Evaluation of analytical and semi-analytical solutions for modeling and mapping of the area of review (AoR)

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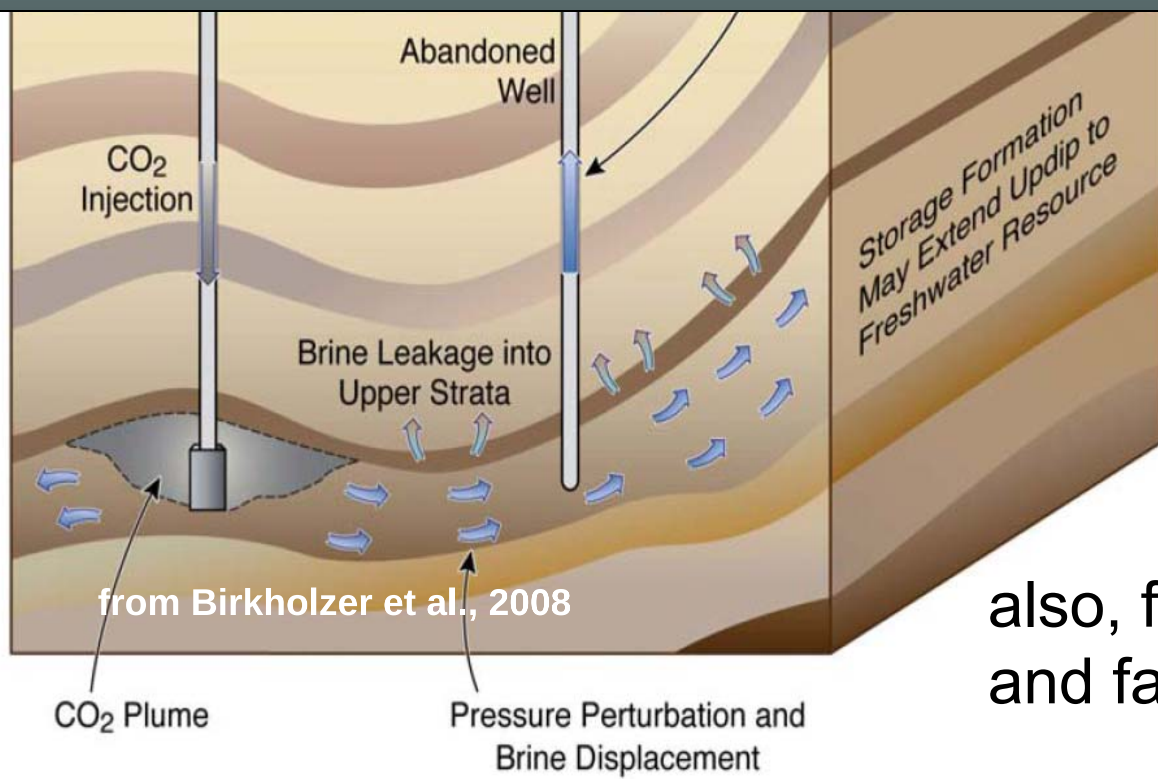
U.S. Environmental Protection Agency

DOE/EPA Collaborative Review, Pittsburgh, PA, 24 March 2010

zones of concern

Underground
Source of
Drinking Water
(USDW)



from Birkholzer et al., 2008

also, fractures
and faults

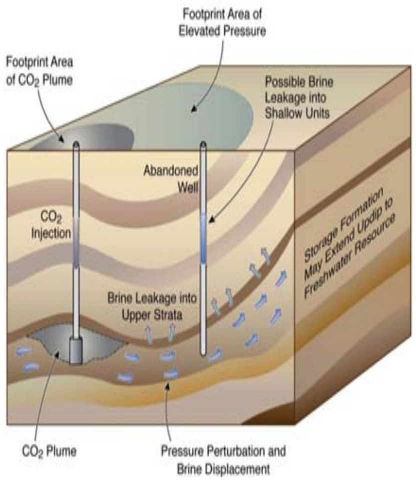
Area of Review (AoR) is a regulatory tool

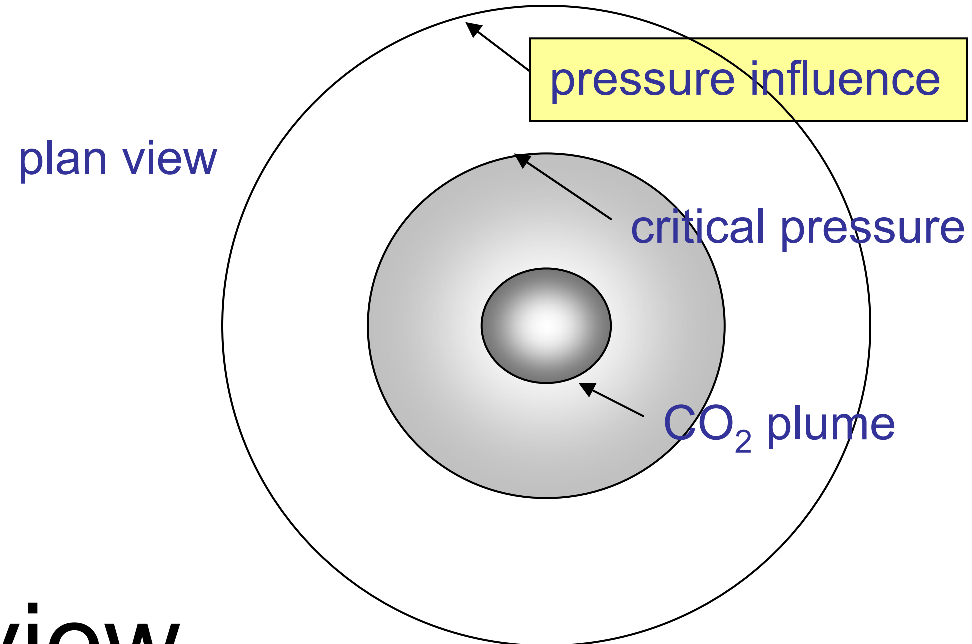
- proposed UIC Class VI (CO_2 injection wells)
- based on the potential for endangerment of the USDW
- AoR focuses the survey for compromises of the sealing layer (fractures, faults, abandoned wells)
- corrective action evaluated for abandoned wells in AoR

Need for Simple AoR Tools

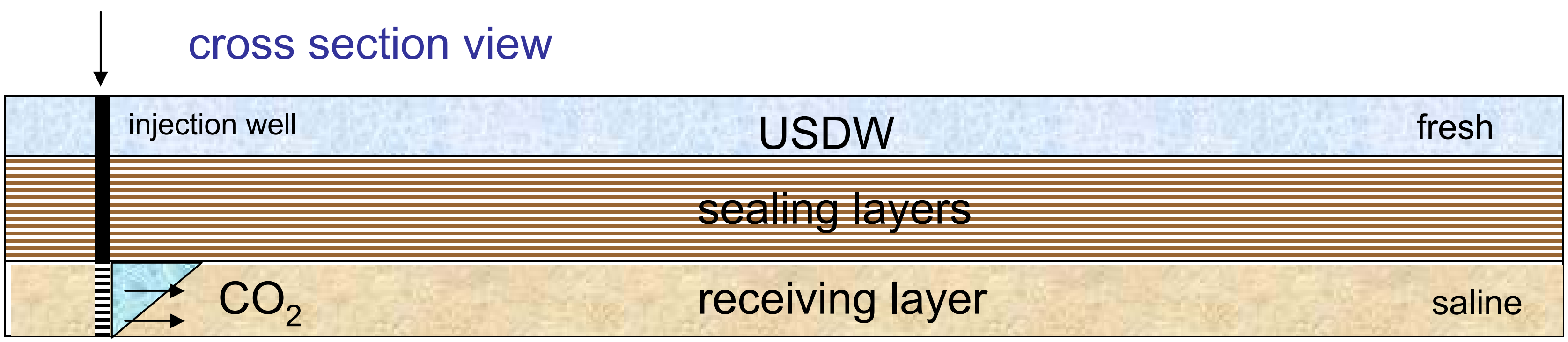
"Keep your models as simple as possible …
but not simpler." --- Albert Einstein

- tools to assist the regulator to evaluate the permit application
- tools to build initial understanding of a site and prepare for detailed numerical simulation
- arbitrary fixed radius (e.g. 2 mile) might be too simple
- analytical and semi-analytical solutions are easy to use and understand and fast





Area of Review



Project Objectives

- Task 1. Investigation of the analytical and semi-analytical solutions for pressure increase and CO_2 plume.
- Task 2. Development of the modeling frameworks (computational engines, user interfaces).
- Task 3. Testing of the AoR tools through comparison to numerical simulations and case studies.

