Multi-Objective Optimization Approaches for the Design of Carbon Geological Sequestration Systems

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Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

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Presentation Outline

- Benefit to the Program
- Project Overview: Goals and Objectives
- Technical Status
- Accomplishments to Date
- Summary
- Appendices

Benefit to the Program

Benefits Statement

– A decision support framework is being developed to analyze – for any given site – the Tradeoffs Between: (a) Minimizing Risk of Carbon Leakage; (b) Minimizing Injections Cost; (c) Maximizing Mass of Carbon Stored.

– The framework relies upon the combination of a multi-phase model and multi-objective optimization algorithms. Ideal for site selection, scoping and evaluation.

– This technology will contribute to the Carbon Storage Program (CSP) effort of ensuring that 99 percent of injected CO_2 remains in the injection zones.

Project Overview: Goals and Objectives

- Statement of Project Objectives.
  - Educational: Provide training opportunities to two graduate students to improve human capital and skills necessary to implement CCS technologies.
  - Research: Development of an integrated simulation-optimization framework to support the planning and management of Carbon Geological Sequestration Systems.

Project Overview: Goals and Objectives

- CGS must be examined with respect to the risk of carbon leakage from storage formations, which increases as CO_2 migrates into regions of brine aquifers where caprock continuity is uncertain or unknown
- Leakage risk increases with mass of carbon injected; CGS feasibility requires identifying tradeoff injection alternatives;
- The simulation-optimization framework aims at identifying these alternatives;
- The percentage of CO_2 mass leaked directly affects the Risk objective (CSP Goal 3);

Technical Status

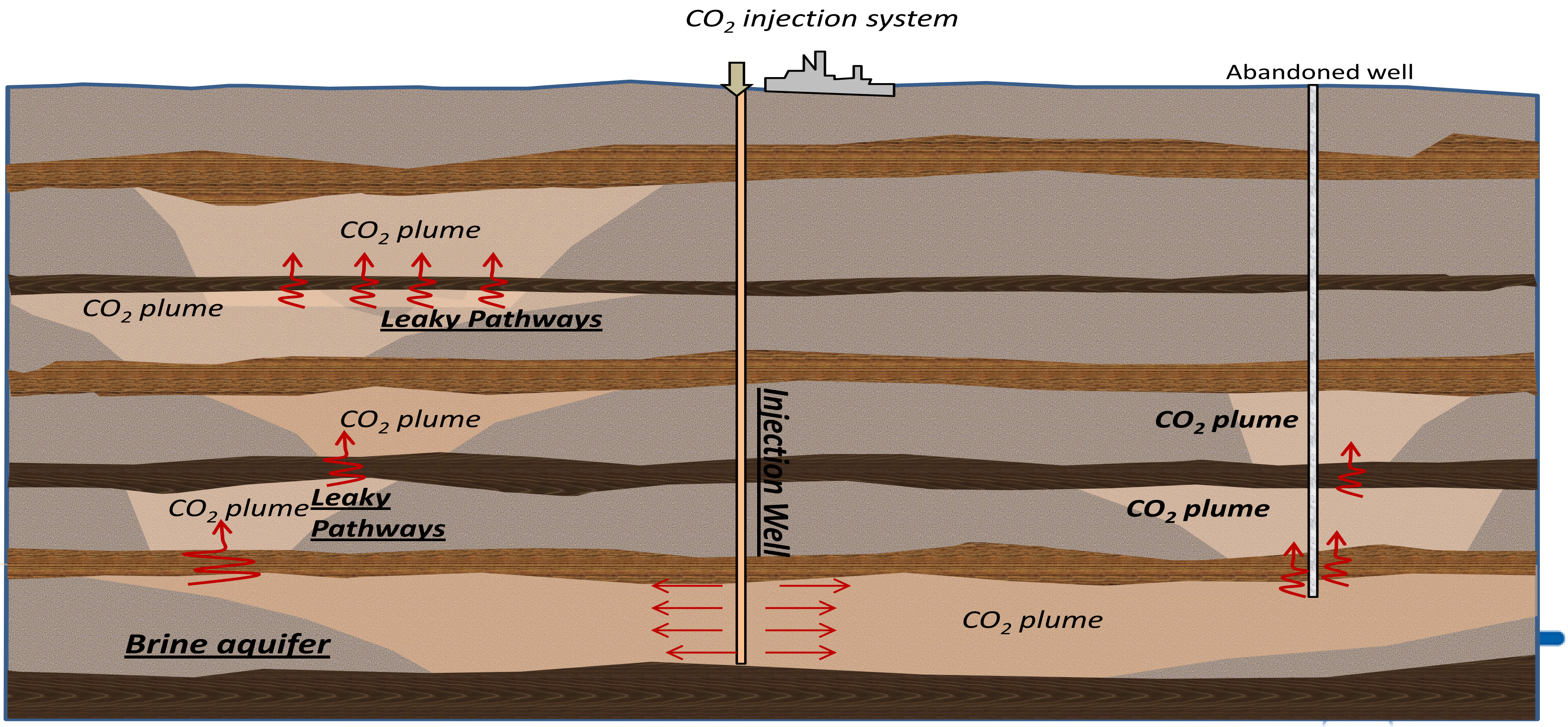
- CGS optimization framework components
  - Multiphase Flow Simulator
  - Multi-Objective Optimization Formulation
  - Multi-Objective Optimization Solver
- Tradeoff Analyses for Synthetic Test Cases to assess framework capabilities.

