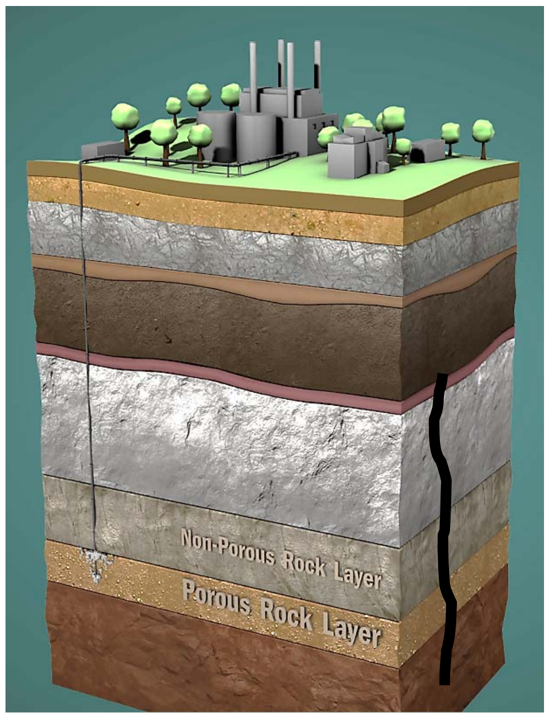
National Risk Assessment Partnership

NRAP leverages DOE's capabilities to help quantify uncertainties and risks necessary to remove barriers to full-scale CO_2 storage deployment.

Building toolsets and improving the science base to address…

- Potential impacts related to release of CO_2 or brine from the storage reservoir
- Potential ground-motion impacts due to injection of CO_2

Technical Team



Stakeholder Group

Wade, LLC

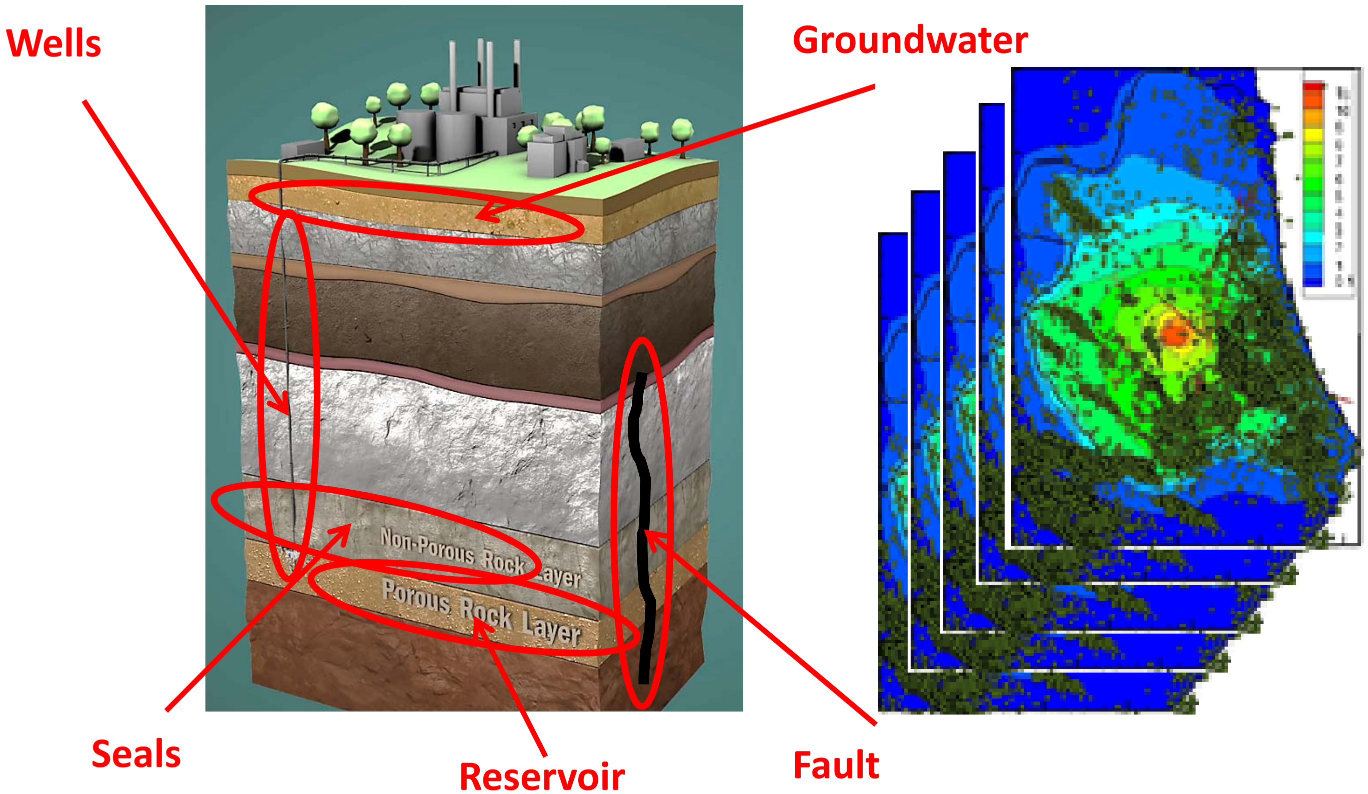
National Risk Assessment Partnership

NRAP leverages DOE's capabilities to help quantify uncertainties and risks necessary to remove barriers to full-scale CO_2 storage deployment.

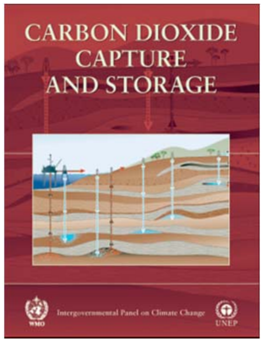
Building toolsets and improving the science base to address…

By simulating risk across the entire carbon storage system;

And generation thousands of realizations to quantify uncertainties.



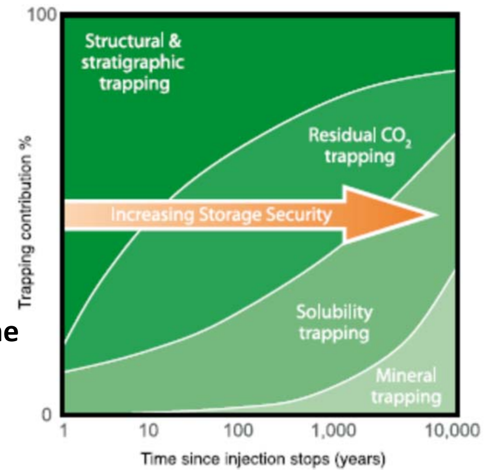
Broad knowledge base provides foundation for confidence in long-term geologic storage security.



IPCC (2005)

“Observations from engineered and natural analogues as well as models suggest that **the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years.”**

Schematic evolution of trapping mechanisms over time (IPCC, 2005)



What do we know?

Multiple trapping mechanisms reduce CO_2 mobility over time

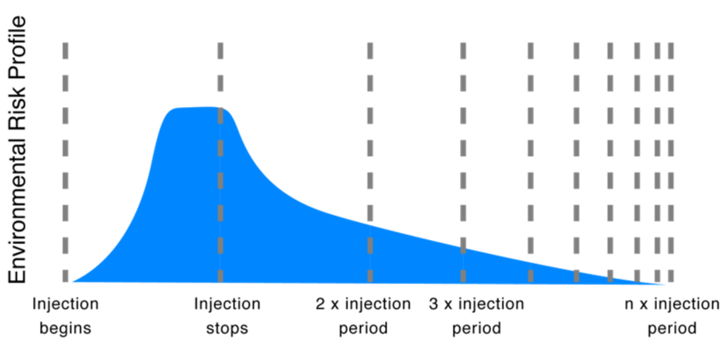
- structural/stratigraphic; residual; solubility; mineralization; sorption

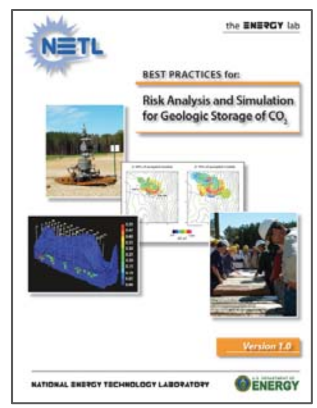
Risk profiles should decline over time

Broad experience base for effective site-characterization & operational strategies

- Decades of successful operational experience (e.g., EOR, gas storage, …)
- RCSPs & DOE Best-Practices
- Early successes with large-scale field demos (e.g., Sleipner, Weyburn)

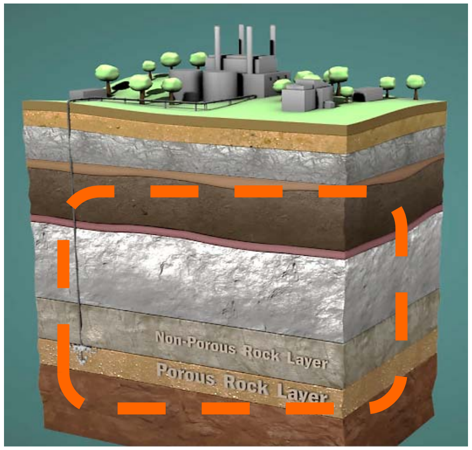
Schematic profile of environmental risk (Benson, 2007)





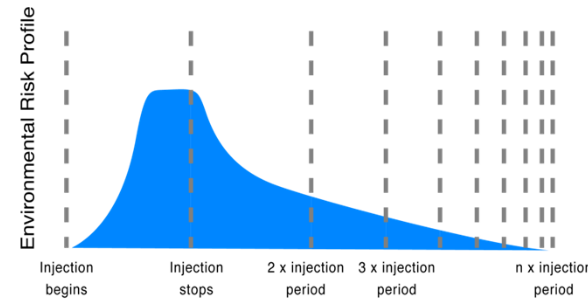
U.S. DEPARTMENT OF ENERGY | NETL | Los Alamos NATIONAL LABORATORY | Pacific Northwest NATIONAL LABORATORY | NRAP National Risk Assessment Partnership

Science-based prediction can build confidence in expected storage security by quantifying system performance for a range of conditions.

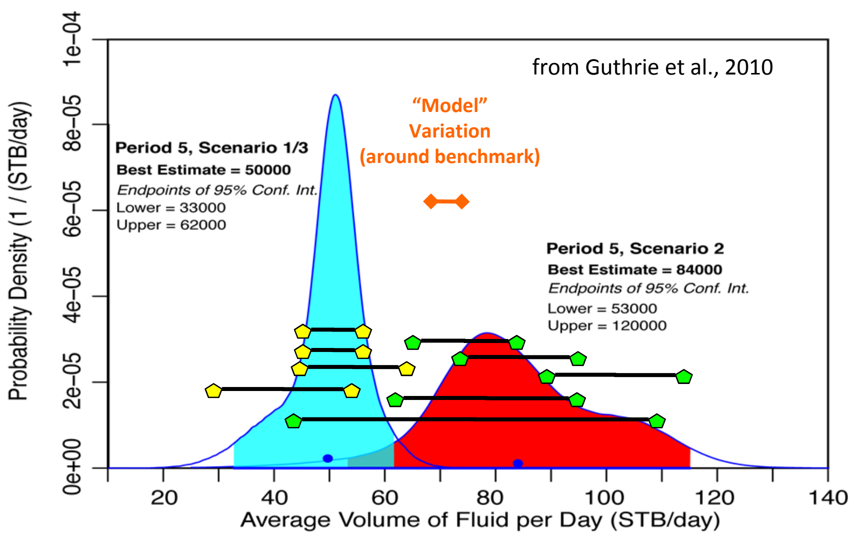


NRAP Goal—to predict storage-site behavior from reservoir to receptor and from injection through long-term storage…

…in order to quantify key storage-security relationships for various site characteristics.

