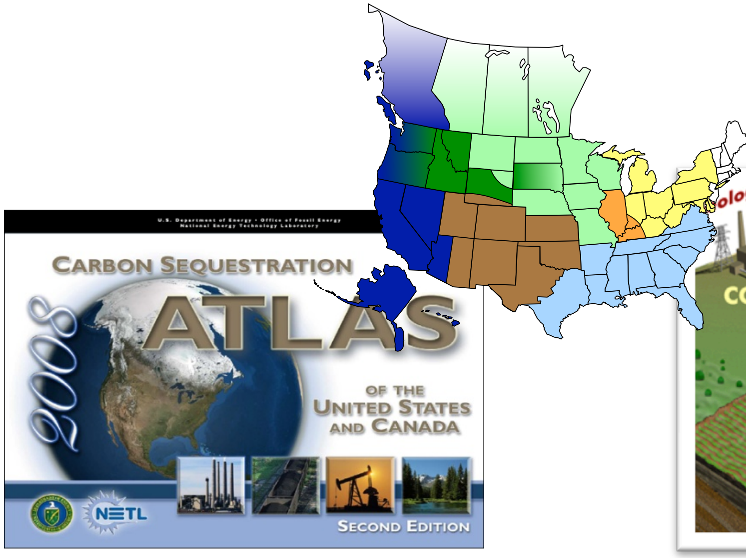

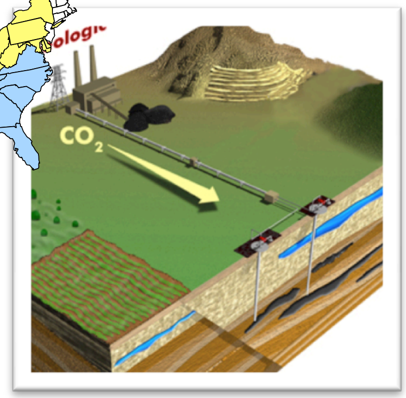

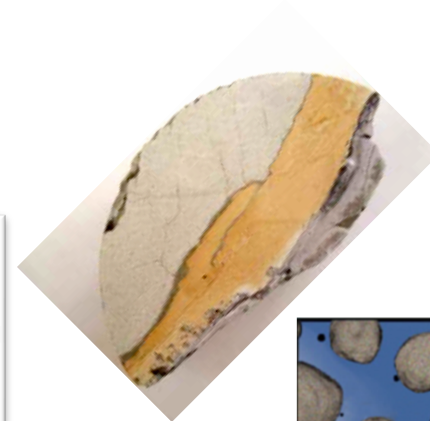

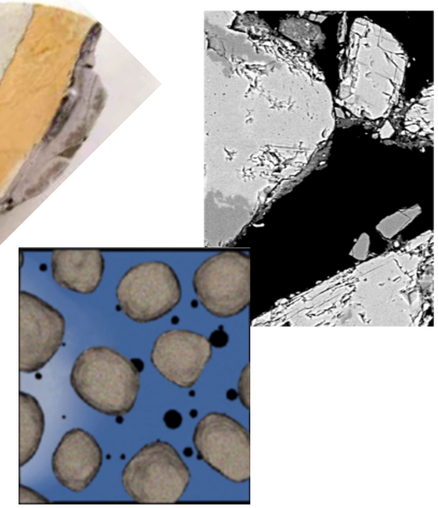

US-DOE’s National Risk Assessment Partnership (NRAP):

Bridging the Gap to Provide the Science Base for Ensuring Successful CO_2 Storage

George Guthrie

National Energy Technology Laboratory

U.S. Dept. of Energy, Office of Fossil Energy

U.S. DEPARTMENT OF ENERGY

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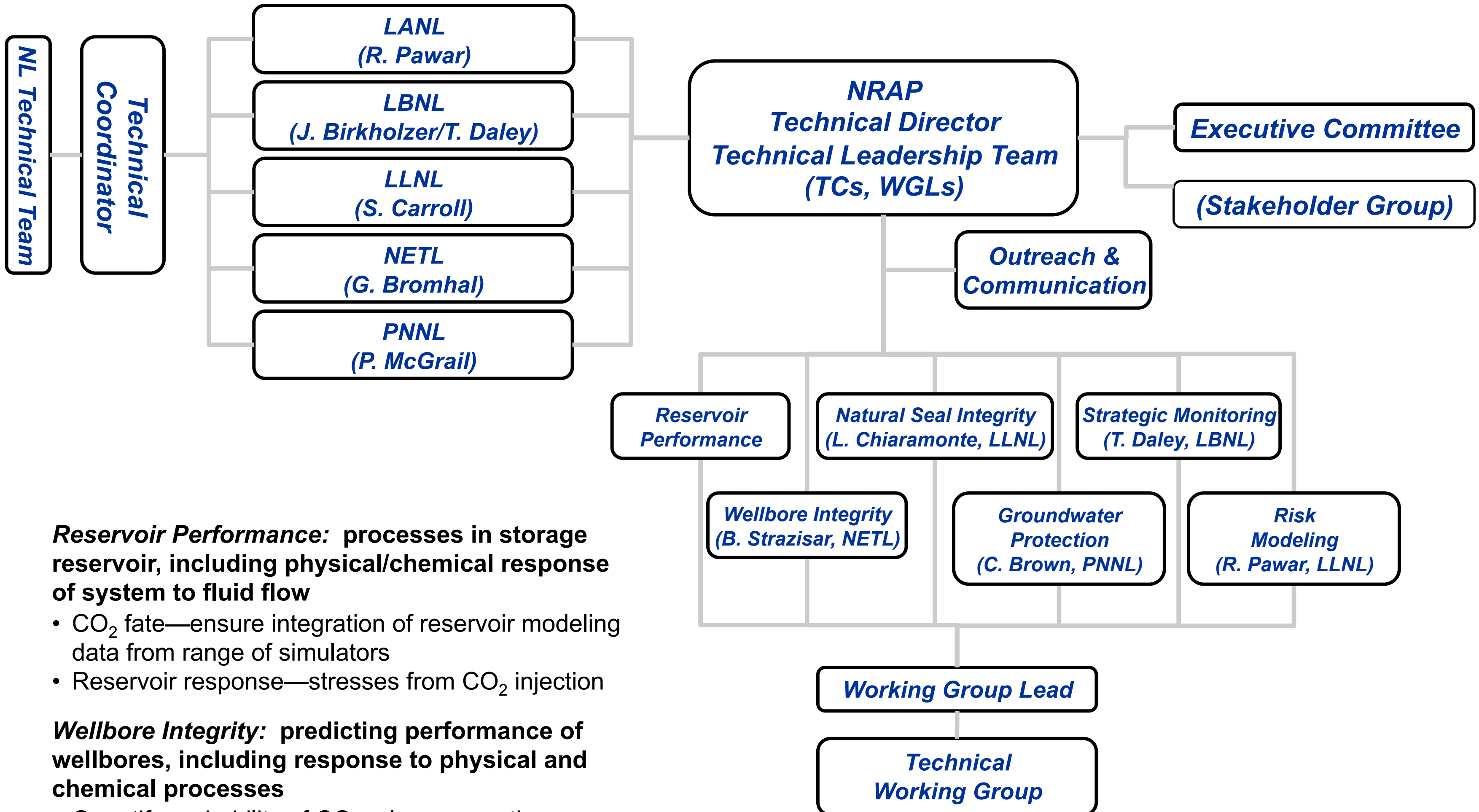
Project Management Structure for NRAP



Reservoir Performance: **processes in storage reservoir, including physical/chemical response of system to fluid flow**

- CO_2 fate—ensure integration of reservoir modeling data from range of simulators
- Reservoir response—stresses from CO_2 injection

Wellbore Integrity: **predicting performance of wellbores, including response to physical and chemical processes**

