

Large-Scale Hydrological Impacts of CO₂ Storage: Basin-Scale Simulations and Pressure Management

ESD09-056

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the
Infrastructure for CO₂ Storage

August 21-23, 2012

Presentation Outline



❖ Benefit to the Program

❖ Project Overview

❖ Technical Status

➤ Task 1:

Develop basin- and local-scale high-performance simulation models for evaluation of storage capacity, brine displacement, and groundwater impact in the Northern Plains – Prairie Basal Aquifer

➤ Task 2:

Develop and test “Impact-Driven Pressure Management” (IDPM) via optimized brine extraction to enhance storage capacity and mitigate other issues related to large-scale pressure increases

❖ Accomplishments to Date

❖ Project Summary

❖ Appendix (Gantt Chart, Bibliography)

Benefit to the Program



- ❖ Both tasks provide methodology that supports industries' ability to predict (or control) CO₂ storage capacity in geologic formations to within ± 30 percent
- ❖ Task 1 applies new simulation capabilities to evaluate dynamic storage capacity for one of the largest CO₂ storage reservoirs in North America
- ❖ Task 2 develops optimization methods, and associated simulation tools, to design pressure management options at minimum cost for brine extraction and disposition

Issues Related to Pressure Buildup

Pressure Buildup and Brine Displacement

Caprock Damage

Induced Seismicity

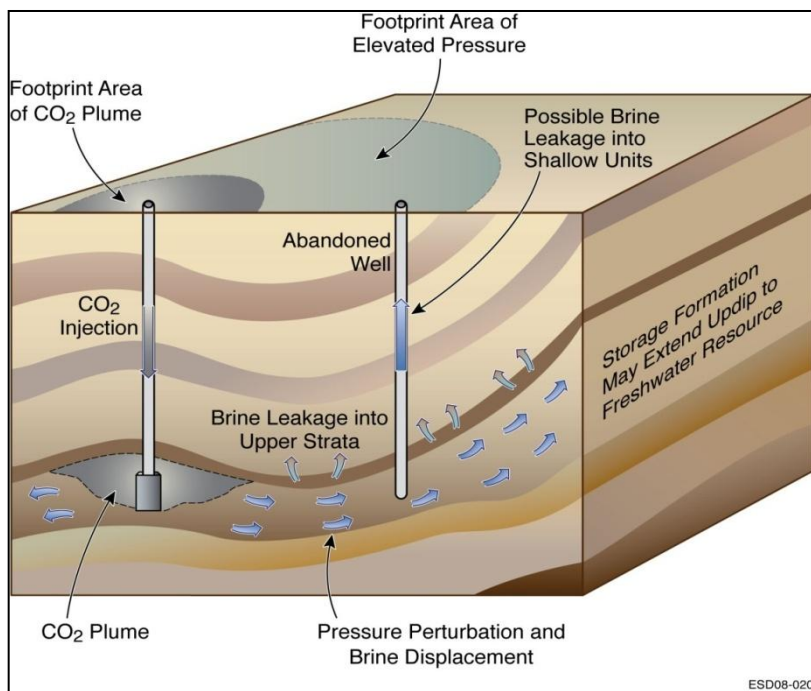
Brine Leakage

Interference Between Storage Sites

Effect on Other Georesources

Permitting and AoR

Reduced Storage Capacity



Task 1: Predictive Tools and Impact Assessment
Task 2: Mitigation via Pressure Management

Task 1. Northern Plains – Prairie Basal Aquifer Project: Modeling and Comparison



- ❖ The Northern Plains – Prairie Basal Aquifer system, extending over nearly 575,000 square miles of the north-central United States and south-central Canada, is considered a very important target for CO₂ storage in North America.
- ❖ A bi-national Canada-USA multi-organizational consortium, led by Alberta Innovates – Technology Futures (AITF) in Edmonton for the Canadian side and the Energy and Environmental Research Center (EERC) in North Dakota for the US side, started a three-year project in FY11 to characterize the saline formation, evaluate its storage potential, and assess environmental impacts
- ❖ LBNL is part of this consortium responsible for development/application of a high-performance basin-scale simulation model to determine the dynamic storage capacity and possible environmental impact of CO₂ storage on resident brine and shallow groundwater resources in areas of aquifer outcrop in Manitoba, South Dakota and Montana.
- ❖ LBNL's modeling work started in late 2011, after CO₂ source evaluation and hydrogeological aquifer characterization performed by the other consortium partners were made available.



Work Plan for Task 1



✓ Basin- and Local-Scale Model Development:

- ✓ Determine the appropriate model domain, including the target and overlying formations, based on scoping simulations
- ✓ Develop a basin-scale model grid with adequate far-field boundaries and local refinement around projected plumes on the basis of the geologic model provided by EERC and AITF
- ✓ Parameterize the model based on existing well data and other geologic and hydrologic information, and constrain the large-scale model parameters
- ✓ Develop a set of potential future injection and storage scenarios:
 - ✓ Low, medium, and high injection rates,
 - ✓ Different injection rates in subregions of the Basal Aquifer,
 - ✓ Staged implementation of CO₂ storage in the region with early and late projects

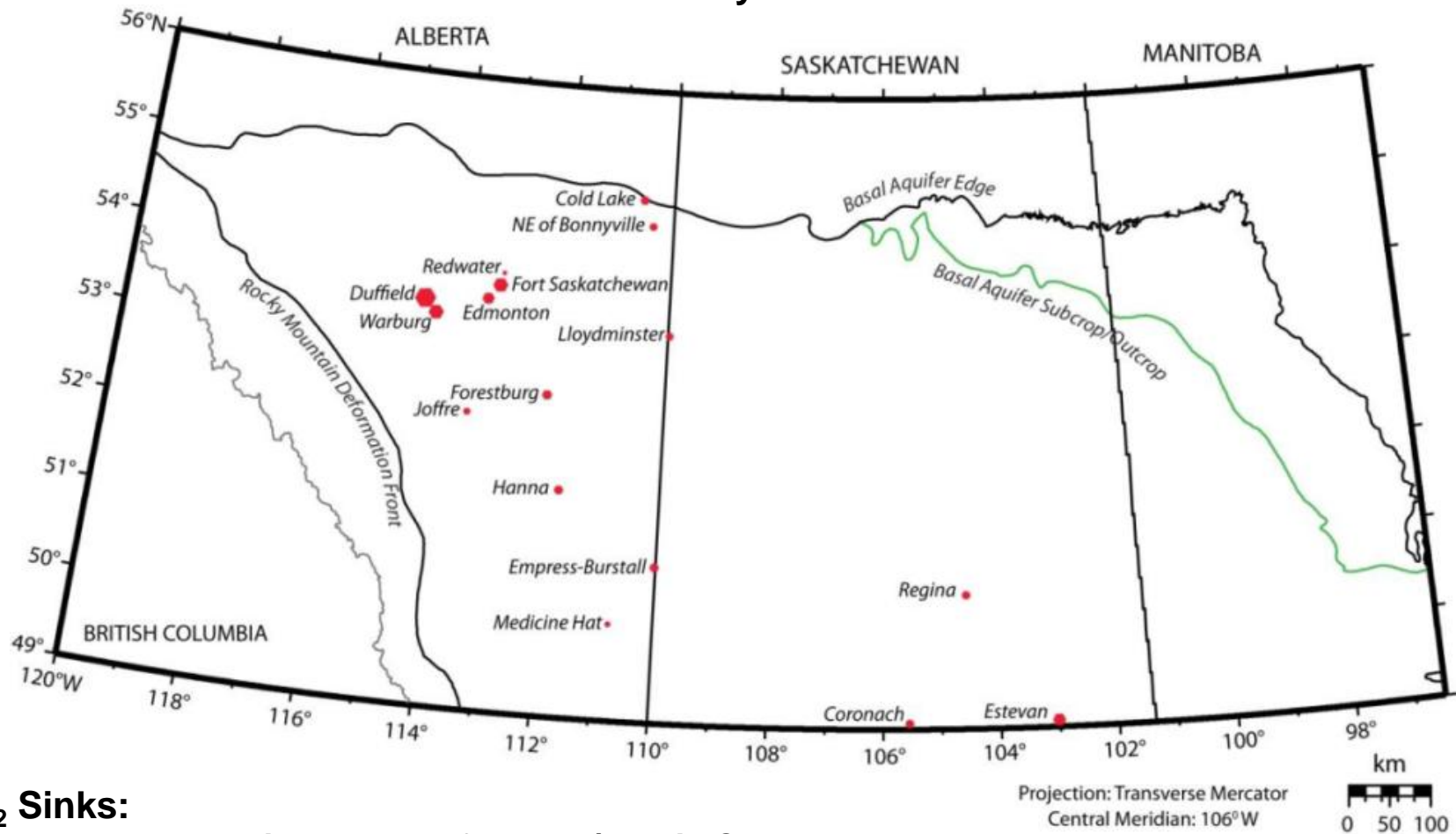
❖ Model Application

- For each storage scenario, conduct simulations with the high-performance TOUGH2/ECO2N simulator to:
 - Determine the distribution, migration, and long-term fate of multiple CO₂ plumes corresponding to large CO₂ sources in the region
 - Evaluate the pressure perturbation and brine migration effect at the basin scale, including the interference between individual storage projects
 - Assess the dynamic storage capacity of the aquifer based on the predicted pressure build-up and brine migration results
- Compare predictions from our regional-scale model with simplified semi-analytical solutions developed by other consortium partners, e.g., the Princeton University Group
- Perform sensitivity simulations to assess model uncertainty

Basal Aquifer – Canadian Part: CO₂ Sources



CO₂ Emissions (> 1 Mt/year) in Canada with a total of 75 Mt/year at 16 locations



CO₂ Sinks:

- 11 areal clusters with storage of 75.1 Mt/year in Canada
- 5 areal clusters for storage of 29.3 Mt/year in United States