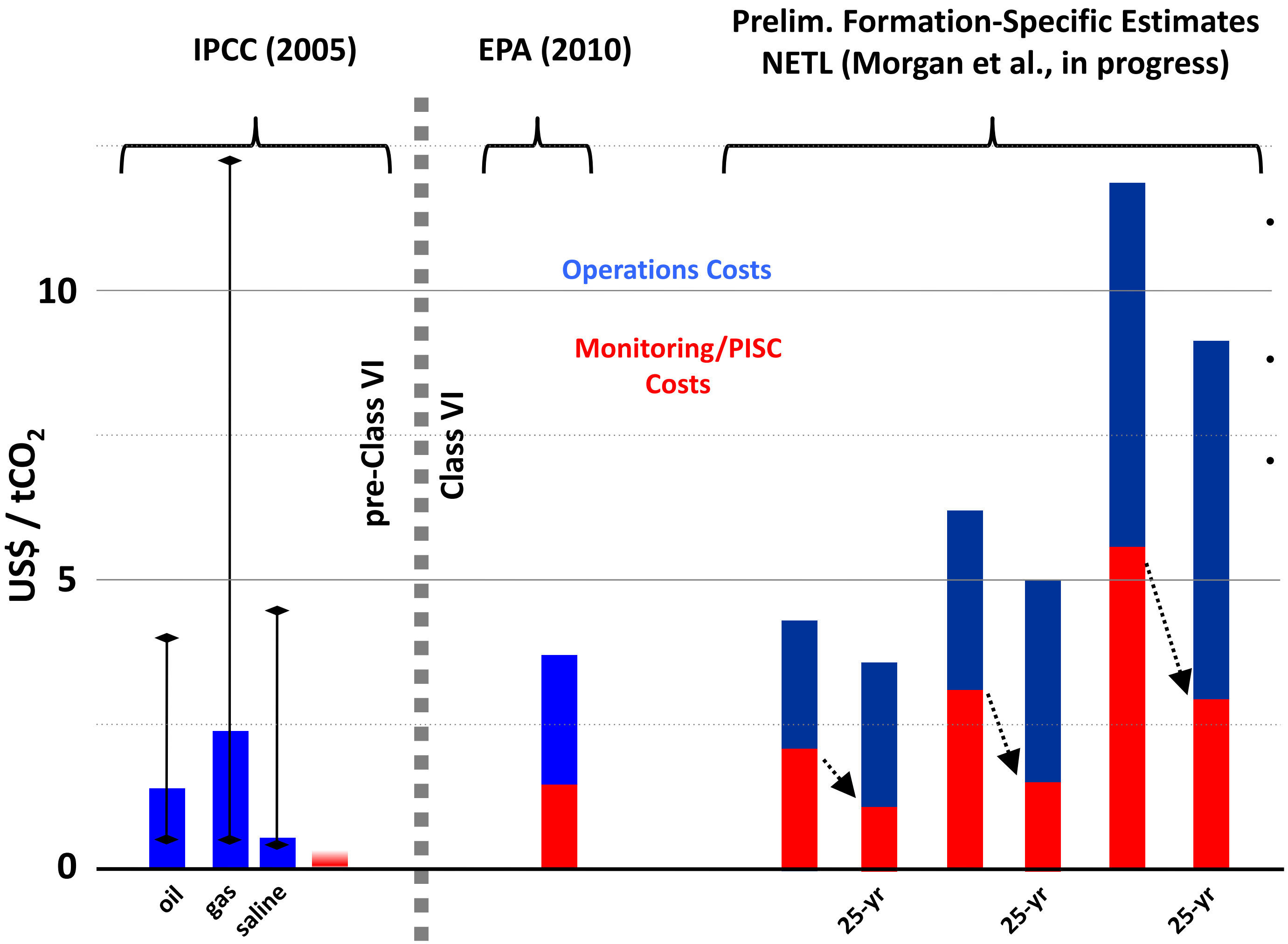


Confidence in uncertain predictions can be built through comprehensive, multi-organizational team assessments.



NRAP is building and applying computationally efficient tools to probe site behavior stochastically, thereby accounting for uncertainties and variability in storage-site characteristics.

What information is needed to provide the confidence necessary to consider an alternative approach to PISC monitoring needs?

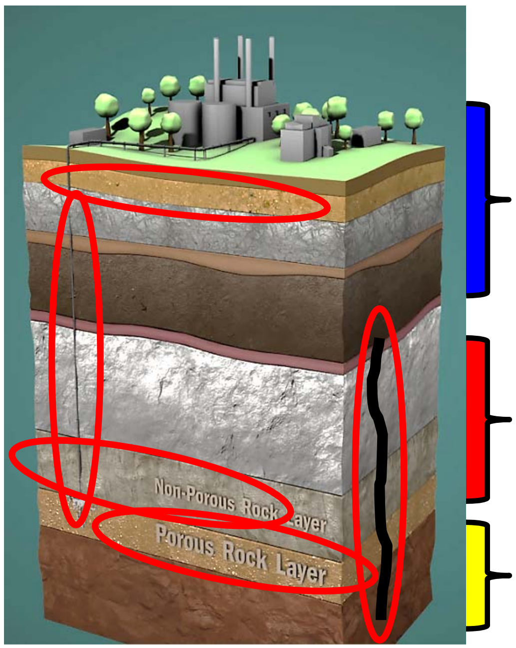


- **IPCC (2005) estimated post-injection monitoring costs to be <10% of project costs.**
- **Post Class VI estimates range from 35–50% of total costs.**
- **Primary drivers for costs include:**
  - long time frame (50 yrs)
  - large area-of-review
  - large battery of techniques

A reduction of 1-2 \$/ton CO_2 would mean a savings of \$50-250 million per project.

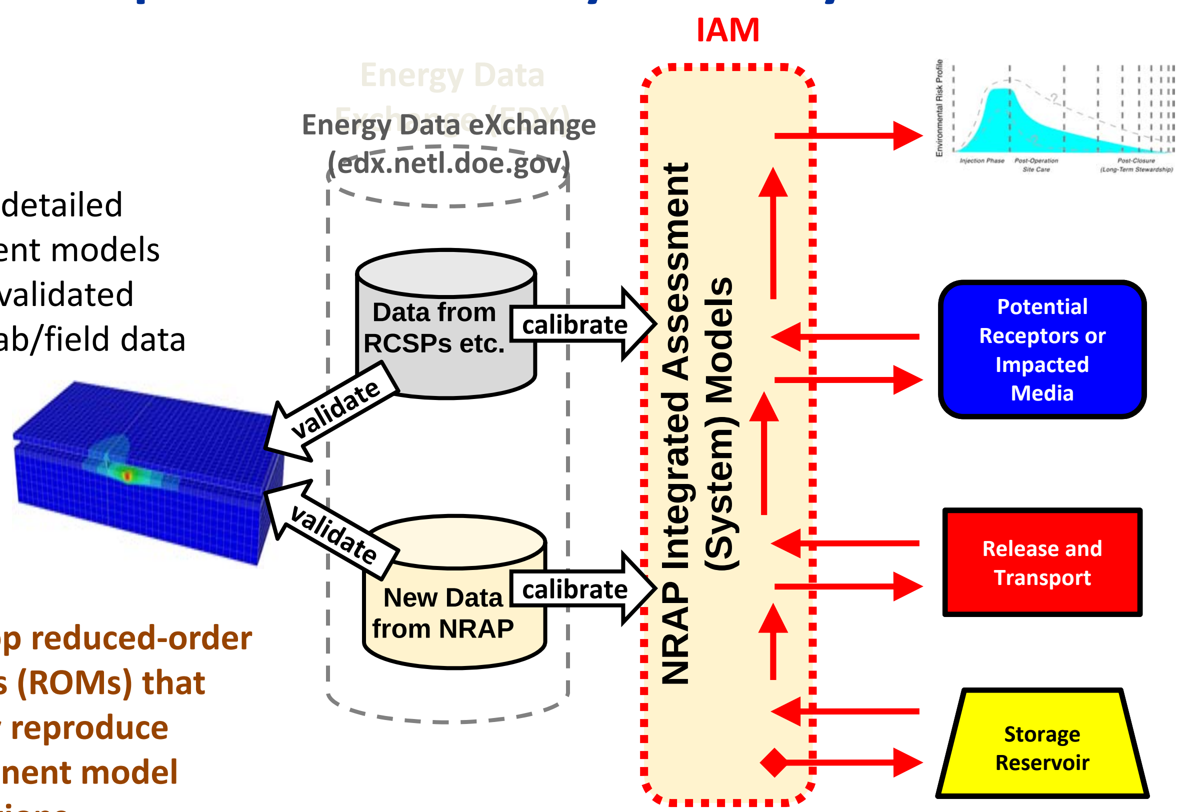
NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.

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

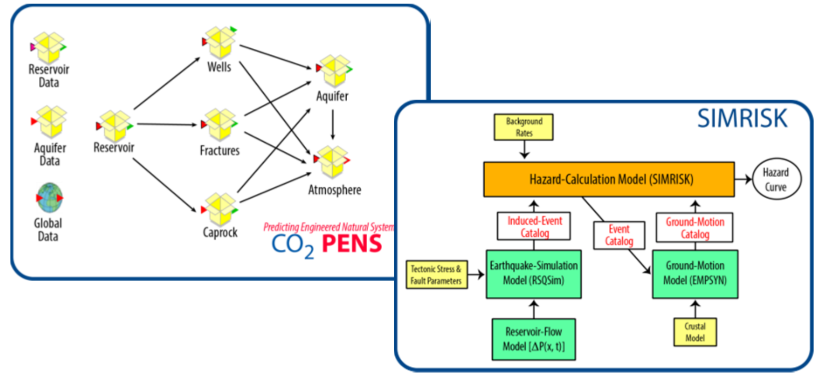


D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

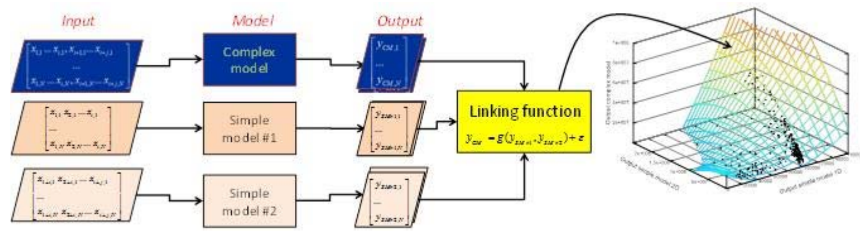
E. Develop strategic monitoring protocols that allow verification of predicted system performance

Key NRAP Accomplishments: Building the Toolsets

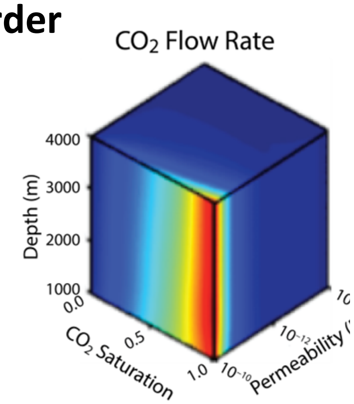
- **First-of-a-kind toolsets for science-based, quantitative evaluation of risks and uncertainties**
  - Leakage risks (reservoirs to receptors)
  - Induced seismic events

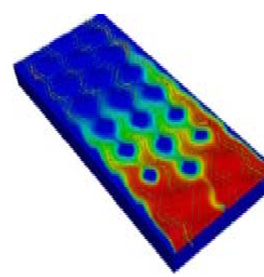


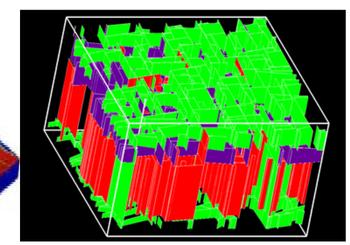
- **Site-specific and adaptable ROMs**
  - Reservoirs (3 classes; 3 injection scenarios)
  - Wellbores (open and cemented)
  - Fractures (discrete and networks)
  - Aquifers (two major types)

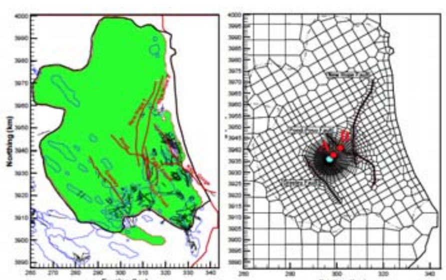


- **Evaluated numerous approaches to reduced-order models (lookup table to artificial intelligence)**
  - Achieve balance between fidelity and speed









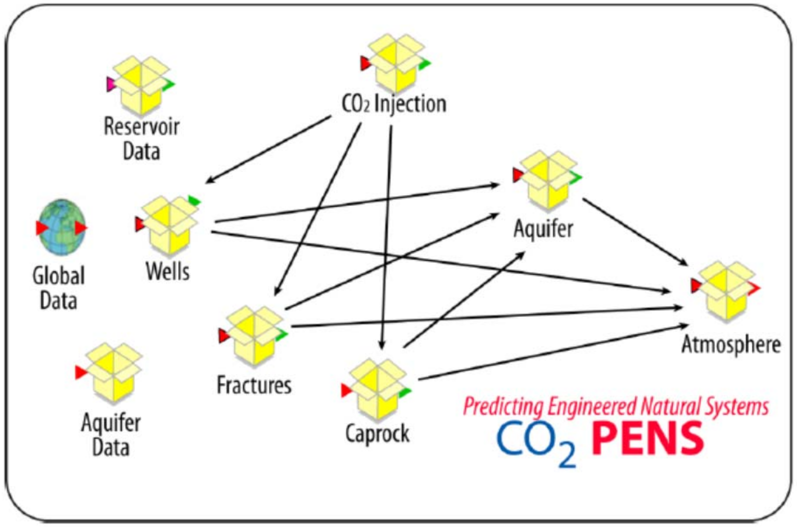
Several NRAP products will be released for use in August 2015.

