NRAP workshop

- Introduction
- Fluid Migration Characterization
- State-of-stress Characterization
- Risk-based Area of Review
- U.S. DOE's SMART Initiative
- Plume Dynamics and Conformance
- Induced Seismicity Management
- Monitoring for Leak Detection
- Site Closure
- Discussion

Application of NRAP's Integrated Assessment Model to Determine Risk-Based Area of Review

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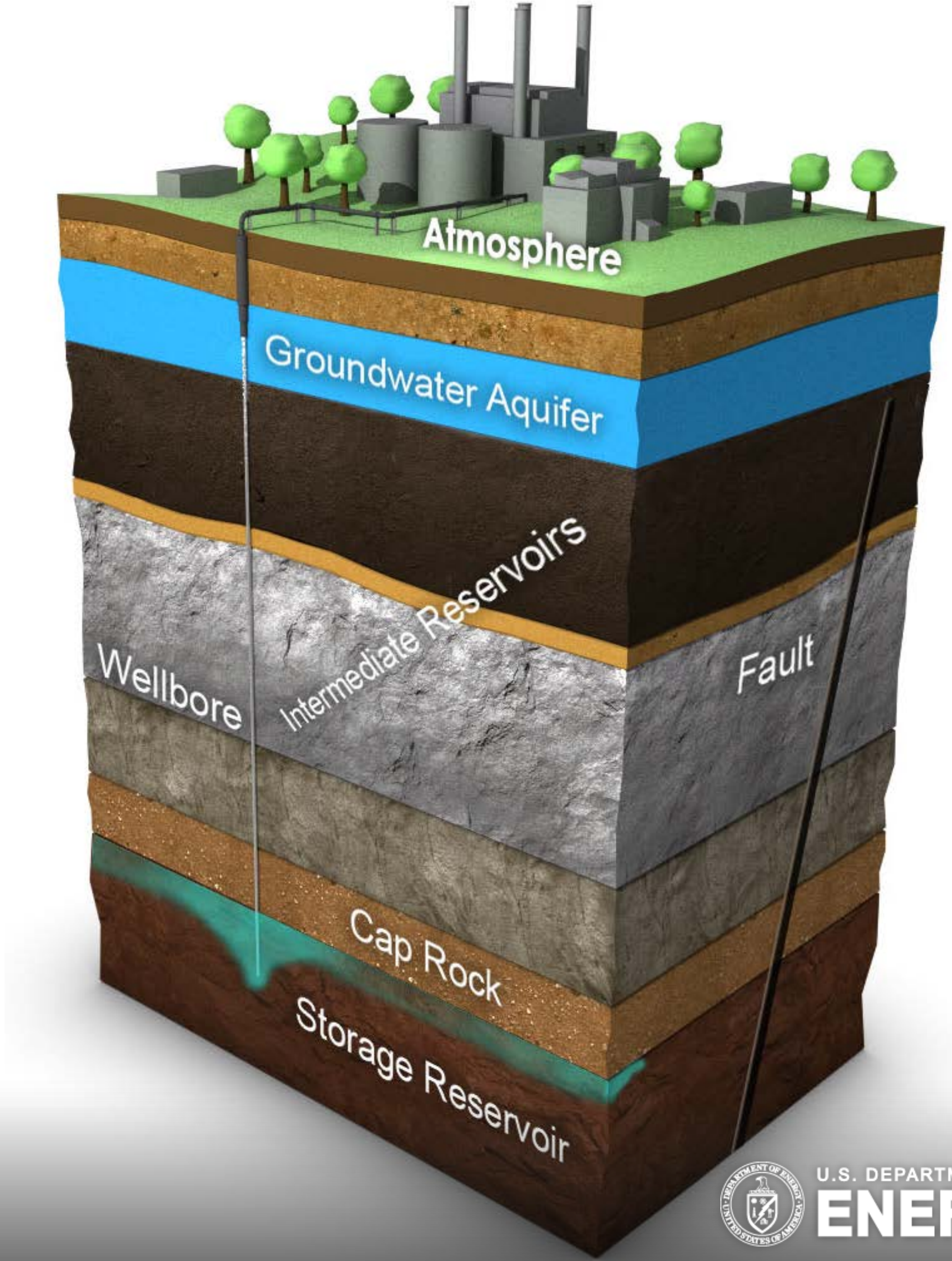

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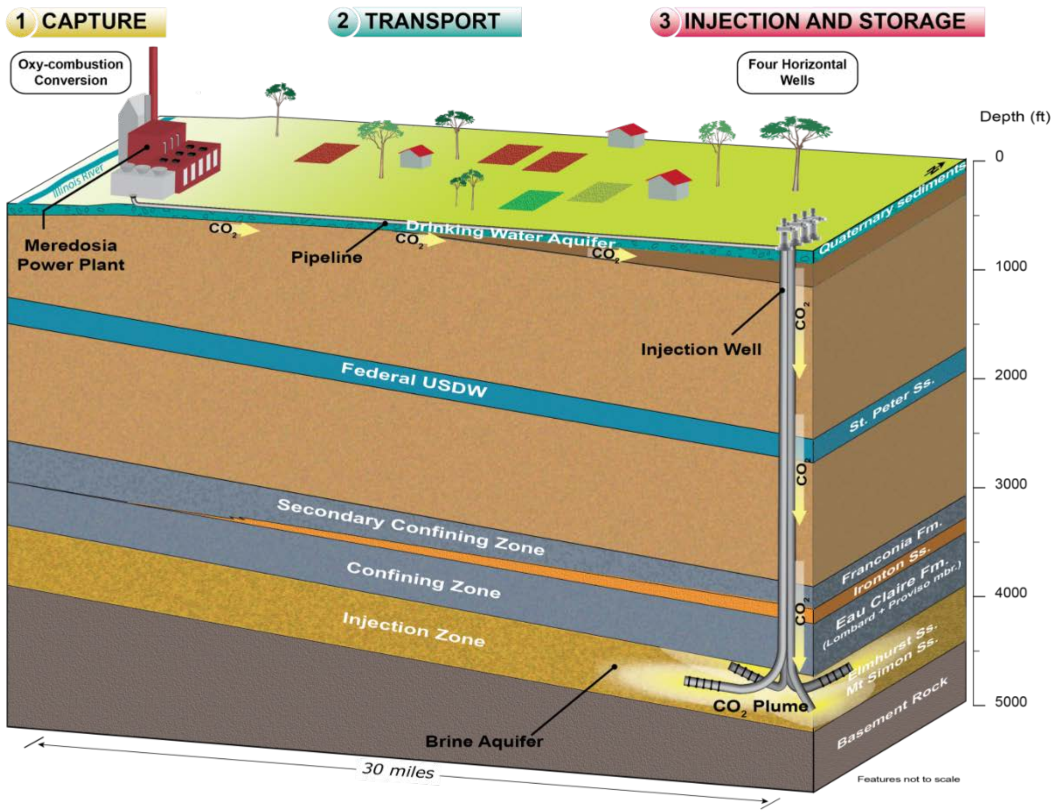
Motivation

- Evaluation of suite of tools developed by National Risk Assessment Partnership for quantitative risk assessment of geologic sequestration of carbon dioxide
- Existing datasets used for this evaluation (FutureGen 2.0)
- Can we use these tools to develop a risk-based methodology for delineating the Area of Review (AoR) for a CCS project?