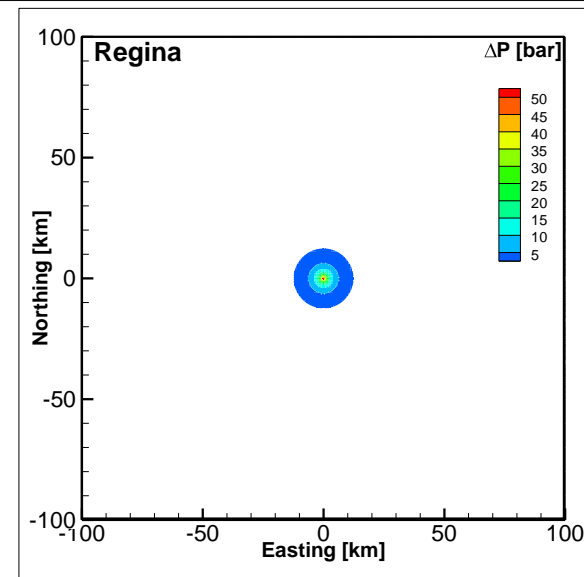
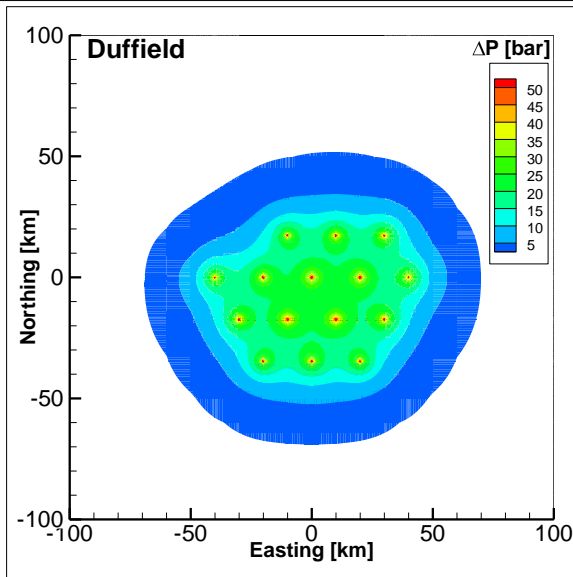
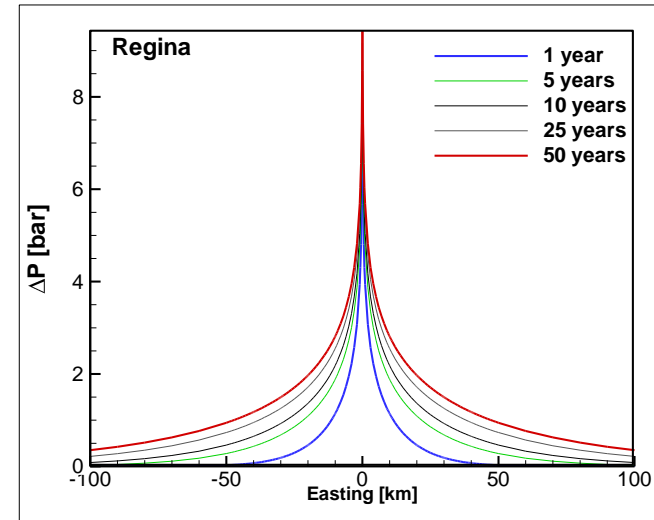
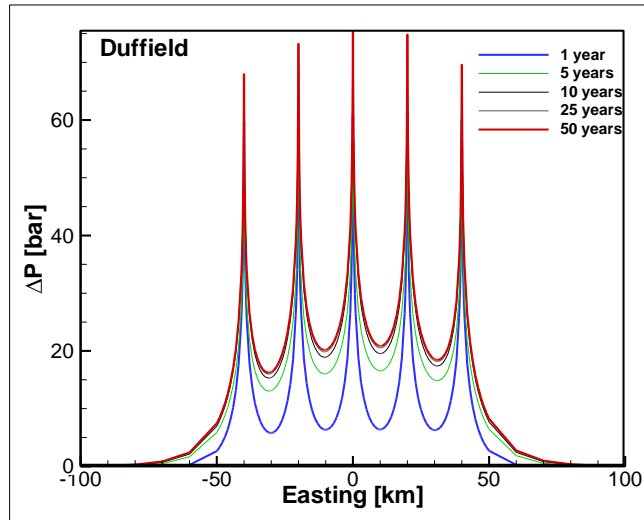
CO₂ Storage Volumes Per Cluster



Location	CO ₂ Mt/y	no. of Injection wells	porosity [%]	permeability [mD]	specific storativity [1/m]	thickness [m]	depth [m]
Cold Lake - Bonnyville, AB	8.3	6	18	1000	1.44 10 ⁻⁶	80	1259
Shell Quest Radway, AB	1.2	1	14.5	500	1.18575 10 ⁻⁶	42	2013
Edmonton - Redwater, AB	9.7	6	12.8	500	9.796 10 ⁻⁷	77	2055
Duffield, AB	23	15	7	100	6.1919 10⁻⁷	36	2964
Lloydminster, SK	2.1	1	22	500	1.76282 10 ⁻⁶	109	1578
Joffre - Forestburg AB	7.1	5	7.5	35	6.65442 10 ⁻⁶	67	2673
Hanna, AB	4.4	3	10	50	8.4366 10 ⁻⁷	48	2427
Regina, SK	1.7	1	14	1000	1.14816 10⁻⁶	48	2235
Medicine Hat - Empress, AB	5.2	3	8	750	8.19331 10 ⁻⁷	142	2010
Estevan, SK	8.6	6	6	50	5.32565 10 ⁻⁷	59	2719
Coronach, SK	3.8	3	5.5	50	4.58578 10 ⁻⁷	75	2667
total	75.1	50	-	-	-	-	-

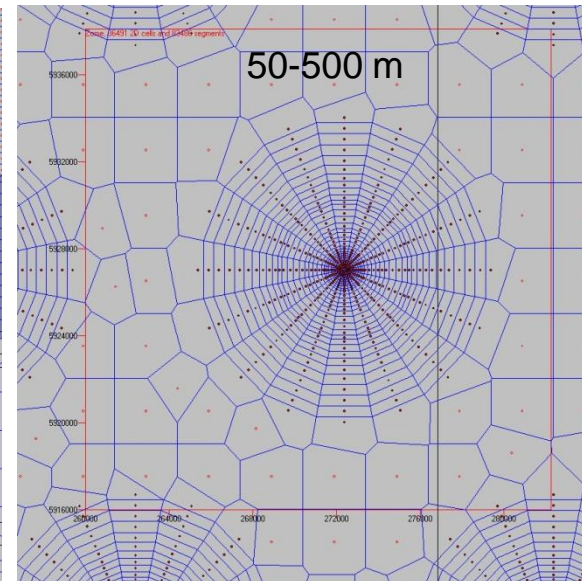
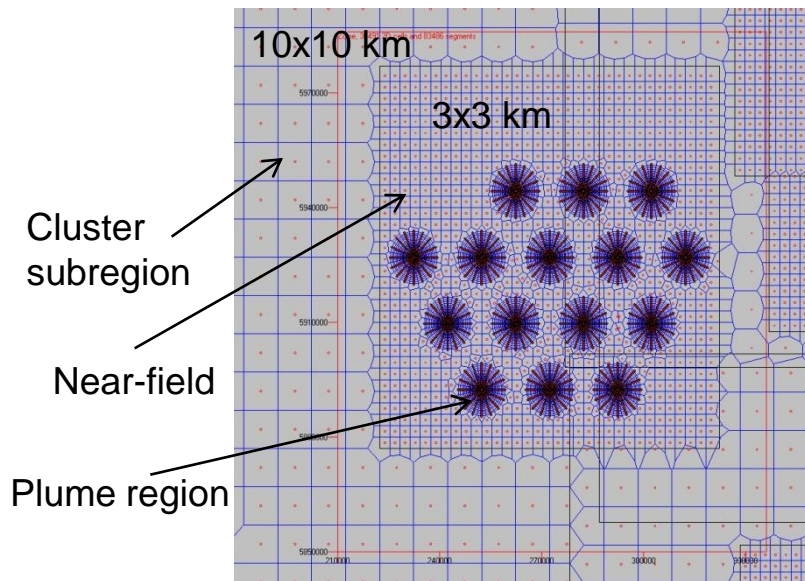
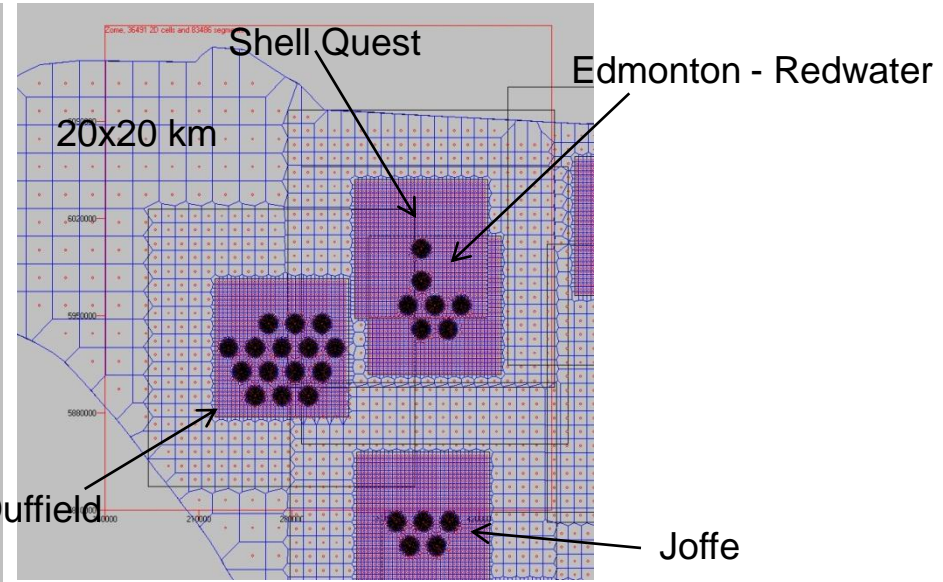
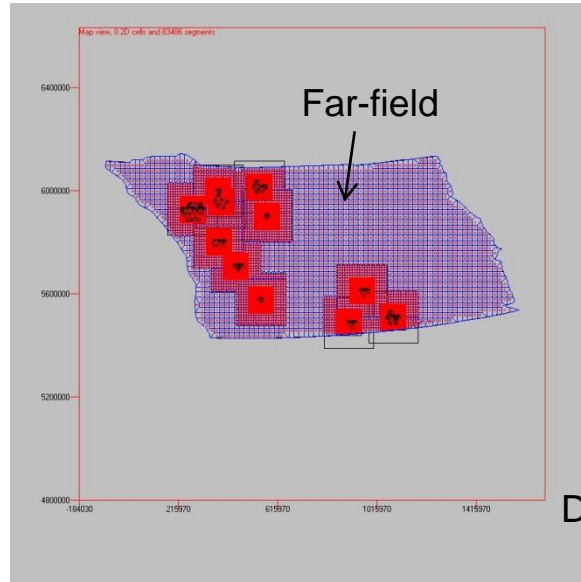
Pressure Screening

Using analytical solution described in Cihan et al. (2011)



The single-phase solution considers both the storage formation and the overlying aquifer, as well as aquitards for pressure attenuation. Superposition is used for multi-well injection.

