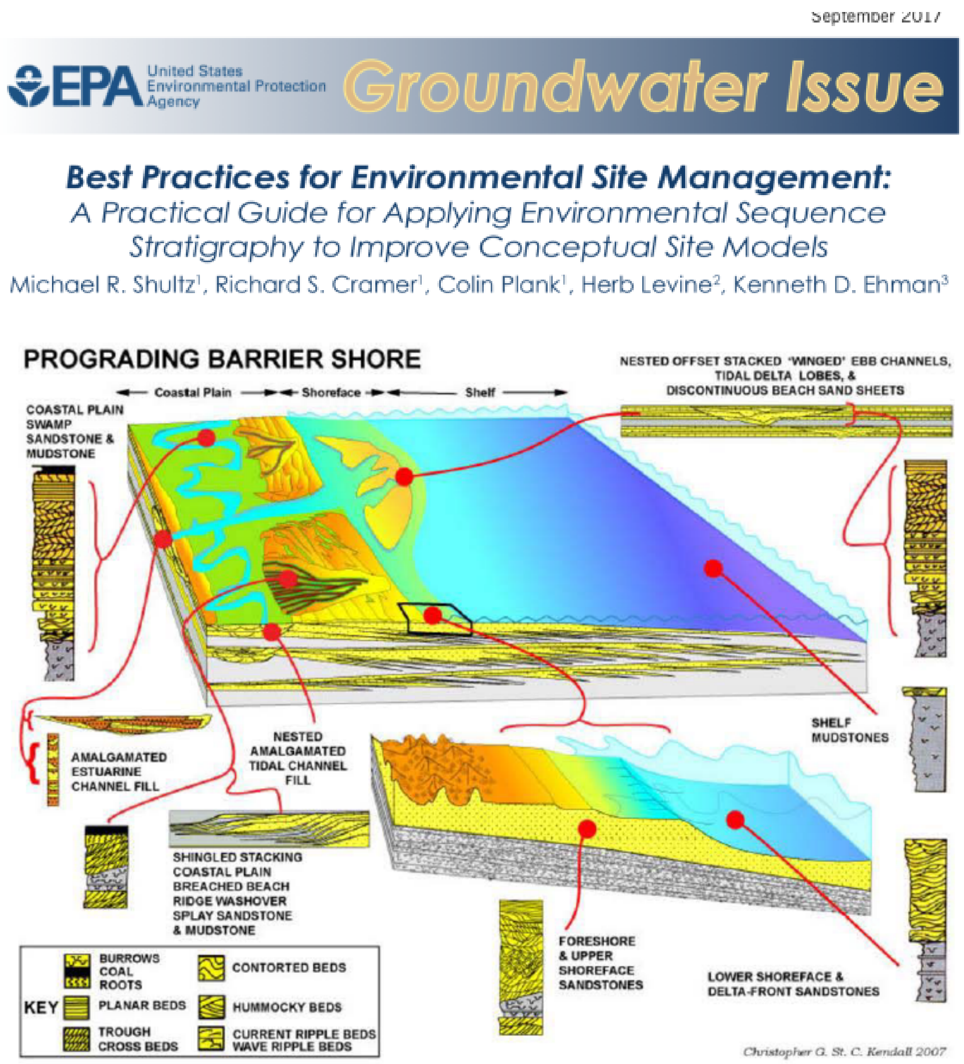
Environmental Sequence Stratigraphy in Numerical Groundwater Models

JP Brandenburg Raghavendra Suribhatla and Murray Einarson
Haley & Aldrich

Sixth International Symposium on Bioremediation and Sustainable Environmental Technologies
May 8-11, Austin, Texas

Environmental Sequence Stratigraphy (ESS)


