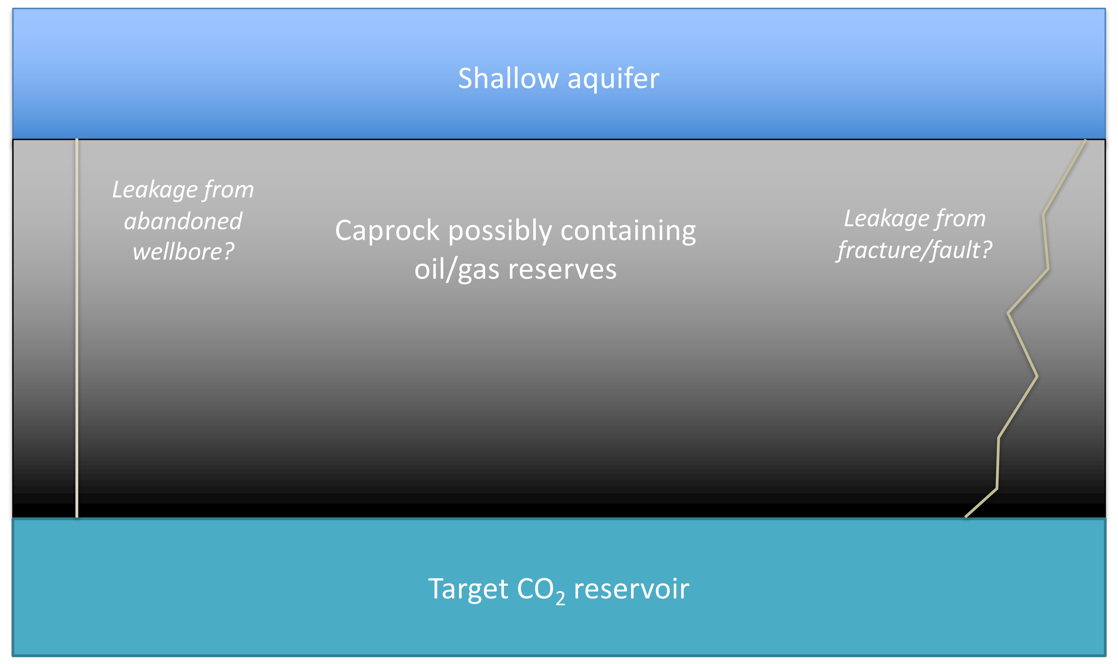
Background

Statement of problem:

Can we confidently detect small leaks in large areas with a limited number of sensors?

Many current challenges in energy require predicting the coupled behavior of multiple subsurface systems (i.e., beyond the reservoir), each of which may be governed by different physics and each with its own heterogeneity and uncertainty. This first aspect requires new simulation strategies that can address physics beyond simple porous flow; and the second aspect means these strategies must be rapid to allow for probing behavior stochastically.

One common challenge involves detection of small leaks in large areas, as shown in the example below from CO storage. Detecting these types of leaks will require new strategies that fuse simulation and monitoring. In this work, we are developing a platform to address this challenge. Predicting the anticipated signals from such leaks requires couples the physics of porous flow to the physics of flow in fracture networks and partially completed wellbores.



Approach:
The development of efficient and accurate approaches to provide decision support for subsurface energy-related challenges requires the coupling of three components:

1. detailed knowledge of *subsurface energy-related processes*,
2. computationally efficient and accurate science-based *full-physics modeling* strategies, and
3. novel *statistical and machine learning* approaches to extract fundamental and essential relationships from full-physics simulations.

