Risk Based Area of Review Delineation with MODFLOW and Groundwater Contaminant Fate and Transport Modeling

Todd Umstot and Gregory Schnaar, Ph.D., P.G.

DBS&A
a Geo-Logic Company

Area of Review (AoR) delineation

- **The AoR is the CO_2 plume and pressure zone that may risk Underground Source of Drinking Water (USDW).**
- **Defined by computational modeling, it covers the predicted maximum extent of the plume and/or pressure front over the project's lifetime.**
- **The pressure front is the pressure in the injection zone high enough to push fluids through a hypothetical conduit into an overlying USDW.**

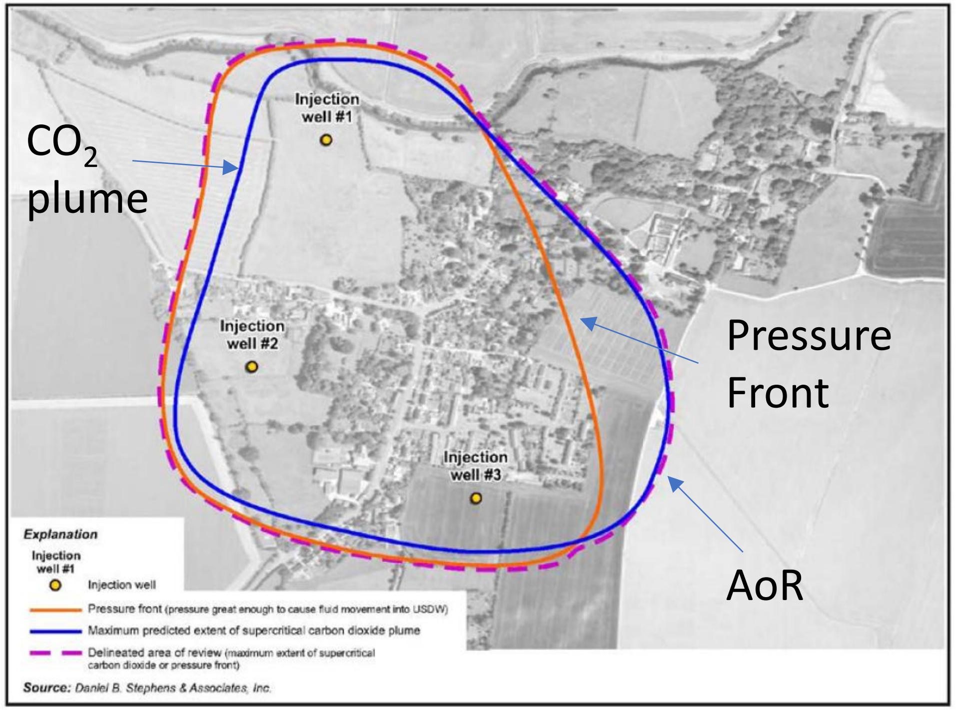


Figure 3-6: Hypothetical Geologic Sequestration Site: Initial Area of Review Based on Model Results.