Technical Status

- Multiphase Flow Simulator
  - Numerical Models are Computationally Intensive, and not adequately suited for CGS simulation-optimization over large-scale sedimentary basins;
  - The framework must rely on a computationally fast flow simulator, however capable to capture major CGS features while reducing problem complexities;
  - A semi-analytical model CO2FLOW has been implemented based upon work by Nordbotten et al. (2009) and Celia et al. (2011).
  - CO2FLOW estimates fluid pressure change, plume distribution and possible CO_2 leakage occurring as carbon migrates in brine aquifers and encounters caprock discontinuities.

Technical Status

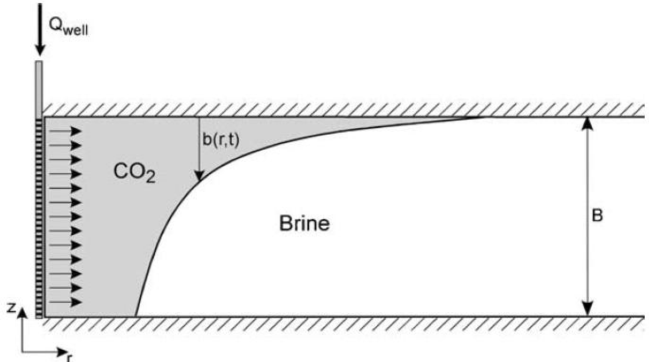
- Multiphase Flow Simulator
  - CO2FLOW assumes the geological system as a sequence of aquifer-caprock layers; caprock layers are homogeneous; aquitards are impermeable, except at leaky pathways.



Technical Status

- Multiphase Flow Simulator
  - CO2FLOW uses Norbotten's pressure model:

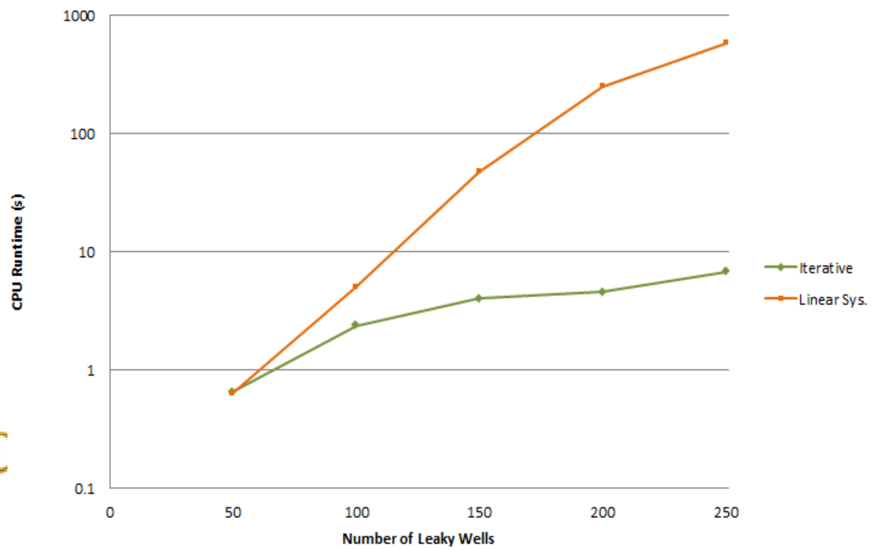
$$\Delta p = \Delta p(g,H,\rho_w,\rho_c,\mu_w,\mu_c,k,S_{res},Q_w,r,t)$$

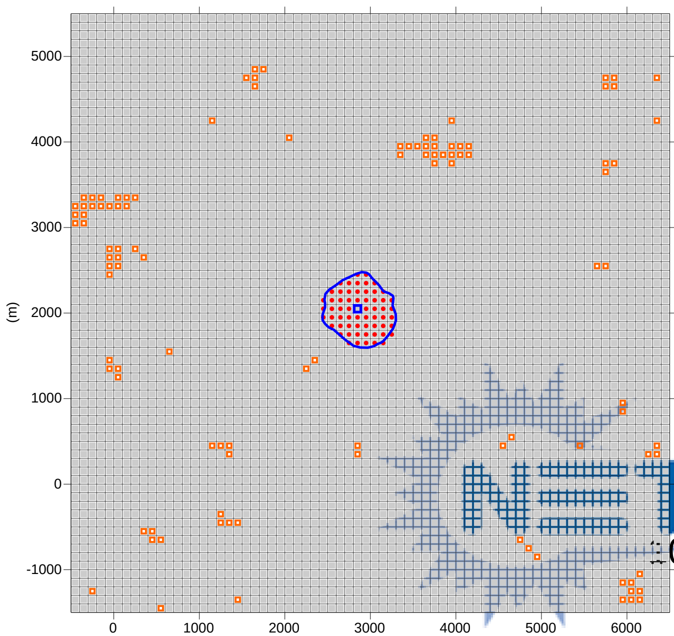


  - Pressure superposition is used to estimate the effect of the presence of leaky wells from which brine and CO_2 can escape;
  - Requires linear system solution at each time step;
  - CO_2 mass flow across leaky wells is estimated using Darcy's law

Technical Status

- Multiphase Flow Simulator
  - Three modifications:
    - » At each time step, a “Picard” iteration is performed to solve the non-linear systems of equations
    - » Pressure is calculated based upon superposition of leakage from both phases;
    - » The solution is extended to generic leaky areas