Why this research is being done at Los Alamos National Laboratory
LANL provides a unique research environment where all three necessary components discussed above coexist. LANL also has a long history of pooling resources with other institutions to tackle subsurface energy related challenges (e.g., NETL, PNNL, LBNL, LLNL). In this poster, we present approaches to solve subsurface energy related challenges that *integrate these three components.*

Tools we are developing and using to address complex, subsurface energy-related challenges:

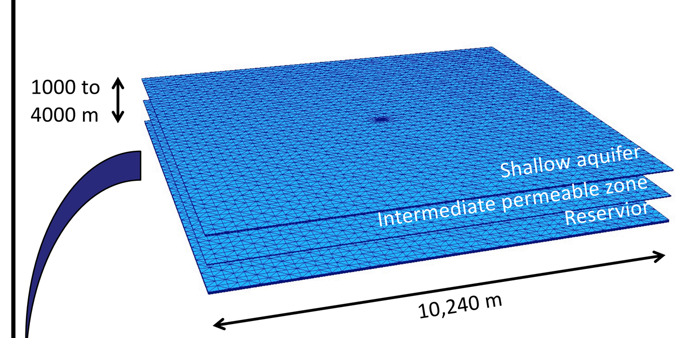
1. FEHM (fehm.lanl.gov) – Multi-component, multi-phase subsurface flow and transport simulator
2. DFNWorks (http://www.lanl.gov/…/dfnworks/index.php)– Discrete fracture network generation code
3. MATK (matk.lanl.gov)– Python package for model analysis and distributed, concurrent model execution

Approach 1: Response surface modeling of leakage along cemented wellbores

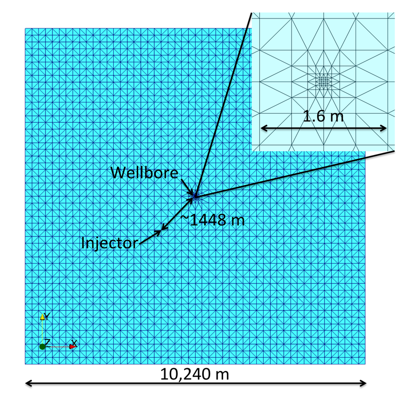
Dylan Harp, Rajesh Pawar, Bill Carey, and Carl Gable

- *Abandoned wellbore leakage* is one of the primary risks in CO2 sequestration.
- *Full-physics simulations* of multi-phase, multi-component brine and CO_2 are *computationally expensive*.
- We use *Multivariate Adaptive Regression Splines* (***MARS***) to *extract the fundamental relationships* between input parameters and brine and CO_2 leakage into *basis function response surfaces*.

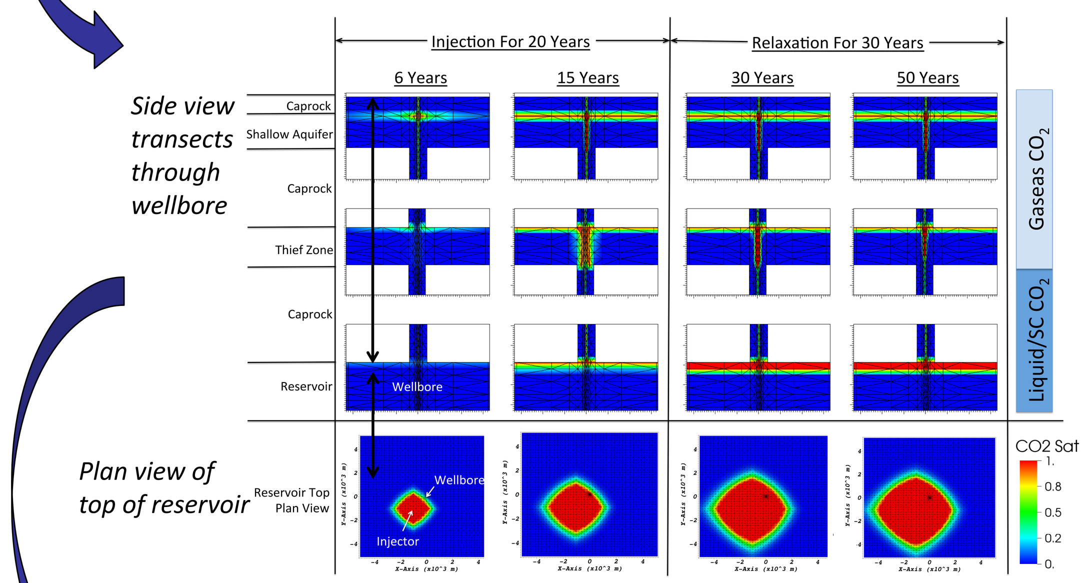
3D view of full-physics computational mesh



