National Risk Assessment Partnership Phase I:

Quantifying the Behavior of Engineered–Natural Systems for CO_2 Storage (Risk Assessment & Quantification)

Grant Bromhal (NRAP Technical Director)

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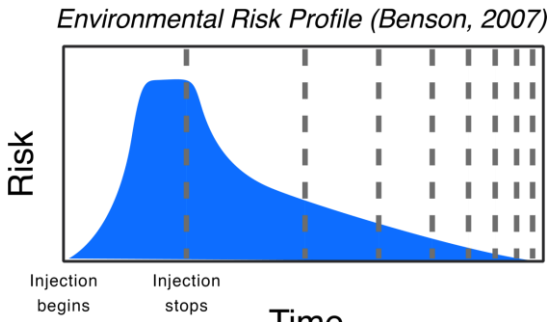
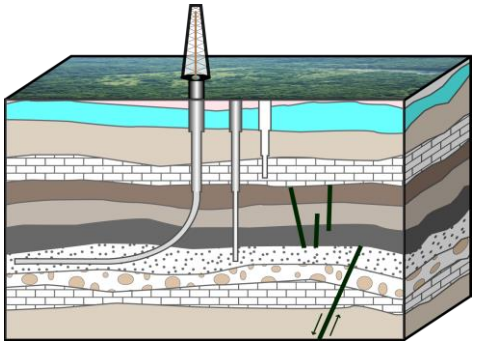
National Energy Technology Laboratory

George Guthrie (NRAP Executive Committee, Chair)

Los Alamos National Laboratory



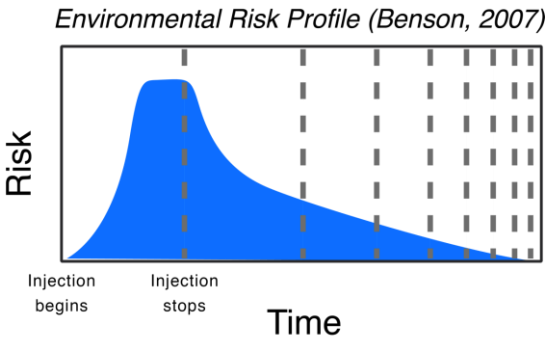


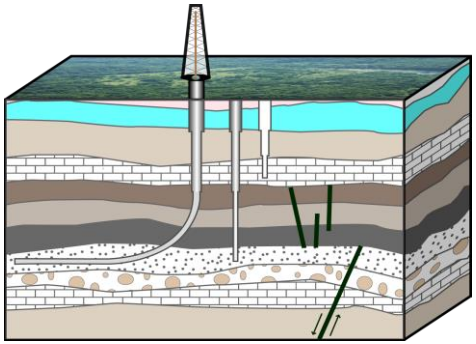
Technical Team

Stakeholder Group

National Risk Assessment Partnership Phase I:

Quantifying the Behavior of Engineered–Natural Systems for CO_2 Storage (Risk Assessment & Quantification)





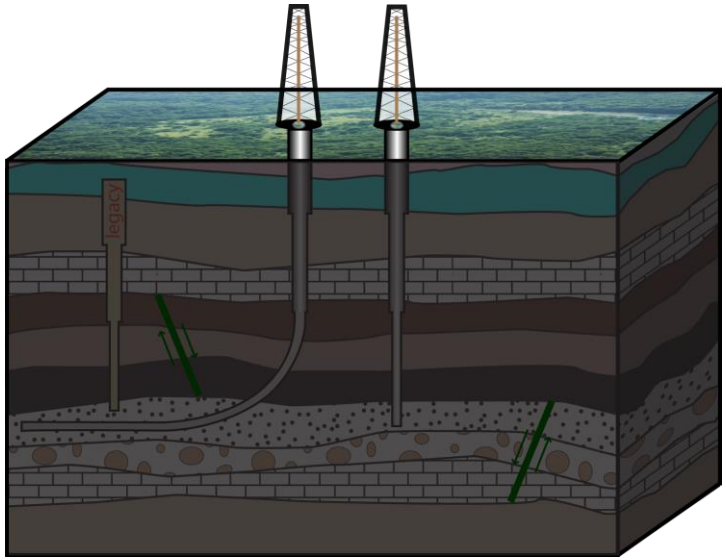
How does risk evolve at a CO_2 storage site?

- timing and distribution of potential impacts

Detailed Physics/Chemistry **vs.** **Uncertain Site Characteristics**

NRAP's Overall Focus:

Using science-based prediction to inform decisions tied to complex and uncertain engineered–natural systems.

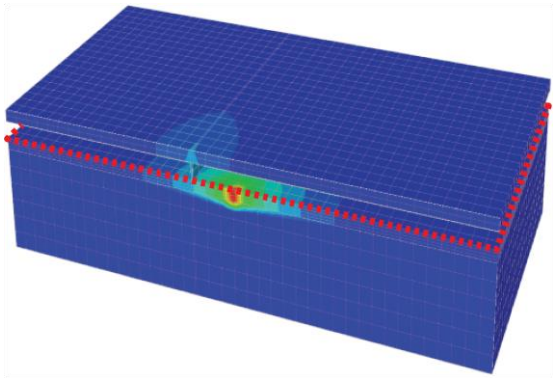


- ***Risk management strategies***
- ***(Post-injection) monitoring strategies***

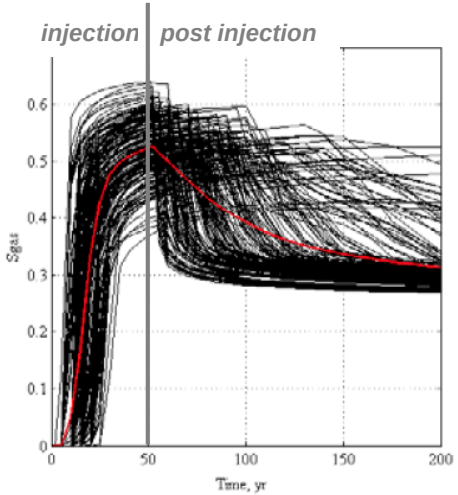
- ***Early stage decisions may have limited site information***
- ***Natural systems are complex and heterogeneous***

Detailed Physics/Chemistry vs. **Uncertain Site Characteristics**

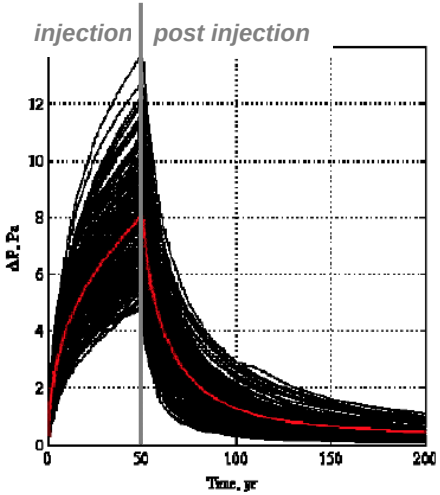
Different choices of permeability (& porosity, …) impact predictions on reservoir behavior related to risk.