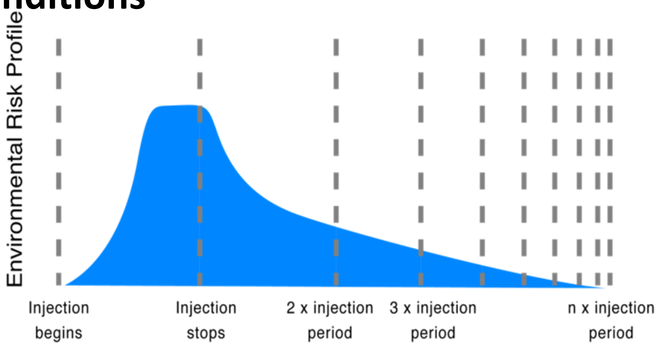
- Integrated Assessment Model – CO2-PENS
- Reservoir Analysis Tool
- Wellbore ROM Tool
- NSealR Model
- Coupled High Plains Aquifer Tool
- Coupled Edwards Aquifer Tool
- Simulation Tools for Optimization and Risk Management (STORM)
- Empirical Seismic Hazard Analysis Tool
- Probabilistic Seismic Risk Assessment Tool (RISKCAT)
- Ground Motion Predictive Tool

www.edx.netl.doe.gov/nrap

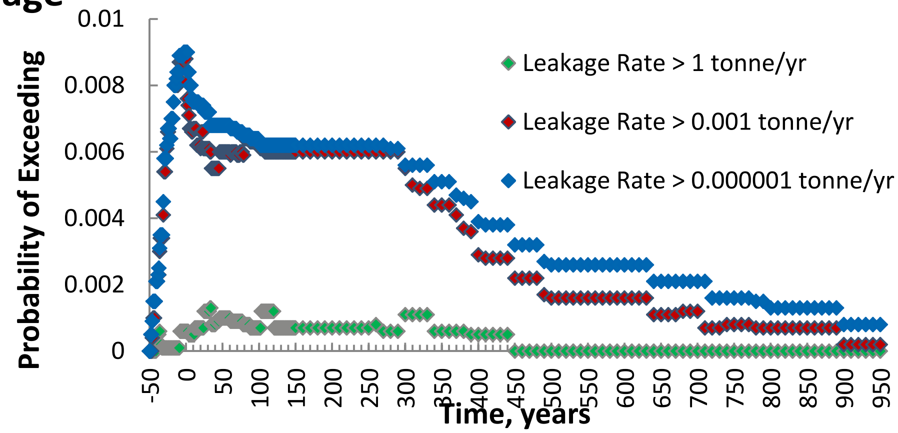
CO2-PENS simulates models carbon storage system behavior.

- **Simulates the entire storage containment system**
  - Reservoir
  - Wellbore and fracture flow
  - Thief zones
  - Groundwater aquifer
  - Release to atmosphere
- **Calculates probability of leak events**
  - For threshold values of choice
  - Over 100s to 1000s of years
- **Thousands of runs to quantify uncertainty**
- **First quantitative risk profiles with realistic storage conditions**





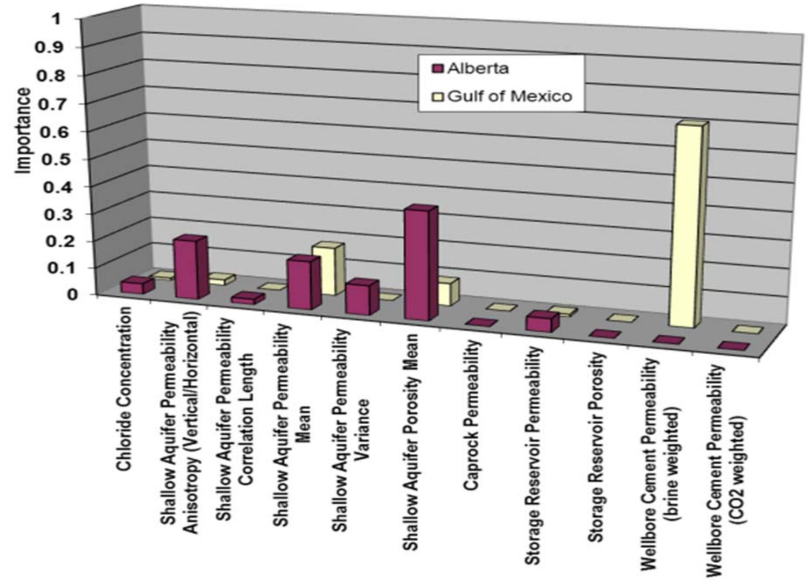
Benson, 2009

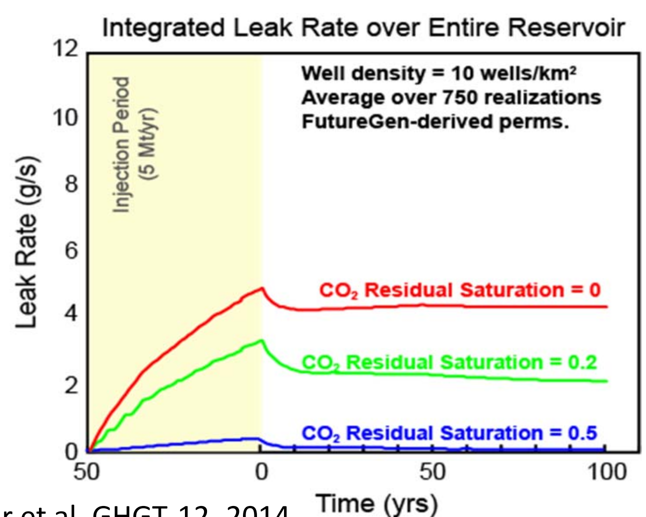


Ref: Bromhal et al, IEAGHG, 2013

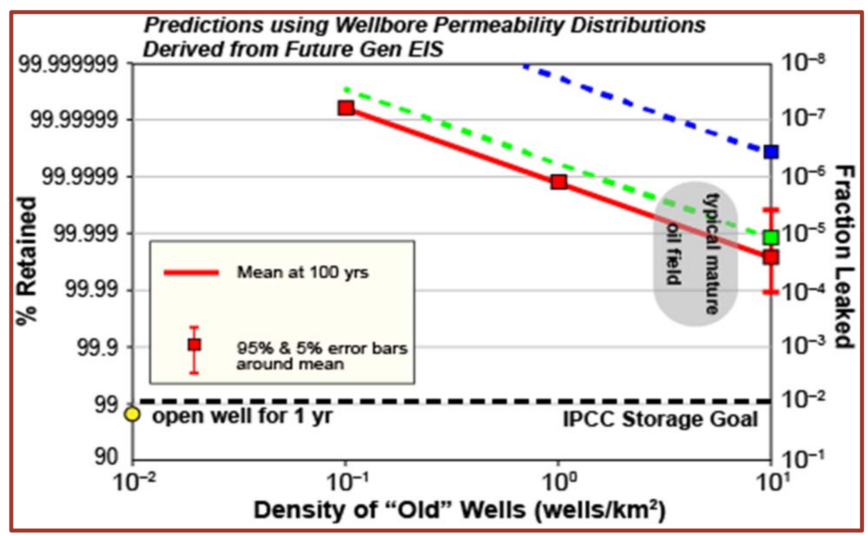
Many system-wide variables can be studied to determine impact on risk.

- **Importance diagrams identify parameters that do and don't have an impact on leakage**
- **Can evaluate impacts in any part of the storage-containment system**
  - E.g., on average, leak rate depends on residual saturation
  - E.g., wellbore transmissivity statistics influence parameter ranking
- **Greenfield vs. brownfield conditions influence likelihood of failure**
  - Open wellbores significantly increase risk