- Quantify probability of CO_2 release over time

Natural Seal Integrity: **predicting performance of various seals, including response to physical and chemical processes**

- Quantify probability of CO_2 release over time

Groundwater Protection: **predicting potential impacts to other subsurface reservoirs**

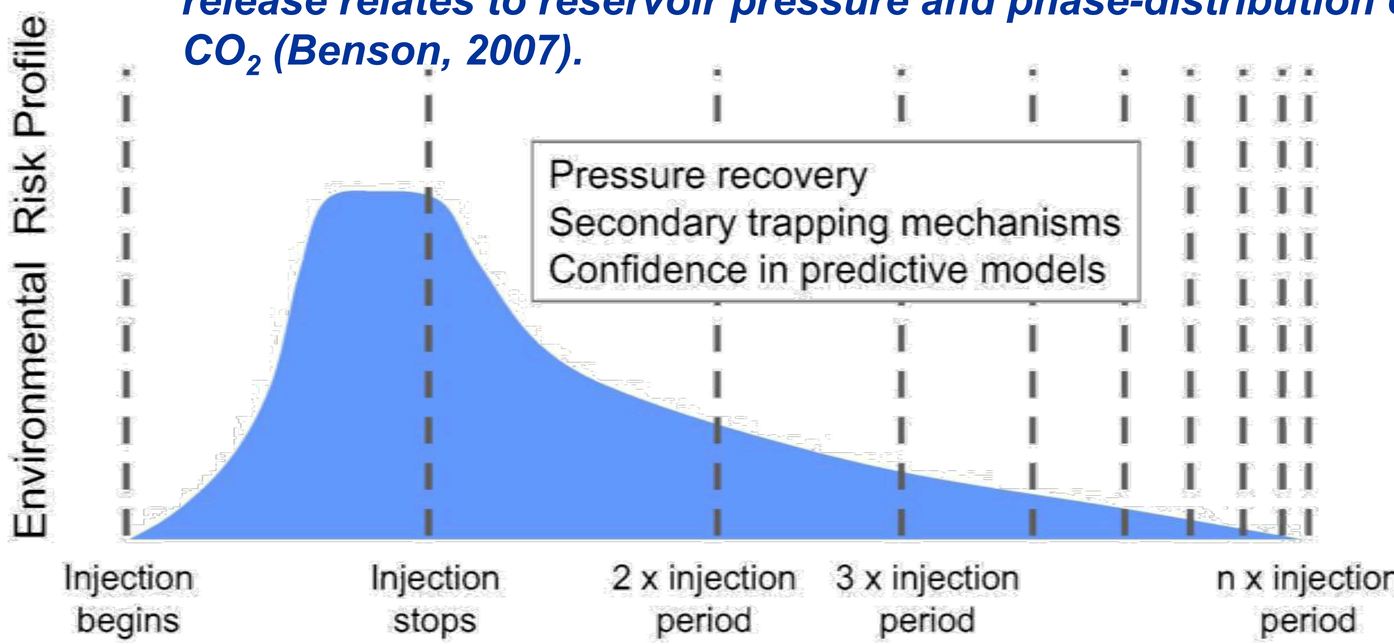
Strategic Monitoring: **identification of key signals that could be monitored at a site**

- to verify predictions, to lower uncertainties, to minimize consequences

Risk Modeling: **system-level modeling strategies for quantifying performance (and risk) at a site**

NRAP Goals: **Develop robust methodologies for calculating defensible, quantitative, site-specific risk profiles and for integrating monitoring & mitigation strategies with risk minimization.**

Schematic description of risk assuming probability of CO_2 release relates to reservoir pressure and phase-distribution of CO_2 (Benson, 2007).



Site Characterization | **Site Operation (e.g., CO_2-EOR)** | **Post Closure** | **Long-Term Stewardship**

10^0 10^1 10^2 10^3

Time (yrs)

Potential risk-related scenarios that could impact the success of a CCS project include…

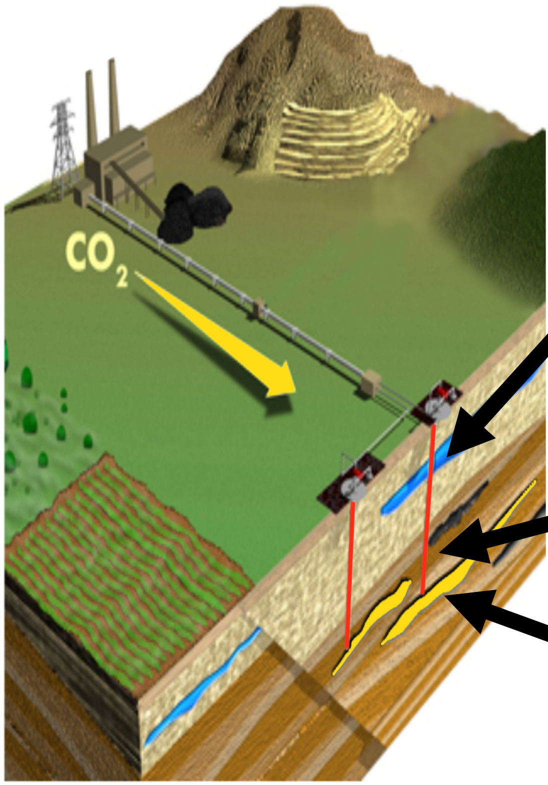
- *insufficient capacity/injectivity over time at a site*
- *impingement on pore space not covered under deed or agreement*
- *impingement on other subsurface resources*
- *change in local subsurface stress fields & geomechanical properties*
- *impact on the groundwater and/or surface water*
- *elevated soil-gas CO_2 in terrestrial ecosystems*
- *accumulation in poorly ventilated spaces or in low lying areas subject to poor atmospheric circulation*
- *CO_2 or other displaced gases (e.g., CH_4) return to the atmosphere*

➢ *Importance of direct impacts from CO_2 vs. indirect impacts (e.g., brines, pressure fronts)*

➢ *Importance of global impacts (e.g., return of CO_2 to atmosphere) vs. local/regional impacts*

** from Carbon Sequestration Leadership Forum Task Force report*

Assessing potential risks for a storage site requires consideration of factors from reservoir to receptor.



Lawrence Berkeley National Lab
Lawrence Livermore National Lab
Los Alamos National Lab
National Energy Technology Lab
Pacific Northwest National Lab

Outside of the Reservoir

- **Strategic monitoring for the site (during injection & post closure)**
- **Potential impacts of CO_2 release**
- **Protection of subsurface resources (groundwater, minerals, etc.)**

Seal

- **Seal characterization**
- **Seal & wellbore integrity**
- **Mitigation strategies**