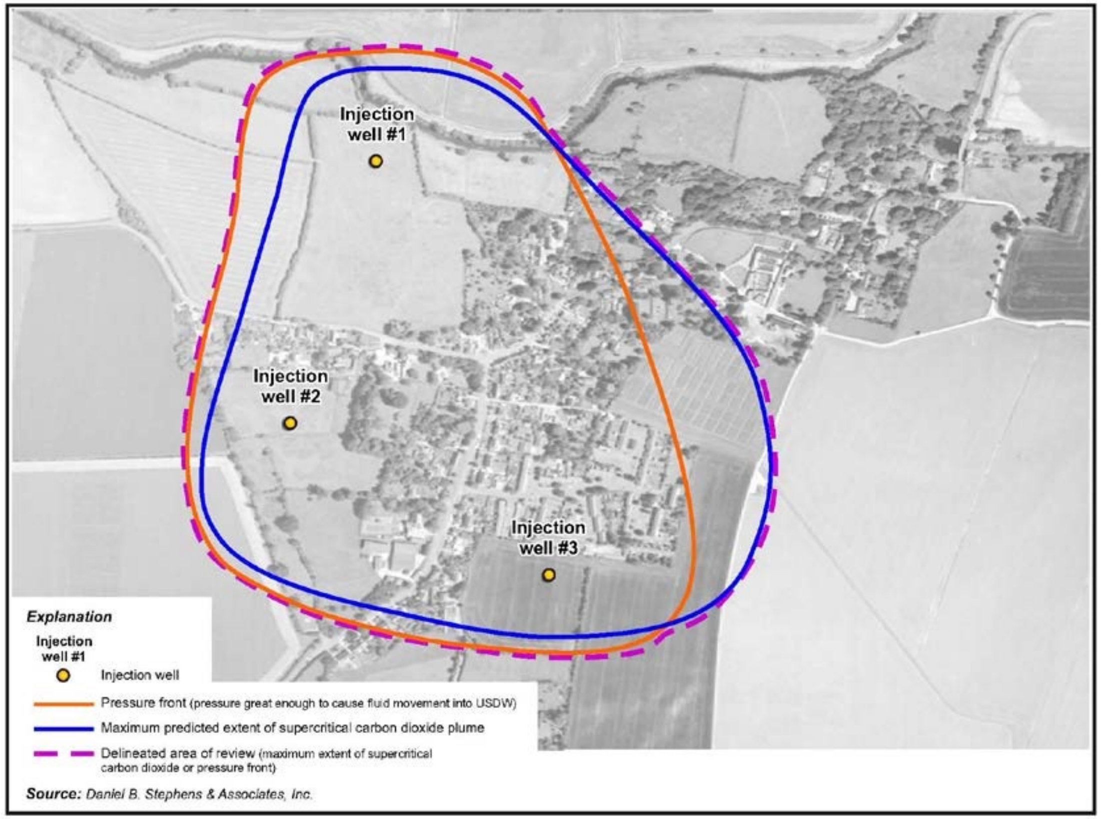
Outline

Risk-based Area of Review

- **Area of Review**
  - Definition
  - Underpressured
  - Hydrostatic
  - Overpressured
  - Critical Pressure Calculation example
- **NRAP-Open-IAM**
  - General description
  - Flow chart
  - Interfaces
- **FutureGen 2.0 Example**
  - Graphical User Interface
  - Python script interface
- **Conclusions**

Area of Review (AoR) for CO_2 Storage Sites

- The area surrounding the injection project where groundwater resources may be endangered by the activity (i.e., project risk area)
- EPA requires operators applying for a Class VI CO_2 injection permit to determine the AoR based on the separate-phase CO_2 plume/pressure evolution predictions from physics-based computational modeling
- AoR is delineated by the maximum extent of CO_2 plume and pressure front over the lifetime of the project to account for risks associated with both CO_2 and/or brine leakage into the overlying groundwater aquifer



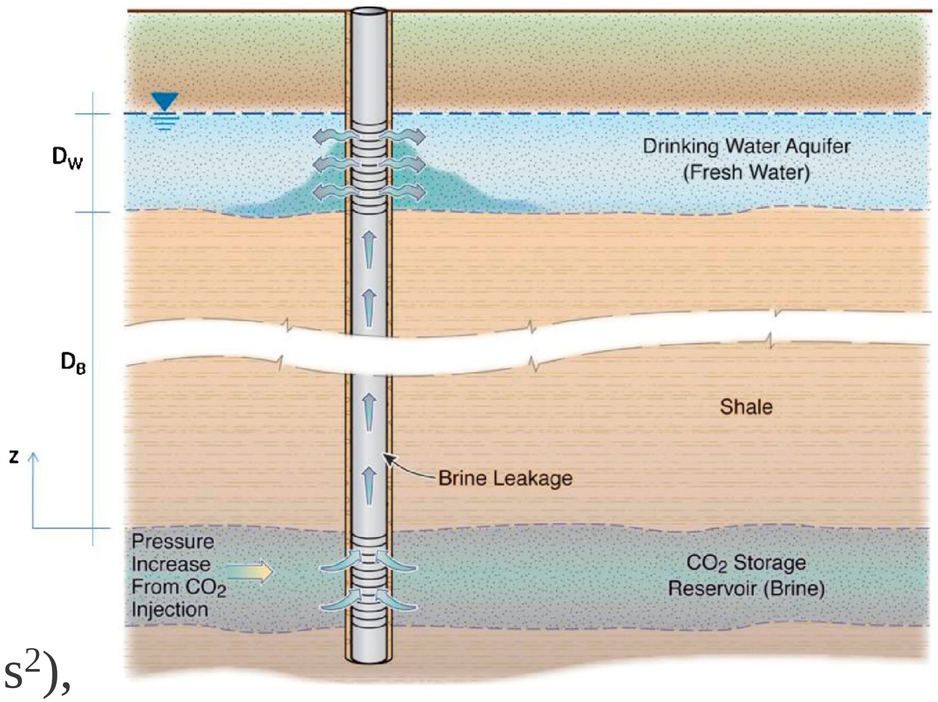
Pressure Front

- **Pressure difference needed to move fluids from reservoir to USDW through an open conduit (Birkholzer et al., 2011)**
- **Assumes density of the fluid in the wellbore is uniform**

$$\Delta P_{if} = P_u + \rho_i g \cdot (z_u - z_i) - P_i \quad (1)$$

where:

P_u = the initial pressure at the base of the USDW (Pa = kg/m·s^2),
ρ_i = the density of the injection zone fluid (kg/m^3),
g = the acceleration of gravity (m/s^2),
z_u = the depth to the base of the lowermost USDW (m),
z_i = the depth to the top of the injection zone (m), and
P_i = the initial pressure in the injection zone (Pa).



$\Delta P_{if} > 0$: Underpressured
$\Delta P_{if} = 0$: Hydrostatic
$\Delta P_{if} < 0$: Overpressured

Pressure Front

- **Pressure difference needed to displace existing fluid in the borehole (Nicot et al., 2009)**

$$\Delta P_c = \frac{1}{2} \cdot g \cdot \xi \cdot (z_u - z_i)^2 \qquad (2)$$

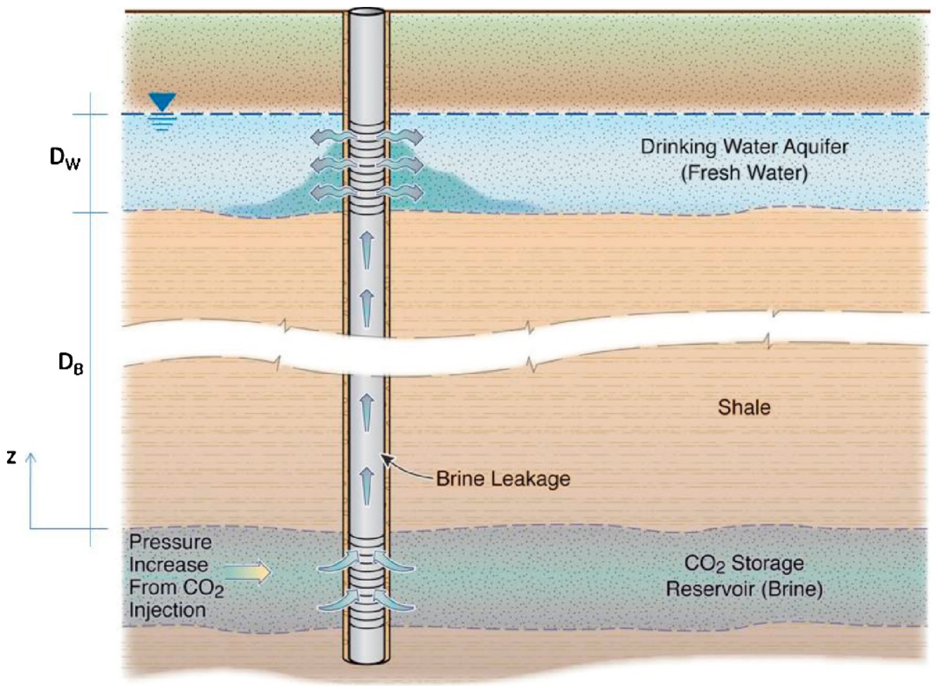
where:

g = the acceleration of gravity (m/s^2),

$\xi = \frac{\rho_i - \rho_u}{z_u - z_i}$ (kg/m^2),

z_u= the depth to the base of the lowermost USDW (m), and

z_i = the depth to the top of the injection zone (m).