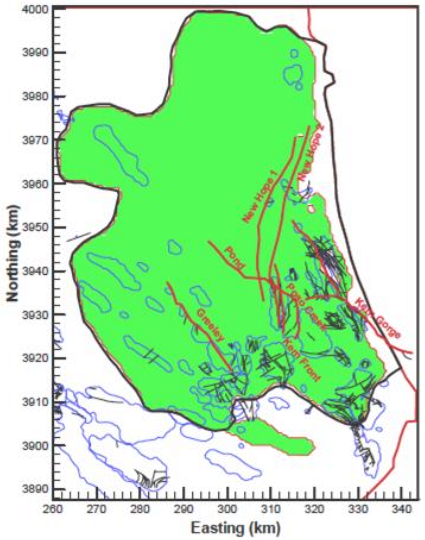
CO_2 Saturation



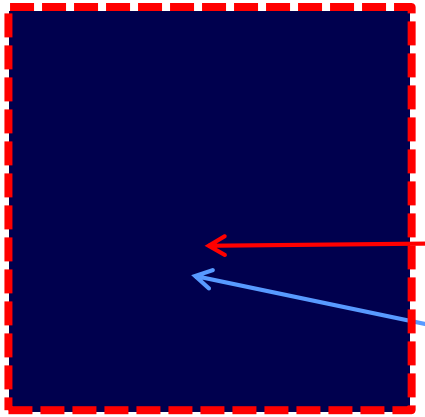
Pressure Buildup



from Wainwright et al. (2012) NRAP-TRS-III-002-2012



Plan View of Reservoir



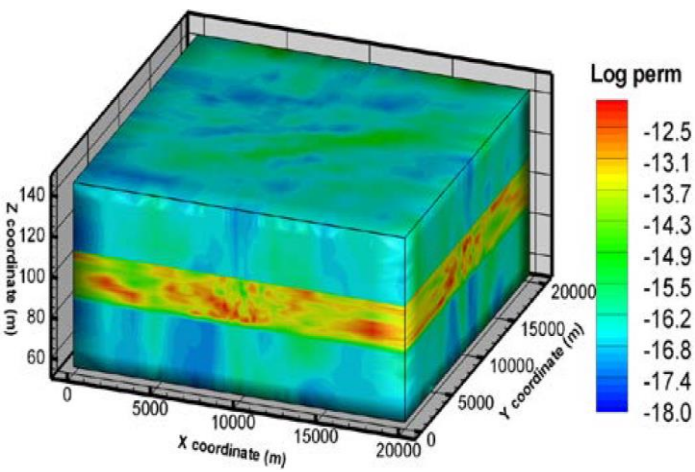
Evolution of Pressure at Top of Reservoir

"Monitoring" location for graphs

Injection location

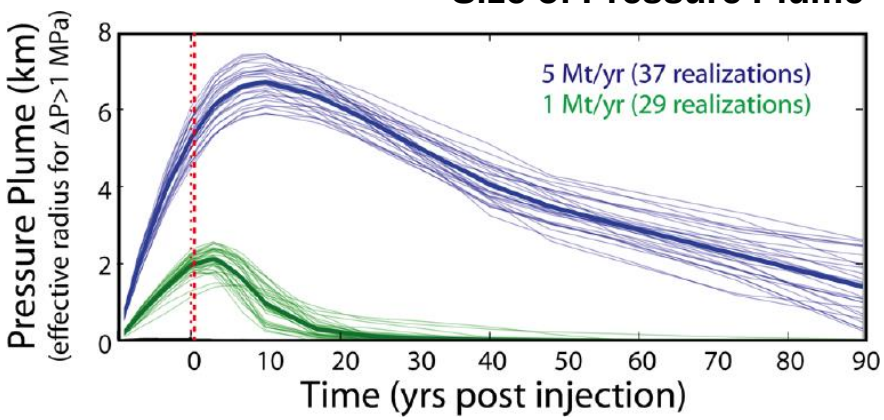
Different choices of permeability (& porosity, …) impact predictions on reservoir behavior related to risk.

Example from Potential Storage Site using Core Data from Four Wells

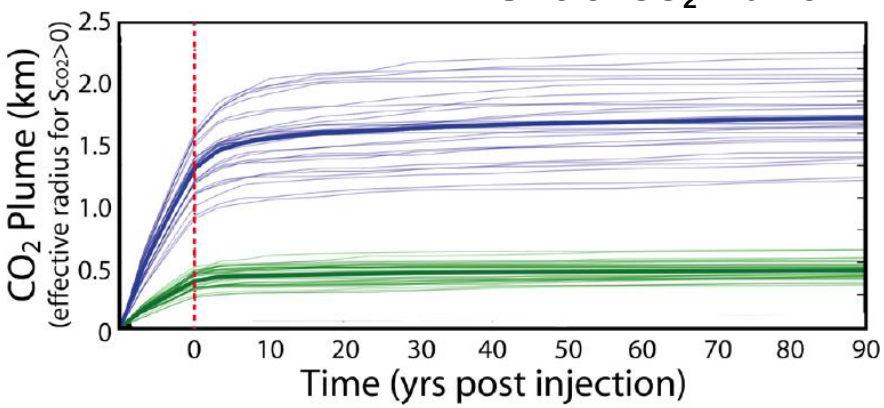


Realizations based on different permeability distributions developed using site data from multiple wells and transition-probability geostatistics.

Size of Pressure Plume



Size of CO_2 Plume



from Pawar et al. (2014) NRAP-TRS-III-in prep based on site model in Deng et al. (2012)

NRAP's first phase has focused on risk quantification and assessment; phase II will focus on risk management and uncertainty reduction.

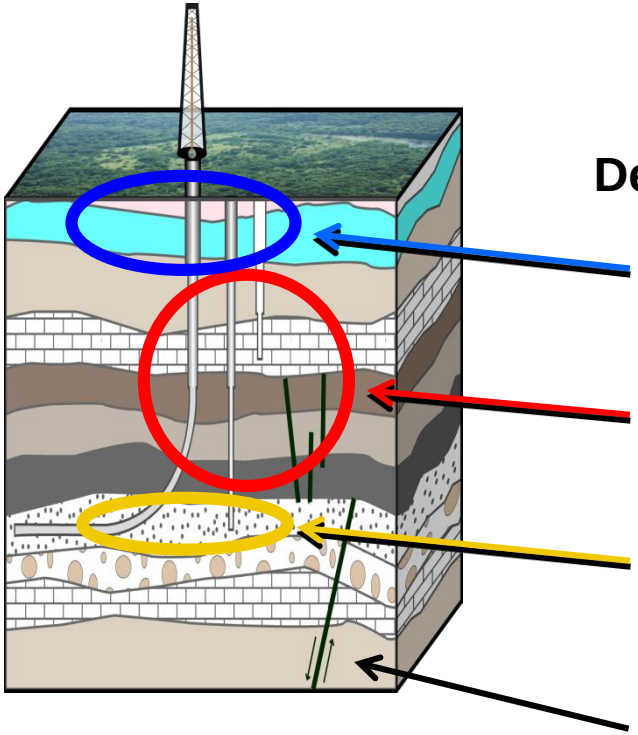
FY2011	FY2012	FY2013	FY2014	FY2015	FY2016

Toolsets and Science Base (Data for Calibration/Validation)

Targeted Assessments through Application

Risk-Based Monitoring Protocols

Phase I



Development of efficient simulation tools for:

Potential Impacts

- Leakage to atmosphere; CO_2 or brine impacts on aquifer

Leakage Pathways

- Multiphase flow along wellbores and fractures

Reservoir Behavior

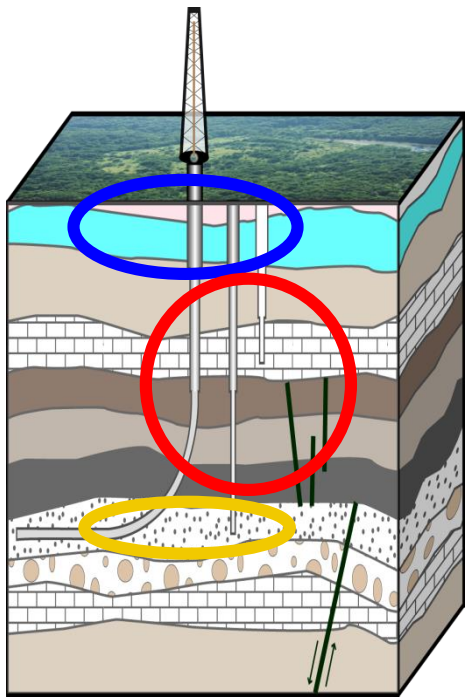
- Evolution of CO_2 plume and pressure plume

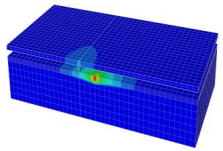
Induced Seismicity

- Pressure-induced impacts to critically stressed faults

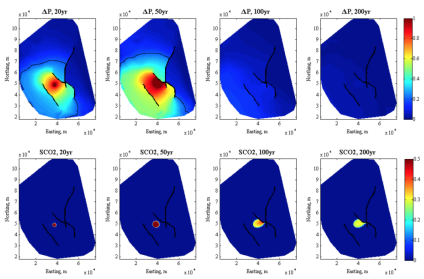
NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.

