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

Diana H. Bacon Pacific Northwest National Laboratory NRAP Workshop February 19, 2020, San Antonio, TX



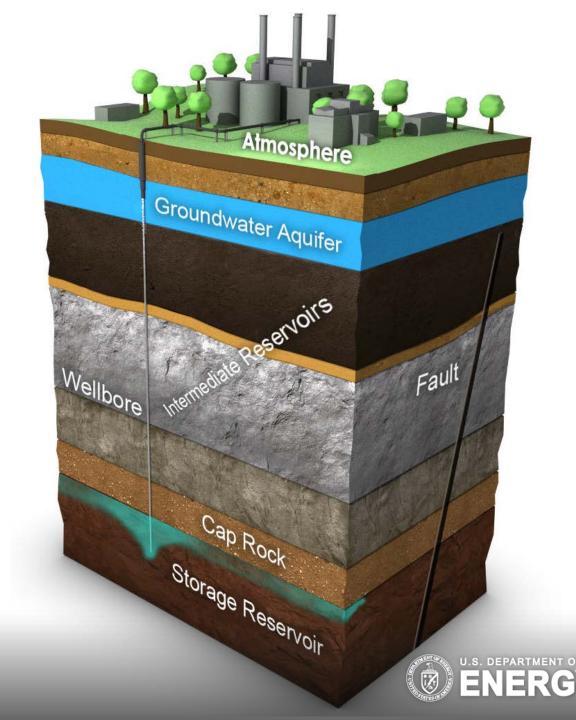
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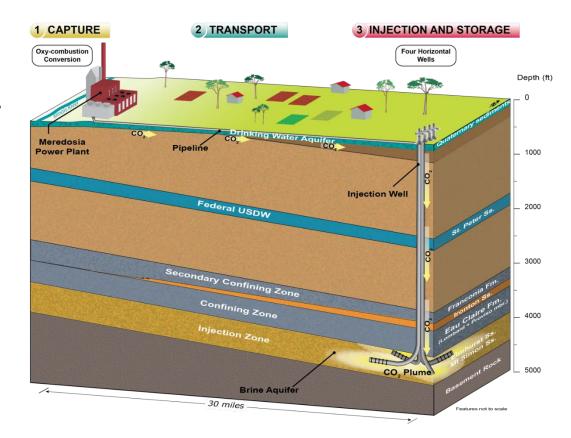






Motivation

- 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

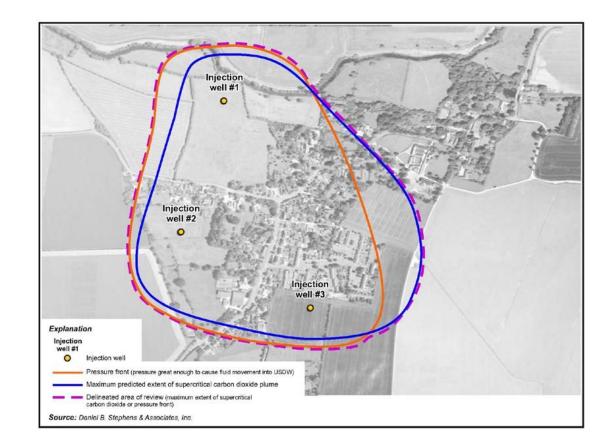
- Graphical User Interface
- Python script interface
- Conclusions





Area of Review (AoR) for CO₂ 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 CO₂ injection permit to determine the AoR based on the separate-phase CO₂ 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







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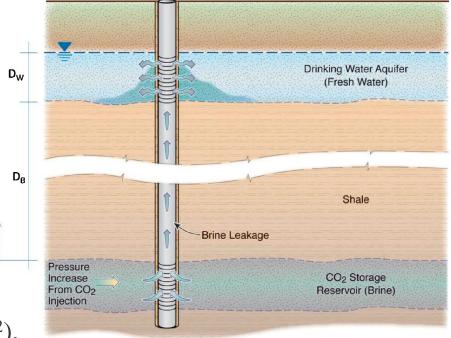
Pressure Front

- 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·s²),
- ρ_i = the density of the injection zone fluid (kg/m³),
- g = the acceleration of gravity (m/s²),
- 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).