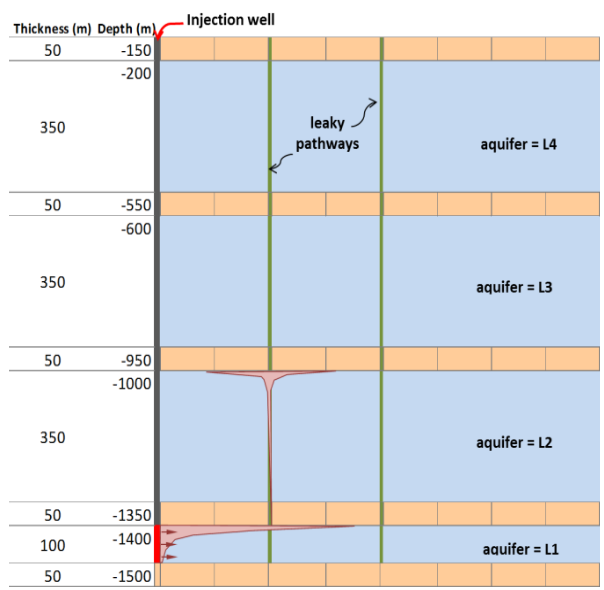


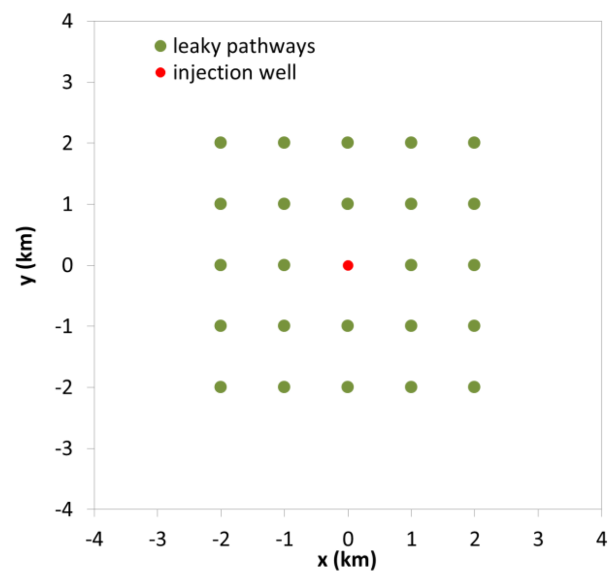
Technical Status

- Multiphase Flow Simulator
  - Stochastic Analysis: quantify effects on mass leakage and fluid overpressure of uncertainty in system parameters such as:
    - » Aquifer Permeability, Porosity, Leakage Pathway Permeability, System Compressibility

Parameter	Value
Aquifer permeability (m^2)	1E-13
Aquifer porosity (/)	0.15
Pathways permeability* (m^2)	1E-13
Radius pathways (m)	0.20
Number of pathways (/)	24
Brine density (kg/m^3)	1000
CO_2 density (kg/m^3)	600
Brine viscosity (Pa·s)	4.5E-4
CO_2 viscosity (Pa·s)	4.6E-5
Brine residual saturation (/)	0.3
System compressibility (m^2/N)	4.6E-10

Scenario	Q_{inj} (kg/s)	Time (years)
S1	100	20
S2	50	40
S3	33.33	60





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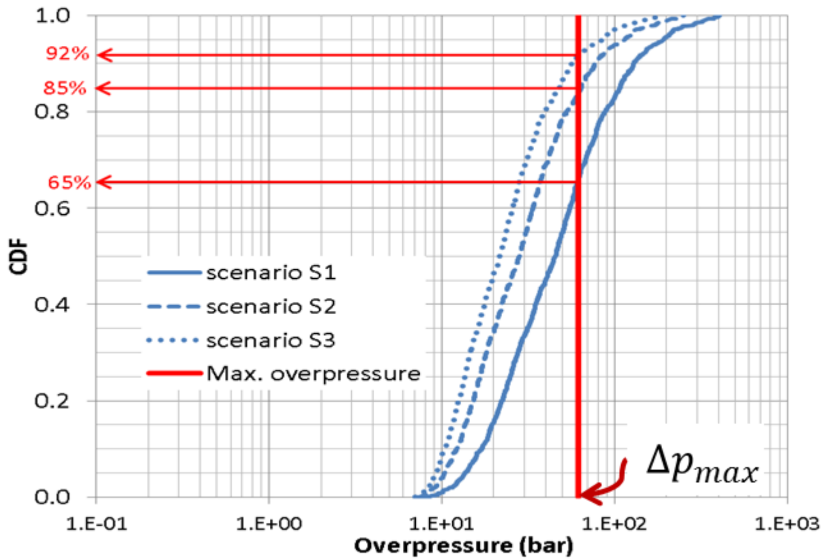
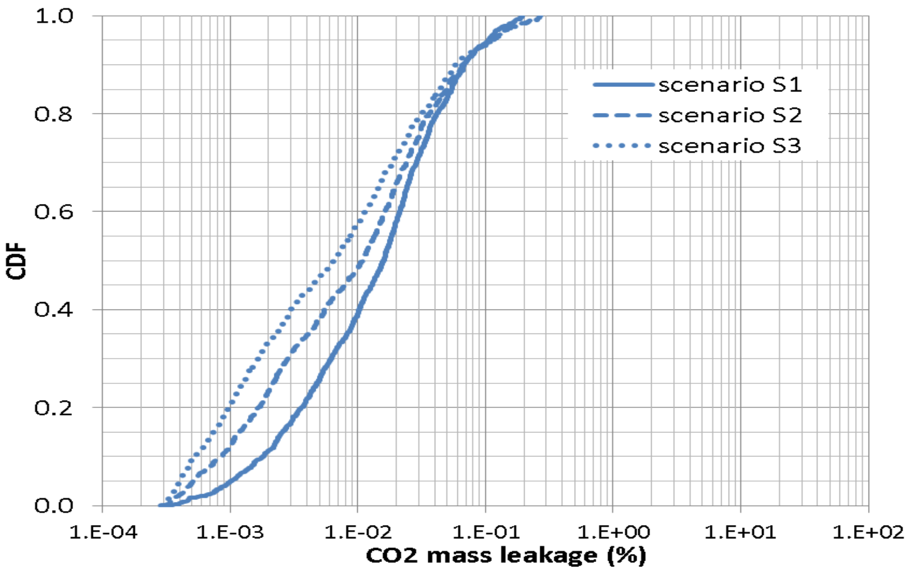
Technical Status

