Axisymmetric Flow and Transport Modeling: Incorporating Well Construction Components and High-Resolution Discretization

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Introduction

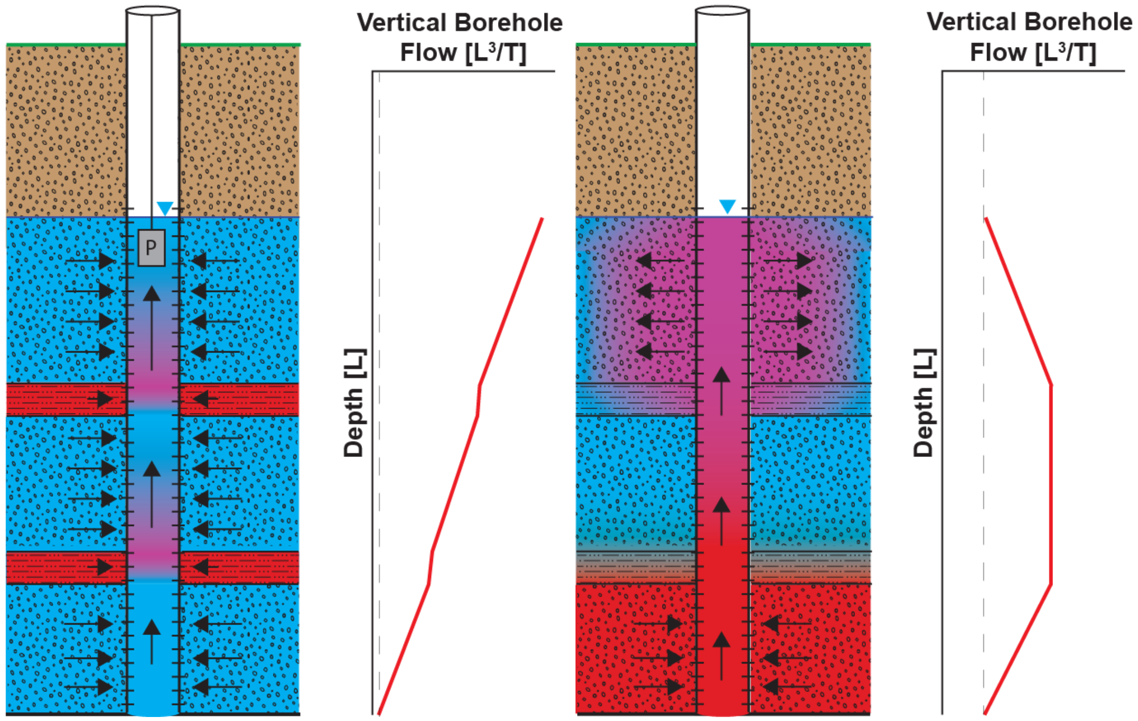
Problem Statement

- Traditional groundwater models oversimplify well representation
  - Neglects key features: filter pack, well diameter, head losses, vertical flow, and solute transport within wells

Why It Matters

Inaccurate modeling leads to poor predictions of:

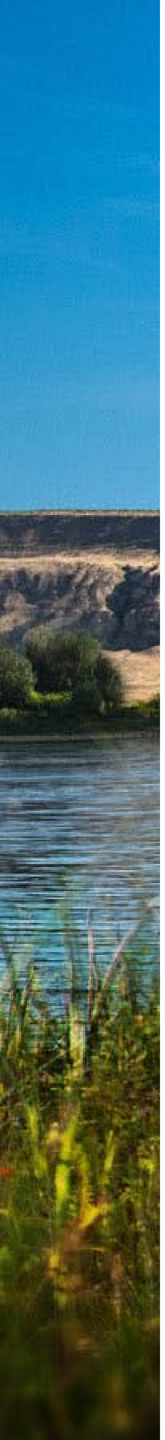
- Vertical flow within filter packs
- Ambient solute movement
- Multi-layer mixing in long-screened wells



Day-Lewis, F. D., R. D. Mackley, and R. Bence. 2024. Sampling in Long-Screened Wells: Issues, Misconceptions, and Solutions. Groundwater 62, no. 5: 669–80, https://doi.org/10.1111/gwat.13427.

These modeling deficiencies result in

- Ineffective remediation system design
- Wrong technology selection
- Cost overruns and schedule delays
- Regulatory compliance failures



Background: Axisymmetric Flow Model

Axisymmetric Groundwater Flow Model

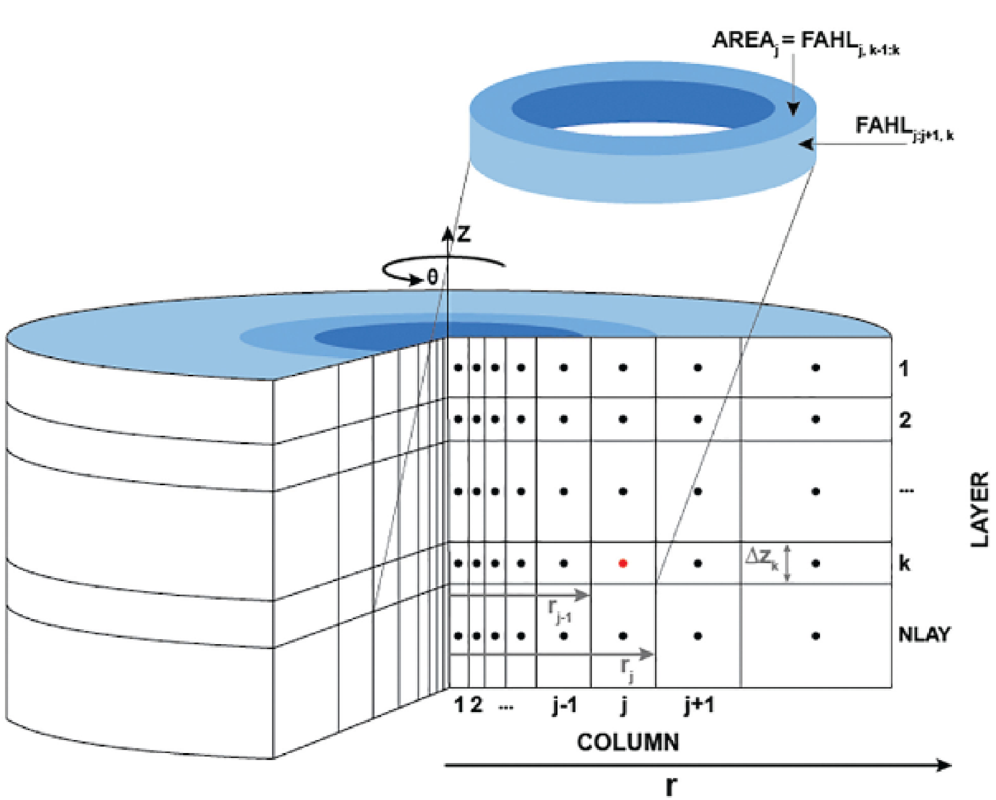
- Benchmark transient radial groundwater flow to a single pumping well using MODFLOW 6 (MF 6)
  - Built upon MF 6's established axisymmetric flow capabilities (Example 59)
    - **We use this example as our starting foundation**