September 2017

United States Environmental Protection Agency

Groundwater Issue

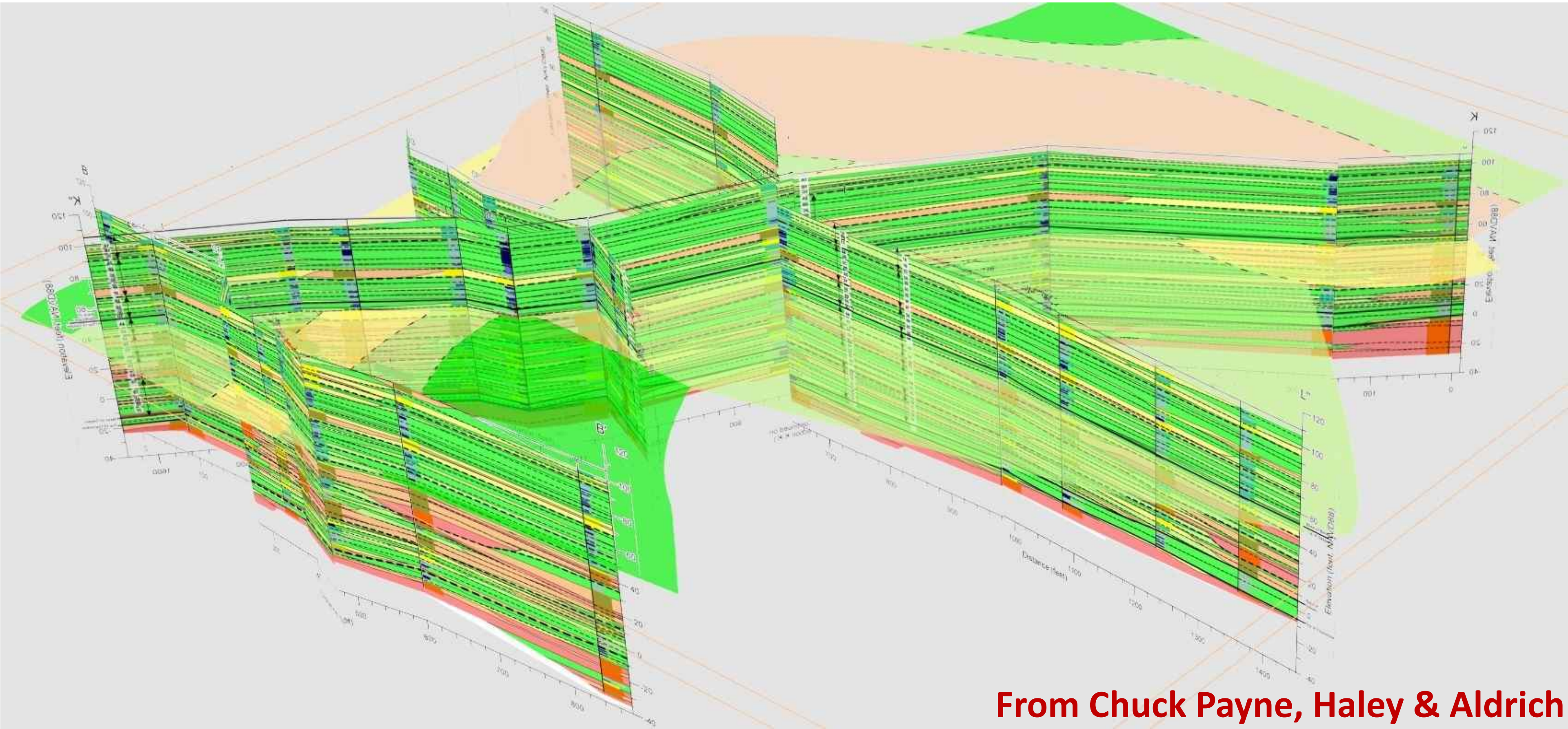
Best Practices for Environmental Site Management:
A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models

Michael R. Shultz[1], Richard S. Cramer[1], Colin Plank[1], Herb Levine[2], Kenneth D. Ehman[3]

- Very useful tools for interpretation and site conceptual models
- Not as easy to apply quantitatively
- Groundwater models that incorporate high-resolution stratigraphy are challenging (and expensive) to construct
- Key limitation: What is the maximum detail of interpretation supported by the data?
- Other geologic disciplines struggle with the same issues

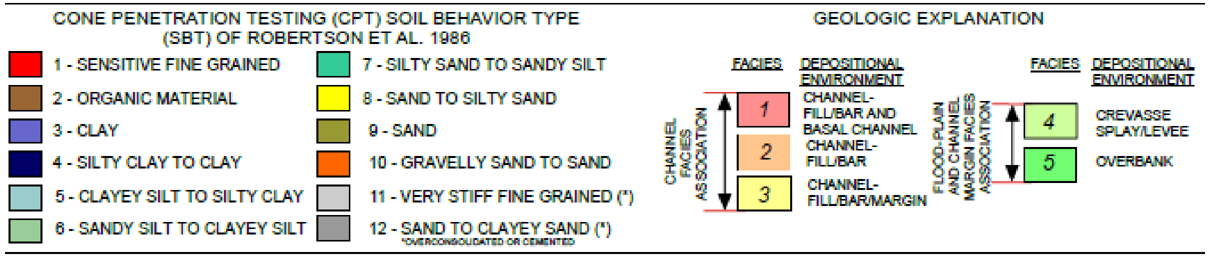
Dominguez sequence aquifer ESS

*Key tool: CPT & EC Logs



From Chuck Payne, Haley & Aldrich

Los Angeles Basin



ESTCP Project ER21-5226

SERDP ESTCP

NEWS BLOGS EVENTS MAILING LIST

About Us Focus Areas Tools & Training Webinars Working With Us

Procedure for Generating Optimized Numerical Models from the New Generation of Advanced Geologic Site Conceptual Models Developed Using Environmental Sequence Stratigraphy (ESS)

