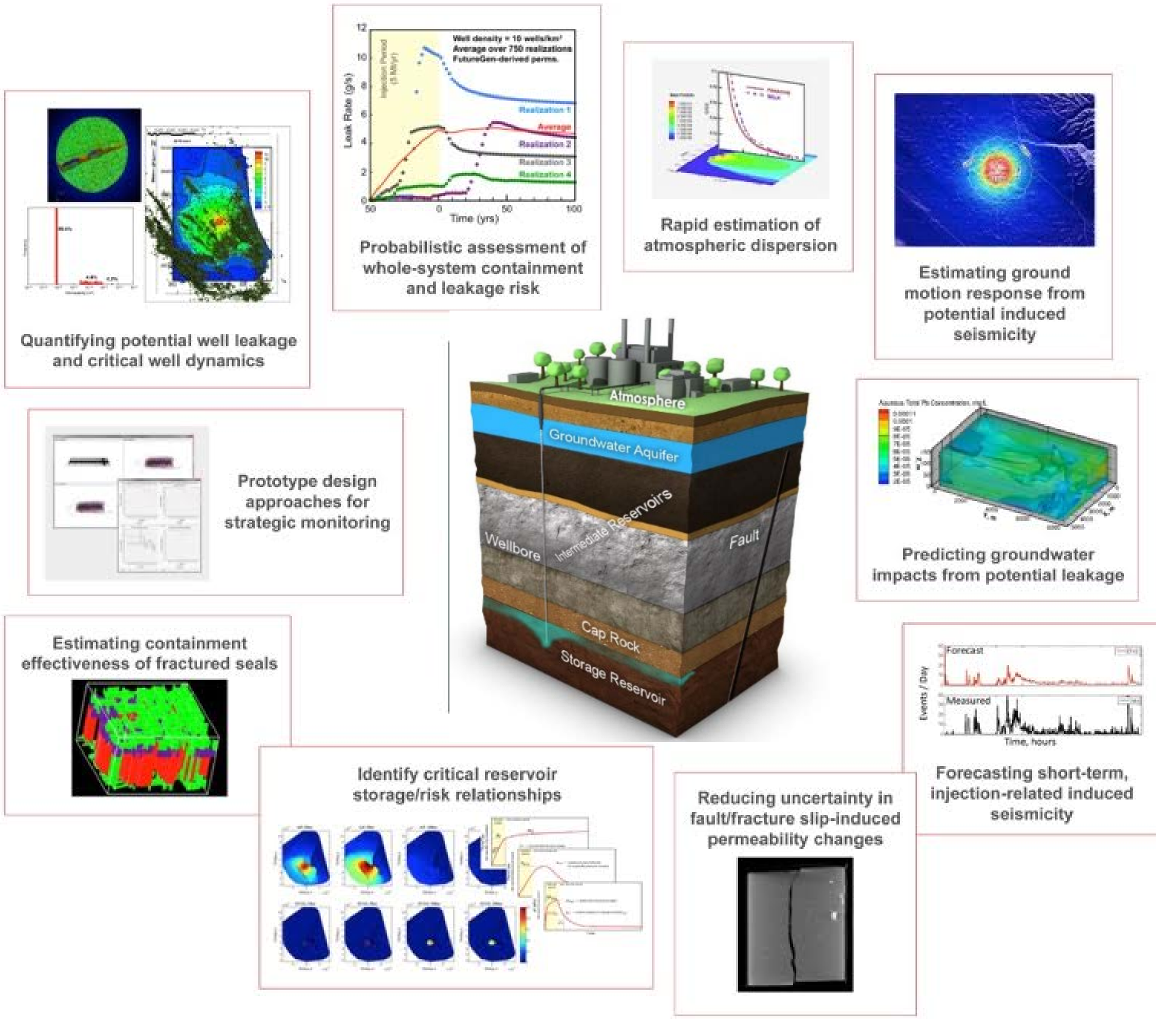
- NRAP is funded through the Carbon Storage R&D Program and managed by National Energy Technology Laboratory (NETL)
- Carbon Storage Program Goals
  - Develop technologies that ensure safe, secure, efficient, and cost effective CO_2 containment in diverse geologic formations for commercial readiness by 2030
    - ensure 99% storage permanence,
    - improve storage efficiency and containment effectiveness, and
    - predict storage capacity to ±30%
- NRAP is leveraging DOE's capabilities to help quantify uncertainties and risks necessary to remove barriers to full-scale CO_2 storage deployment

NRAP Organizational Structure

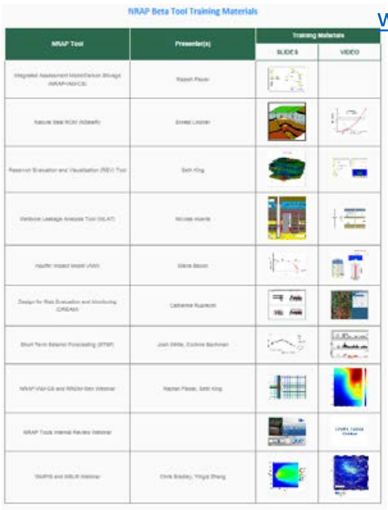


- **Executive Committee (EC)**
  - Provide technical and strategic guidance to the NRAP Director and TLT
  - Generate and demonstrate support for NRAP within each of the Labs
  - Key conduit for information with NRAP Stakeholder Group and other stakeholders
- **Stakeholder Group (SG)**
  - Provide perspectives for consideration by NRAP's TLT, reflecting a spectrum of key stakeholders related to CCS
  - Provide guidance on proposed future priorities and other topics as needed back to the chair of the NRAP EC
- **Technical Leadership Team (TLT)**
  - Identify NRAP goals and research priorities
  - Lead research activities in each Lab
- **Project Coordination Team**
  - Coordinates project activities among labs and with the Technical Director

NRAP Phase I Accomplishments



NRAP Tools Available at:
www.edx.netl.doe.gov/nrap



IJGGC Virtual Special Issue (August, 2016)

NRAP Toolset Overview

2017 R&D 100 Award Winner

NRAP Toolset: A suite of computational tools to inform decision making for geologic carbon storage sites amidst uncertainties