Key Features & Setup

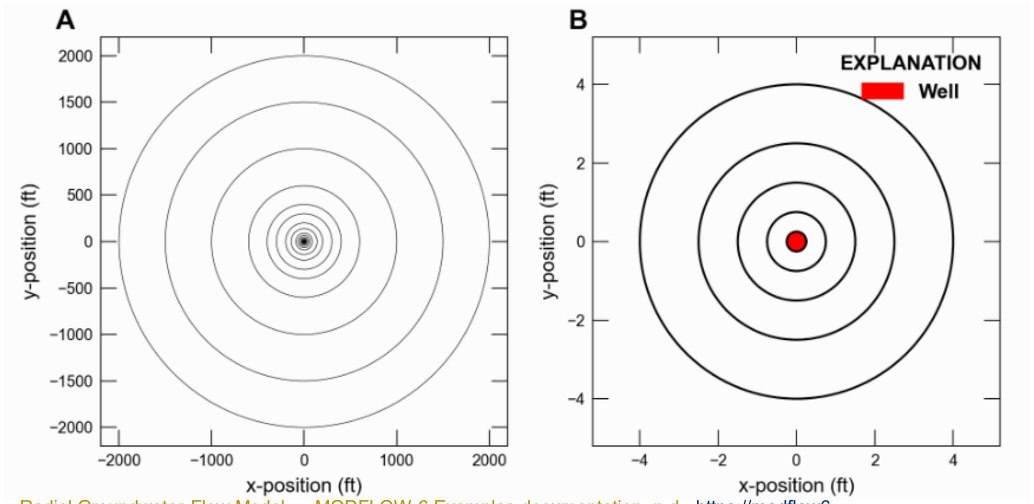
- Grid: DISU (Unstructured Radial Mesh)
- Resolution: Logarithmic spacing for fine detail near the wellbore (steepest gradients)
- Central Pumping Well (WEL)

MODFLOW 6 Packages Used

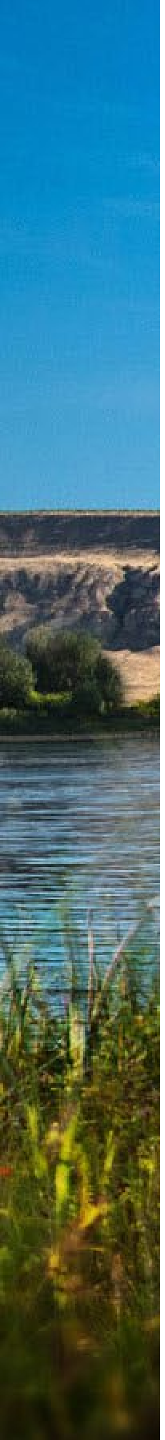
- Core Packages: DISU, groundwater flow (GWF), WEL



Bedekar, V., L. Scantlebury, and S. Panday. 2019. Axisymmetric Modeling Using MODFLOW-USG. Groundwater 57, no. 5: 772–77, https://doi.org/10.1111/gwat.12861.



Radial Groundwater Flow Model — MODFLOW 6 Examples documentation. n.d., https://modflow6-examples.readthedocs.io/en/master/_notebooks/ex-gwf-radial.html, retrieved 7/10/2025.



Methodology

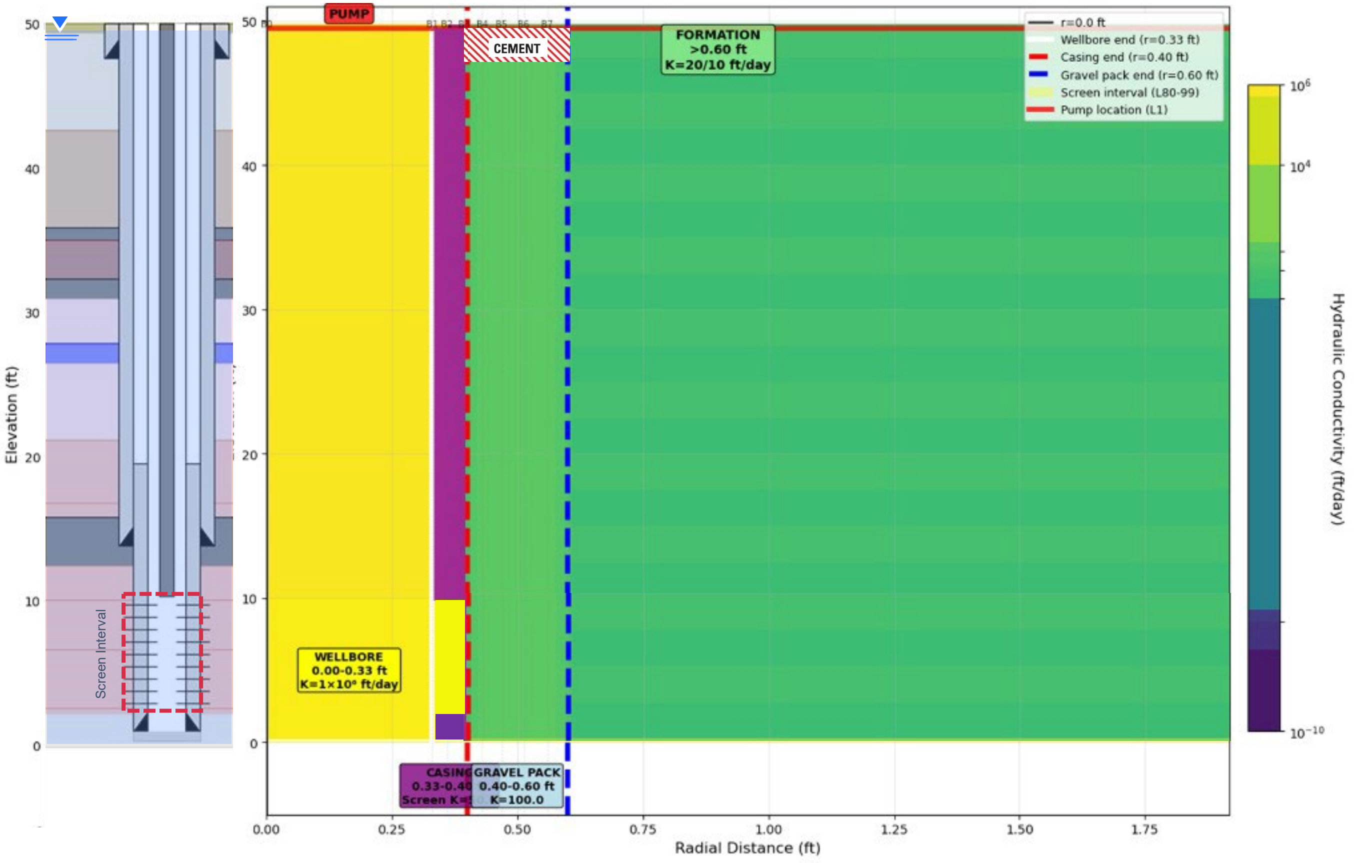
Enhanced (1) MF 6 Axisymmetric Flow Model

