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National Risk Assessment Partnership: Maturing Tools and Recommended Practices for Site- and Basin-Scale Risk Management

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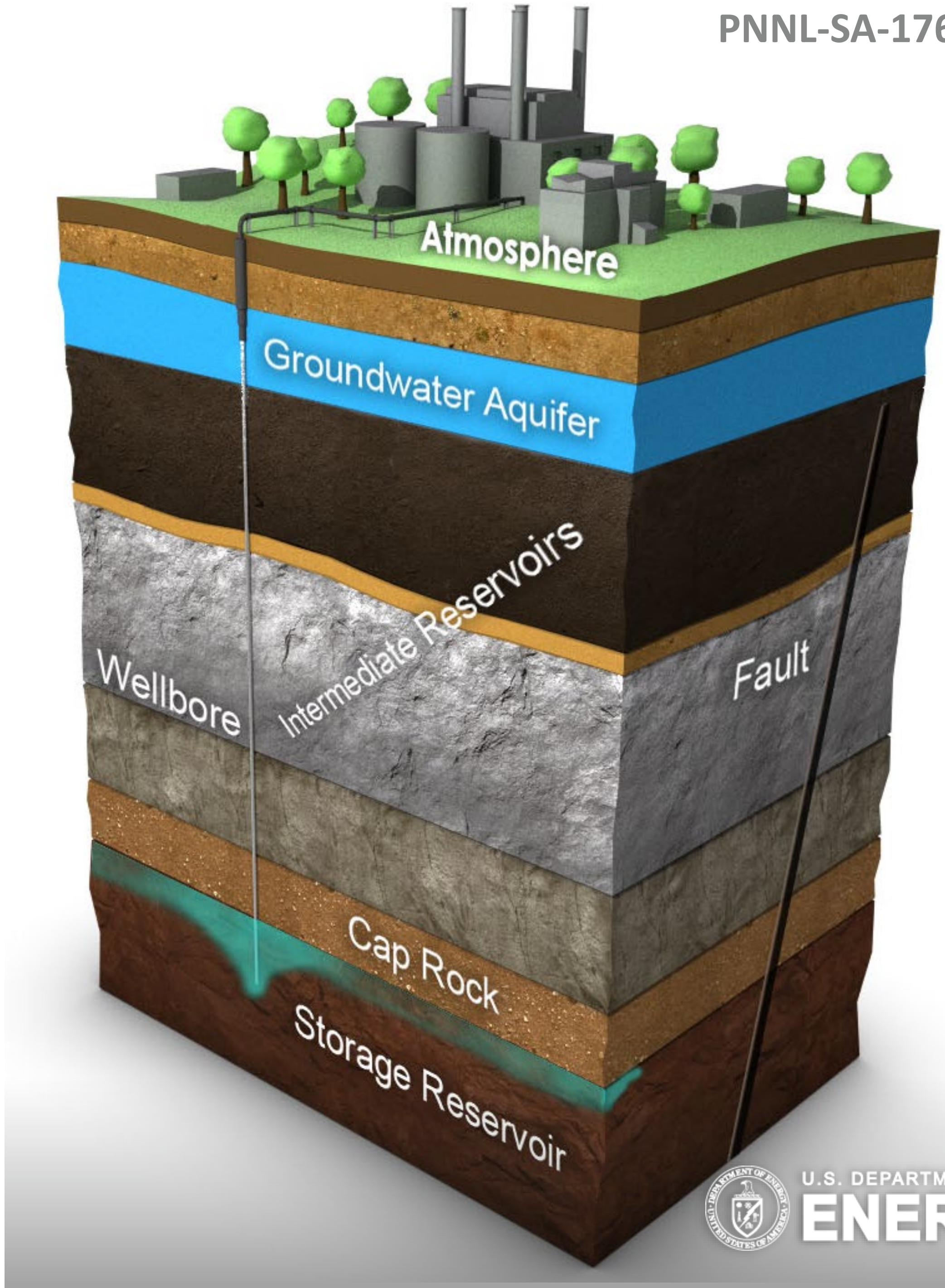
NRAP
National Risk Assessment Partnership

NATIONAL ENERGY TECHNOLOGY LABORATORY · Berkeley Lab · LLNL · Los Alamos National Laboratory · Pacific Northwest National Laboratory



U.S. DEPARTMENT OF ENERGY

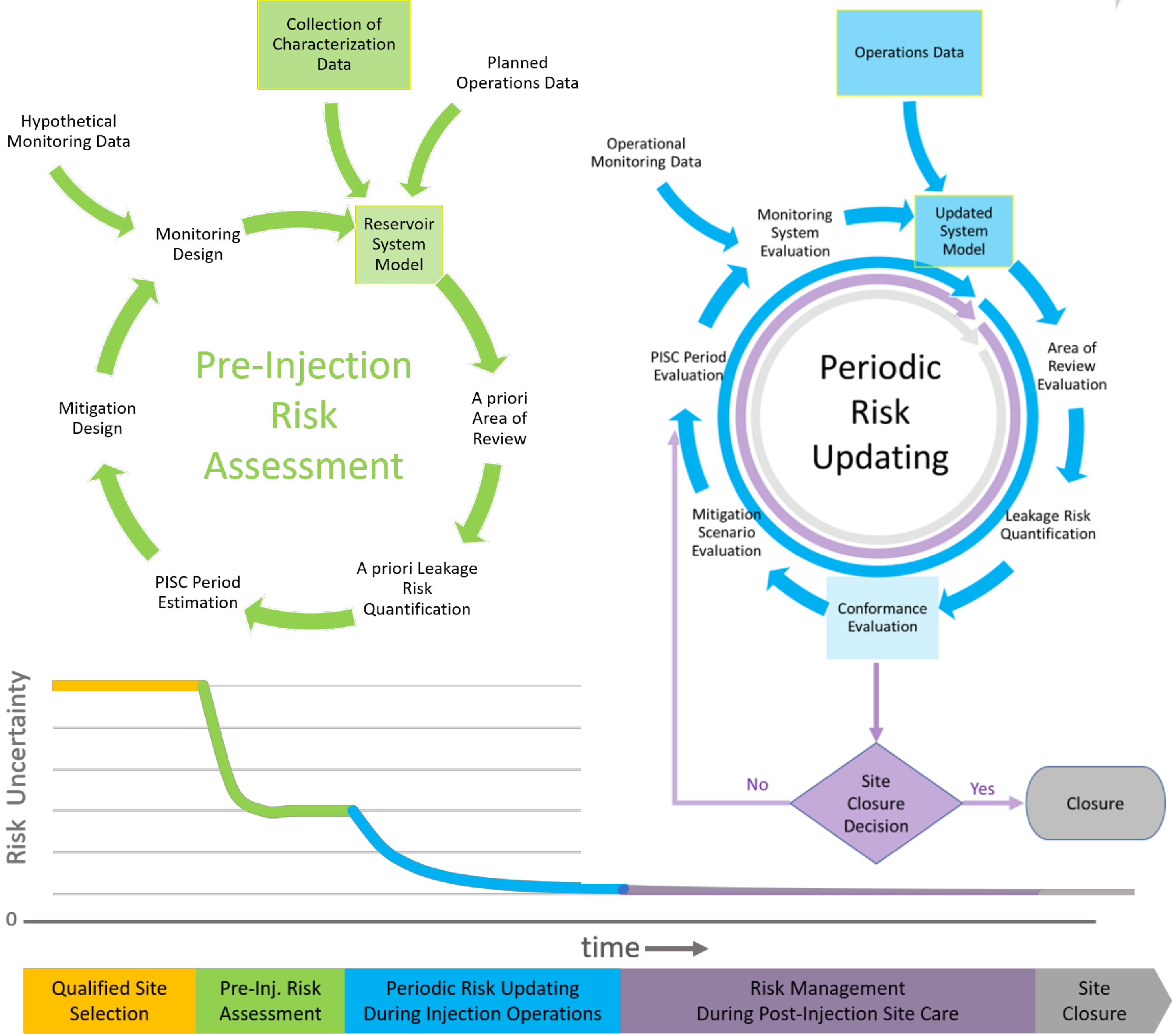
Overview

Maturing Tools and Recommended Practices for Site- and Basin-Scale Risk Management

- **Recommended Practices**
  - Burt Thomas, NETL
- **Containment Assurance**
  - Rajesh Pawar & William Cary, LANL
- **Strategic Monitoring**
  - Erika Gasperikova, LBNL
- **Field Applications & Basin-scale Risk Management**
  - Diana Bacon, PNNL