NRAP Technical Team

R&D 100

55 Years of Invention

NRAP Phase I CO_2 Storage Risk Assessment Toolset

Multiple Source Leakage ROM

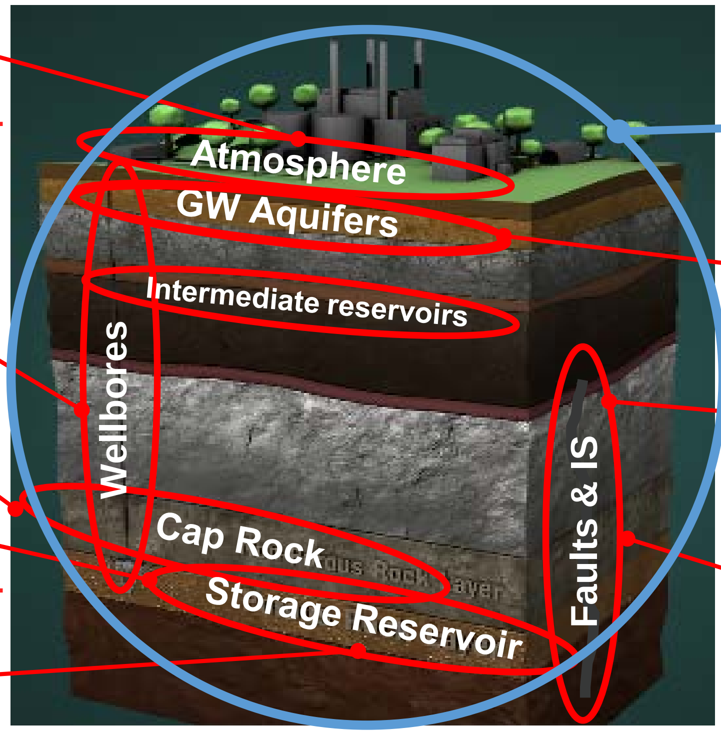
Designs for Risk Evaluation and Management

Wellbore Leakage Analysis Tool

Natural Seal ROM

Reservoir Evaluation and Visualization

Reservoir ROM Generator



NRAP Integrated Assessment Model for Carbon Storage

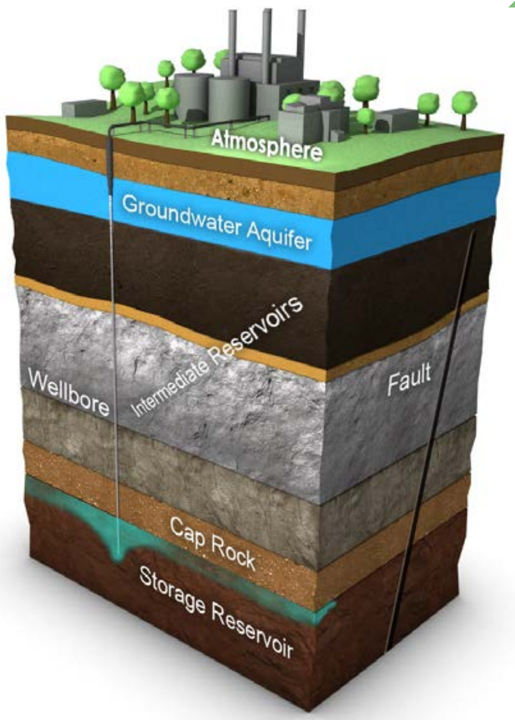
Aquifer Impact Model

Short Term Seismic Forecasting

Ground Motion Prediction for potential Induced Seismicity

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

A. Divide system into discrete components



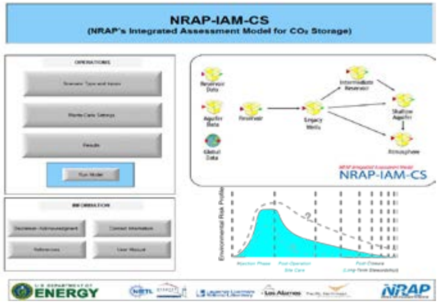
B. Develop detailed component models that are validated against lab/field data

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

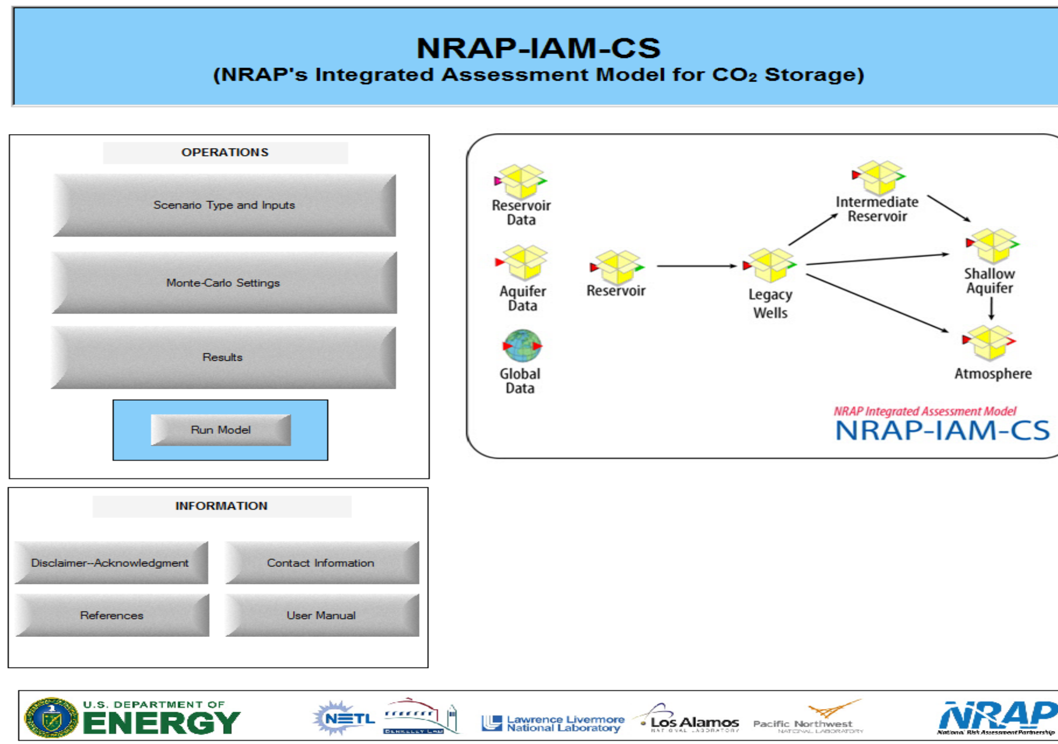
NRAP Integrated Assessment (System) Model