Pressure Influence (1) simplest

(Theis, 1935)

$$\Delta p = \frac{Q}{4\pi KH} W(u);$$

$$u = \frac{S\ r^2}{4KHt}$$

Δp is the change in pressure [FL^{-2}]

Q is the injection rate (positive into the aquifer) [L^3T^{-1}]

K is the hydraulic conductivity of the aquifer [L^2]

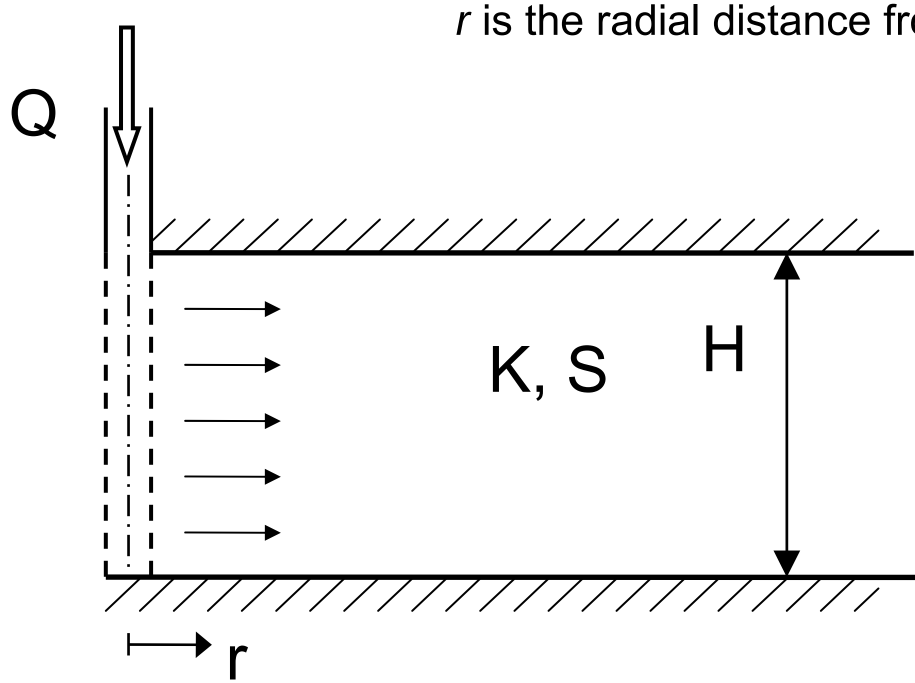
S is the storativity of the aquifer [-]

r is the radial distance from the center of the injection well [L]

H is the aquifer thickness [L]

t is time since injection started [T]

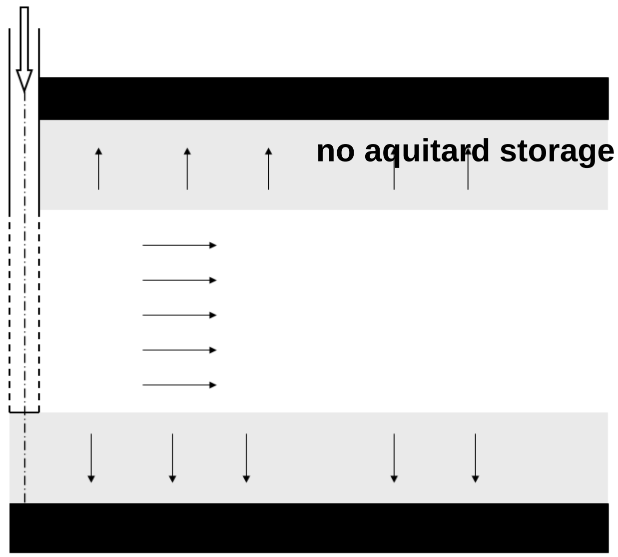
W() is the well function



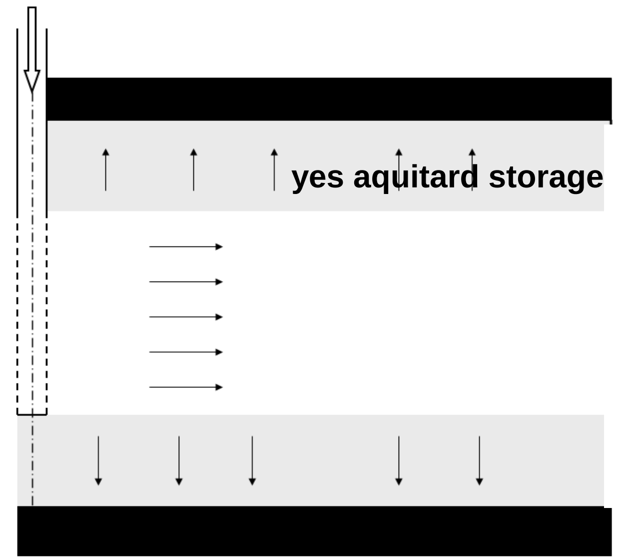
Note: given a constant mass injection rate goal for CO_2, an equivalent injection volume rate of brine is informed by ECO2N.

Pressure Influence (2)

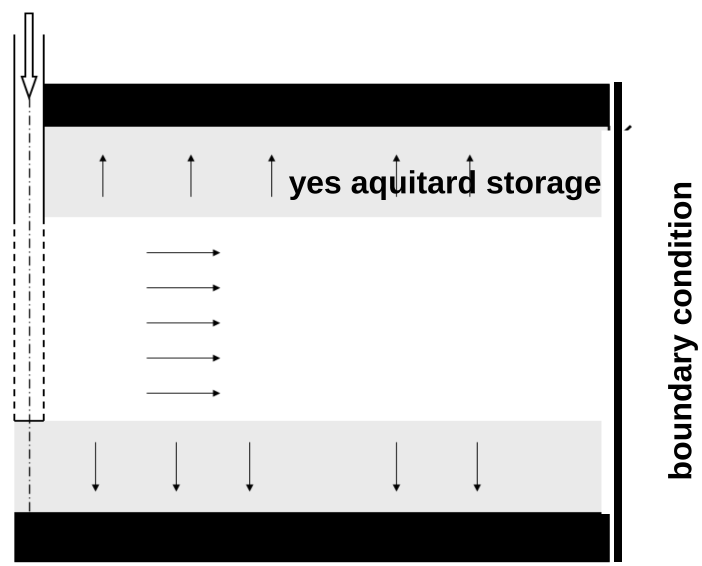
Hantush-Jacob
1955



Moench
1985



Zhou et al.
2009



also working on
- multi aquifer layers

Critical Pressure (1) simplest

$$\Delta p_c = 0.433[\gamma_B D_B + \gamma_W (D_W - L)] - p_0$$

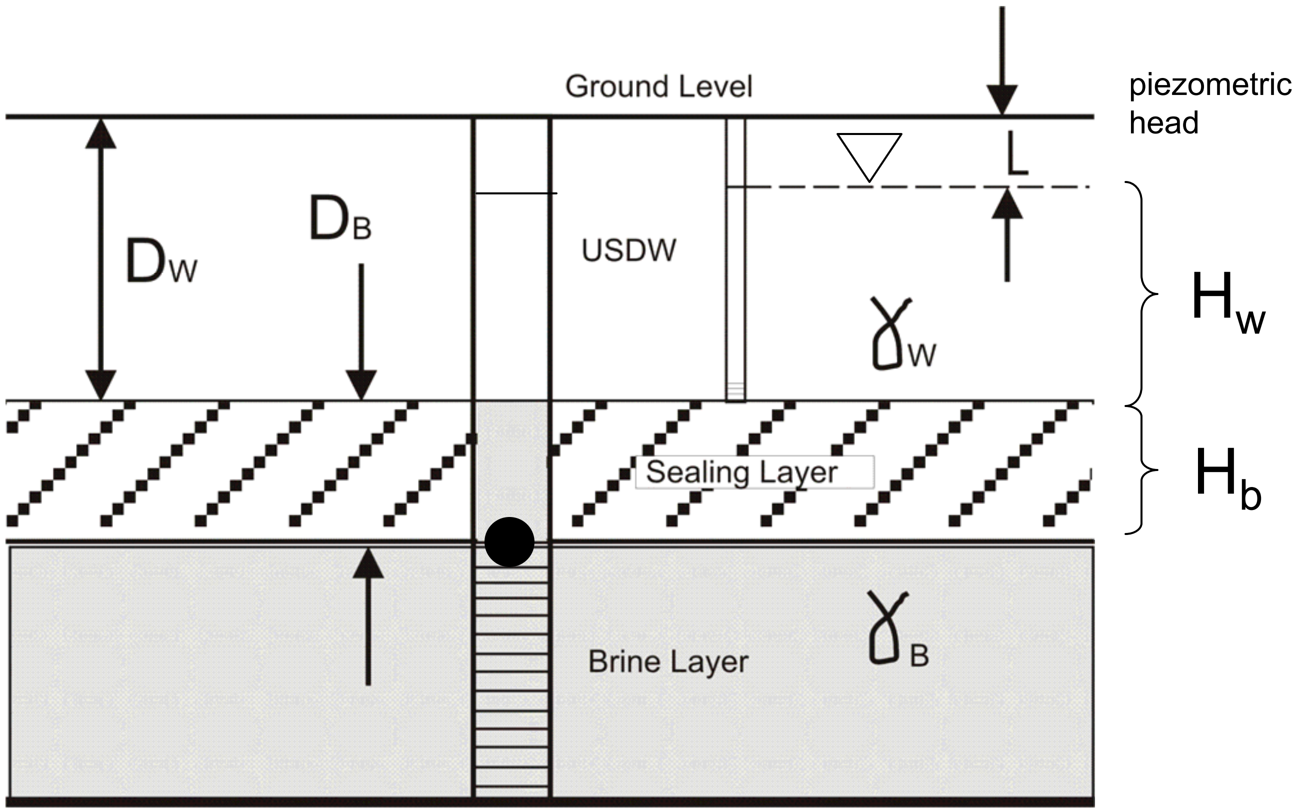
psi pressure distance units ft

or relative density

$\gamma_B \equiv$ *average specific gravity of the brine* → RD_b

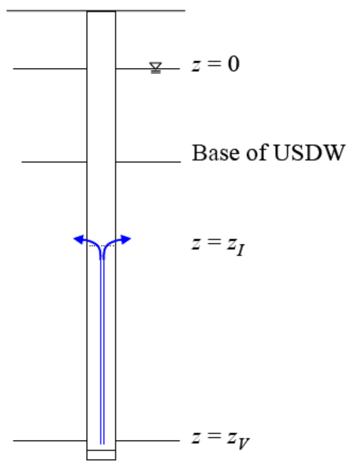
$\gamma_W \equiv$ *average specific gravity of freshwater* → RD_w