ER21-5226

POINT OF CONTACT

Murray Einarson

Principal Investigator

Haley and Aldrich

Phone: (510) 879-4546

meinarson@haleyaldrich.com

Objective

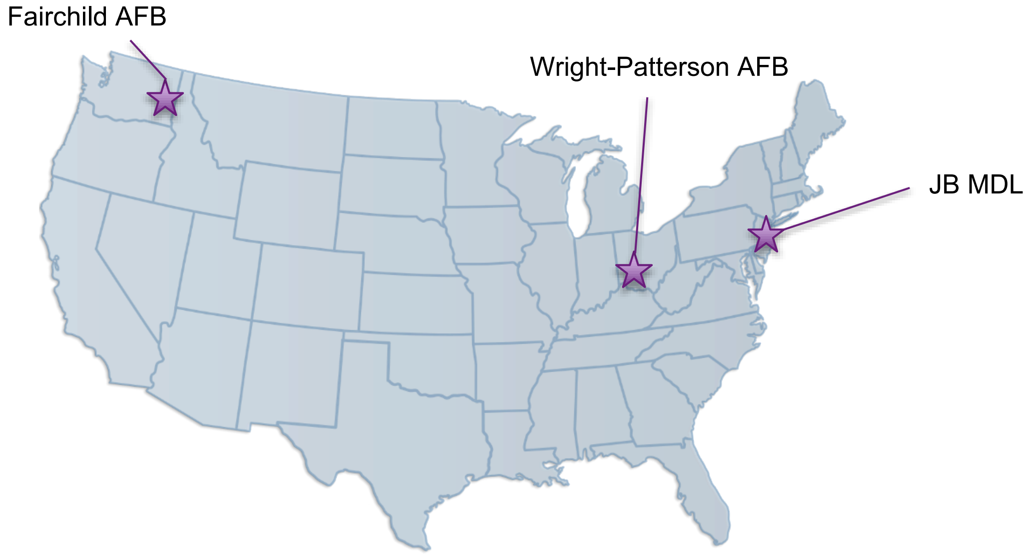
This project will develop and publish a practical guide for Department of Defense (DoD) contractors to evaluate and incorporate advanced geologic models into more efficient, accurate numerical models of groundwater flow and contaminant fate and transport that are scaled appropriately for the purpose of the models.

Technology Description

Examples of the flexibility of unstructured grids. At top, unstructured gridding of a valley fill aquifer. At bottom, unstructured grid refinement of a buried channel.

Advanced models of subsurface geology are being developed at many DoD sites using advanced stratigraphic analyses such as Environmental Sequence Stratigraphy. Manual construction of numerical groundwater model grids from these new geologic models is tedious and inefficient. In recent years, there has been strong development in software packages used by geologists to create three-dimensional geologic models of the subsurface. Outputs from these geologic modeling software packages now include rectangular grids or meshes that can be directly imported into conventional finite difference and finite element groundwater models. On other projects, especially those with complex geology and a need to accurately simulate contaminant partitioning and transport processes that occur at fine scales (e.g., matrix diffusion), simulations using numerical models with unstructured grids are necessary.