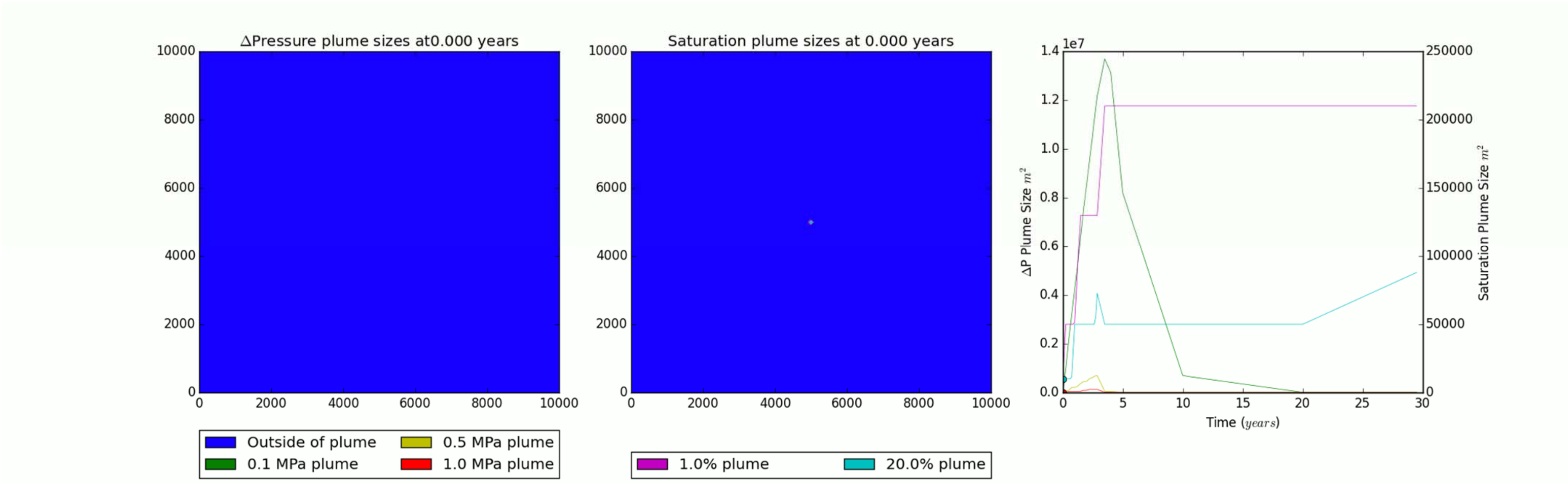




Ref: Pawar et al, GHGT-12, 2014

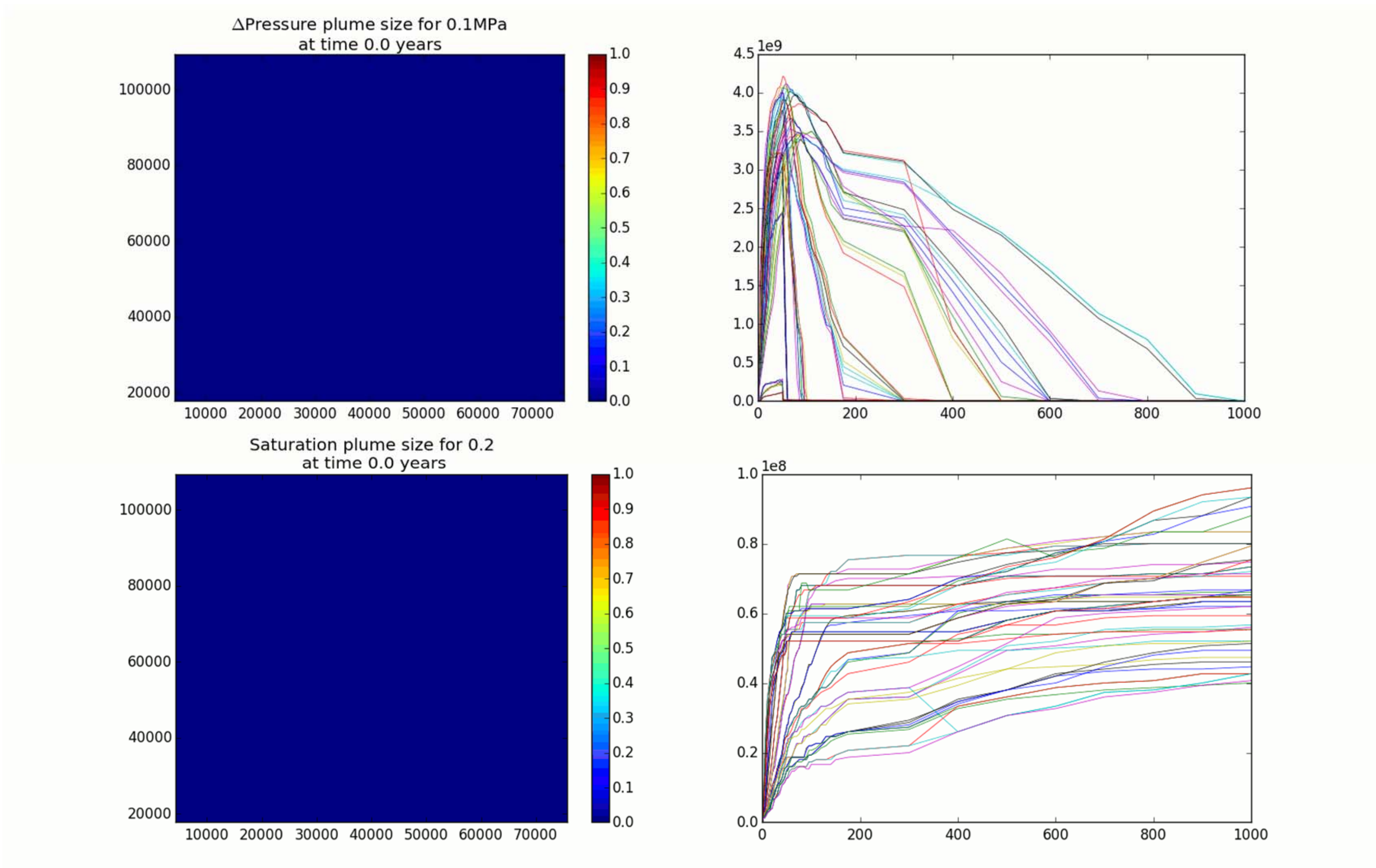


The reservoir analysis toolkit is used to track performance metrics for reservoirs.



- **Produces simple metrics from reservoir simulations that can be used to evaluate reservoir performance as it relates to risk.**
  – Takes in Pressure and Saturation values output 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.

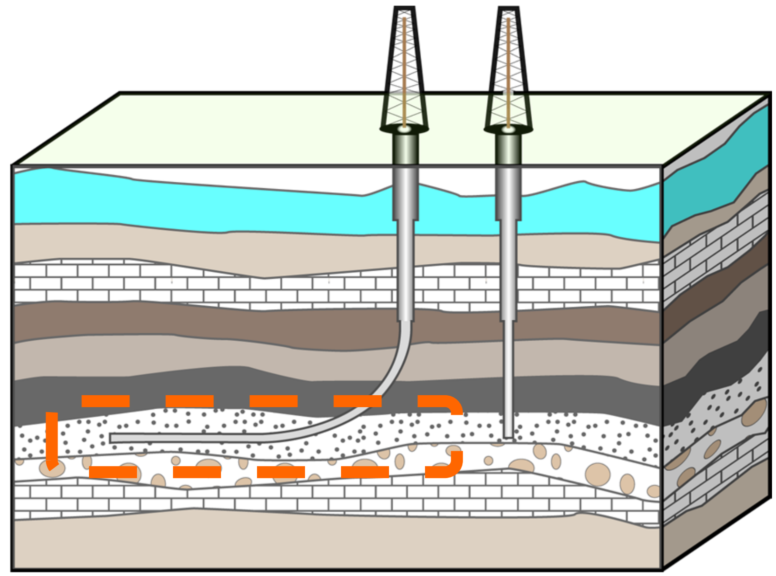
Addresses multiple simulations probabilistically.

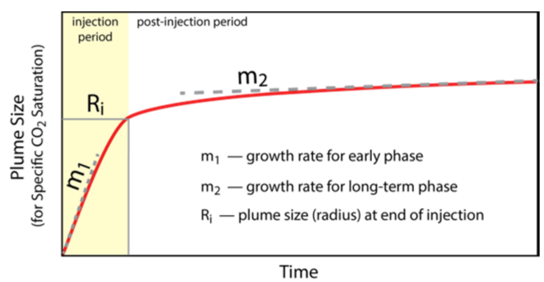


- **Colors based on likelihood of exceeding user-defined thresholds in each grid block**

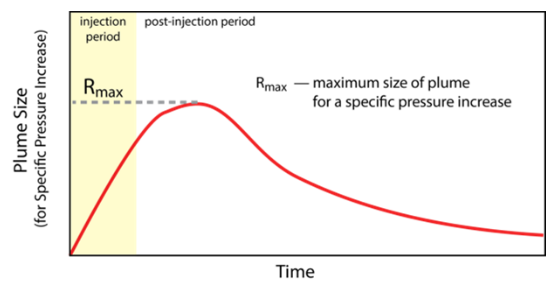
Using Science-Based Prediction to Probe Reservoir Behavior: Metrics Analyzed

- **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

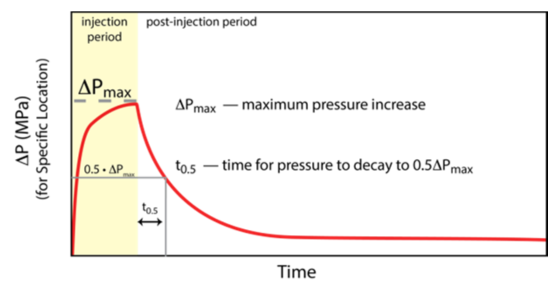




Size of CO_2 Plume



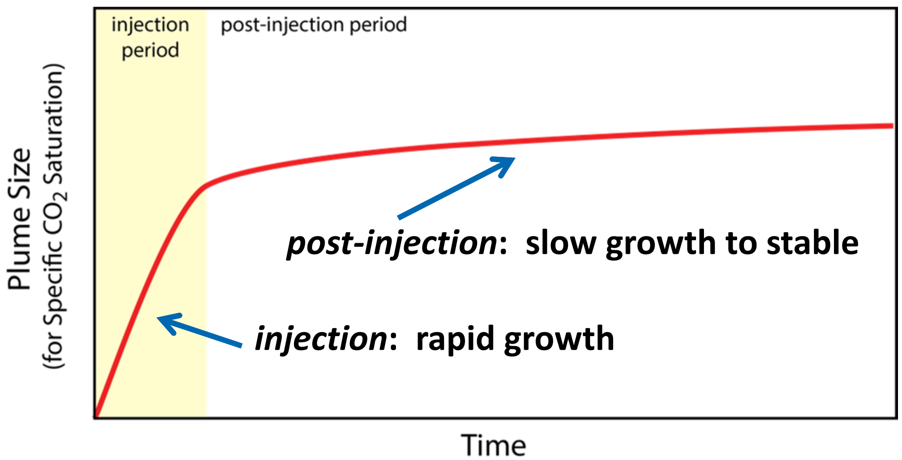
Size of Pressure Plume



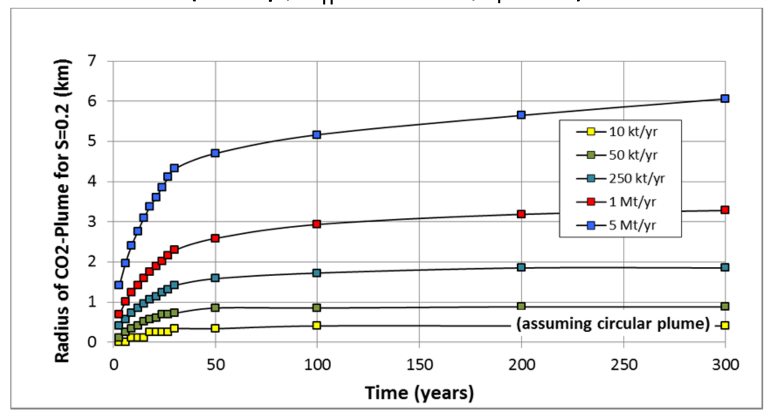
Pressure at at a Location

Ref: Bromhal et al, NRAP-TRS, 2014

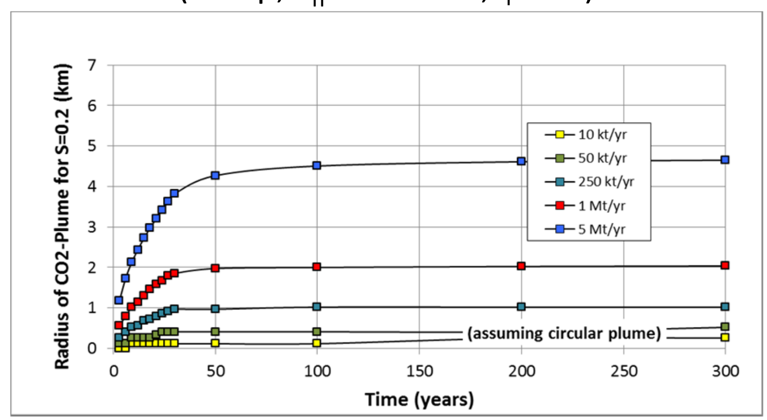
Growth of CO_2 plume has a characteristic behavior, albeit details vary between sites.



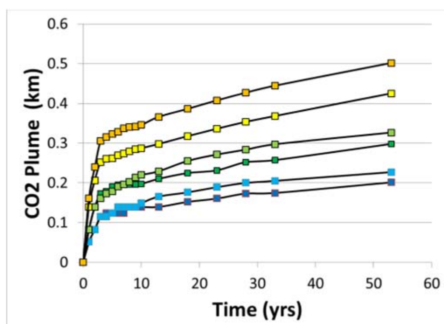
Unbound Sandstone, Regional Dip
(0° dip; k_h=100 mD; ϕ=0.2)



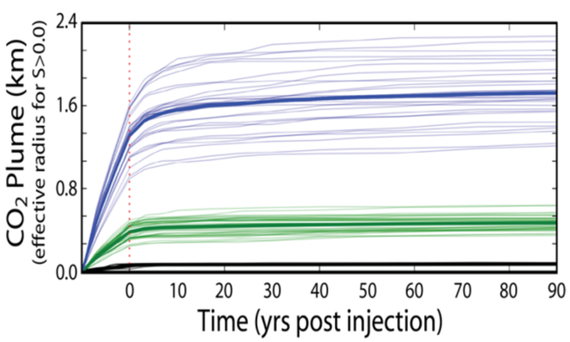
Unbound Sandstone, Regional Dip
(0° dip; k_h=1000 mD; ϕ=0.2)