p_0 = *original reservoir pressure injection interval*



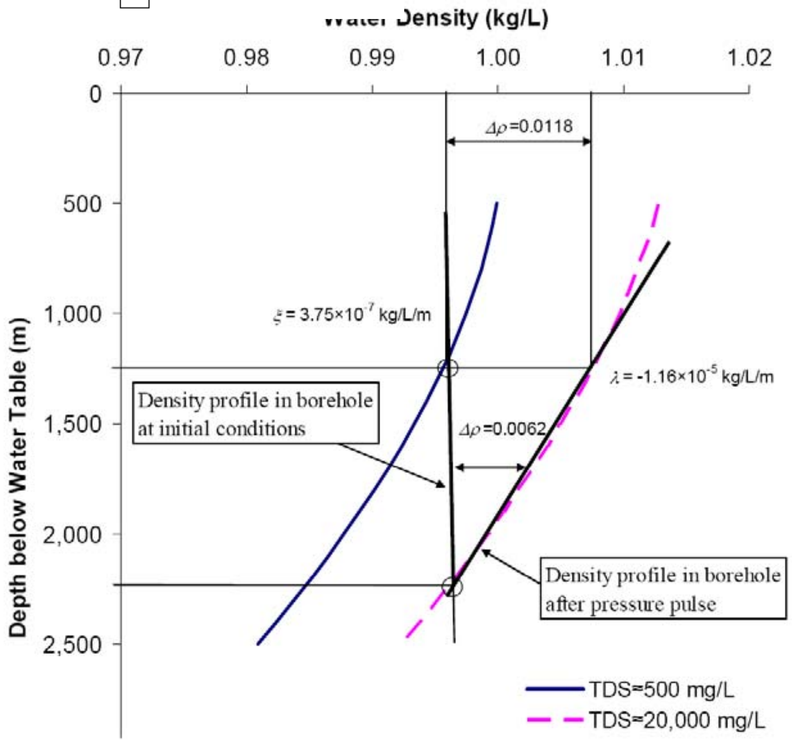
Critical Pressure (2)

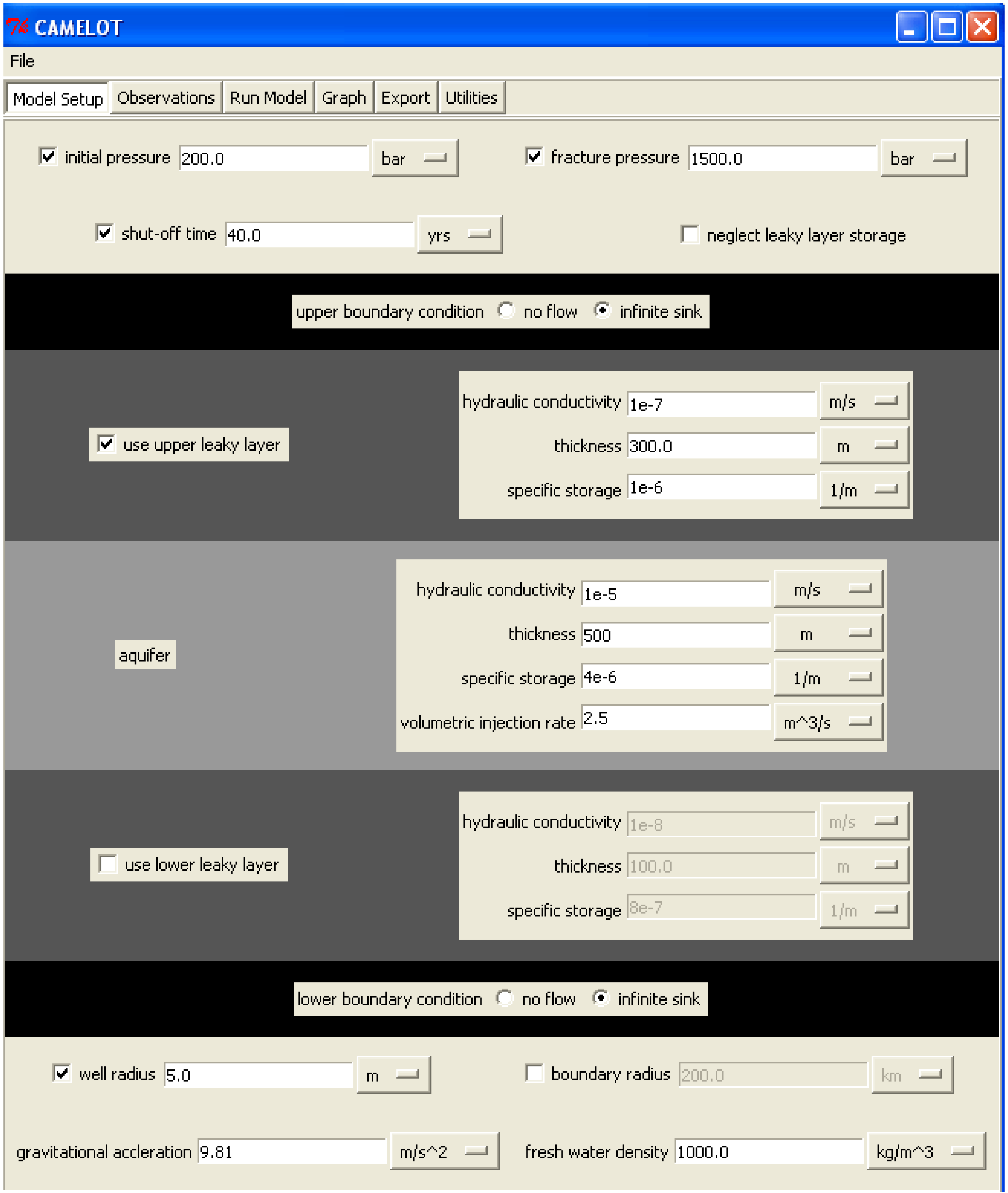
(Nicot et al., 2008)



$$\frac{\Delta P}{g} = (z_v - z_I)\left(\frac{\lambda - \xi}{2}(z_v - z_I) + \underbrace{\rho_{I,\lambda} - \rho_I}_{\text{density difference}}\right)$$

Parameter
Top of injection Fm. (m) Z_V
Base of USDW (m) Z_I
Injection Fm. TDS (g.L^{-1})
Borehole range of salinity (g.L^{-1})
Density gradient λ at constant TDS (kg.L^{-1}.m^{-1})
Initial density gradient ξ in borehole (kg.L^{-1}.m^{-1})
Final density difference at base of USDW (kg.L^{-1})
Maximum admissible pressure (bar)
Distance from injection well (km)





CAMELOT

(Karl Bandilla, 2010)

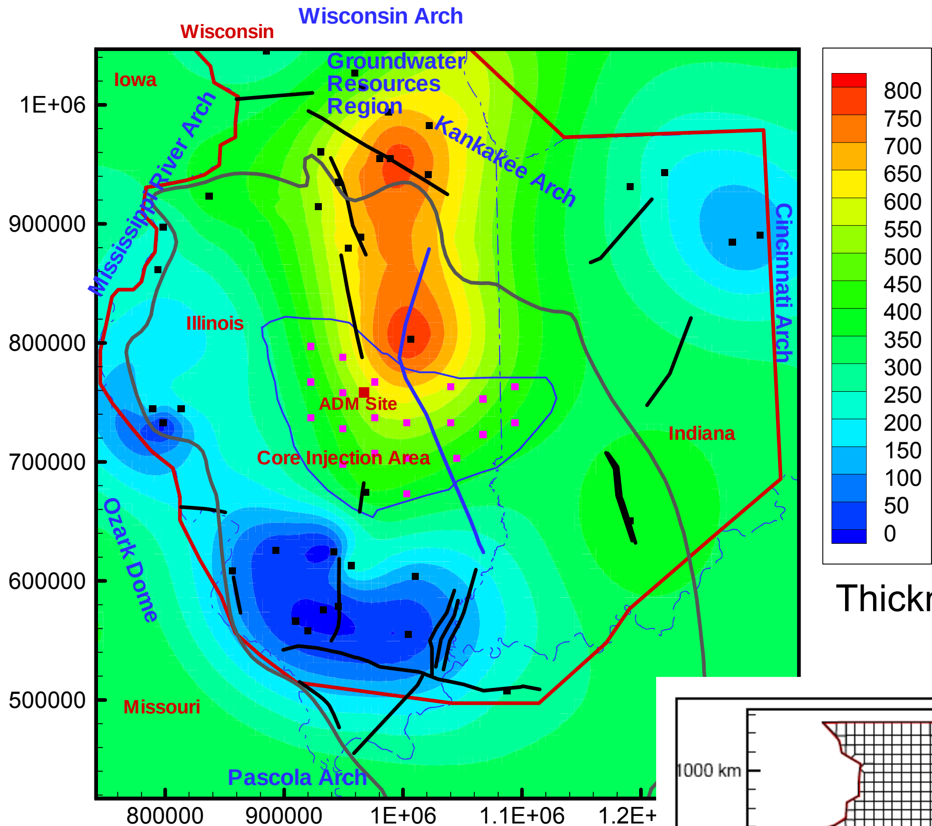
-Theis, Hantush-Jacob, Moench, Zhou (Fortran)