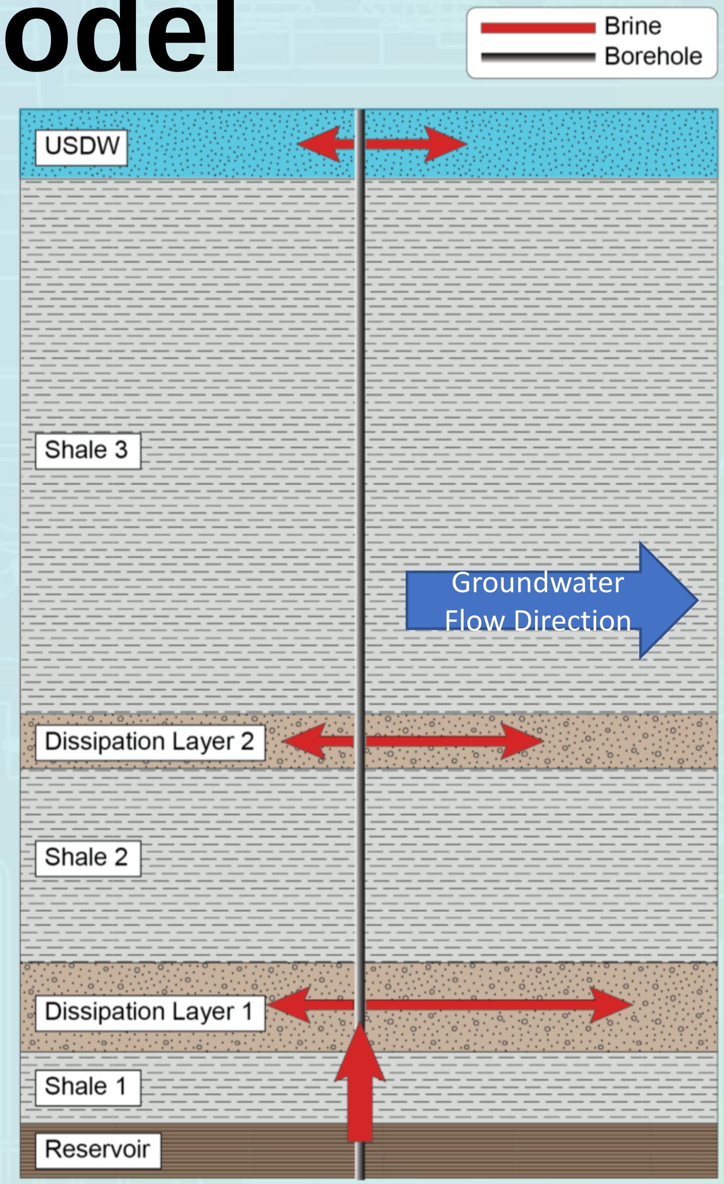
Source: EPA, 2013 after DBS&A

General Steps for Risk Based AoR

1. **Model brine leakage rates through a hypothetical improperly abandoned well at specified pressure increases within the injection zone.**
2. **Model the distribution of elevated salinity within the USDW resulting from leakage.**
3. **Compare estimated increase in USDW salinity to established screening levels and/or background values.**
4. **Map the maximum extent of the pressure front that impacts the USDW above screening levels and/or background levels.**

Conceptual Model

- **A single wellbore connects the injection zone to the USDW, dissipation zones, and shales.**
- **Dissipation zones receive most brine leakage due to proximity to injection zone.**
- **Shale zones are assumed impermeable outside of the wellbore.**
- **Salinity migrates with groundwater flow but a fraction also disperses upgradient.**