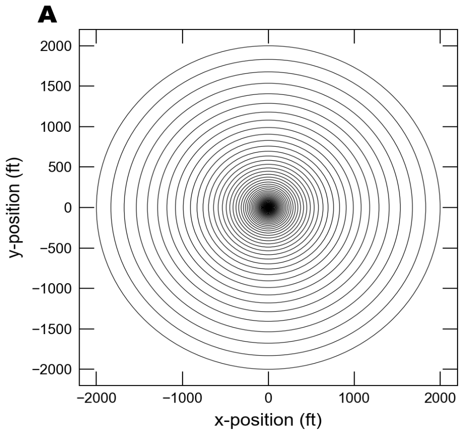
Unstructured Grid enhancement

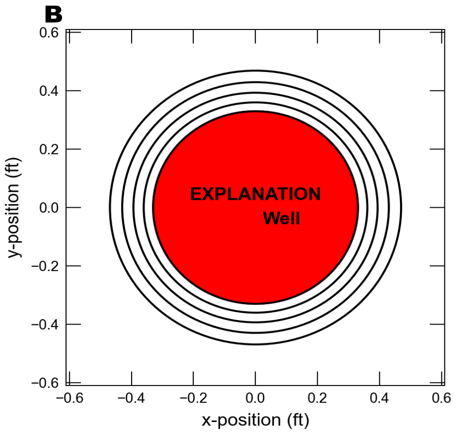
- Multi-Zone Discretization: 25×22 → 100×100 cells
  - Wellbore → Casing → Gravel Pack → Formation (logarithmic spacing)
  - Logarithmic radial grid: 100 bands

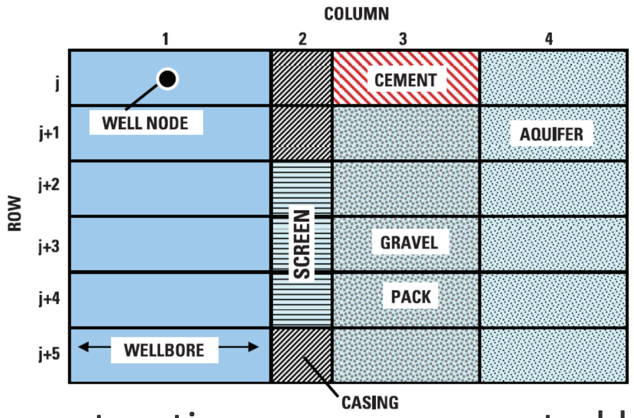
Well construction zones (similar to Halford (2009))

- Wellbore: K = 10^9 (enhanced vertical flow)
- Casing/Screen: K = 10^{-6}/50
- Gravel Pack: K = 100
- Formation: K = 10-20 (heterogeneus)