-ECO2N EOS utilities

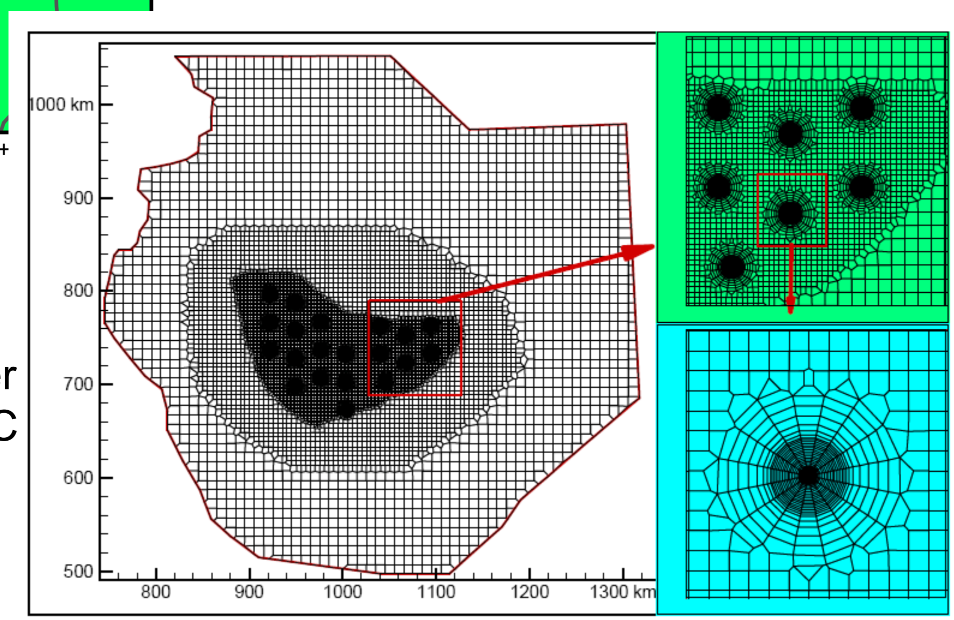
- Python solvers

- Tkinter interface

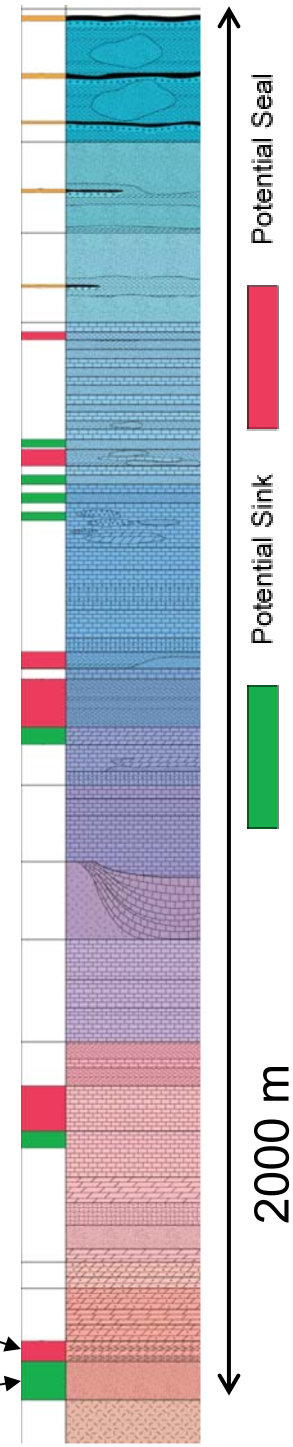
Hypothetical Case Study Illinois Basin



Thickness Mt. Simon (m)



TOUGH2/ECO2N
supercomputer



Eau Claire seal

Mt. Simon Sandstone

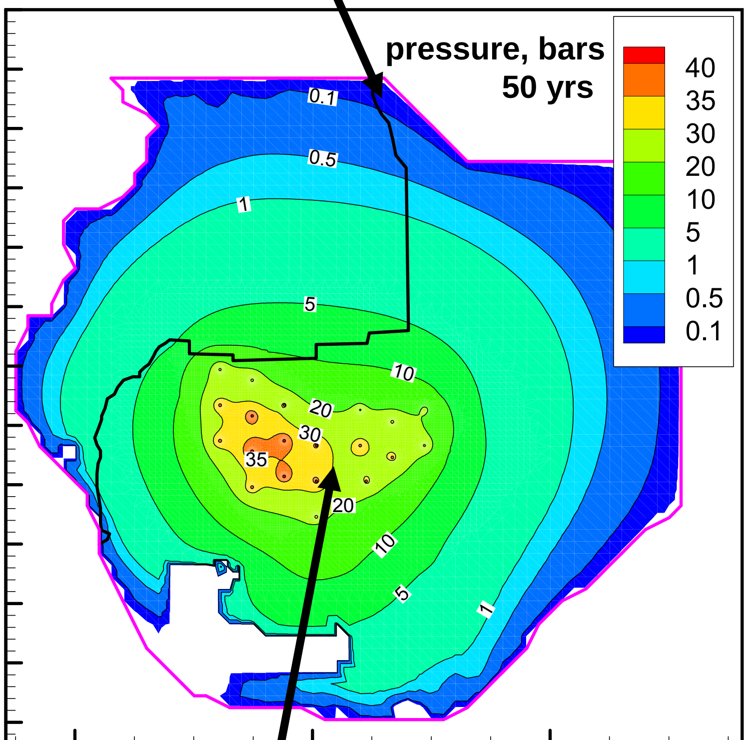
Jens Birkholzer, Quanlin Zhou, LBNL

Zhou et al., 2009, Ground Water

Birkholzer, Zhou, 2009, IJGHGC

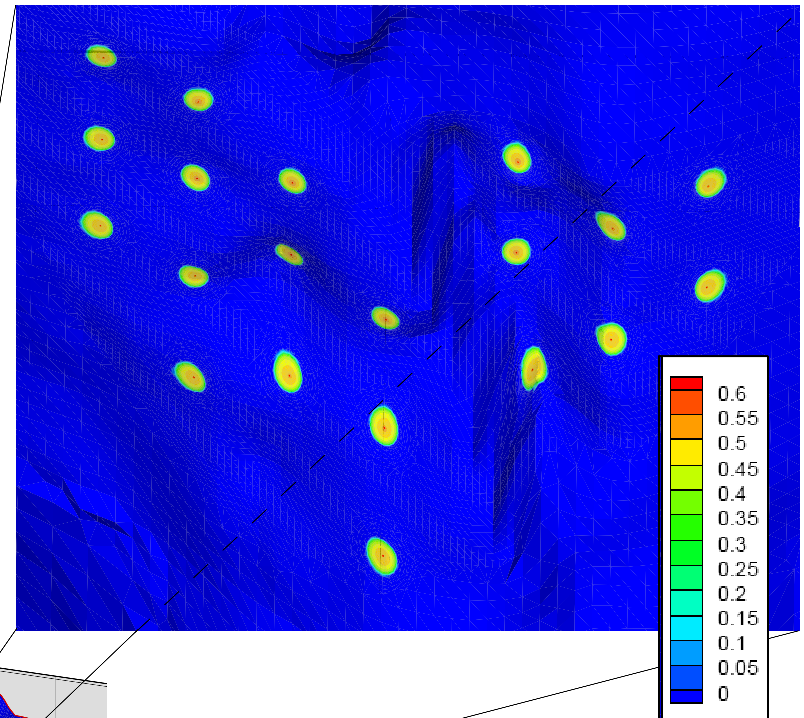
Pressure fronts are basin scale, CO_2 fronts are local scale