Numerical Grid for High-Performance Multi-Phase Simulations



Task 2. Impact-Driven Pressure Management (IDPM) Via Optimized Brine Extraction

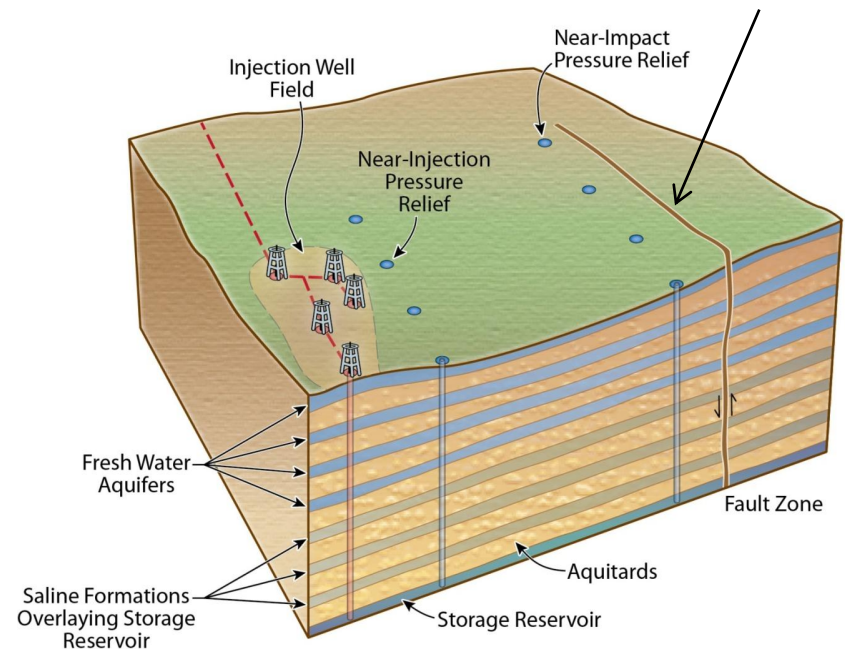
❖ IDPM Goal

- Conduct pressure management with minimal brine extraction volumes while meeting desired pressure reduction goals (as well as other reservoir performance goals)
- Minimize need for infrastructure, pumping, transportation, and surface disposal

❖ IDPM Approach

- Define specific (local) performance criteria (e.g., maximum pressure increase near fault zone)
- Automatically optimize extraction rates and well locations to meet performance criteria
- Evaluate suitability of passive pressure relief wells
- Investigate feasibility of brine transfer into overlying/underlying formation

Example: Critically stressed fault

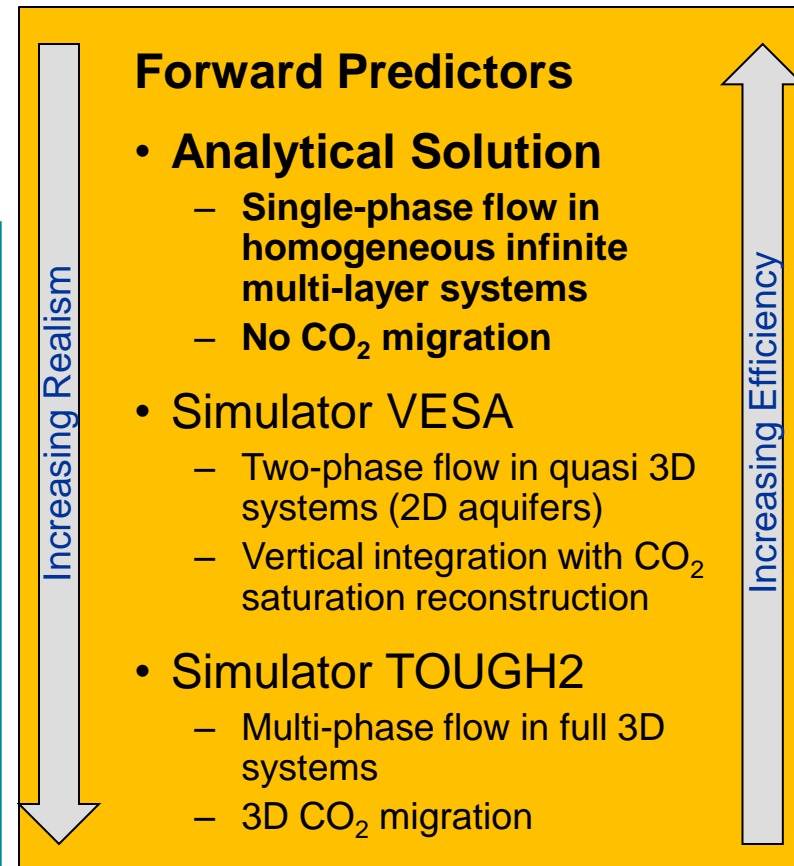
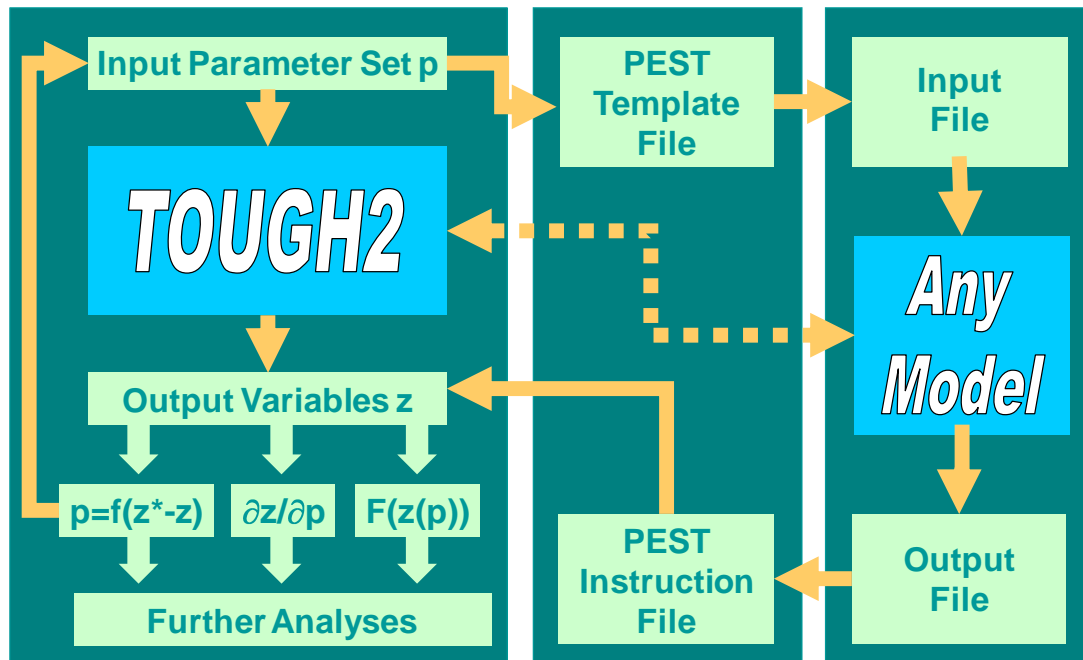


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Automatic Optimization Using Inverse Modeling Code iTOUGH2



- Use iTOUGH2 inverse modeling and optimization code with PEST interface for model-independent optimization
- Develop modular optimization framework that has alternative forward prediction tools ranging from simple analytical solutions to full multi-physics models (most example studies shown here use an analytical solution for single-phase pressure)



Work Plan for Task 2



✓ IDPM Methodology Development

- ✓ Develop inverse modeling and optimization methodology using iTOUGH2 coupled to analytical solution for simplified proof-of-concept studies
- Incorporate higher-fidelity simulators such as VESA and TOUGH2 into optimization framework for complex applications
- Improve optimization efficiency for well placement scenarios coupling global and gradient-based methods

✓ Proof-of-Concept Studies

- ✓ Single and multiple performance criteria
- ✓ Active pumping with optimization as well as passive relief
- ✓ Given well locations as well as optimized well placement
- ✓ Transfer of extracted brine surface versus transfer into other formations
- ✓ Post-optimization simulations to assess CO₂ breakthrough

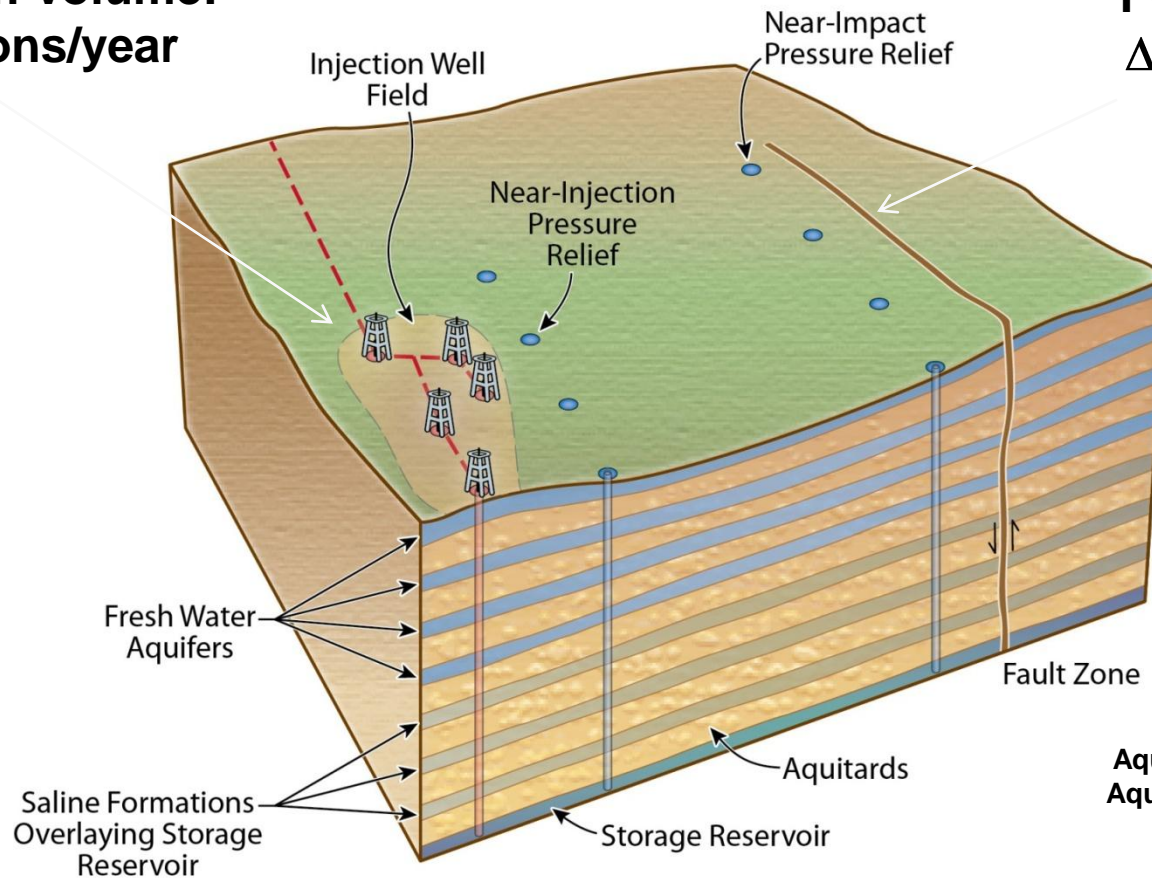
❖ Application to More Complex and Realistic Scenarios

- Direct optimization with VESA and TOUGH2 to handle more complexity (e.g., complex geology, heterogeneity, boundary conditions, CO₂ breakthrough)
- IDPM optimization of one real CO₂ sequestration site