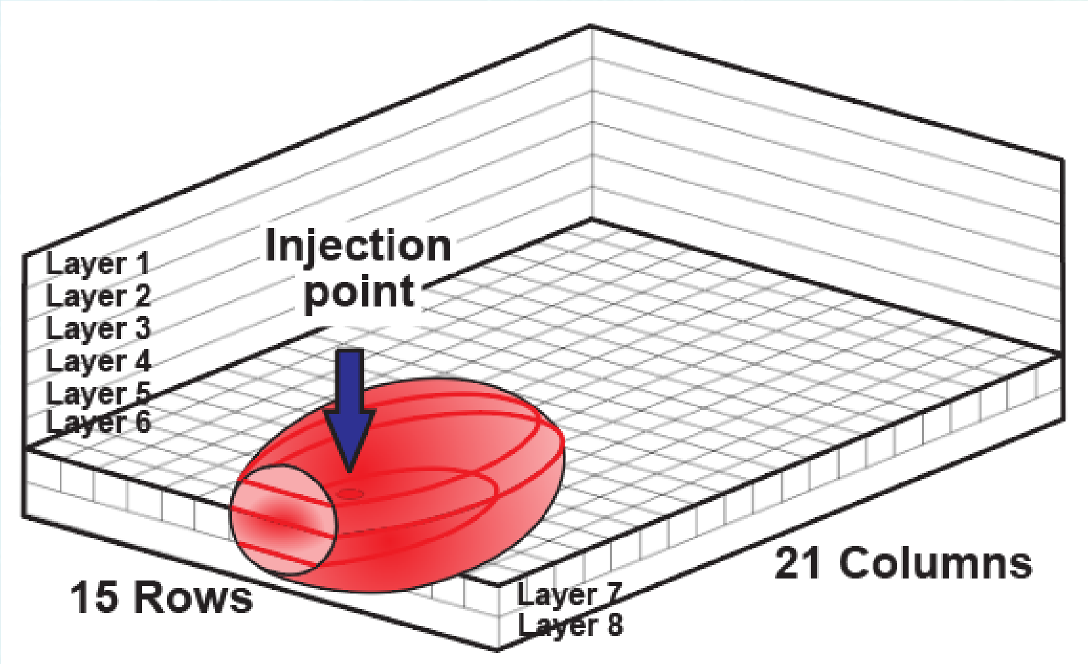
Brine Leakage Modeling Approaches

- **Approach 1: Hybrid Numerical and Analytical Modeling**
  - **Use MODFLOW to estimate brine flow and corresponding TDS flux rates from borehole to the dissipation zones and USDW.**
  - **Use analytical solutions to model fate and transport of TDS in the USDW from the borehole.**
- **Approach 2: Numerical Modeling**
  - **Use variable density, non-isothermal numerical model to model brine flow and fate and transport of TDS in the USDW.**
- **Both methods assume borehole is outside of CO_2 plume but within the area of increased pressure so that multiphase modeling is not required.**

Hunt/Wexler Analytical Solution

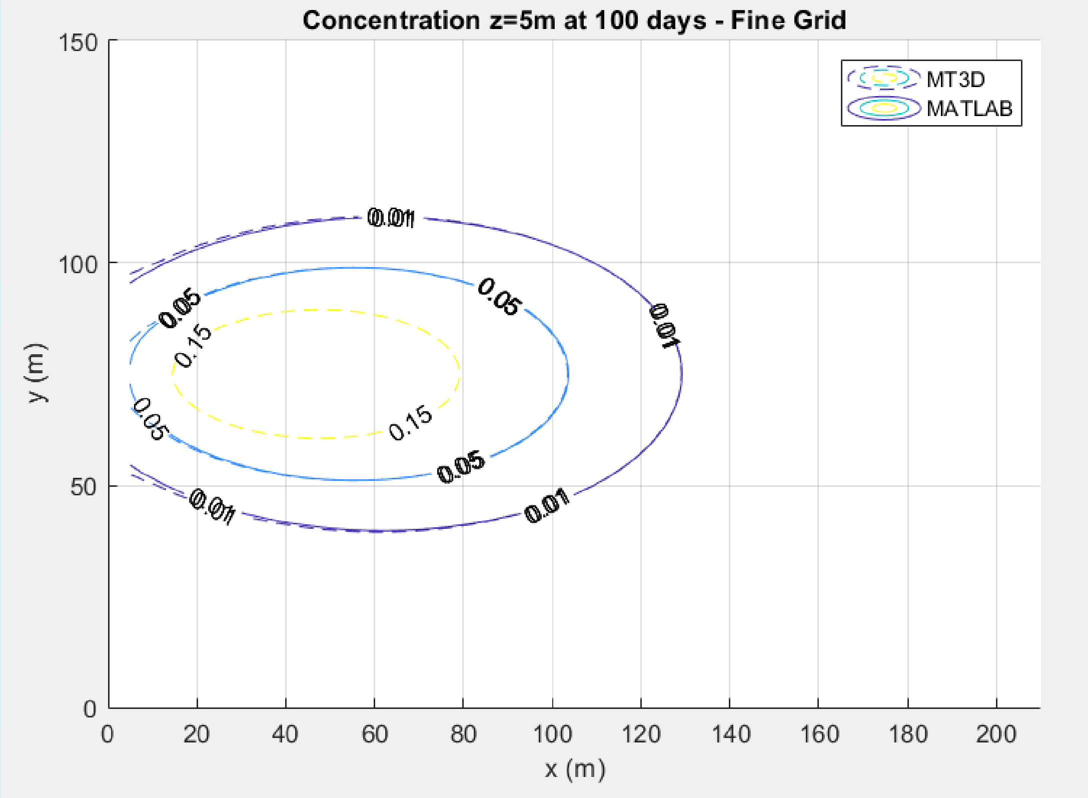
- **Hunt (1978) solves the advection-dispersion equation with decay.**
- **Uses a point flux boundary.**
- **Wexler (1992) added sorption.**
  - **Sorption and decay can apply to other contaminants but not salinity.**
- **Assumes uniform flow, an infinite aquifer, and isothermal conditions.**
  - **Does not consider density-driven flow.**