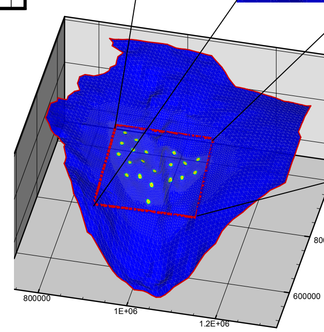
Chicago



FutureGen,
Mattoon, IL

CO_2 saturation at 50 yrs

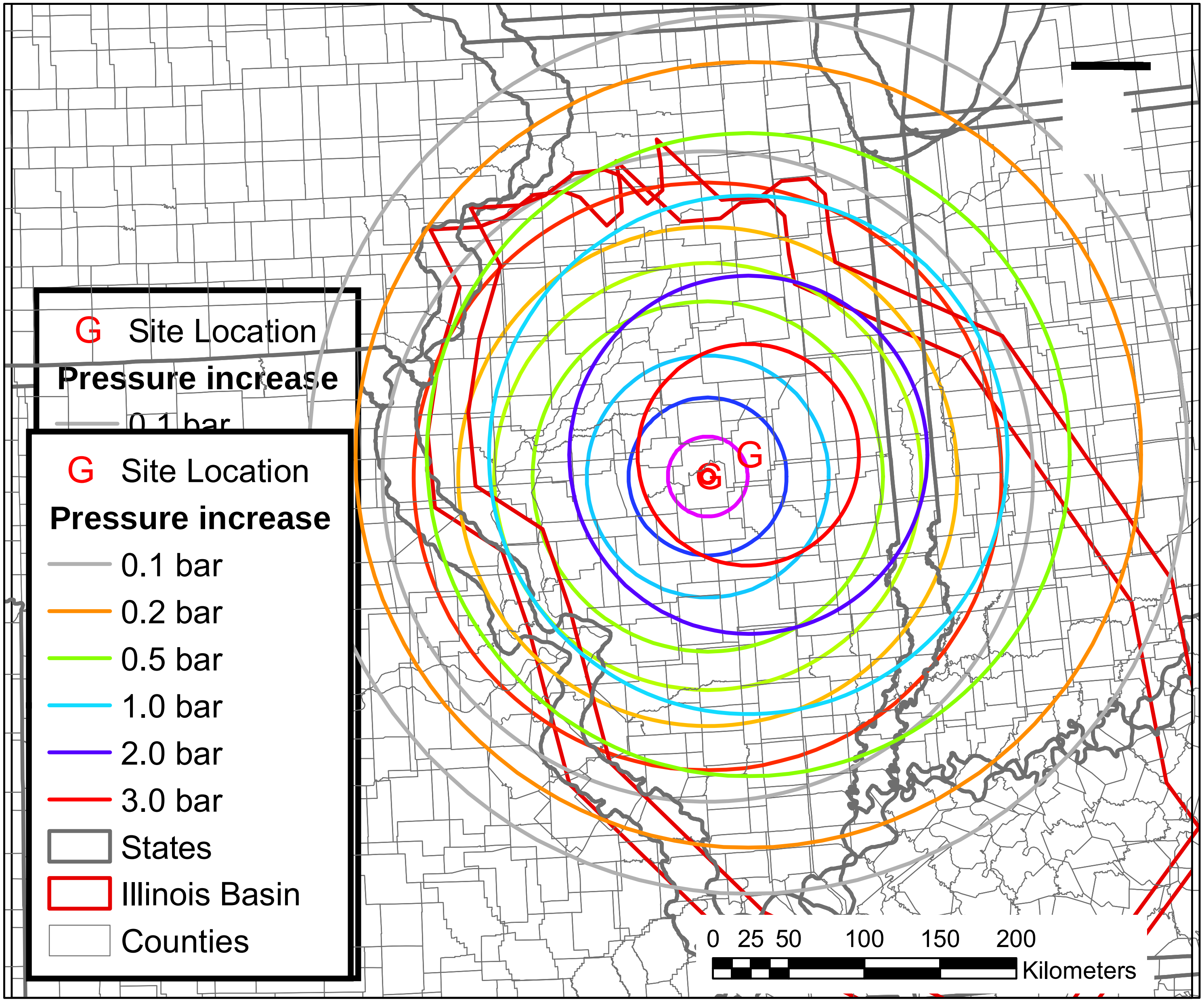




20 hypothetical injection wells
5 Mt CO_2/yr each
Total 100 Mt/yr

Zhou, Birkholzer, LBNL

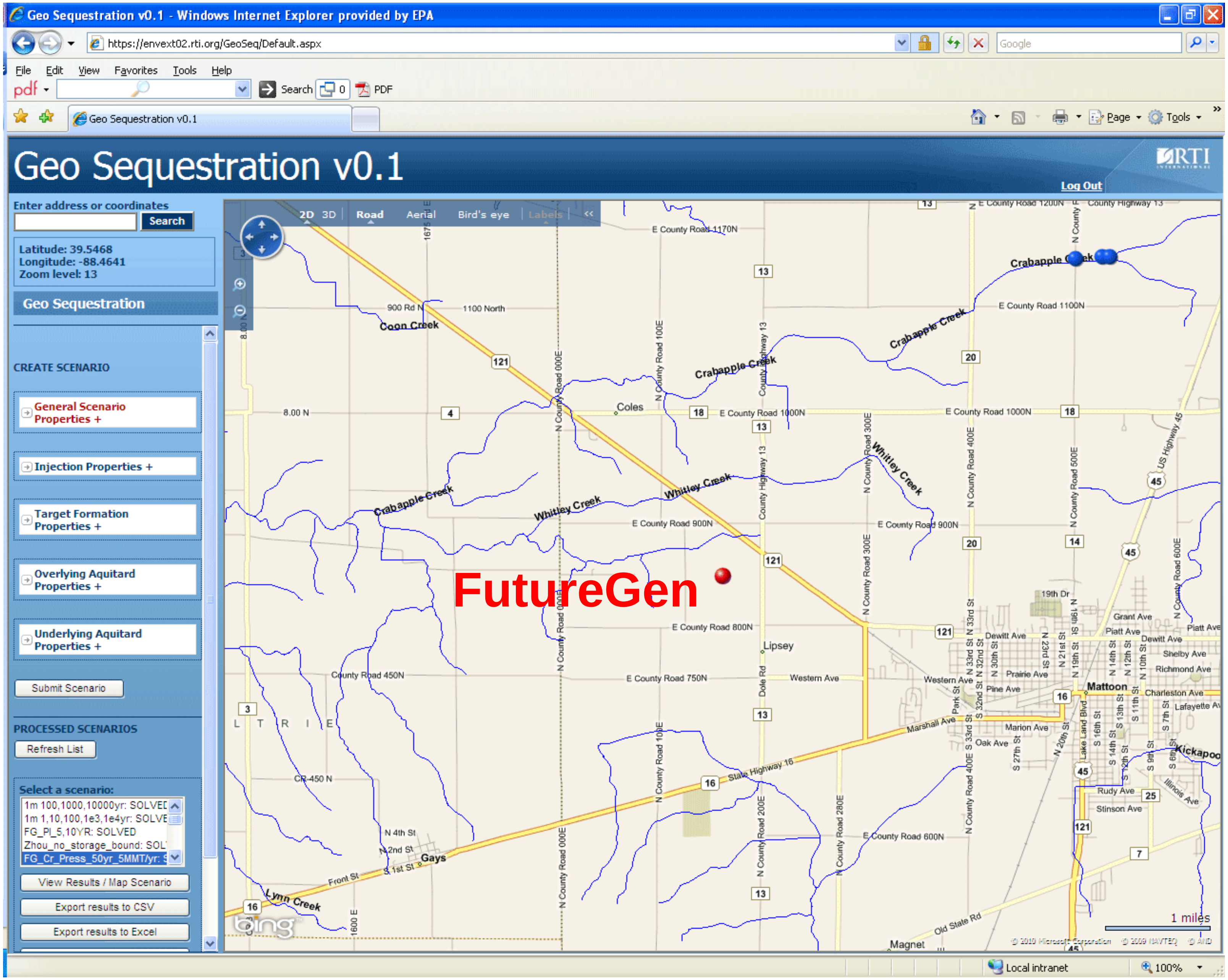
Pressure influence



100 yrs
50 yrs

CAMELOT
Moench
solution

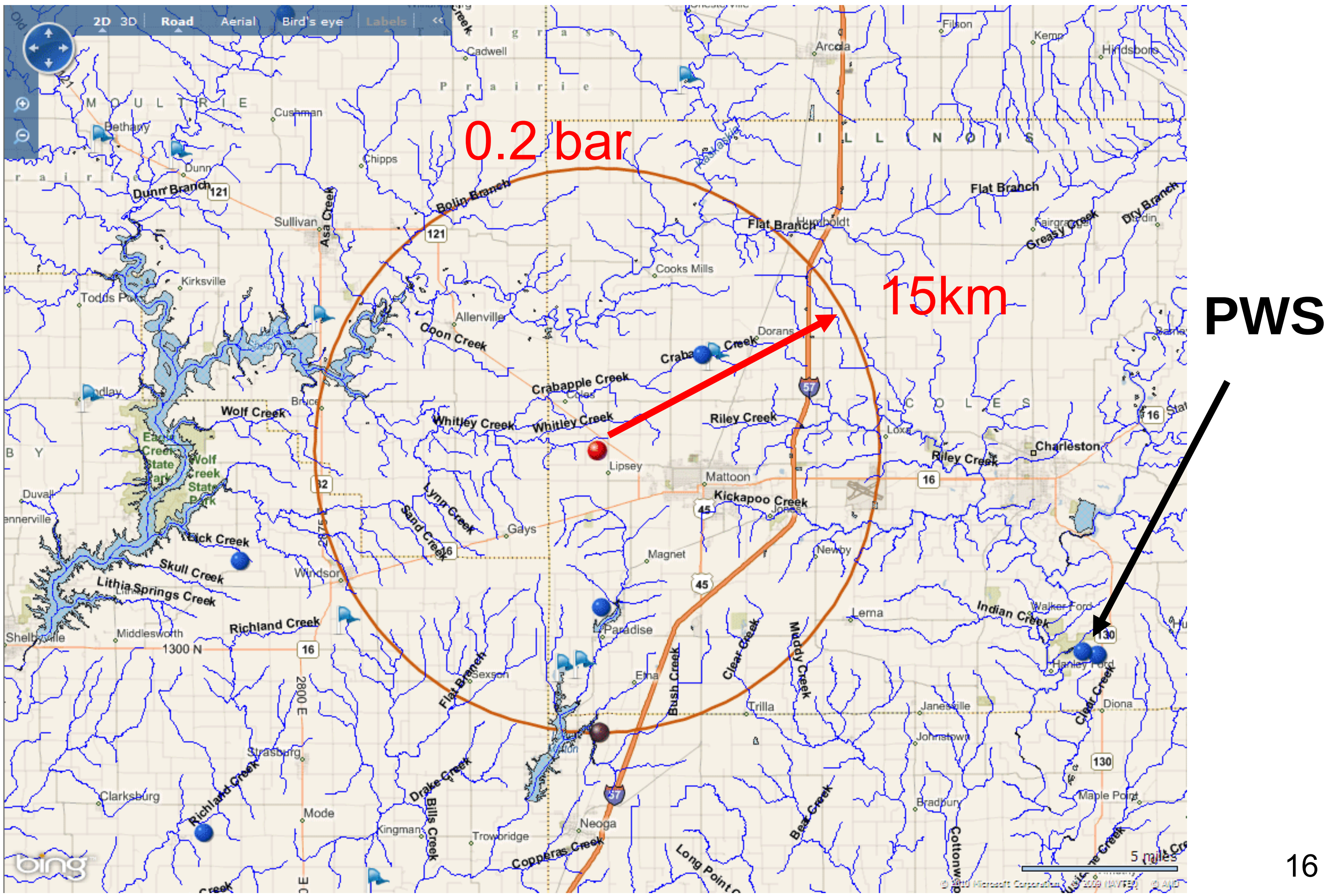
AoR web interface



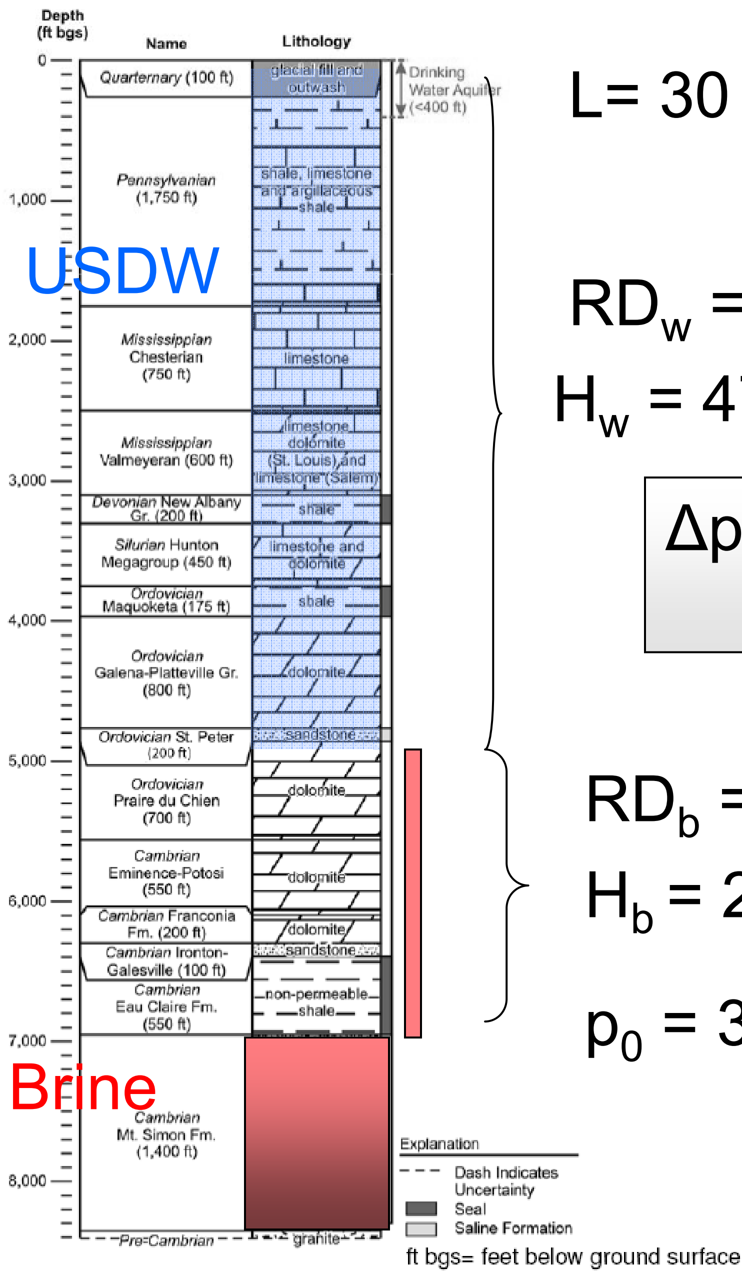
Data source:DOE/EIS-0394, 2007