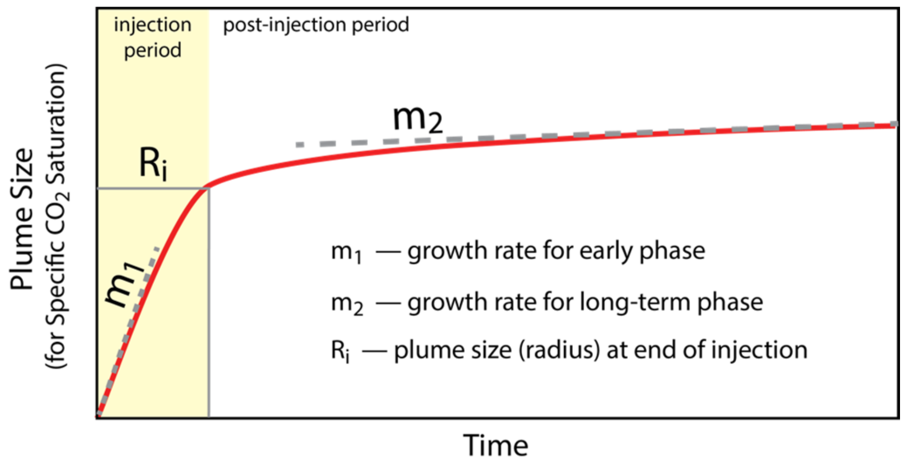
Multi-layer, Domal Sandstone
(3-yr injection; 0.1-10 Mt)

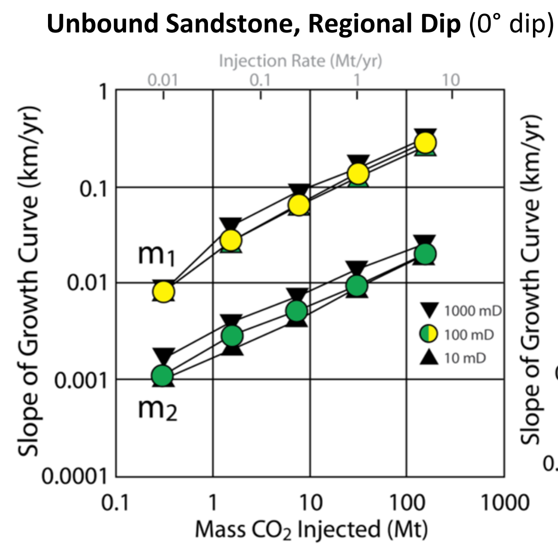


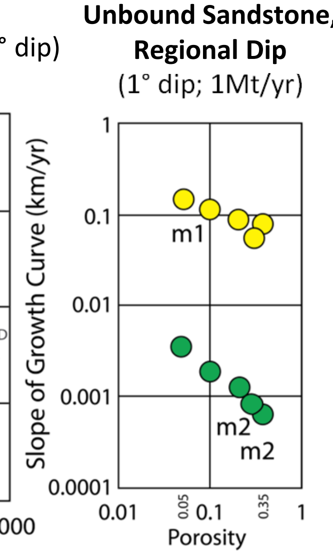
Domal Sandstone-Limestone
(10-yr injection; 1-50 Mt)



Amount of CO_2 injected is primary factor in the growth rate and size of CO_2 plume.





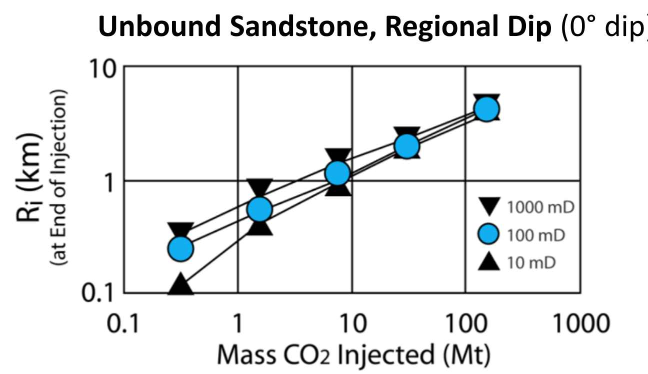


- Increase in mass of CO_2 increases the growth rate for the CO_2 plume (both early and long-term rates)

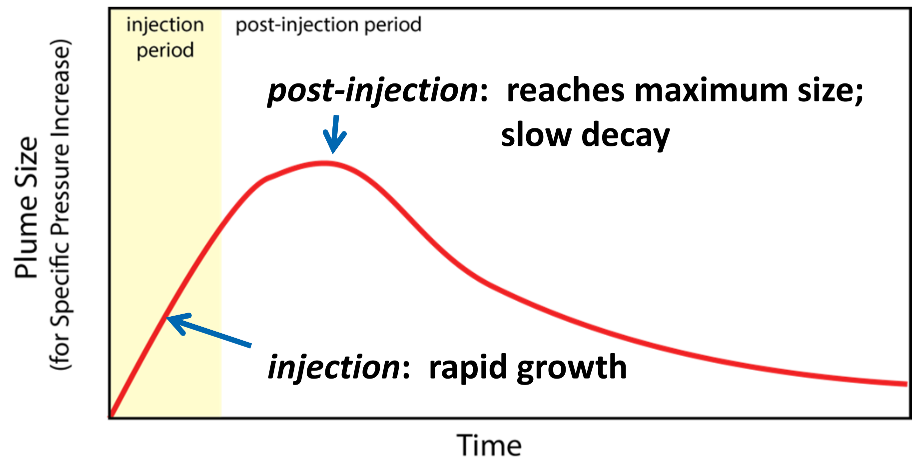
operational

- Increase in porosity decreases growth rate
- Permeability has minimal impact on growth rate but impacts size of CO_2 plume

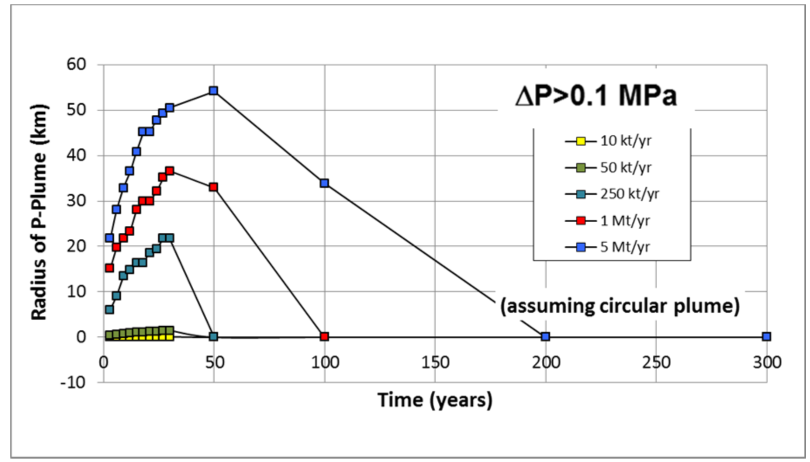
geological



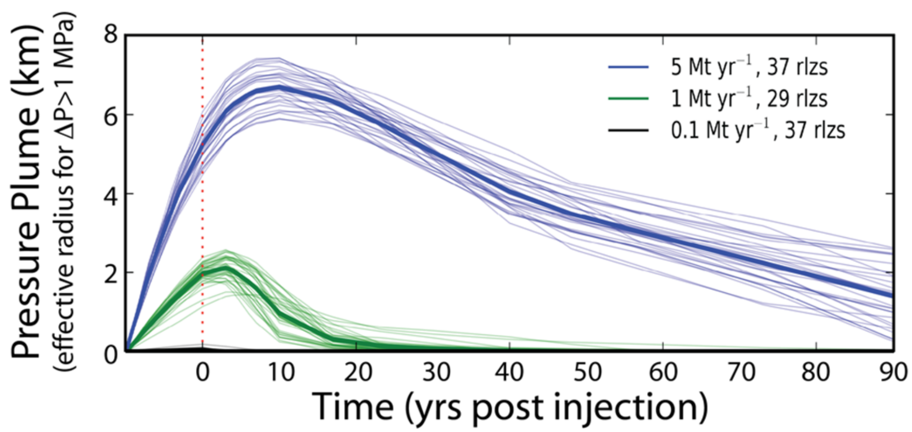
Growth of pressure plume has a characteristic behavior, albeit details vary between sites.



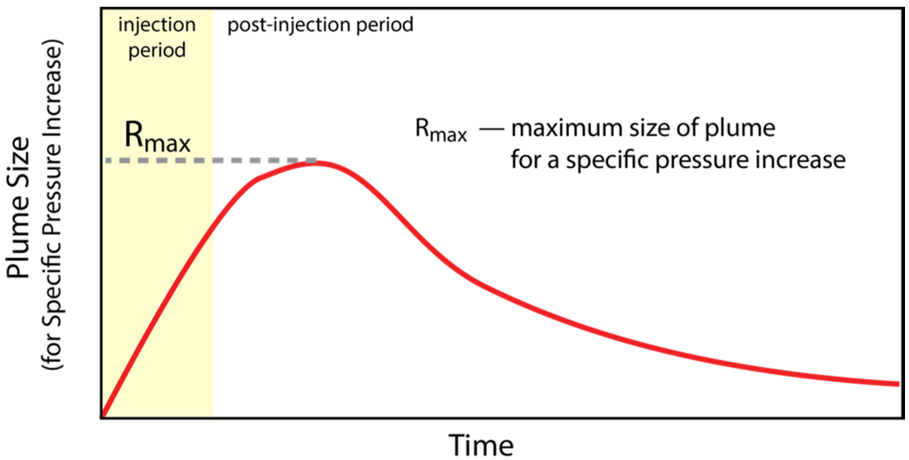
Unbound Sandstone, Regional Dip (0° dip)



Domal Sandstone-Limestone



Amount of CO_2 injected and geologic details each impact the area/distance for pressure effects.



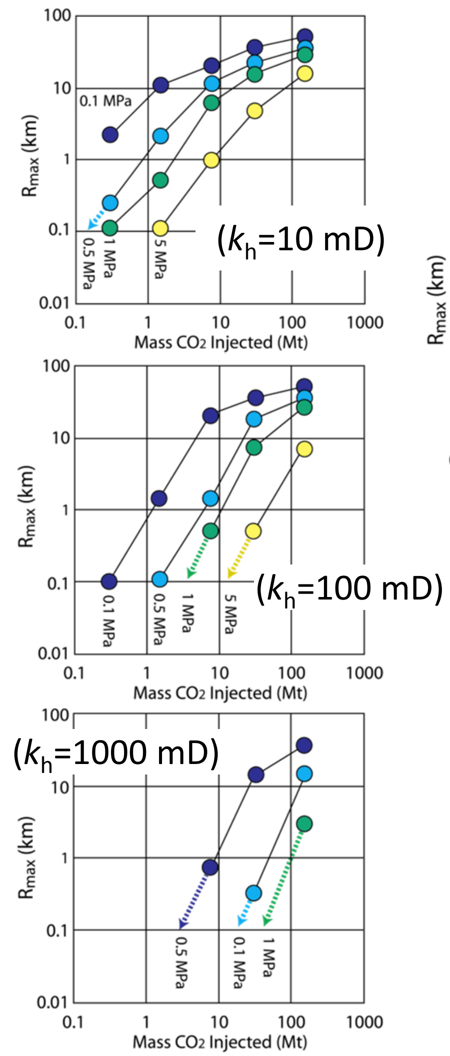
operational

- Increase in mass of CO_2 increases the distance of pressure effects for a given threshold

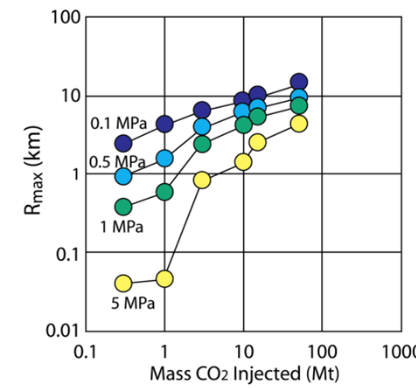
geological

- Decreasing permeability can significantly increase distance (or size) of pressure effects
- Increasing the permeability can dramatically decrease distance (or size) of pressure effects

Unbound Sandstone, Regional Dip (0° dip)



Domal Sandstone-Limestone



General Observations

Two questions

- How does reservoir performance change as a function of injection volumes & rates?
- How does a reservoir respond as a function of time when injection stops?

Impact of operational variables…

- Reservoir response varies with amount of injected CO_2
  1. Size of CO_2 Plume—rapid growth during injection; slower growth post injection
  2. Size of Pressure Plume—rapid growth during injection; reaches maximum and decays post
  3. Change in Pressure over Time—rapid growth during injection; rapid decline post injection
- Potential to exceed some pressure thresholds depends on size of injection

Impact of geologic variables…

- Reservoir response varies with geologic type
- Rate of CO_2 plume growth depends on reservoir porosity
- Potential to exceed some pressure thresholds depends on reservoir permeability

Impact of geologic variables is on the same order as operational variables.