Plan view of full-physics computational mesh

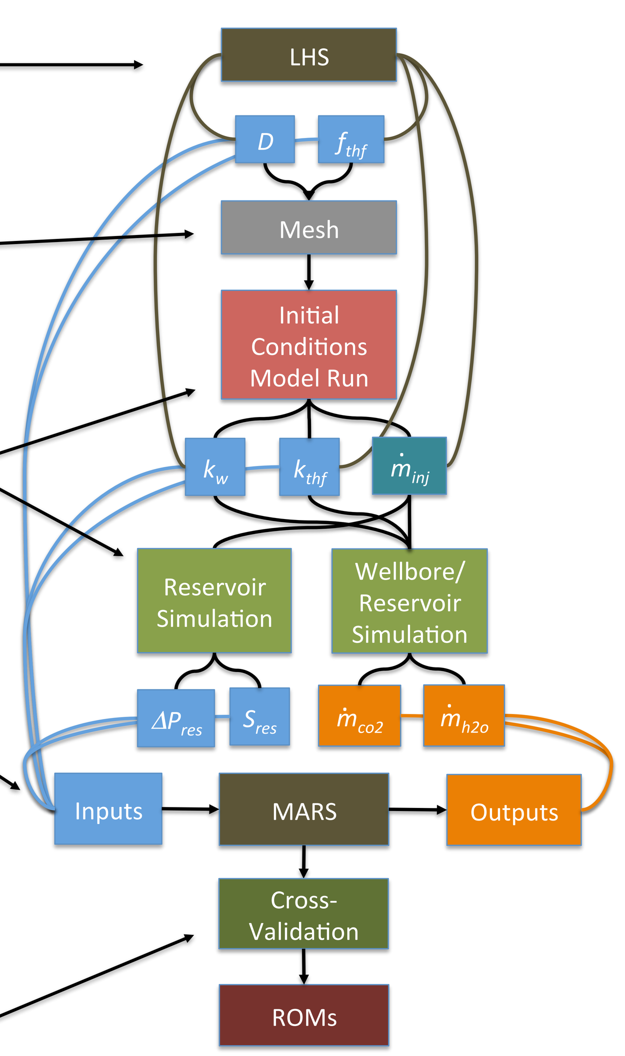


Example simulation of full-physics simulations of CO_2 leakage



Flow diagram of response surface generation

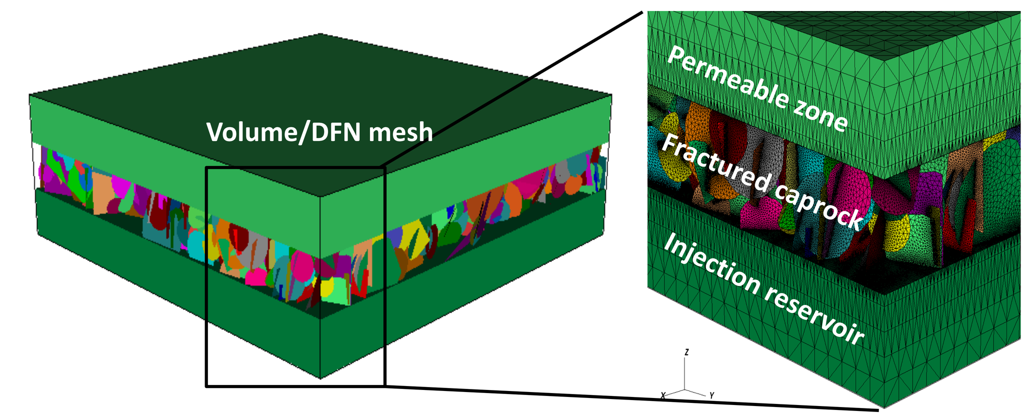
- Latin Hypercube Sampling of parameters
- Automatically generated mesh
- Science-based full-physics simulations
- Inputs and outputs are collected and processed into a basis function response surface using MARS.
- Cross-validation is used to verify the predictive capability of the response surface



Approach 2: Improved modeling of CO_2 flow in fractures

Nataliia Makedonska and Rajesh Pawar

- *Fractures provide dominant transport pathways* in many scenarios such as fractured caprock above CO_2 injection reservoirs. *Discrete Fracture Networks (DFNs)* allow us to model fracture flow more accurately and realistically.
- *Coupling DFN model with continuum approach* to study CO_2 flow is a computationally complex system, which provides *an example of risk quantification*.