 ΔP_{if} > 0: Underpressured ΔP_{if} = 0: Hydrostatic ΔP_{if} < 0: Overpressured

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Pressure Front

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

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

where:

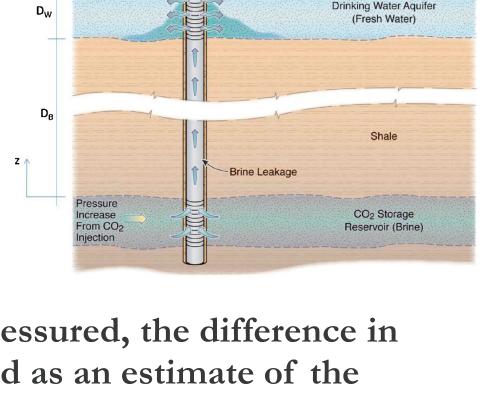
g = the acceleration of gravity (m/s²),

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

 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

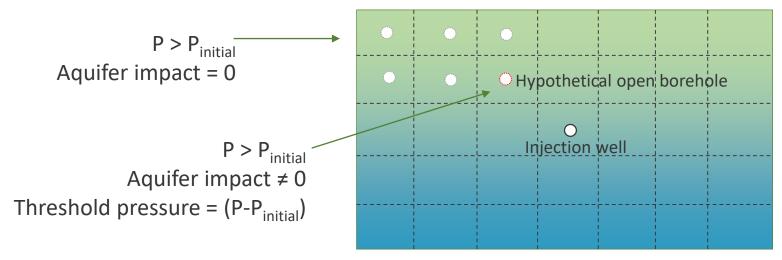
Input Parameter	PAB Site	PMB Site
Depth to top of injection zone (m)	1,969	3,158
Depth at base of the lowermost USDW (m)	152.5	609
Initial pressure in injection zone (MPa)	21.03	32.57
Initial pressure at the base of the lowermost USDW (MPa)	0.43	2.964
Fluid density in the injection zone (kg/m ³)	1,270	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



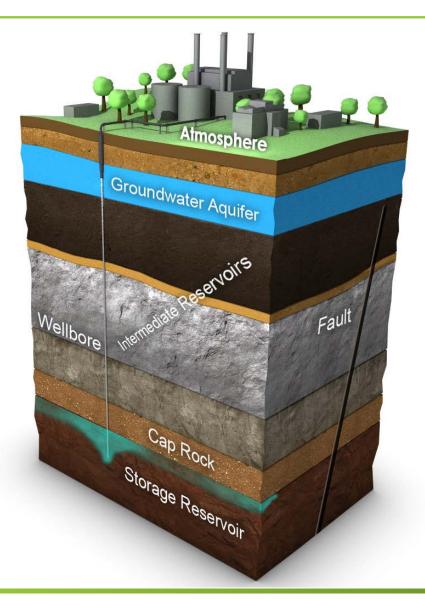




NRAP-Open-IAM is an opensource integrated assessment model developed by National Risk Assessment Partnership Phase II to facilitate

- Risk assessment
- Risk management
- Containment assurance

for geologic carbon storage projects













Risk-based AoR using NRAP-Open-IAM

• Reservoir Lookup Table Component

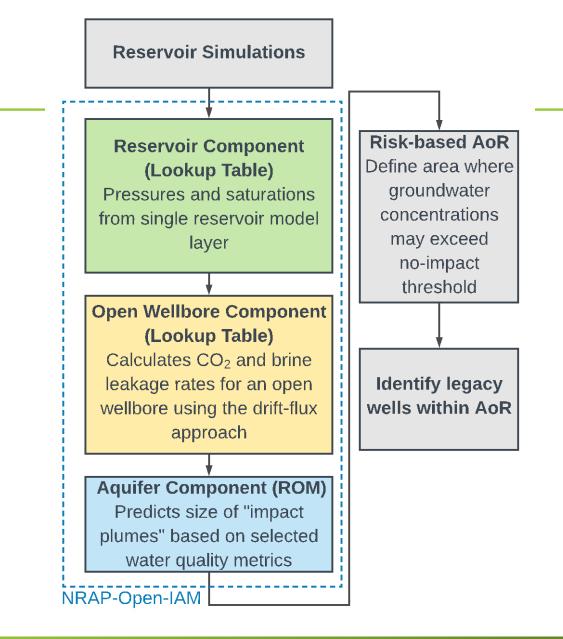
- Uses user supplied simulation results
- Simple CSV file format
- Flexible grid options

• 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 (CO₂) and brine leakage from a CO₂ storage reservoir might have on overlying aquifers. The model predicts the size of "impact plumes" according to specific water quality metrics.













