Stanford University

Global Climate & Energy Project

Remediation Technologies

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Storage in Saline Formations R&D Workshop
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Events Where Contingency Planning and Remediation is Needed

Emergency Management

- Well blowouts
- Low energy surface releases

Project Conformance

- Plume migration

Leakage Cleanup

- Groundwater
- Vadose zone
- Surface water
- Ecosystems

Leakage Containment

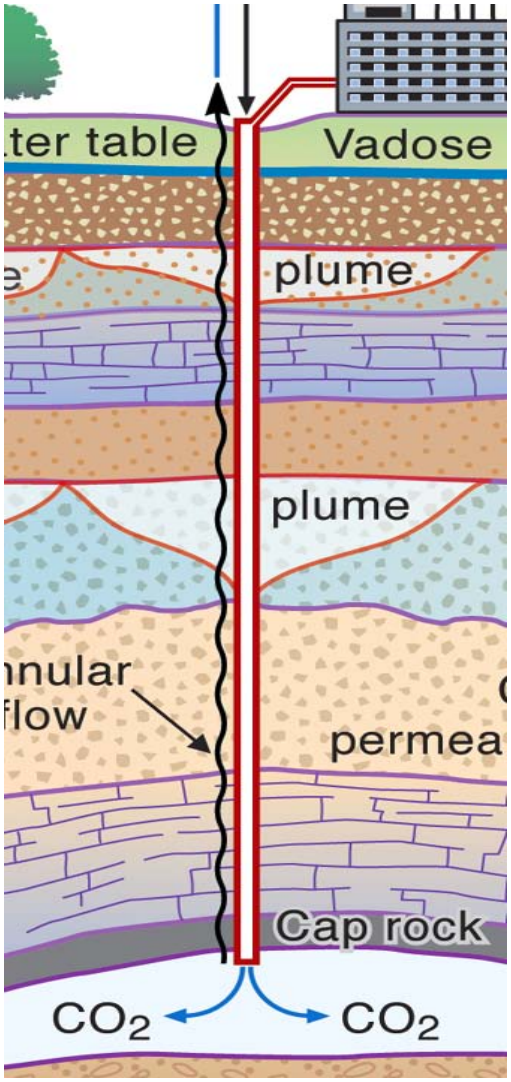
- Leaking wells
- Flow up faults and fractures
- Flow through seals
- Fracturing of caprock

Hazard Mitigation

- Induced seismicity
- Land surface deformation
- Brine migration

Remediation Options: Leakage from Active or Abandoned Wells

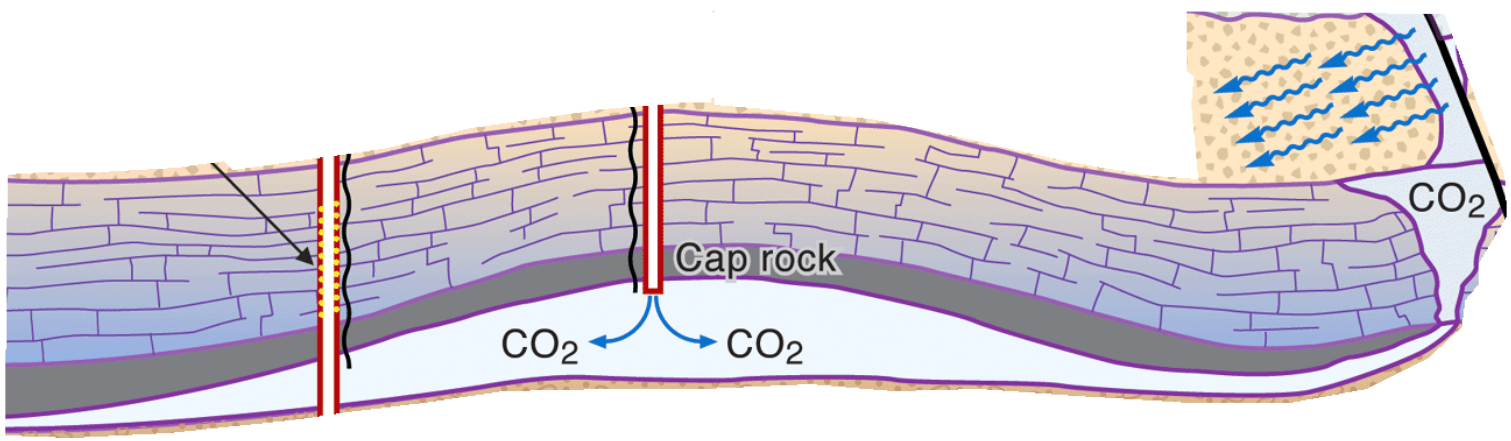
- Methods for repairing wells are used routinely in oil, gas, natural gas storage and waste disposal industries:
  - Replace the injection tubing and packers
  - Plug leaks behind well casing with cement
  - Plug and abandon injection wells that cannot be repaired
  - Plug abandoned wells with cement
  - Inject heavy mud into well casing to stop blowouts



S.M. Benson and R. Hepple (2005) "Prospects for Early Detection and Options for Remediation of Leakage from CO_2 Sequestration Projects," *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results from the CO_2 Capture Project*, *Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification*, Elsevier Publishing, UK, p. 1189-1203.

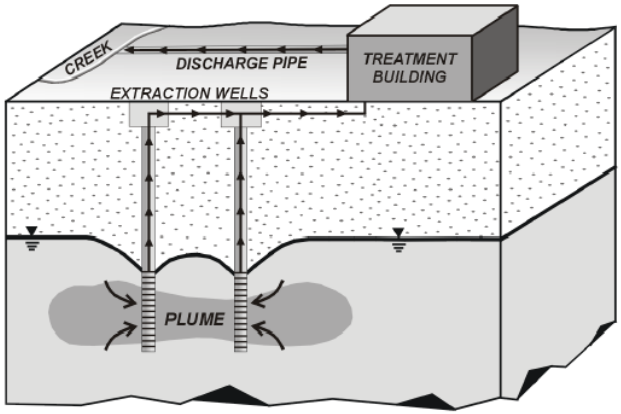
Remediation Options: Leakage from the Storage Reservoir

- Potential methods to stop or reduce leakage from storage reservoir:
  - Reduce pressure in the storage formation by slowing or stopping injection
  - Increase pressure in overlying aquifer
  - Intercept and extract plume from reservoir before it leaks
  - Plug region where leakage is occurring with low permeability materials (e.g. cement, biofilms, foam, gels)
  - Inject water to dissolve the CO_2 at release location
  - Lower pressure to create an exsolved phase with low relative permeability



Remediation Options: Groundwater

- Passive methods
  - Natural attenuation by dissolution, migration, and mineralization
- Active methods
  - Gas phase pumping
  - Groundwater extraction to dissolve plume
  - Single well dissolution system: inject and produce water
- Methods to deal with other contamination due to dissolution of minerals by CO_2
  - Pump and treat wells
  - Containment by managing hydraulic heads
  - Treatment walls