Merging Discrete Fracture Network (DFN) and Volume Mesh

- The DFN is generated using dfnWorks simulation tool
- The 2D fracture network is meshed by conforming Delaunay triangulation (LaGriT)
- The simulation domain size can be extended up to kilometers
- Different fracture densities can be considered ($0.1 < P_{32} < 0.6$)

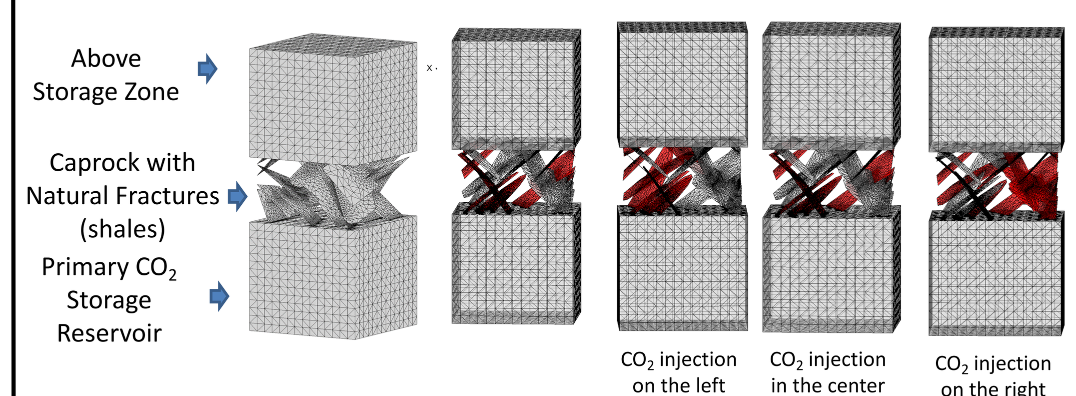
Application to Characterize Caprock Leakage

Realistic simulations, representing not only geologic complexity but also operational conditions