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
рН	2	12	рН	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

					NRAP-Open-IAM					
	Model	Stratigraphy	Add (Components	SimpleReservoir1	OpenWellbo	re1 Car	bonateAquifer1		
Stratigraphy										
Number of shale layers:		3	٢							
Shale 1 thickness [m]:		Uniform	\$	Minimum:	900.0		Maximu	Ā		
Shale 2 thickness [m]:		Uniform	\$	Minimum:	900.0		Maximu			
Shale 3 thickness [m]:		Fixed Value	\$	Value:	11.2				-	-Shale 4 Aquifer
										-Shale 3
										Aquifer :
			_							-Shale 2
Aquifer 1 thickness [m]		Fixed Value	٢	Value:	120.0					-Aquifer -Shale 1
Aquifer 2 thickness [m]	:	Fixed Value	\$	Value:	450.0		- 1			Storage
							- 1			S
										19
										<i>9</i> //
			_							
Reservoir thickness [m]	:	Fixed Value	٢	Value:	51.2					
				-						
Datum pressure [Pa]:	10	1325.0								
				Next						
Save									Return	to Dashboard

Python Script Interface

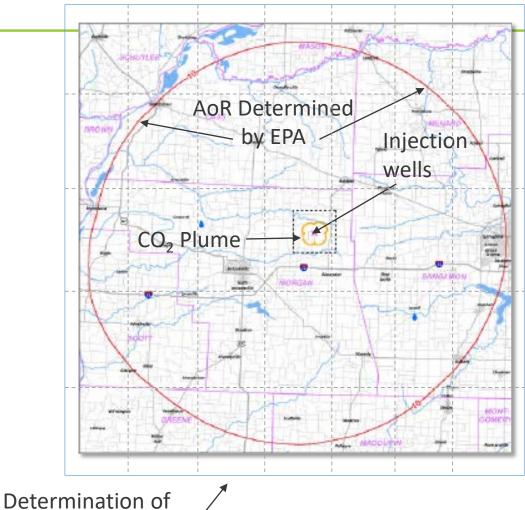
		iam_sys_reservoir_openwell_aquifer_lhs.py
 	iam_s	ys_reservoir_openwell_aquifer_lhs.py ×
32		# Add reservoir component
33		<pre>sres = sm.add_component_model_object(SimpleReservoir(name='sres', parent=sm))</pre>
34		
35		# Add parameters of reservoir component model
		<pre>sres.add_par('numberOfShaleLayers', value=3, vary=False)</pre>
37		<pre>sres.add_par('shale1Thickness', min=900.0, max=1100., value=1000.0)</pre>
38		<pre>sres.add_par('shale2Thickness', min=900.0, max=1100., value=1000.0)</pre>
39		# Shale 3 has a fixed thickness of 11.2 m
40		<pre>sres.add_par('shale3Thickness', value=11.2, vary=False)</pre>
41 42		<pre># Aquifer 1 (thief zone has a fixed thickness of 22.4) sres.add par('aquifer1Thickness', value=22.4, vary=False)</pre>
42		# Aquifer 2 (shallow aquifer) has a fixed thickness of 19.2
43		<pre>sres.add par('aquifer2Thickness', value=500, vary=False)</pre>
45		# Reservoir has a fixed thickness of 51.2
46		<pre>sres.add par('reservoirThickness', value=51.2, vary=False)</pre>
47		
48		# Add observations of reservoir component model
		sres.add_obs('pressure')
		<pre>sres.add_obs('C02saturation')</pre>
51		<pre>sres.add_obs_to_be_linked('pressure')</pre>
52		<pre>sres.add_obs_to_be_linked('CO2saturation')</pre>
53		
54		# Add open wellbore component
55		<pre>ow = sm.add_component_model_object(OpenWellbore(name='ow',parent=sm))</pre>
56		
57 58		<pre># Add parameters of open wellbore component ow.add par('wellRadius', min=0.001, max=0.002, value=0.0015)</pre>
59		ow.add_par('logNormalizedTransmissivity', min=-1.0, max=1.0, value=0.0)
60		# The following two parameters are for the new version of open wellbore
61		ow.add_par('logReservoirTransmissivity', min=-11.0, max=-9.0, value=-10.0)
62		ow.add_par('logAquiferTransmissivity', min=-11.0, max=-9.0, value=-10.0)
63		ow.add_par('brineSalinity', value=0.1, vary=False)
64		
		# Add keyword arguments of the open wellbore component model
		<pre>ow.add_kwarg_linked_to_obs('pressure', sres.linkobs['pressure'])</pre>
67		<pre>ow.add_kwarg_linked_to_obs('CO2saturation', sres.linkobs['CO2saturation'])</pre>
	57. Co	lumn 48 V docs 1 Tab Size: 4 Python
	0,00	t adds () i i i adds () i adds (