Reservoir

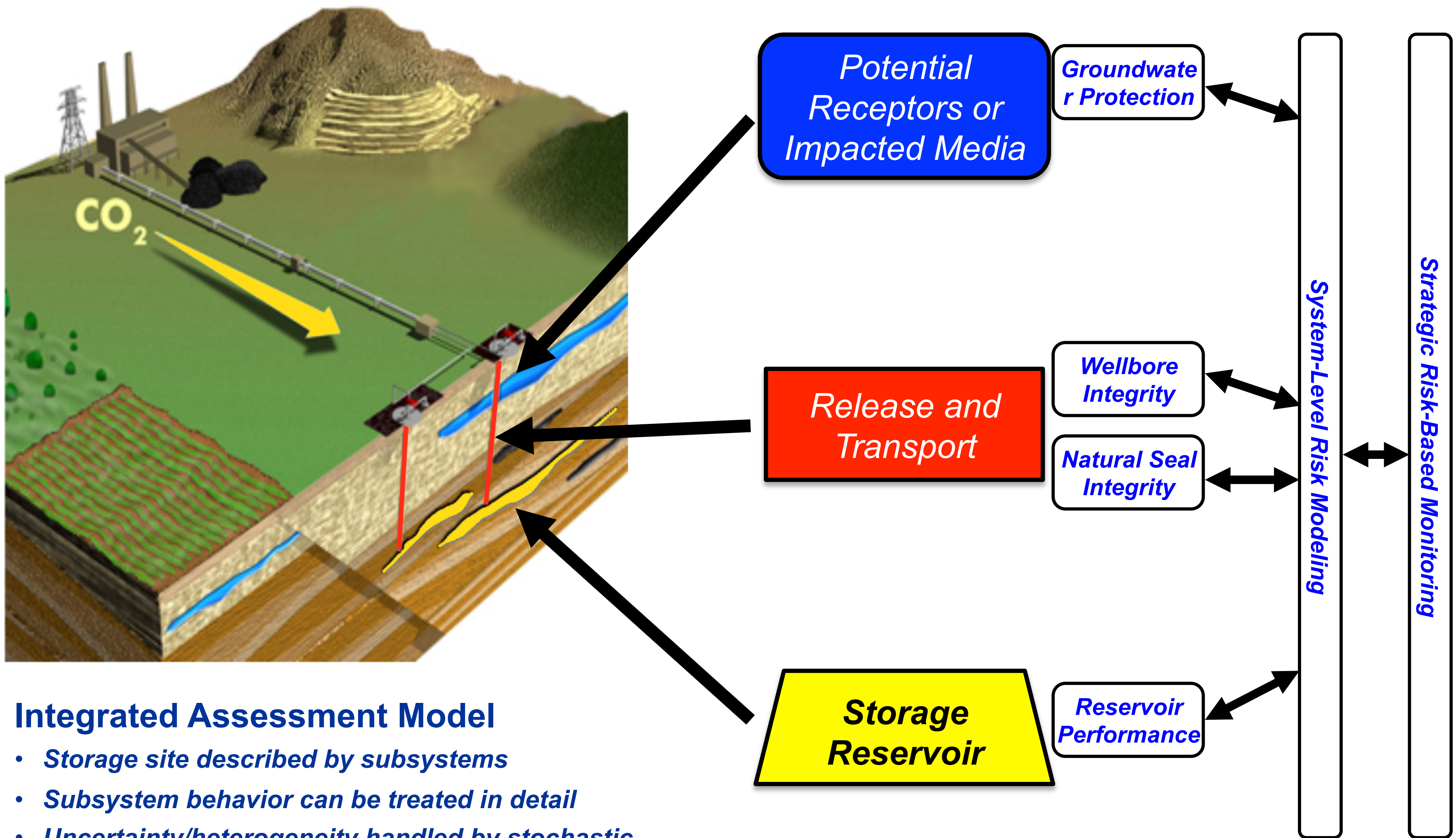
- **Strategic site characterization**
- **Capacity & injectivity over time**
- **Plume movement in reservoir (CO_2, brine, pressure front)**
- **Impacts from introducing CO_2 into the reservoir**

+/–30% Capacity

99% Permanence

Quantitative Risk Assessment

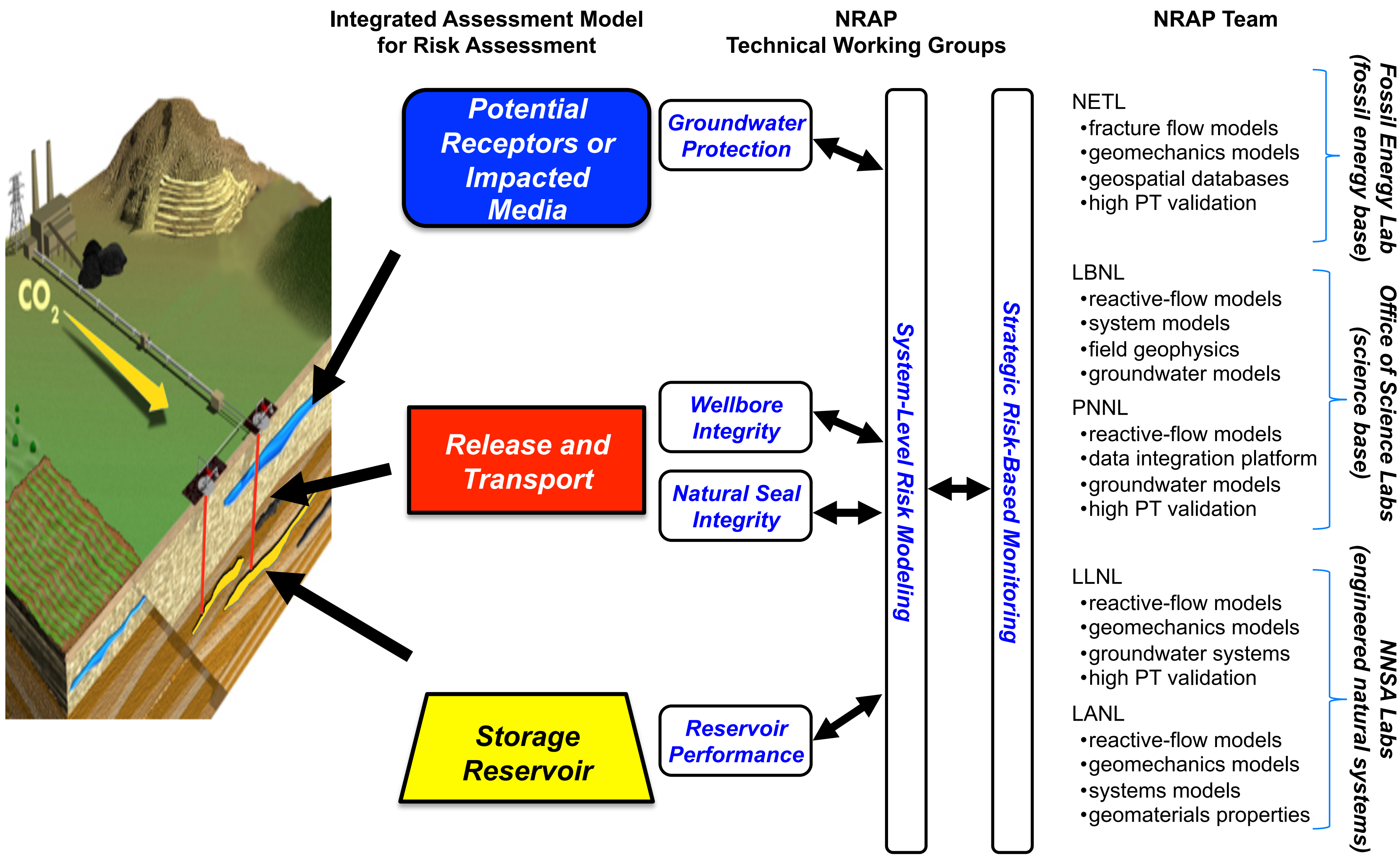
NRAP is an initiative that harnesses the breadth of DOE's expertise in engineered-natural systems to predict the storage-site performance.