NRAP's Integrated Assessment Model for Carbon Storage

NRAP-IAM-CS

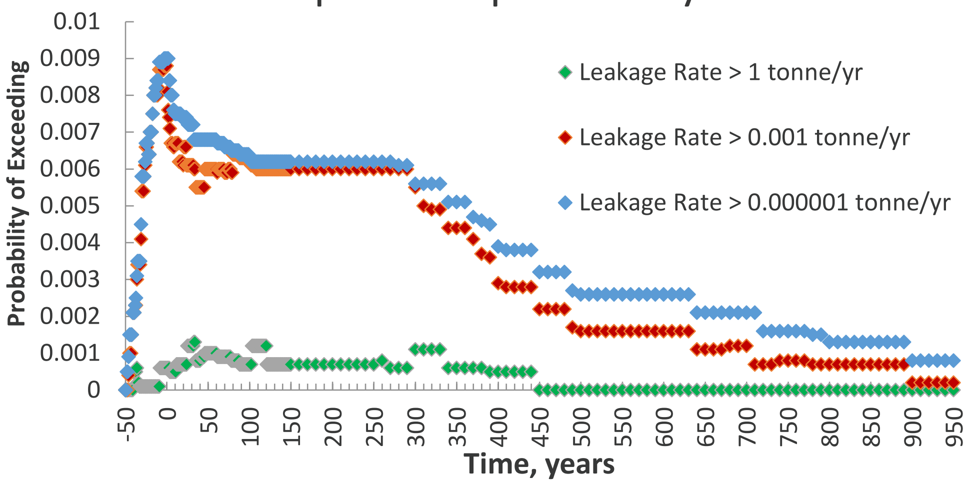
- Simulates long-term full system behavior (reservoir to aquifer/atmosphere)
- Results can be used to:
  - Compute risk profiles (time-dependent probability of leakage and GW impact)
  - Quantitatively estimate storage permanence amidst system uncertainty
  - Identify key drivers of risk in context of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



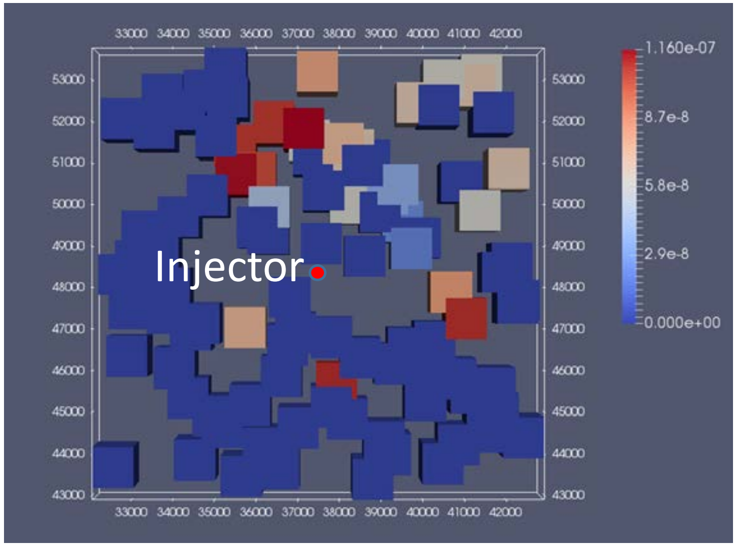
Pawar et al, IJGGC 2016

NRAP-IAM-CS Example Results

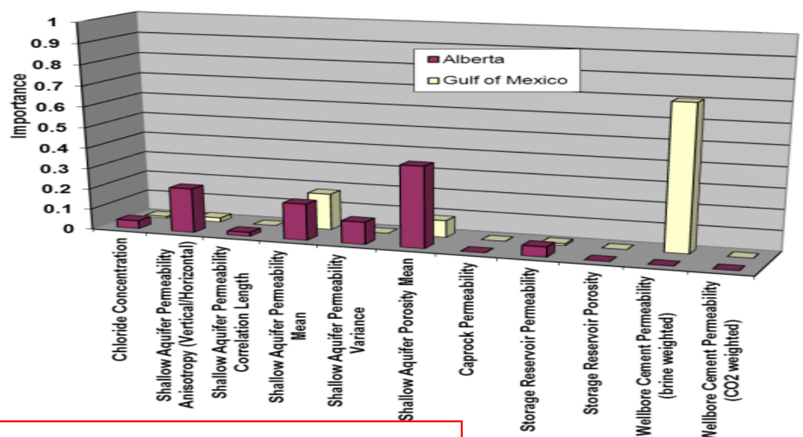
Time-dependent probability



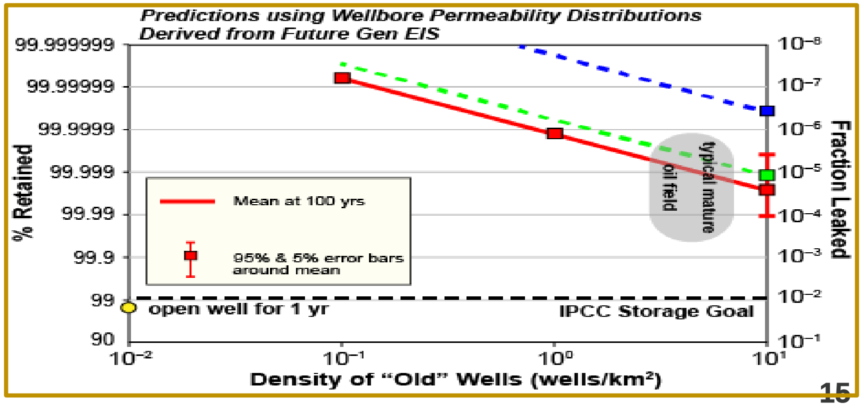
Variability of leakage potential around injector