A. Divide system into discrete components

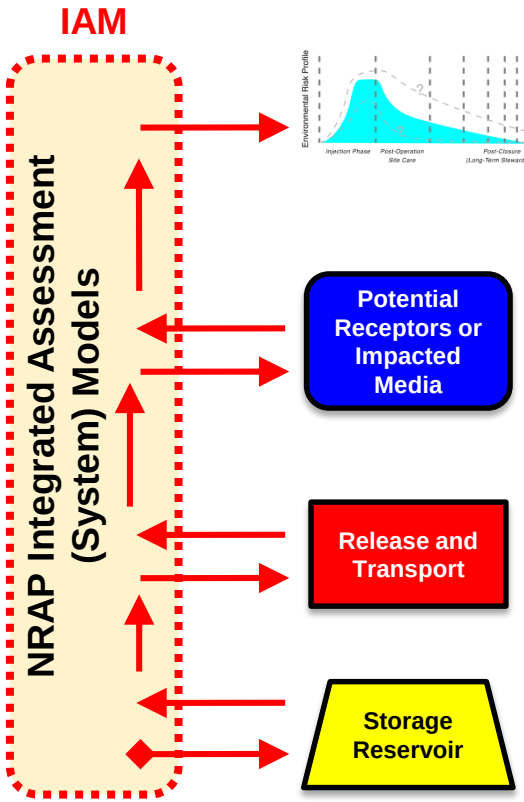




B. Develop detailed component models that are validated against lab/field data



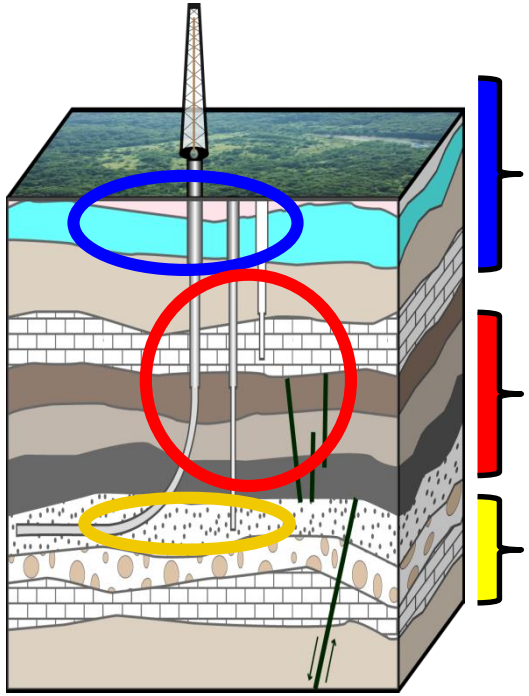
C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions



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

NRAP's Approach

A. Divide system into discrete components

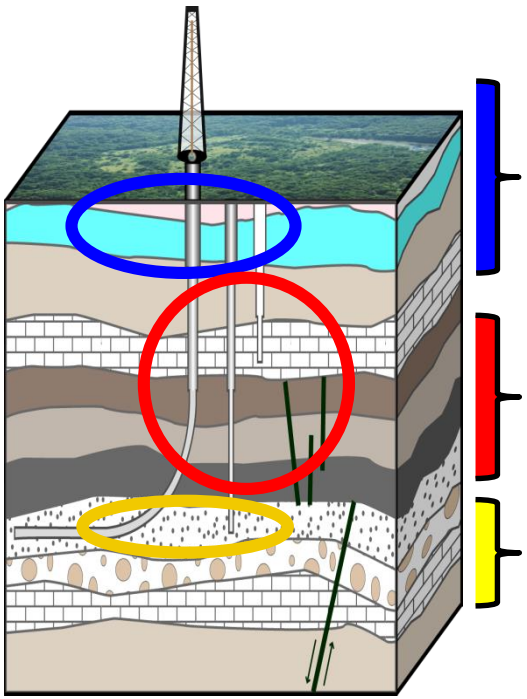


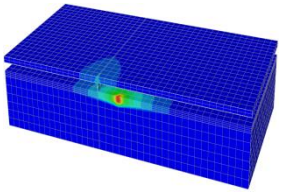
System behavior stems from the behavior of individual components.

NRAP's Approach

A. Divide system into discrete components

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

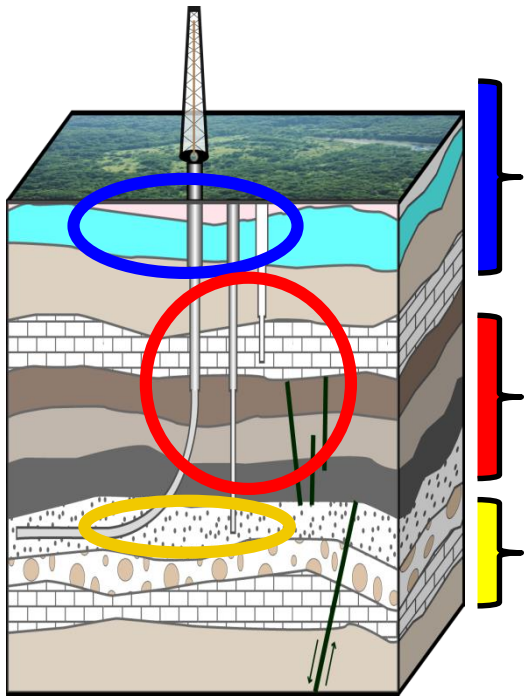




Science-based prediction can be used to characterize component behavior for specific conditions.

NRAP's Approach

A. Divide system into discrete components



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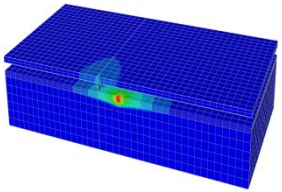
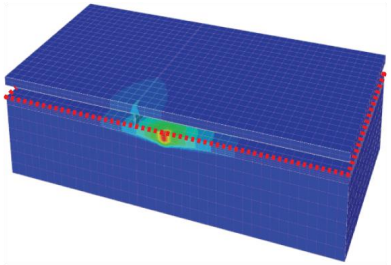


C. **Develop reduced-order models (ROMs) that rapidly reproduce component model predictions**

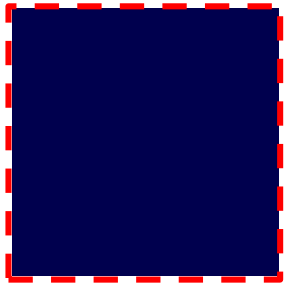


Detailed Simulations

- physics based
- detailed behavior for specific conditions

Calibrate ROM

Validate ROM

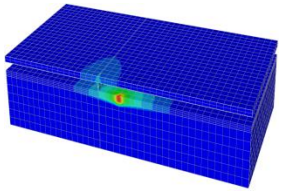


Reduced-order Models

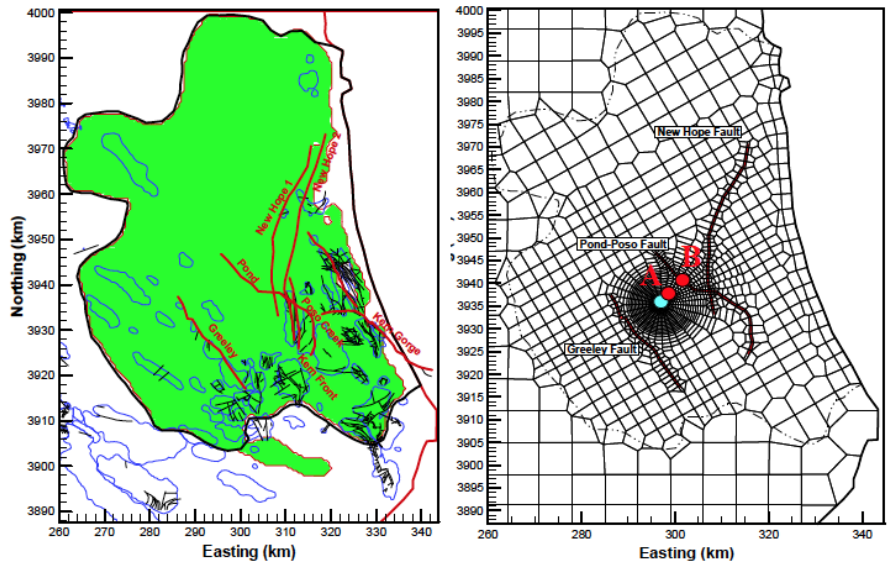
- simplified; rapid
- stochastic behavior for range of conditions

Reduced-order models (ROMs) are used to allow rapid evaluation of component behavior over conditions of interest.