Integrated Assessment Model

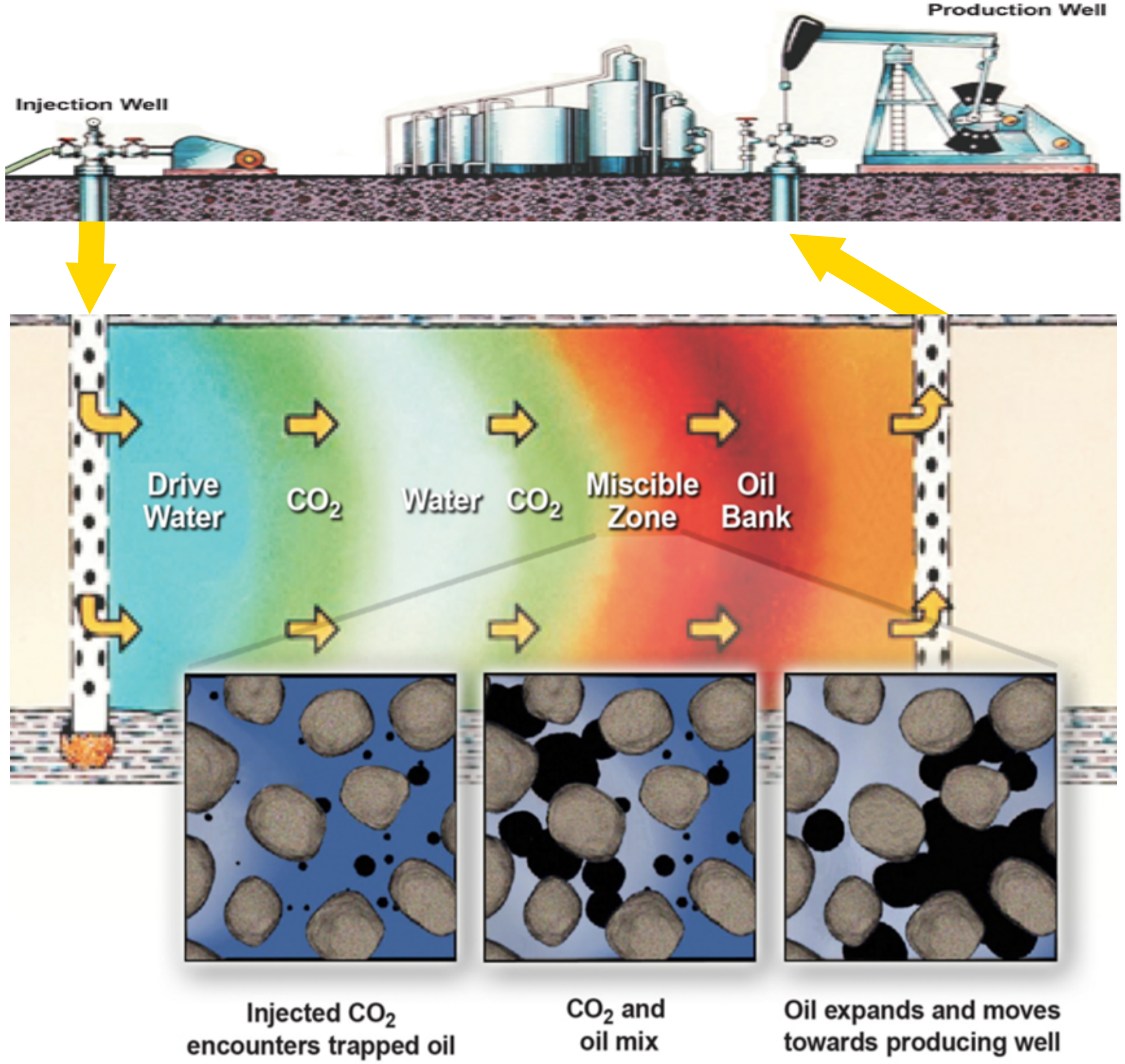
- *Storage site described by subsystems*
- *Subsystem behavior can be treated in detail*
- *Uncertainty/heterogeneity handled by stochastic descriptions of subsystems*

NRAP is leveraging broad DOE capabilities to develop science based quantification for residual risk at CO_2 storage sites.



Over decades, CO_2-EOR has developed tools/understanding needed to manage CO_2 injection into geologic reservoirs.

- ✓ multiphase flow of CO_2, brine, oil during EOR operation
  - EOR = injection + production

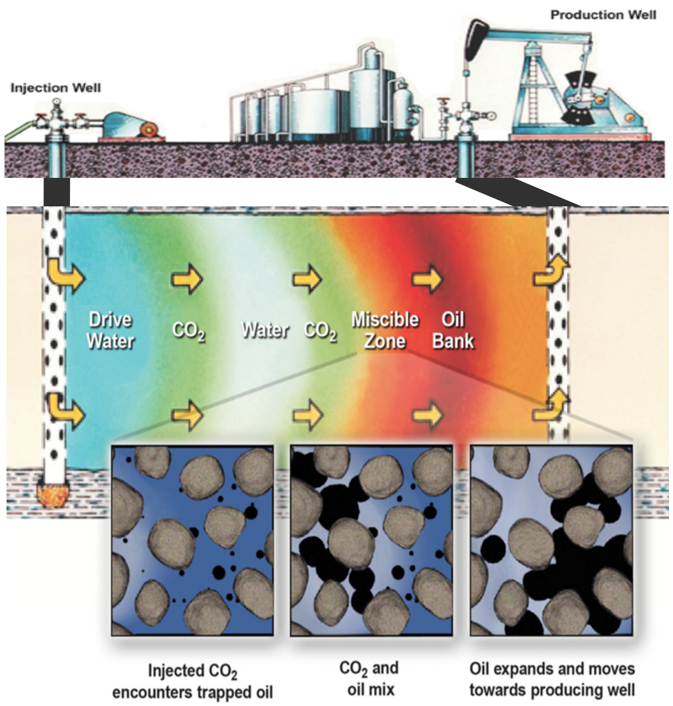


Figures from US-DOE/NETL 2009 (“Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution”)

New (beyond EOR) tools/understanding are needed for CCS.

✓ *multiphase flow of CO_2, brine, oil during EOR operation*

- *EOR = injection + production*



coupled flow–reaction–stress/strain

? *variable flow dynamics*

- *pressure driven regimes vs. buoyancy driven regimes*
- *viscosity of CO_2 < H_2O (fingering)*
- *hydrophobic vs. hydrophyllic minerals*
- *porous flow and fracture flow*

? *site characterization*

- *deeper reservoirs; new environments; need to prove seal*
- *quantification of CO_2 fate*

? *dynamics from reservoir to surface*

- *multiple coupled subsystems*

? *geomechanical behavior coupled to flow*

- *flow-stress are linked through permeability and P*

? *long-term CO_2-water interactions coupled to flow*

- *CO_2 dissolves into water over days (diffusion)*
- *denser CO_2-water develops plumes (advection)*
- *CO_2 mixes in reservoir over $10^{2–3}$ yrs*

? *long-term CO_2-water-rock(-cement) reactions coupled to flow*

- *CO_2+water causes dissolution and precipitation, which changes permeability*
- *reactions in desiccating brine or supercritical CO_2*

Figures from US-DOE/NETL 2009 ("Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution")

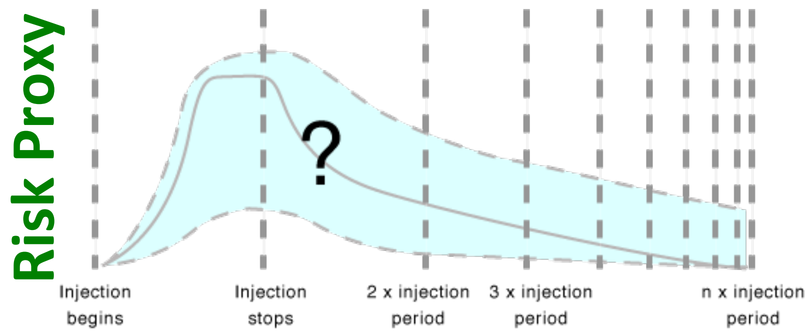
NRAP Goals: Develop robust methodologies for calculating defensible, quantitative, site-specific risk profiles and for integrating monitoring & mitigation strategies with risk minimization.