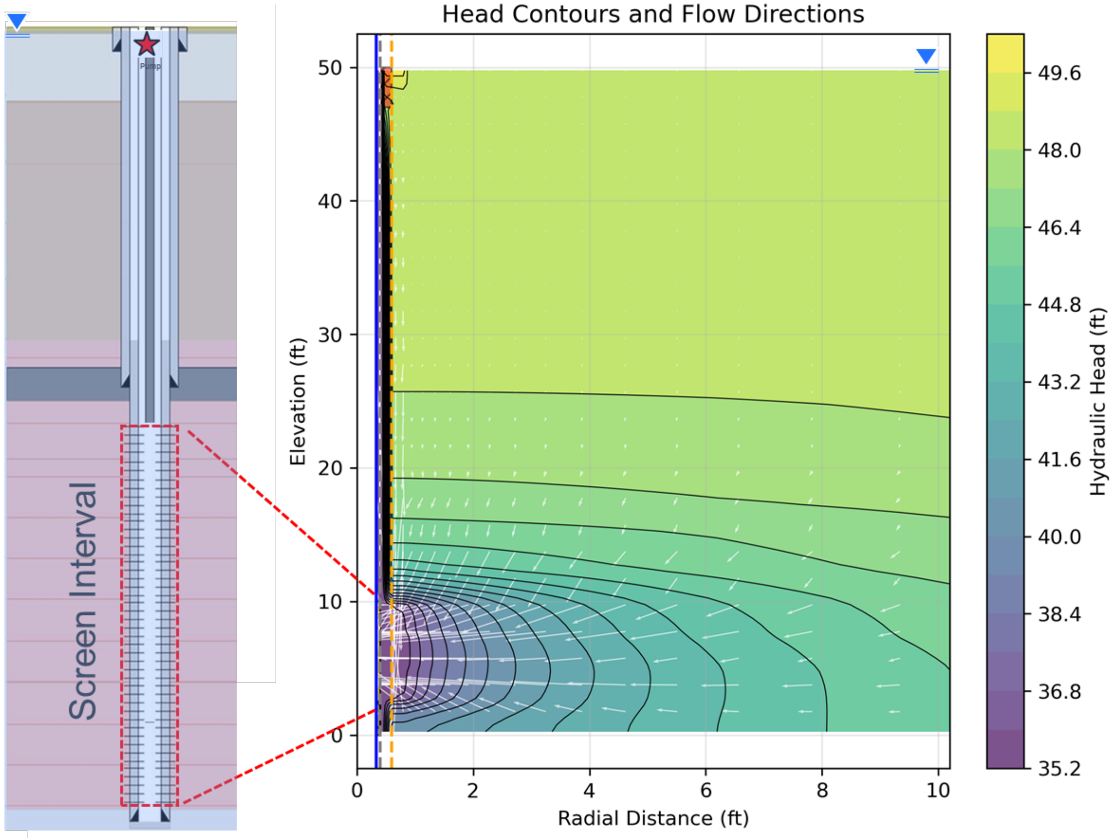


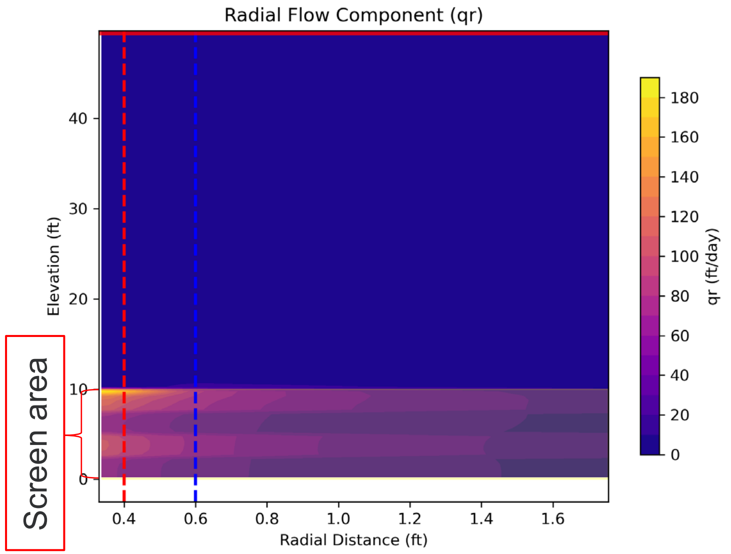
Keith, H. n.d. AnalyzeHOLE—An Integrated Wellbore Flow Analysis Tool. U.S. Geological Survey Techniques and Methods 4–F2, https://pubs.usgs.gov/tm/tm4f2/

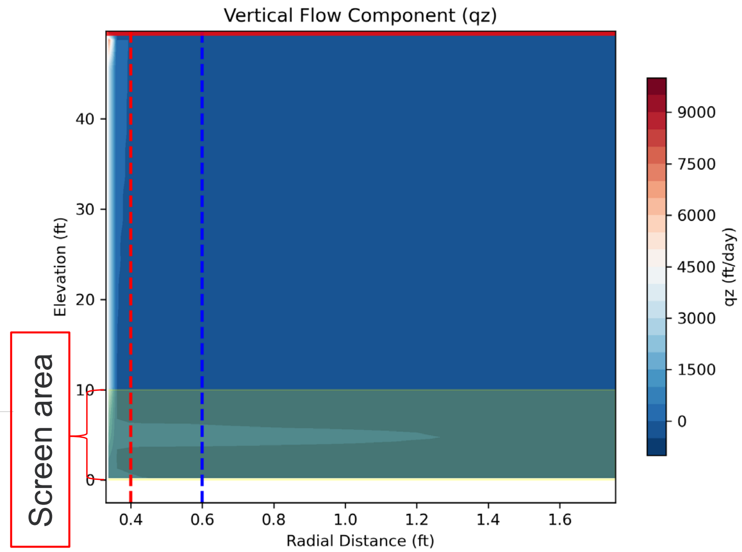
- Similar well construction zones as reported by Halford (2009)

Preliminary Results: Enhancement 1

- Enhanced model can now properly simulate the controlled flow entry at the screen
- Realistic flow patterns achieved
- Well construction zones working as designed
- Flow concentration at screen depth