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



- **4D (3D+time) to 3D**
- **Only key variables**
- **Finite-element to simplified solution**



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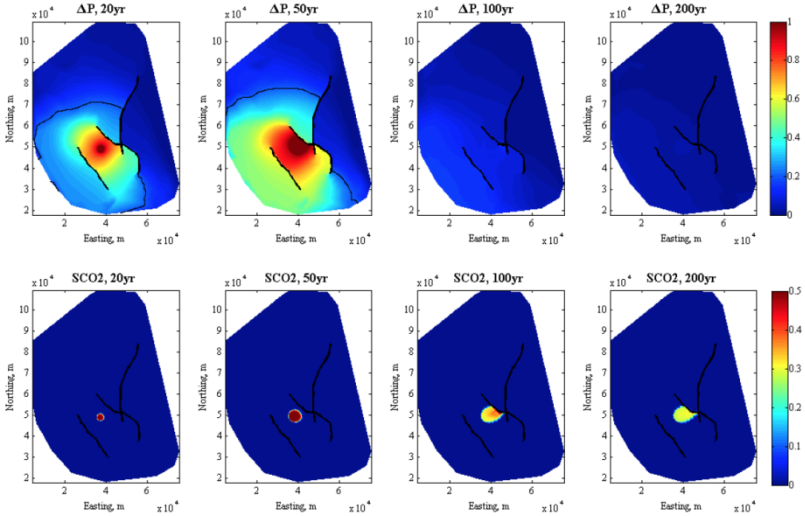
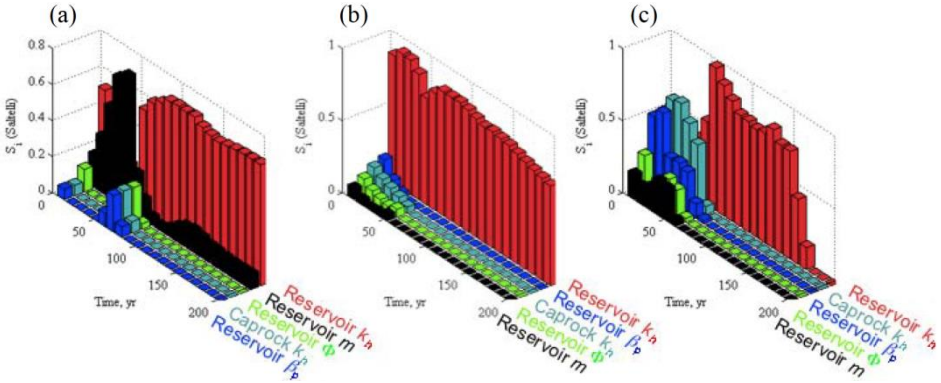


ROM focuses on P and saturation at reservoir-seal interface.



Sensitivity analysis allows ROM to focus only on key variables.

NRAP's Approach

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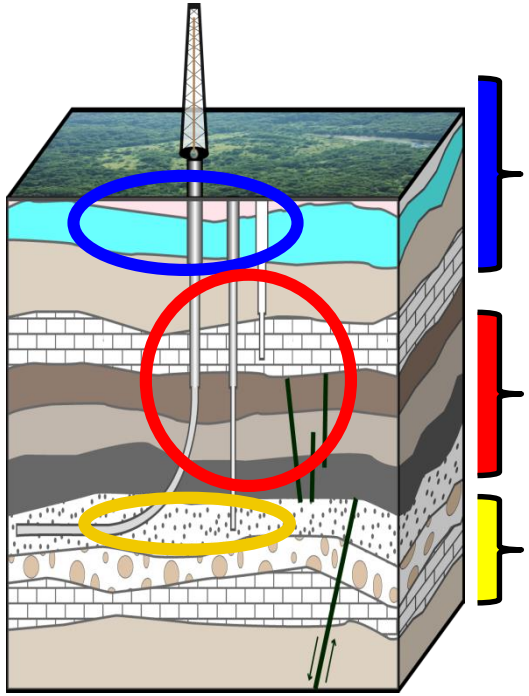

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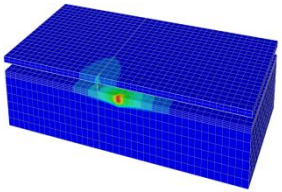

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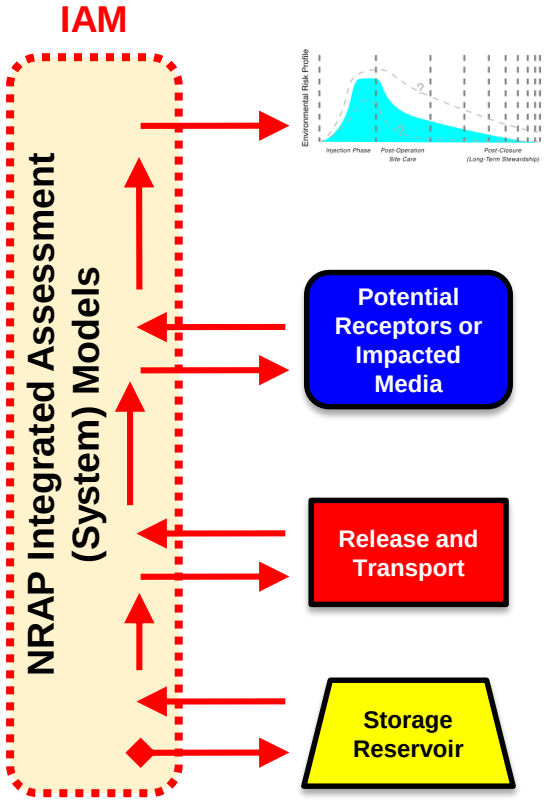
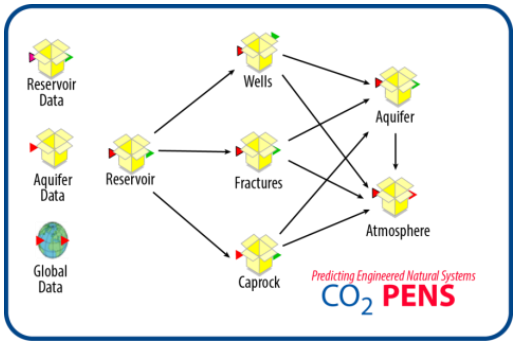
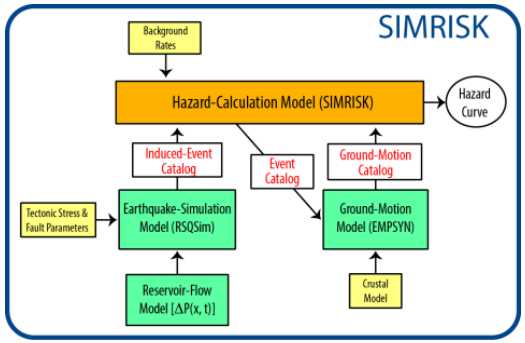
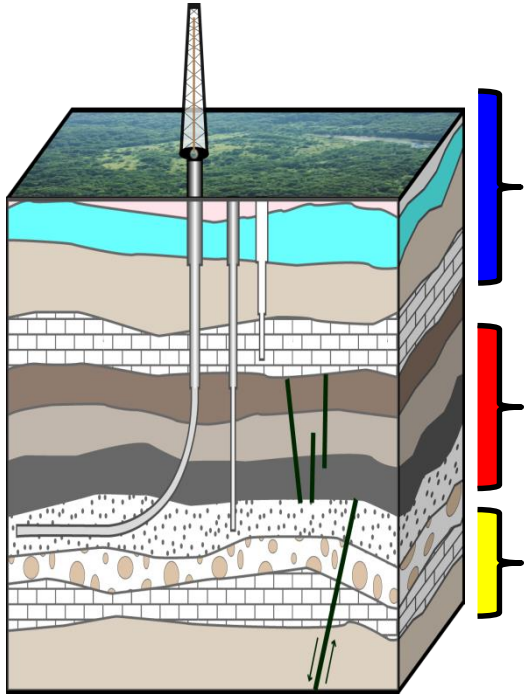


D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk

NRAP is focused on quantification of two types of IAMs, based on coupling reservoir behavior to other system components.