Example Applications for Proof-of-Concept Studies

**CO₂ Injection Volume:
5 million tons/year**

**Performance Criterion
 $\Delta h < 40$ m along fault
at 20 km distance**



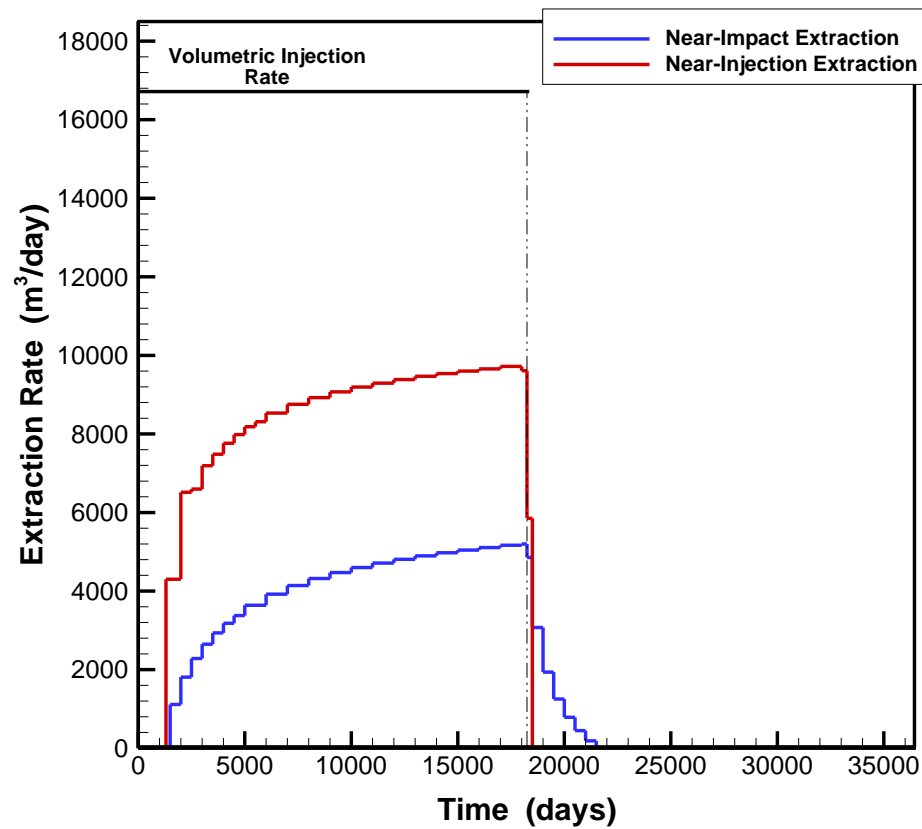
**Aquifer Permeability: 300 millidarcy
Aquitard Permeability: 1 microdarcy**

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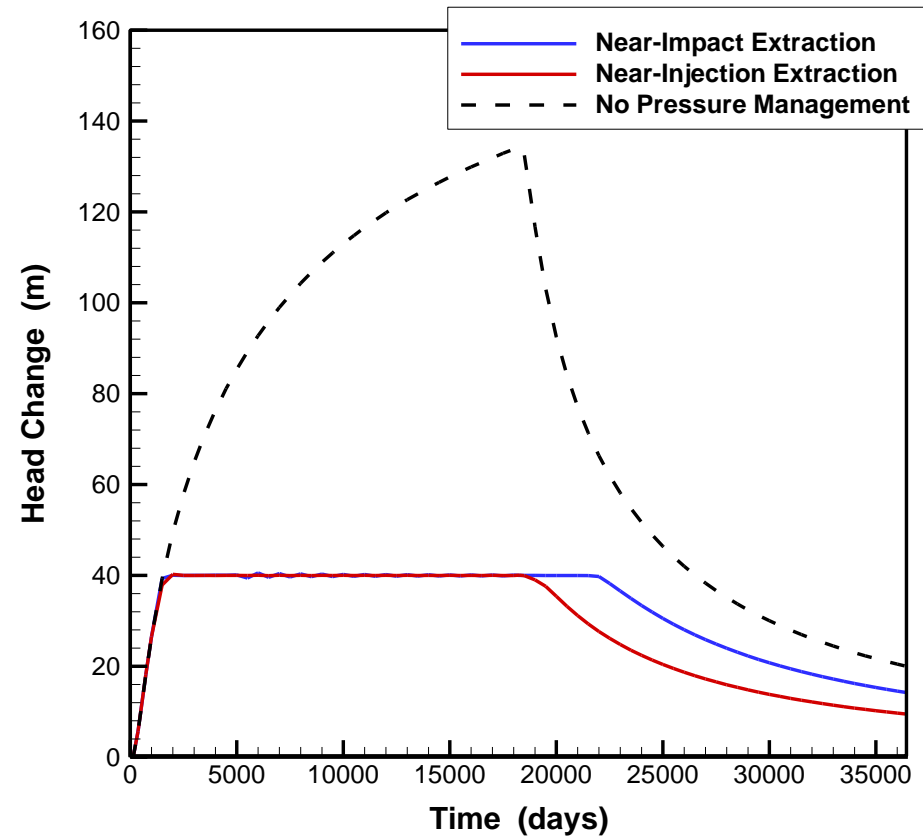
Active Extraction for Fixed Well Location (Optimized Pumping)



Comparison between near-impact and near-injection arrays. Pumping rates are optimized in a step-wise manner with iTOUGH2 inversion using Levenberg-Marquardt algorithm.



Pumping Rate

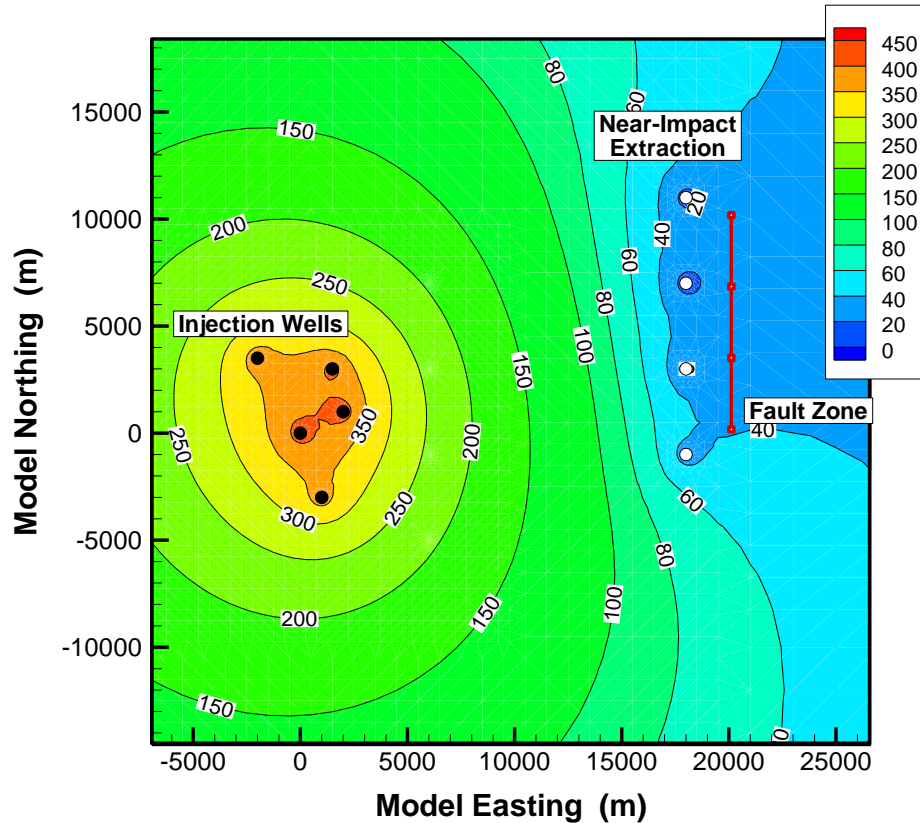


Head Change in Fault

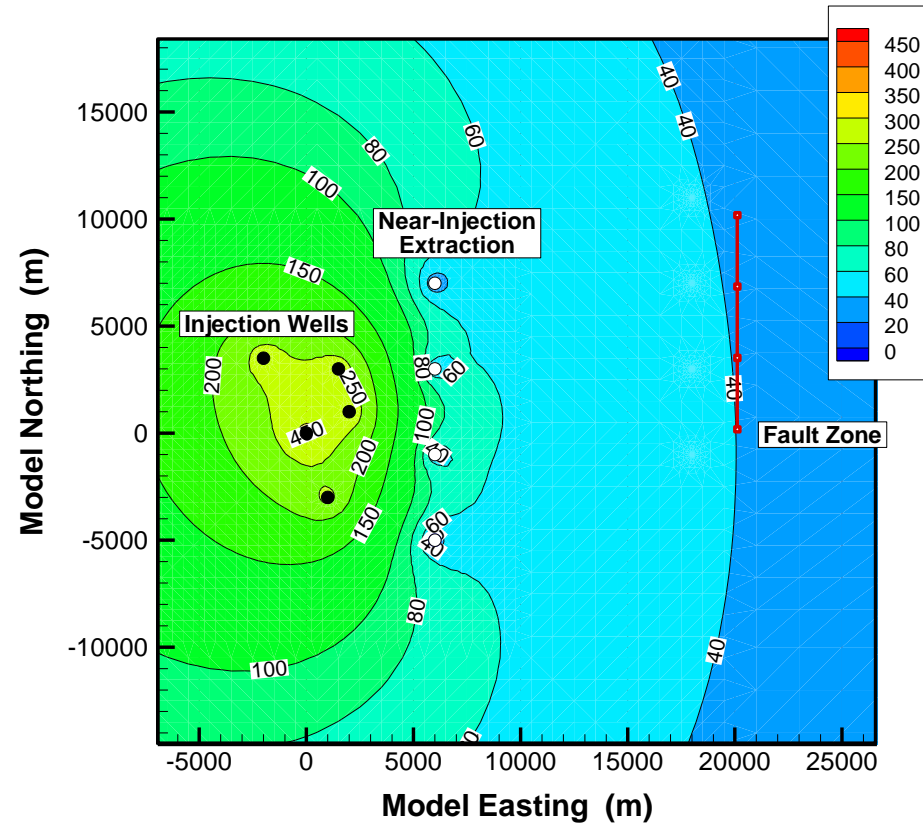
Active Extraction for Fixed Well Location (Optimized Pumping)