Recommended Practices for Containment Assurance and Leakage Risk Quantification

- Reduction in risk uncertainty with time



NRAP Recommended Practices and Tools

CCS Project Phases

Recommended Practices	Siting / Evaluation	Permitting and Construction	CO_2 Injection Operations	Post-Injection Site Care	Post Closure
Risk-Based Site Characterization	NRAP-Open-IAM, SOSAT	NRAP-Open-IAM, SOSAT	NRAP-Open-IAM, SOSAT		
Geomechanical Risks Assessment	SOSAT	SOSAT	SOSAT		
Risk-Based AoR	NRAP-Open-IAM	NRAP-Open-IAM	NRAP-Open-IAM		
Induced-Seismicity Risk Management	RiskCAT, STSF	RiskCAT, STSF	RiskCAT, STSF	RiskCAT, STSF	
Risk-based Monitoring		DREAM, RiskCAT, PSTM, NRAP-Open-IAM	DREAM, RiskCAT, PSTM, NRAP-Open-IAM	DREAM, RiskCAT, PSTM, NRAP-Open-IAM	
GCS System Conformance			DREAM, SOSAT, STSF, NRAP-Open-IAM	DREAM, SOSAT, STSF, NRAP-Open-IAM	
Risk Management/Mitigation to Inform Risk Management Decisions		NRAP-Open-IAM, STSF	NRAP-Open-IAM, STSF	NRAP-Open-IAM, STSF	
Risk-Based PISC Definition			NRAP-Open-IAM		

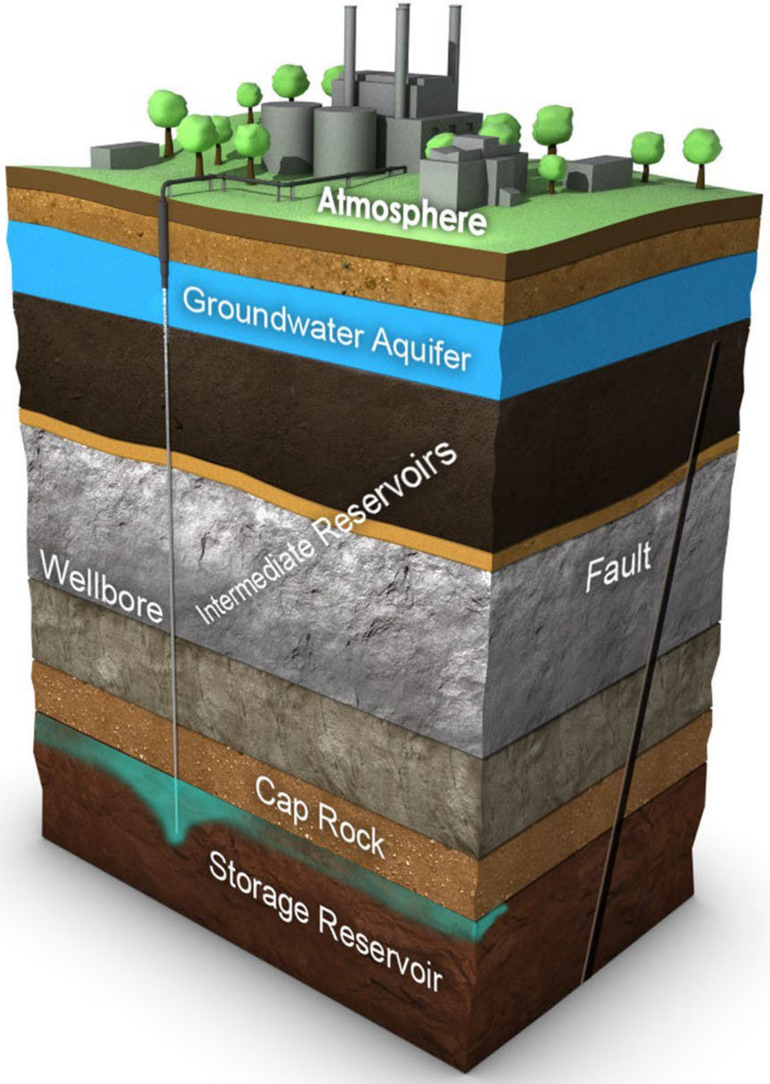
NRAP TOOLS

- State-of-Stress Analysis Tool (SOSAT)
- Short-Term Seismic Forecasting (STSF)
- RiskCAT
- NRAP-Open-IAM
- DREAM
- Passive Seismic Monitoring Tool (PSTM)

Risk-Based Site Characterization

Best Practice

- Characterize system features (reservoir, confining zones, leakage pathways, potential receptors)
- Define potential unintended migration pathways
- Simulate response to planned injection
- Quantify unintended migration risks and potential impacts



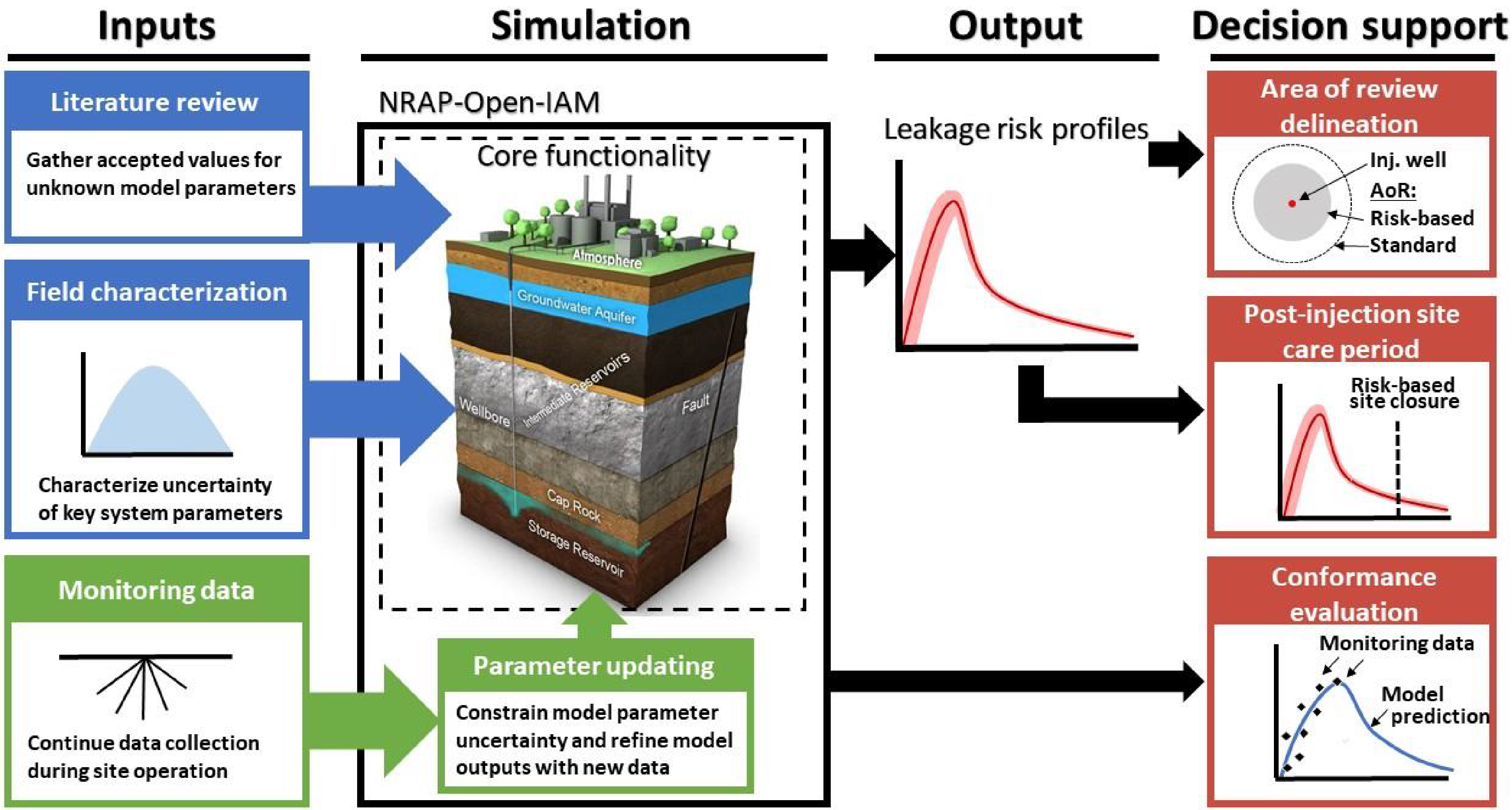
Receptors of Concern
- Groundwater aquifers
- Atmosphere

Potential Migration Pathways
- Wells and boreholes
- Fractures and faults
- Intermediate reservoirs

Storage System
- Storage reservoir
- Cap rock

NRAP-Open-IAM

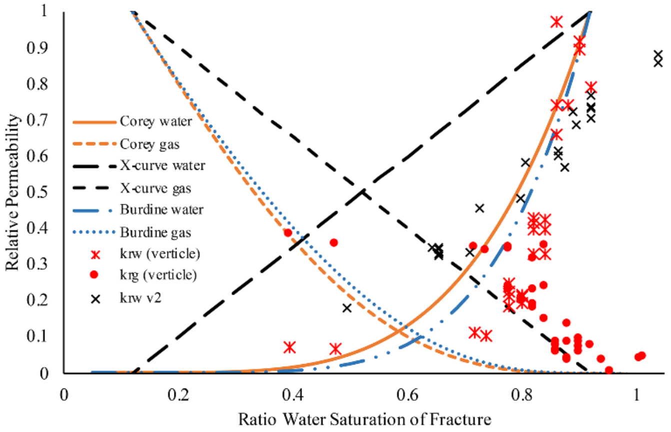
Vasylkivska, V., R. Dilmore, G. Lackey, Y. Zhang, S. King, D. Bacon, B. Chen, K. Mansoor and D. Harp (2021). "NRAP-open-IAM: A flexible open-source integrated-assessment-model for geologic carbon storage risk assessment and management." *Environmental Modelling & Software* 143.