Potential Leakage Impacts
(Atmosphere; Groundwater)

⇧ *fluid propagation*

Release/Transport of Fluids

⇧ *fluid propagation*

Reservoir (plume/pressure evolution)

Potential Ground-Motion Impacts
(Ground Acceleration)

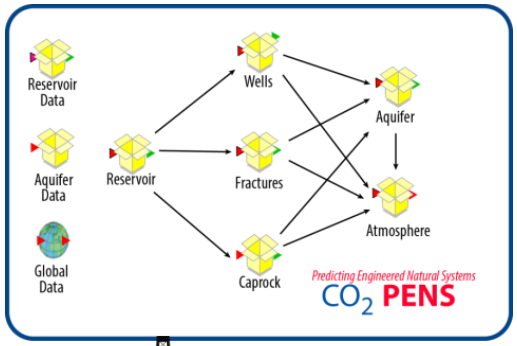
⇧ *seismic-wave propagation*

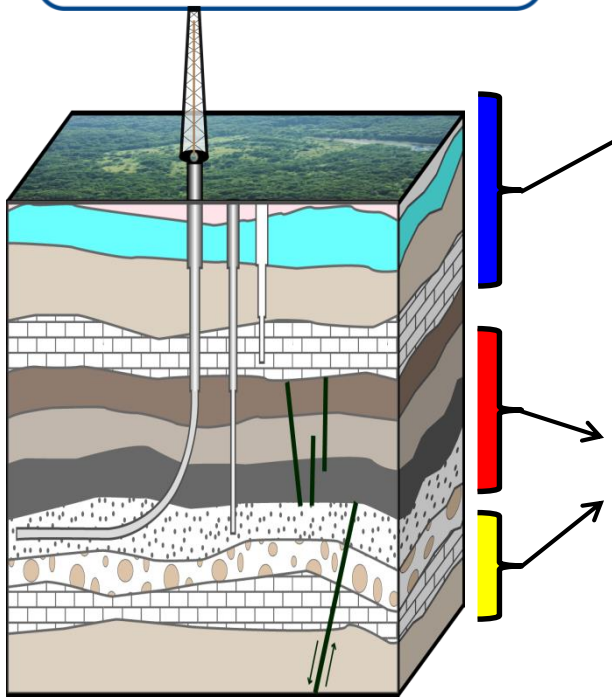
Slip along a Fault Plane

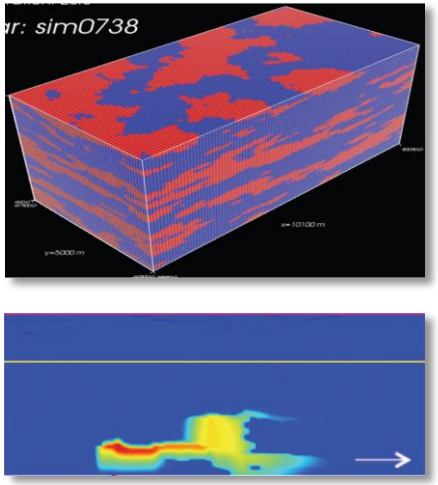
⇧ *stress/pressure propagation*

Reservoir (plume/pressure evolution)

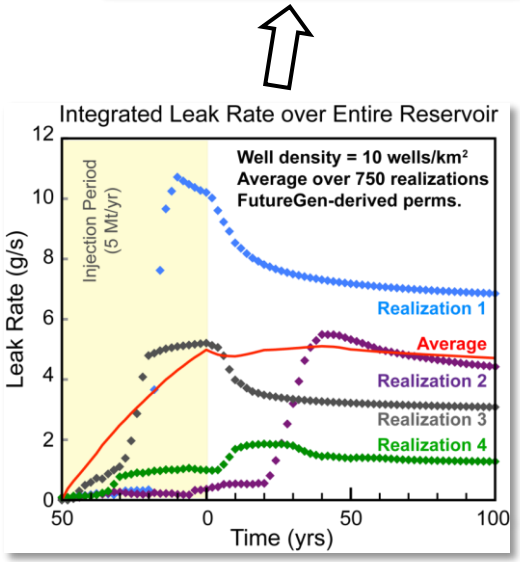
Putting the Pieces Together: Leakage Example



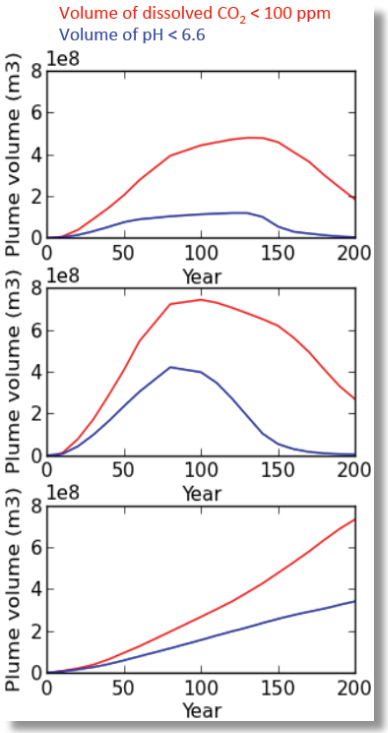




Sizes of Potential Plumes in Aquifer (e.g., CO_2 ,brine, …)



Potential Leakage Rate through Legacy Wells



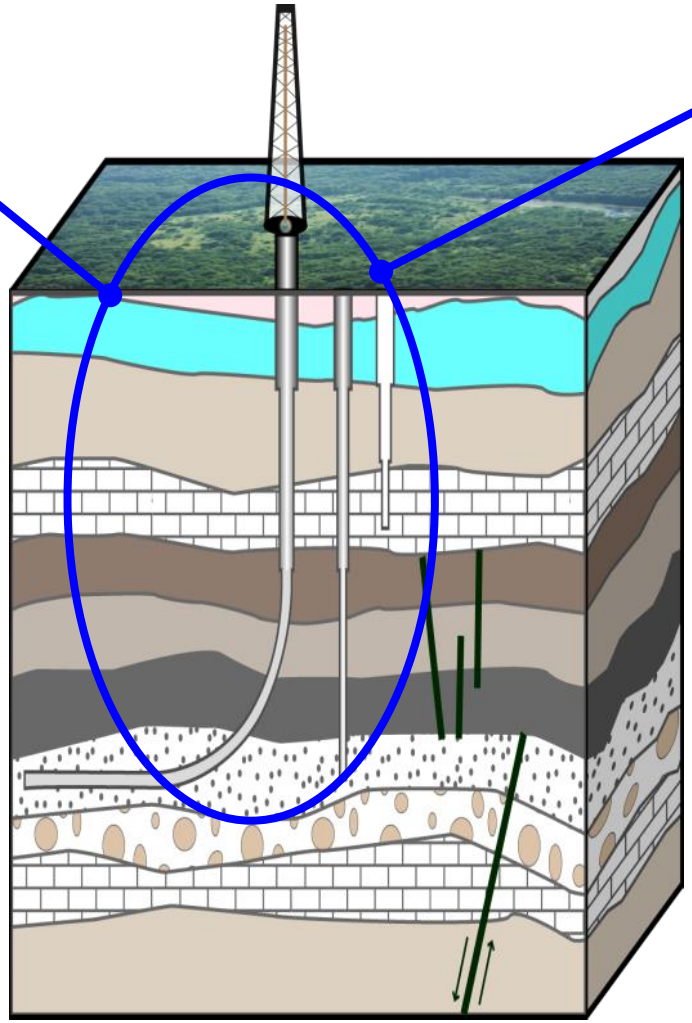
Plume Size over Time/Space

NRAP Tools

Now available for beta testing!