Head Change in storage reservoir after 50 years of injection



Near-Impact Active Extraction

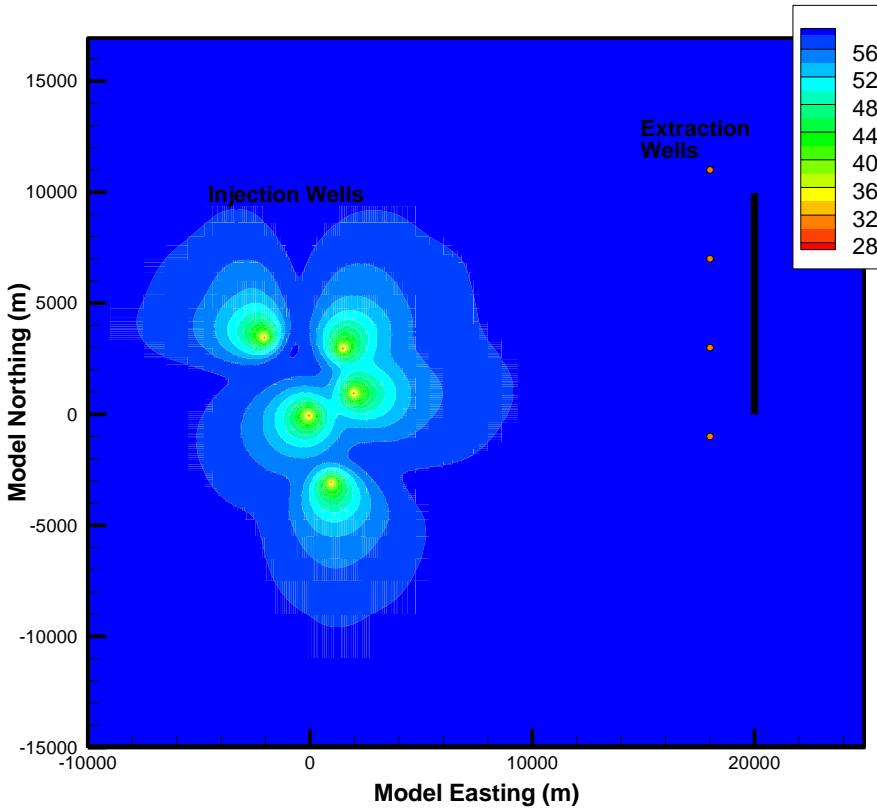


Near-Injection Active Extraction

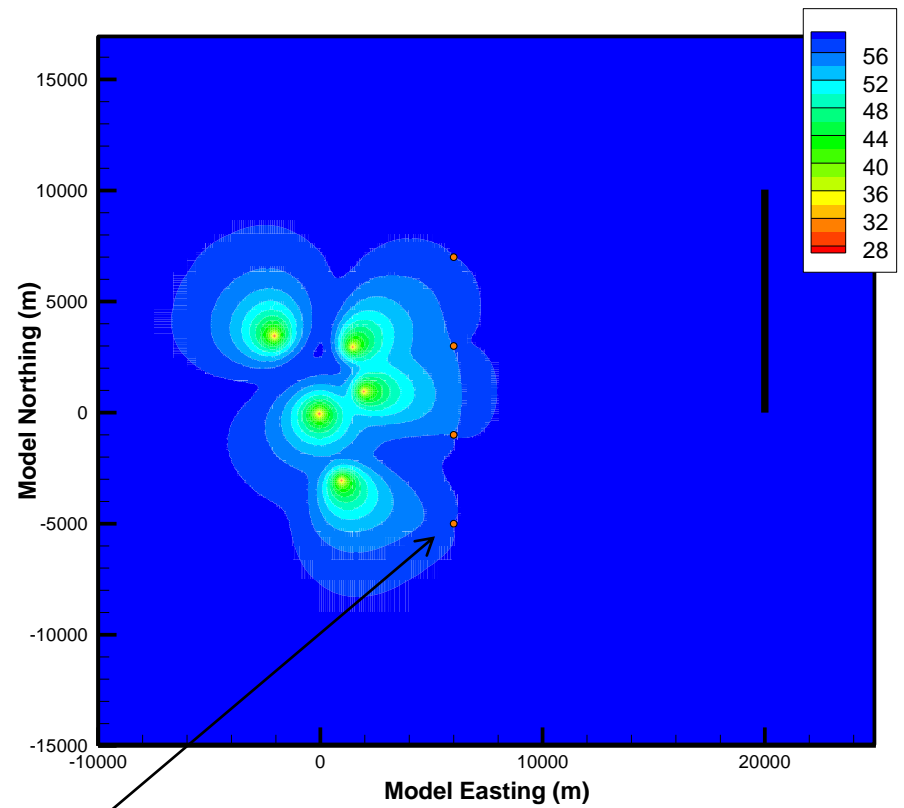
Testing of CO₂ Breakthrough Using Sharp-Interface Model



Distance to CO₂/Brine Interface from Bottom of a 60m-Aquifer at 50 Years



Near-Impact Active Extraction



Near-Injection Active Extraction

Additional studies show that partially-penetrating wells screened below the phase CO₂ can prevent breakthrough during brine extraction

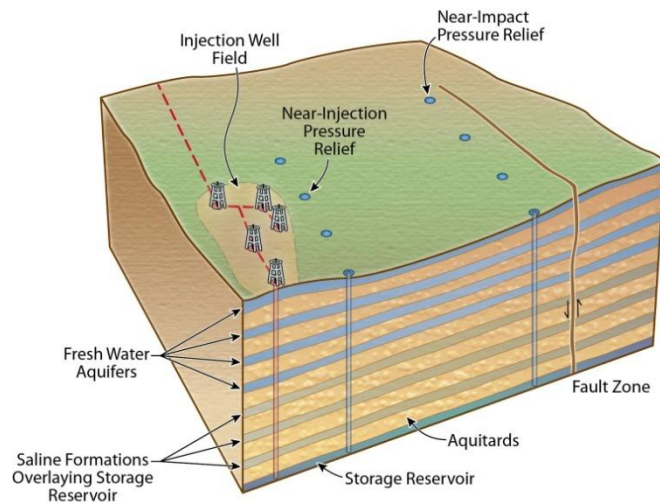
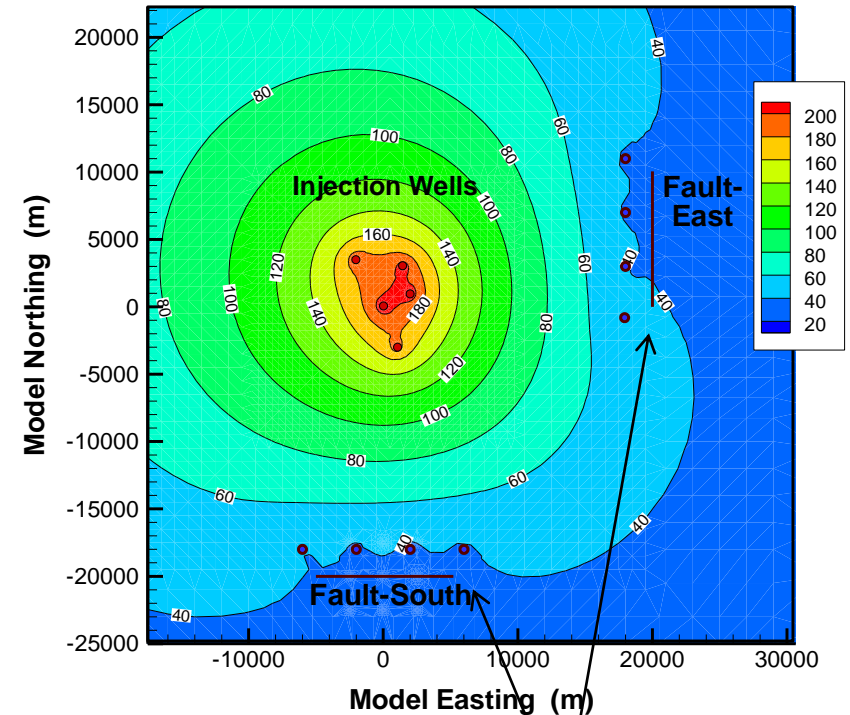
Comparison of Pumping Rates



Pressure Management Scenario	Performance Objective	Total Brine Volume Pumped to the Surface	Percentage of Injected Fluid Volume (Extraction Ratio)
Active with Near-Injection Wells	One Fault	148.0 million	48.5 %
Active with Near-Impact Wells	One Fault	70.9 million	23.2 %
Active with Passive Extraction	One Fault	36.3 million	11.9 %
Active with Near-Injection Wells	Two Faults	140.8 million	46.1 %
Active with Well Placement Optimization	Two Faults	109.8 million	36.0 %

Optimization Problems with Multiple Performance Criteria

- 1) Optimization of pumping rate for a case with two critically stressed faults
- 2) Optimization of pumping rate AND well placement for a case with two critically stressed faults



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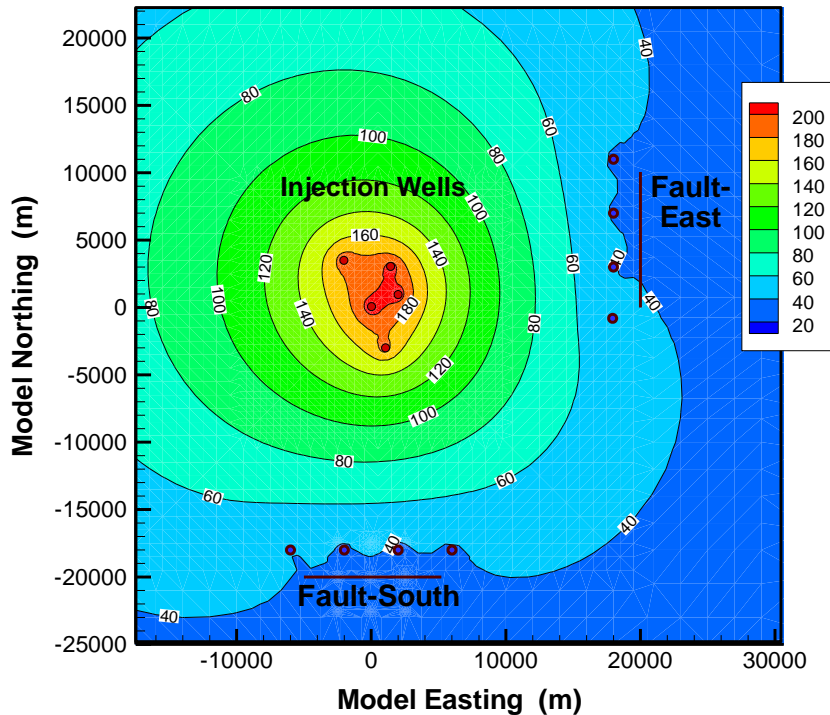
All cases assume active pumping to the surface.