Impacts of uncertain parameters



Effect of number of legacy wells on CO_2 retention



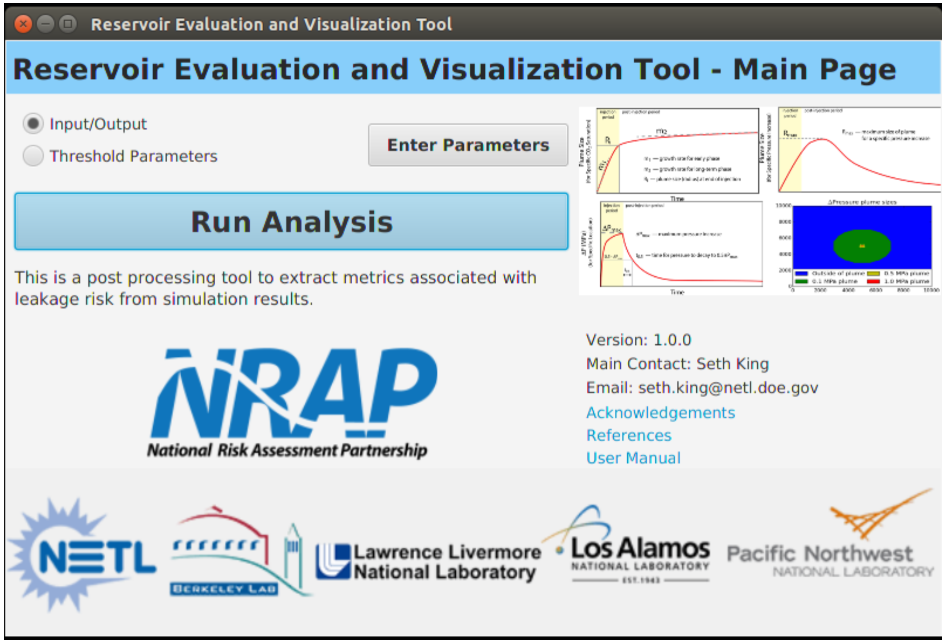
Hypothetical Illustrative Examples

Storage Reservoir Response

Reservoir Evaluation & Visualization (REV) Tool

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

- Uses pressure and saturation values from simulation software (modular design accommodates different file types)
- Can accept single or multiple reservoir simulation outputs
- Outputs at user-defined thresholds

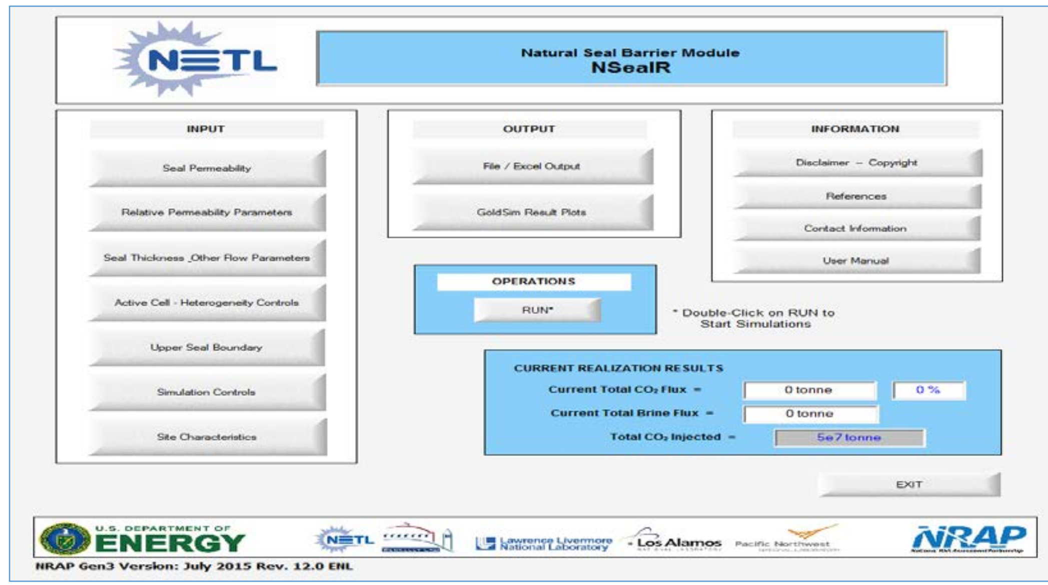


Caprock Leakage Potential

NSealR Tool

- Estimates flux through a fractured or perforated caprock
- 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
- Allows for various levels of complexity to model barrier response
- Accounts for effective stress dependence of aperture



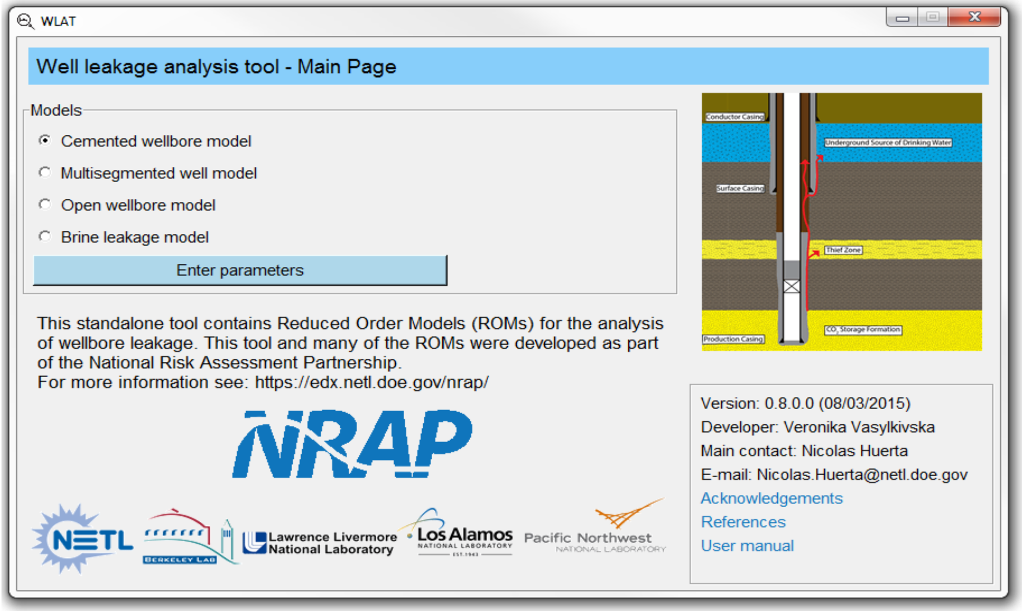
(Lindner, 2016; Namhata et al., 2017)