Design for Risk Evaluation and Monitoring (DREAM)

- *Estimates time to detection for a monitoring system*
- *Evaluates various monitoring designs*

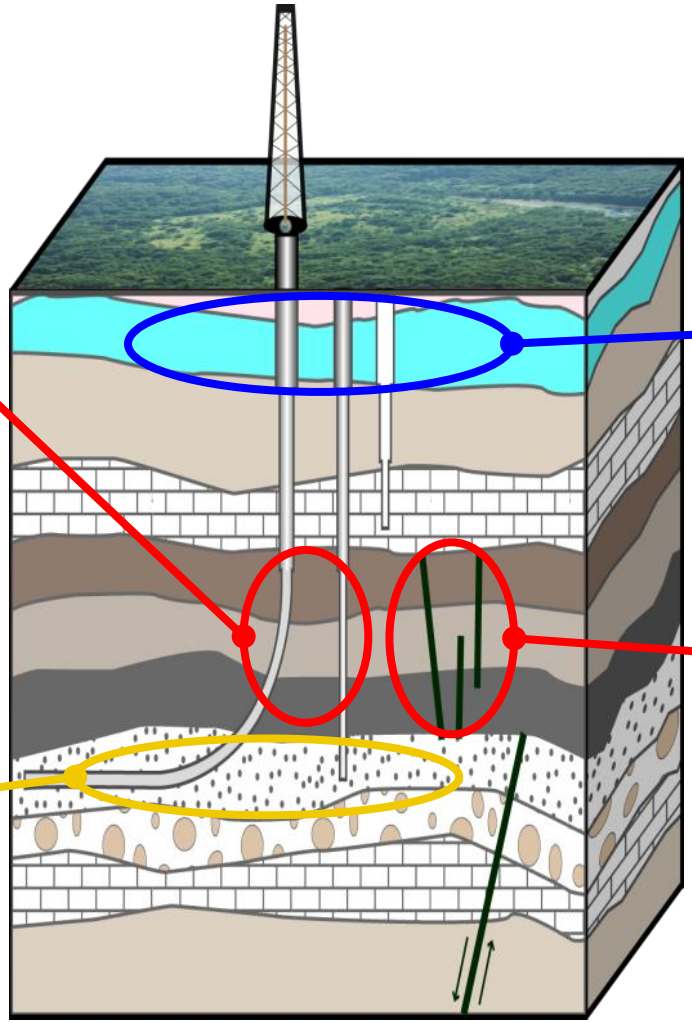


NRAP-IAM-CS

- *Generates risk profiles (time-lapse probability of leakage and impact)*
- *Quantifies flux & impacts of CO_2 & brine to overlying receptors (groundwater; atmosphere)*
- *Identifies key drivers of risk amidst system uncertainty*

NRAP Tools

Now available for beta testing!



Wellbore Leakage Analysis Tool

- *Models migration of brine and/or CO_2*
- *Predicts flowrate into intermediate zone and/or groundwater aquifer*

Reservoir Evaluation and Visualization

- *Generates pressure/CO_2 plumes sizes over time*
- *Visualizes reservoir behavior probabilistically*

Aquifer Impact Model

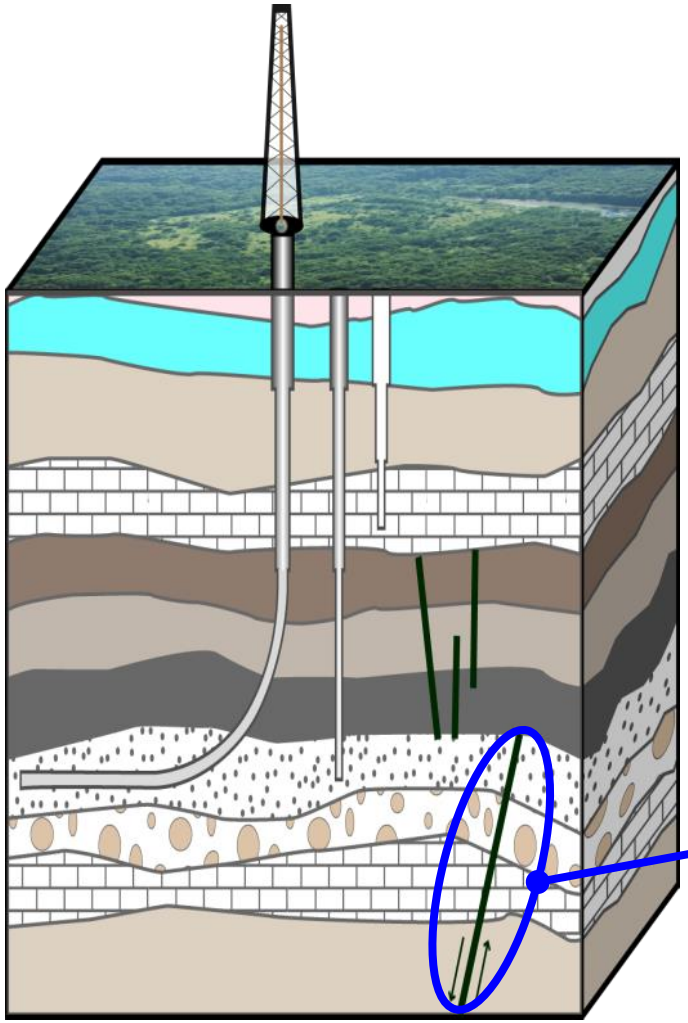
- *Estimates aquifer volume impacted for different potential leak scenarios*

Natural Seal ROM (NSealR)

- *Estimates flux through a fractured or perforated seal*

NRAP Tools

Now available for beta testing!



Short Term Seismic Forecasting

- ***Forecasts near-term seismic event frequency***

For more information…

www.edx.netl.doe.gov/nrap

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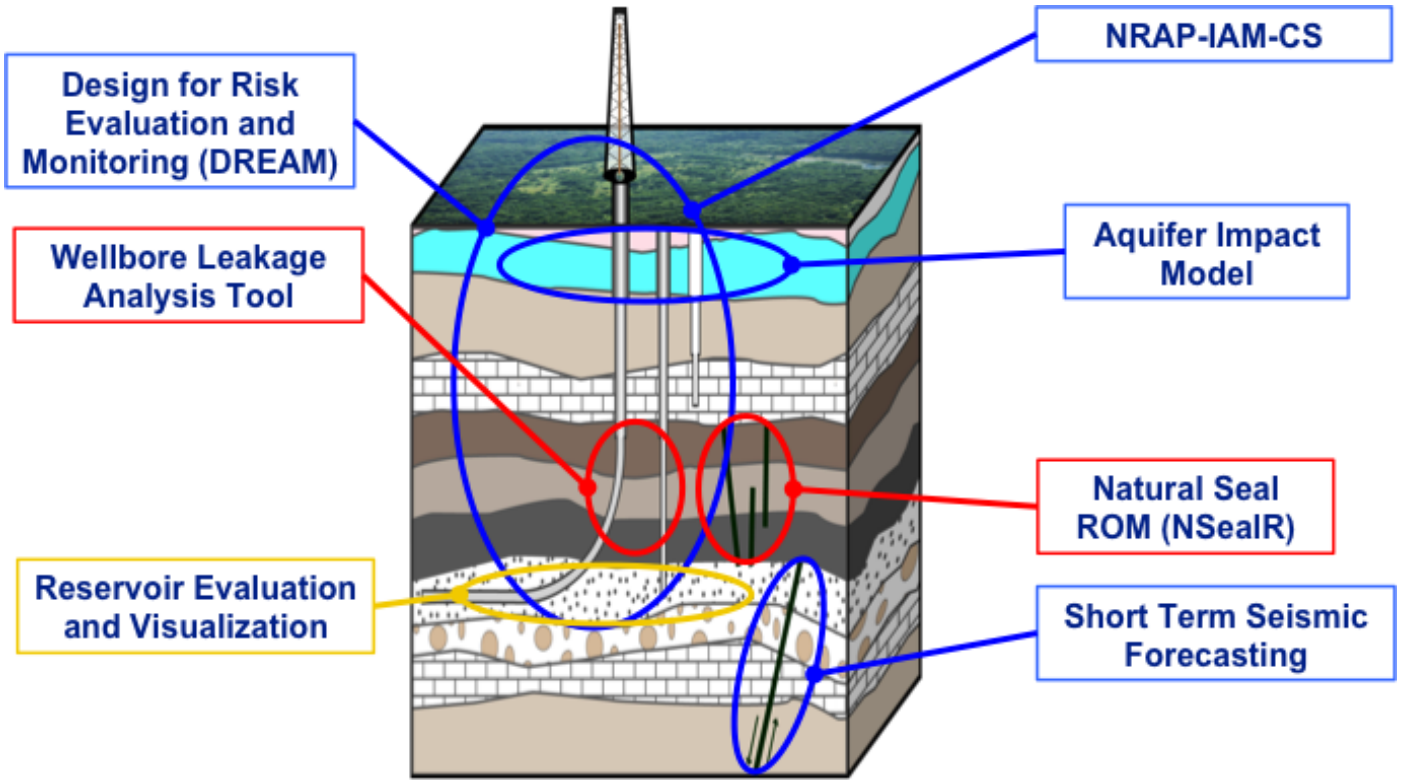
Bob Dilmore (robert.dilmore@netl.doe.gov)