Optimization of Well Placement and Pumping Rate

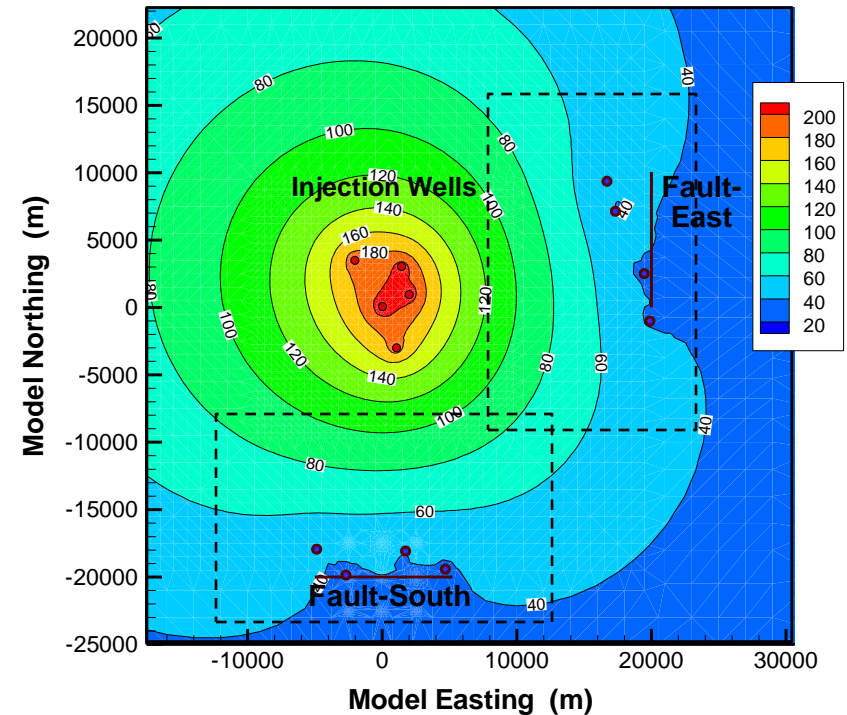


Well placement optimization is based on minimizing total extracted brine volume. The search starts with a given number of wells and initial placement, and then searches for better solutions within a defined area.

Fixed Well Location



Optimized Well Placement



Head Change at 50 Years

Comparison of Pumping Rates



Pressure Management Scenario	Performance Objective	Total Brine Volume Pumped to the Surface	Percentage of Injected Fluid Volume (Extraction Ratio)
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❖ Task 1: Basin- and Local-Scale Simulation Models

- Developed hydrogeologic model of the Northern Plains – Prairie Basal Aquifer in close collaboration with project partners
- Developed storage scenarios with 16 clusters of injection wells by CO₂ source-sink mapping and screening modeling
- Developed a 3D numerical model for a very large region, using unstructured gridding with local refinement for CO₂ plumes

❖ Task 2: Pressure Management Via Brine Extraction

- Developed and applied “Impact-Driven Pressure Management” (IDPM) as an optimization method that minimizes brine extraction volumes while meeting defined reservoir management targets
- Developed automated optimization framework for IDPM based on iTOUGH2-PEST alternatively coupled to a multi-layer analytical solution

❖ Task 1: Key Findings and Future Plans

- Work conducted so far suggests that high-performance simulators can successfully handle a very large-scale model domain with unstructured gridding and local refinement
- The high-fidelity model will be applied to assess dynamic storage capacity and environmental impact of several storage scenarios in the Northern Plains – Prairie Basal Aquifer
- Comparison with simpler models will provide guidance on model selection for future projects

❖ Task 2: Key Findings and Future Plans

- Pressure management via optimized brine extraction allows for significant reduction in brine extraction volumes if pressure is a concern at local targets with known locations (i.e., critically stressed fault, distant oil and gas field, other CO₂ storage projects)
- The methodology, if successfully demonstrated for more complex scenarios, can be a useful planning and design tool for CO₂ storage projects where pressurization is a concern
- Next steps are applications to more complex scenarios and a real sequestration site

Appendix: Gantt Chart for FY12 and FY13



Year Quarter	FY12				FY13			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Basin-Scale and Local-Scale Simulation Models								
Basin-scale model - development phase: Data collection and integration plan	A							
Basin-scale model - development phase: Basin-scale model setup			B					
Basin-scale model - application phase: Assess dynamic storage capacity						E		
Basin-scale model - application phase: Assess pressure buildup and environmental impact for a variety of realistic scenarios								F
Task 2: Evaluate Pressure Management Schemes via Brine Extraction								
Develop and apply automated optimization method to optimize IDPM options for: Simplified sequestration scenarios		C						
and apply automated optimization method to optimize IDPM options for: Complex sequestration scenarios				D				
Develop and apply automated global optimization methods to optimize IDPM options for heterogeneous systems and variable well locations						G		
Design and optimize IDPM options for a real field site								H

Appendix: Milestone Log for FY12 and FY13



Milestone A (Task 1), Q1 (12/31/11)

Title: Develop data collection and integration plan (including data formats and schedule) for model inputs to be provided by EERC and AITF

Milestone B (Task 1), Q3 (6/30/12)

Title: Finalize setup of basin-scale simulation model including model domain, boundaries, and grid development

Milestone C (Task 2), Q2 (3/31/12)

Title: Develop and apply automated inverse modeling method (such as iTOUGH2) coupled to an analytical solution to design and optimize IDPM options for simplified sequestration scenarios

Milestone D (Task 2), Q4 (9/30/12)

Title: Develop and apply automated inverse modeling method (such as iTOUGH2) coupled to a multi-phase numerical simulation model to design and optimize IDPM options for complex scenarios

Milestones E (Task 1), Q2 (3/31/13)

Title: Apply the developed basin-scale model for the worst-storage scenario to assess dynamic storage capacity

Milestones F (Task 1), Q4 (9/30/13)

Title: Apply the developed basin-scale model to a variety of future storage scenarios to assess pressure buildup and environmental impact

Milestone G (Task 2), Q2 (3/31/13)

Title: Develop and apply automated global optimization methods to optimize IDPM options for heterogeneous systems and variable well locations

Milestone H (Task 2), Q4 (9/30/13)

Title: Design and optimize IDPM options for a real field site

Appendix: Bibliography 2008-2012

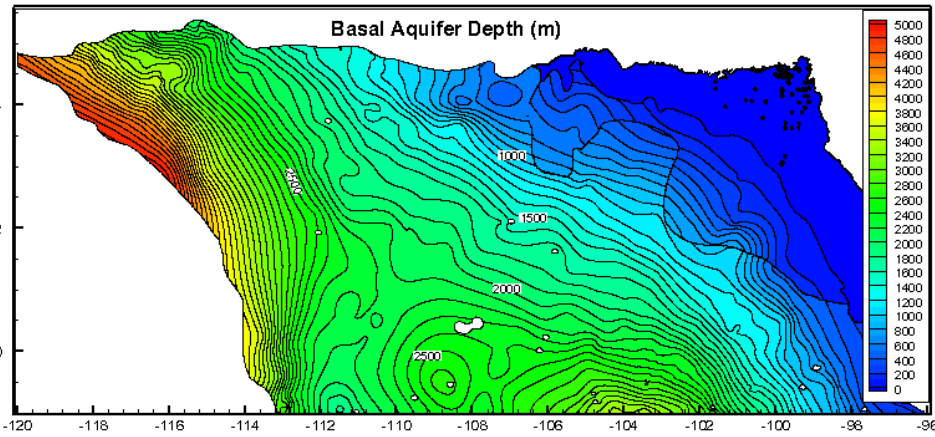


- ❖ Cihan, A., Zhou, Q., Birkholzer, J.T., Kraemer, S.R., 2012, Flow in anisotropic multilayered aquifer systems with leaky wells and aquitards: *Water Resources Research* (submitted)
- ❖ Cihan, A., Birkholzer, J.T., and Zhou, Q., 2012, Pressure buildup and brine migration in CO₂ storage systems with multiple leakage pathways: Application of a new analytical solution. *Ground Water*, doi: 10.1111/j.1745-6584.2012.00972.x, available at [onlinelibrary.wiley.com/journal/10.1111/\(ISSN\)1745-6584/issues](http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1745-6584/issues)
- ❖ Birkholzer, J.T., Cihan, A., and Zhou, Q., 2012, Impact-driven pressure management via targeted brine extraction – Conceptual studies of CO₂ storage in saline formations, *International Journal of Greenhouse Gas Control*, 7(March), 168-180, doi:10.1016/j.ijggc.2012.01.001. available at <http://www.journals.elsevier.com/international-journal-of-greenhouse-gas-control/>
- ❖ Cihan, A., Zhou, Q., and J.T. Birkholzer, 2011, Analytical solutions for pressure perturbation and fluid leakage through aquitards and wells in a multilayered system, *Water Resources Research*, 47, W10504, doi:10.1029/2011WR010721. available at www.agu.org/
- ❖ Birkholzer, J.T., Nicot, J.-P., Oldenburg, C.M., Zhou, Q., Kraemer, S., and Bandilla, K., 2011, Brine flow up a well caused by pressure perturbation from geologic carbon sequestration: Static and dynamic evaluations, *International Journal of Greenhouse Gas Control* 5(4), 850-861, doi:10.1016/j.ijggc.2011.01.003. available at <http://www.journals.elsevier.com/international-journal-of-greenhouse-gas-control/>
- ❖ Zhou, Q., and Birkholzer, J.T., 2011, On scale and magnitude of pressure build-up induced by large-scale geologic storage of CO₂, *Greenhouse Gases: Science and Technology* 1, 11-20, DOI: 10.1002/ghg3.001. available at [http://onlinelibrary.wiley.com/journal/10.1002/\(ISSN\)2152-3878](http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)2152-3878)
- ❖ Zhou, Q., Birkholzer, J.T., and Tsang, C.-F., 2011, Reply to Comments by Veling on “A Semi-Analytical Solution for Large-Scale Injection-Induced Pressure Perturbation and Leakage in a Laterally Bounded Aquifer-Aquitard System” by Zhou, Birkholzer, and Tsang, *Transport in Porous Media* 86, 357-358. available at <http://www.springerlink.com/content/100342/?MUD=MP>
- ❖ Zhou, Q., Birkholzer, J.T., Mehnert, E., Lin, Y.-F., and Zhang, K., 2010, Modeling basin- and plume-scale processes of CO₂ storage for full-scale deployment, *Ground Water*, 48(4), 494-514. available at [onlinelibrary.wiley.com/journal/10.1111/\(ISSN\)1745-6584/issues](http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1745-6584/issues)
- ❖ Birkholzer, J.T., and Zhou, Q., 2009, Basin-scale hydrogeologic impacts of CO₂ storage: Regulatory and capacity implications, *International Journal of Greenhouse Gas Control* 3 (6), 745–756. available at <http://www.journals.elsevier.com/international-journal-of-greenhouse-gas-control/>
- ❖ Zhou, Q., Birkholzer, J.T., and Tsang, C.-F., 2009, A semi-analytical solution for large-scale injection-induced pressure perturbation and leakage in a laterally bounded aquifer-aquitard system, *Transport in Porous Media*, 78(1), 127-148. available at <http://www.springerlink.com/content/100342/?MUD=MP>
- ❖ Birkholzer, J.T., Zhou, Q., and Tsang, C.-F., 2009, Large-scale impact of CO₂ storage in deep saline aquifers: A sensitivity study on pressure response in stratified systems, *International Journal of Greenhouse Gas Control* 3, 181-194. available at <http://www.journals.elsevier.com/international-journal-of-greenhouse-gas-control/>
- ❖ Zhou, Q., Birkholzer, J.T., Tsang, C.-F., and Rutqvist, J., 2008, A method for quick assessment of CO₂ storage capacity in closed and semi-closed saline aquifers: *International Journal of Greenhouse Gas Control* 2, 626-639. available at <http://www.journals.elsevier.com/international-journal-of-greenhouse-gas-control/>