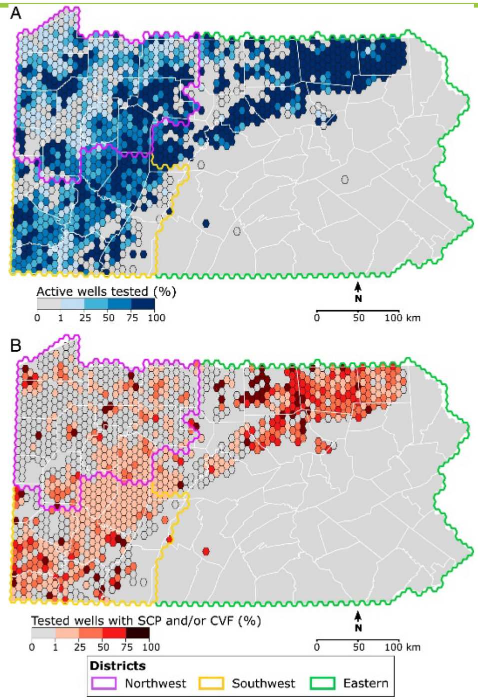


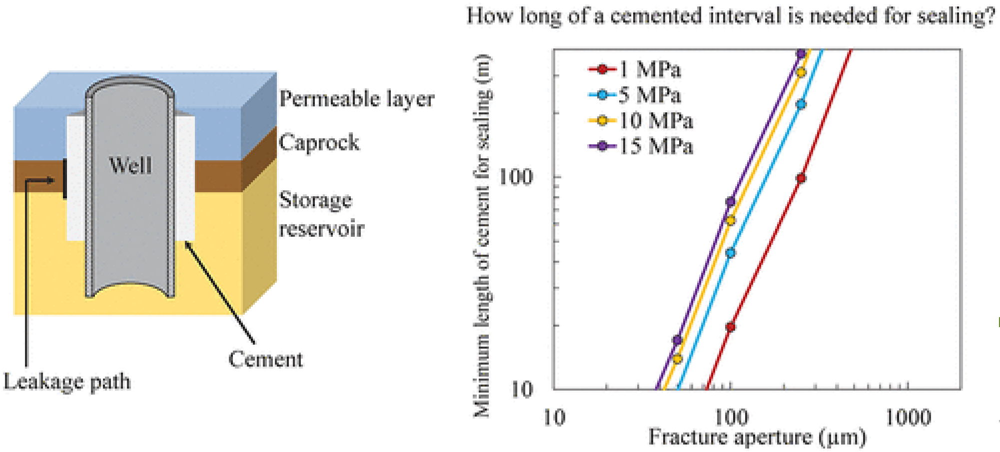
Improvements of the scientific knowledge related to wellbore interactions at CO_2 storage sites

- Experimentally quantified the hydraulic, chemical and mechanical characteristics of CO_2 leaking from fractures in cement
  - https://doi.org/10.1371/journal.pone.0210741
  - https://doi.org/10.1016/j.ijggc.2020.102978
  - https://doi.org/10.1016/j.ijggc.2021.103340

  Self-sealing in ordinary cement can limit CO_2 leakage (for fractures of appropriate apertures and length)
- Developed models characterizing the flow, chemistry and mechanics of leakage through damaged wellbores
  - https://doi.org/10.1016/j.ijggc.2020.103025
  - https://doi.org/10.1021/acs.est.9b05039
  - https://doi.org/10.3390/computation8040098
  - https://doi.org/10.1016/j.ijggc.2018.04.006
- Quantified the regional well leakage frequencies in three US states
  - https://doi.org/10.1073/pnas.2013894118

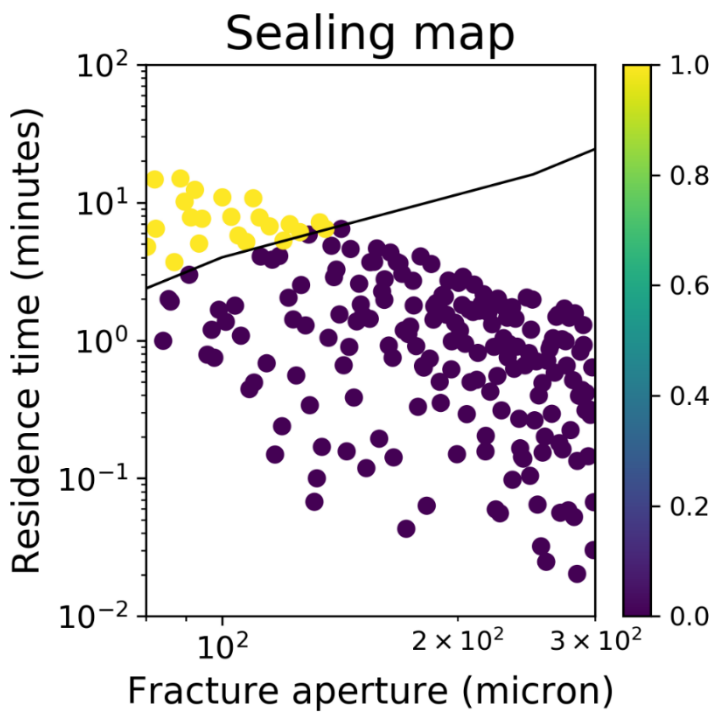






Development of reduced order models (ROMs) to quantify legacy well, seal and fault leakage

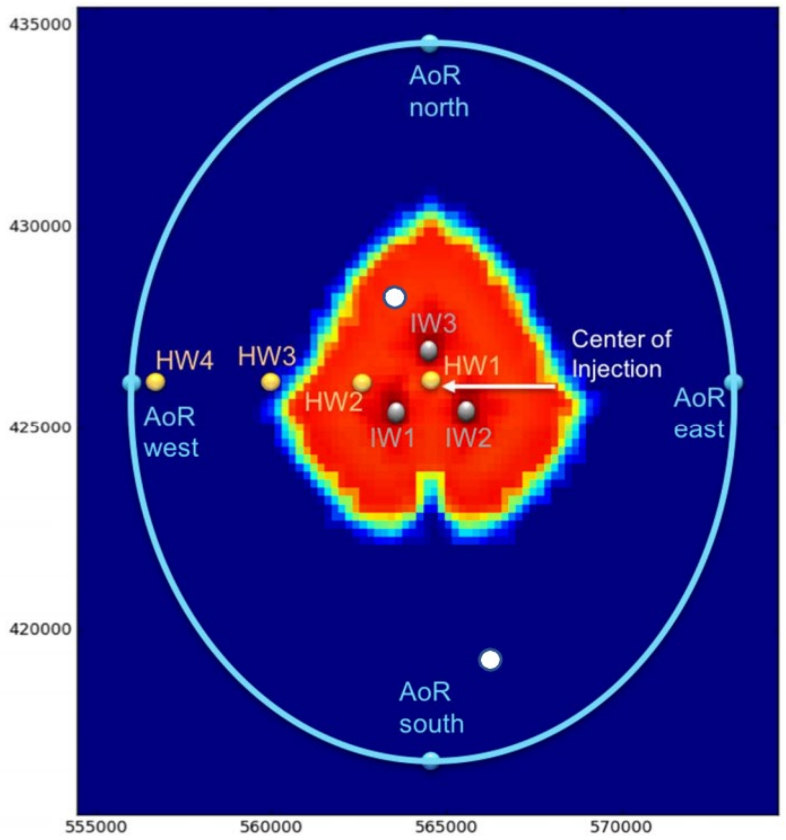
- New leakage ROMs
  - Seal_Flux ROM: predicts leakage through a seal (caprock)
  - Fault ROMs: analytical and high-fidelity simulation-based
  - Chemical sealing wellbore ROM: predicts if a damaged wellbore will self-seal
- Expanded parameter range and accuracy of Phase I Wellbore Leakage ROMs
- Quality assurance documents for the well leakage ROMs
- Wellbores at hydrocarbon-bearing reservoirs (Class II to Class VI conversion)



Risk Based Area of Review (AoR)

Best Practice

- Use site characterization data to define the conventional AoR
- Incorporate leakage pathways and hydrologic units into a carbon storage system model
- Analyze dynamic model results
- Delineate risk-based AoR based on modeled impact to USDWs