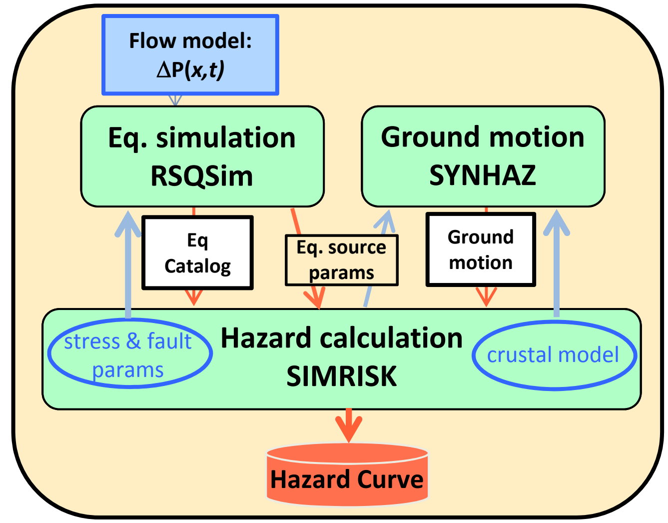
Induced Seismicity

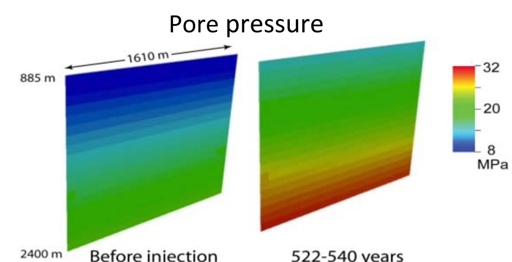
Tool & Method Development

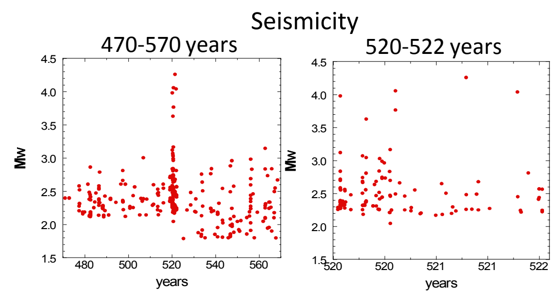
- Developed a probabilistic seismic hazard assessment (PSHA) tool for induced seismicity
  - adapted widely accepted conventional PSHA approach
- Extending development to assess damage and nuisance (felt event) risks
  - demonstration application to realistic CO_2 injection scenarios based on In Salah (Algeria)

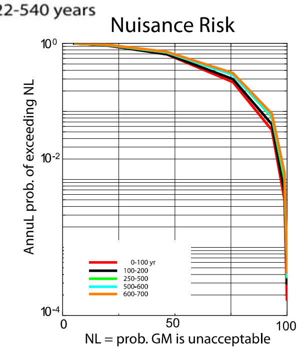
General Trends & Relationships

- Rates of occurrence and sizes of earthquakes are determined by tectonic stress and reservoir pressure
  - sensitive to fault permeability and a few key parameters in the law governing the evolution of fault frictional strength
- Risk of CO_2 leakage may be coupled to slip on faults during earthquakes









High costs and large uncertainties suggest a phased approach to seismicity management

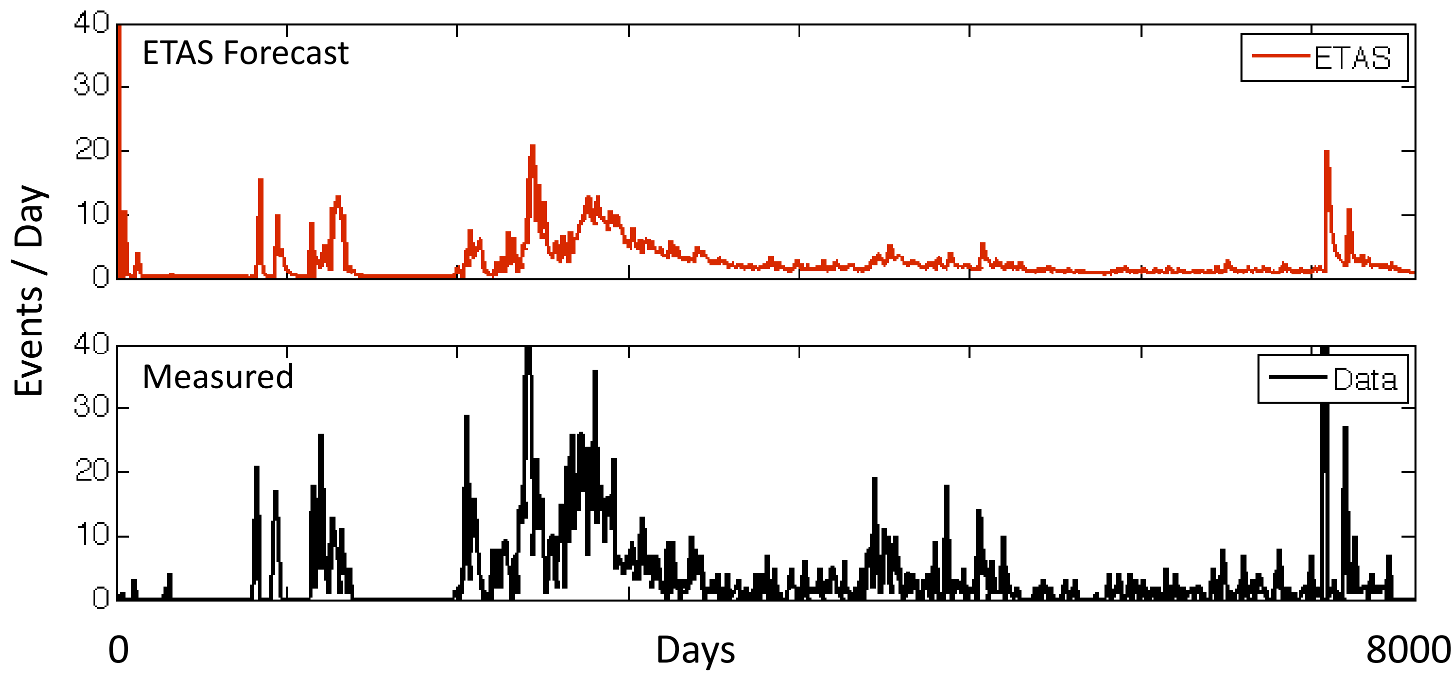
Phase	Characterization & Monitoring	Modelling	Risk Assessment
• Site-screening	• Regional stress estimates • Fault density estimates	• Back-of-the-envelope	• Red-flags • Atlas
• Pre-injection	• 3D seismic • XLOTs • FMI • Limited microseismic	• Simple models	• Qualitative Assessments • PSHA
• Injection & PISC	• 4D seismic • Full microseismic	• Sophisticated models	• Traffic-light • PSRA

-- Cost/benefit of additional methods assessed based on evolving project conditions.

-- Baselines are important.

-- Timely processing and interpretation of data are important.

Empirical short-term forecasting tool helps determine risk of induced seismicity.

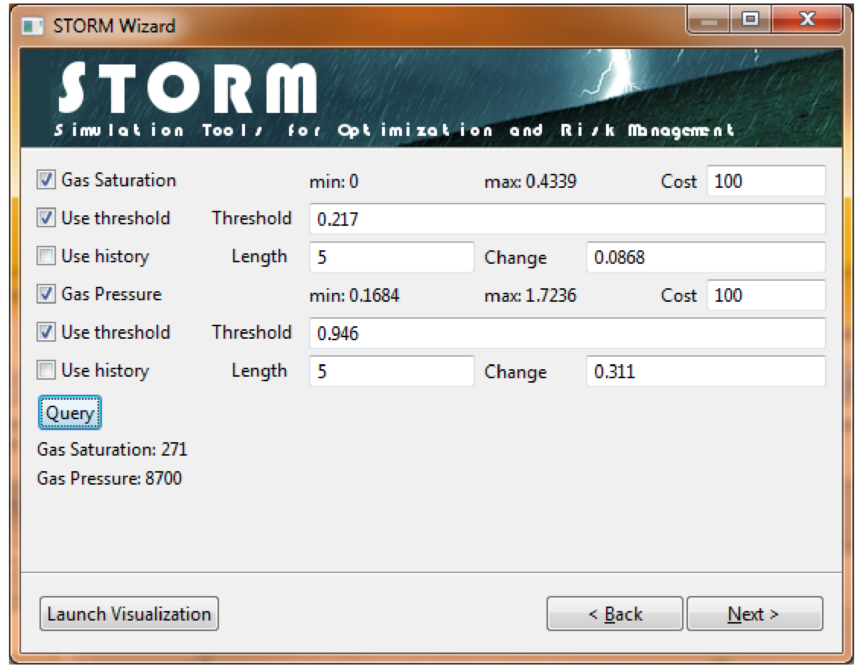


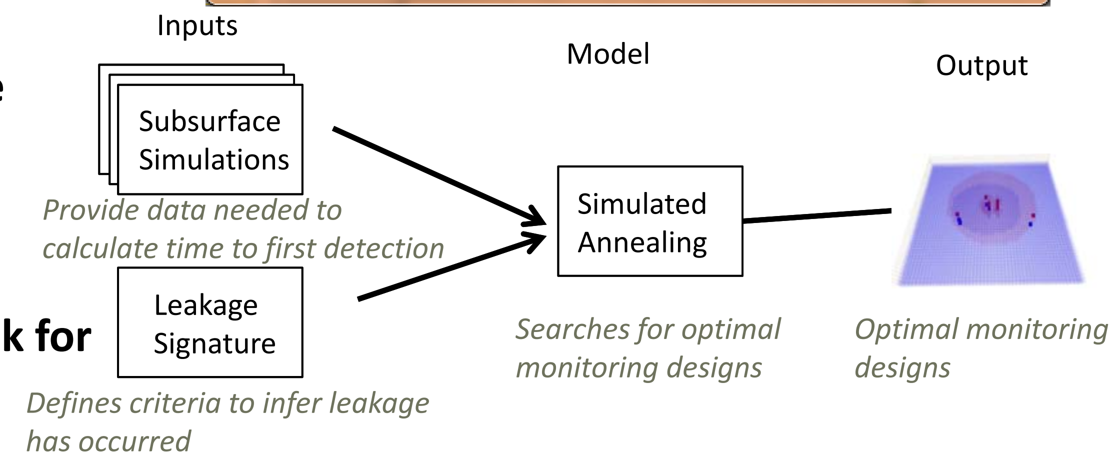
- **Based on Gutenburg-Richter and Omori laws**
- **Originally an aftershock models**
- **Reads a seismic event catalog**
- **Typically used for a window of a few days.**
- **Would complement a stoplight protocol**
- **Forecasts seismic frequency**

Ref: Bachmann et al, 2014

NRAP future focus is on the incorporation of monitoring and mitigation.

- **Optimizes subsurface monitoring design for a specified CCS site**
- **Finds monitoring design that yields minimum expected time to first detection of CO_2 leakage (E[TFD])**
  - Subsurface monitoring design includes well locations and type/depth of sensors deployed in each well
  - Subject to constraints like budget, number of wells, physical limitations
- **Uses a collection of subsurface realizations**
- **User defined alarm and inference criteria**
  - What causes sensor to alarm
  - How many sensors imply a leak
- **Uses simulated annealing to check for optimum design**





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Thank you.