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



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impact or no impact



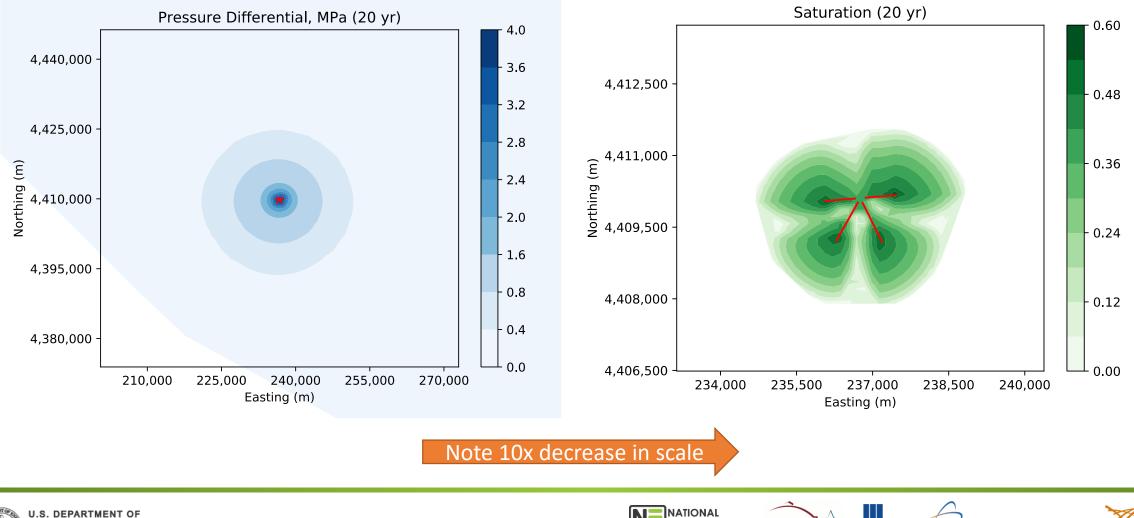


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User-Supplied Reservoir Simulation Results

Reservoir Lookup Table Component

Horizontal injection wells shown in red



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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

NRAP-Open-IAM	NRAP-Open-IAM	
NRAP-Open-IAM - Main Page	Model Stratigraphy Add Components SimpleReservoir1 OpenWellbore1 CarbonateAquifer1	
Inter Parameters Load Simulation Post Processing ARA-Open-IAM is an open-source Integrated Assessment Model (IAM) for Pase II of the National Risk Assessment Partnership (NRAP). The goal of this software is to go beyond risk assessment into risk management assurance. RUN SIMULATION FOR Standard S	Mode Stratigraphy Add Components SimpleReservoir1 OpenWellbore1 CarbonateAquife1 Components SimpleReservoir1 OpenWellbore1 CarbonateAquife1 Stratigraphy Number of shale layers: 3 0 Shale 1 thickness [m]: Uniform Minimum: 900.0 Maximu Shale 2 thickness [m]: Uniform Minimum: 900.0 Maximu Shale 3 thickness [m]: Fixed Value Value: 11.2 Maximu Aquifer 1 thickness [m]: Fixed Value Value: 120.0 Image: CarbonateAquife1 Aquifer 2 thickness [m]: Fixed Value Value: 450.0 Image: CarbonateAquife1 Acknowledgements Aquifer 2 thickness [m]: Fixed Value Value: 450.0 Image: CarbonateAquife1	-Shale -Aquifi -Shale -Shale -Shale -Shale -Stora
LABORATORY DECRETES LATE CONCLUSIVE LATE CONCLUSIVE LATE	User Manual Reservoir thickness [m]: Fixed Value S Value: 51.2 Datum pressure [Pa]: 101325.0	
	Next Return	urn to Dashbo