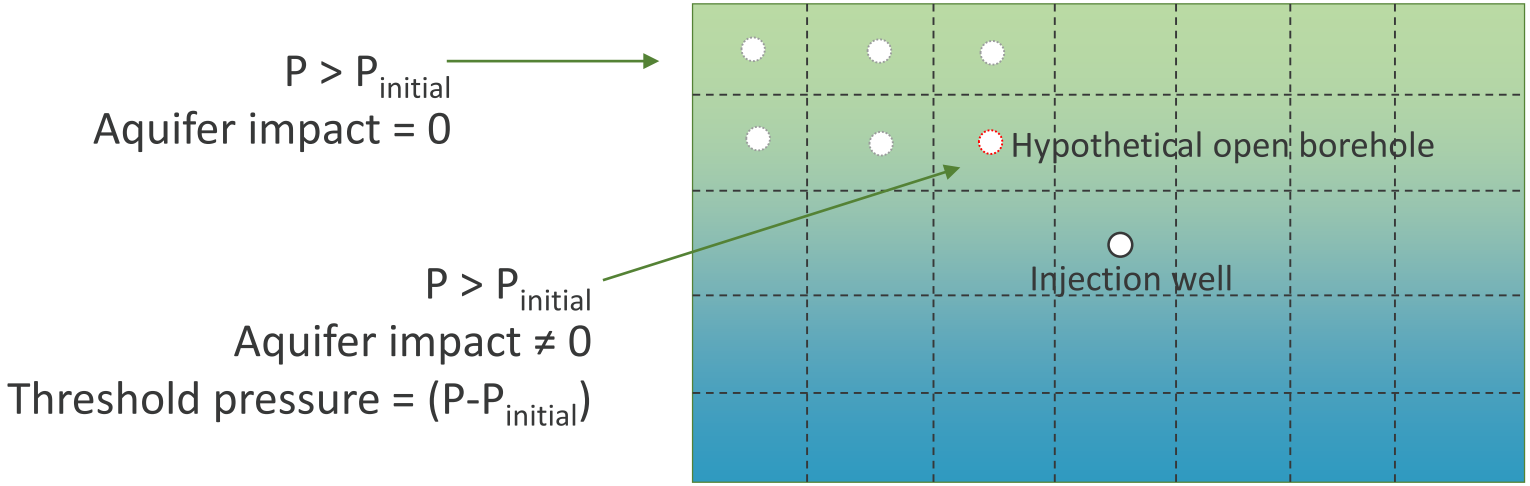
- **In cases where the reservoir is slightly overpressured, the difference in magnitude between ΔP_c and ΔP_{if} may be used as an estimate of the allowable overpressure**

Critical Pressure Calculation

Input Parameter	PAB Site	PMB Site
Depth to top of injection zone (m)	1,969	3,158
Depth at base of the lowermost USDW (m)	152.5	609
Initial pressure in injection zone (MPa)	21.03	32.57
Initial pressure at the base of the lowermost USDW (MPa)	0.43	2.964
Fluid density in the injection zone (kg/m^3)	1,270	1,144
Fluid density in the USDW (kg/m^3)	1,000	1,004
Pressure increase (ΔP_{if}) from Eqn. (1) (MPa)	2.01	-1.013
Pressure increase (ΔP_c) from Eqn. (2) (MPa)	NA	1.749
Allowable pressure increase for overpressured injection zone	NA	0.74
Critical Pressure (P_{crit}) used to define AoR (MPa)	23.04	33.31

Pressure Front (Over-Pressurized Conditions)

- **Determination of an "allowable pressure increase" (EPA Guidance) that causes fluid leakage into the aquifer and impact on the water quality**
- **Calculated based on:**
  - A multiphase numerical model designed to model leakage through wellbore(s)
  - A numerical or analytical approach to determine the threshold above which an impact to aquifer occurs

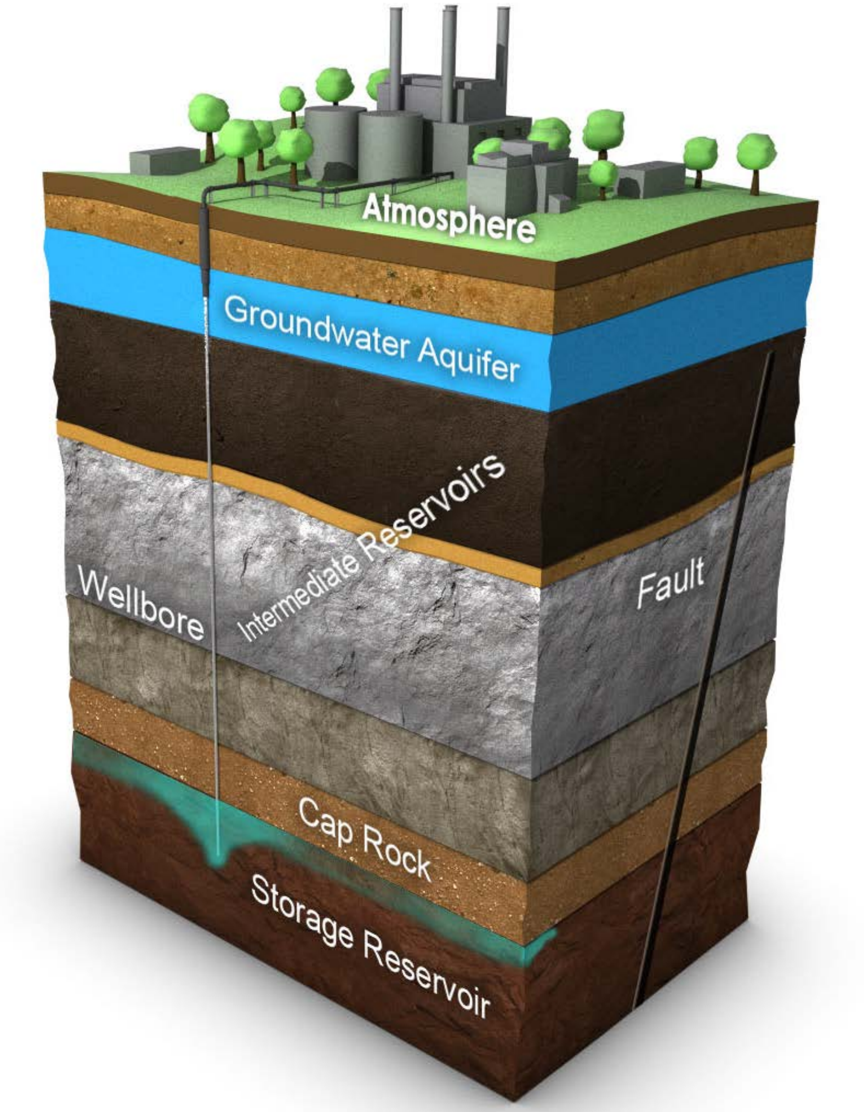


NRAP-Open-IAM

NRAP-Open-IAM is an open-source integrated assessment model developed by National Risk Assessment Partnership Phase II to facilitate