Well Leakage Potential

Well Leakage Analysis Tool (WLAT)

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

- Models migration of brine and/or CO_2 through wellbores
- Takes inputs of reservoir pressures and saturations
- Predicts flowrate into overlying reservoir, groundwater aquifer and atmosphere
- Incorporates chemistry to identify flowrate changes as a function of time



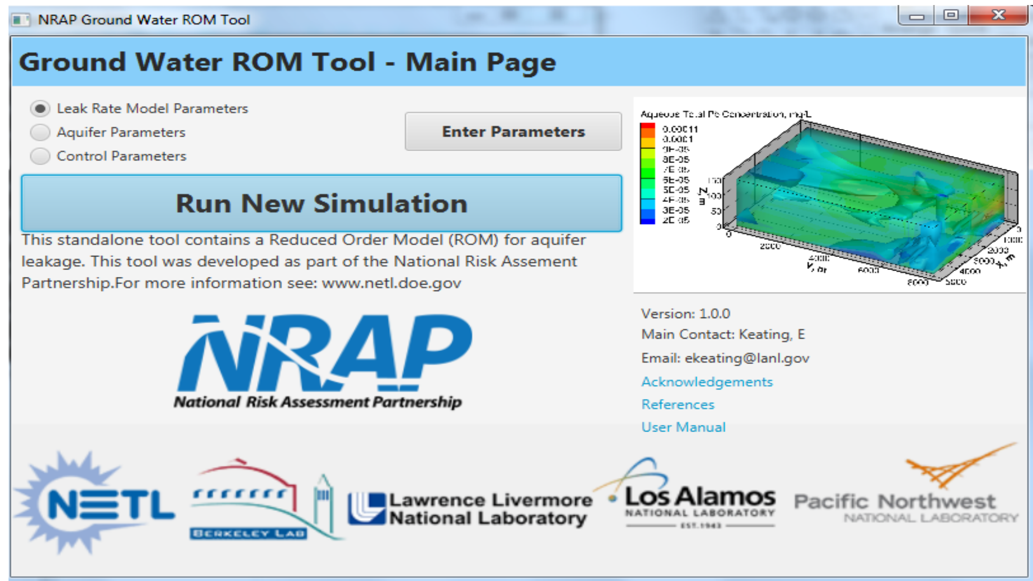
Harp et al, IJGGC, 2016

Rapid Prediction of Receptor Response: Groundwater

Aquifer Impact Model (AIM)

- Rapidly estimates volume of aquifer impacted by a leak
- Distinguishes between CO_2 and brine leaks
- Used to determine impact of threshold criteria

- Takes inputs of CO_2 and brine leak rates from wellbore or similar models
- Includes two different end member aquifer types (carbonate & sandstone)
- Accounts for flow and chemistry
- Metrics include: pH, TDS, metals concentrations, organics concentrations

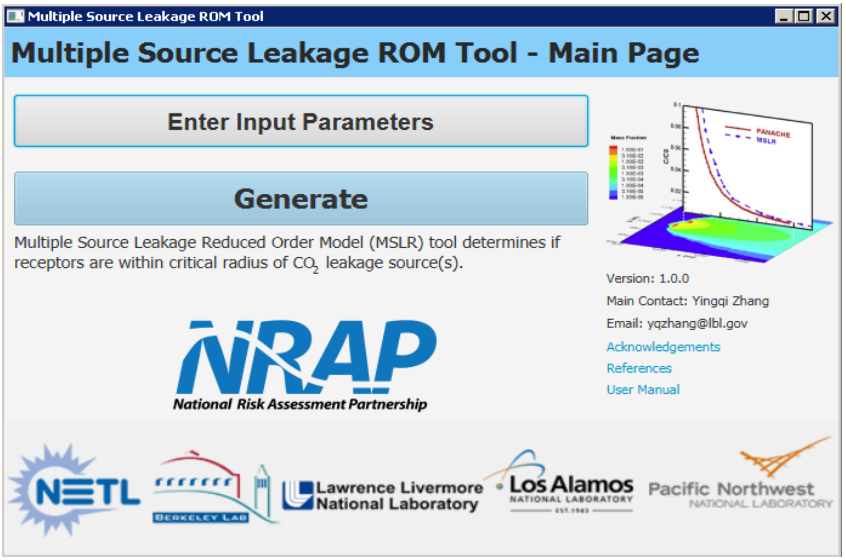


Rapid Prediction of Receptor Response: Atmosphere

Multiple Source Leakage Response (MSLR) Tool

- Determines if any receptors are within the plume of CO_2 with concentration above a cutoff in case of leak
- Handles single-source or multiple-source CO_2 leakage