Pressure influence –

hypothetical 5 MMt/yr CO_2 injection, 50 yrs



Test problem : critical pressure simple



L= 30 ft

RD_w = 0.998 **(assume TDS 10,000 *mg/l*)**

H_w = 4770 ft

$$\Delta p_c = (H_w * RD_w + H_b * RD_b) * 0.433 \text{ psi/ft} - p_0$$

RD_b = 1.09 **(assume TDS brine approx 140,000 *mg/l*)**

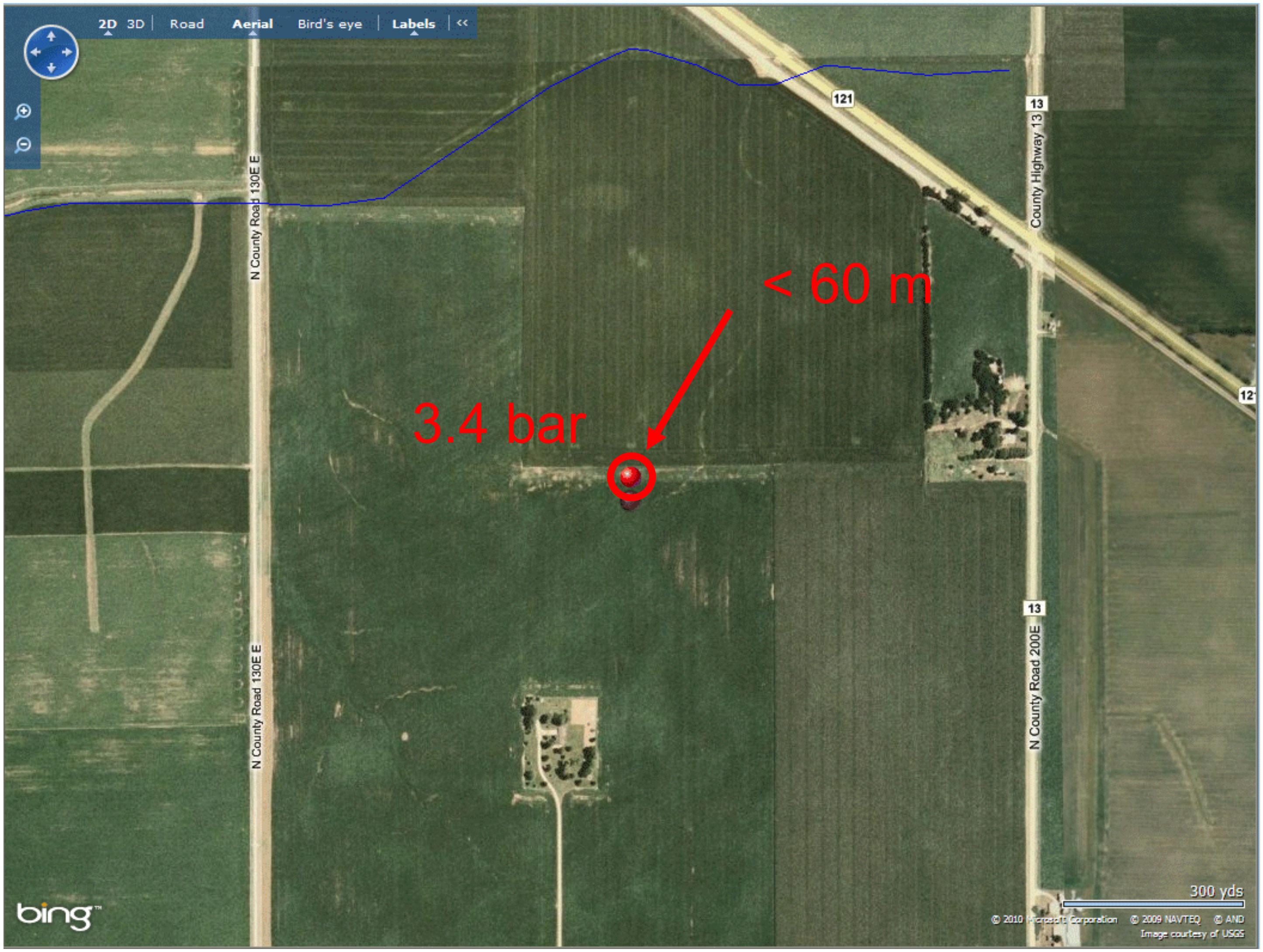
H_b = 2200 ft

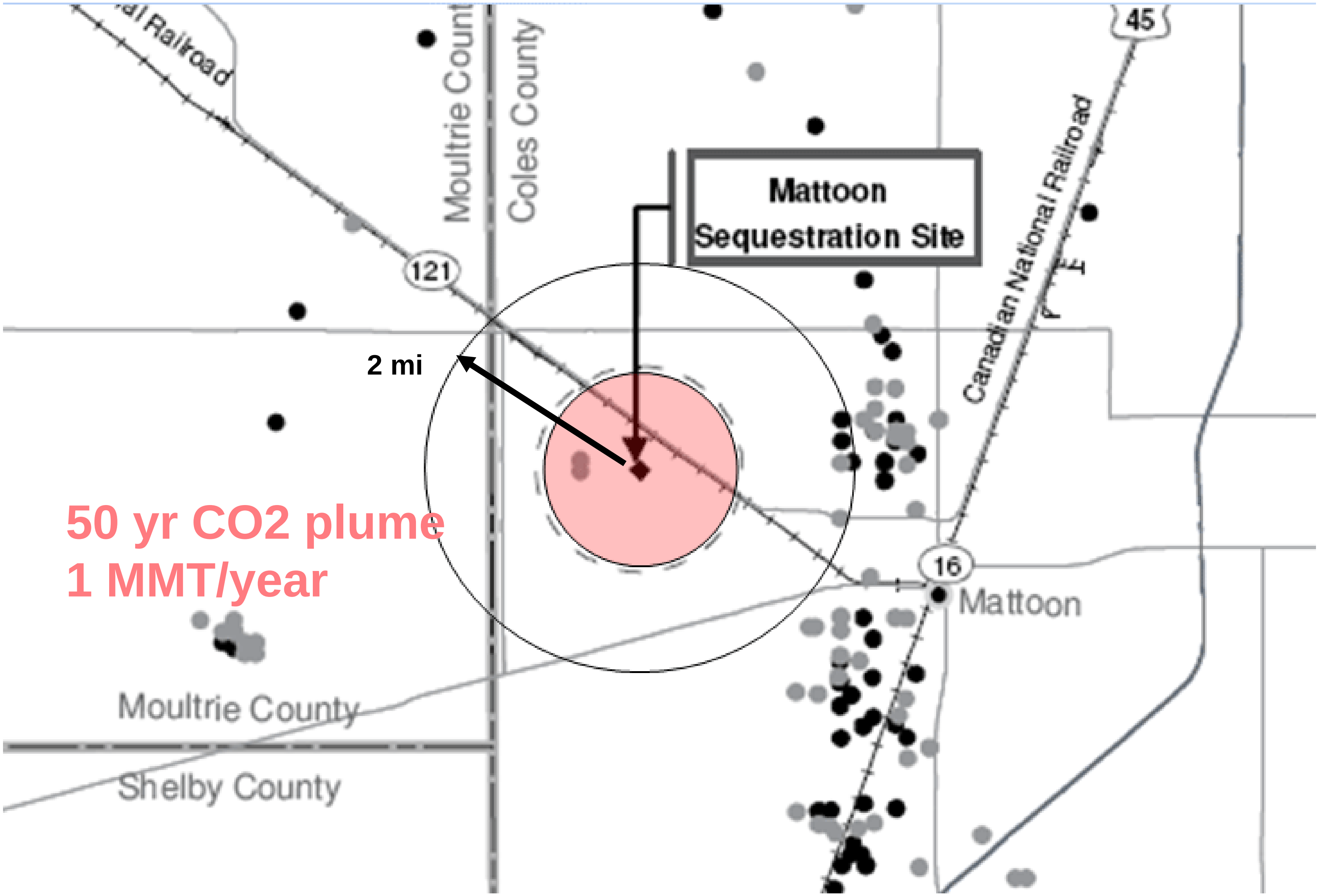
p_0 = 3031 psi **(assuming hydrostatic 0.433 psi/ft @ 7000 ft)**