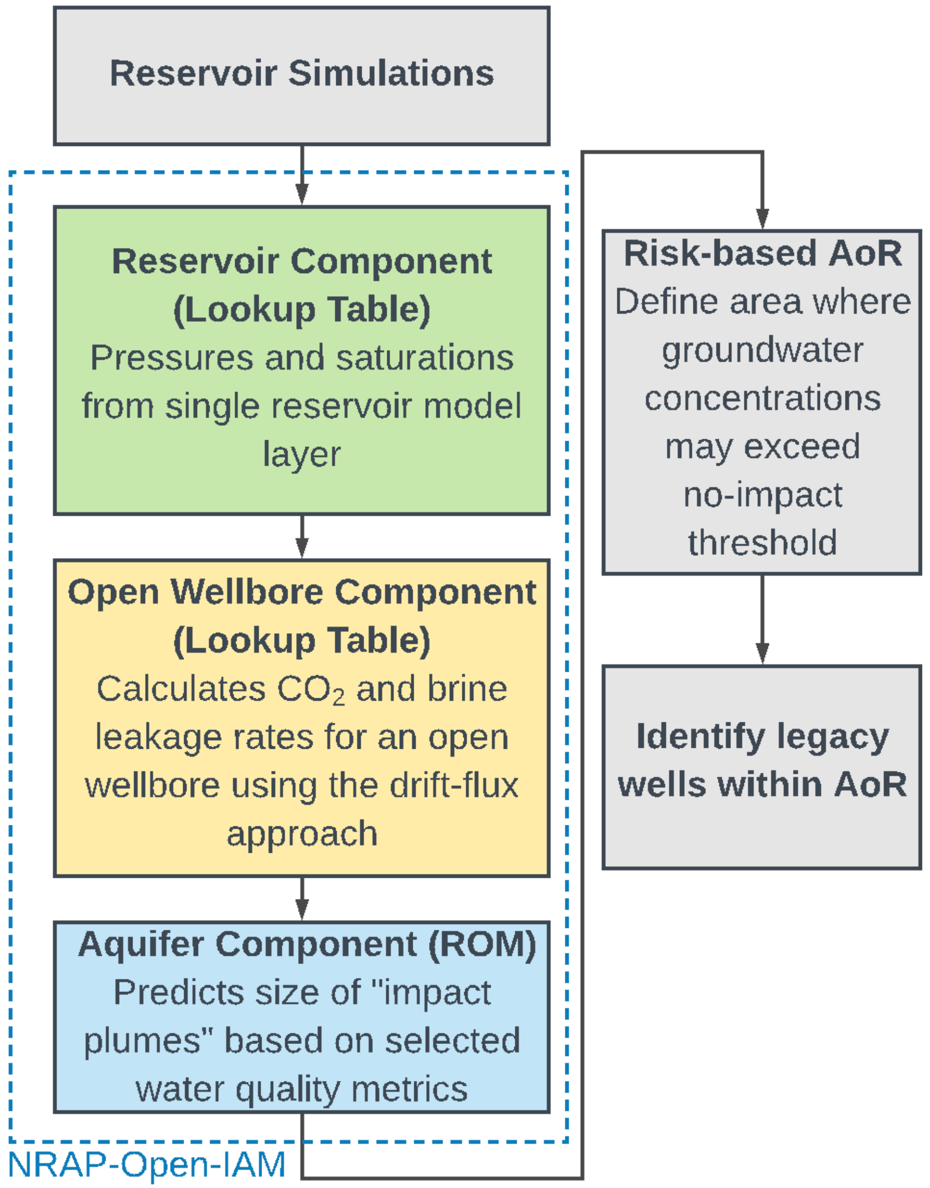
- Risk assessment
- Risk management
- Containment assurance

for geologic carbon storage projects



Risk-based AoR using NRAP-Open-IAM

- **Reservoir Lookup Table Component**
  - Uses user supplied simulation results
  - Simple CSV file format
  - Flexible grid options
- **Open Wellbore Component**
  - Model is a lookup table reduced order model based on the drift-flux approach
- **Aquifer Component**
  - Determine the impact that carbon dioxide (CO_2) and brine leakage from a CO_2 storage reservoir might have on overlying aquifers. The model predicts the size of "impact plumes" according to specific water quality metrics.



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Impact Plumes

FutureGen2 aquifer/AZMI ROMs

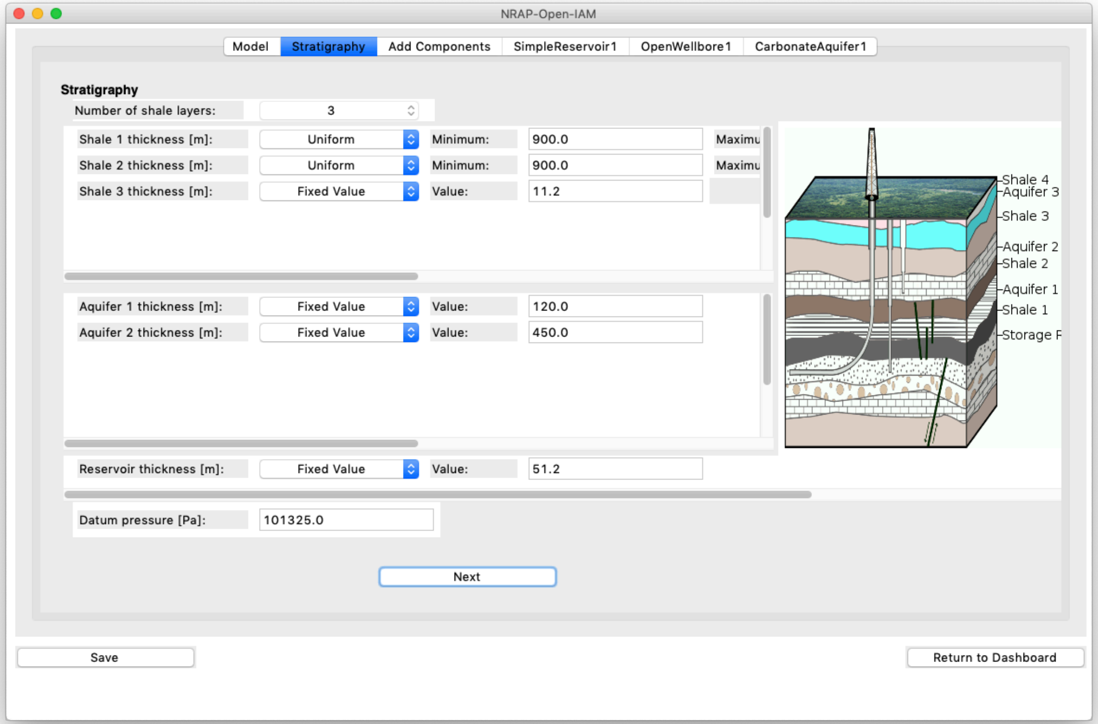
- **For each aquifer/AZMI simulation (single set of input parameters):**
  - Calculate plume volume and dimensions (dx, dy, dz) per time step
    - Pressure, Temperature, DIC, pH, TDS

					ROM	
	Min	Max	Unit	Precision +/-	Indicator	Threshold
Pressure	0	2500	psi	0.065%	relative	0.00065
Temperature	0	150	F	0.03%	relative	0.0003
DIC	0.2	--	mg/L	20%	relative	0.2
pH	2	12	pH	0.2	absolute	0.2
TDS	10	--	mg/L	10%	relative	0.1