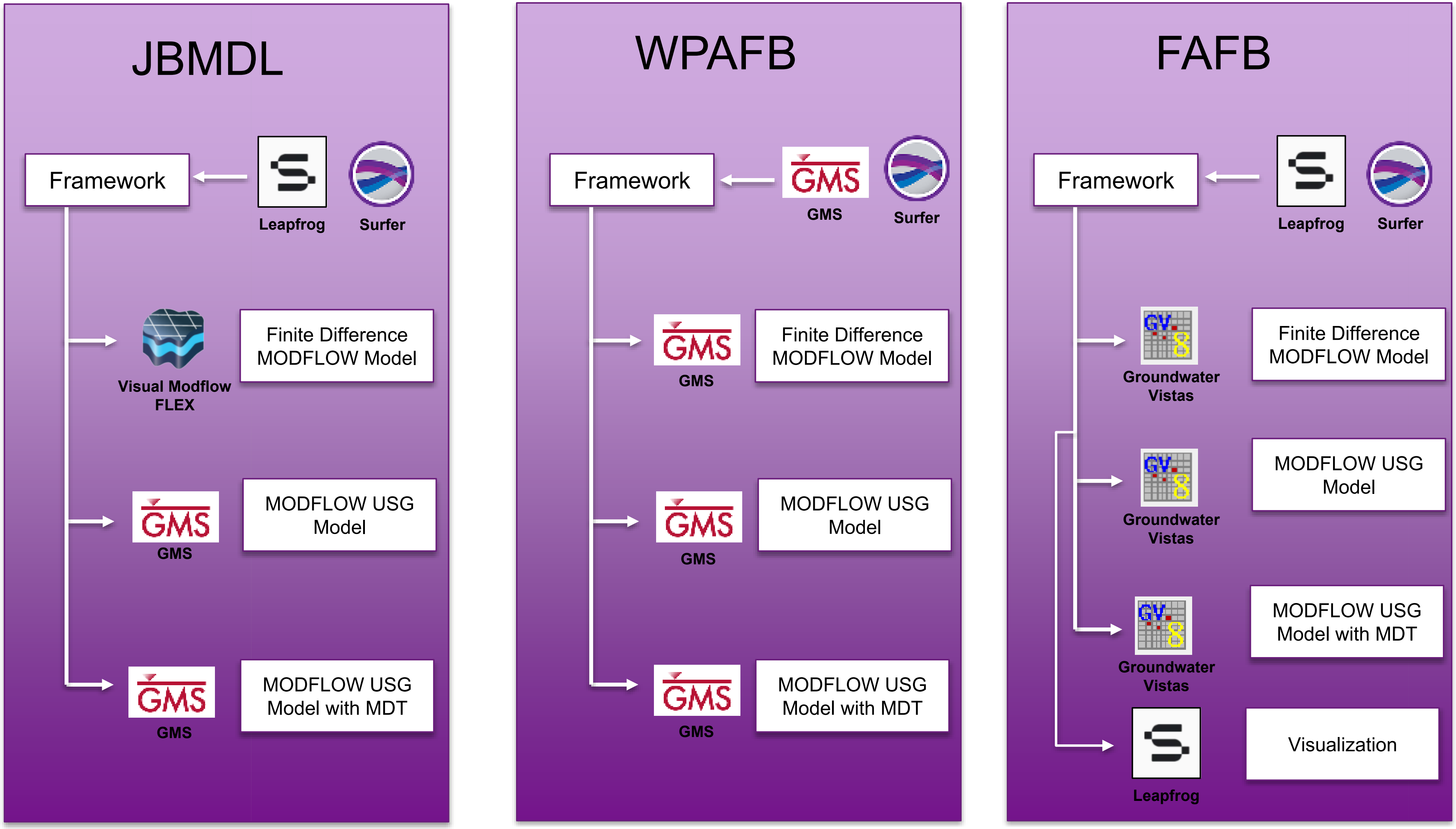
The project team plans to construct and run three numerical models for three sites (a total of nine models), with all three models from each site incorporating the same advanced geologic conceptual site model. The first set of models will be conventional MODFLOW models with rectangular grids. The second set of models will be MODFLOW 6 models constructed using unstructured grids. The third set of models will be similar to the second set with a significantly reduced grid refinement in the low hydraulic conductivity zones where the matrix diffusion process can be modeled through the REMChlor-MD semi-analytic method. The gridded output from the geological modeling software will be optimized to honor geological contacts between geological materials that control groundwater flow and plume development along both horizontal and vertical migration