3D View of Hunt Analytical Solution with Grid for comparison



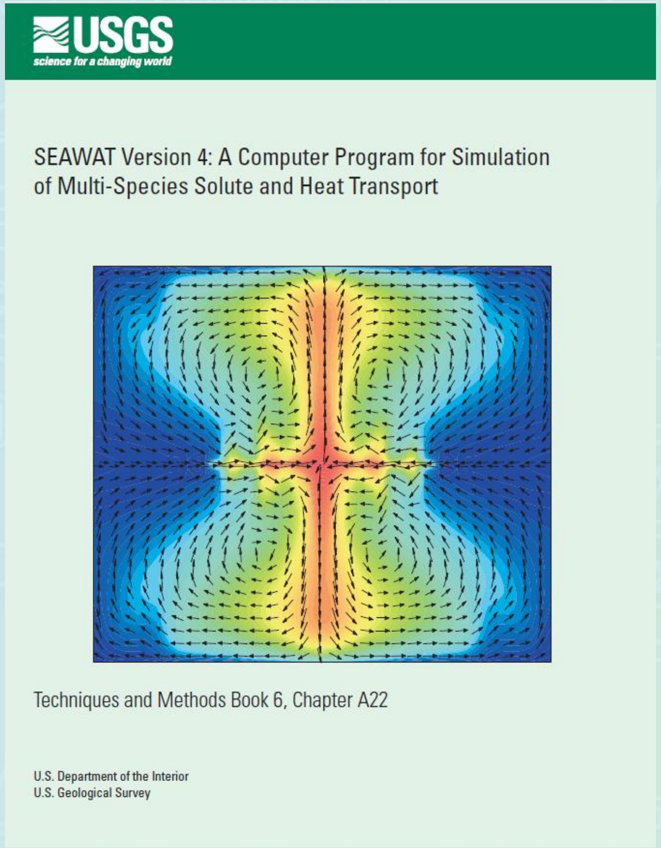
Implementation of Hunt/Wexler

- **Coded in MATLAB and Python.**
- **Uses superposition/image theory for boundary conditions and time-varying brine flux.**
- **Verified with MT3D.**
- **Compared to MODFLOW-SEAWAT for density-driven flow threshold.**
  - **Can be applied for brines < 15,000 mg/L TDS**



Approach 2
MODFLOW-SEAWAT Numerical Model

- Use MODFLOW-SEAWAT when density (>15,000 mg/L TDS) or non-isothermal effects impact brine flow.
- MODFLOW-SEAWAT integrates MODFLOW (flow) and MT3DMS (transport) for 3D variable-density simulation.
- Models heat transport, density changes from solute/temperature variations, and viscosity shifts due to temperature and salinity.



Key Input Parameters for Brine Leakage Modeling

- **Stratigraphy**
- **Permeability of the USDW and Dissipation Zones**
- **Wellbore Permeability and Diameter**
- **Brine density and temperature**
- **Reservoir pressure at the wellbore**
- **Initial Total Dissolved Solids (TDS) for each formation**
- **Dispersivity**

Permeability of Borehole

- **Open borehole permeability is often assumed to be ≤10^{-10} m^2 (101,325 mD), a conservative estimate exceeding reported values for leaking wells.**
  - **Celia et al. (2011) classify deep leakage potential from "low" to "extreme," with extreme cases ranging from 8 to 10,000 mD (8·x 10^{-15} to 1·x 10^{-11} m^2).**
- **Plugged wellbores are conservatively assumed to have a permeability of 10^{-13} m^2 (101 mD).**

Table 2
Mapping of well score to mean effective well permeability. Data in columns marked with * from Watson and Bachu (2008).