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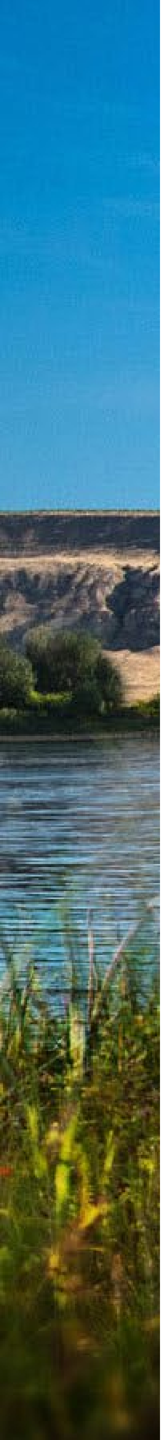
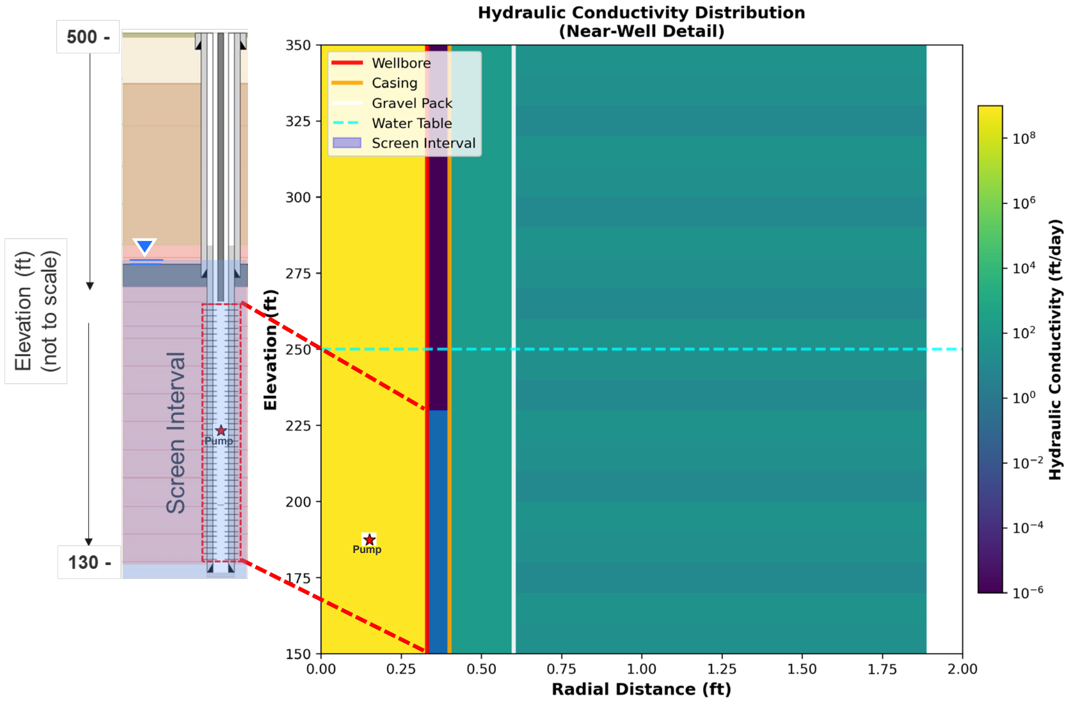
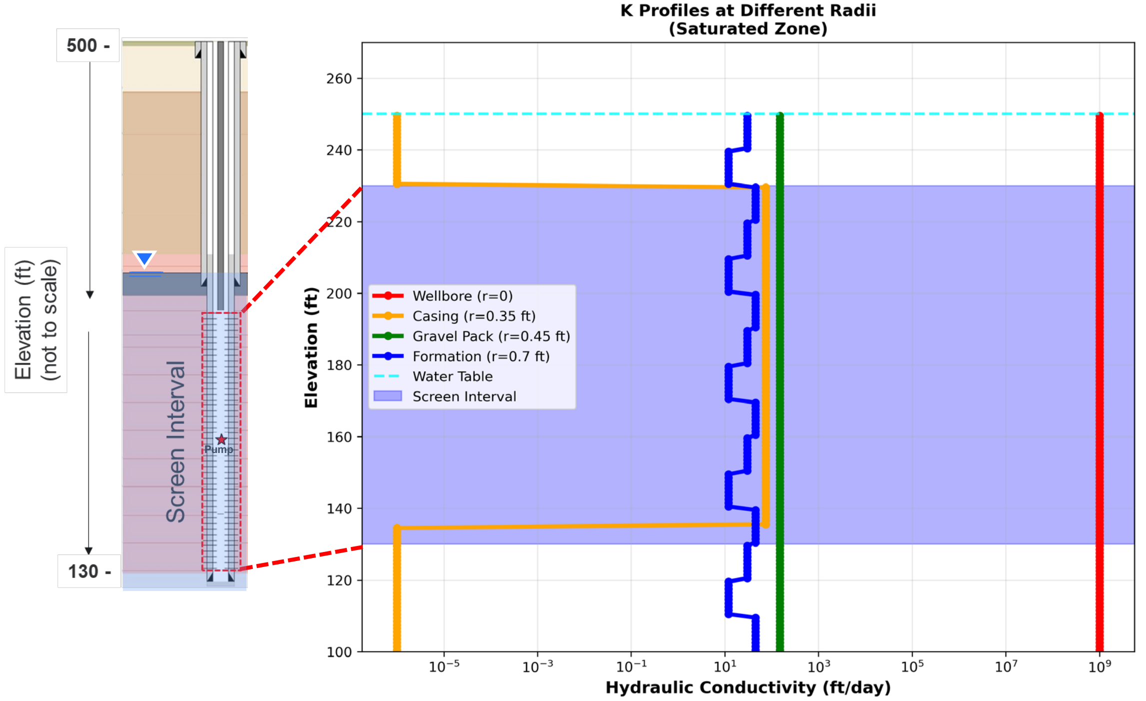


Methodology: Model Enhancement (2)

Implementing Similar Hanford Site, WA, Hydrogeological Conditions

Discretization Parameter	Enhancement #1	Enhancement # 2	Improvements
Total Layers	100	400	4× increase
Layer Thickness	0.5 ft	1.0 ft	2× thicker
Model Depth	50 ft	400 ft	8× deeper
Total Nodes	10,000	40,000	4× larger
Active Nodes	10,000	15,000	Optimized
Water Table	Surface	250 ft deep	Deep aquifer
Vadose Zone Handling	N/A	IDOMAIN (inactive layers)	
Screen Length	7.5ft	100 ft	~13× longer
Water table depth	50	250	5× deeper
Pump depth	0.5	300 ft	
Pumping rate	4,000 ft³/day	8,000 ft³/day	
Time discretization	1 stress period, 20 Tstps		
Heterogeneous formation (K-values)	10/20 ft/day	45/30/12 ft/day	