- Multiphase Flow Simulator
  - Stochastic Analysis: quantify effects on mass leakage and fluid overpressure of uncertainty in system parameters such as:
    - » Aquifer Permeability, Porosity, Leakage Pathway Permeability, System Compressibility

Cumulative Distribution Functions: k (m^2) ---» log(k) є N(-13,0.5)



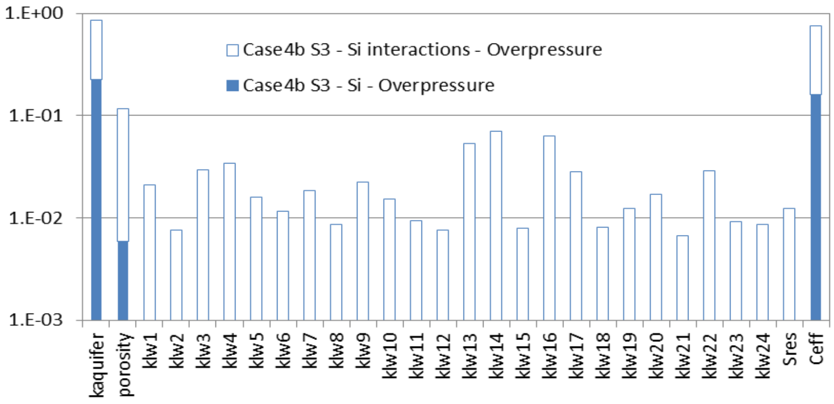


$\downarrow Q_{injection}$ - $\downarrow overpressure$ - $\downarrow leakage$

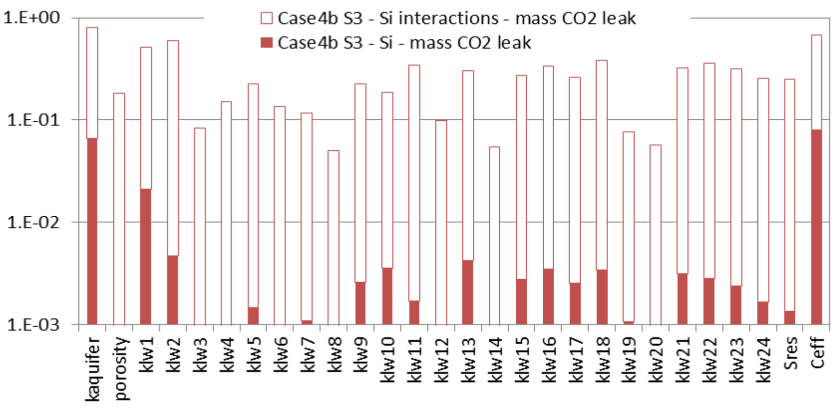
Technical Status

- Multiphase Flow Simulator
  - Sensitivity Analysis: Fourier Amplitude Sensitivity Test (FAST, Saltelli et al., 2000)

Influence on near-well overpressure



Influence on mass % CO_2 leakage



Technical Status

- Multi-Objective Optimization Formulation

Identify Injection Schemes that:

- **Objective 1**: Maximize {*CO_2 mass storage*}
- **Objective 2**: Minimize {*Total Cost*}

  » *Total Cost* = Installation Cost (N.wells)
  + Operation/Maintenance (CO_2 mass stored)
  + Leakage Recourse (CO_2 mass leaked)

Subject to **Constraints** on:

- CO_2 mass storage (minimum and maximum)
- Maximum CO_2 injection rates
- Maximum Fluid overpressure in proximity of Injection Units
- Number and Location of Candidate Wells