- 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

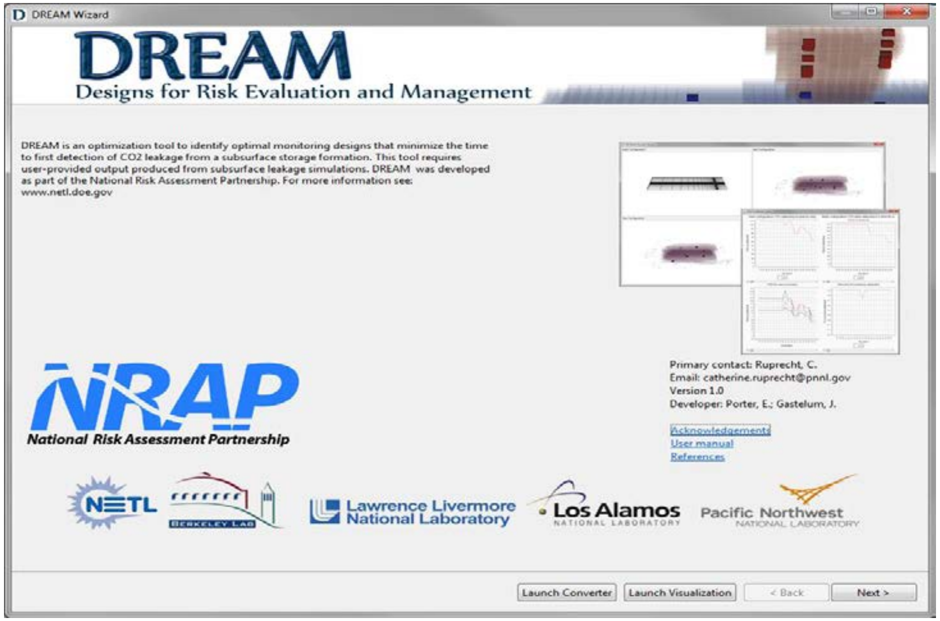


Monitoring Optimization

Designs for Risk Evaluation and Management (DREAM) Tool

- Estimates time to detection for a monitoring system
- Evaluates and select optimal monitoring designs

- Optimizes subsurface monitoring design for a specified CCS site:
  - monitoring design (well location and depth, sensor type) that yields minimum expected time to first detection of CO_2 leakage (E[TFD])
- Can incorporate budget and operational constraints
- Uses a collection of realizations of a subsurface simulation
- User defined alarm and inference criteria
  - Sensor detection threshold
  - How many sensors imply a leak

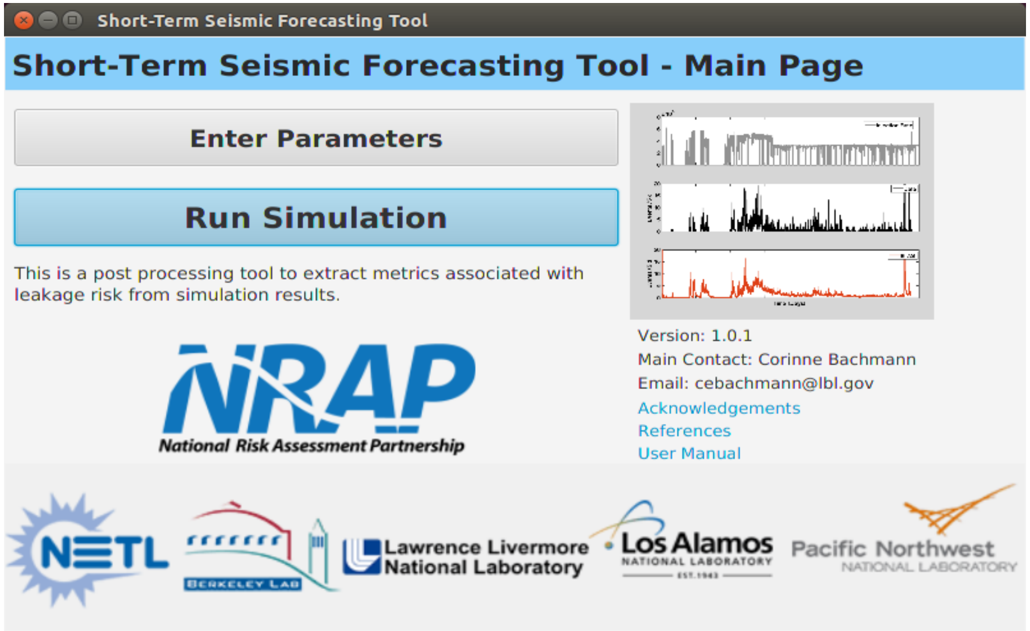


Potential Induced Seismicity

Short Term Seismic Forecasting (STSF) Tool

- Forecasts seismic event frequency over short term operational period
- Potential to complement stoplight approach for induced seismicity planning and permitting

- Based on Gutenberg and Omori laws
- Originally an aftershock model
- Reads a seismic event catalog and incorporates basic injection information
- Forecasts seismic frequency for a window of a few days

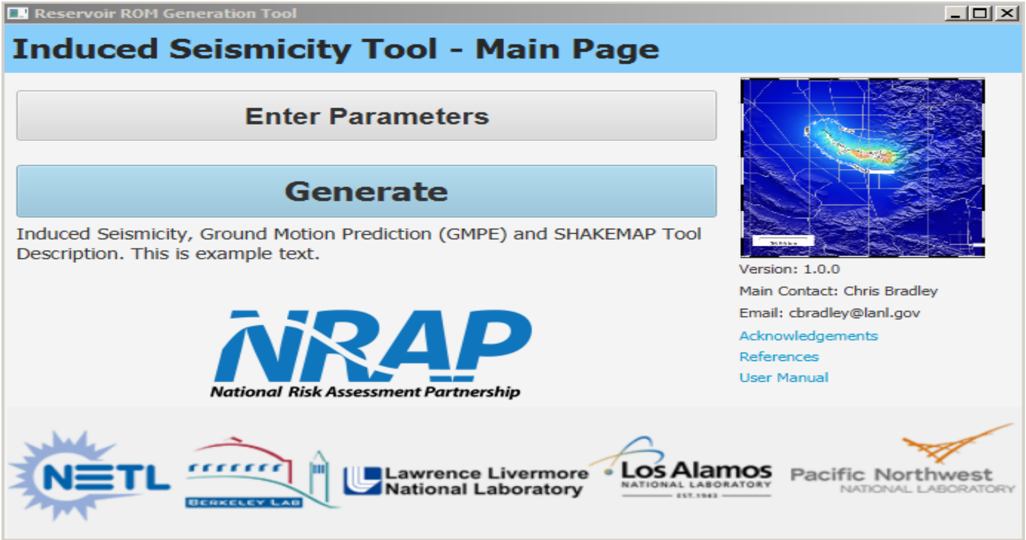


Potential Induced Seismicity

Ground Motion Prediction from Induced Seismicity (GMPIS) tool

- 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

- 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, with credible prediction in the Mw 1-4 range
- Incorporates published models for site-specific amplification corrections (Boore and Atkinson, 2008; Abrahamson and Silva; 2008.)