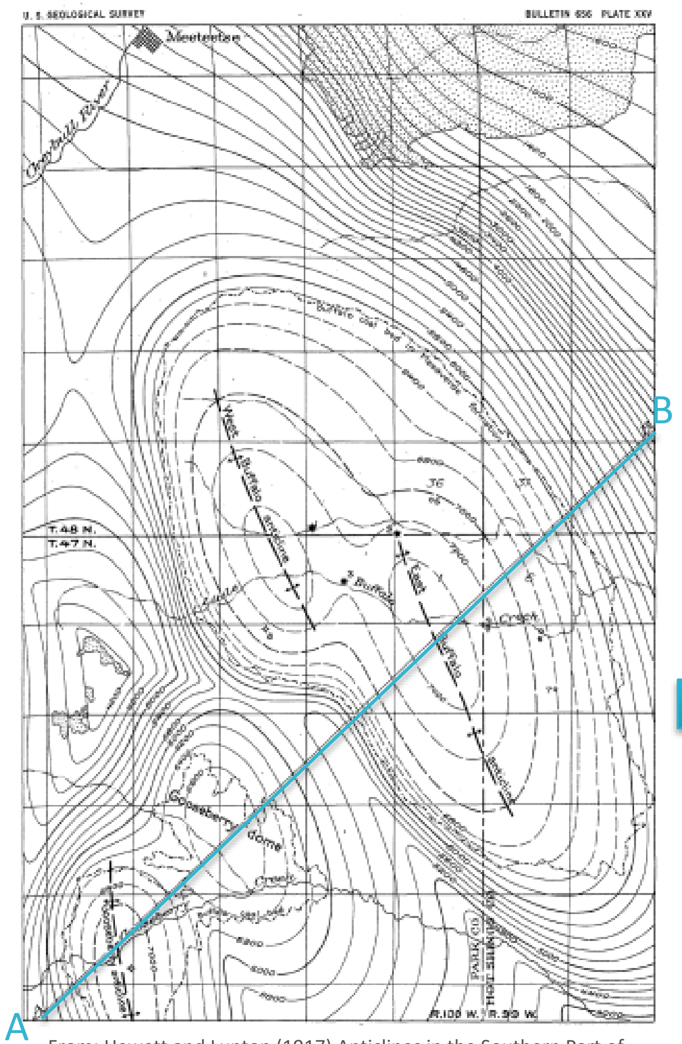
https://www.serdp-estcp.org/projects/details/3b222eba-f922-4cc9-9c1e-c6f6701afdd3/er21-5226-project-overview

(or search for ER21-5226 on Google)

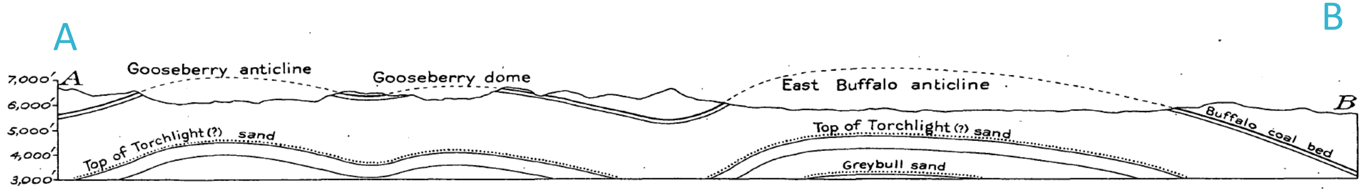
Workflows


JBMDL
Framework
Leapfrog
Surfer
Visual Modflow FLEX
Finite Difference MODFLOW Model
GMS
MODFLOW USG Model
GMS
MODFLOW USG Model with MDT
WPAFB
Framework
GMS
Surfer
GMS
Finite Difference MODFLOW Model
GMS
MODFLOW USG Model
GMS
MODFLOW USG Model with MDT
FAFB
Framework
Leapfrog
Surfer
Groundwater Vistas
Finite Difference MODFLOW Model
Groundwater Vistas
MODFLOW USG Model
Groundwater Vistas
MODFLOW USG Model with MDT
Leapfrog
Visualization