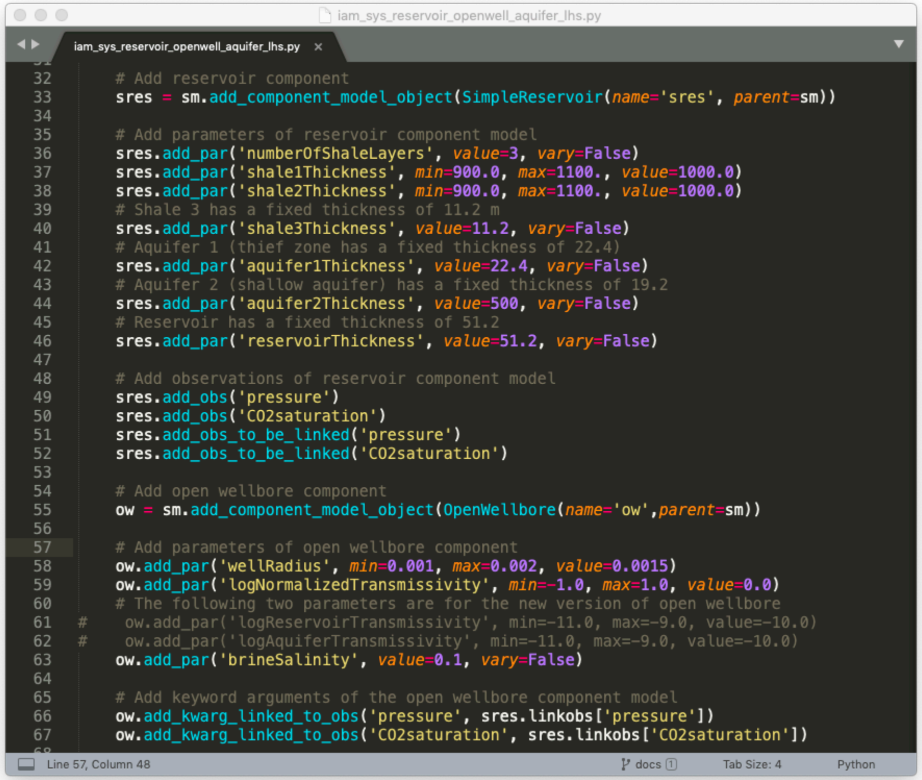
Table A.5 & A.7 (FutureGen Industrial Alliance, 2013a)

NRAP-Open-IAM User Interfaces

Graphical User Interface

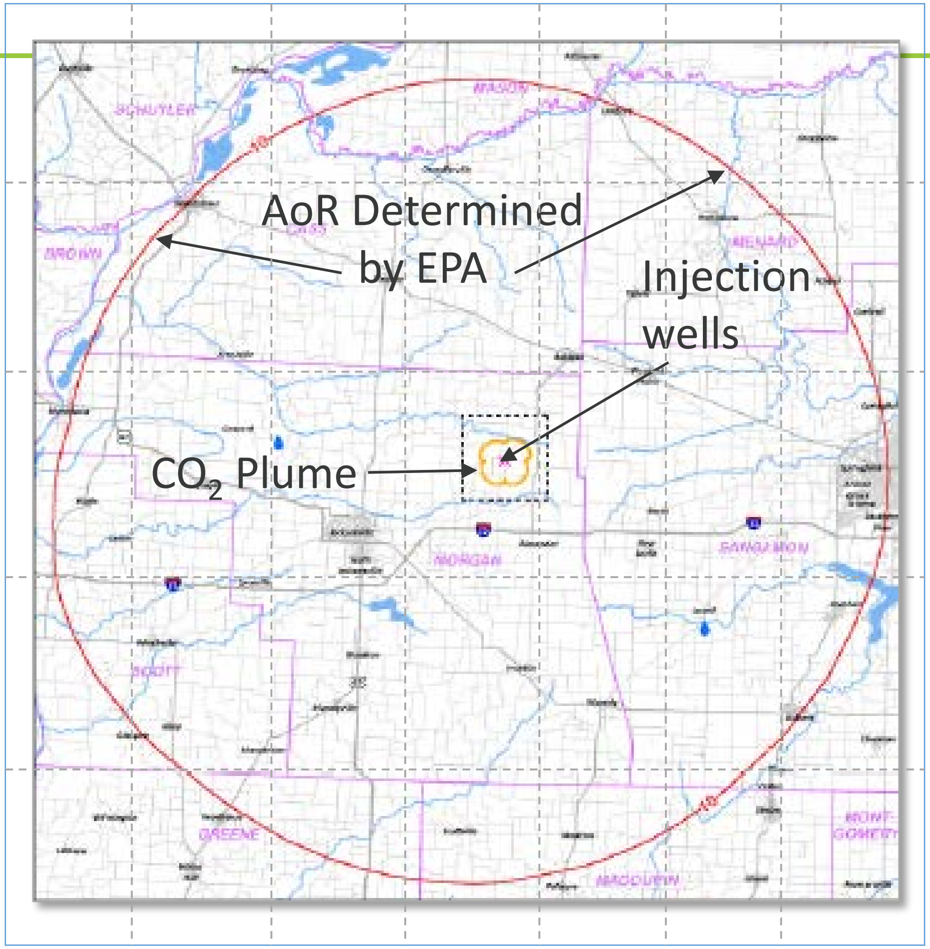


Python Script Interface



Risk-based AoR Using FutureGen 2.0 Site Data

- **Mt. Simon: Over-pressurized reservoir with respect to the lowermost USDW**
- **Pressure front and AoR determined by EPA**
  - Based on 10 psi critical pressure
- **Determination of project risk associated with leakage into the aquifer using the NRAP Open Integrated Assessment Model (NRAP-Open-IAM)**
  - Use of physics-based multiphase modeling for plume and pressure predictions
  - An open wellbore leakage assessment and evaluation of aquifer impact