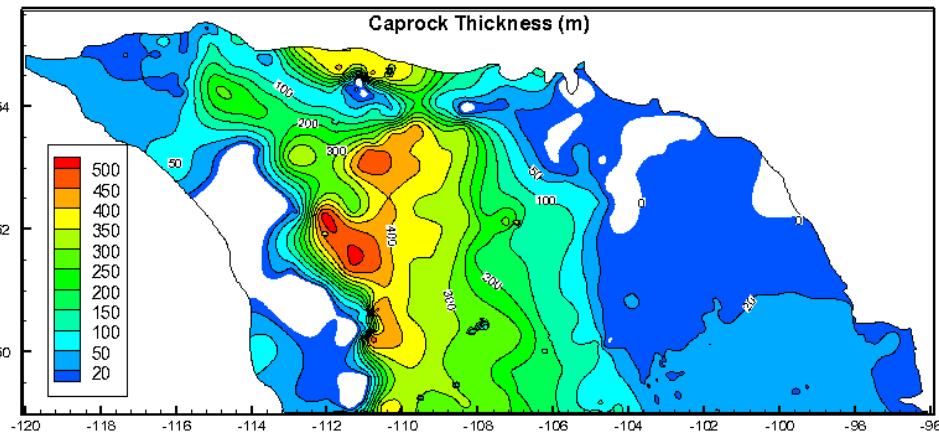
Backup



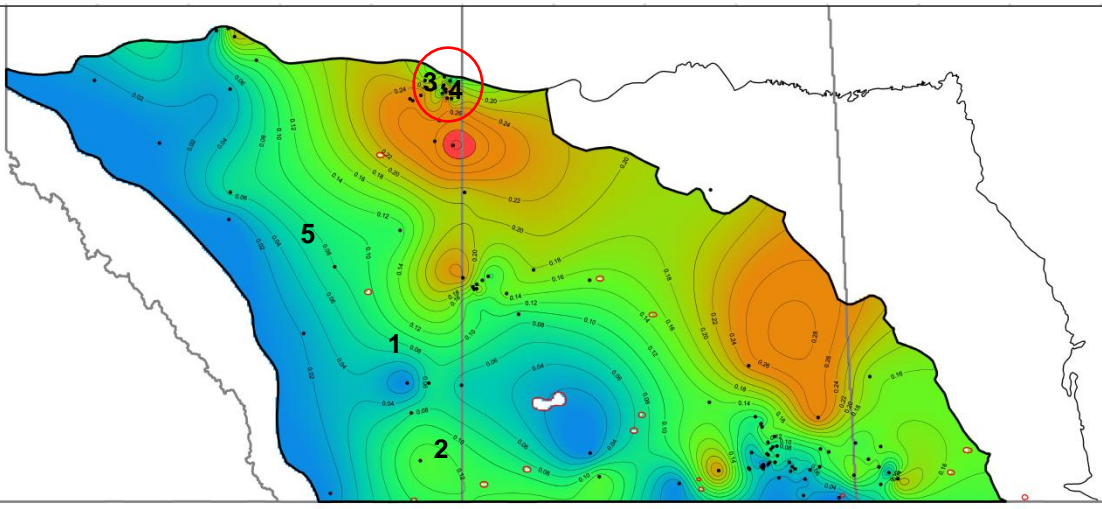
Basal Aquifer – Canadian Part



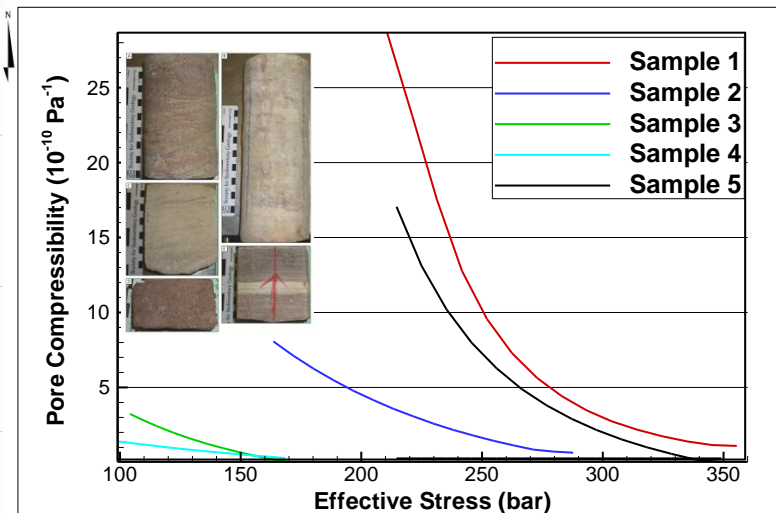
Basal Aquifer Depth



Caprock Thickness



Porosity



Pore Compressibility

Brine Extraction and Disposition Economics



- Construction of wells and treatment/disposal facilities
- Operating cost (pumping, treatment, disposal, discharge)
- Transportation
- Permitting, monitoring, reporting

Management Practice	Cost Range (\$/bbl)*	Cost to CCS (\$/ton CO ₂)
Reverse Osmosis	\$1.00-\$3.50	\$8.80-\$31.00
Thermal Distillation	\$6.00-\$8.50	\$53.00-\$75.00
UIC Injection	\$0.05-\$4.00	\$0.45-\$35.00
Evaporation	\$0.40-\$4.00	\$3.50-\$35.00

*Costs do not include transportation

Brine extraction can be a significant factor in the economic viability of a CCS project

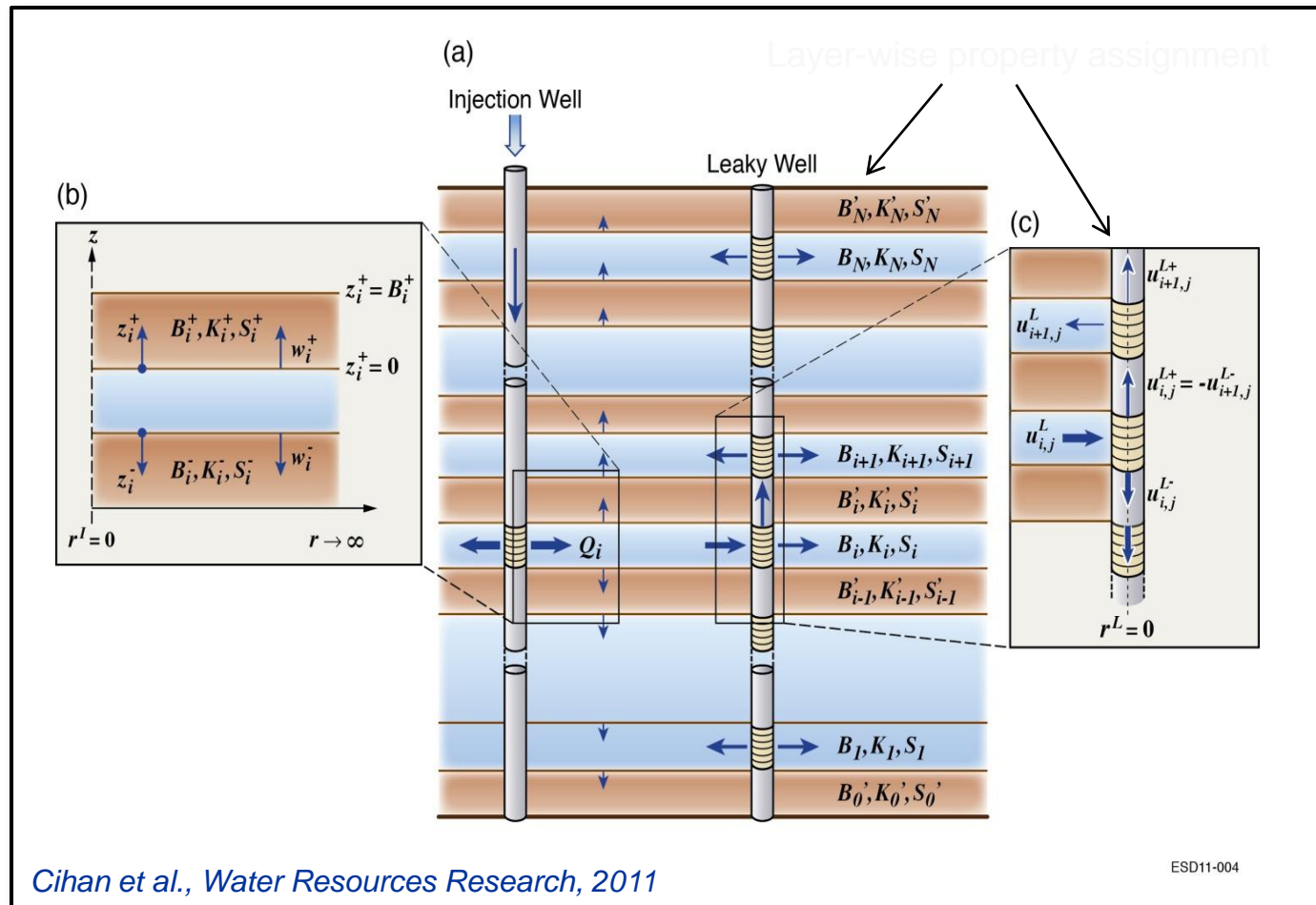
Based on Harto et al., 10th Annual Conference on CCS, Pittsburgh, May 2011