Picture taken from *http://www.clu-in.org/download/remed/542r01021b.pdf*

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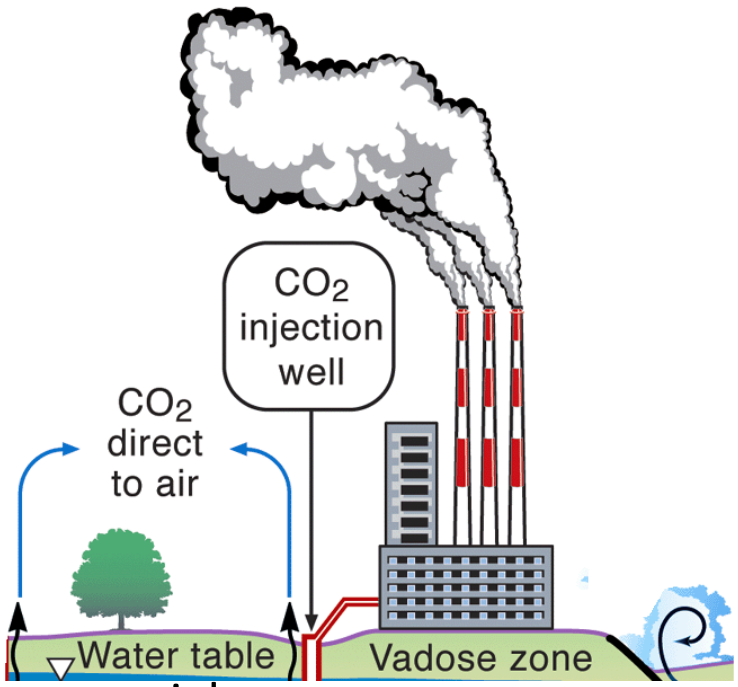
Remediation Options: Vadose Zone

- Passive methods
  - Diffusive flux to surface
  - Baroballs
- Active methods
  - Soil gas extraction
    - Vertical wells
    - Horizontal wells
    - Drainage systems
  - Covers
    - Landfill cover—low permeability material
    - Collection system below cover



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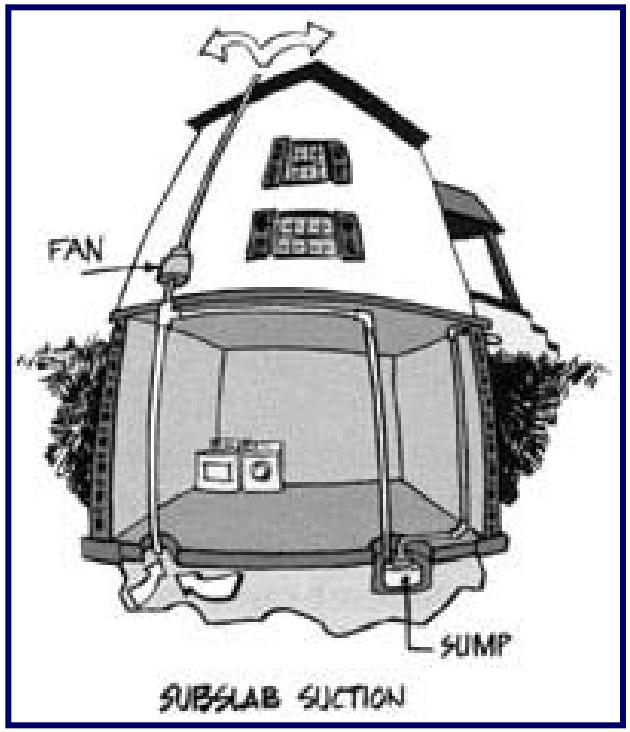
Remediation Options: Indoor Air

- Remediation of indoor air contaminants has been studied extensively (radon gas mitigation)
- Two major techniques for remediation
  - Subsurface or subslab pressurization
  - Subslab depressurization with venting



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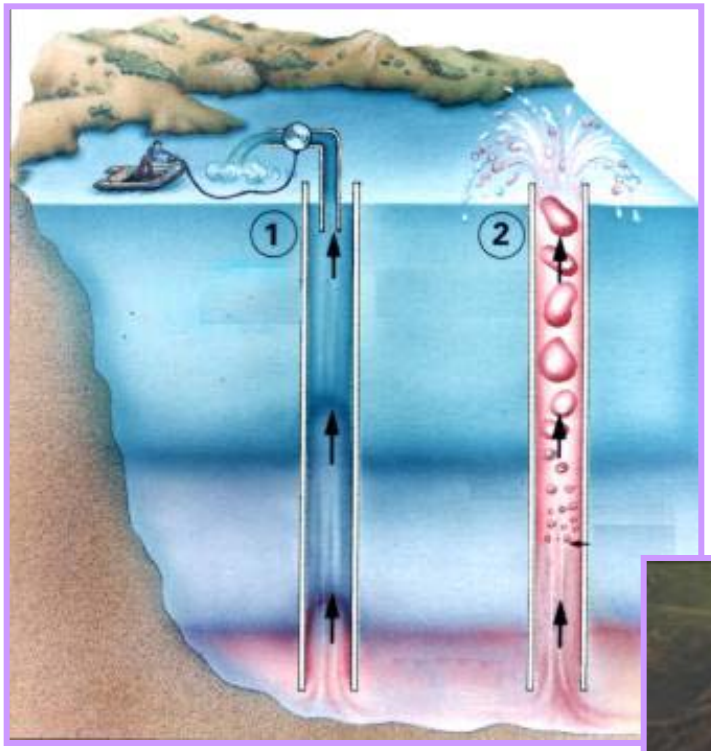
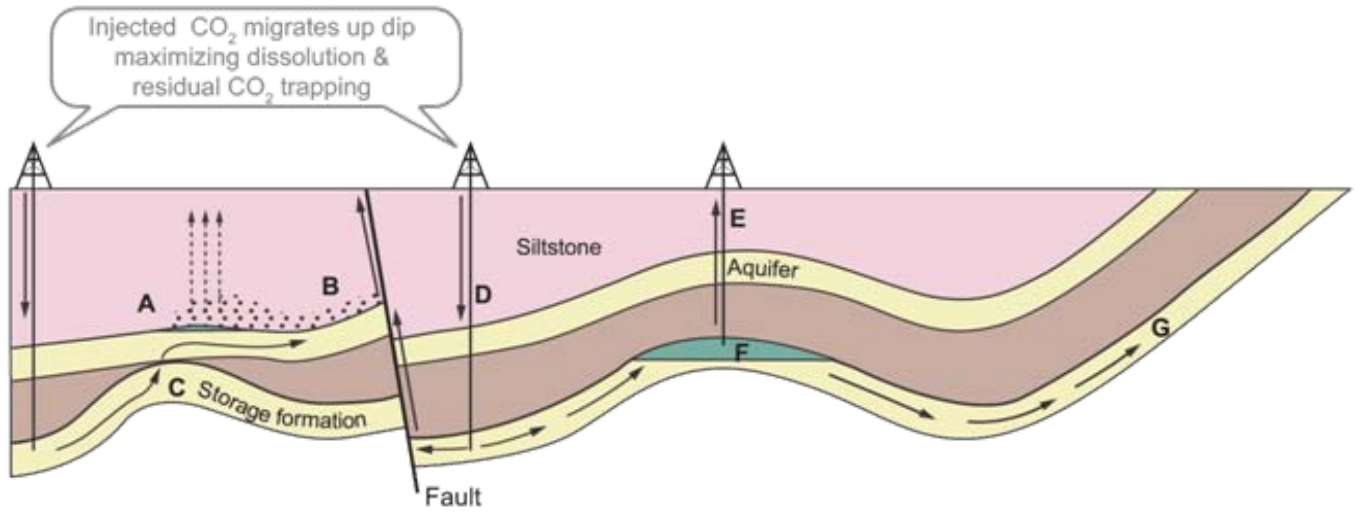
Remediation Options: Surface Water