① pH (function of CO_2 only)

② TDS (function of both brine & CO_2)

③ return of CO_2 to the atmosphere

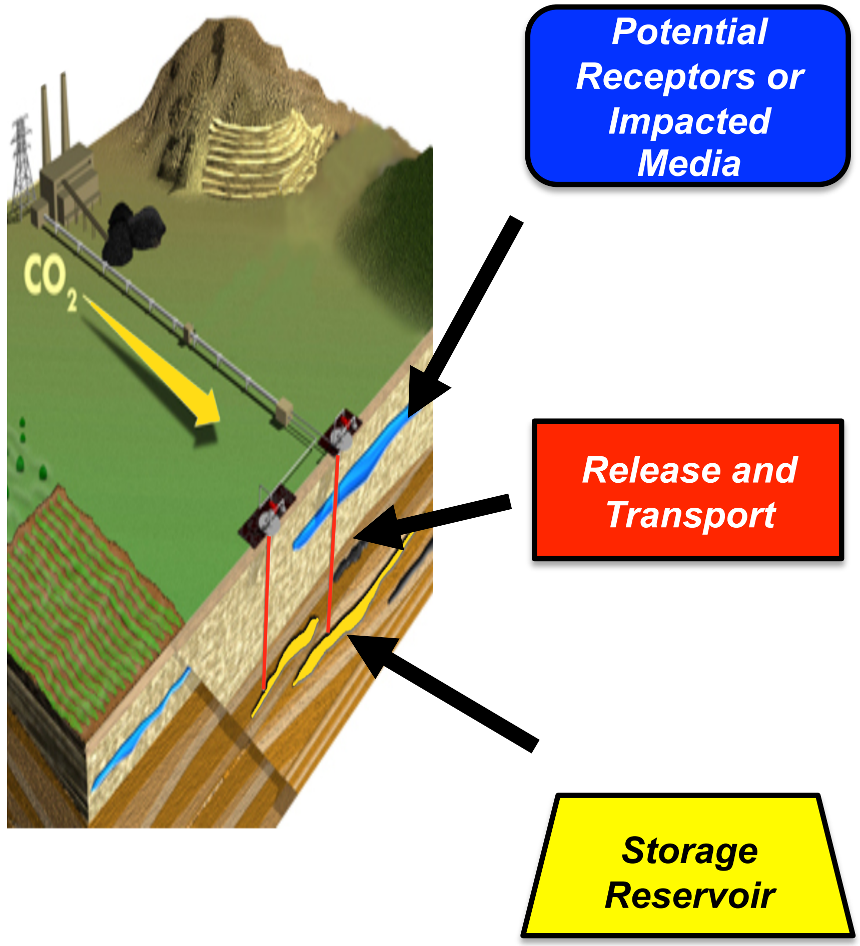
④ reservoir stress



- **identify parameters that are proxies for various risk components**
  - based on risk framework
- **predict curves for generic, idealized sites using simulation**
  - determine effect of permeability, heterogeneity, lithology, wellbore distribution, fracture density, open/closed system, …
  - evaluate magnitude of uncertainties
  - evaluate impact on profile from other sites within a basin
- **confirm predictions using analog case studies**
  - natural analog sites; anthropogenic sites; etc.
- **develop risk profiles for field demo sites**
- **develop best-practice methodology for risk profile**
  - includes identification of key site characterization and monitoring data needs

Preliminary risk profiles have been calculated to guide key FY11 research areas needed to develop 1st generation risk profiles.

Integrated Assessment Model for Risk Assessment

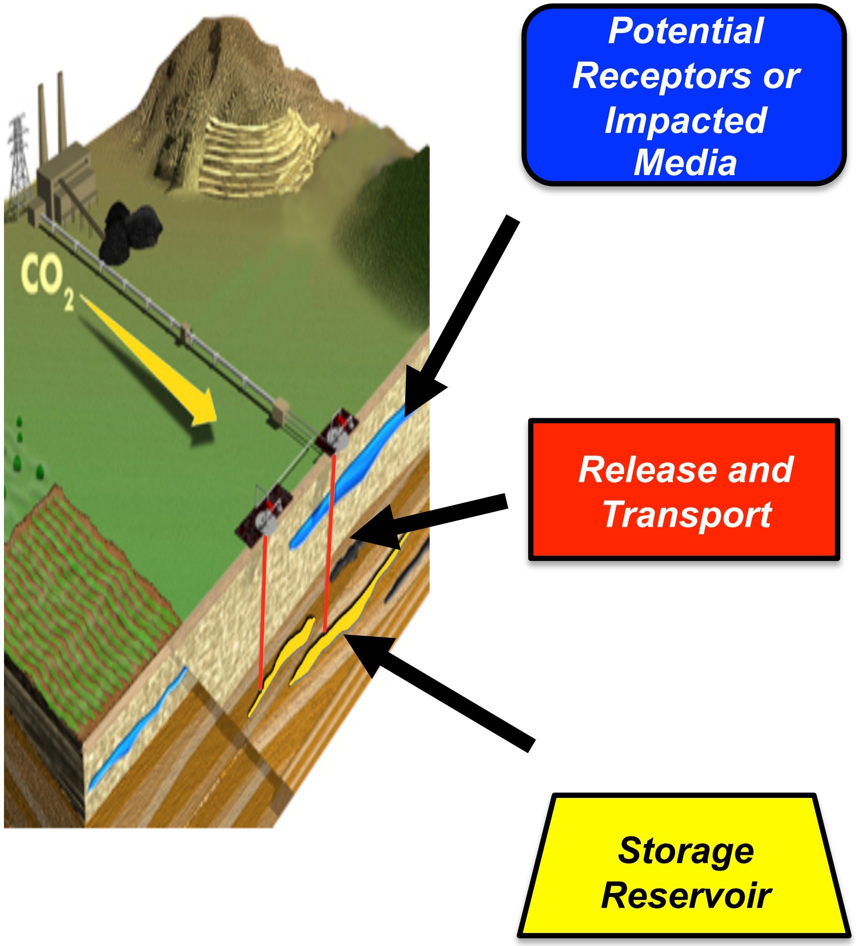


- equilibrium geochemistry groundwater model based on two real aquifers
  - High Plains aquifer in LLNL's NUFT
  - A Coastal Sandstone aquifer in LBL's TOUGH2
- CO_2/brine leak rates from CO_2-PENS used as boundary conditions

- wellbore release model
- multiple realizations using wellbore cement characteristics provided by wellbore working group
- CO_2/brine leak rates calculated using abstraction for wellbore leak in CO_2-PENS and reservoir model results

- continuum-scale reservoir model based on real site
- used to predict CO_2:brine ratio (saturation), pressure

Integrated Assessment Model for Risk Profiles in Groundwater Systems



CO_2/brine leakage rates used as boundary conditions in detailed reactive-flow models to calculate dynamic evolution of pH & TDS

- equilibrium-geochemistry, continuum-scale reactive flow; based on two real aquifers
  - High Plains aquifer in LLNL's NUFT
  - A Coastal Sandstone aquifer in LBNL's TOUGH2

Wellbore-release model used to calculate CO_2/ brine leakage rates based on predicted reservoir pressure and saturation

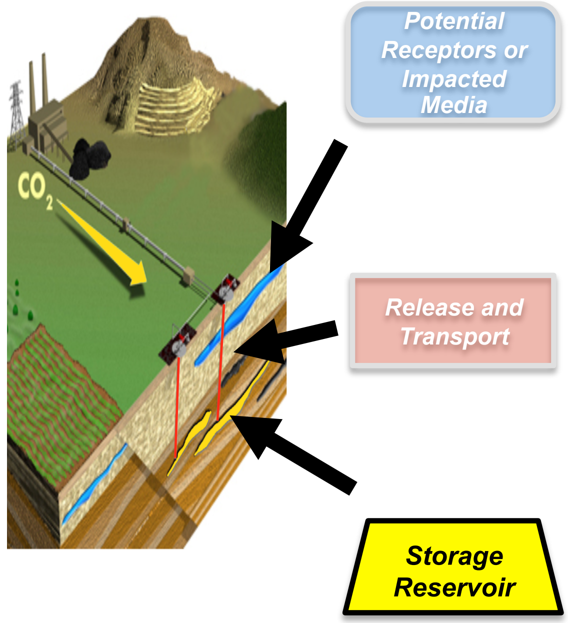
- abstraction based on continuum-scale multiphase-flow model plus Monte Carlo analysis
  - Multiple realizations using wellbore cement characteristics
  - CO_2/brine leak rates calculated in LANL's CO_2-PENS using abstraction for wellbore flow output from reservoir model