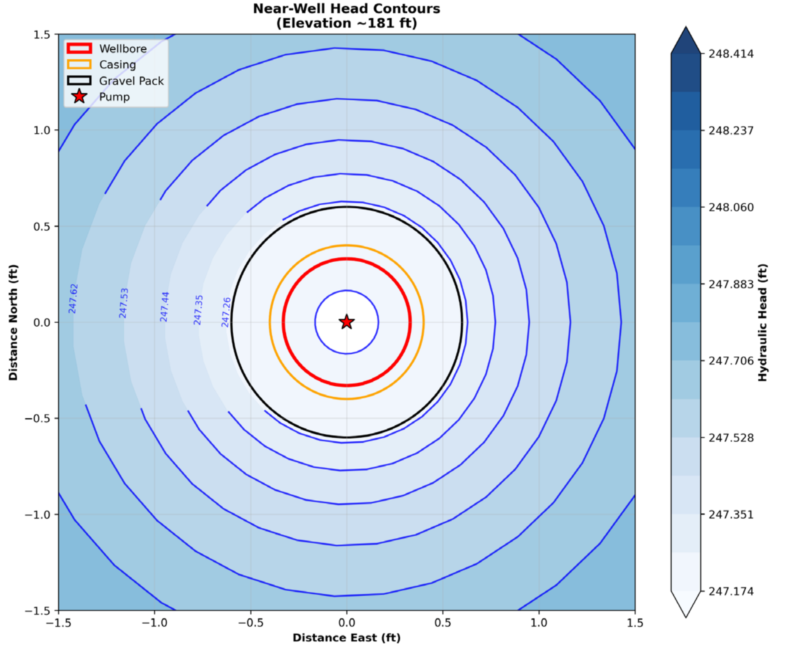


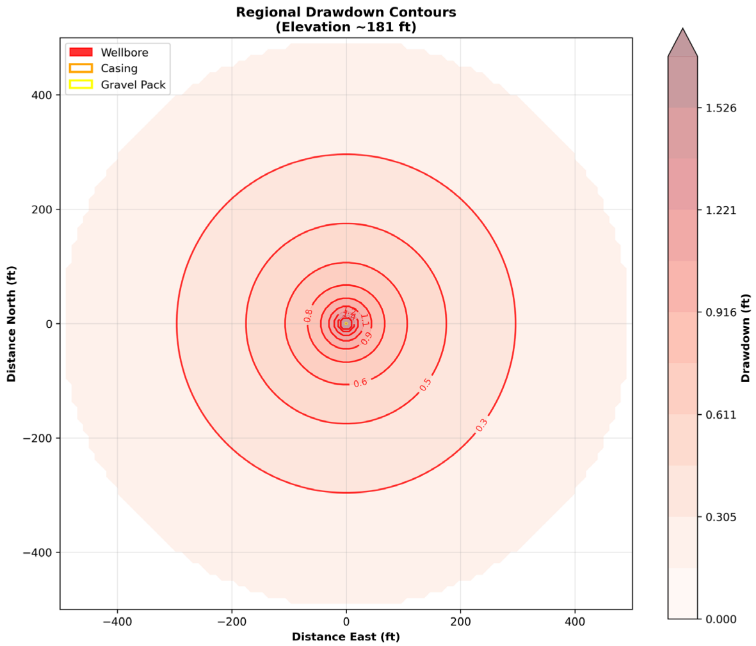


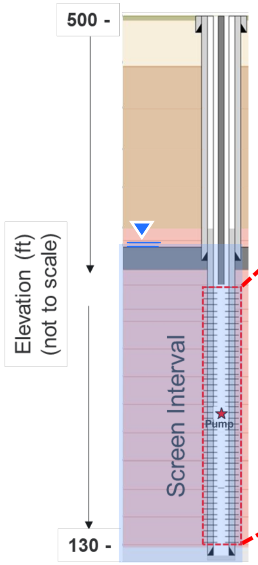
Model Results: Enhancement 2

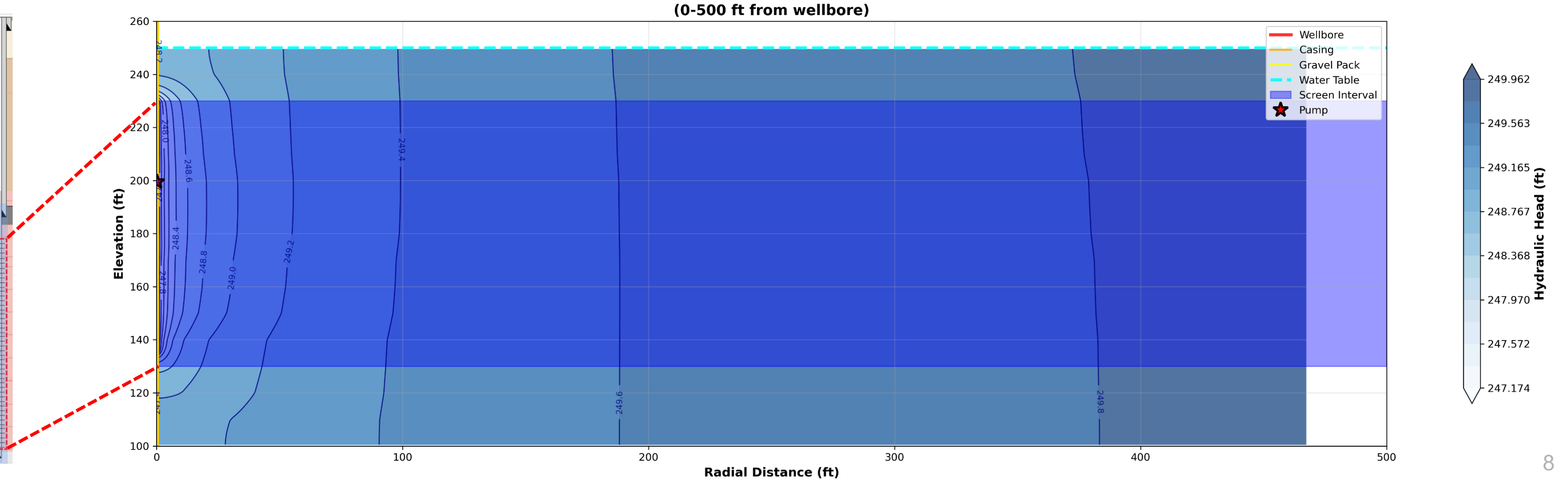
Analysis

- Head contours
- Drawdown contours
- Head distribution cross-section

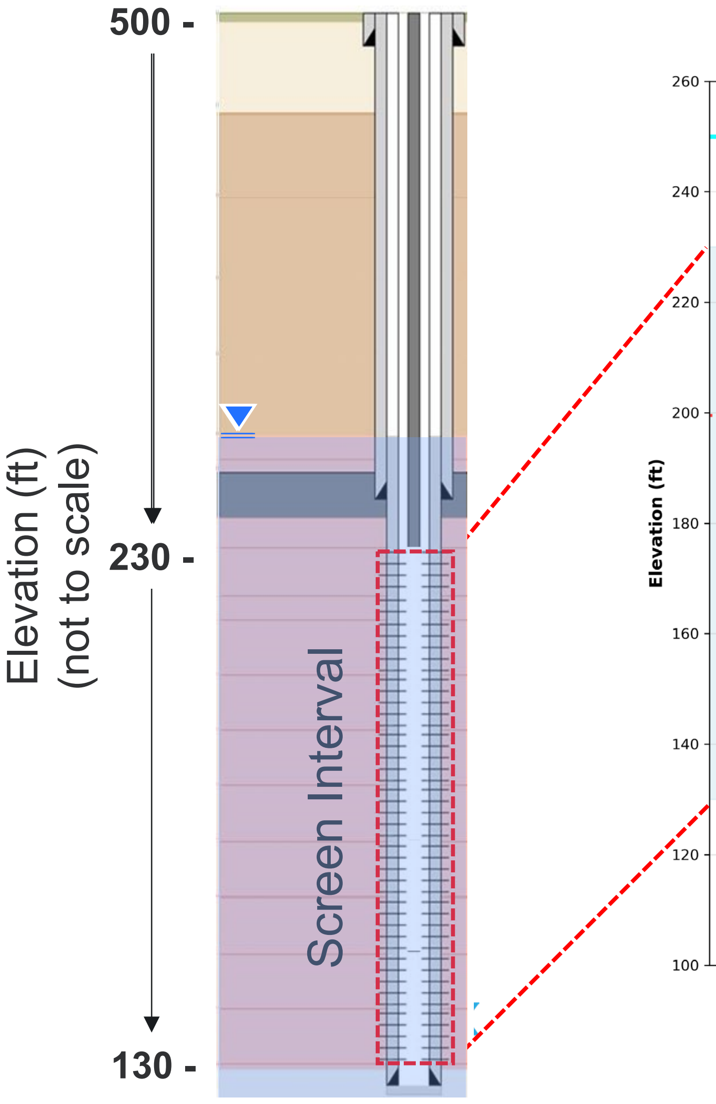


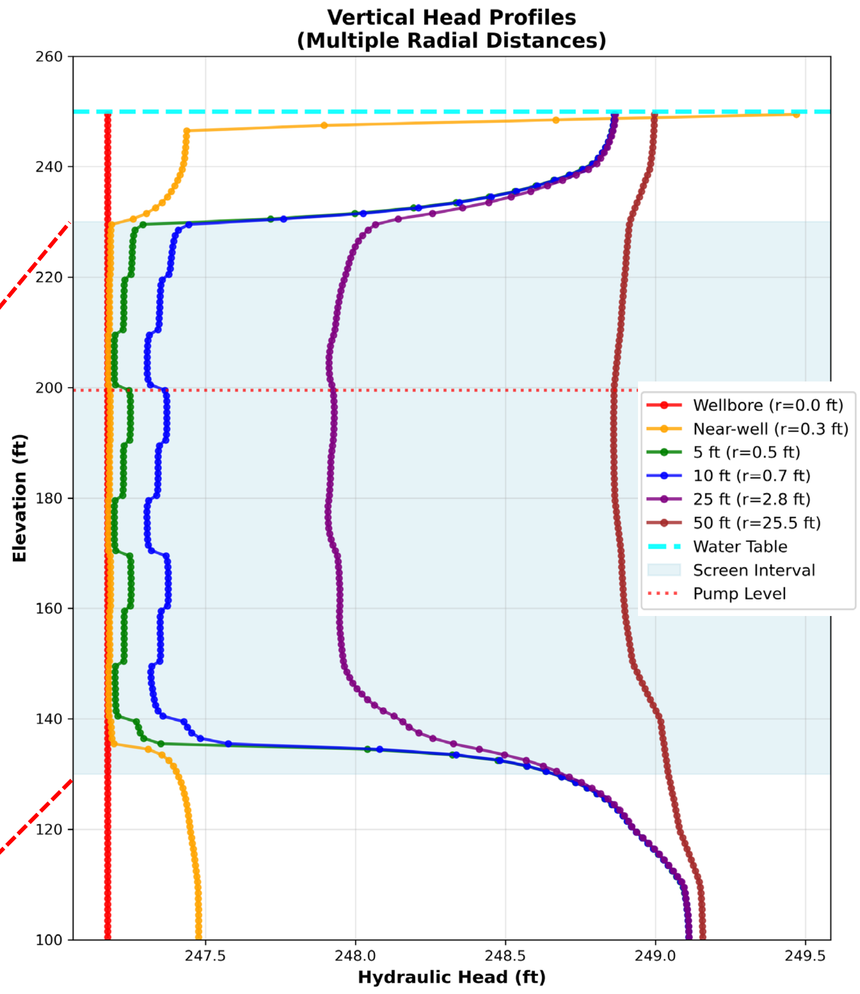


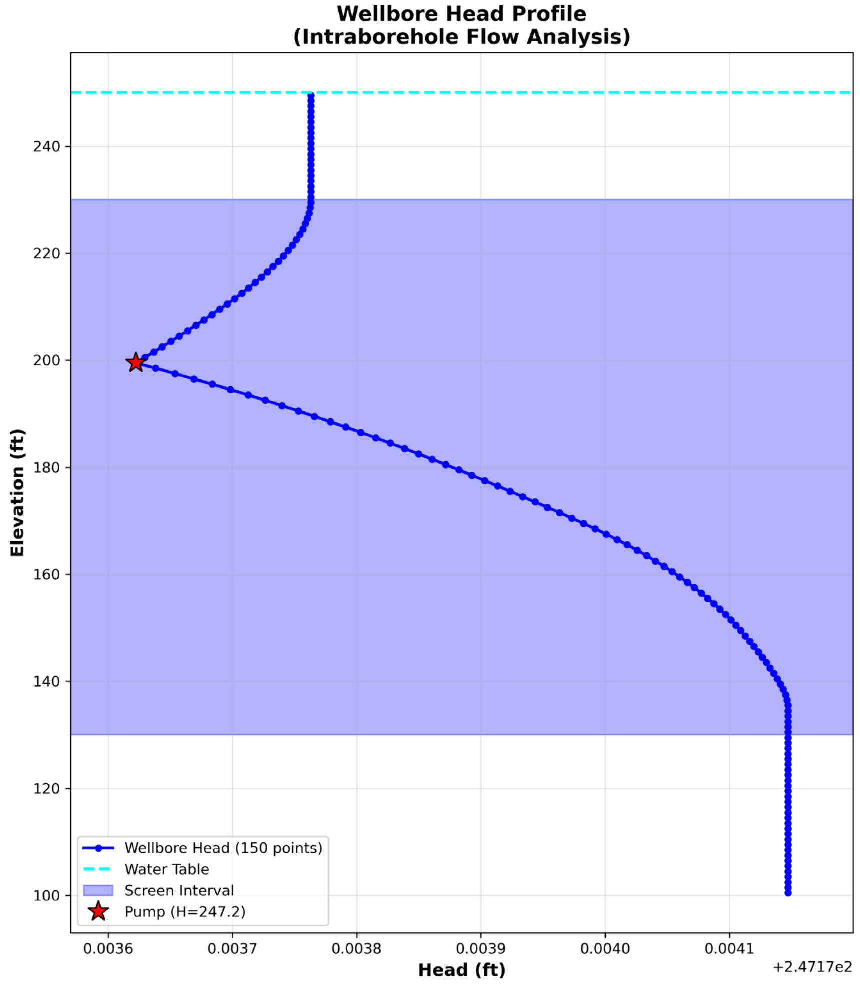




Model Results: Enhancement 2







Next Steps

Transport Modeling Integration

- GWT package implementation: Contaminant fate and transport analysis
- Hanford contaminants: Contamination scenarios
- Capture zone analysis: Pump effectiveness and plume interception
- Breakthrough curve analysis: Wellbore concentration monitoring

Enhanced Hanford Site Conditions

- Extended screen designs: 200+ ft screens for deep contamination
- Complex stratigraphy: Hanford formation layering
- Implement multi-screen wells
- Multi-aquifer systems: Confined/unconfined layer interactions
- Realistic boundary conditions: Regional flow and recharge patterns

Advanced Operational Scenarios

- Multi-stress period analysis: Pump on/off cycling optimization
- Implement PEST
- Variable pumping rates: Seasonal and operational adjustments