- Safely venting deep lakes involves water column degassing
- Degassing tests are underway at Lake Nyos and a nearby smaller lake named Monoun

Photo from: http://perso.wanadoo.fr/mhalb/nyos/project/indexproj.htm

Methodologies for Intervention (IPCC, Special Report, 2005)



Potential Escape Mechanisms

A. CO_2 gas pressure exceeds capillary pressure & passes through siltstone	**B.** Free CO_2 leaks from A into upper aquifer up fault	**C.** CO_2 escapes through 'gap' in cap rock into higher aquifer	**D.** Injected CO_2 migrates up dip, increases reservoir pressure & permeability of fault	**E.** CO_2 escapes via poorly plugged old abandoned well	**F.** Natural flow dissolves CO_2 at CO_2 / water interface & transports it out of closure	**G.** Dissolved CO_2 escapes to atmosphere or ocean

Remedial Measures

A. Extract & purify ground-water	*B. Extract & purify ground-water*	*C. Remove CO_2 & reinject elsewhere*	*D. Lower injection rates or pressures*	*E. Re-plug well with cement*	*F. Intercept & reinject CO_2*	*G. Intercept & reinject CO_2*

Since that time …some real-world experiences, and new studies

- IEA-GHG remediation study (Kuuskraa, 2007)
- Exploration well P&A at In Salah (2010)
- Snohvit injection well recompletion (2010)
- Groundwater and vadose zone remediation studies
  - Vadose zone remediation (Zhang et al., 2004)
  - Strategies for groundwater cleanup (Esposito and Benson, 2010; Rohmer et al., 2010; EPRI, 2011)
  - Sintef research facility (Lindeberg et al., 2010-)
- Regulatory Guidelines
  - USEPA Regulations "Remediation Plans"
  - European Directive "Remediation Plans"
- CCP 3 2011 Workshop on Contingency Planning

Growing awareness that this is an important topic

Costs for Managing the Issues can be Large(Kuuskraa, 2007)

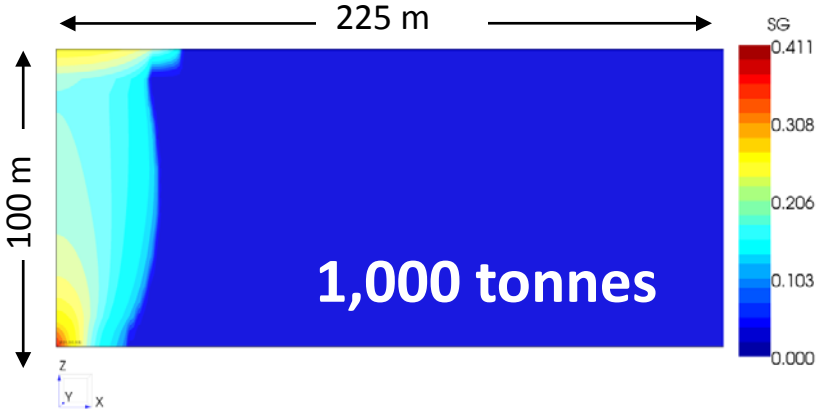
Remediation Activity	Costs ($ Million)	Assumptions
1. Locating Sources of CO_2 Leaks		
Locating Old, Abandoned Wells	$1.0 to $2.0	Assumes 5 to 10 leak location surveys
New CO_2 Injection Wells	$3.0 to $6.0	Assumes 10 to 20 sets of diagnostic logs
2. Well Plugging		
Plugging Old, Abandoned Wells	$1.0 to $2.0	Includes plugging of 10 to 20 old wells
3. Well Problems		
Remediation	$2.00	Includes remediating 20 CO_2 injection wells
New Wells	$7.0 to $14.0	Includes drilling 2 to 4 new CO_2 injection wells
4. Geologic/Caprock Leakage		
Diagnostic Survey	$3.0 to $6.0	Includes 1 to 2 20 mi^2 seismic surveys
Horizontal Leak Detection Wells	$8.0 to $16.0	Includes 2 to 4 horizontal wells
Pressure Boundary	$10.0 to $18.0	Includes 2 to 4 horizontal wells plus one water plant
Other Problems	Large	May need to abandon original storage site and build a new site
Sub-Total	**$35 to $66**	