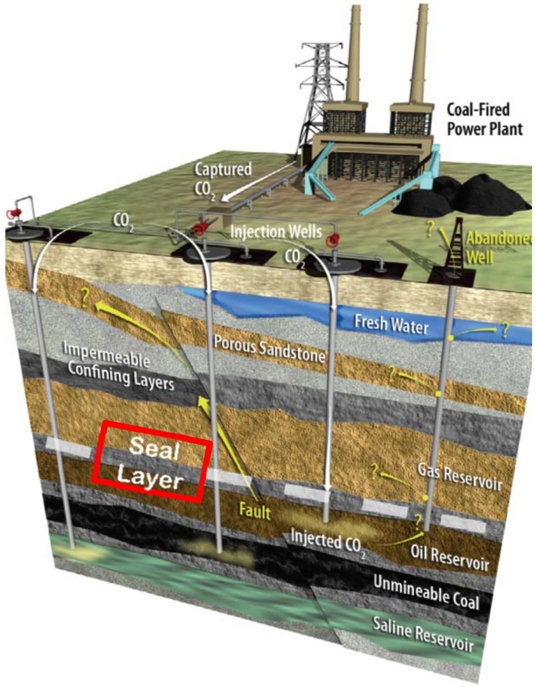
NRAP Products for planned August release.

- Integrated Assessment Model – CO_2-PENS
- Reservoir Analysis Tool
- Wellbore ROM Tool
- NSealR Model
- Coupled High Plains Aquifer Tool
- Coupled Edwards Aquifer Tool
- Simulation Tools for Optimization and Risk Management (STORM)
- Empirical Seismic Hazard Analysis Tool
- Probabilistic Seismic Risk Assessment Tool (RISKCAT)
- Ground Motion Predictive Tool

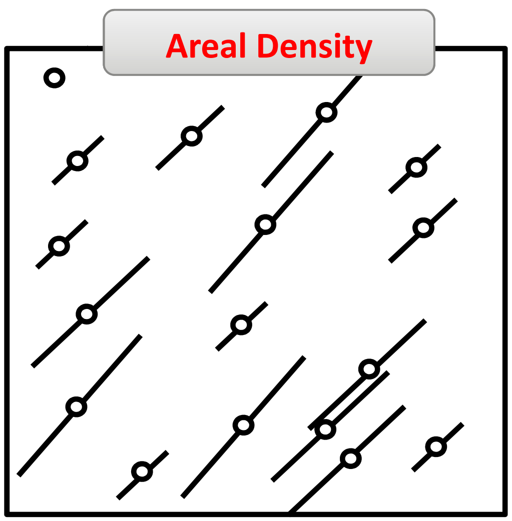
More information at:

www.edx.netl.doe.gov/nrap

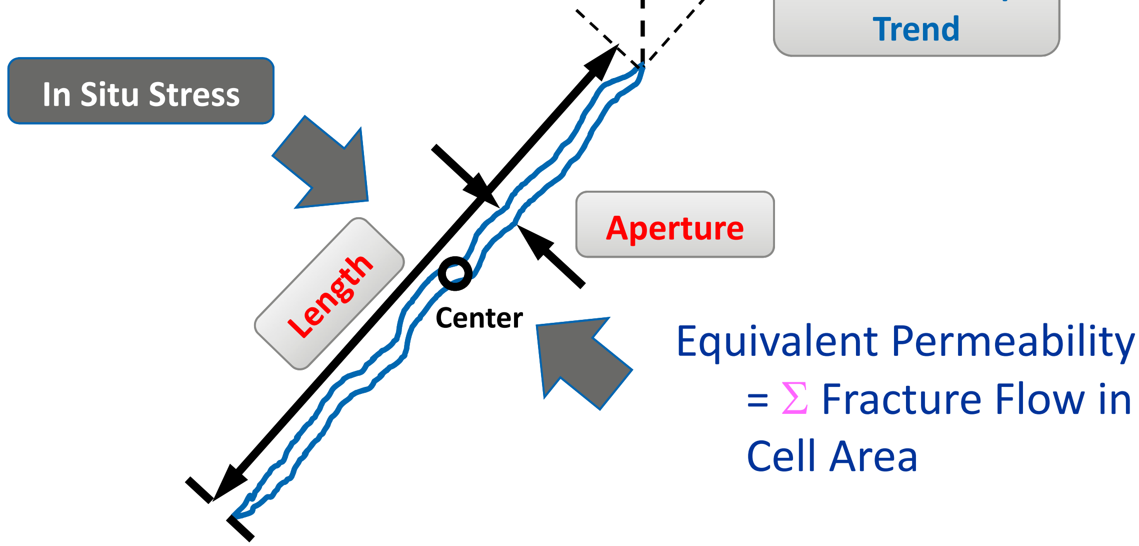
NSealR Computer Code



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

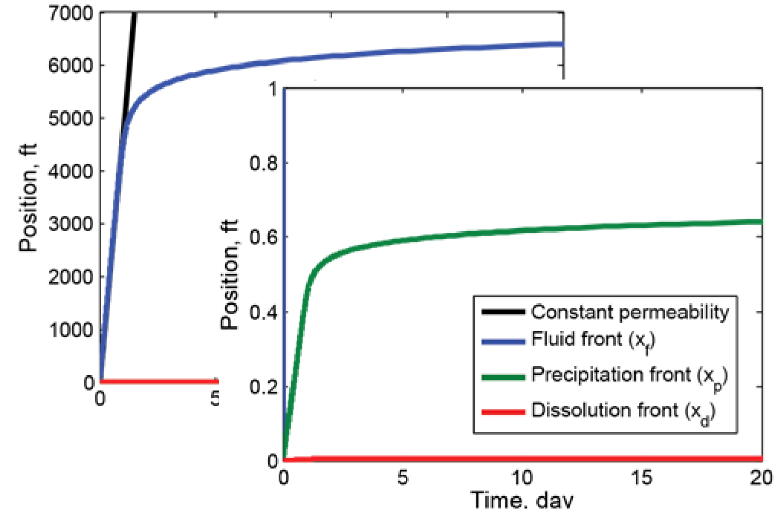


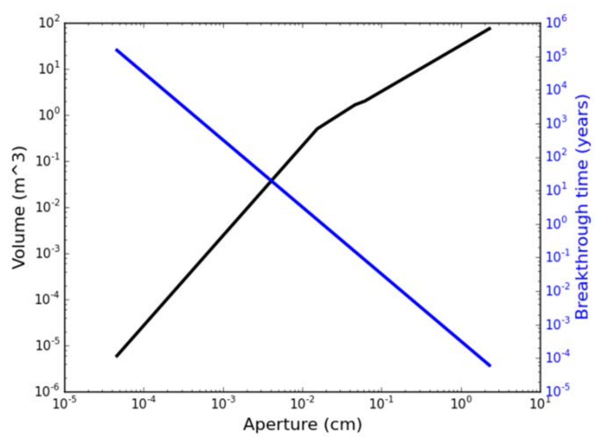
Vertical Fracture

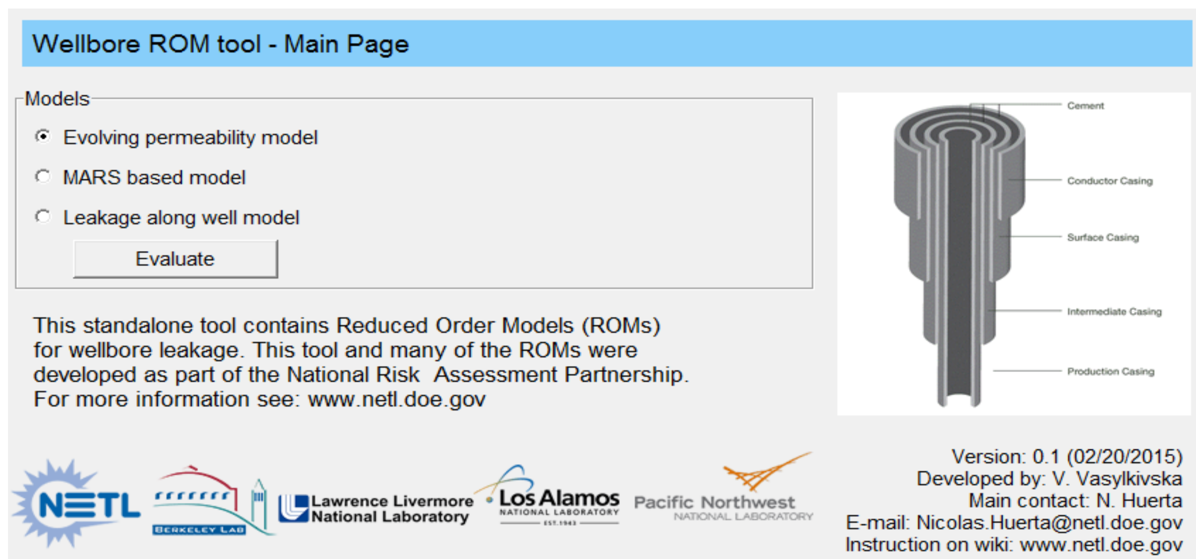


Wellbore ROMs address vertical migration for a variety of conditions.

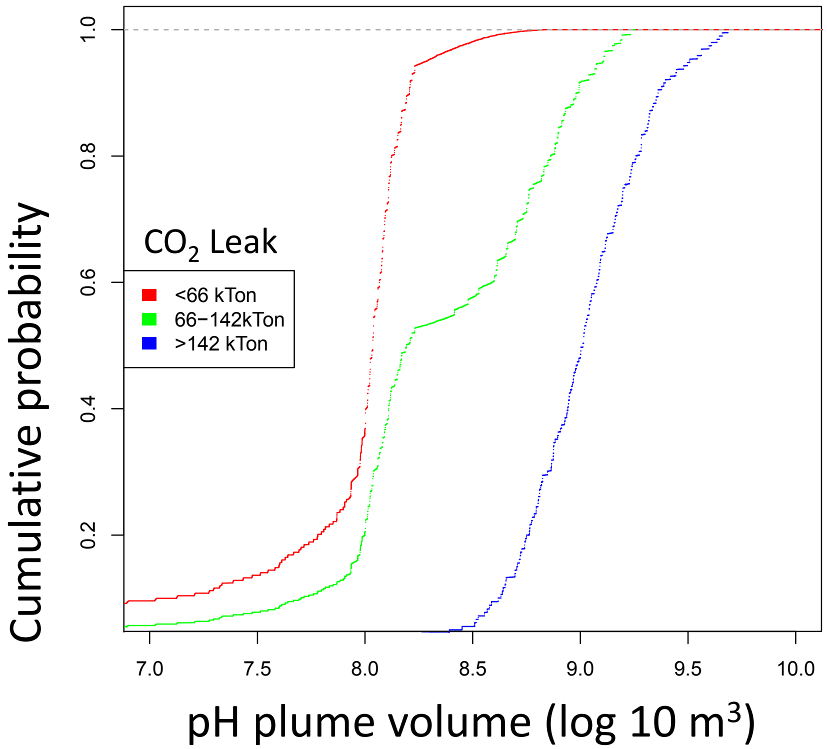
- **Models migration of brine and/or CO_2 outside of storage reservoir**
- **Inputs of reservoir pressures and saturations**
- **Predicts flowrate into thief zone and groundwater aquifer**
- **Incorporates chemistry to identify flowrate changes as a function of time**