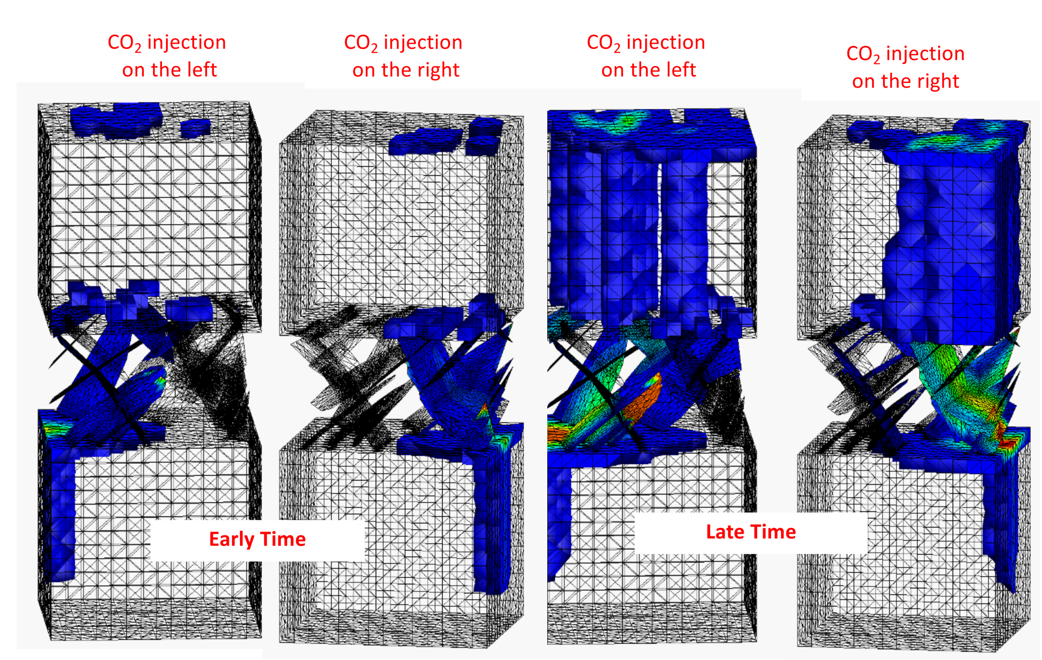
Important insights

Not all fractures contribute to flow

Operational scenario and plume evolution in reservoir affect fluid migration



Example of CO_2 Saturation at Earlier and Later Times After CO_2 Injection

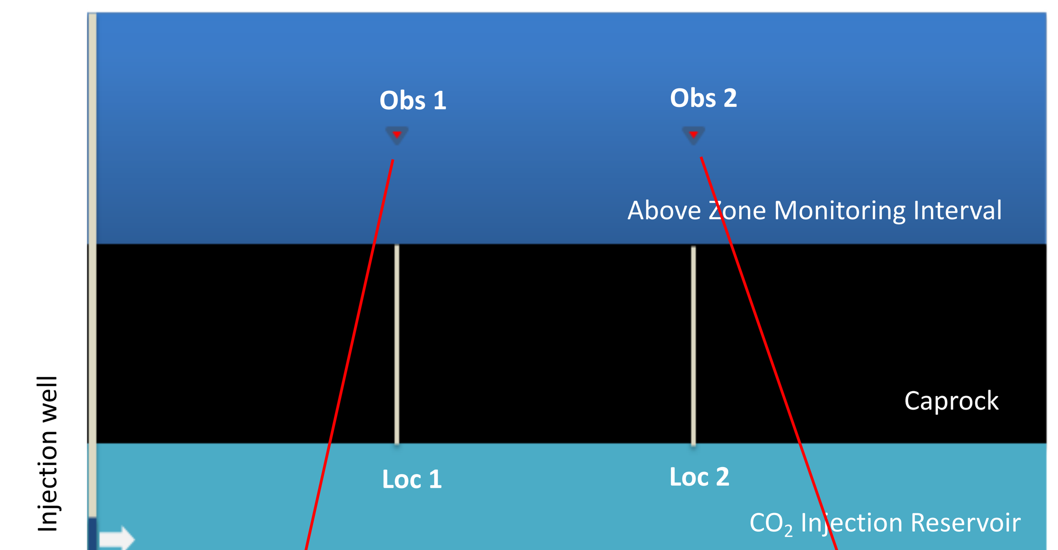


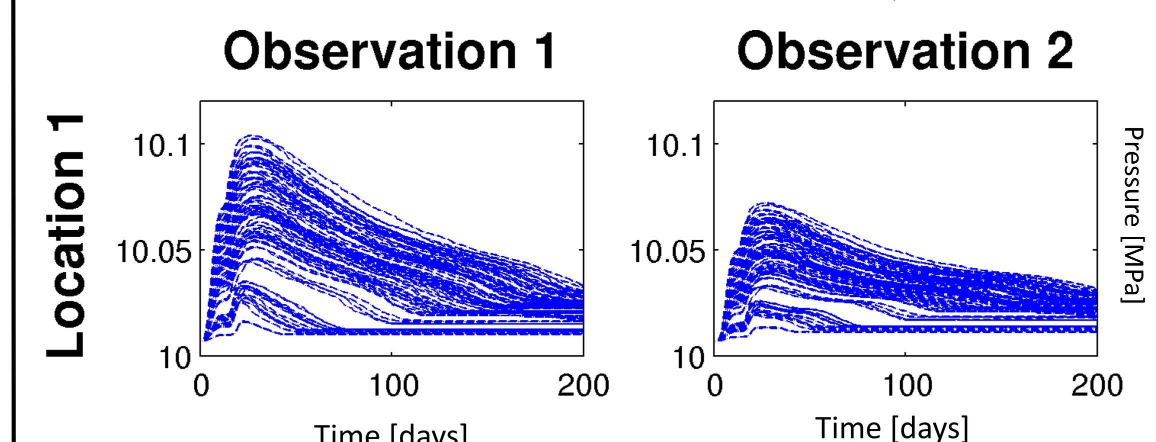
Approach 3: Using machine learning to detect CO_2 leakage

