Hypothesis, Research Motivation, and Planned Methods

Given only boundary fluxes from a site-specific mine model, inverse modeling can (in principle) recover both the spatial locations and asynchronous pumping schedules of multiple wells. However, the reliability of that recovery, assessed by identifiability and parameter uncertainty, declines as hydrogeological complexity increases. This project fills a gap in parameter-estimation research: most identifiability and uncertainty studies assume source/sink locations are known a priori, whereas we explicitly address the more realistic and substantially harder problem of inferring the existence and attributes (location, timing, rate) of multiple asynchronous pumping wells from boundary flux observations alone.

Regulatory regional groundwater models commonly omit or underrepresent mine dewatering predictions (pumping locations and schedules) because those details are retained in consultant- and operator-owned mine-scale models. Yet regional models that inform regulatory decisions and affect broad water-use interests would benefit from access to such information. There is limited understanding of whether, and to what extent, those withheld pumping schedules can be inferred from the boundary fluxes reported in regional models, particularly under realistic complexity (multiple asynchronous wells, heterogeneity, anisotropy, and measurement or representation error). We will show that, in many practical cases, identifiability from boundary fluxes is sufficiently poor that operators can safely disclose aggregate boundary-flux information to regulators without exposing proprietary well locations or schedules.

Scientifically, the project advances inverse hydrogeological modeling by developing robust inverse-modeling workflows and uncertainty-quantification methods that explicitly account for model error and non-uniqueness when sources are unobserved. Methodologically, we will proceed from analytic to numerical models: starting with synthetic time series generated from the Theis (1935) solution (single and multiple wells in an infinite, homogeneous, isotropic, radial domain) and performing initial manual inversions then pyEMU-based analyses (White, Fienen, & Doherty, 2016). We will then transition to inverting site-inspired transient numerical models (e.g., MODFLOW), incrementally increasing domain complexity (variable boundaries, heterogeneity, anisotropy, layered structure, and partially penetrating wells) (Figure 1).

Identifiability will be quantified in stages consistent with model fidelity (Figure 1). For analytical solutions we will analyze the Jacobian (least-squares optimality) and derive basic sensitivity measures. For numerical solutions we will employ null-space mapping and Bayesian posterior summaries (e.g., credible regions and information-gain metrics) to identify unobservable parameter subspaces and to define disclosure-safe thresholds. Ensembles of heterogeneous realizations will be generated using state-of-the-art parameter estimation software such as PEST (Doherty, 2015) to test robustness to measurement noise and parameter uncertainty.

A plausible alternative explanation is the presence of significant, unmodeled external sources or sinks, such as irrigation, other permitted pumping, or leakage. The presences of these would confound the attribution of boundary fluxes to mine dewatering. We will test for this by inserting synthetic confounders into twin experiments and evaluate how auxiliary observations in the numerical model (heads, boundary conditions) change identifiability. Large changes in identifiability when confounders are included would indicate that unmodeled fluxes drives poor recovery.

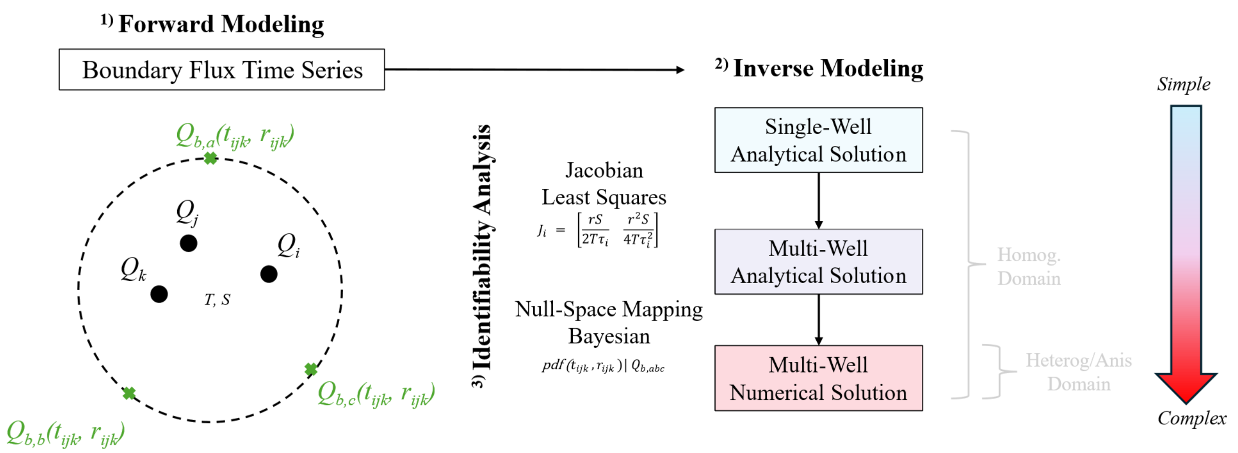

Figure 1. Project flow-chart illustrating progression from forward modeling to inverse modeling and identifiability analysis with increasing complexity.

Timeline and Milestones

February

- Meet with Piteau re: using Southwestern U.S. mine models as realistic bases for project models.

March

- Meet with U.S. Geological Survey staff with inverse-modeling expertise re: co-advising.
- Build single-well Theis analytical solution model using Python.
- Construct data visualization workflows using Python.
- Develop single-well manual inversion (radius from well to boundary, elapsed time since the start of pumping) method using Python.
- Conduct single-well model sensitivity analysis (storativity, transmissivity) on boundary flux (Q_b).
- Repeat previous three steps for multi-well Theis analytical solution model.

April

- Develop multi-well inversion (radius from well to boundary, elapsed time since the start of pumping) method using pyEMU.
- Build multi-well numerical solution using MODFLOW, modeled after a few real Southwestern U.S. mine models.
- Conduct inversion and sensitivity analysis with increasing complexity (variable boundary conditions, heterogeneity, anisotropy, geological structure, partially penetrating wells) added to the multi-well numerical solution model.

May

- Write thesis and submit draft to research committee.

June

- Finalize and defend thesis.