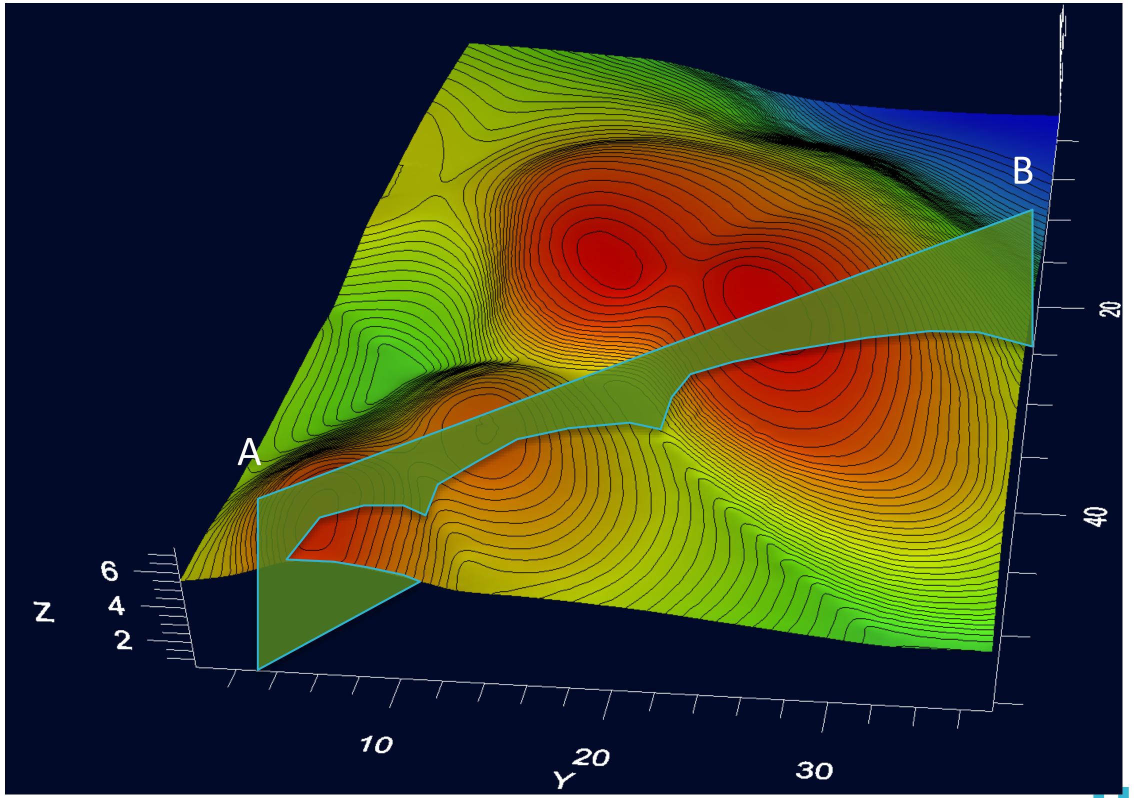
An Important (and Timeless Tool): Structural Contours



From: Hewett and Lupton (1917) Anticlines in the Southern Part of the Big Horn Basin, Wyoming. USGS Bulletin 656