White et al., 2019

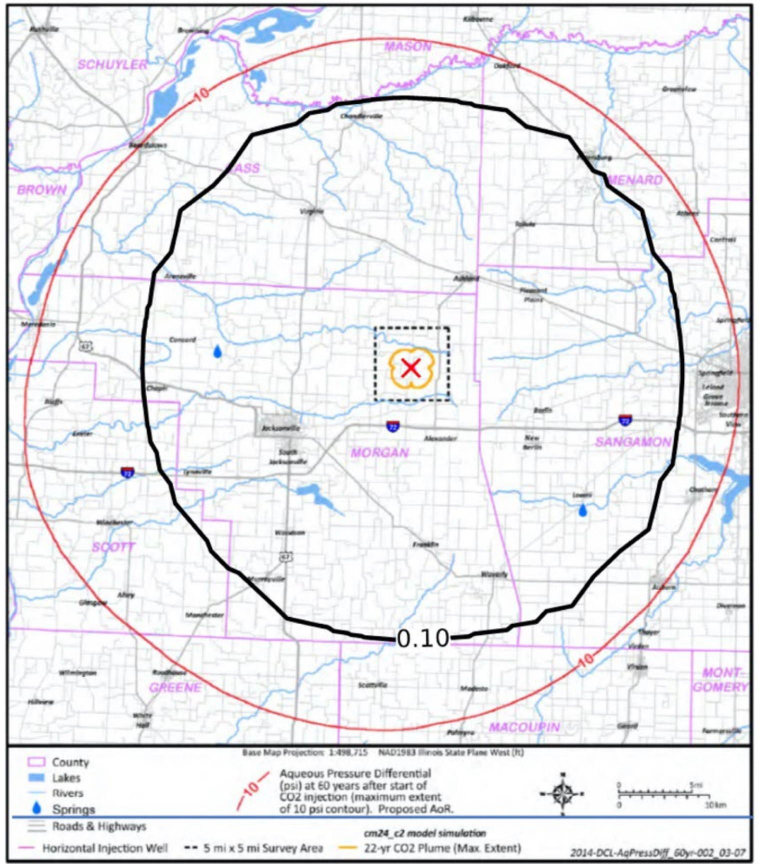
Workflow: Developing a Risk-Based Area of Review

Bacon, DH, DI Demirkanli, and SK White. 2020. "Probabilistic risk-based Area of Review (AoR) determination for a deep-saline carbon storage site", *International Journal of Greenhouse Gas Control*, 102: 103153.

Key Findings

- Uncertainty in reservoir and aquifer characteristics used to determine the probability of aquifer impacts based on leakage from an open conduit
- Workflow is demonstrated using characterization and modeling data from a permitted carbon storage project
- Probabilistic risk-based analysis yields smaller Area of Review

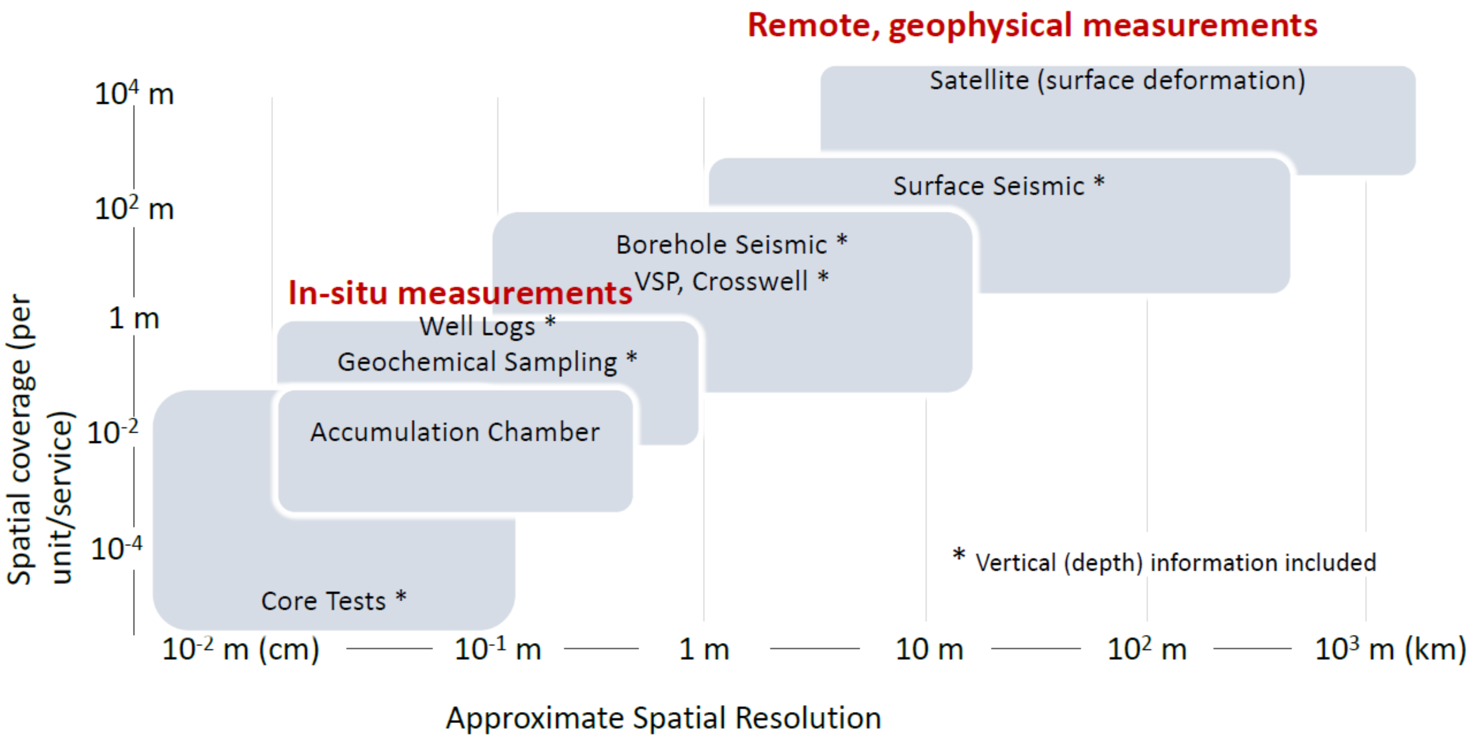
Risk-Based AoR (0.1 MPa/14.5 psi (black)
Class VI Permit AoR 0.69 MPa/10 psi (red)



Risk-Based Strategic Monitoring

Best Practice

- Characterize the site and develop an a priori system model
- Define conditions to detect unintended migration
- Select monitoring technologies
- Define threshold criteria for detection
- Design adaptive site monitoring network



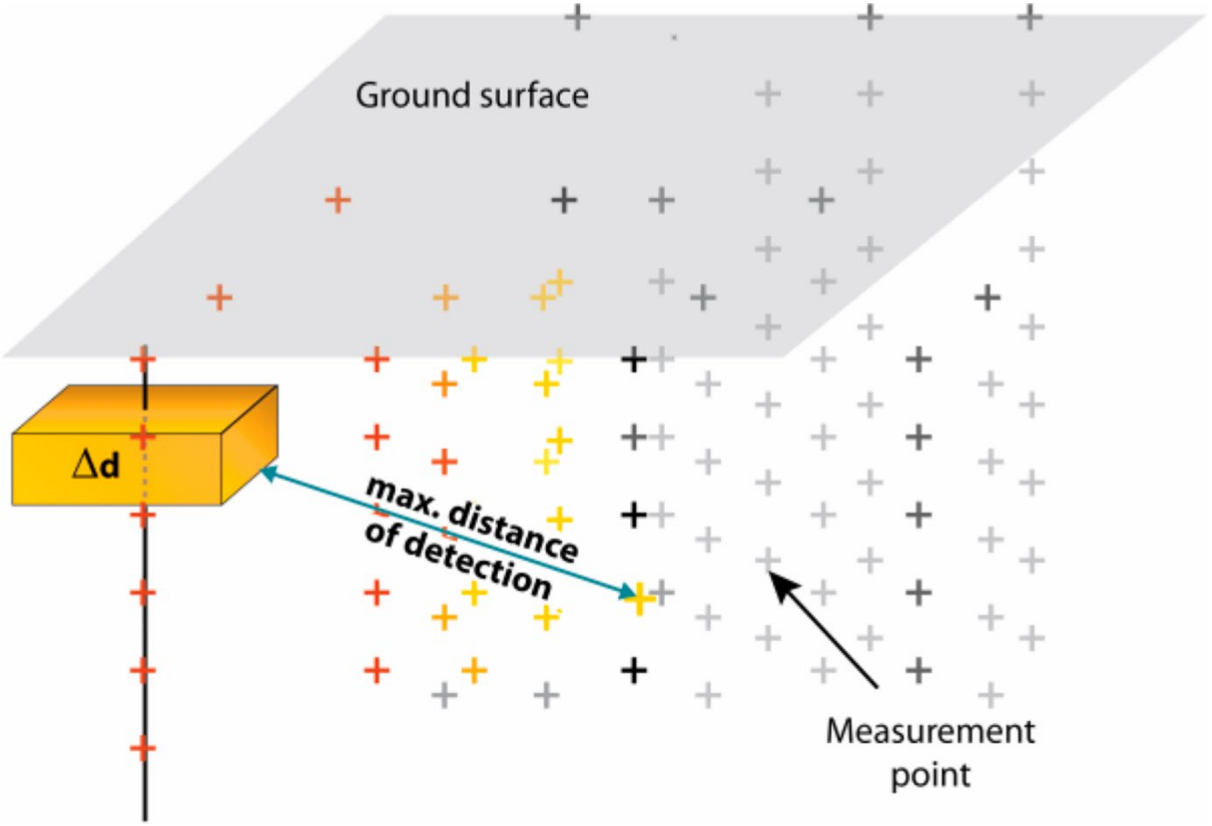
Gasperikova et al. 2020.