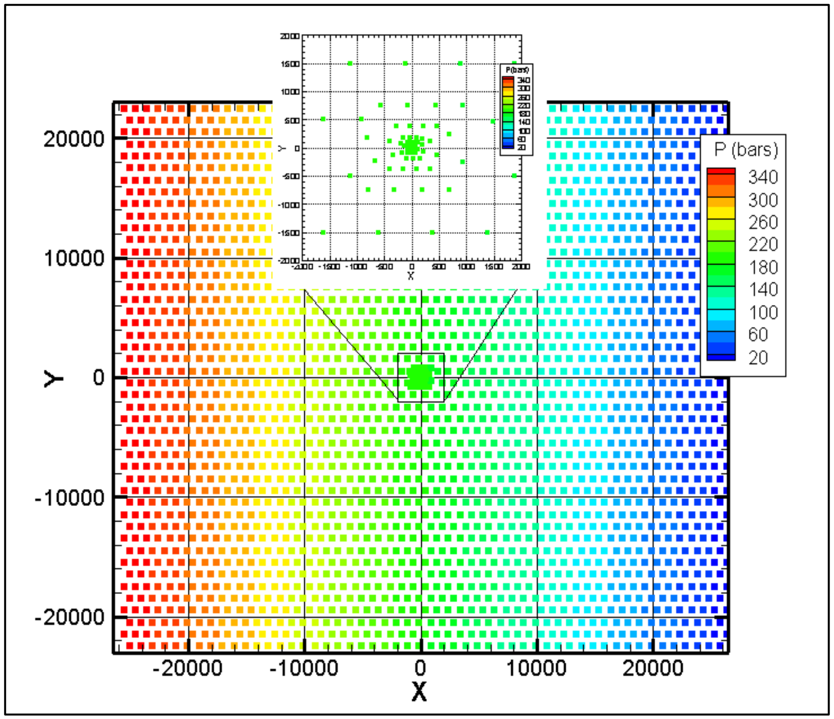
Detailed reservoir model used to predict pressure & saturation at reservoir–caprock interface

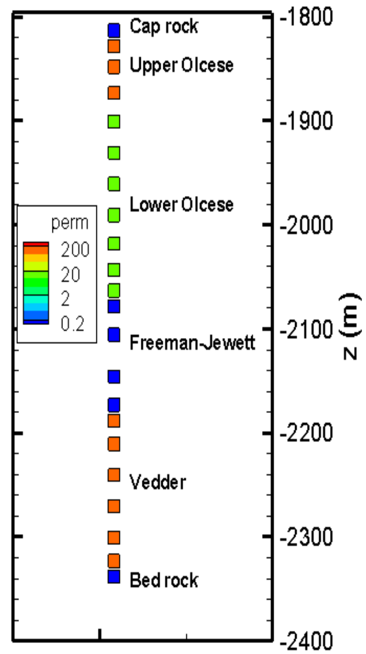
- continuum-scale multiphase-flow model
  - based on real site
  - used to predict CO_2:brine ratio (saturation), pressure

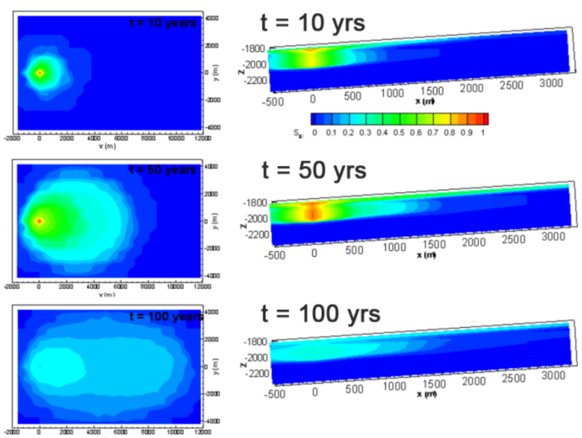
Approach assumes that mass traveled across sub-system boundary does not significantly affect mass balance within individual sub-systems.

Integration of reservoir behavior through continuum-scale reservoir model to predict pressures and saturations at bottom of caprock.









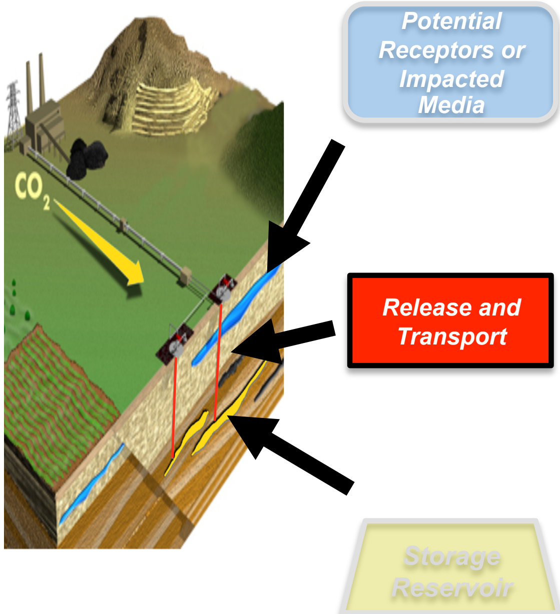
TOUGH2 model of potential storage formations at a site in the Southern San Joaquin Valley

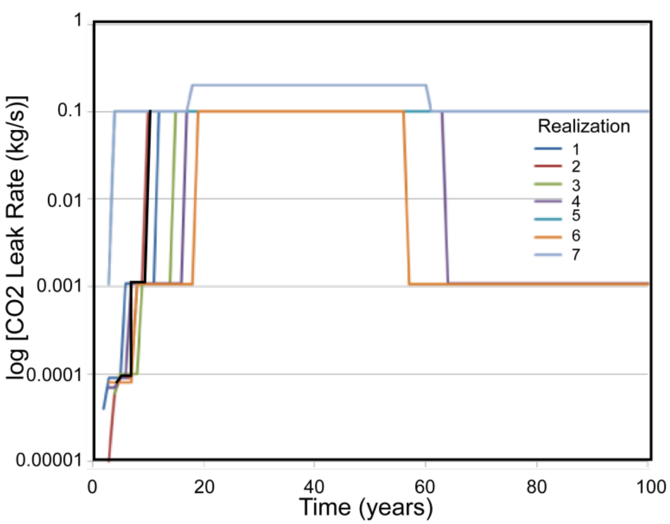
- Lateral extent 53 km by 46 km with 3.85º dip;
  22-layer model with total thickness = 540 m; depth 1805–2345 m
- Hydrostatic pressure (~220 bars at Vedder); geothermal temperature gradient (T=71 ºC at Vedder)

Injection of 1 million metric tons CO_2/yr for 50 yrs; followed reservoir evolution for 50 yrs post-closure

- Pressures & saturations at the top formation layer at 20 time intervals

Integration of release processes through wellbore-release model based on abstracted multiphase physics and assumed wellbore permeability.