$$\Delta p_c = 3080 - 3031$$
$$= 49.4 \text{ psi } (3.4 \text{ bar})$$

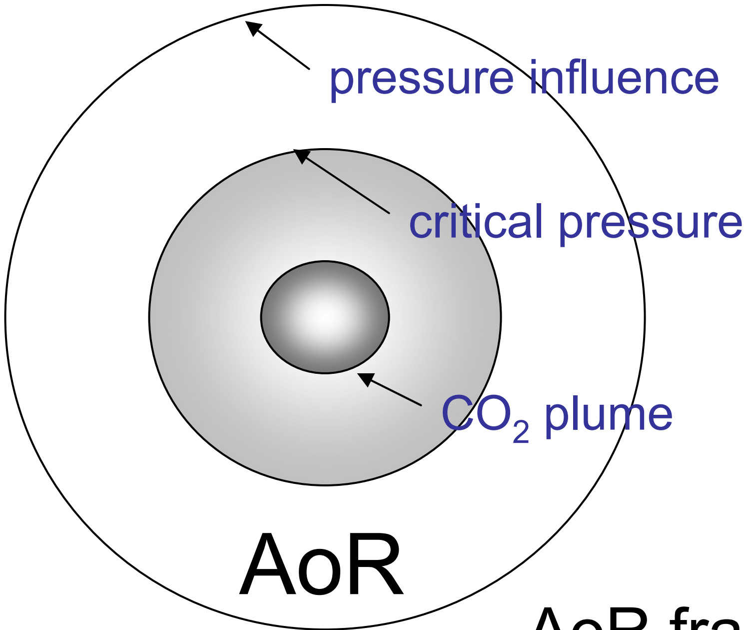
Critical Pressure –

hypothetical 5 MMt/yr CO_2 injection, 50 yrs





DOE/EIS-0394, 2007



Summary

AoR solutions

- Camelot tool
  - Python solvers, Karl Bandilla
  - pressure influence, Theis, Hantush-Jacob, Moench,Zhou
- working on, critical pressure, LBNL
- working on, CO_2 front, Princeton

AoR frameworks

- GeoSequestration tool (web-based)
  - Bing maps, RTI
- working on BAEM, analytic element solutions, Mark Bakker
  - MapWindow GIS (desktop), Dan Ames
- working on, uncertainty analysis, Justin Babendreier,
  -EPA SuperMUSE, FRAMES

AoR testing

- TOUGH2/ECO2N (LBNL)
- FutureGen, Mattoon, IL
- possible Kimberlina, CA

Acknowledgements

Audrey Levine, Ph.D.
National Program Director
Drinking Water, Wash. DC

Candida West, Ph.D., Acting Director
EPA/ORD/NERL/ERD-Athens

Macarthur Long, Ph.D.,
Acting Deputy Director

John M. Johnston, Ph.D., Chief
Regulator Support Branch

Jeff McDonald,
USEPA R5 Chicago

Stephen Kraemer, Ph.D.
Lead Principal Investigator
ERD-Athens

- project schedule, progress coordination
- quality assurance project plan
- documentation

Justin Babendreier, Ph.D.
Co Principal Investigator
ERD-Athens

- uncertainty analysis, SuperMUSE

Janice Sims
ERD Tech Info Manager

Jim Kitchens
ERD QA Manager

Dominic DiGiulio, Ph.D.
Co-Principal Investigator
EPA/ORD/NRMRL/GWERD-Ada,OK

- technical monitor, review

Jens Birkholzer, Ph.D.
Quanlin Zhou, Ph.D.
LBNL Earth Sciences Div
EPA/DOE IAG

- semi-analyical solvers
- TOUGH2/ECO2N solvers
- pressure response/leakage
- applications: Illinois Basin, Kimberlina, CA

Michael Celia, Ph.D. & team
Princeton University
EPA STAR cooperative agreement
Barbara Klieforth

- mixed semi-analytical numerical solvers
- web interface
- separate phase CO2 transport

Karl Bandilla, Ph.D.
National Research Council
Research Associate, Athens, GA

- Python toolkit of semi-analytic solvers
- analytic element modeling

Cadmus (Patricia Hertizer) &
RTI International (Jay Rineer)
EPA OW contract

- web-based interface, DWMA database

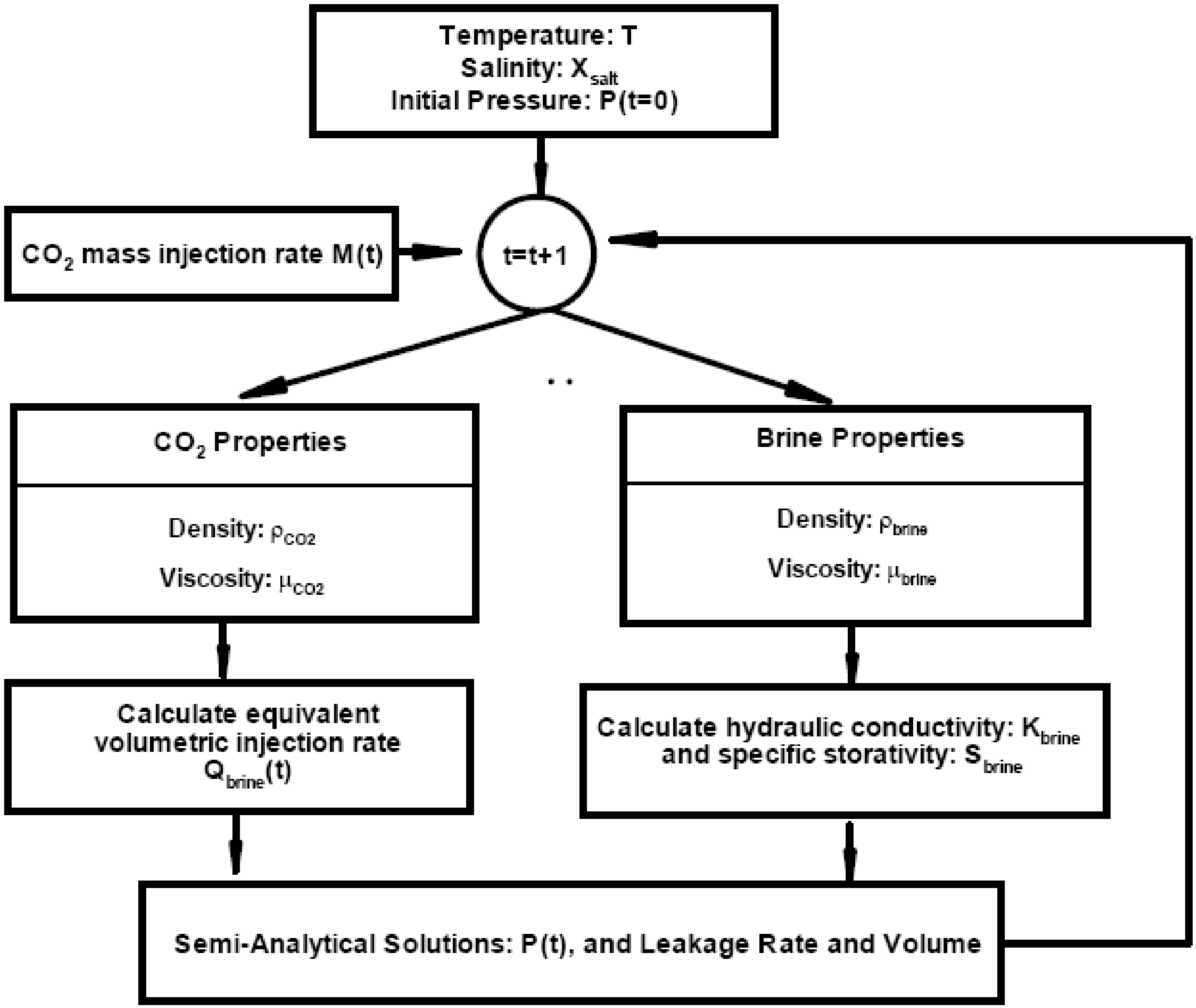
RTI International (Bill Cooter,
Robert Truesdale)
EPA NWPP contract