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Technical Status

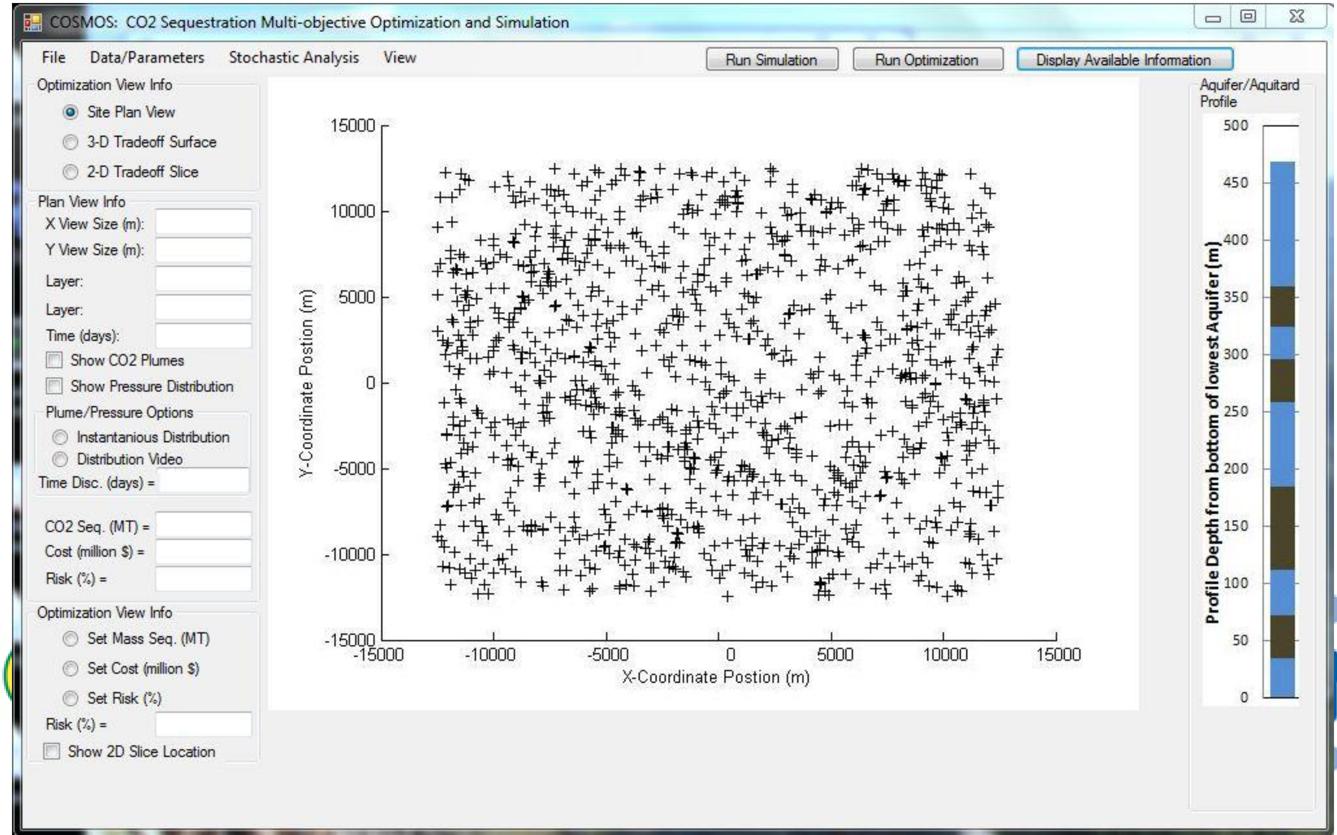
- Multi-Objective Optimization Formulation
  - Formulation is deterministic only for algorithm testing purposes
  - CO_2 mass leakage enters the CGS cost as a “penalty” to sustain, which is assumed to increase non linearly as leaked CO_2 mass increases.
  - This approach is suited to including cap-and-trade benefits, which can reduce cost.
  - In the solution to the two-objective constrained optimization problem, the flow simulator is required to estimate leaked CO_2 mass and fluid overpressure for each injection alternative being tested.

Technical Status

- Multi-Objective Optimization Algorithm
  - Non-dominated Sorting Genetic Algorithm-II (NSGA-II) (Deb, 2002)
    - » Based upon evolutionary optimization operators: natural selection, reproduction (crossover, mutation), and elitism
    - » Suited for mixed-integer problems with non-linear discontinuous objective functions and constraints
    - » Provides optimal or close-to-optimal Pareto sets
    - » Requires preliminary simulations for tuning optimization parameters
    - » Global optimization requires an elevated number of “calls” to the simulation model, which increases with the number of decision variables
    - » Computationally fast simulators are required (CO2FLOW)