- Long-term simulations: Multi-year remediation timeframes
- Response scenarios: Rapid response pumping strategies
- Professional Visualization & Tools

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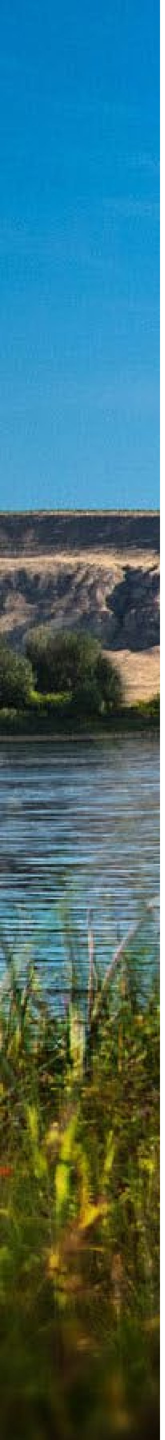

Summary

Original Repository Model (MF 6 Example)→ Enhanced Hanford Model

Scale Transformations:

- Grid Size: 550 nodes → 40,000 nodes (73× increase)
- Water Table: 50 ft (surface) → 250 ft deep (realistic Hanford)
- Model Depth: 50 ft → 400 ft total depth (8× deeper)
- Screen Design: 10 ft basic → 100 ft professional long-screen

How This Work Addresses the Problem

• Developing enhanced modeling capabilities that capture realistic well construction effects previously ignored in standard models

• Building tools to predict where contamination will migrate during remediation

• Creating foundation for transport modeling that will simulate contaminant mixing and capture more accurately

Mission Impact - Why This Development Matters

• Hanford remediation planning - When completed, this tool will help design pump-and-treat systems that capture contamination as predicted

• Cost avoidance potential - Better flow predictions mean avoiding expensive system redesigns when wells underperform