Wellbore leak-rate was treated as a stochastic variable using Monte Carlo analysis

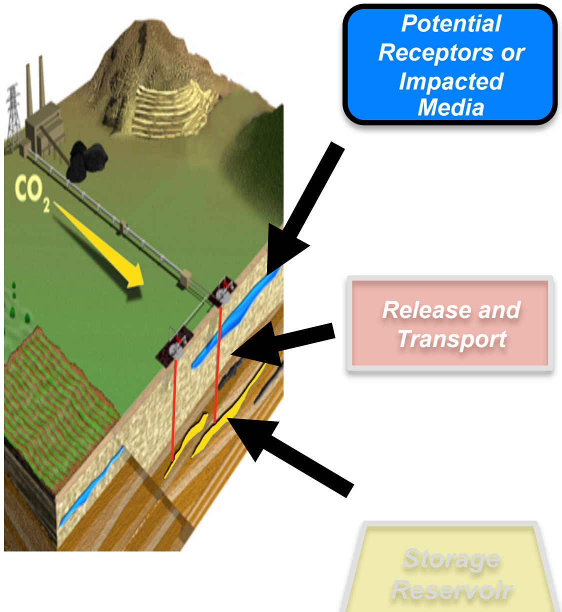
- Wellbore response surface generated from high-fidelity, multi-phase flow of CO_2/brine through wells using LANL's continuum-scale FEHM
  - Leak-rate variability was function of pressure, saturation, and permeabilities of reservoir, wellbore cement, and aquifer.
- Monte-Carlo methods using LANL's CO_2-PENS system model and wellbore response surface
- Coupling to storage reservoir via simulation results from TOUGH2 (time dependent pressure and saturation)

Wellbores were assumed to have spatial density of a typical EOR site (based on site in west Texas)

- 10 randomly distributed abandoned wells (injection well is not considered as potential flow path)
- 90% of wells with good (low permeability) cement; 10% wells with poor cement
- Values used for wellbore cements based on preliminary assessment of one available field data set
  - good cement permeability – 10^{-17} m^2 (10 μD)
  - poor cement permeability – 10^{-10} m^2 (100 D)

Time-dependent CO_2 & brine leakage rates into shallow aquifer were based on multiple (but limited) realizations

Integration of aquifer processes through equilibrium-geochemistry, continuum-scale, reactive-flow model.



Two different sets of calculations with two models

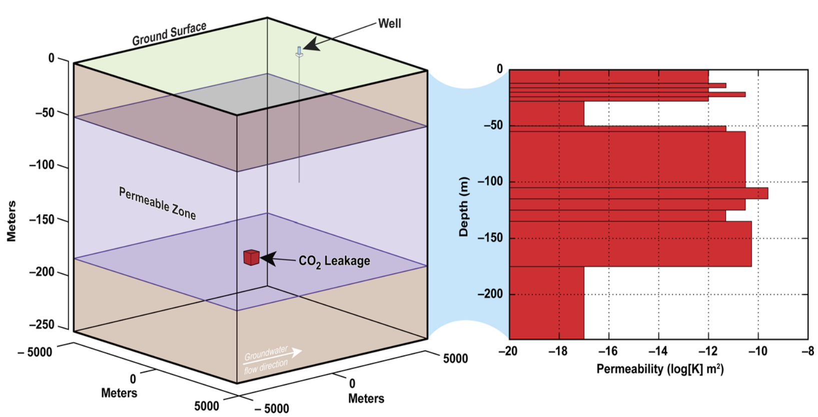
- High Plains aquifer using LLNL's NUFT (Caroll et al., 2009)
- Coastal sandstone aquifer using LBNL's TOUGH2 (Zheng et al, 2009)

Both models used time-dependent CO_2 & brine leakage rates as boundary conditions to predict time-dependent change in pH and TDS

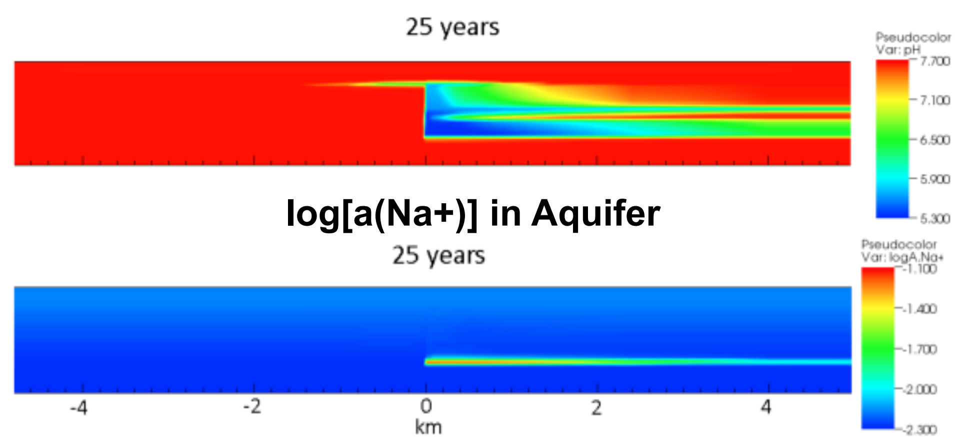
Reactive transport calculations with assumed mineralogy and fluid compositions

- quartz-calcite aquifer; quartz-feldspar-clay aquifer

Background flow to account for regional groundwater flow

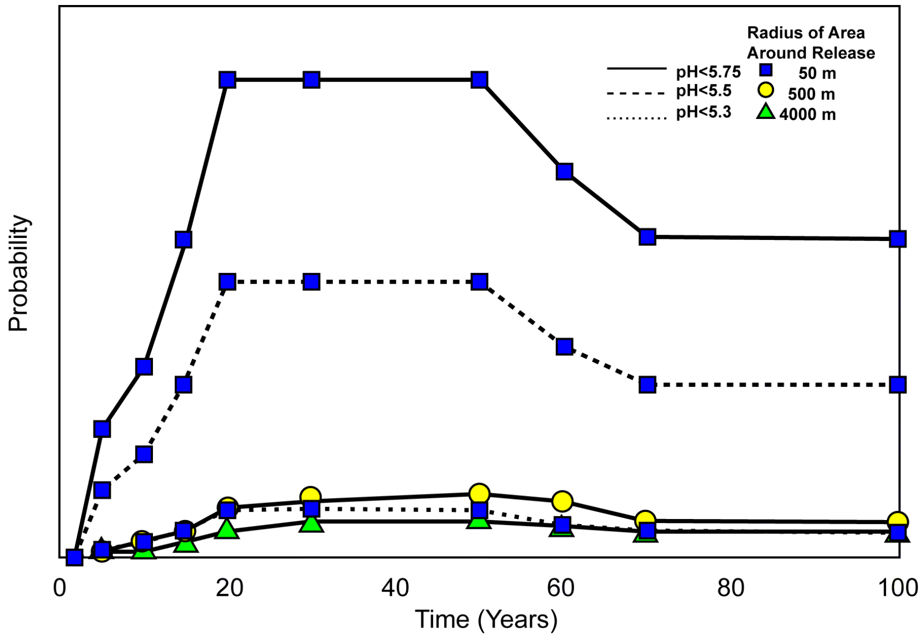


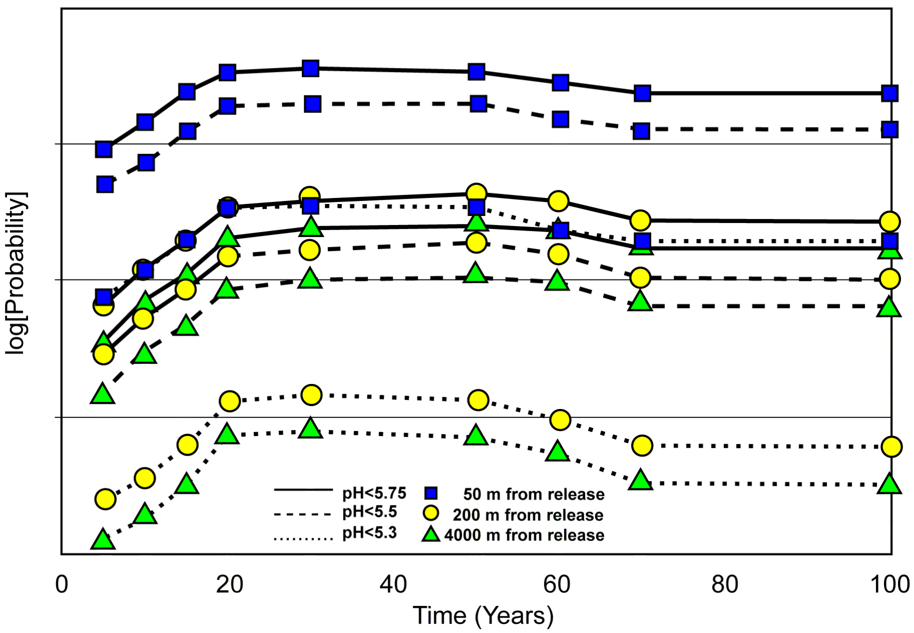
pH in Aquifer



Preliminary* Risk Profiles for pH in Groundwater System

- probability of pH impact goes down with distance from release point
- recovery initiates after injection ceases