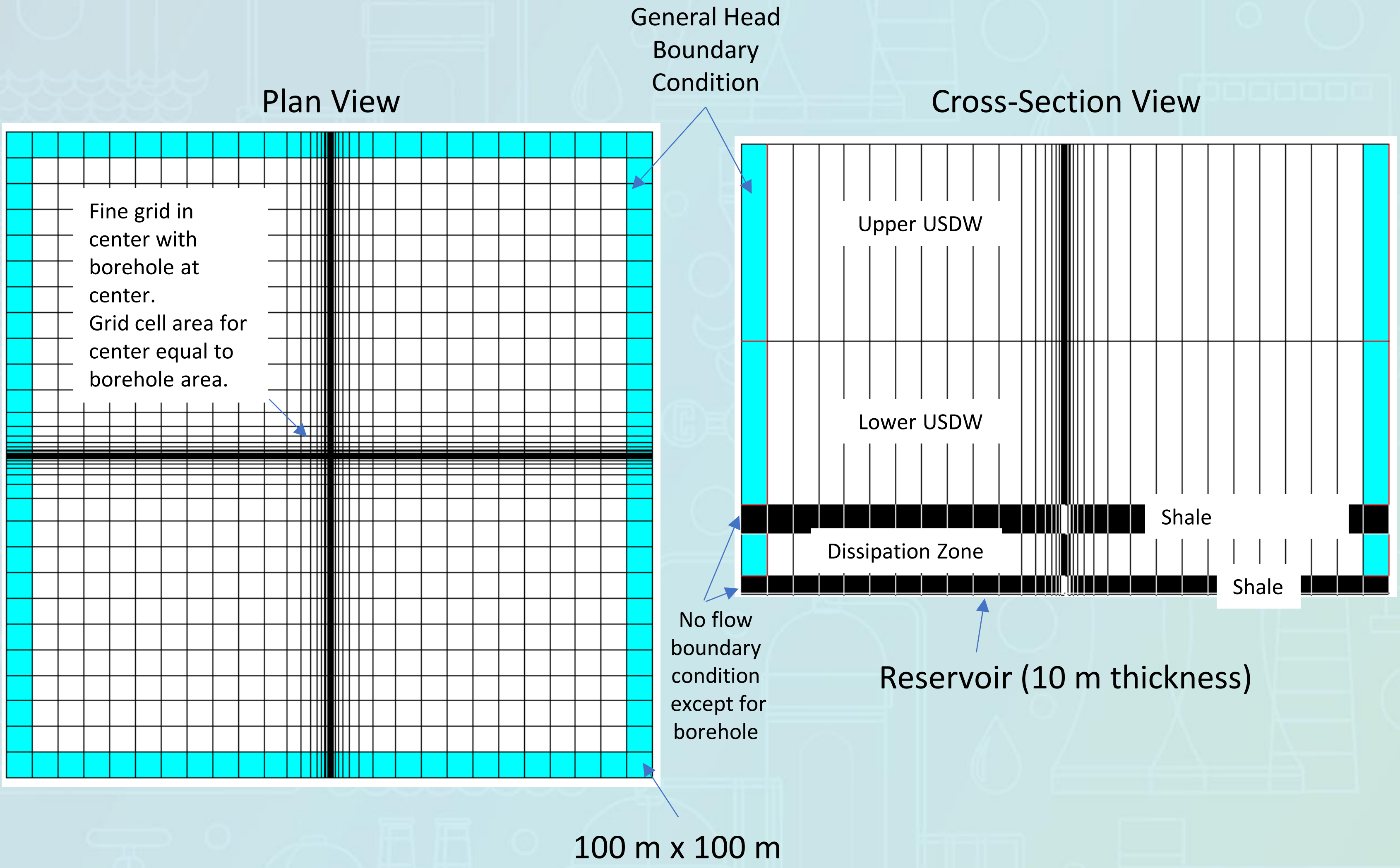
Deep leakage potential*	Score range*	Well effective permeability mean [mD]
Low	<2	0.01–0.02
Medium	2–6	0.02–0.5
High	6–10	0.5–8
Extreme	>10	8–10,000

M.A. Celia et al. / International Journal of Greenhouse Gas Control 5 (2011) 257–269