• Risk reduction - More accurate capture zone predictions help ensure contamination doesn't migrate beyond treatment areas

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HANFORD SITE MODEL PERFORMANCE

Model Configuration:
• Total Depth: 400 ft below surface
• Water Table Depth: 250 ft below surface
• Screen Length: 100 ft
• Screen Depth: 270-370 ft
• Pumping Rate: 8,000 ft³/day

Well Performance Results:
• Water Table: 250.0 ft
• Head at Pump: 247.17 ft
• Total Drawdown: 2.83 ft
• Wellbore Head Range: 0.001 ft

Data Quality & Diagnostics:
• Total Model Nodes: 40,000
• Valid Head Points: 15,000
• Wellbore Points: 150
• Invalid/Dry Cells: 25,000
• Head Data Shape: (20, 1, 1, 40000)
• Time Steps: 20

Model Health:
• Saturated Layers: 150
• Vadose (Inactive) Layers: 250
• Valid Head Range: 247.2 to 250.0 ft

Cement Seal Configuration:
• Radial Extent: 0.40-0.60 ft
• Vertical Extent: 0-20 ft depth (top 20 layers)
• K-value: 1e-06 ft/day (impermeable)

Model Efficiency:
• Active Cells: 15,000
• Inactive Cells: 25,000
• Total Model Cells: 40,000
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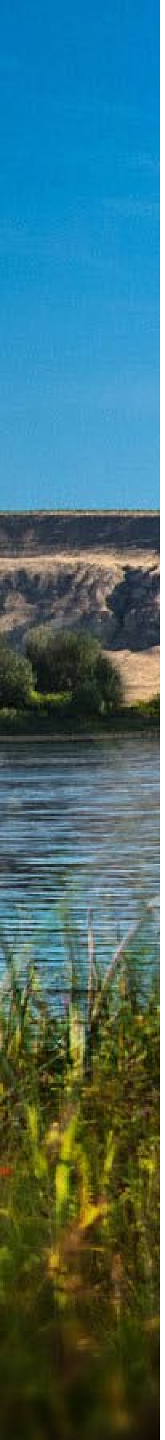

Miguel E. Valencia
Postdoctoral Research Associate

Let’s connect!

Thank you