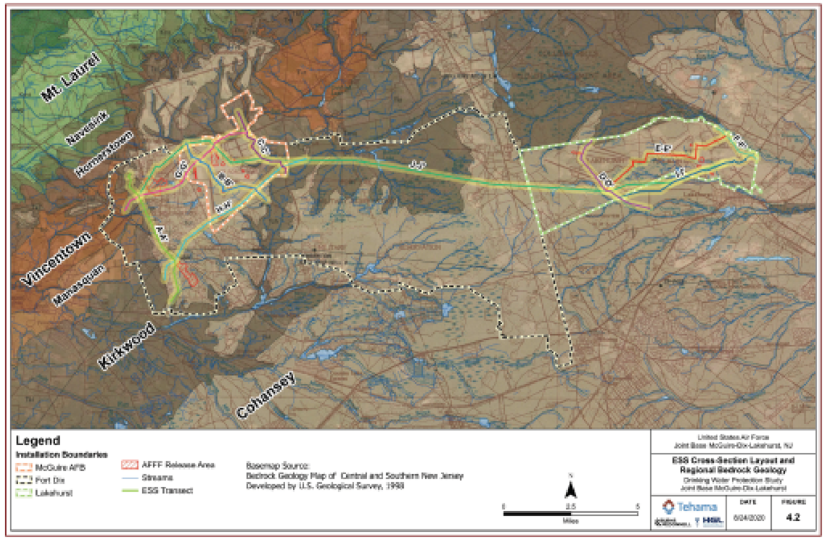


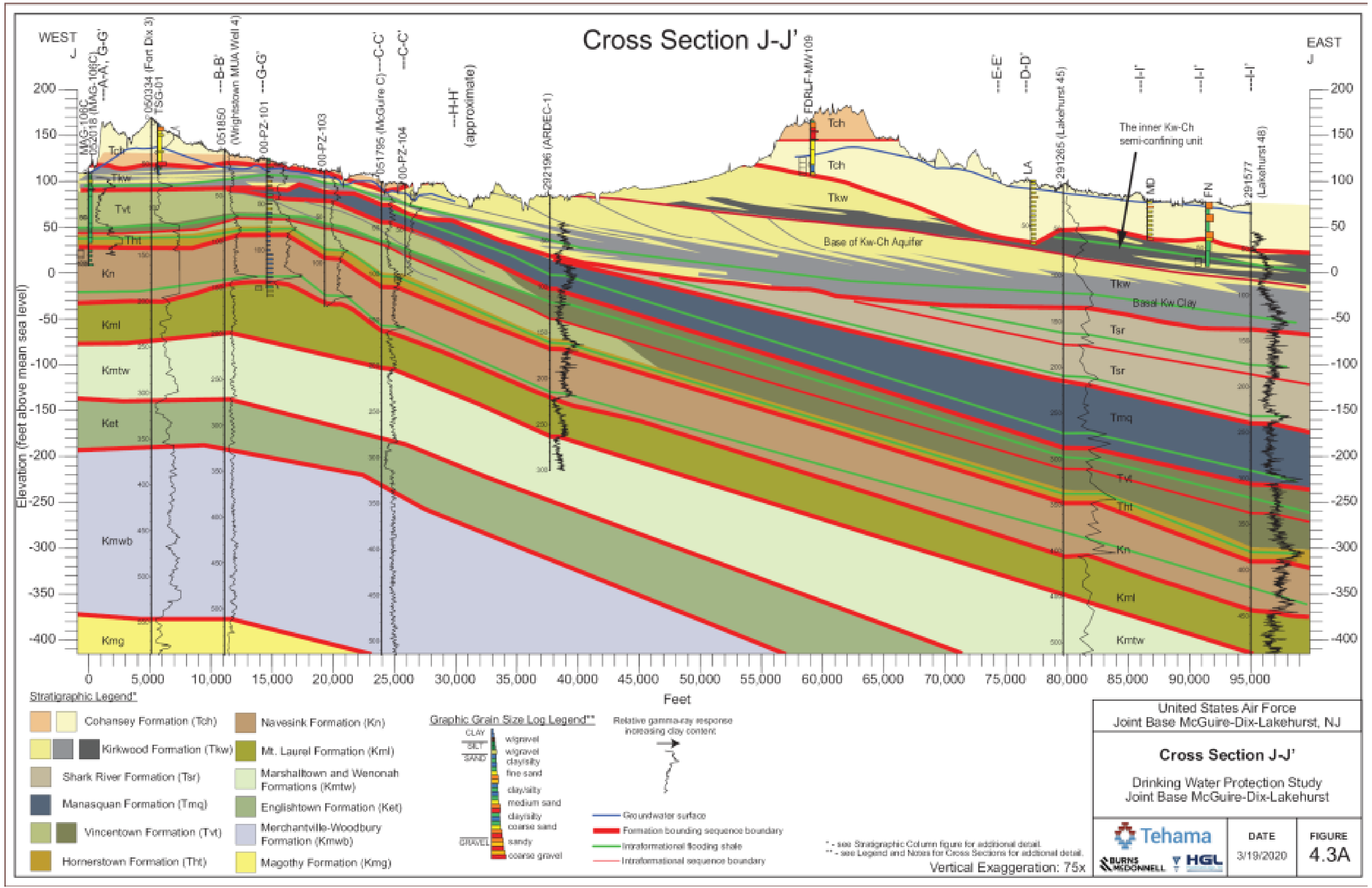
- It is a very simple process to convert well constructed graphical structural contours to digital surfaces using modern software (e.g., Surfer, ArcGIS)

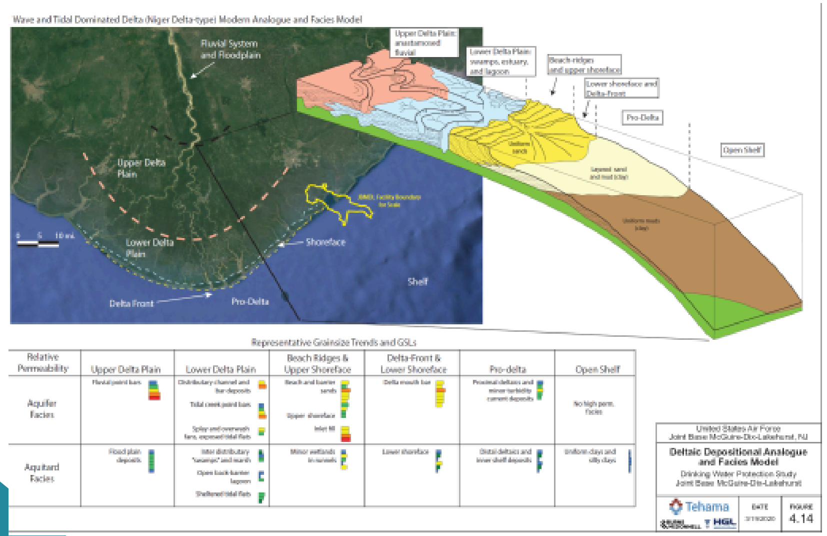


Joint Base McGuire-Dix-Lakehurst (MDL)