Youzuo Lin, Dylan Harp, and Rajesh Pawar

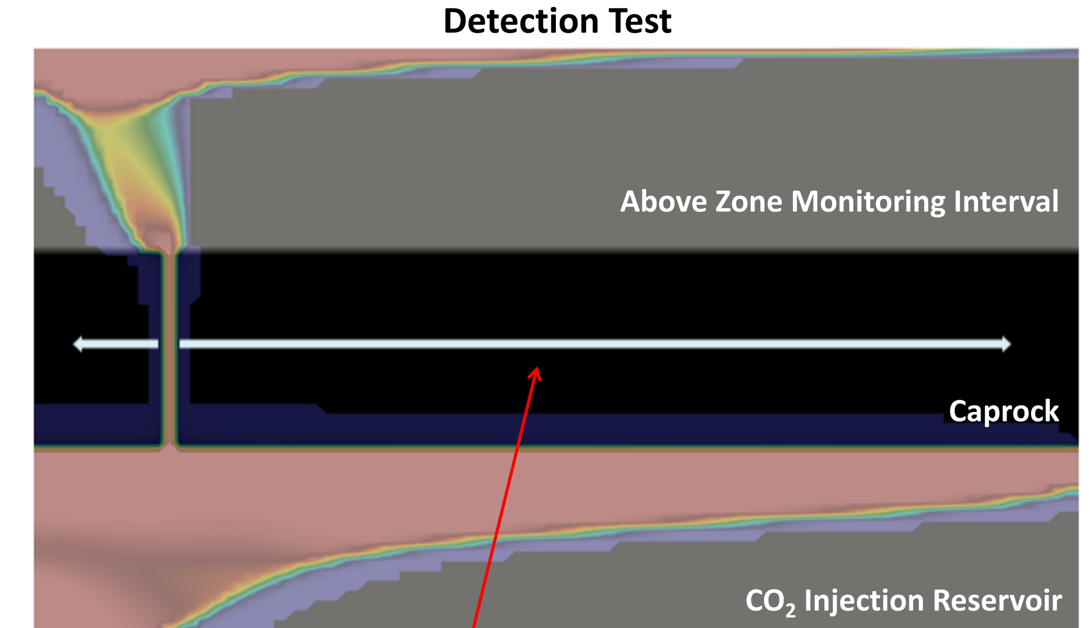
- *Machine learning* is a powerful tool to effectively detect unknown pattern from datasets.
- We employ machine-learning to *detect the leak location* of the stored CO_2.
- We generate training datasets using FEHM to simulate the actual leaks of CO_2.
- Our detection algorithm is trained with pressures resulting due to leaks at 2 locations only, but can detect leakage from any location in the caprock based on monitoring observations at 2 locations.

Model and Training Data



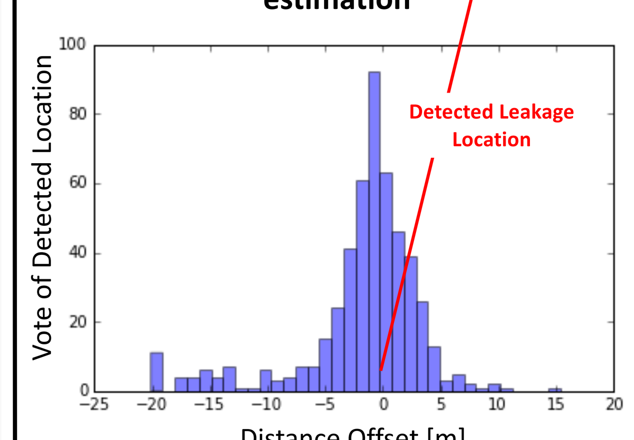


Detection Test



Methods and Results

Example histogram of error in location estimation



- We employ the above training data to train our supervised learning methods.
- 500 unknown leak cases are created by varying the CO_2 injection rate.
- Prediction error is measured by Mean Absolute Error (MAE):

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |y_i^{gt} - y_i^{pred}|}{n}$$

- **Overall MAE ≈3** grid points.
- Detection error:
  - within 1 grid point: **41.4%**
  - within 2 grid points: **60.6%**
  - within 3 grid points: **72.8%**

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- Computer clusters at Los Alamos National Laboratory supported by the Los Alamos National Laboratory High Performance Computing Environments Group were utilized during this research.