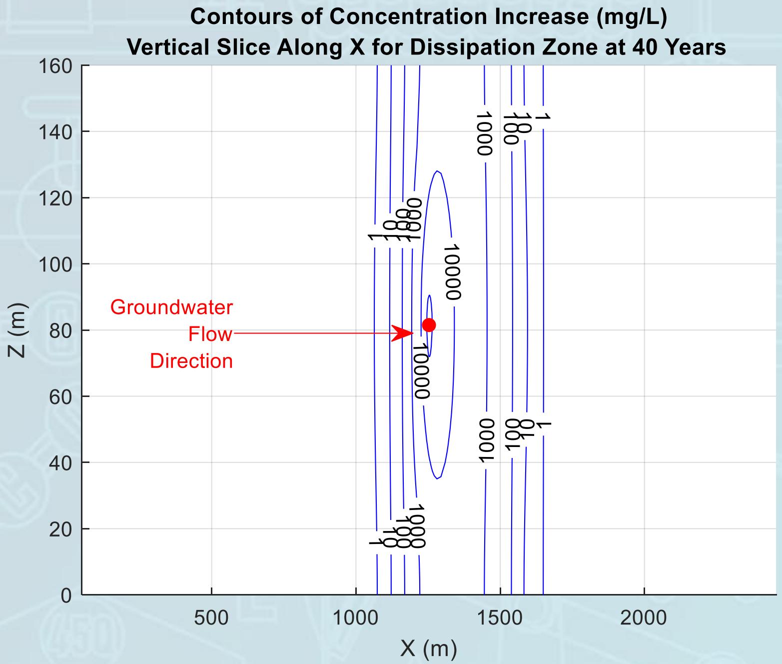
Case Study

- **Used Hybrid approach with MODFLOW and Hunt/Wexler.**
- **Model location with minimum distance between injection zone and USDW outside of CO_2 plume.**
- **Reservoir pressure set to constant 3,000 pounds per square inch (psi), which is 525 psi above hydrostatic conditions.**
- **MODFLOW simulations were conducted for 40 years, which is ten years longer than the planned injection timeframe.**

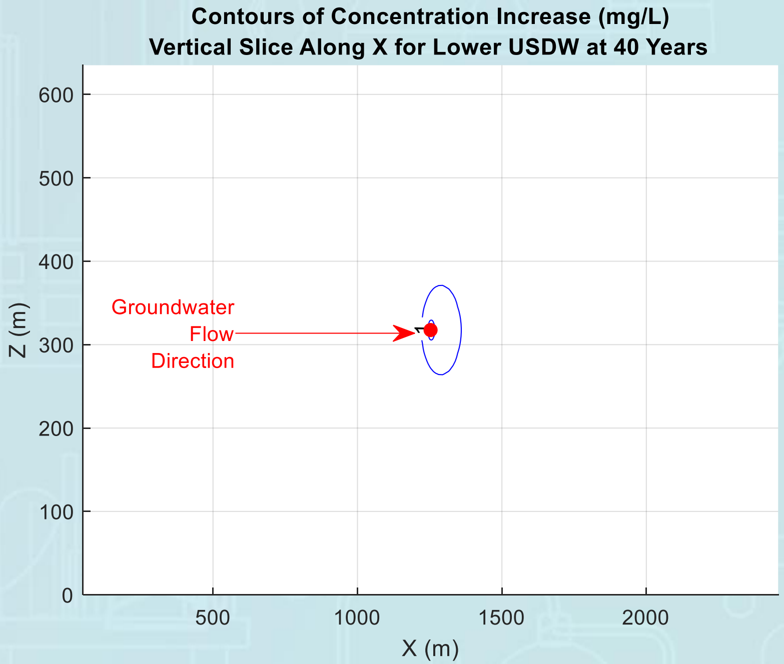
MODFLOW Grid and Conceptual Model



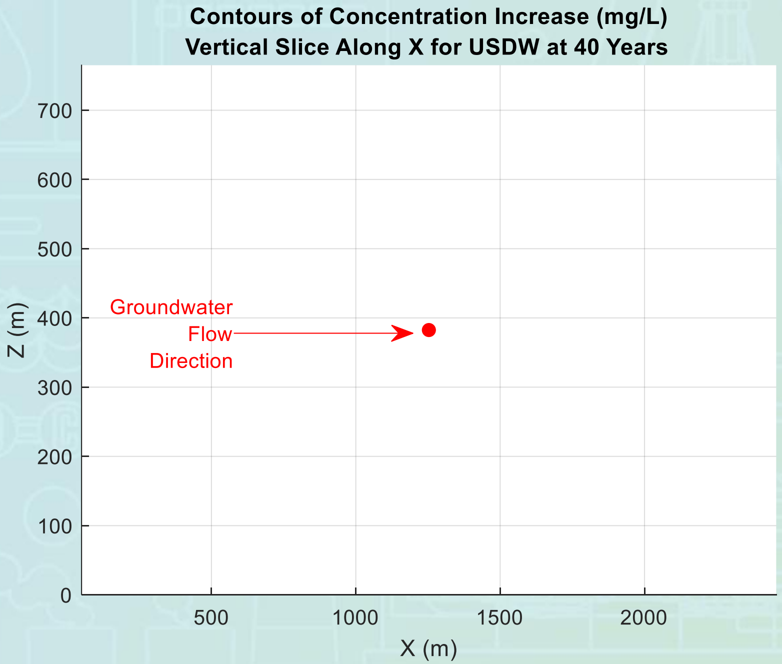
Results



Large TDS increase in Dissipation Zone



Small TDS increase in Lower USDW



Negligible TDS increase in USDW

The predicted increase in TDS within USDWs, when averaged over the aquifer thickness, is expected to be less than 1 mg/L.