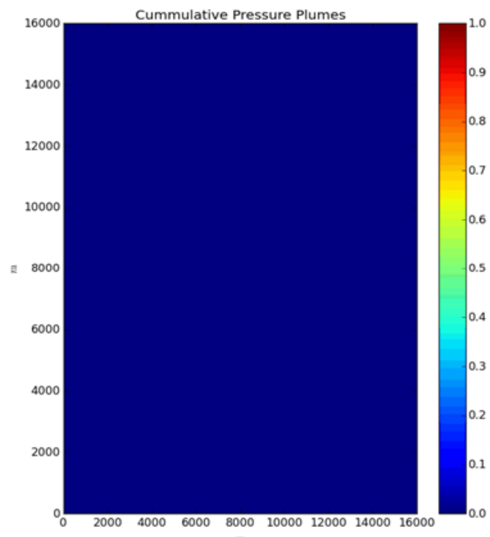


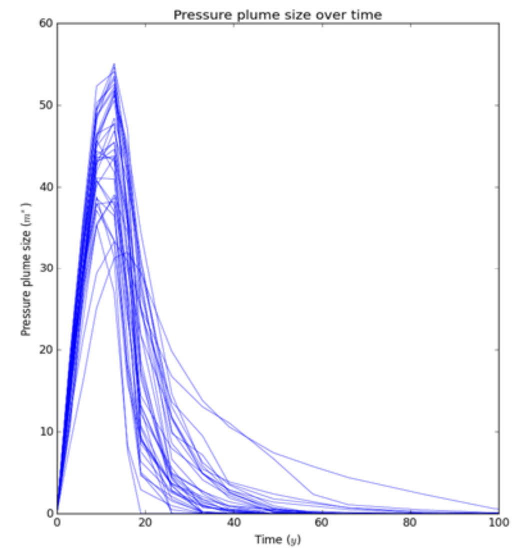
NRAP is building the science base for effective risk quantification and uncertainty reduction

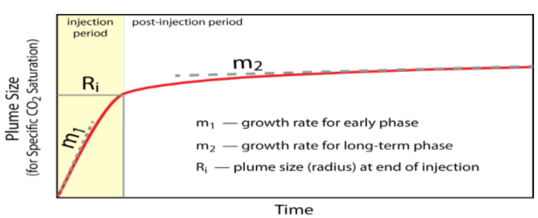
NRAP analyzed key risk-based metrics for the reservoir component of the storage system using REV tool

- **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
    - Brine rise
    - Fault-slip criteria
- **Pressure at a location**
  - Maximum pressure increase

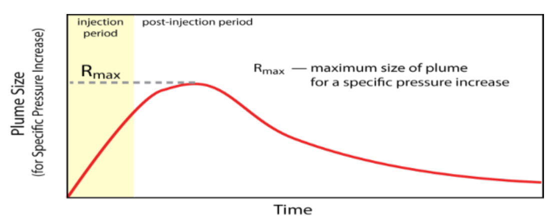
Pressure plume evolution for 10 year of injection at 1 MT/year



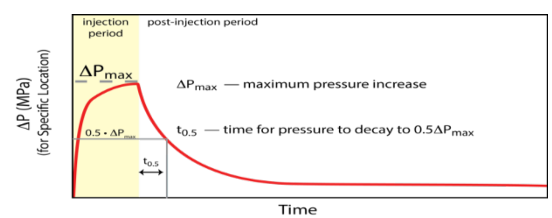




Size of CO_2 Plume

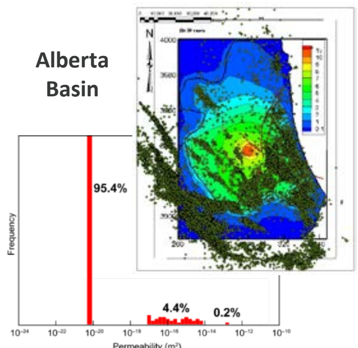


Size of Pressure Plume

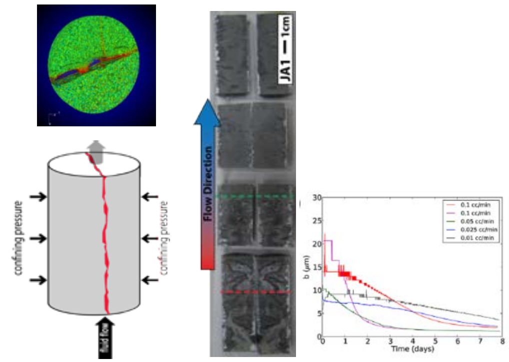


Pressure at at a Location

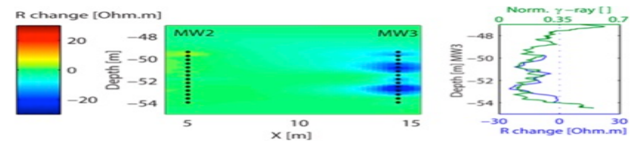
NRAP is building the science base for effective risk quantification and uncertainty reduction



Geostatistical studies on wellbore characteristics

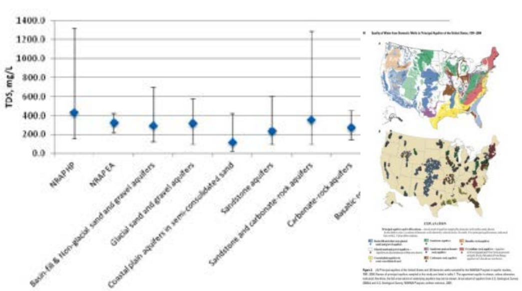


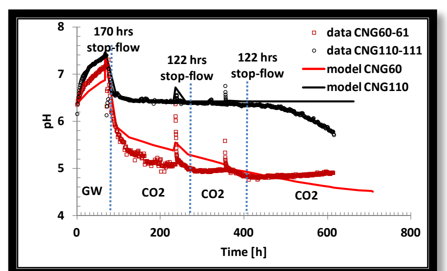
Experimental observation of cement fracture self-healing