Estimating Leak Detection Thresholds of Monitoring Techniques

Gasperikova, E.; Appriou, D.; Bonneville, A.; Feng, Z.; Huang, L.; Gao, K.; Yang, X.; Daley, T. Sensitivity of geophysical techniques for monitoring secondary CO_2 storage plumes, *International Journal of Greenhouse Gas Control* 2022, 114, Article 103585.

Key Findings

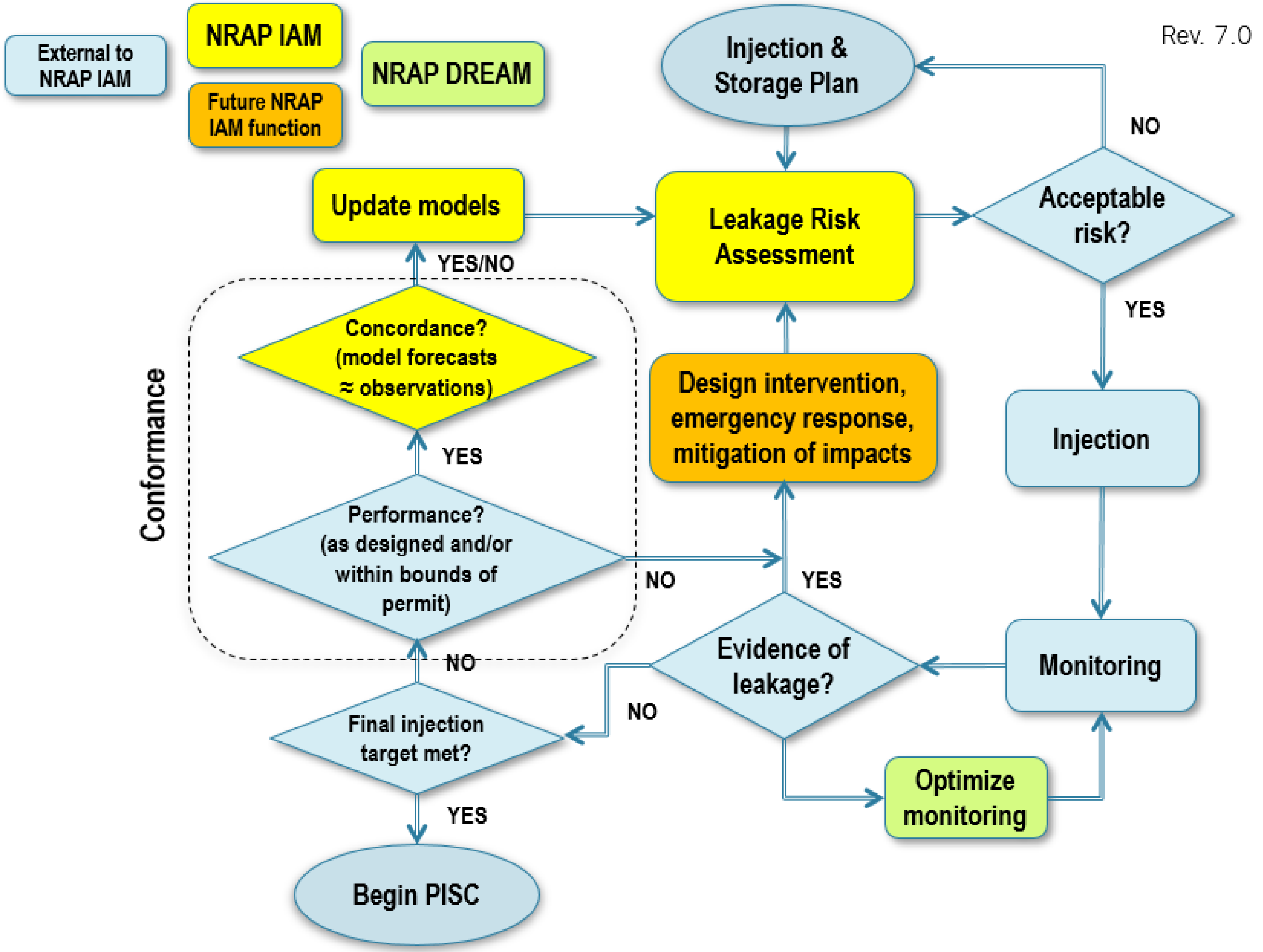
- Advanced imaging of surface seismic data has great potential to locate secondary CO_2 plumes
- Borehole-to-surface electromagnetic or surface gravity are feasible for time-lapse monitoring of deep secondary CO_2 plumes
- Demonstrates forward modeling approaches to evaluate post-injection monitoring configurations



Geologic Carbon Storage System Conformance

Best Practice

- Collect appropriate characterization and monitoring data
- Develop storage system model
- History match for concordance
- Check that system performance is within agreed upon thresholds

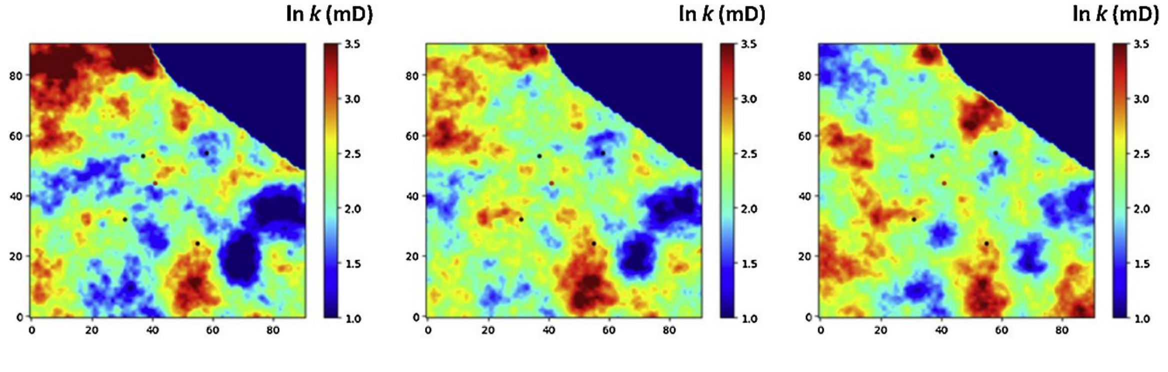


Reducing Risk Uncertainty

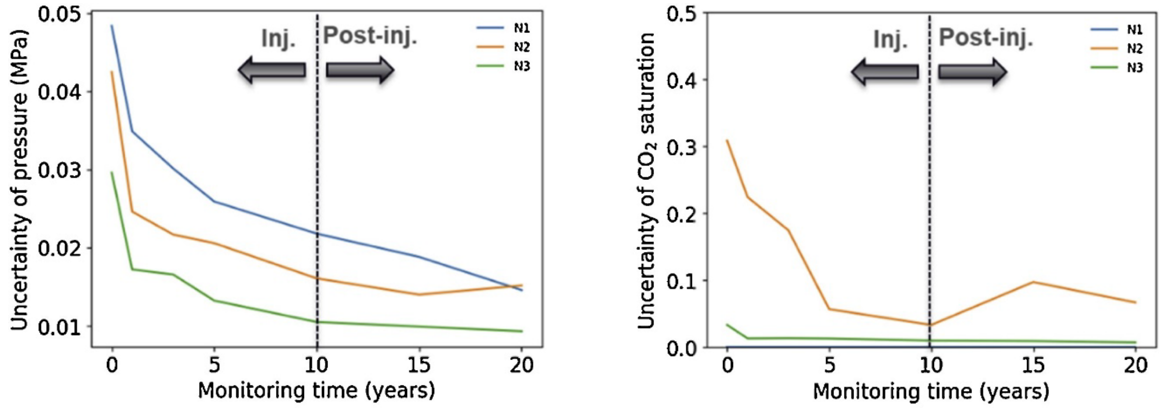
Chen, B.; Harp, D. R.; Lu, Z.; Pawar, R. J. Reducing uncertainty in geologic CO_2 sequestration risk assessment by assimilating monitoring data. *Int. J. Greenh. Gas Control*. 2020, 94, Article 102926.