Analytical Solution

Single-Phase Flow in Multi-Layer Systems with Multiple Active and/or Leaky Wells

Assumptions

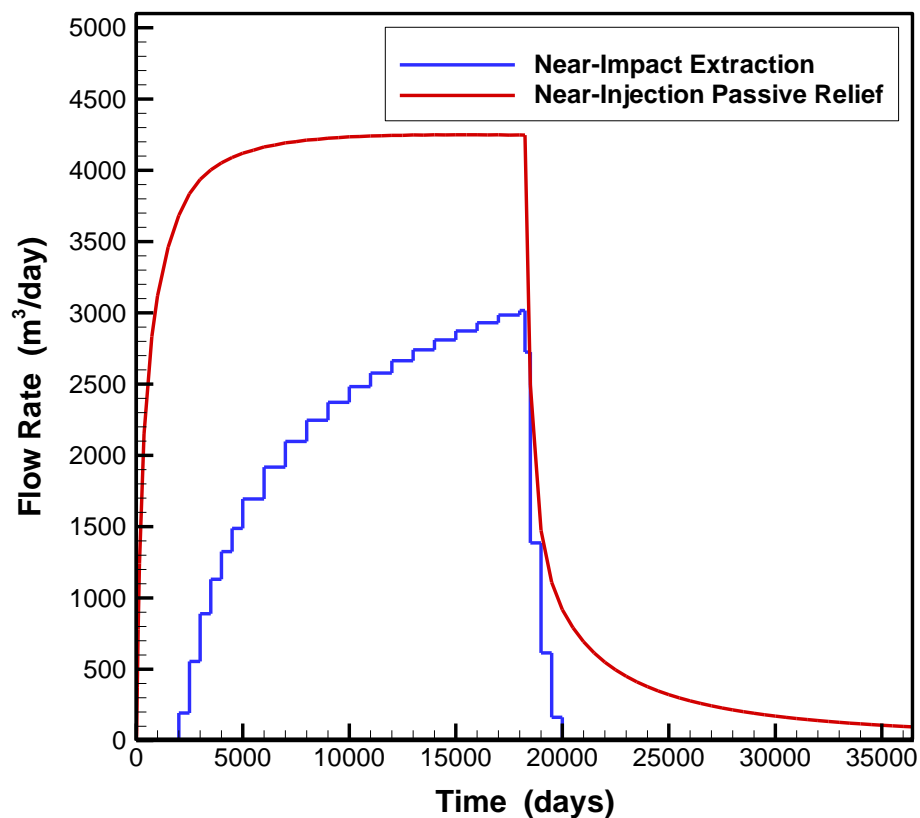
- Far-field pressure change in response to CO₂ injection approximated by single-phase model with volume-equivalent injection
- Aquifers and aquitards are homogeneous and isotropic, and have uniform thickness and infinite horizontal extent
- Flow is horizontal in aquifers, and vertical in aquitards
- Flow through leaky wells is laminar and governed by Darcy's law



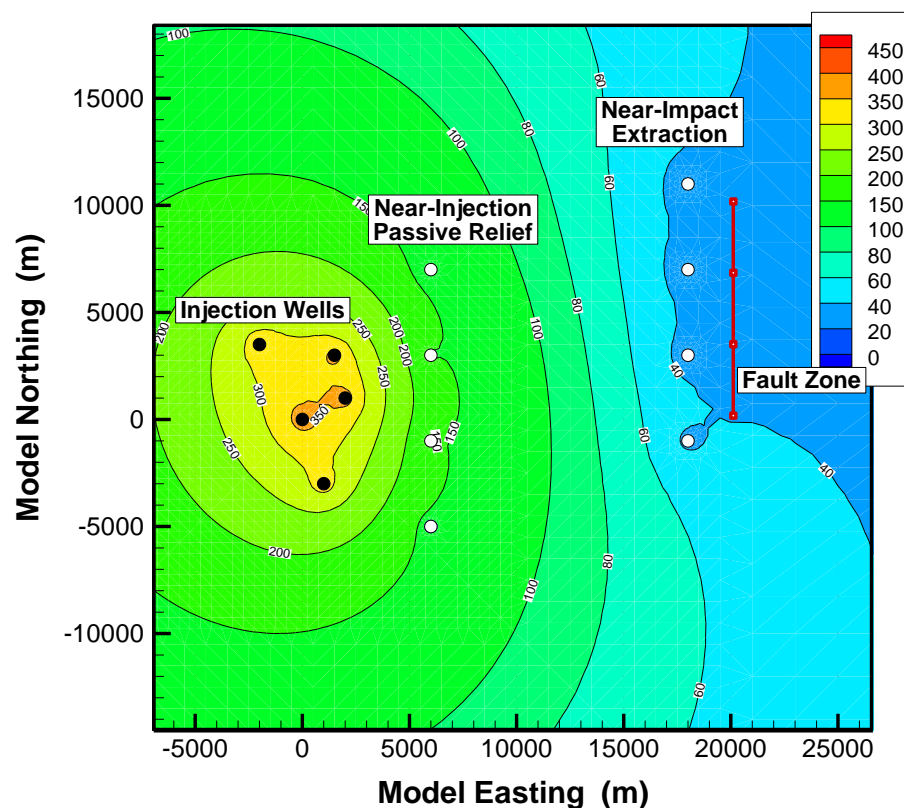
Combined Passive Relief and Active Extraction for Fixed Well Location



Near-impact active pumping and near-injection passive pressure relief. Pumping rates optimized with iTOUGH2 inversion and Levenberg-Marquardt algorithm.



Flow Rate



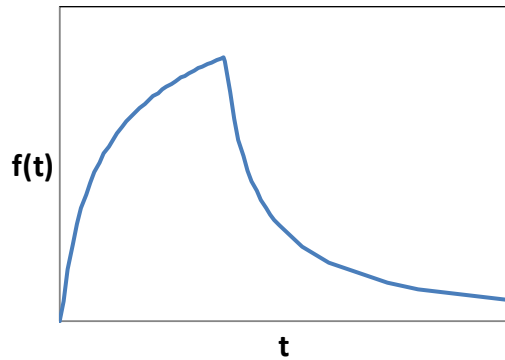
Head Change at 50 Years

Improvements to Solution Procedure

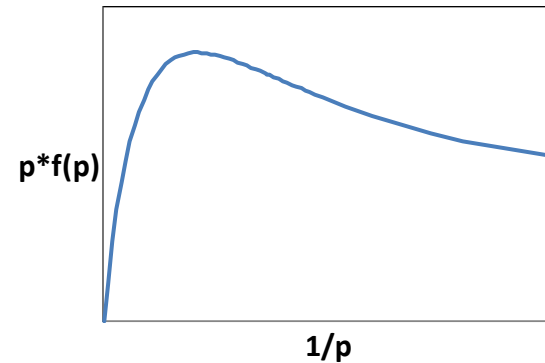


Efficiency: Parameter Estimation in Laplace Domain

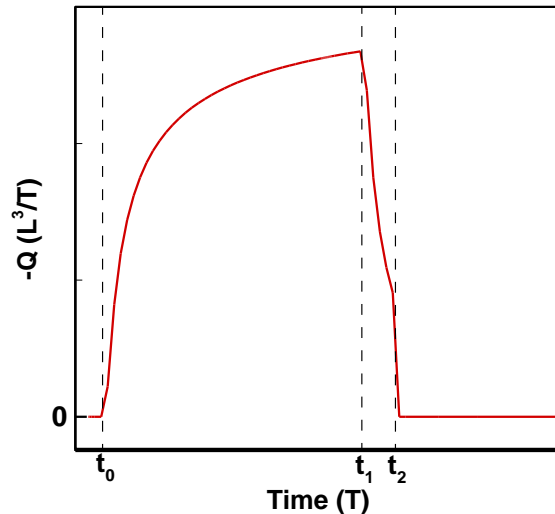
Pressure or Flow Rate in Real Time Domain



Laplace Pressure or Flow Rate



Stability: Represent evolution of extraction rate with empirical continuous function

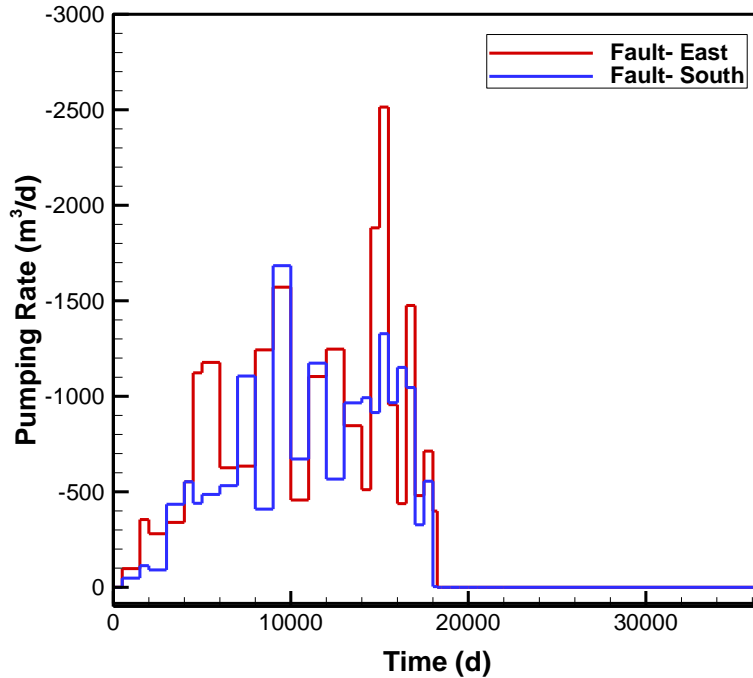


Function with Six Fitting Parameters

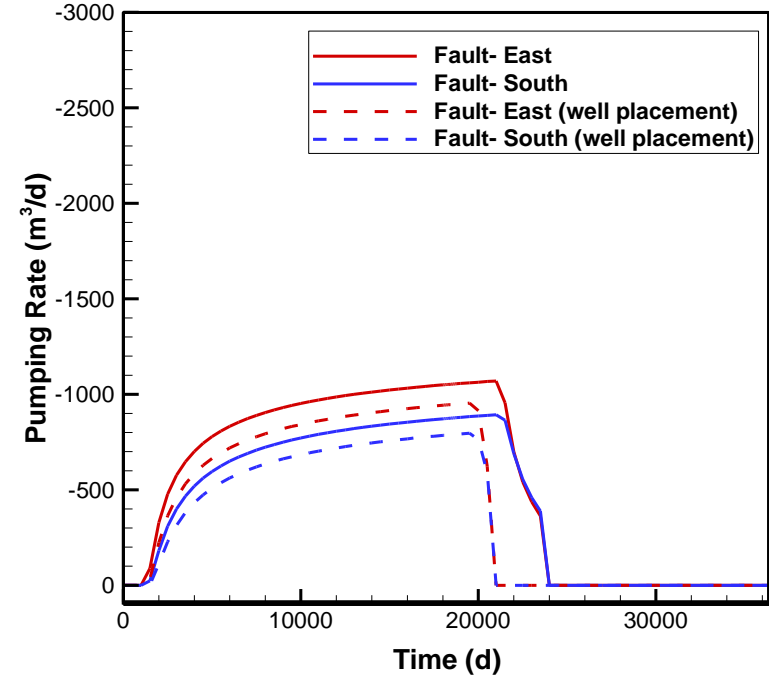
$$Q(t) = \begin{cases} 0 & ; 0 < t \leq t_0 \\ Q_0 \operatorname{erfc} b / \sqrt{t-t_0} & ; t_0 < t \leq t_1+t_0 \\ Q_0 \operatorname{erfc} b / \sqrt{t-t_0} - Q_1 \operatorname{erfc} b / \sqrt{t-t_1-t_0} & ; t_0+t_1 < t \leq t_2 \\ 0 & ; t_2 < t \end{cases}$$

Empirical Continuous Function for Pumping Evolution

Stepwise Independent Inversion



Continuous Function Inversion



Pumping Rate