Interpretation Methods

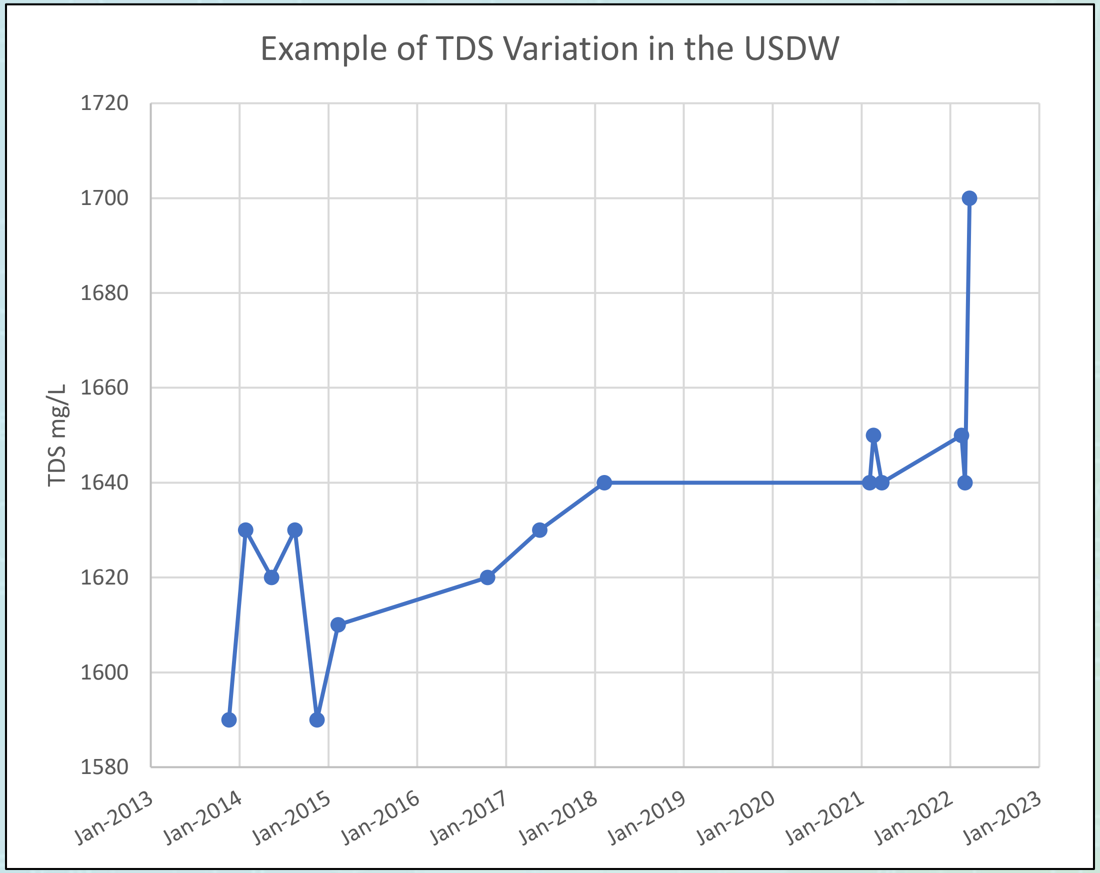
- **Method 1: Evaluate TDS concentration increase compared to regulatory groundwater quality standards.**
- **Method 2: Statistical analysis to evaluate TDS concentration increase compared to typical TDS variability in the USDW:**
  - **Method 2A: Comparison to typical well concentration fluctuation.**
  - **Method 2B: Comparison to Aquifer TDS Variability, Statistical Analysis (Last et al., 2016).**