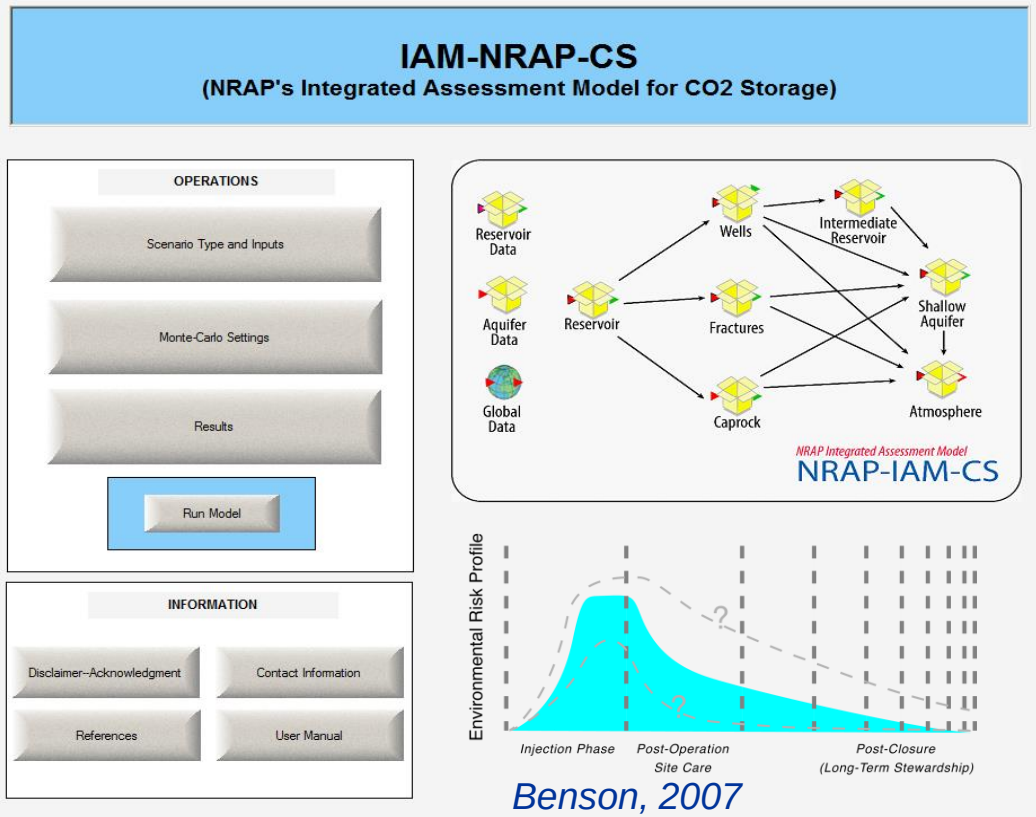
George Guthrie (geo@lanl.gov)



Integrated Assessment Model for Carbon Storage (NRAP-IAM-CS)

- Simulates long-term full system behavior (reservoir to aquifer/atmosphere)
- Generates risk profiles (time-lapse probability of leakage and GW impact)
- Estimates storage permanence quantitatively amidst system uncertainty
- Identifies key drivers of risk amidst system uncertainty

- ***Integrates ROMs of system components including: storage reservoir, cemented & open wellbores, faults, and groundwater aquifer***
- ***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***



Benson, 2007

DREAM—Prototype tool for evaluating monitoring strategy

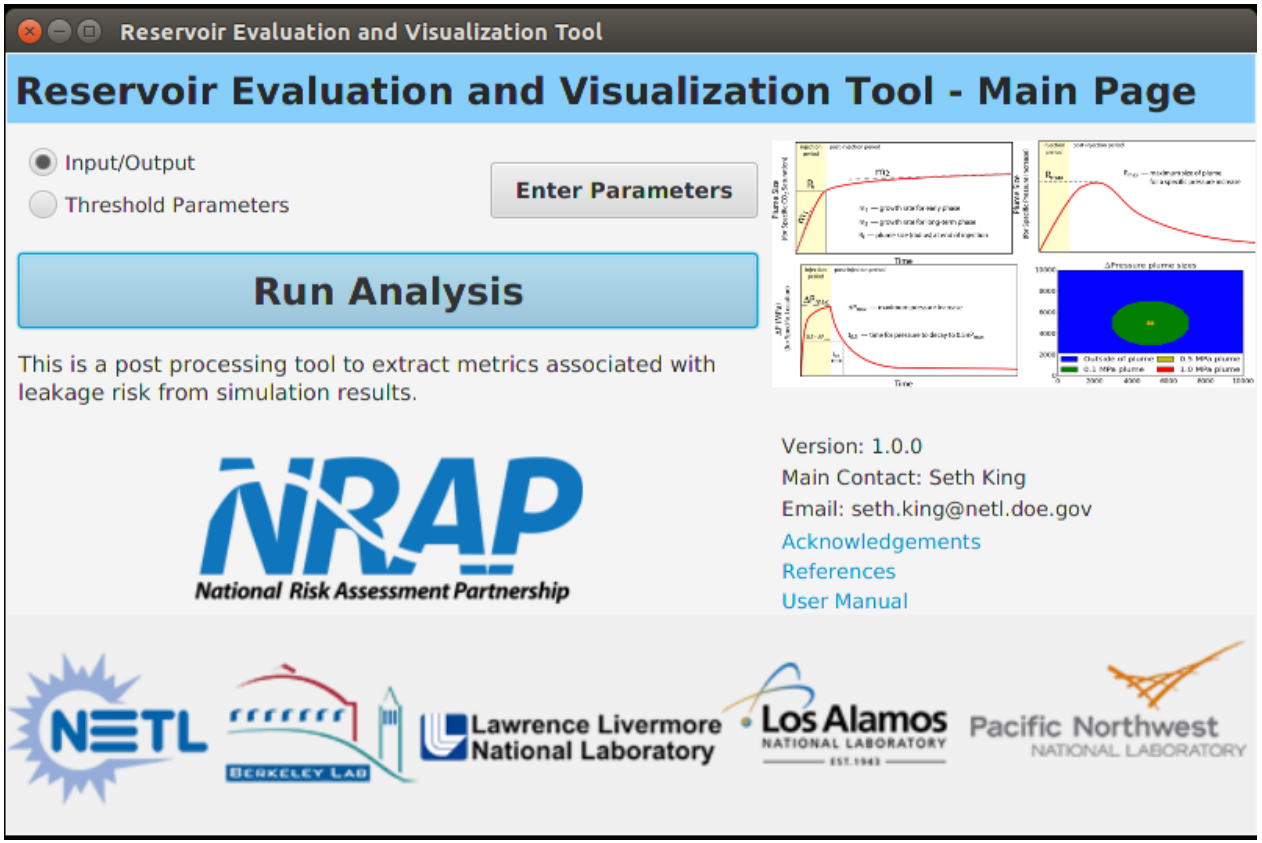
- Estimates time to detection for a monitoring system
- Evaluates various monitoring designs