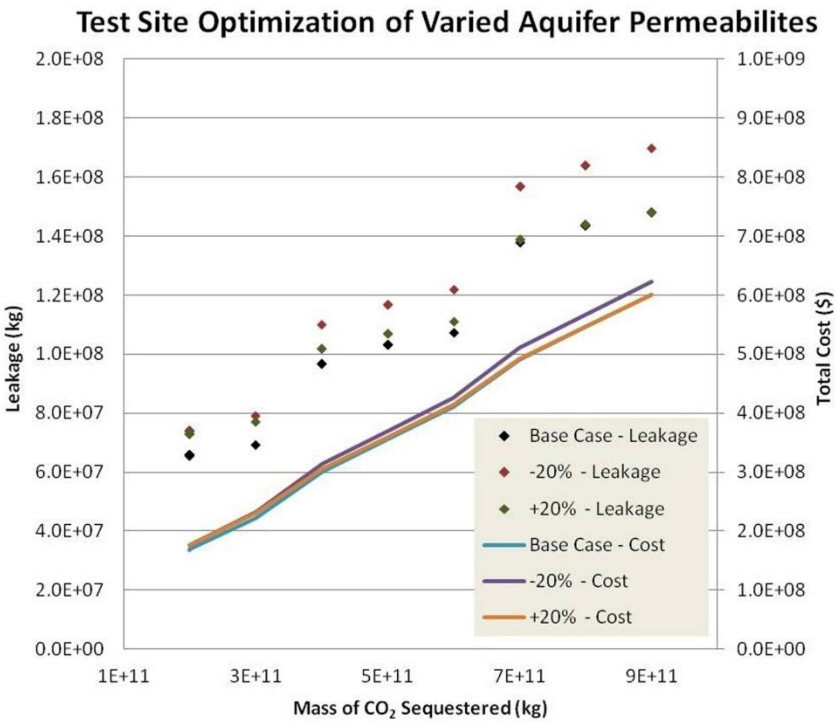
Technical Status

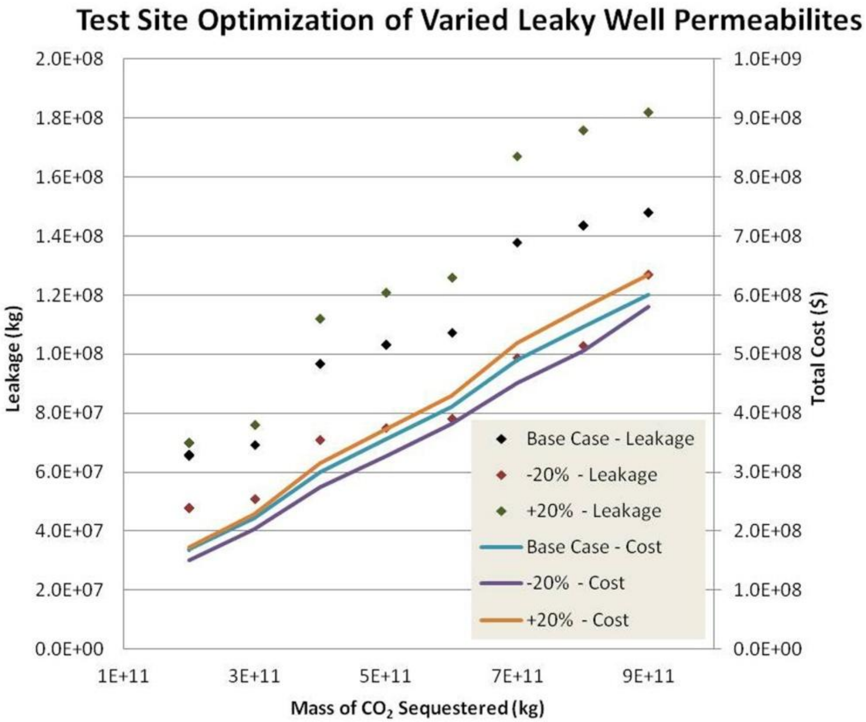
- CGS Multi-Objective Optimization
  - CO2FLOW + NSGA-II
  - Tradeoff “Pareto” Sets
  - Graphic Unit Interface (GUI) (being developed)



Technical Status

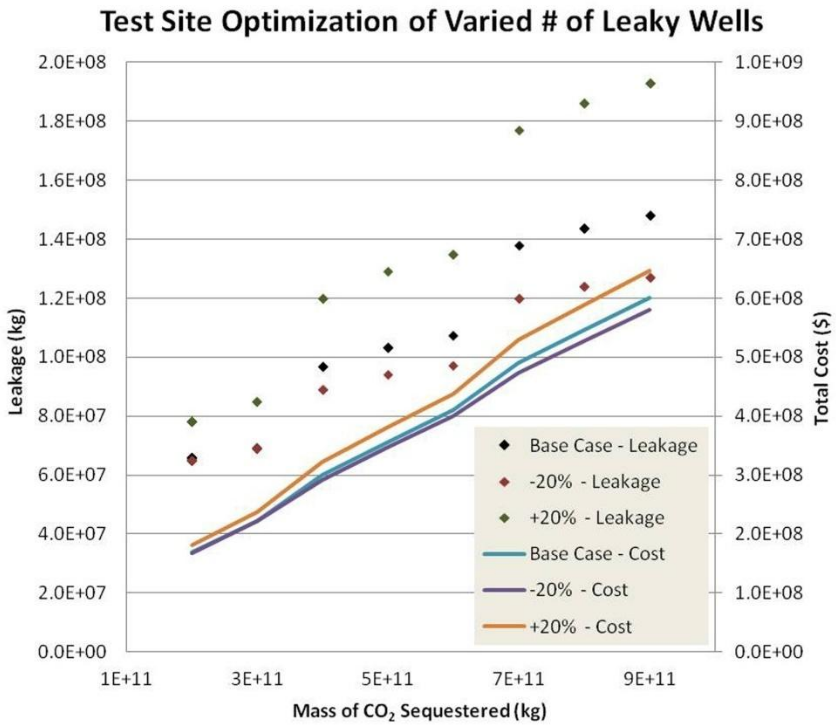
- CGS Multi-Objective Optimization
  - Example Tradeoff Pareto Sets