Key Findings

- Ensemble Smoother with Multiple Data Assimilation (ES-MDA) can be used to assimilate the data collected from CO_2monitoring operation
- Uncertainty reduction (UR) analysis is used to quantify UR in risk quantities
- Assimilation of monitoring data can reduce the uncertainties in risk quantities
- The models can be improved with repeated assimilation of monitoring data
- The extent of model improvement is dependent on the number of monitoring wells



(a) Prior (b) 3 years (c) 10 years



(a) Uncertainty of pressure (b) Uncertainty of CO_2 saturation

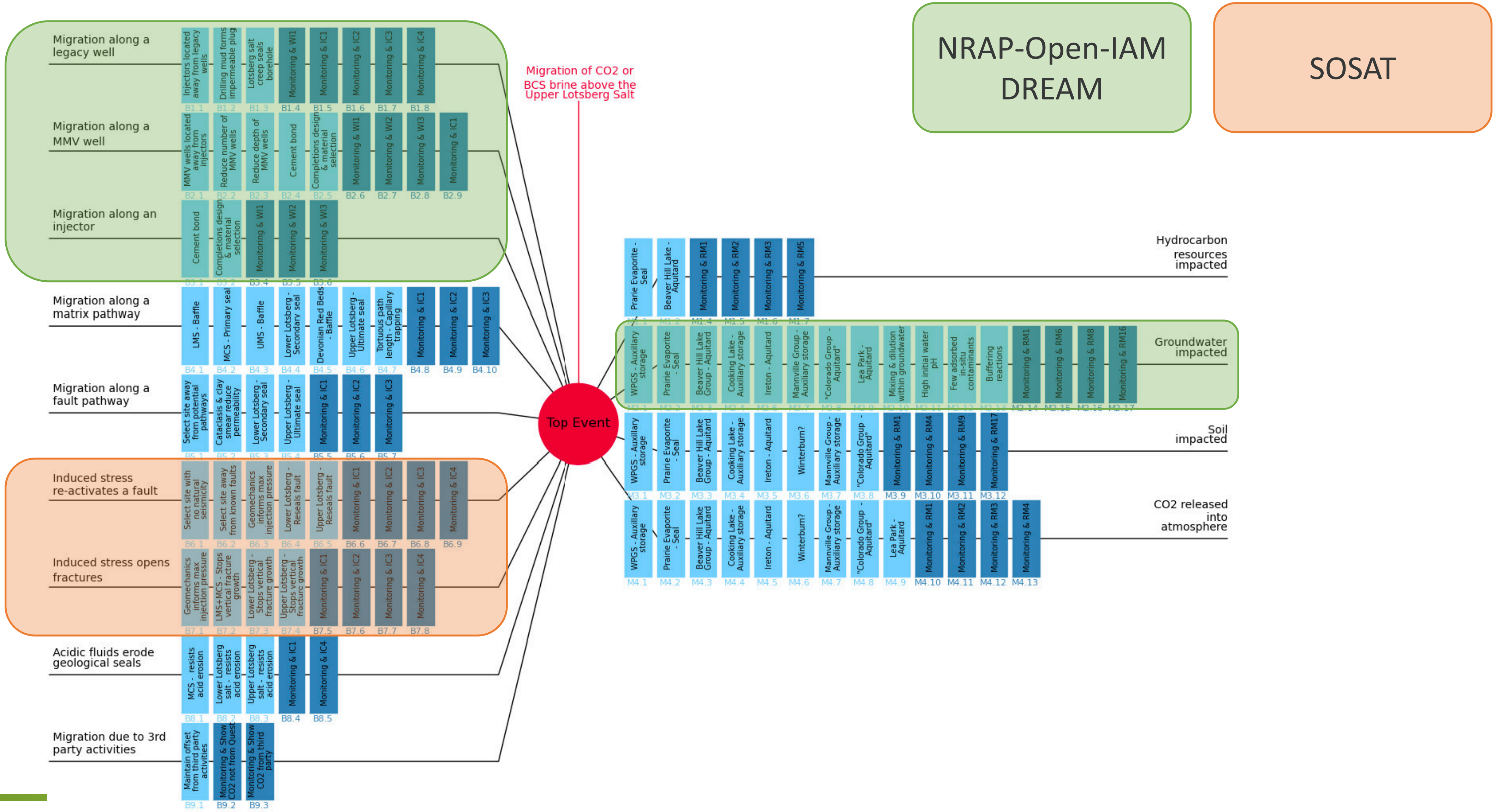
Evaluating Risk Management/Mitigation Scenarios

Best Practices

- Characterize potential leakage pathways
- Develop monitoring plan
- Estimate the acceptability of risk for the base case
- Rank failure probability, severity, and detectability
- Define acceptable responses for a set of unlikely, but possible emergency situations

- Emergency & Remedial Response Plans
  - "Kill" or plug the legacy well
  - Drill a production well to remove brine from the reservoir near the leakage pathway
  - Reperforate the well to redirect injection and modify flow and pressure distribution
  - Drill a new injection well to distribute pressure buildup
  - Lower the injection volume or rate
  - Shut the injection well in

Where NRAP tools can inform existing Risk Managment Frameworks: Shell *Quest* bow-tie risk assessment



Bourne et al., 2014

Risk-based Post-Injection Site Care Period and Closure

Best Practice

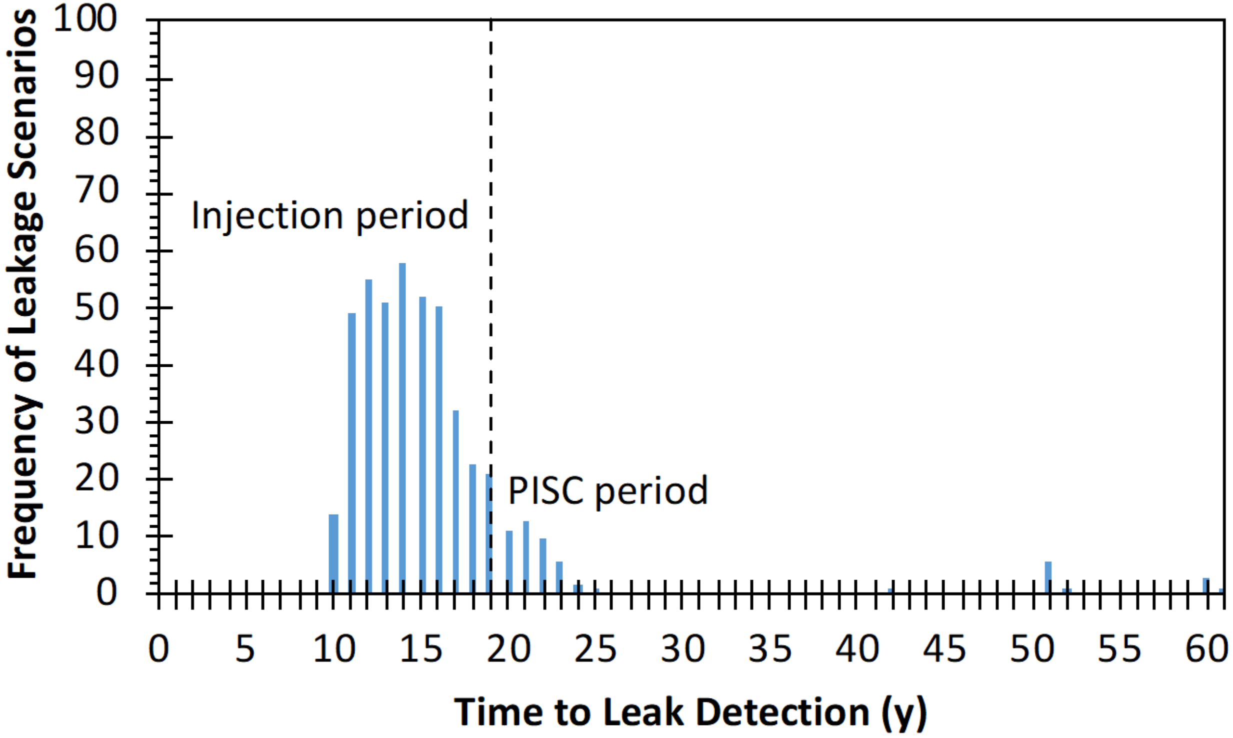
- **Initial PISC Period Determination**
  - Develop system model
  - Evaluate site leakage risks over time
  - Determine leak impact
  - Define risk-based PISC period
- **Closure Decision-Making**
  - Evaluate conformance
  - Evaluate site leakage risks over time
  - Determine leak impact
  - Closure decision

Workflow: Defining a Risk-Based Period of Post-Injection Site Care in Support of Site-Closure Decision-Making

Bacon DH, CMR Yonkofski, CF Brown, DI Demirkanli, and JM Whiting. 2019. "Risk-based post injection site care and monitoring for commercial-scale carbon storage: Reevaluation of the FutureGen 2.0 site using NRAP-Open-IAM and DREAM." *International Journal of Greenhouse Gas Control* 90:102784. 10.1016/j.ijggc.2019.102784.