- ***Finds 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*

Reservoir Evaluation & Visualization (REV) Tool

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

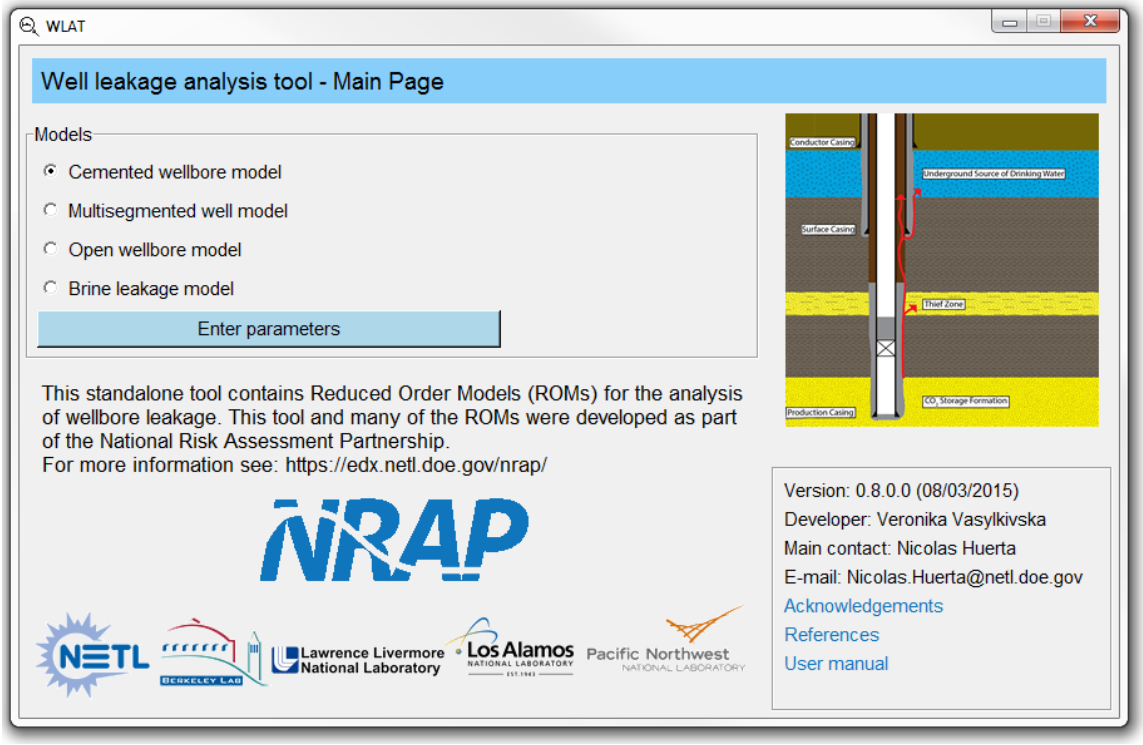
- ***Uses pressure & saturation values from simulation software (modular design accommodates different file types).***
- ***Outputs plume sizes through time and pressure values in specified grid blocks at each time step.***
- ***Functions for a single reservoir or accepts multiple simulations and outputs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



Wellbore Leakage Analysis Tool

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

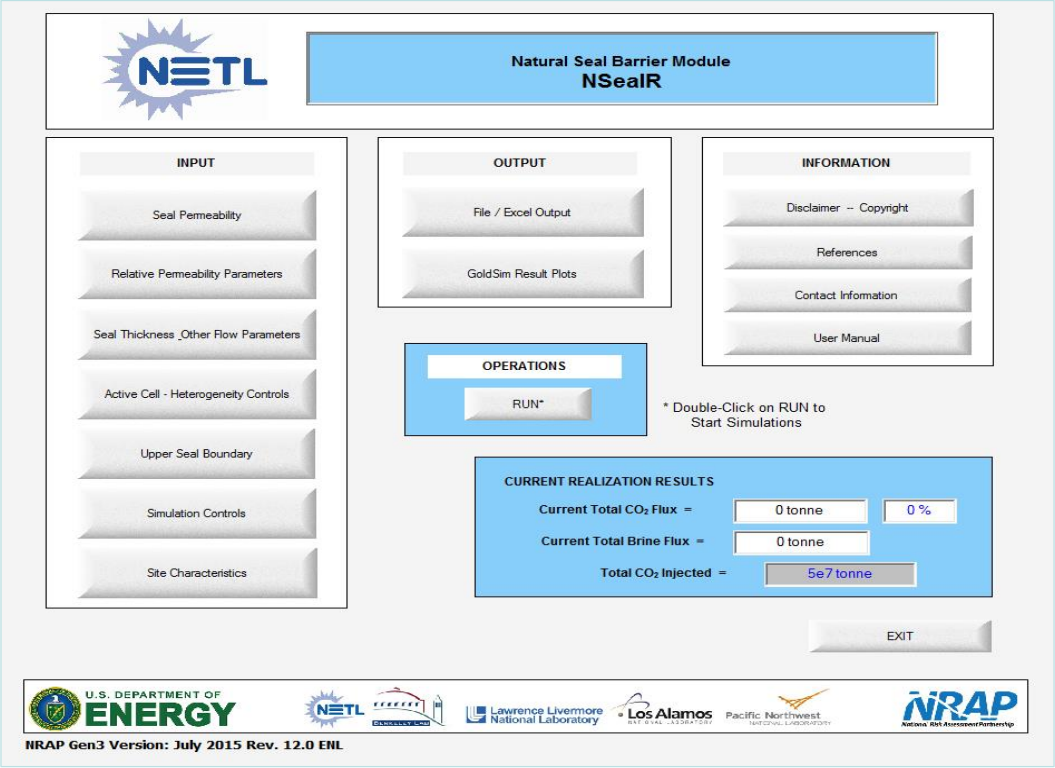
- ***Models migration of brine and/or CO_2 outside of storage reservoir***
- ***Uses reservoir pressures and saturations at top of reservoir as input***
- ***Predicts flowrate into intermediate zone and/or groundwater aquifer***
- ***Incorporates chemistry to identify flowrate changes as a function of time***



NSealR—Tool for estimating leakage through fractured seal

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

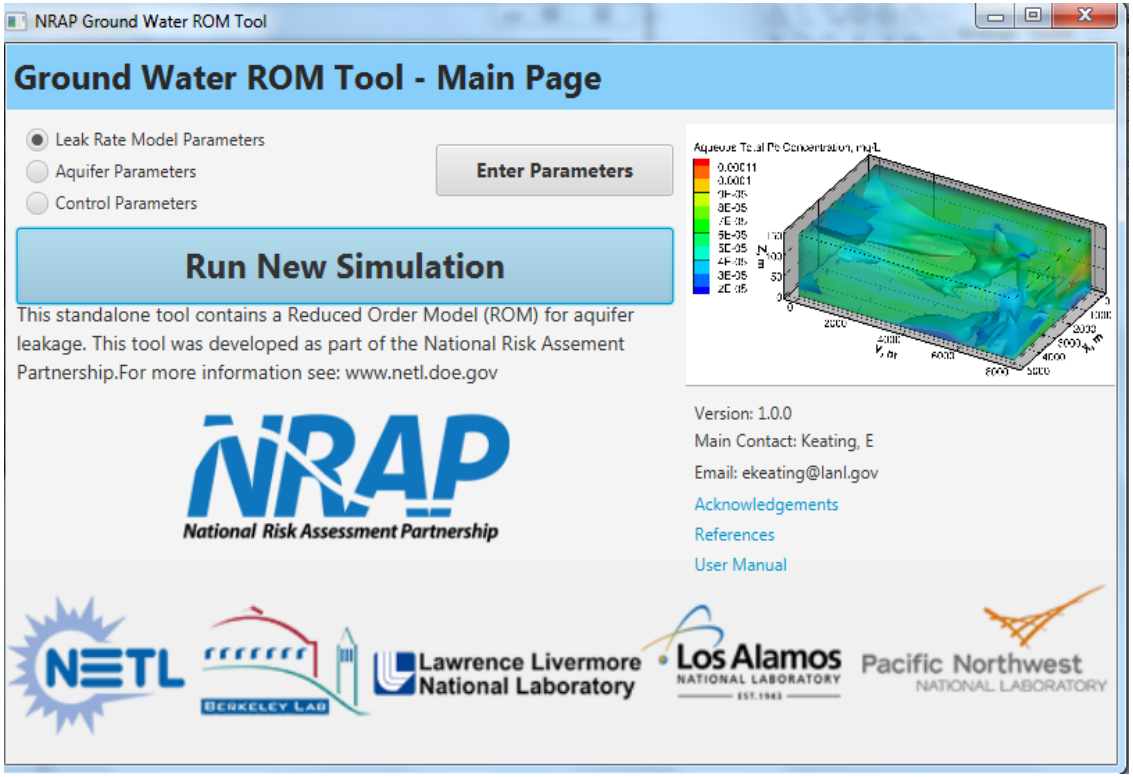
- ***Uses inputs of pressure and saturation at the reservoir/seal interface***
- ***Computes two-phase (brine and supercritical CO_2) flux, Including fluid thermal/pressure dependence***
- ***Module to compute leakage through a Barrier (Seal) Layer***
- ***Various levels of complexity to model barrier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



Aquifer Impact Model (AIM)

- Estimates aquifer volume impacted for different potential leak scenarios
- Distinguishes between CO_2 and brine leaks
- Used to determine impact of threshold criteria.

- ***Inputs migration rate and concentrations from wellbore or similar models***
- ***Includes two different end member aquifer types***
- ***Incorporates flow and chemistry***
- ***Metrics include: pH, TDS, metals concentrations, organics concentrations***



Short Term Seismic Forecasting (STSF) Tool

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

- ***Based on Gutenberg and Omori laws***
- ***Originally an aftershock models***
- ***Reads a seismic event catalog***
- ***Forecasts seismic frequency for a window of a few days***