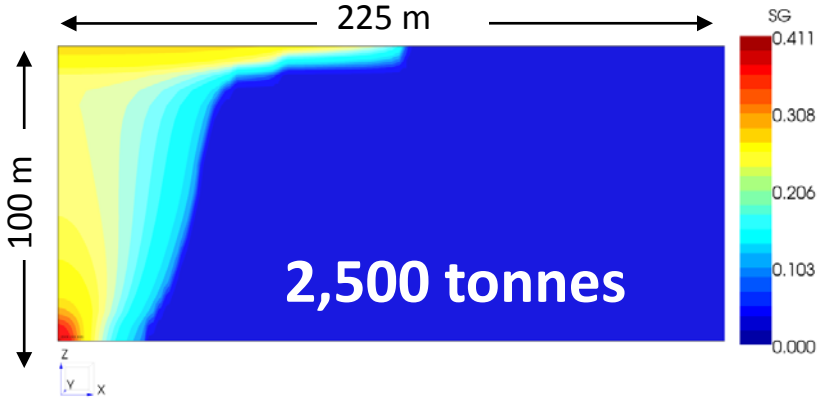
Groundwater: Possible Leakage Impacts

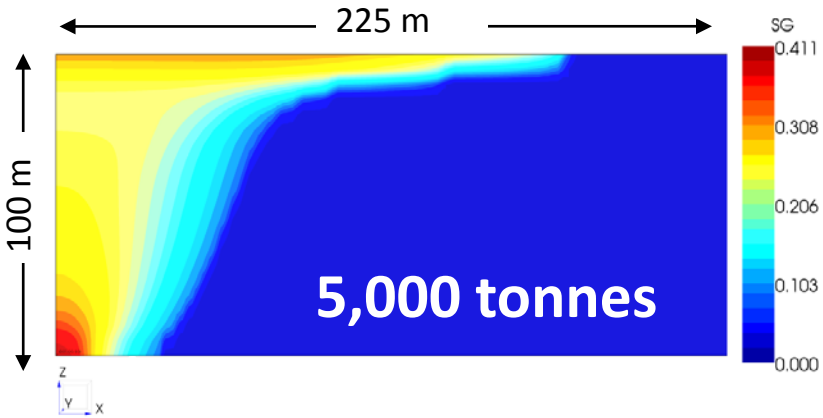
- Degrades groundwater quality
  - Decreased pH due to formation of carbonic acid
  - Increased dissolution of trace metals such as Lead and Arsenic
  - Possible mobilization of organics
- Interferes with groundwater extraction for agricultural and drinking water purposes
- Release pathway to the surface

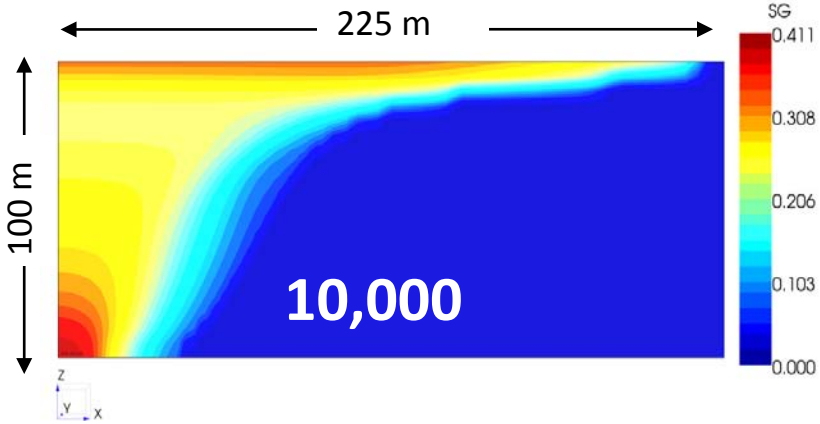
Ariel Esposito, MS Thesis, Department of Energy Resources Engineering
Esposito and Benson, International Journal of Greenhouse Gas Control, in review.

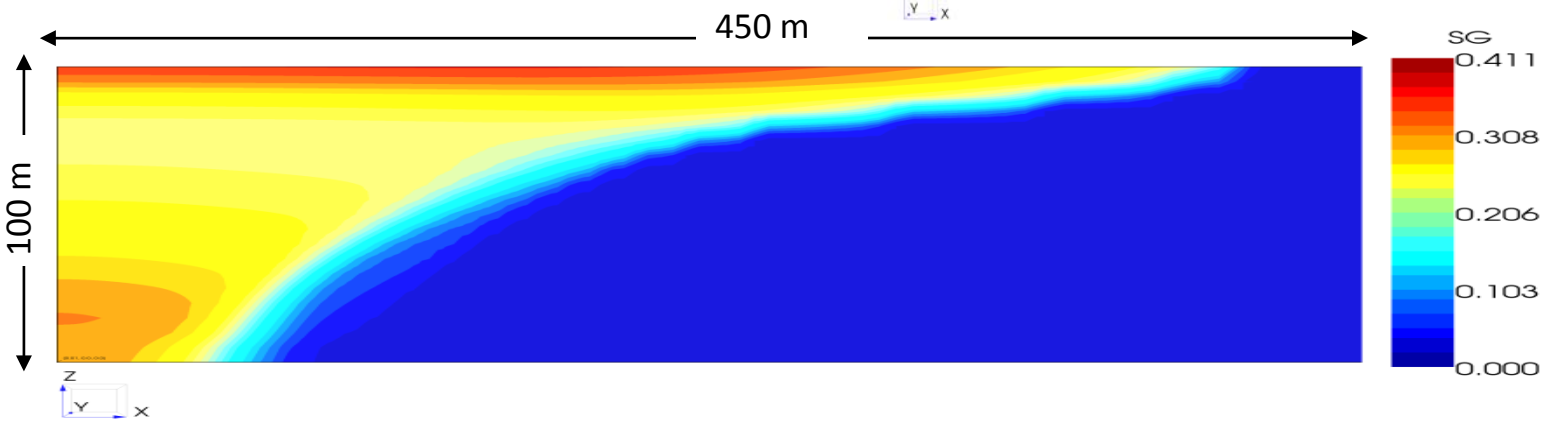
Leakage Cases: Total Leakage Over 5 Years