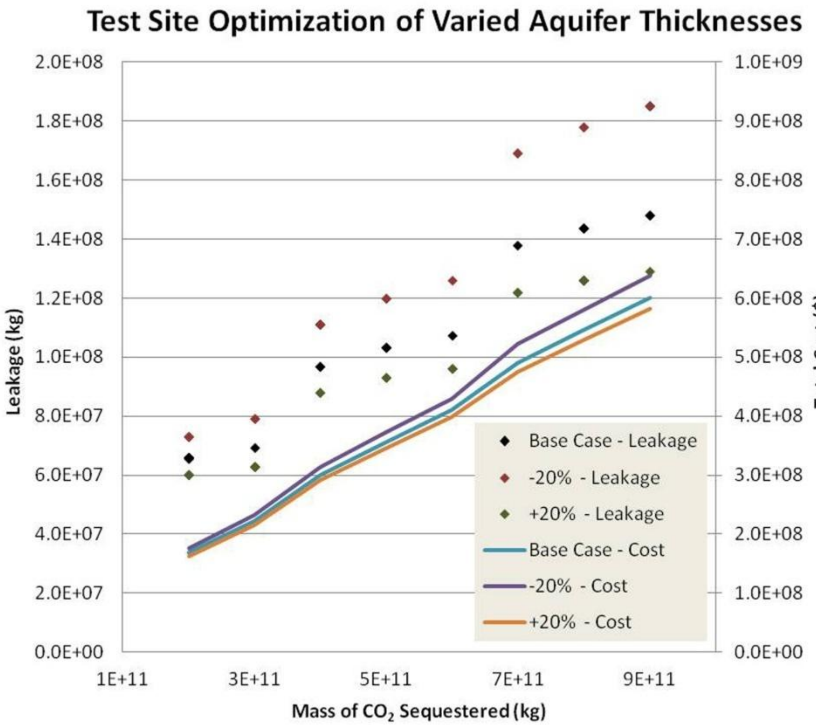




Technical Status

- CGS Multi-Objective Optimization
  - Example Tradeoff Pareto Sets





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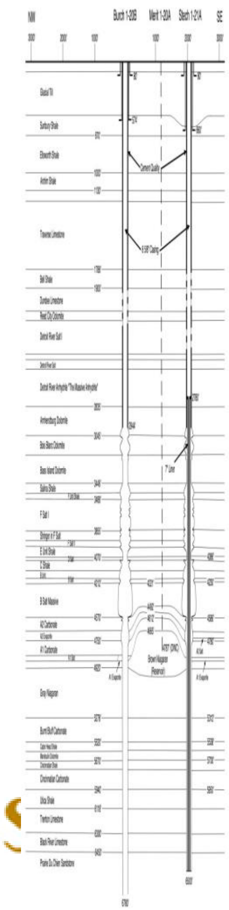
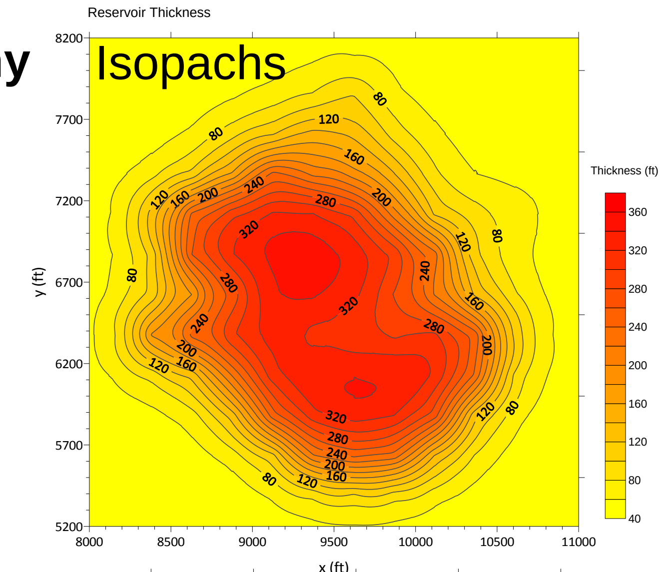
Technical Status

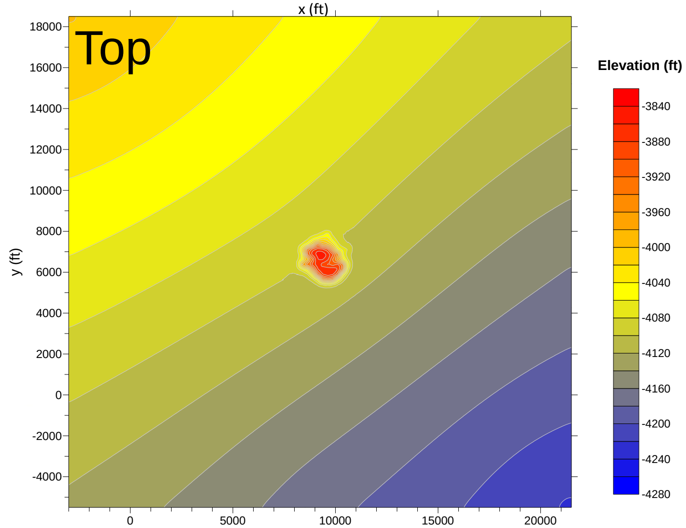
- Application to MTU Test site:

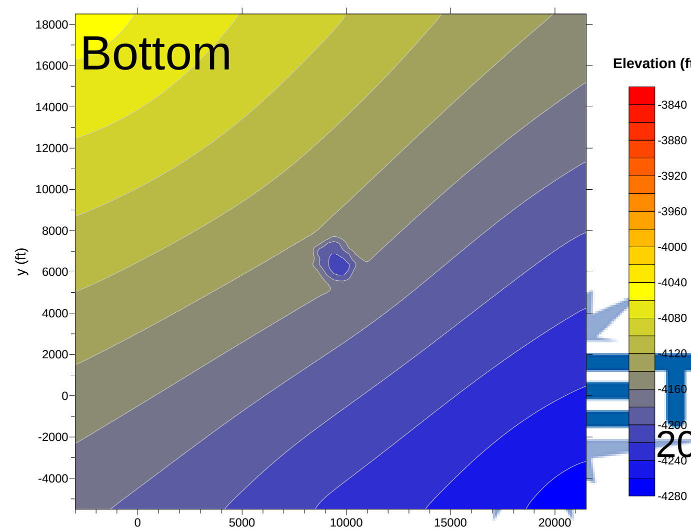
Stratigraphy





- Scarce data on lateral aquifer
- No information on caprock continuity outside the (depleted) reservoir
- Resort to geostatistical conceptual model approach to represent uncertainty