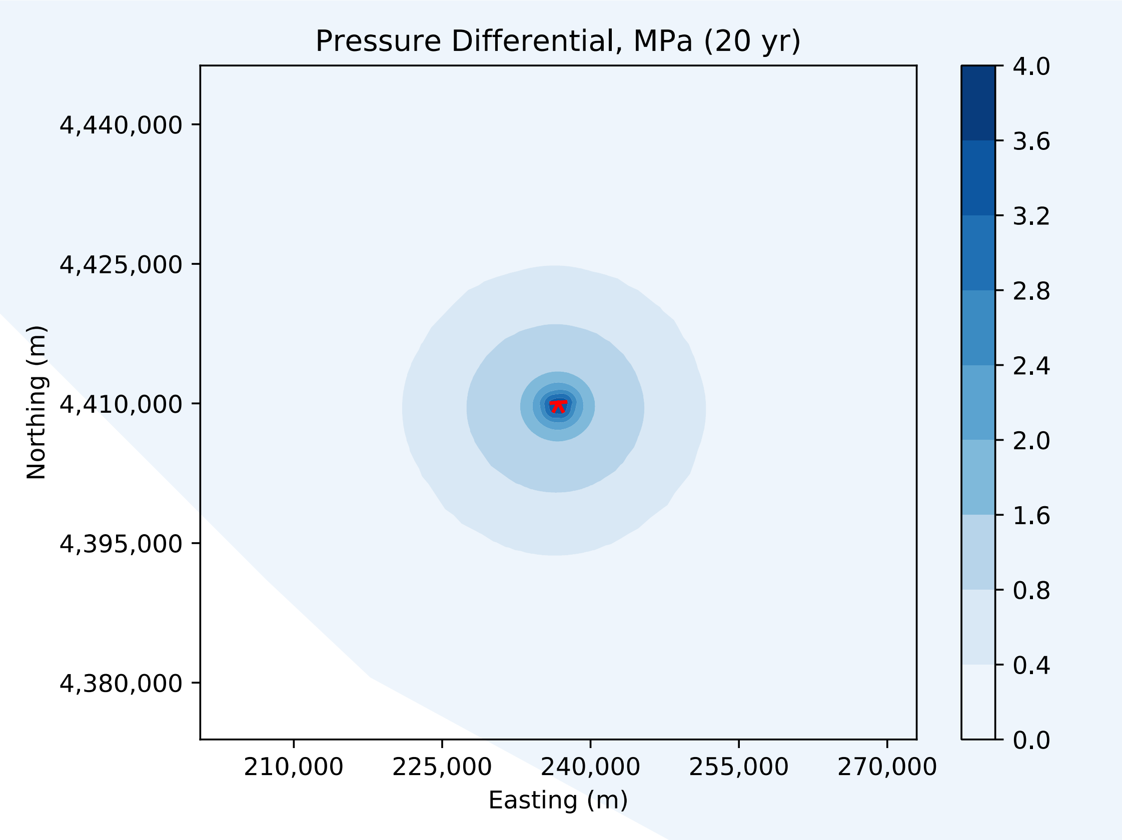


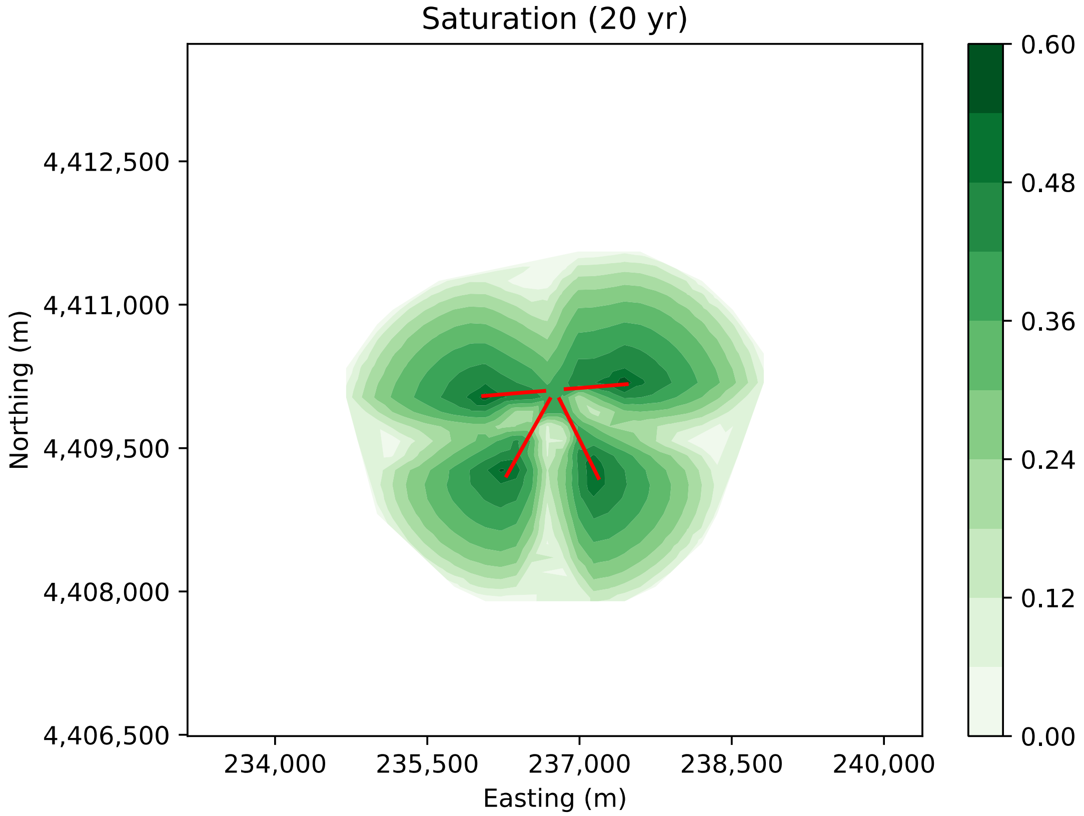
Determination of impact or no impact

User-Supplied Reservoir Simulation Results

Reservoir Lookup Table Component

Horizontal injection wells shown in red





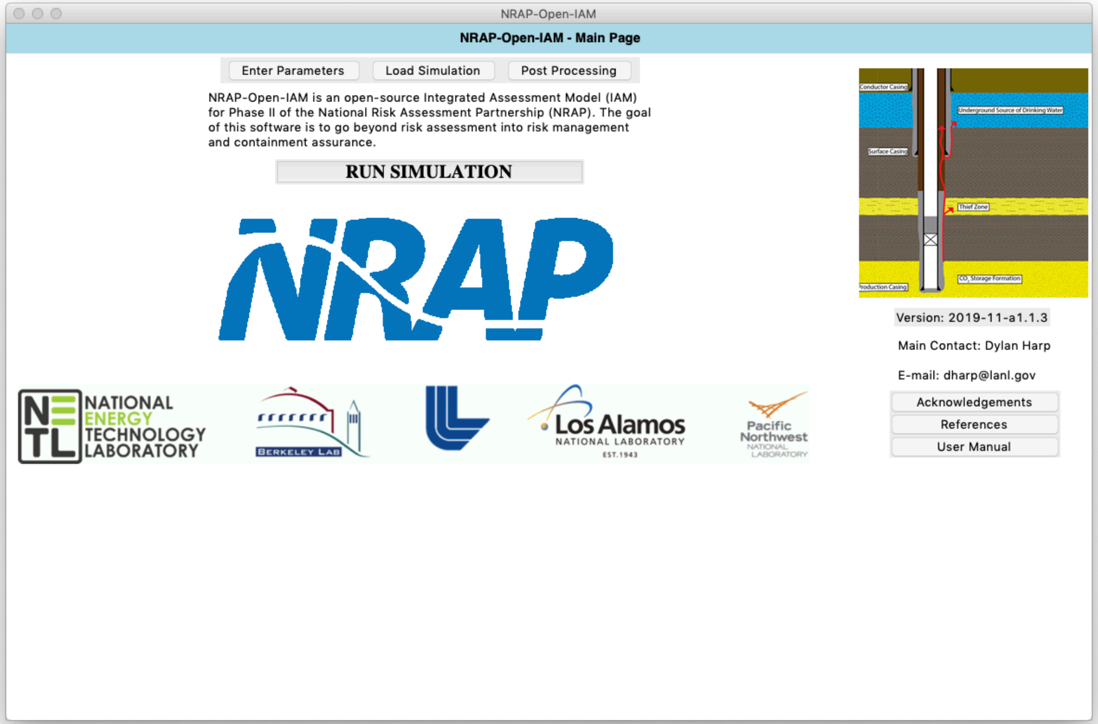
Note 10x decrease in scale

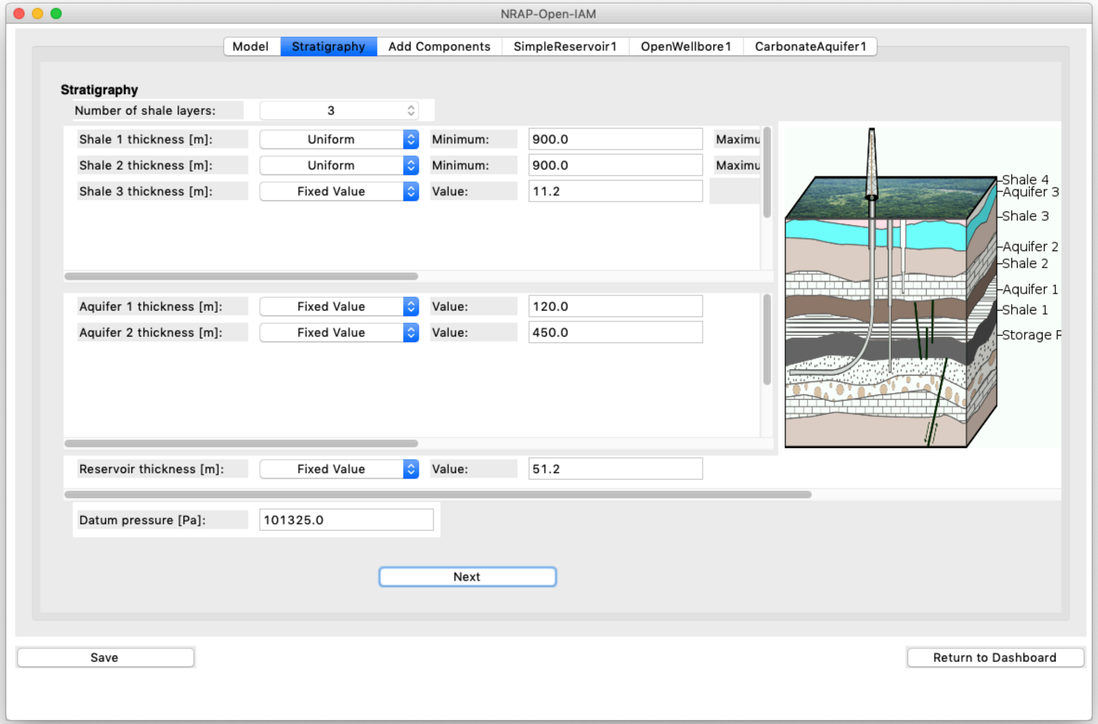
User-Supplied Input Parameters

For NRAP-Open-IAM: Stratigraphy, Open Wellbore ROM, FutureGen2 Aqufer/AZMI ROM

	Reservoir	Intermediate Strata	USDW
Thickness	Yes	Yes	Yes
Depth to Top	Calculated	Calculated	Yes
Permeability	Yes	Yes	Yes
Porosity	No	Yes, if high-permeability	Yes
Anisotropy	No	Yes, if high-permeability	Yes
Relative volume fraction of calcite	No	Yes, if high-permeability	Yes
Salinity	Yes	Calculated by ROM based on depth	Calculated by ROM based on depth