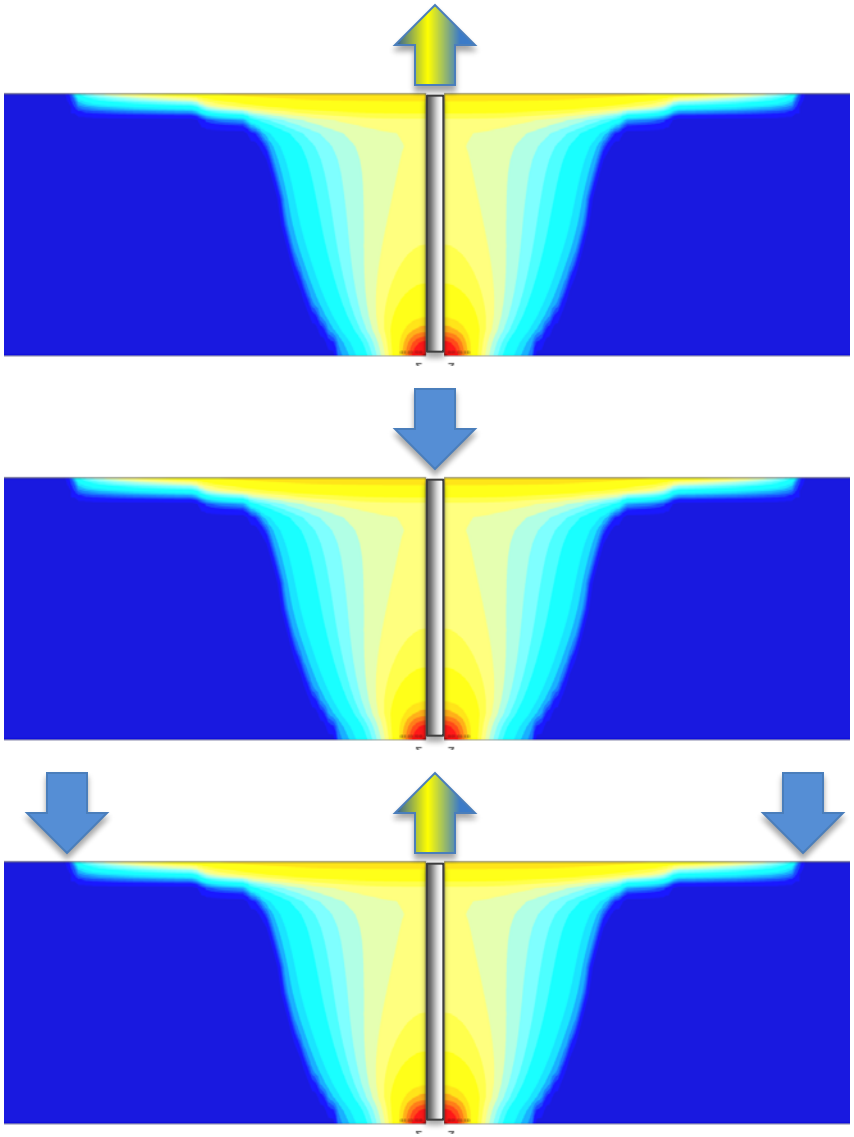


Remediation Options Evaluated

Extract CO_2 and brine

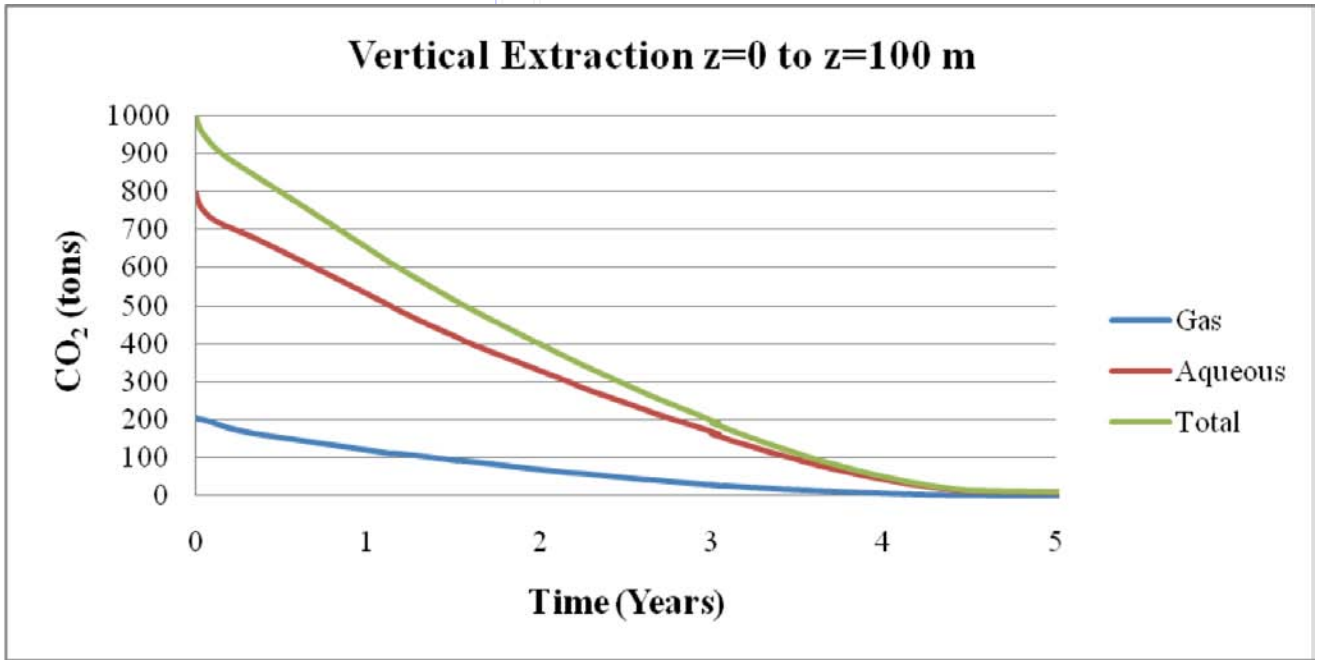
Inject brine

Sequentially or concurrently extract CO_2/brine and inject brine



Small Plumes Can Be Removed Effectively with Extraction Wells