Key Findings

- NRAP-Open-IAM and DREAM were used to determine an optimized monitoring network for a commercial-scale CO_2 storage project
- NRAP-Open-IAM revealed that maximum simulated leakage rates of brine were small and could be detected during the injection phase
- These NRAP tools can be used to define a risk-based, and substantially shorter, PISC period for the site



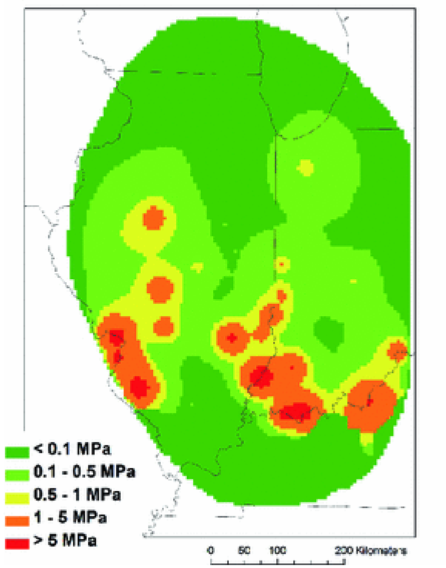
Assessing and managing risks of rapid basin-scale deployment

Motivation

- **Pressure increases from adjacent carbon storage sites are likely to overlap**
- **Pressure build up from industrial-scale injection of CO_2 into saline formations in sedimentary basins increases the risks associated with CO_2 storage:**
  - Wellbore leakage
  - Fault leakage
  - Induced seismicity
- **Pressure buildup could also increase the cost of GCS by**
  - limiting CO_2 injection rates, requiring more injection wells
  - constraining dynamic storage capacities to be far below estimates based on accessible pore volume
  - requiring adaptive pressure management measures (e.g. brine extraction)

Sector	Annual emissions		Number of sites	
	(Mt/year)	(%)	(#)	(%)
Electricity	289.0	79.1	129	37.5
Ethanol	13.7	3.7	32	9.3
Industrial	38.4	10.5	106	30.8
Petroleum/gas	1.8	0.5	43	12.5
Refineries	14.0	3.8	11	3.2
Cement	7.55	2.0	11	3.2
Agricultural	0.6	0.2	7	2.0
Other	0.2	0.1	5	1.5
Total	365.3	100.0	344	100.0

(a)



Illinois Basin

Birkholzer & Zhou, 2011

Bandilla et al., 2012

Anderson and Jahediesfanjani, 2019

Task 6 Assessing and Managing Risks of Rapid, Basin-Scale GCS Deployment

Objective To develop and demonstrate a first-of-kind tool to assess and mange subsurface environmental basin-scale risks associated with rapid commercial-scale deployment of GCS.

EY20	EY21	EY 2022	EY 2023	EY 2024	EY 2025	EY 2026

NRAP Phase II
Open-IAM
SoSAT
ORION v1

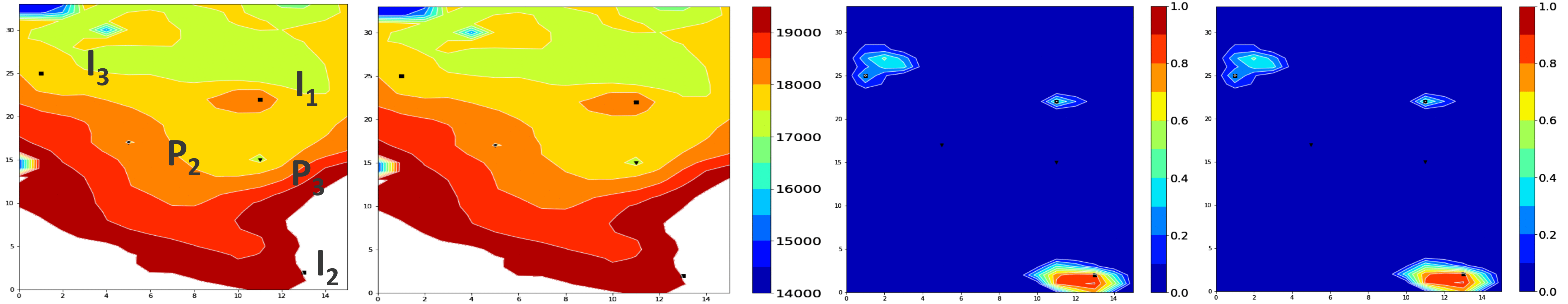
- Prototype risk assessment for credible basin-scale commercial deployment scenario.
- Beta risk assessment and risk mitigation scenario evaluation for first sedimentary basin
- Revised beta risk assessment/ management scenario evaluation for second sedimentary basin
- Final risk assessment and risk mitigation scenario evaluations
- Upload final basin-scale risk assessment data and tool to EDX

Outcome: Tool / workflows to assess and manage risks of basin-scale deployment

Use Cases

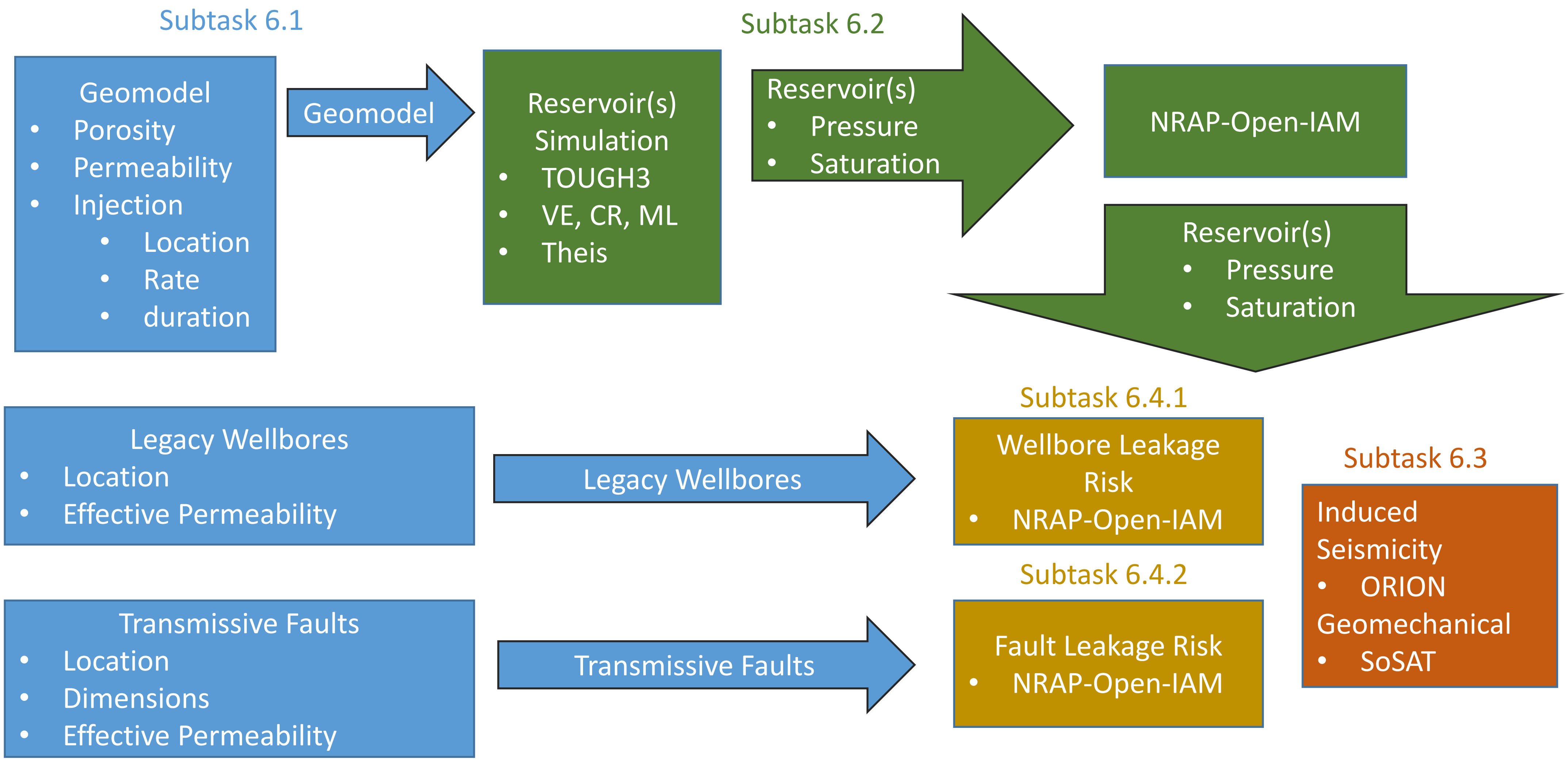
NRAP Basin Scale Integrated Assessment

- **Plan a new storage site**
  - Estimate impact of preexisting storage sites on risk
  - Evaluate pressure management strategies
- **Existing site can update risk assessment as new projects come online**
- **Evaluate potential to store CO_2 from all existing emitters**
- **Compare dynamic estimates of basin storage potential with static capacity estimates**
- **Look at benefits of unitization (sharing risk across sites)**