Risk-based AoR using Graphical User Interface





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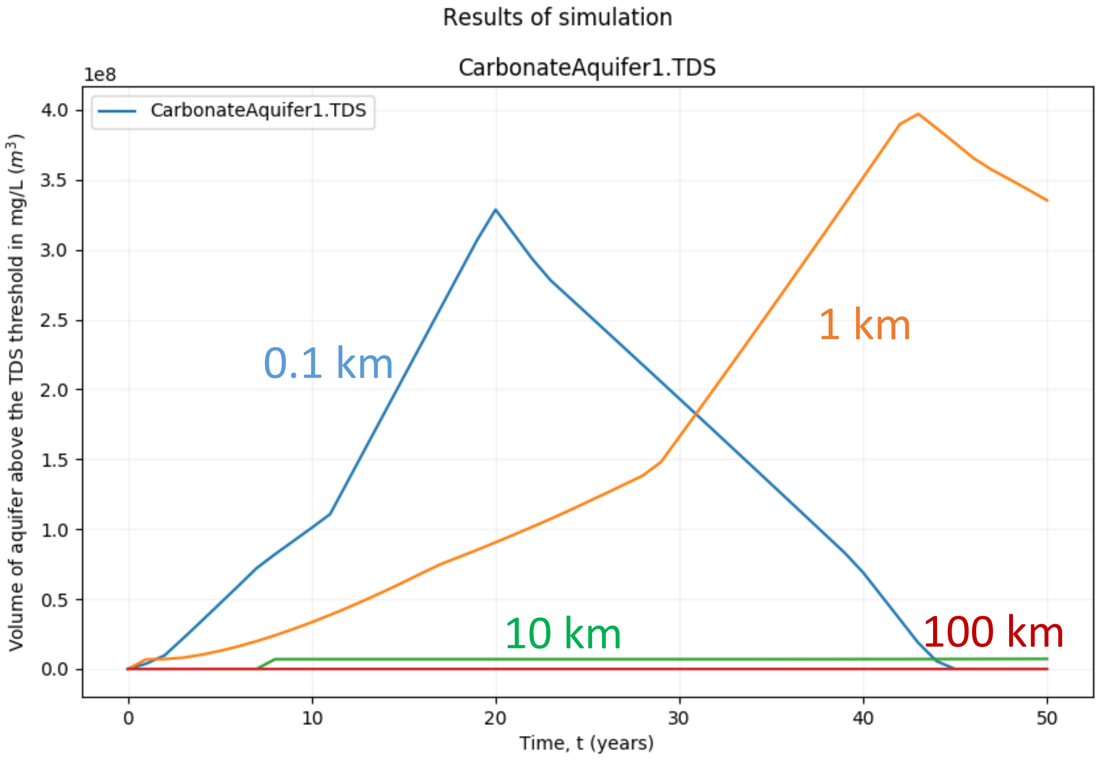
Risk-based AoR using Graphical User Interface

Place open wellbore at increasing distance from injection well

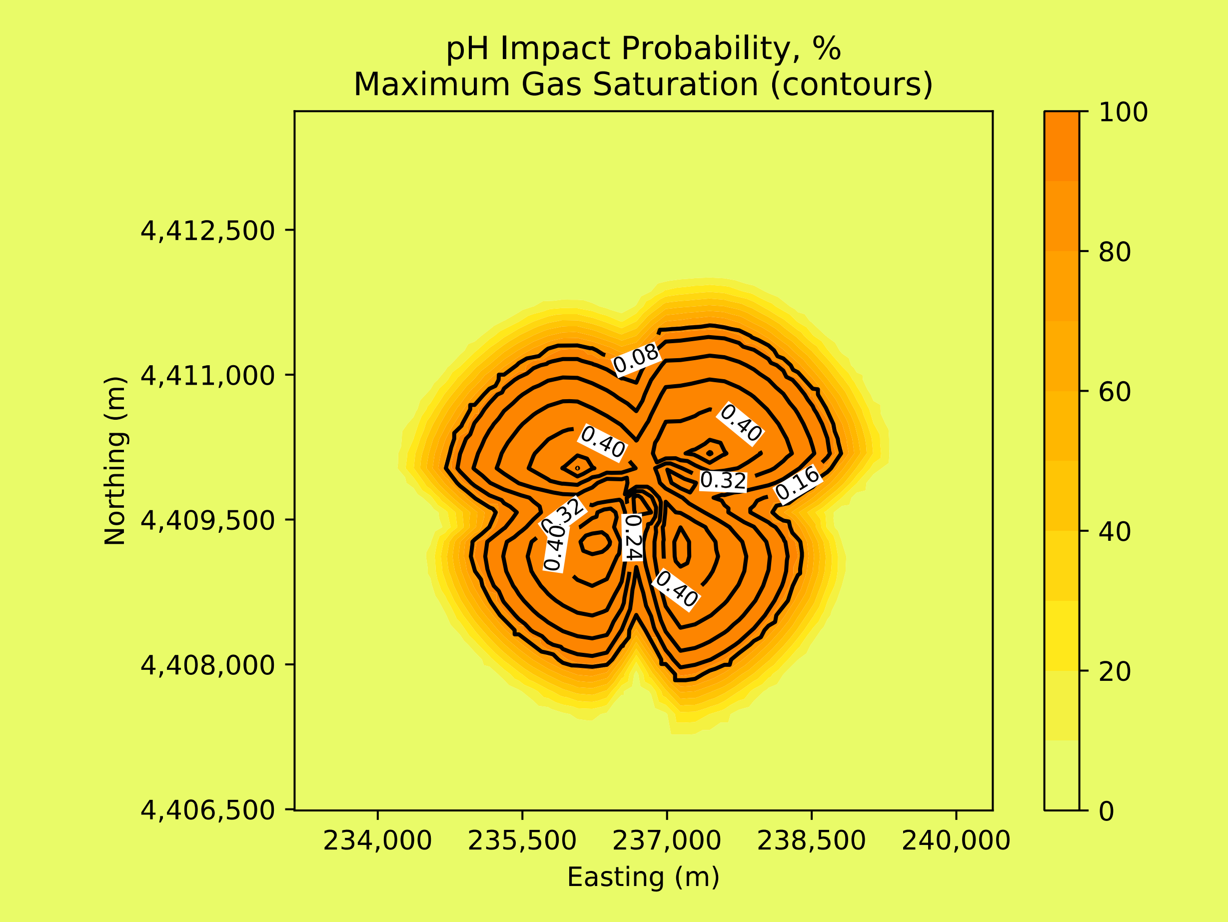


- Impact volume decreases as hypothetical leaking well is placed further from injection well

Probabilistic Risk-based AoR

NRAP-Open-IAM: Python script interface

- **Base AoR delineation on impact to the aquifer if a well is placed at a particular location**
- **Loop through all X,Y locations in reservoir model layer**
  - Find pressure and saturation in reservoir model
  - Use Open Wellbore model to determine CO_2 and brine leakage rates to aquifer
  - Calculate pH and TDS impact volumes vs. time and location
- **Map maximum pH and TDS impact volumes on X,Y grid for each realization**
- **Calculate probability of aquifer impact for each grid location**