Extraction at constant pressure: 10 m hydraulic head above the aquifer

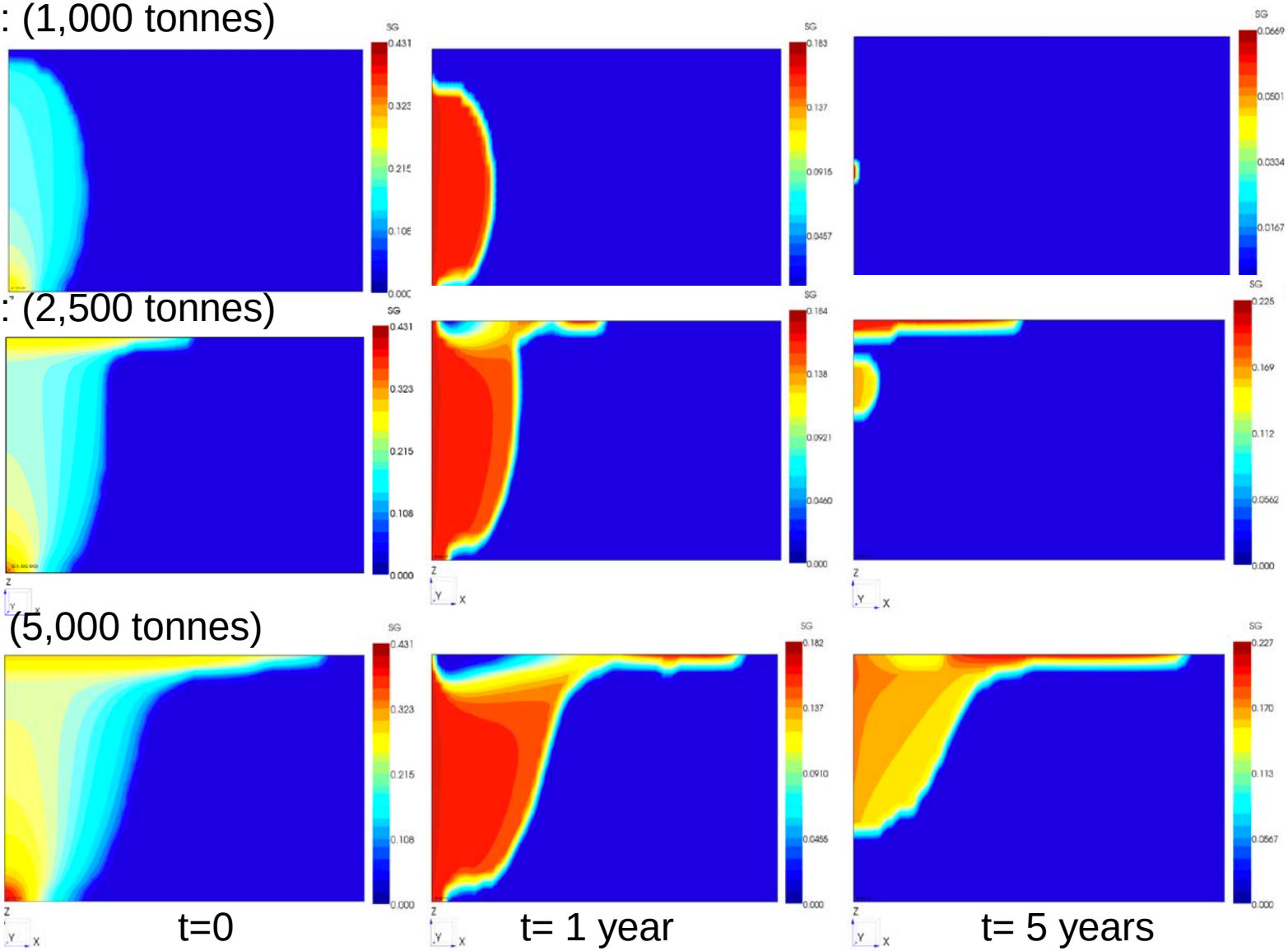


Extraction From Plume with Large Gravity Tongues is Difficult

Case 1: (1,000 tonnes)

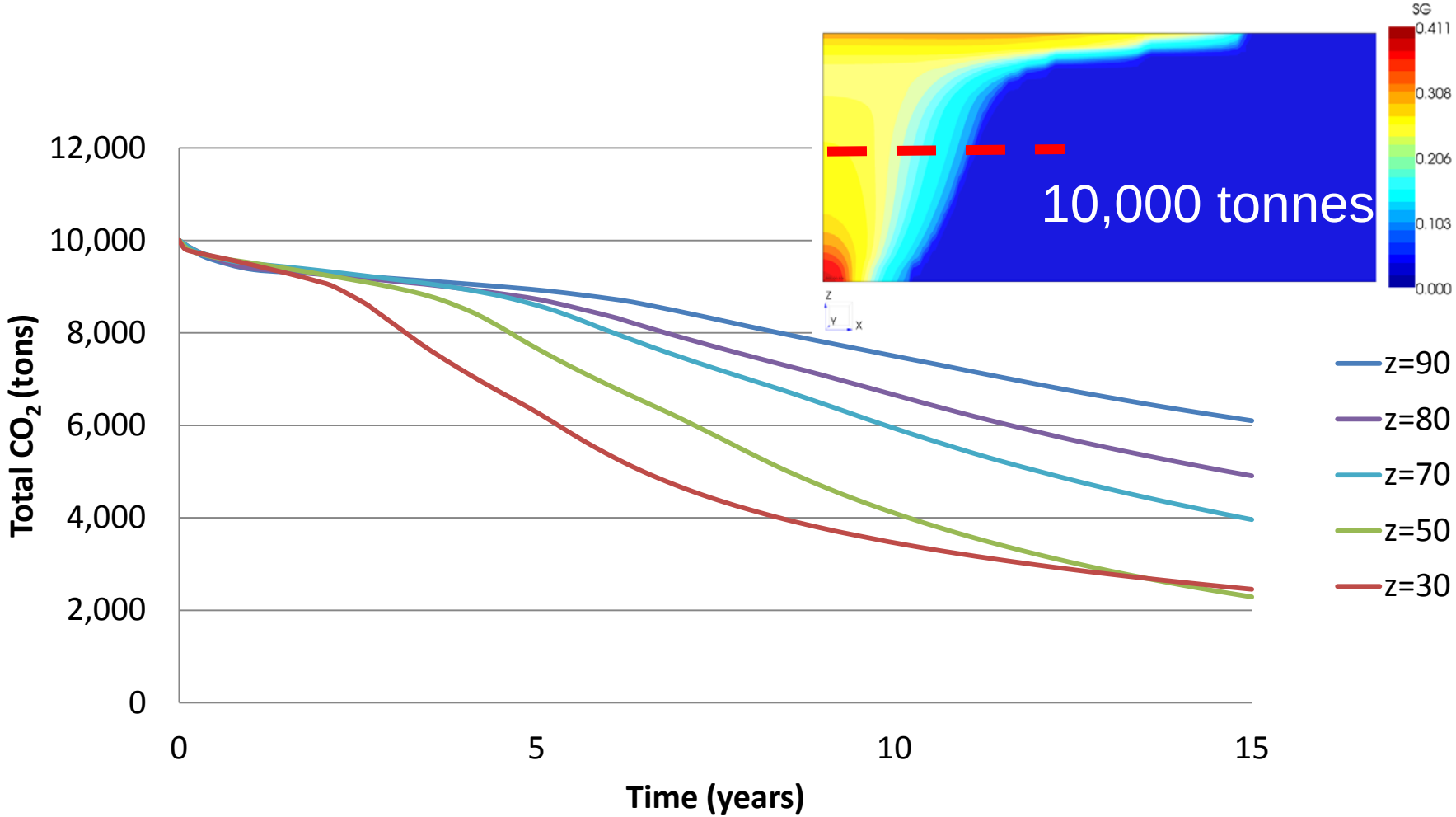
Case 2: (2,500 tonnes)

Case 3: (5,000 tonnes)