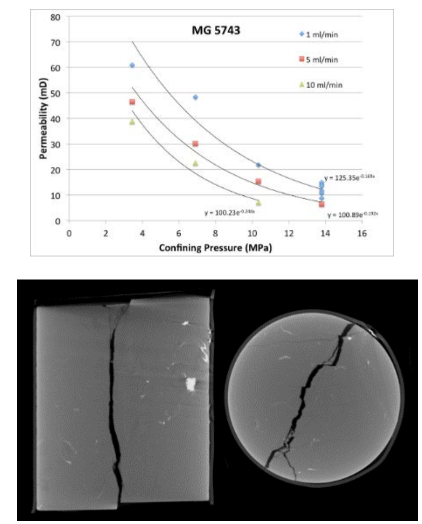
Investigating quality of monitoring technologies

Established "no-impact" threshold values for two major aquifer classes





Laboratory measurements of changes to groundwater quality



Permeability measurements of fracture during slip

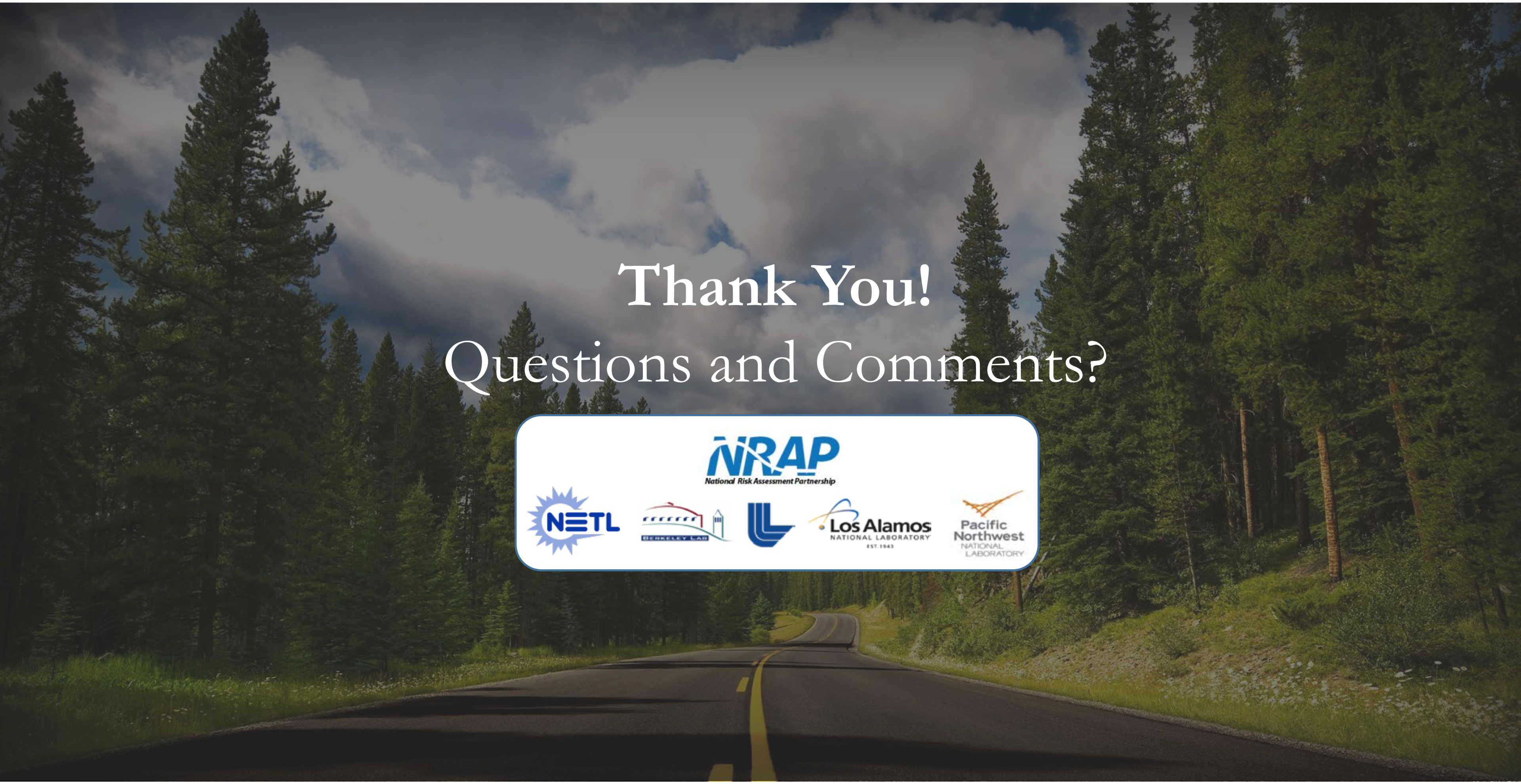
NRAP Phase-II Focus

Risk Management & Uncertainty Reduction

- Demonstrate Risk Assessment Tools Applicability to Field Projects
  - Ongoing work with Regional Partnership, CarbonSAFE & BEST Projects
  - Open to international collaboration opportunities
- Containment Assurance:
  - Approaches for risk management through integration of risk quantification, strategic monitoring, risk mitigation
  - Risk-based framework for pressure and plume management
  - Leakage potential through damaged wellbores, Caprock/AZMI response to stress/leakage
- Induced Seismicity:
  - Real time hazard forecasting
  - Active seismicity management & seismicity management protocols
  - Fault leakage due to seismicity
- Strategic Monitoring for Uncertainty Reduction
  - Integrate monitoring with risk assessment to reduce uncertainty
  - Effective monitoring designs
  - Post-injection monitoring protocols
- Critical Questions Related to Environmental Risk Assessment and Management
  - Develop knowledge-base for making decisions on PISC

Acknowledgement

- Funding for NRAP is provided by the US DOE's Fossil Energy Program Office through the CO_2 Storage R&D Program. The funding is managed by National Energy Technology Laboratory



Thank You!

Questions and Comments?