Probabilistic Risk-based AoR

NRAP-Open-IAM: Python script interface

- **Base AoR delineation on impact to the aquifer if a well is placed at a particular location**
- **Loop through all X,Y locations in reservoir model layer**
  - Find pressure and saturation in reservoir model
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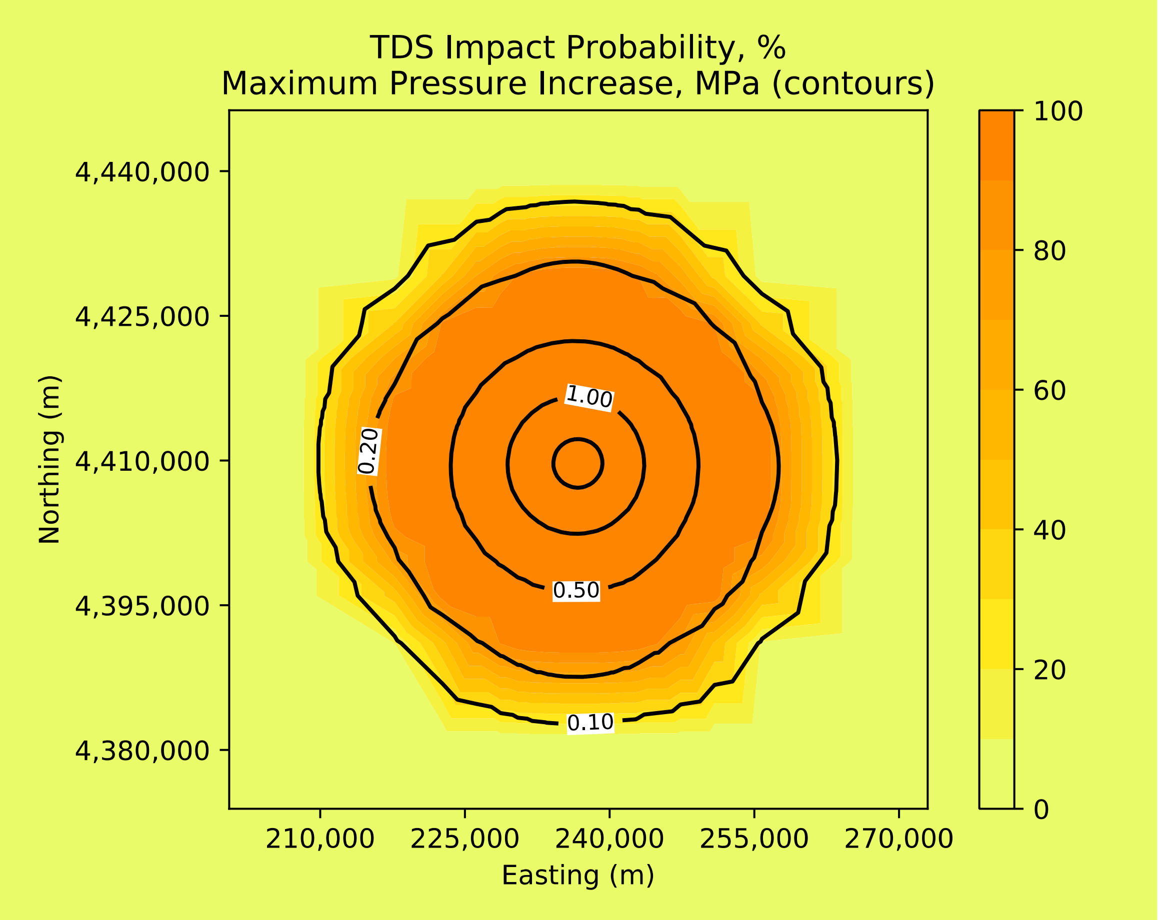
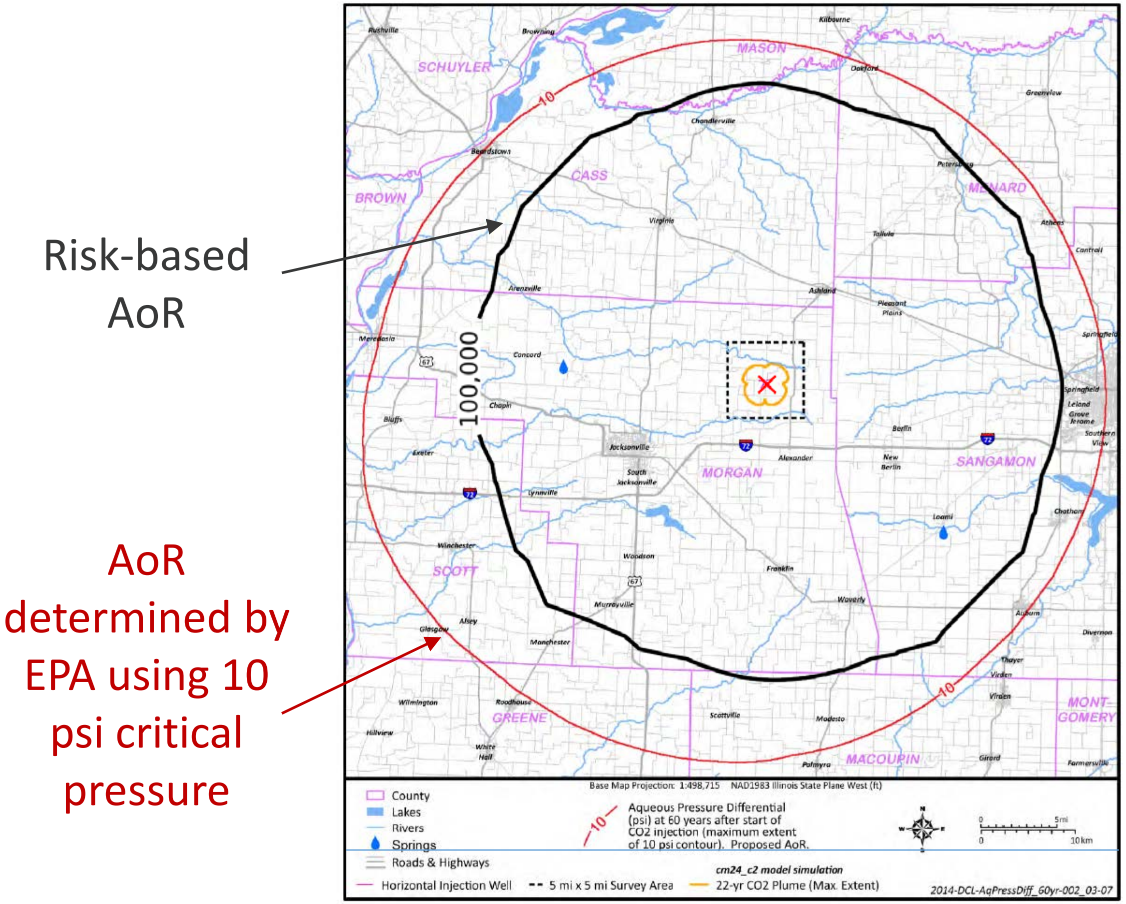


AoR Comparison

Risk-Based AoR (100,000 Pa / 14.5 psi (black)
Class VI Permit AoR 68,974 Pa / 10 psi (red)



- **Area of potential aquifer impact predicted to be smaller than AoR based on 10 psi critical pressure**
- **Results sensitive to model assumptions**
  - wellbore diameter
  - impact threshold
  - duration of leak

Conclusions

- **Area of aquifer impact analysis using OpenIAM provides a risk-based AoR estimate for a geologic sequestration site**
- **Area of aquifer impact based on probability of change in aquifer pH is**
  - Equivalent to plume footprint
- **Area of aquifer impact based on probability of change in aquifer total dissolved solids (TDS) is**
  - Smaller than large AoR determined with critical pressure of 10 psi
  - Still much larger than plume footprint

Contributors

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