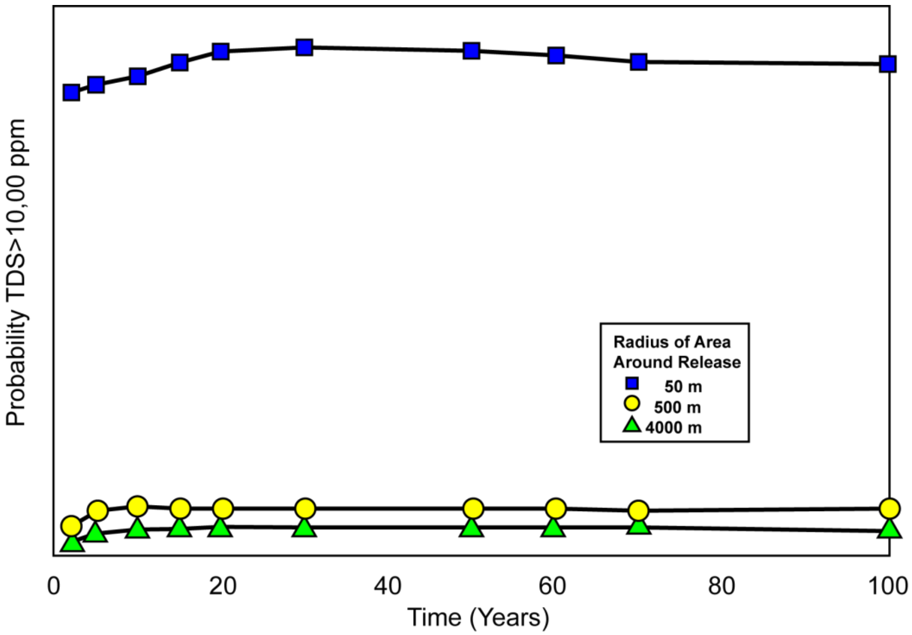


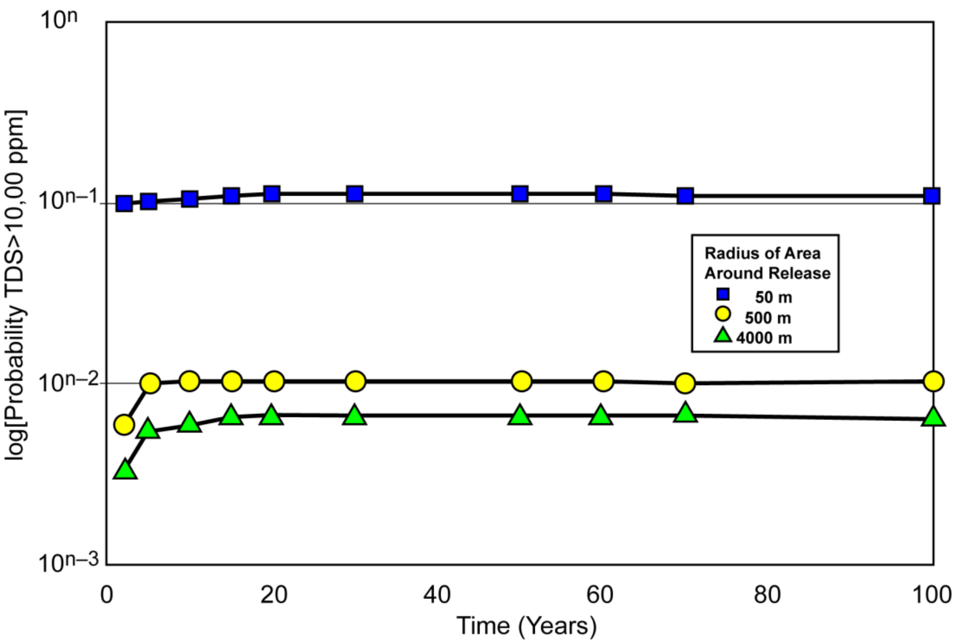


* ***Although these profiles were derived from quantitative simulations, they embody limitations due to numbers of runs, level of detail, single release process, comprehensiveness with respect to uncertainty, etc. They, however, form the basis for NRAP's initial work to develop 1st generation, quantitative risk profiles.***

Preliminary* Risk Profiles for TDS in Groundwater System

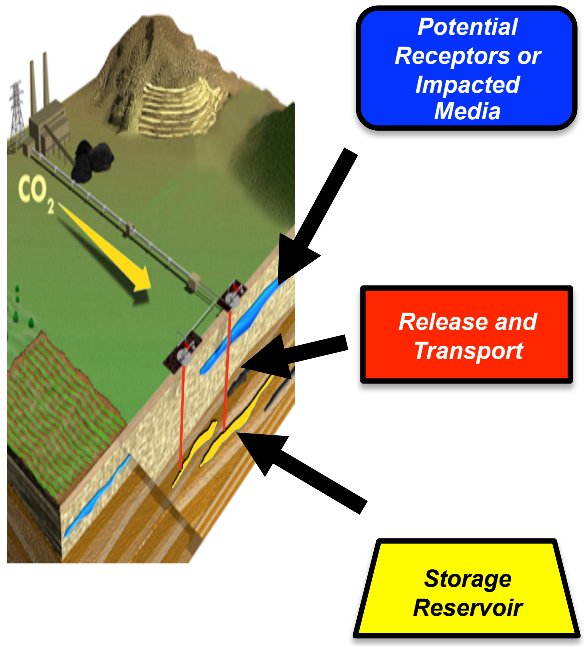
- Similar pattern to pH impact (e.g., goes down with distance from release point)
- recovery initiates after injection ceases





* ***Although these profiles were derived from quantitative simulations, they embody limitations due to numbers of runs, level of detail, single release process, comprehensiveness with respect to uncertainty, etc. They, however, form the basis for NRAP's initial work to develop 1st generation, quantitative risk profiles.***

Key NRAP Focus for First Generation Risk Profile Development



Receptors

- *Groundwater/Atmosphere*
  - perform systematic realizations across ranges in key parameters
  - develop robust abstractions of responses as functions of key parameters
  - develop robust protocol for integrating information to/from multiple simulators
  - evaluate assumption that mass transfer between sub-systems has negligible impact;
- *Ground Motion*
  - develop robust numerical models for simulating ground deformation as function of stress changes
  - perform systematic realizations across ranges in key parameters
  - develop robust abstractions of responses as functions of key parameters
  - develop robust protocol for integrating information to/from multiple simulators

Release/Transport

- *Wellbores*
  - perform systematic realizations across ranges in key parameters
  - conduct robust analysis of effective wellbore permeabilities observed in various environments
  - develop time-varying permeability models
  - develop coupled geomechanics models to estimate change in permeability
- *Faults/Fractures*
  - perform systematic realizations across ranges in key parameters
  - conduct robust analysis of effective permeabilities for various types of seals
  - develop time-varying permeability models
  - develop coupled geomechanics models to estimate change in permeability

Storage Reservoirs

- *Pressure/Saturation/Stress*
  - develop robust protocols for passing information to/from multiple simulators
  - develop abstractions for pressure-saturation evolution for coupled flow-reaction-geomechanics