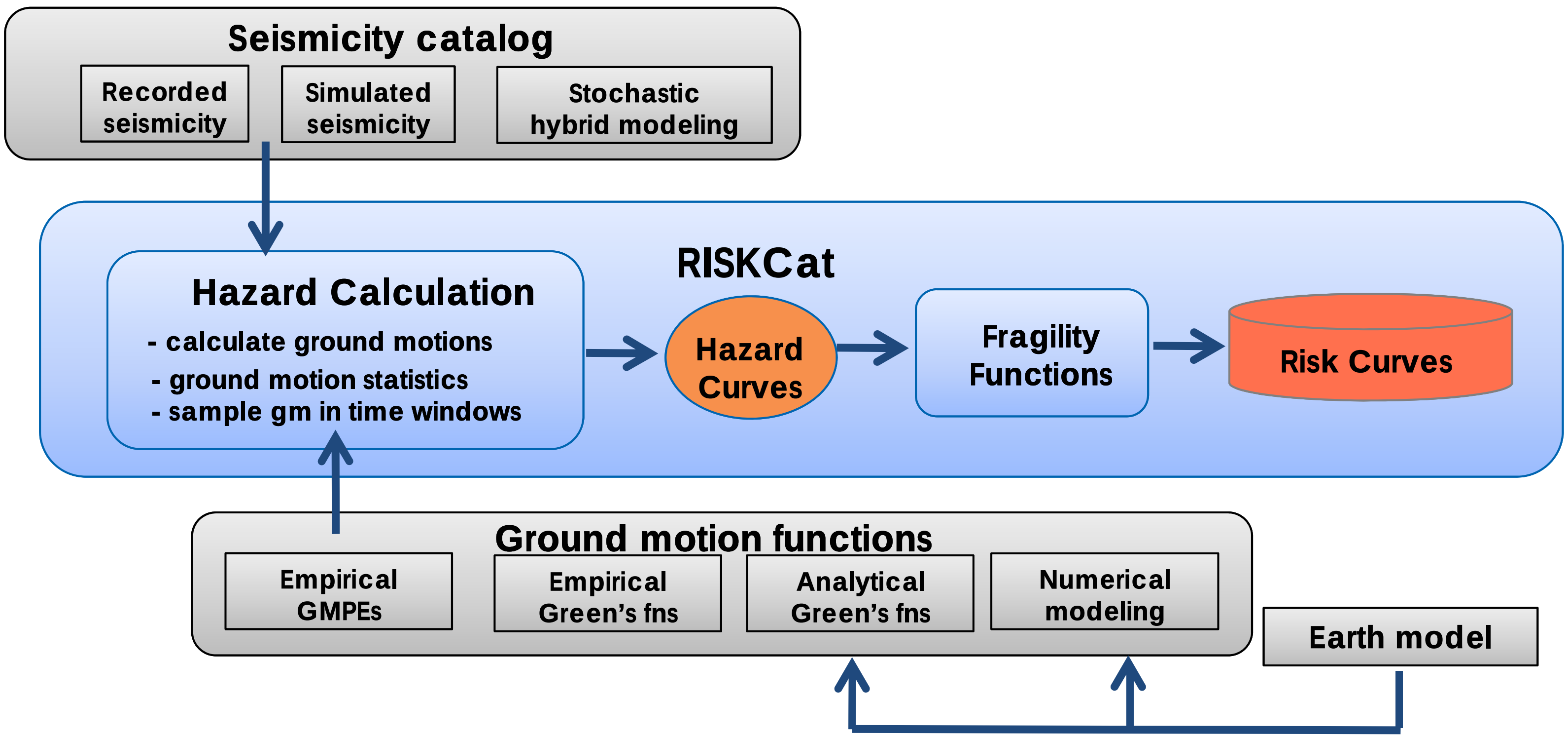
Groundwater ROMs predict volume of aquifer impacted.



- Shallow aquifer pH plume volume, considering uncertain aquifer parameters and leakage scenarios
- *Note higher uncertainty for small leaks*

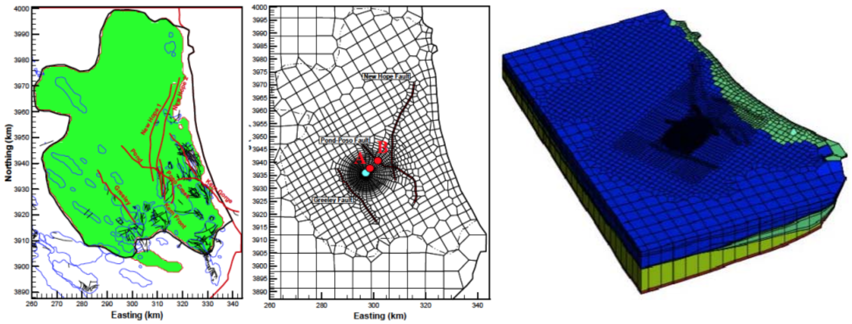
- **Inputs migration rate and concentrations from wellbore or similar models**
- **Includes two different end member aquifer types**
- **Incorporate flow and chemistry**
- **Metrics include: pH, TDS, metals concentrations, organics concentrations**

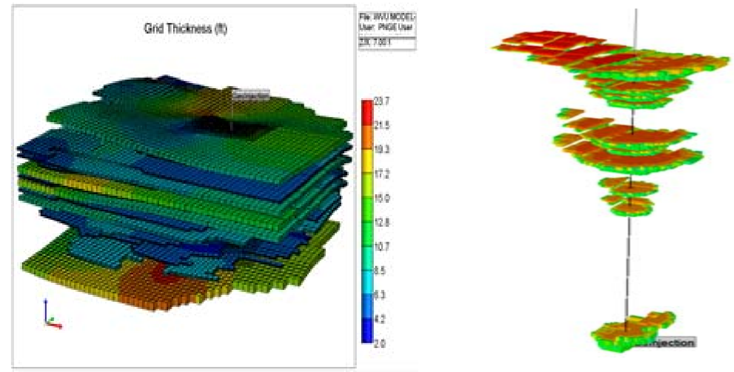
Other preliminary induced seismicity codes incorporate seismic hazard and ground motion.



- Uses probabilistic seismic hazards assessment (PSHA)
- Incorporated multiple sources and ground motion realizations
- Coupled hydro-mechanical modeling
- Injection-induced incremental hazard is calculated

Initial Reservoirs for AoR and PISC Studies



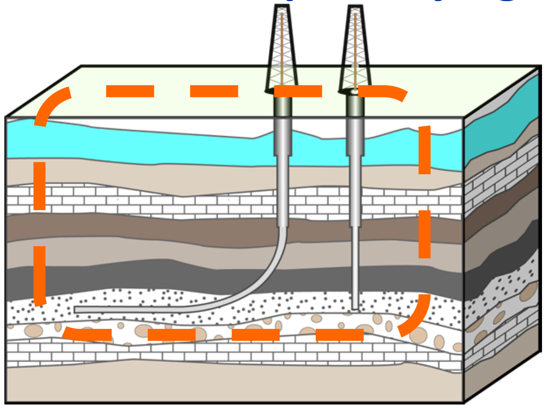


- **Unbound Sandstone Reservoir**
  - Sandstone formation
  - No lateral structural trap
  - Horizontal or dipping units bound by caprock
  - Homogeneous, moderate permeability
- **Based on generic reservoir off structure**
  - Initial geologic model developed in TOUGH2
- **Single, vertical injector**
  - Perforated along entire reservoir interval
  - Constant-rate injection
  - Varying Injection Rates
  - Varying Injection Times
  - Post Injection: Monitoring pressures and CO2 at various time points

- **Domal, Multilayer Sandstone Reservoir**
  - Multilayer sandstone formation
  - Domed structural bound by shale caprock
  - Heterogenous, variable layer permeability
- **Based on candidate site from RCSP, ARRA**
  - Citronelle-like conditions in reservoir
  - Initial geologic model leveraged from RCSP and ARRA project and developed in CMG
- **Single, vertical injector**
  - Multiple perforations along reservoir interval
  - Constant rate injection with pressure constraint
  - Varying Injection Rates
  - Varying Injection Times
  - Post Injection: Monitoring pressures and CO2 at various time points

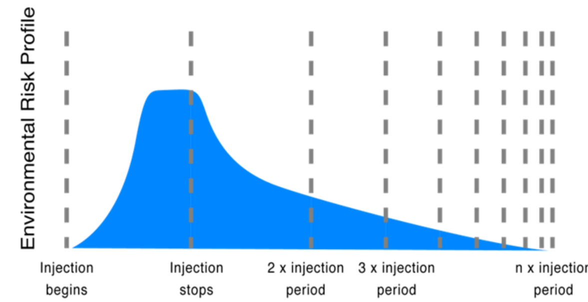
NRAP Value Proposition 1:

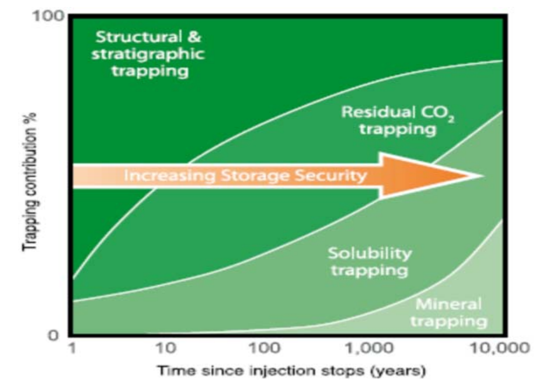
Science-based prediction can build confidence in expected storage security by quantifying system performance for a range of conditions.



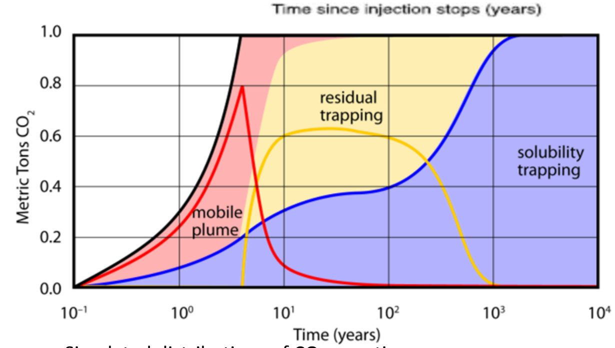
NRAP Goal—to predict storage-site behavior from reservoir to receptor and from injection through long-term storage…

…in order to quantify key storage-security relationships for various site characteristics.





- **Storage-security relationships are a function of the behavior of the coupled storage-site system**
  - reservoir behavior (e.g., evolution of CO_2 & pressure plumes)
  - nature of seal and potential fastpaths (e.g., fractures, wells)
  - response of receptors (e.g., aquifer)
- **Storage-site characteristics vary & are incompletely known**
  - uncertainty in characteristics leads to uncertainty in behavior



Simulated distributions of CO_2 over time
(adapted from BPM on Risk Analysis; DOE/NETL-2011/1459)

Approach to Development of Reduced-Order Models (ROMs):
Case Study at a Candidate Field Site

Define Key Parameters for ROM

Sensitivity analysis
Identify key variables that control component behavior

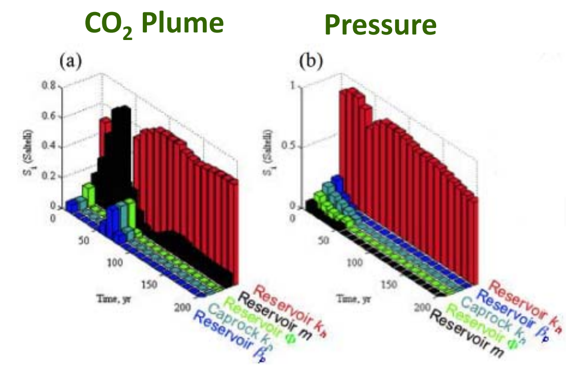
↓

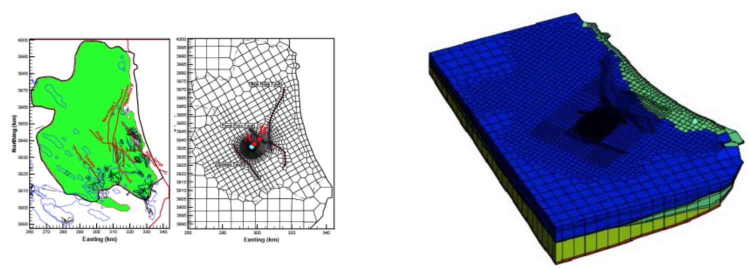
Detailed Simulations
Multiple simulations of detailed component models (reservoir, wellbores, faults, aquifer)

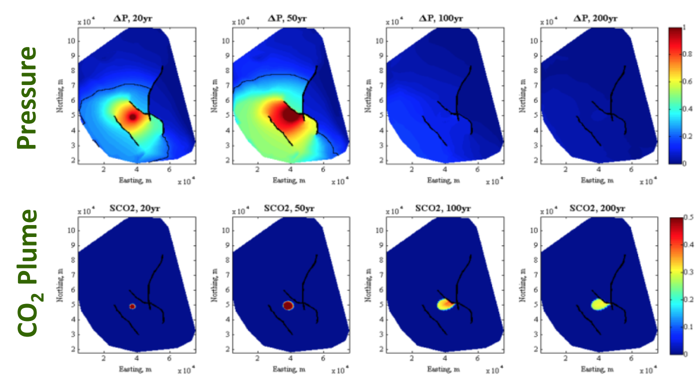
↓

ROM Development
- Look-up tables (LUTs)
- Response surfaces (e.g. via PSUADE)
- Artificial intelligence approaches
- Analytical relationships (e.g., polynomial chaos expansion)

Validate ROM against simulations







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