References

- Harp, D. R., R. Pawar, J. W. Carey, and C. W. Gable (2016, February). Reduced order models of transient CO2 and brine leakage along abandoned wellbores from geologic carbon sequestration reservoirs. *International Journal of Greenhouse Gas Control 45*, 150-162.
- Harp, D. R., P. Stauffer, D. O'Malley, Z. Jaio, E. P. Egenolf, T. A. Miller, D. Martinez, K. A. Hunter, R. S. Middleton, J. M. Bielicki, and R. Pawar. "Development of Robust Pressure Management Strategies for Geologic CO_2 Sequestration". International Journal of Greenhouse Gas Control. In Review.
- Jordan, Amy B., Philip H. Stauffer, Dylan Harp, J. William Carey, and Rajesh J. Pawar. "A response surface model to predict CO 2 and brine leakage along cemented wellbores." International Journal of Greenhouse Gas Control 33 (2015): 27-39.
- Keating, Elizabeth, Diana Bacon, Susan Carroll, Kayyum Mansoor, Yunwei Sun, Liange Zheng, Dylan Harp, and Zhenxue Dai. "Applicability of aquifer impact models to support decisions at CO 2 sequestration sites." International Journal of Greenhouse Gas Control 52 (2016): 319-330.
- Keating, Elizabeth H., Dylan H. Harp, Zhenxue Dai, and Rajesh J. Pawar. "Reduced order models for assessing CO 2 impacts in shallow unconfined aquifers." International Journal of Greenhouse Gas Control 46 (2016): 187-196.
- Pawar, R.J., Bromhal, G.S., Chu, S., Dilmore, R.M., Oldenburg, C.M., Stauffer, P.H., Zhang, Y., Guthrie, G.D., The National Risk Assessment Partnership's integrated assessment model for carbon storage: A tool to support decision making amidst uncertainty, International Journal of Greenhouse Gas Control, 52, 175-189, 2016.
- Pawar, Rajesh, James Carey, Steve Chipera, Julianna Fessenden, John Kaszuba, Gordon Keating, Peter Lichtner et al. "Development of a framework for long-term performance assessment of geologic CO2 sequestration sites." In Eighth International Conference on Greenhouse Gas Control Technologies (GHGT-8), pp. 19-22. 2006.
- Stauffer, P.H., Viswanathan, H.S, Pawar, R.J. and Guthrie, G.D., A system model for geologic sequestration of carbon dioxide. Environmental Science & Technology, 43 (3), 565-570, 2009.
- Makedonska, N., Hyman, J. D., Karra, S., Painter, S. L., Gable, C. W., & Viswanathan, H. S. (2016). Evaluating the effect of internal aperture variability on transport in kilometer scale discrete fracture networks. Advances in Water Resources, 94, 486-497.
- Hyman, J. D., Karra, S., Makedonska, N., Gable, C. W., Painter, S. L., & Viswanathan, H. S. (2015). dfnWorks: A discrete fracture network framework for modeling subsurface flow and transport. Computers & Geosciences, 84, 10-19.
- Hyman, J. D., Gable, C. W., Painter, S. L., & Makedonska, N. (2014). Conforming Delaunay triangulation of stochastically generated three dimensional discrete fracture networks: a feature rejection algorithm for meshing strategy. SIAM Journal on Scientific Computing, 36(4), A1871-A1894.
- Lin, Y., B. Wolhberg and V. Vesselinov (2017), "ADMM penalty parameter selection with Krylov subspace recycling technique for sparse coding," in Proceeding of IEEE International Conference on Image Processing.
- Lin, Y. , S. Wang, J. Thiagarajan, G. Guthrie and D. Coblentz (2017), "Towards Real-Time Geologic Feature Detection from Seismic Measurements using a Randomized Machine-Learning Algorithm," in Proceeding of the Society of Exploration Geophysics Annual Meeting, Houston, Texas.

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