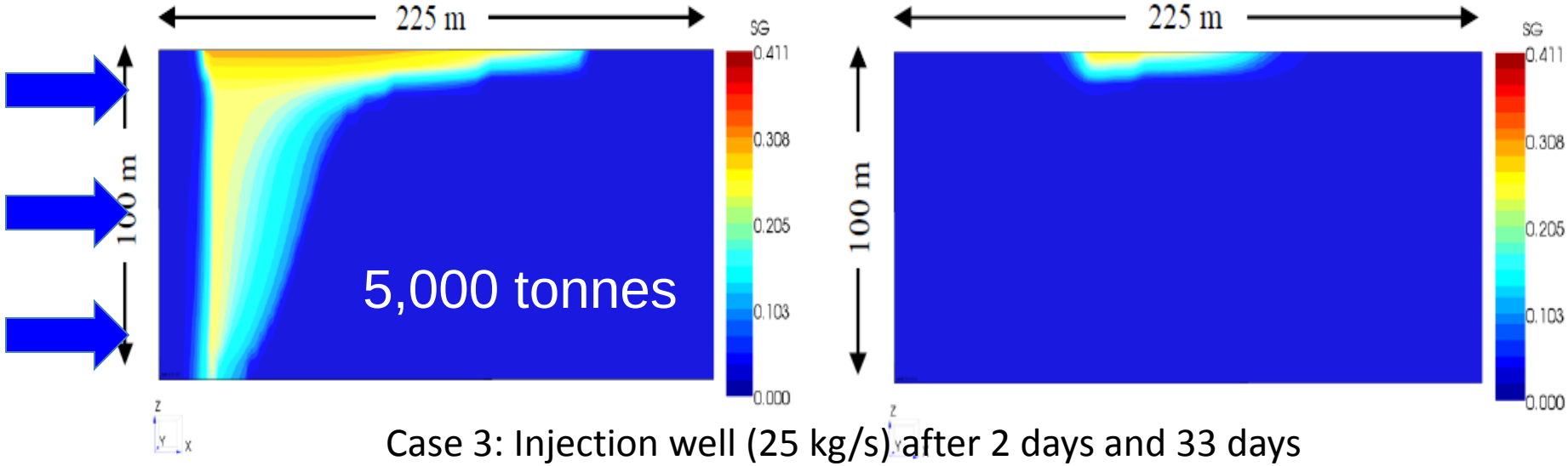


t=0 t= 1 year t= 5 years

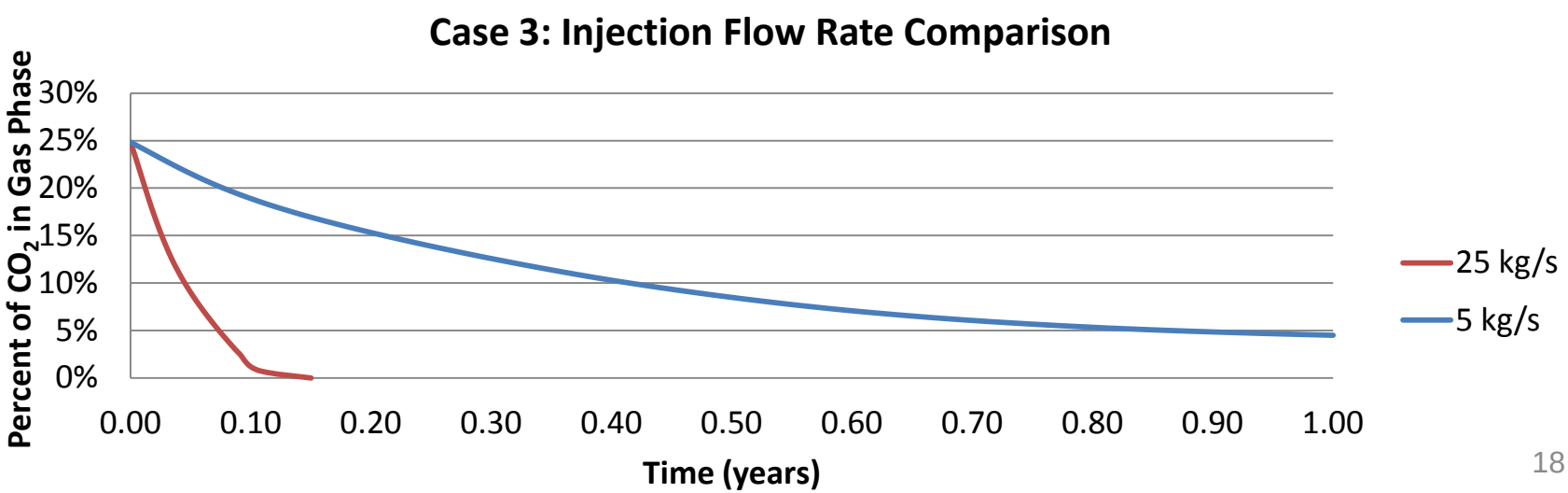
Extraction Using Horizontal Wells



Dissolution with an Injection Well

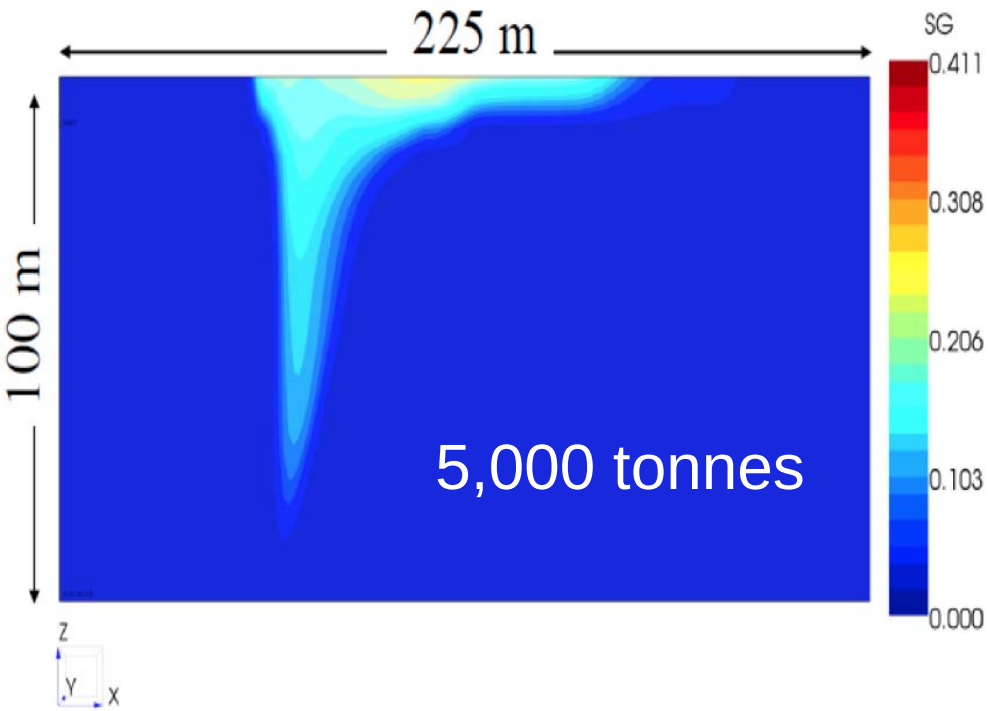


Case 3: Injection well (25 kg/s) after 2 days and 33 days

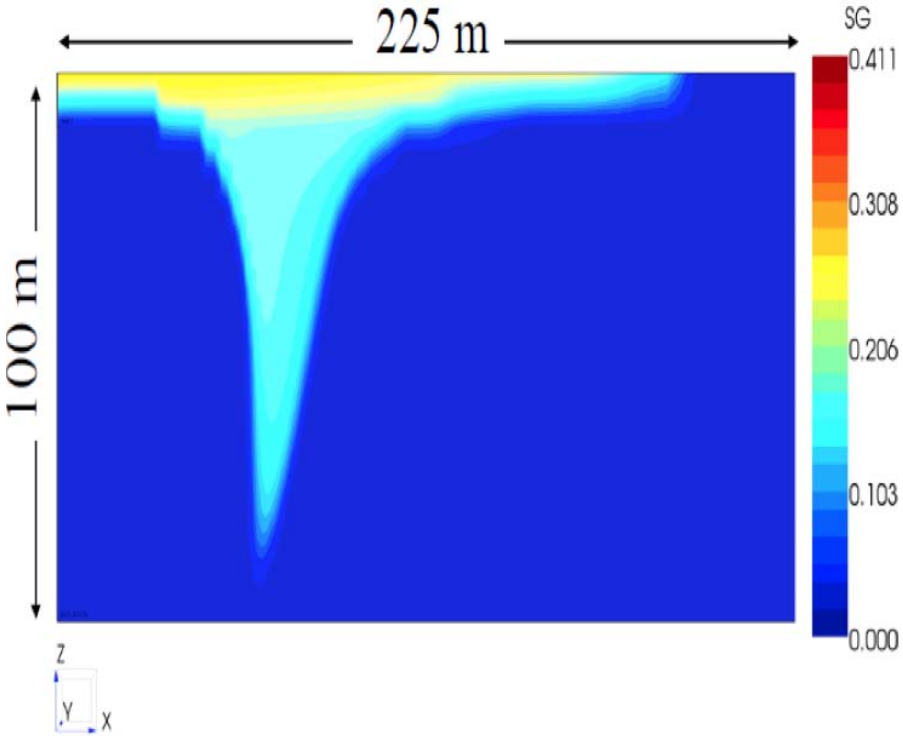


Huff-Puff Not Effective for Plume Extraction

CO_2 Saturation Maps

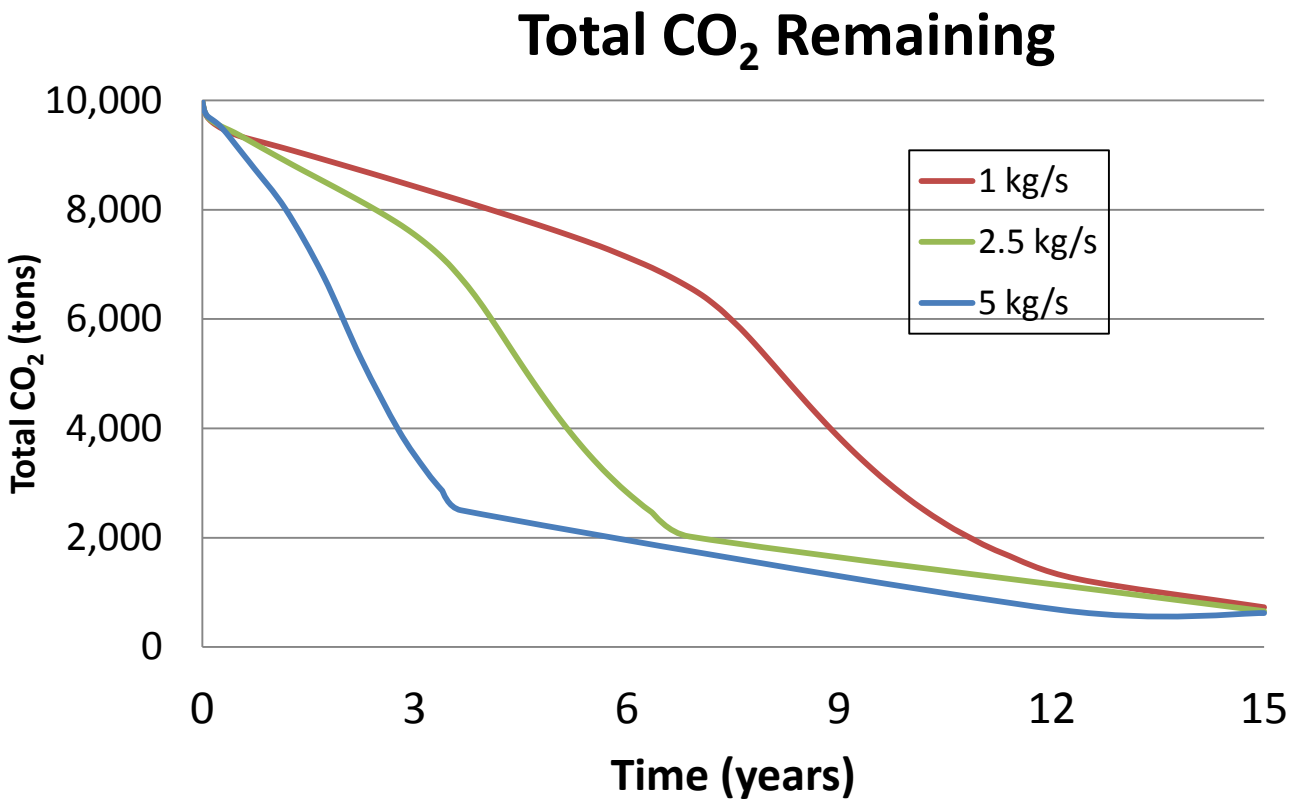


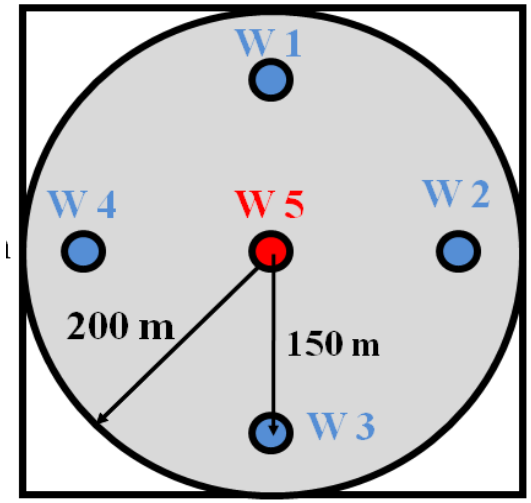
After 62 days of extraction



After 365 days of extraction

Simultaneous Injection and Extraction is Effective for Removing Larger Plumes





Overall Conclusions

- Well P&A procedures well known and effective
  - But, costs can be high
- Stopping leakage from faults and fractures more challenging
  - Little direct experience
  - Stopping injection near the leak is the best short term option
  - Other ideas need to be developed and tested
- Remediation of groundwater, vadose zone, and ecosystems is possible
  - Costs and time are key issues
  - More and lower cost options are needed
  - Best to avoid the need for remediation through early leak detection and curtailment
- More work is needed in this general area to be prepared to manage unforeseen events quickly and cost effectively