- desktop interface

Mark Bakker, Delft TU
GSA contract

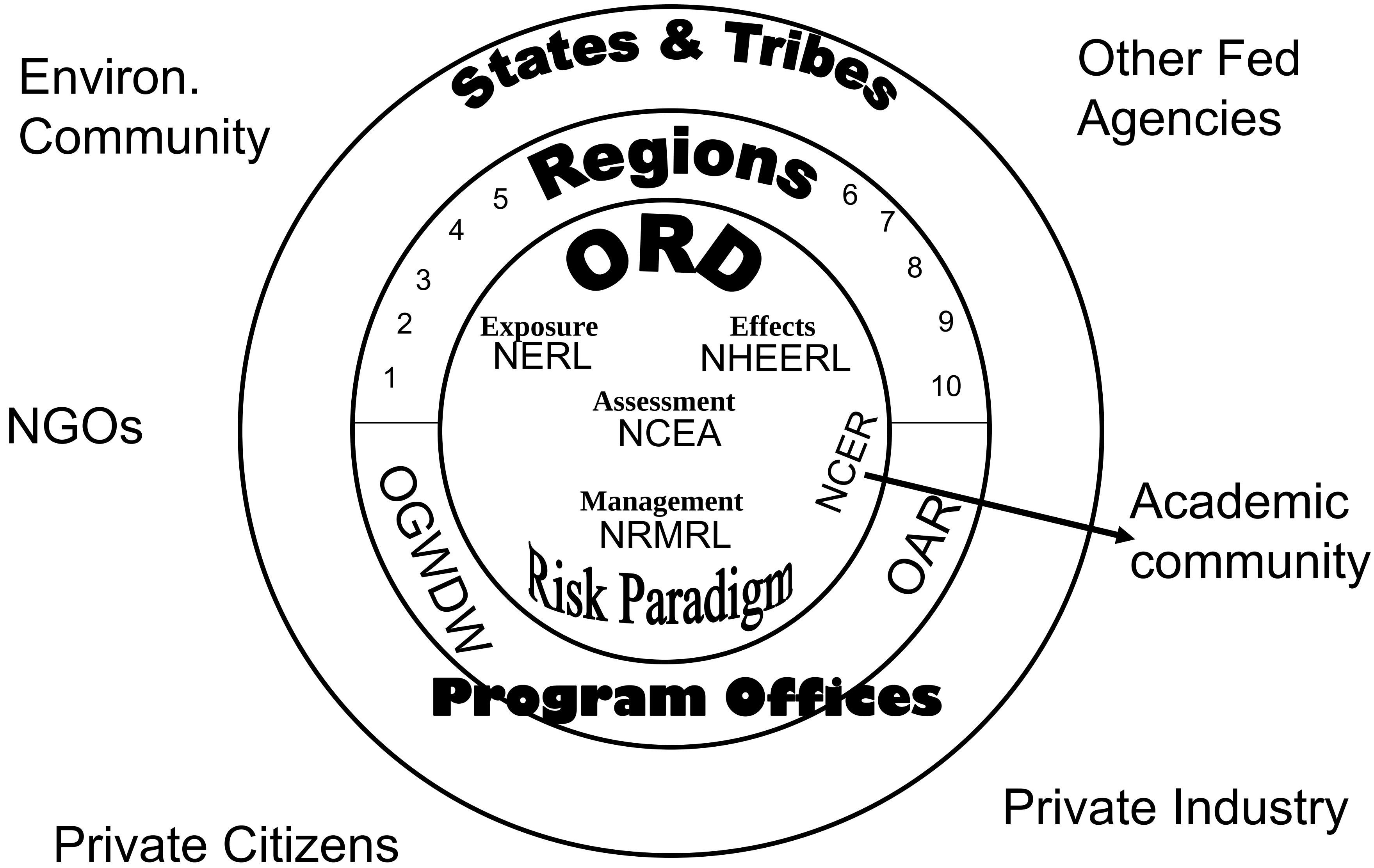
- transient multi-layer analytic element solution

AoR_Project_Management3.cdr


Temperature: T
Salinity: X_{salt}
Initial Pressure: P(t=0)
CO_2 mass injection rate M(t)
t=t+1
CO_2 Properties
Density: ρ_{CO2}
Viscosity: μ_{CO2}
Brine Properties
Density: ρ_{brine}
Viscosity: μ_{brine}
Calculate equivalent volumetric injection rate $Q_{brine}(t)$
Calculate hydraulic conductivity: K_{brine} and specific storativity: S_{brine}
Semi-Analytical Solutions: P(t), and Leakage Rate and Volume

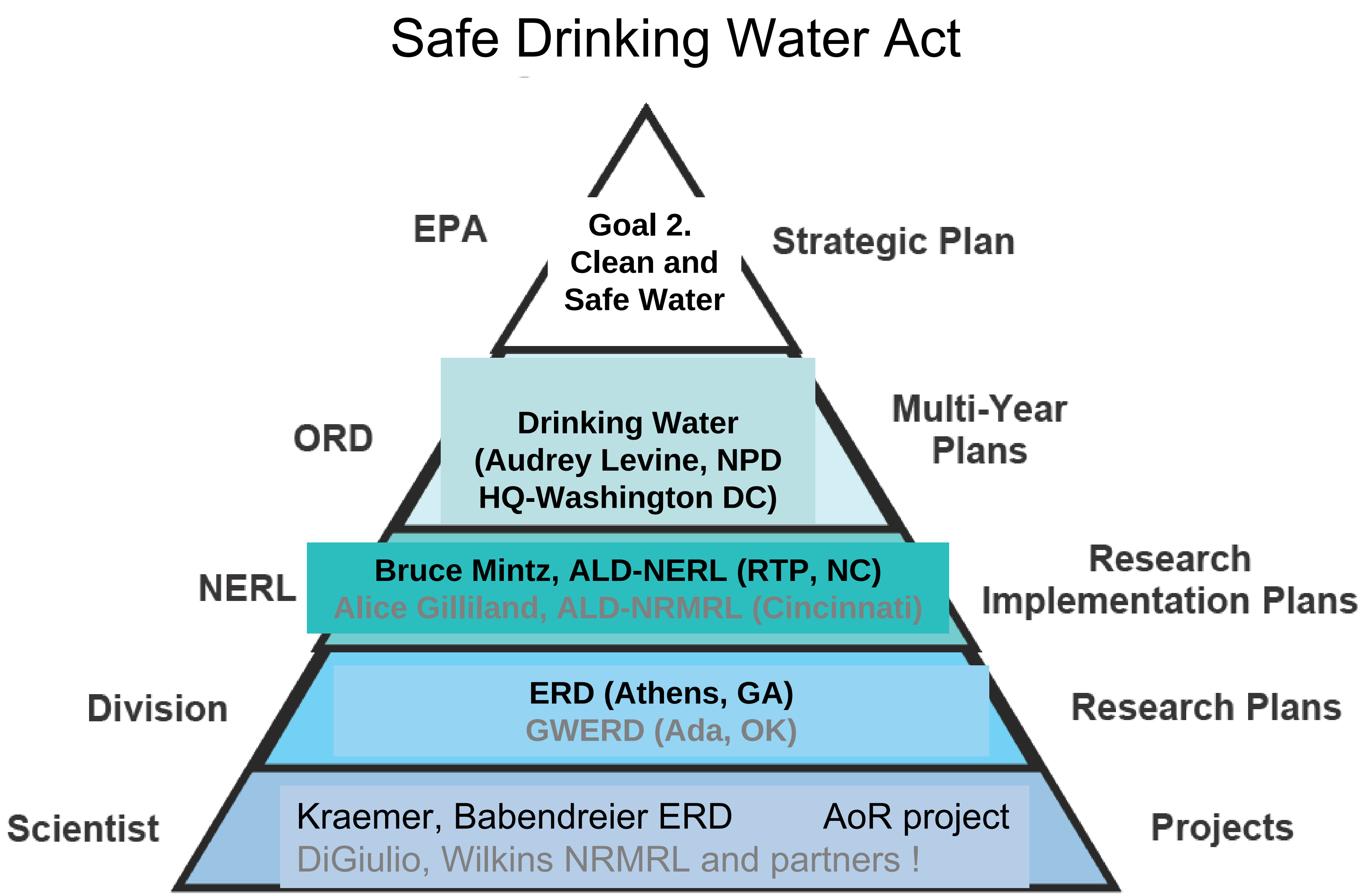
ECO2N

Clients Map

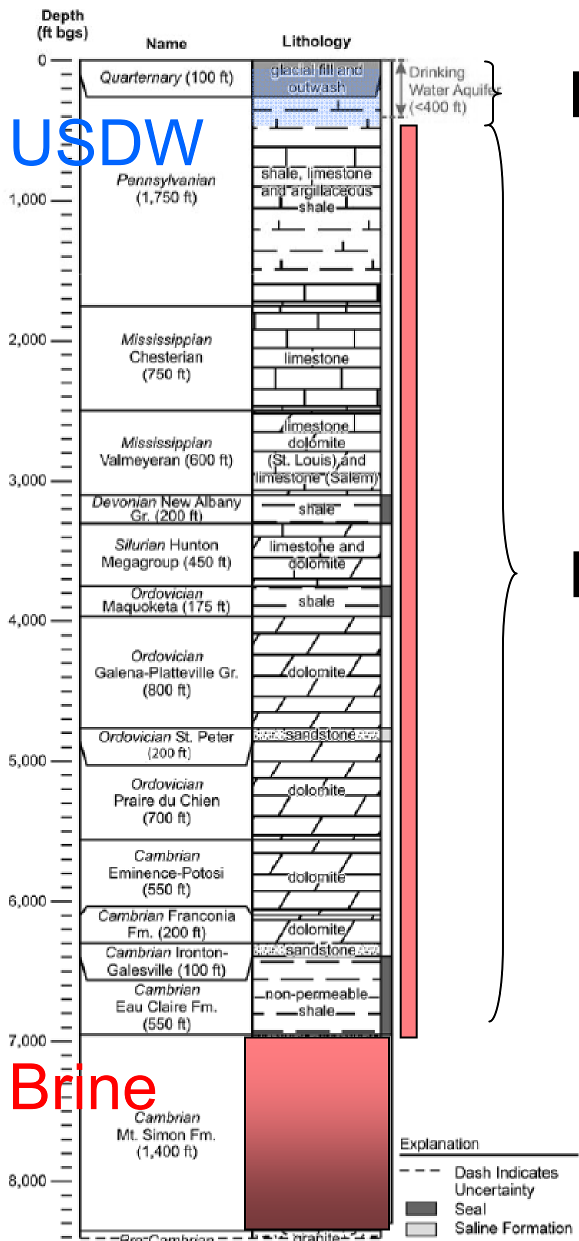


Environ. Community
Other Fed Agencies
States & Tribes
Regions
5
4
3
2
1
6
7
8
9
10
ORD
Exposure
NERL
Effects
NHEERL
Assessment
NCEA
Management
NRMRL
Risk Paradigm
NCER
OAR
OGWDW
Program Offices
NGOs
Academic community
Private Industry
Private Citizens

EPA Research Map



Critical Pressure FutureGen



ft bgs= feet below ground surface

L= 30 ft

H_w = 370 ft

RD_w = 1.0

$$\Delta p_c = (H_w * RD_w + H_b * RD_b) * 0.433 \text{ psi/ft} - p_0$$

H_b = 6,600 ft

RD_b = 1.07 **(assume TDS brine approx 140,000 *mg/l*)**

p_0 = 3031 psi **(assuming hydrostatic 0.433 psi/ft @ 7000 ft)**

$$\Delta p_c = 3218 - 3031 = 187 \text{ psi } (12.89 \text{ bar})$$