Method 1: Comparison to Water Quality Standards

- **TDS has a recommended drinking-water secondary maximum contaminant (Secondary MCL) of 500 mg/L (22 CCR 64449).**
  - **Secondary MCLs are not health-based standards, but are guidelines for aesthetic considerations such as taste, color, and odor.**
  - **Site USDW already exceeds secondary MCL for TDS due to natural existing conditions.**
- **TDS tolerance levels for agriculture irrigation supply is generally less than 1,000 mg/L.**
  - **No predicted increase above 1,000 mg/L agricultural use limit beyond the plume footprint (215–230 mg/L increase).**

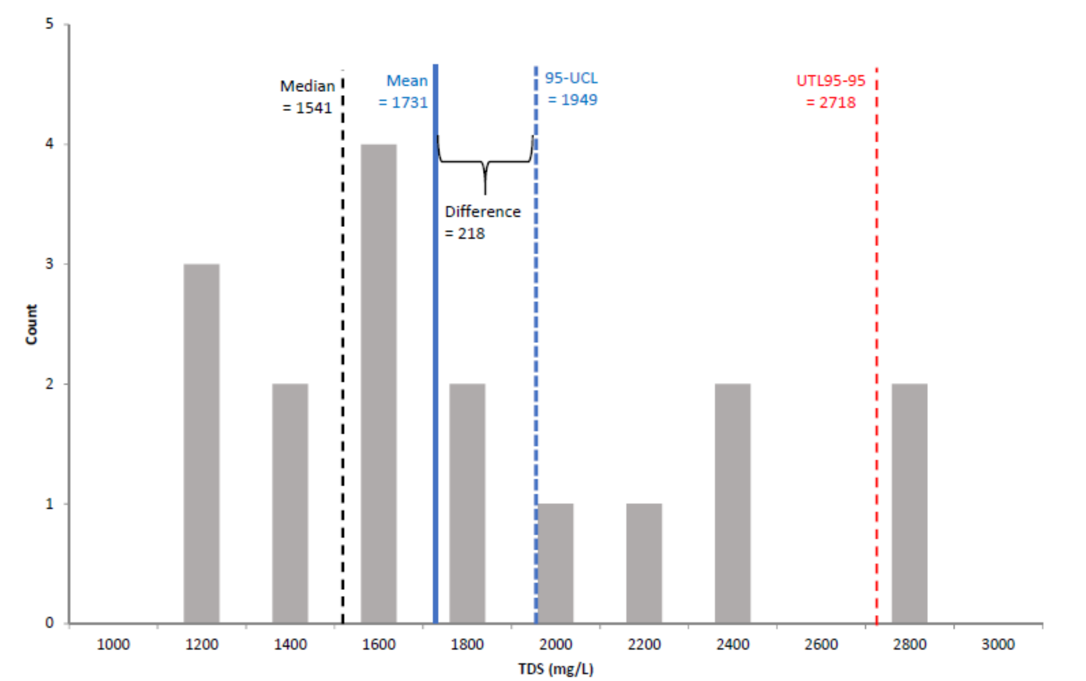
Method 2A: Comparison to Aquifer TDS Variability, Observed Fluctuation

- **TDS fluctuates in local groundwater wells due to natural variability.**
- **10-year TDS range (within 10 miles of injection site):**
  - **Average range: 131 mg/L**
  - **Maximum range: 700 mg/L**
- **Increase (<1 mg/L) is smaller than natural fluctuations and would be undetectable.**



Method 2B: Statistical Analysis

- **Last et al. (2016) methodology for deriving groundwater threshold values.**
- **Median or average represents initial aquifer condition.**
- **Upper tolerance limit with 95 percent confidence and 95 percent coverage (UTL95-95) or 95 upper confidence limit (95-UCL) are upper end of background concentrations.**
- **Any TDS change from leakage, even under conservative assumptions, would be undetectable.**



TDS Histogram, Median and 95-percent Upper Confidence Level

Conclusions

- **Risk-based AoR delineation provides a structured approach to evaluate potential groundwater impacts and is consistent with Class VI guidance.**
- **Hybrid numerical and analytical modeling effectively assesses brine leakage and contaminant transport where source TDS is less than 15,000 mg/L.**
- **Numerical modeling with MODFLOW-SEAWAT can be used to incorporate variable density and temperature effects in brine flow modeling for high TDS cases.**
- **Statistical methods help differentiate natural variability from potential project impacts.**

Questions?

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