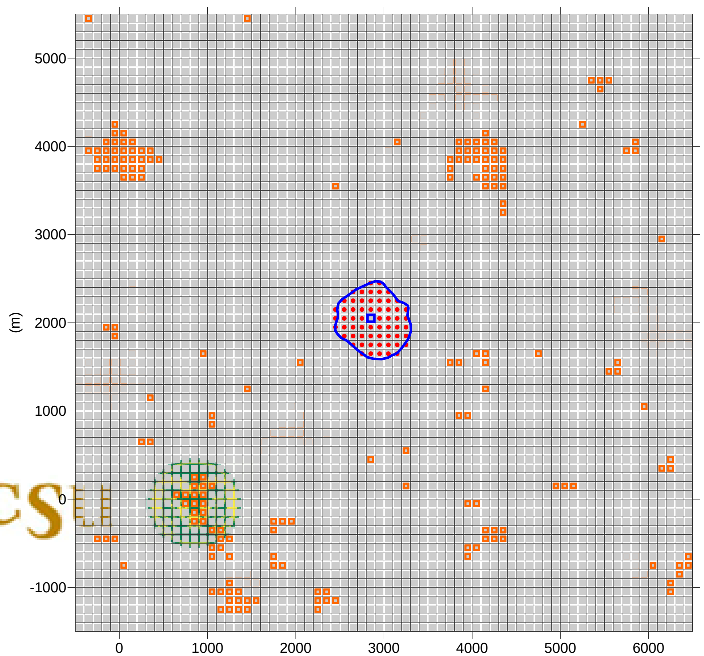


Technical Status

- Application to MTU Test site:
  - Developed *Ad Hoc* Categorical Indicator Kriging Simulation Algorithm (CIKSIM)
  - Generate Equally likely Realizations of Leakage Pathways based upon a prescribed spatial stationary covariance model

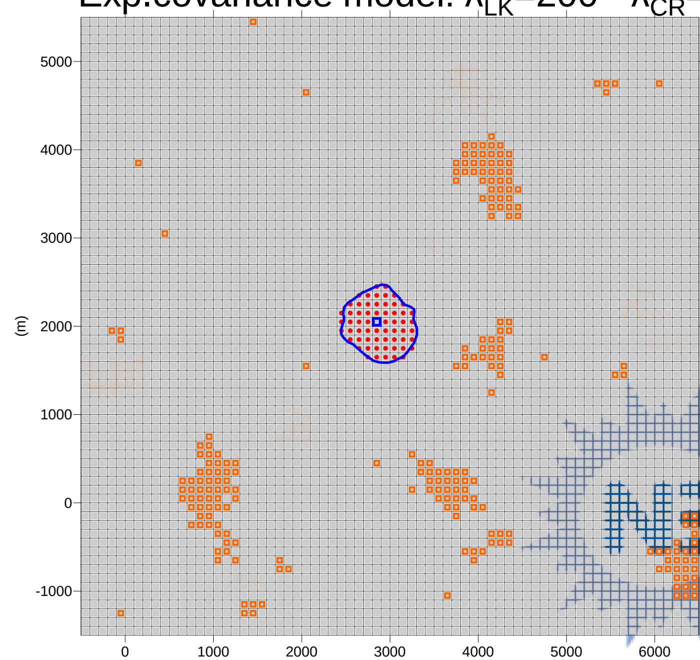
Example 1

- Bi-modal PDF: P_{LK}=0.03; P_{LK}=0.97
- Exp.covariance model: λ_{LK}=100 - λ_{CR}=1000.



Example 2

- Bi-modal PDF: P_{LK}=0.03; P_{LK}=0.97
- Exp.covariance model: λ_{LK}=200 - λ_{CR}=1000.



Accomplishments to Date

- Training of Two PhD Students Completed
- Implemented Multi-phase Semi-Analytical Flow Model
- Performed Stochastic-Sensitivity Analysis to Identify Key Parameters Affective Safety of Geological Carbon Sequestration
- Developed Multi-Objective Optimization Based Planning Framework based upon CO2FLOW and NSGA-II
- Collected and Assimilated MTU test site data
- Developed Categorical Indicator Kriging Simulation Algorithm to Model Geostatistically Cap Rock Continuity at MTU Test site

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Summary

– Lessons Learned

- Scoping calculations and optimal planning of large scale CGS is possible only by using computationally efficient brine-CO_2 flow models.
- Key Parameters affecting storage safety features are the formation permeability, its compressibility, the location and the conductivity of CO_2 escape pathways

Summary

– Future Plans

- Complete development of multi-objective framework including uncertainty in model parameters and leakage pathways characteristics
- Development of GUI for preliminary CGS design calculation and identification of “Pareto-optimal” injection alternatives
- Application to MTU test site
- Submit results to peer-review journals
- Students successfully graduate.

Appendix

Organization Chart

- Project participants:
  - Dr. Domenico[1] Baù (PI)
  - Brent M. Cody[1], M.Sc. (Ph.D. student)
  - Ana Gonzalez-Nicolas[1], M.Sc. (Ph.D. student)

[1] Colorado State University, Dept. of Civil and Environmental Engineering

- Program Officer: Robert Vagnetti, DOE-NETL

Gantt Chart

Task	**Description**	**Project Duration: Start: 12/01/2009; End: 11/30/2012.**													
		Year 1				Year 2				Year 3				Year 4	No-Cost Extention
		Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**End**
		12/09	1/10	4/10	7/10	10/10	1/11	4/11	7/11	10/10	1/11	4/11	7/11	10/12	5/12
1	*Project Management Plan*														
2.1	*Student Selection*														
2.2	*Students training on MFLOW3D*														
3.1	*Collection of MTU Test-Site Data*														
3.2	*Assimilation of MTU Test-Site Data*														
4.1	*CCS Multi-objective framework*														
4.2	*Application to the MTU test site*														

Bibliography

– Brent Cody, Ana Gonzalez-Nicolas, Domenico Baù (2013), Stochastic Multi-Objective Optimization for the Design of Carbon Geological Sequestration Systems , In preparation.

– Ana González-Nicolás, Brent Cody, Domenico Baù (2013), Stochastic Sensitivity analysis of factors affecting the leakage of CO2 from injected geological basins, In preparation.

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