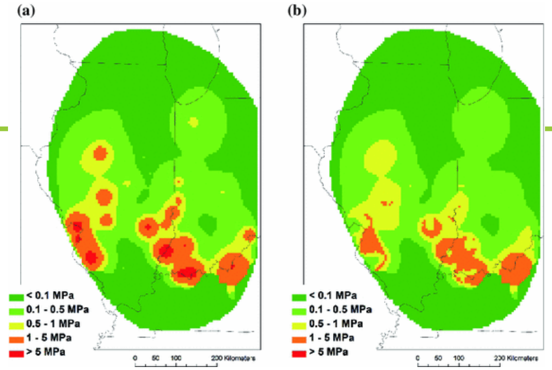
Prototype Data-flow

NRAP Phase 3 Task 6: Assessing and managing risks of rapid basin-scale deployment



Illinois Basin

First Sedimentary Basin



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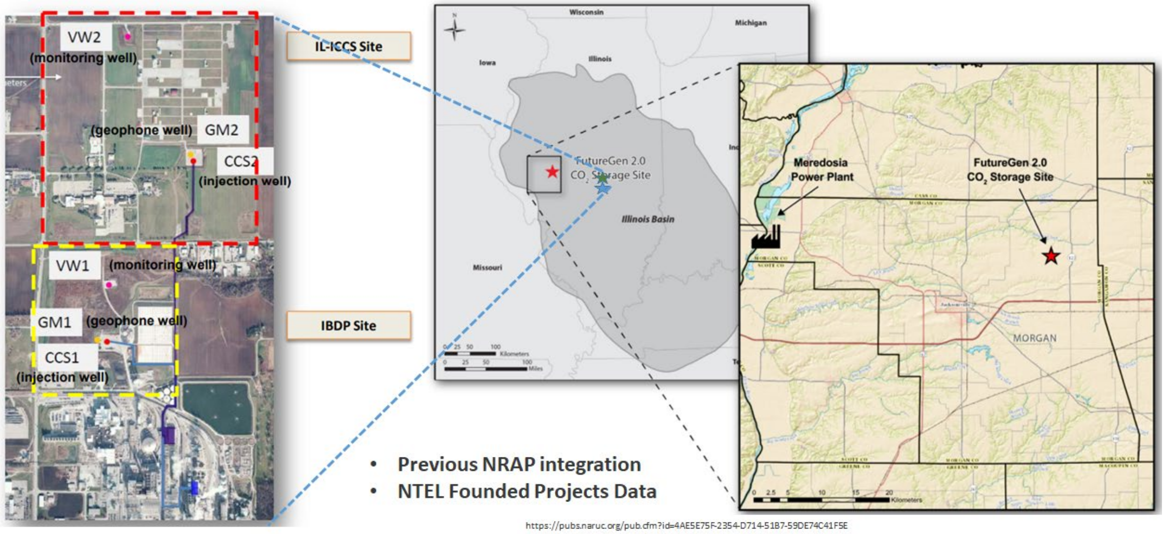
Electricity	289.0	79.1	129	37.5
Ethanol	13.7	3.7	32	9.3
Industrial	38.4	10.5	106	30.8
Petroleum/gas	1.8	0.5	43	12.5
Refineries	14.0	3.8	11	3.2
Cement	7.55	2.0	11	3.2
Agricultural	0.6	0.2	7	2.0
Other	0.2	0.1	5	1.5
Total	365.3	100.0	344	100.0

- Previous basin-scale injection simulations
  - (Bandilla et al. 2012; Birkholzer and Zhou 2009; Person et al. 2010; Zhou et al. 2009)
- Multiple carbon storage operations
  - IDBP; ADM; Illinois Storage Corridor CarbonSAFE
- Multiple emitters
- No previous basin-scale risk analyses

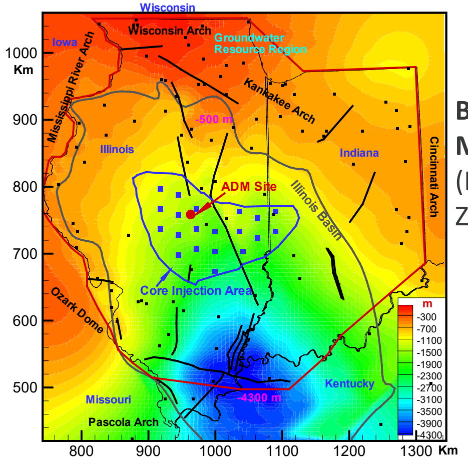


https://pubs.naruc.org/pub.cfm?id=4AE5E75F-2354-D714-51B7-59DE74C41F5E

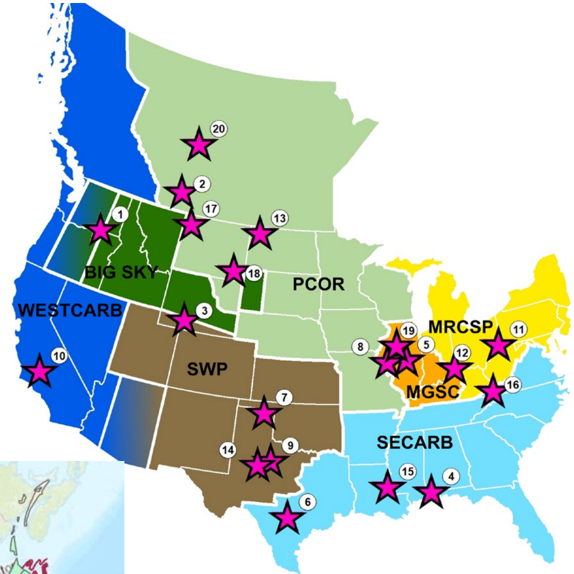
Illinois Basin Existing and Potential Data Sources

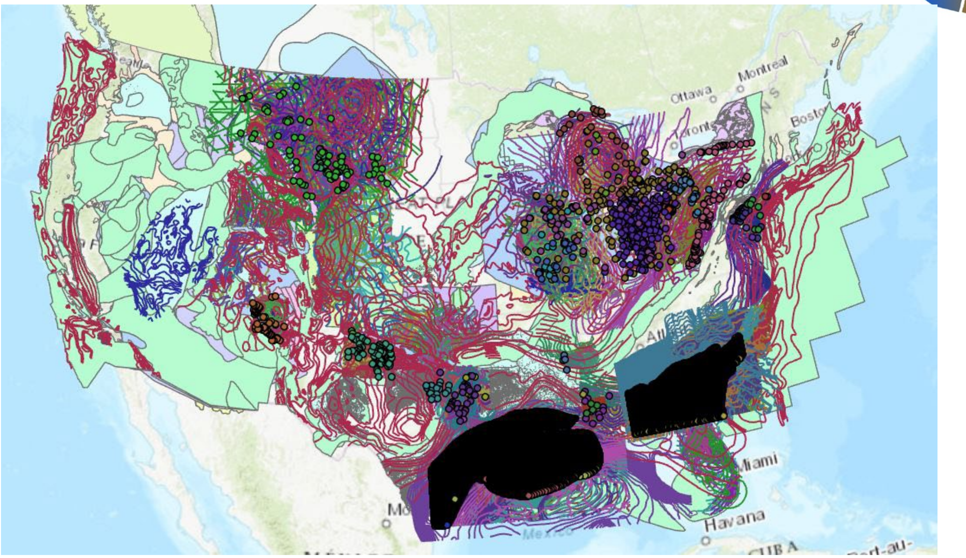
Building on previous work from Phase II to build out basin-scale datasets

- **Birkholzer & Zhou 2009 and Zhou 2010 for Illinois Basin and ADM site**
  - Basin-scale geological model of the Mt. Simon sandstone and Eau Clair shale will serve as example of data types, needs, and data organization
- **NRAP CCS Site Catalog data**
  - Cataloged data resources for 20 sites across USA
- **Carbon Storage Open Database**
  - Scraped from public websites
  - 800+ Spatial layers on ArcGIS Online
  - CCS related geologic data at multiple scales
- **Pulling data from other sources:**
  - 4 Regional Initiatives
  - EDX4CCS cross-cuts
    - Use of data from the Subsurface Trend Analysis tool to fill data gaps in subsurface properties
    - Use of data from the SIMPA tool to produce fracture/damage zone analyses
  - Reach out to state geologic surveys, USGS, and others to meet data needs
  - And more…



Basin-Scale Geological Model (Birkholzer & Zhou, 2009; Zhou et al., 2010)





Current updates for **Carbon Storage Open Database**, Morkner et al. 2022

Key Findings & Next Steps

NRAP Phase II & III

- NRAP Recommended Practices and Tools facilitate risk quantification and management at each stage of a geologic carbon storage project
- NRAP Basin Scale Risk Management System will extend these capabilities to assist site operators to manage risks arising from other storage operations in the same geologic basin

Thank You

Comments and Questions:

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NRAP Website: https://edx.netl.doe.gov/nrap/

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