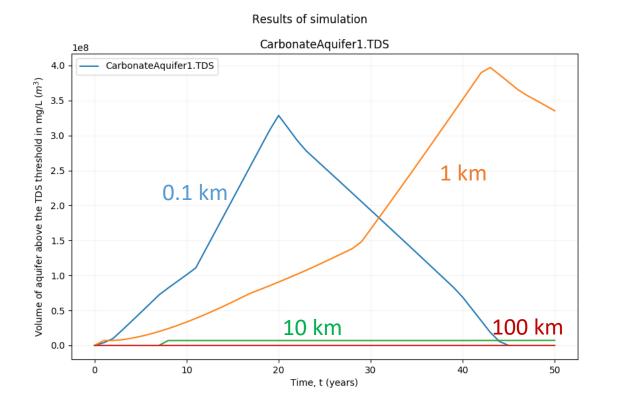




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Risk-based AoR using Graphical User Interface

Place open wellbore at increasing distance from injection well



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



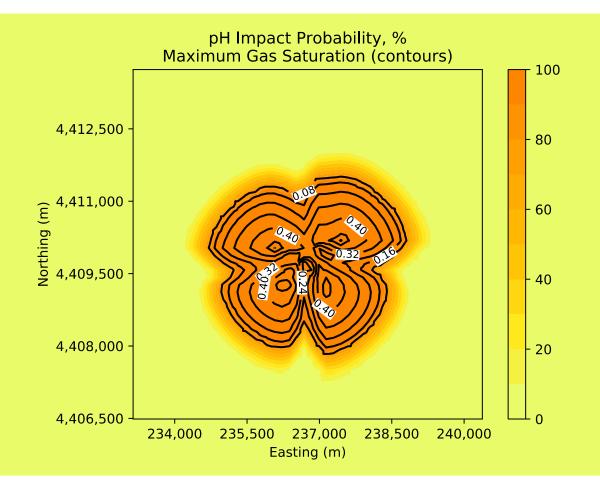


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Probabilistic Risk-based AoR

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 CO₂ 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

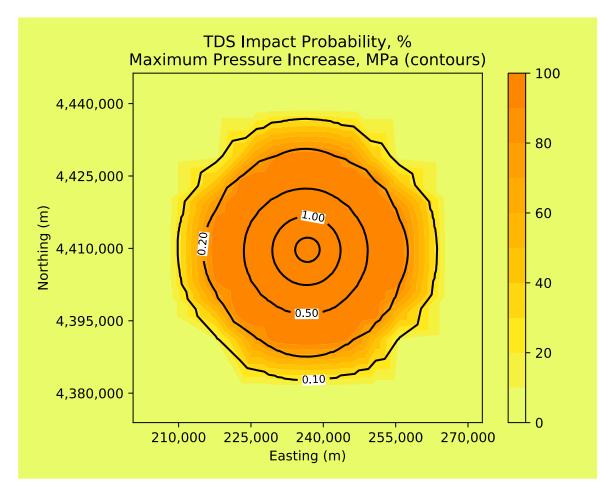




Probabilistic Risk-based AoR

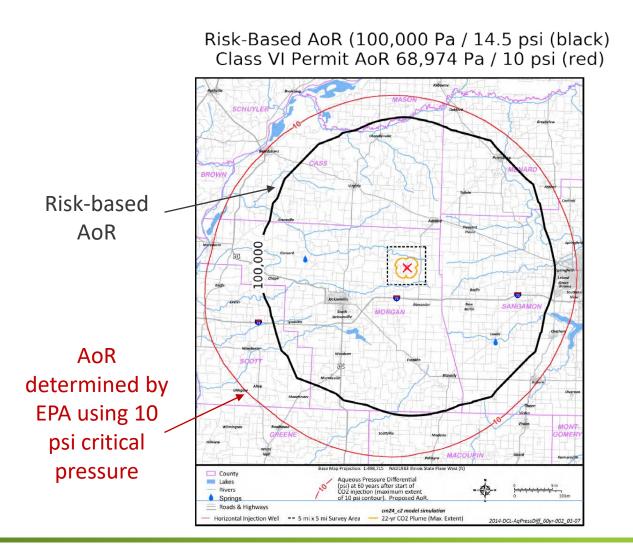
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 - Calculate pH and TDS impact volumes vs. time and location
- Map maximum pH and TDS impact volumes on X,Y grid for each realization
- Calculate probability of aquifer impact for each grid location





AoR Comparison



- 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





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