From Colin Plank, Burns & McDonnell

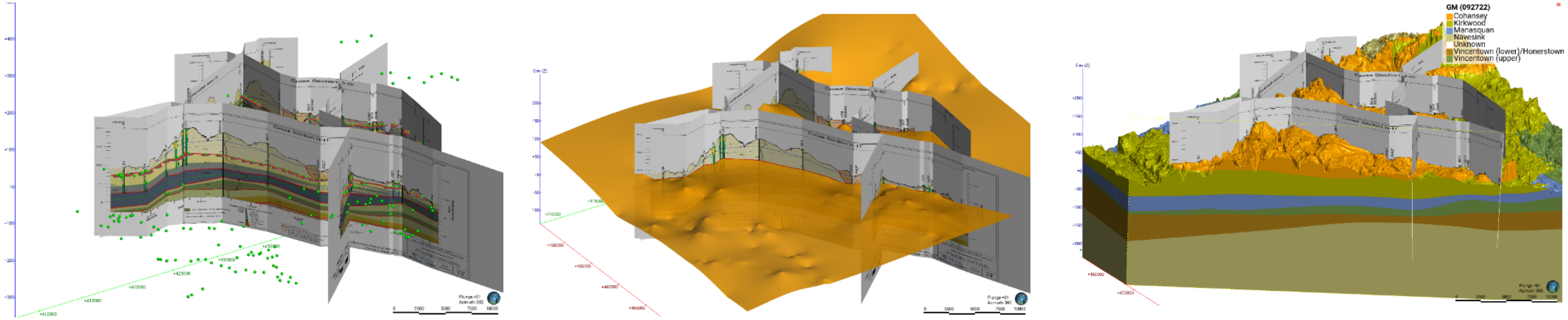




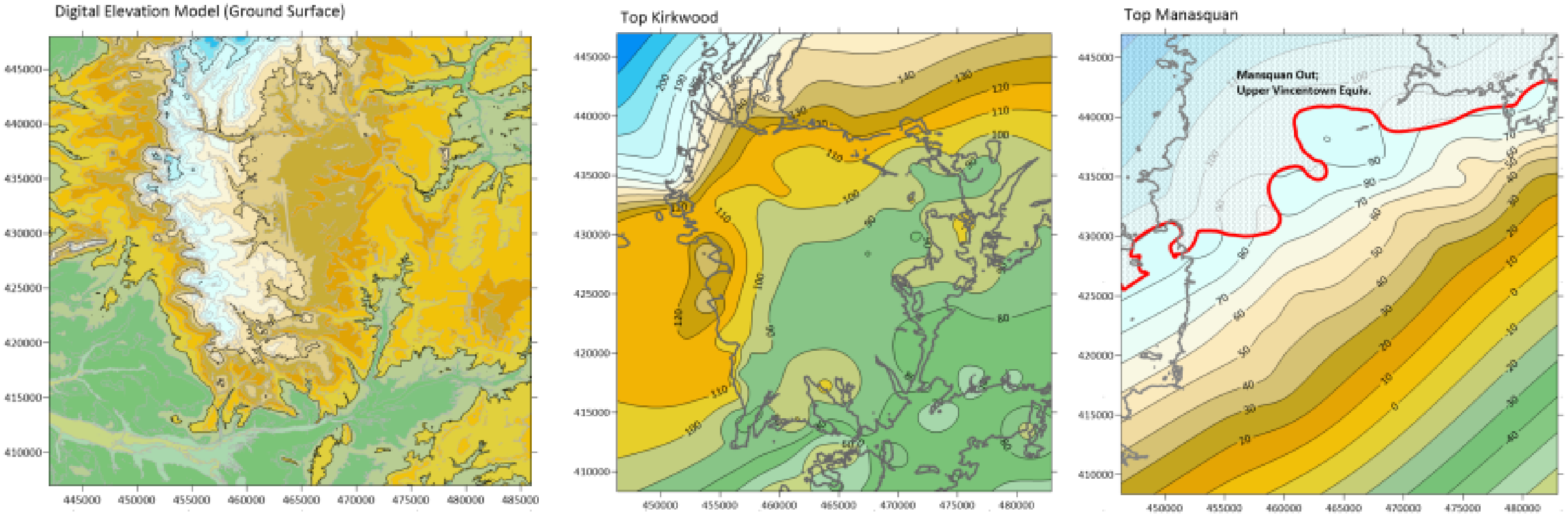


JBMDL: Framework Modeling

1. Build 3D framework in LeapFrog



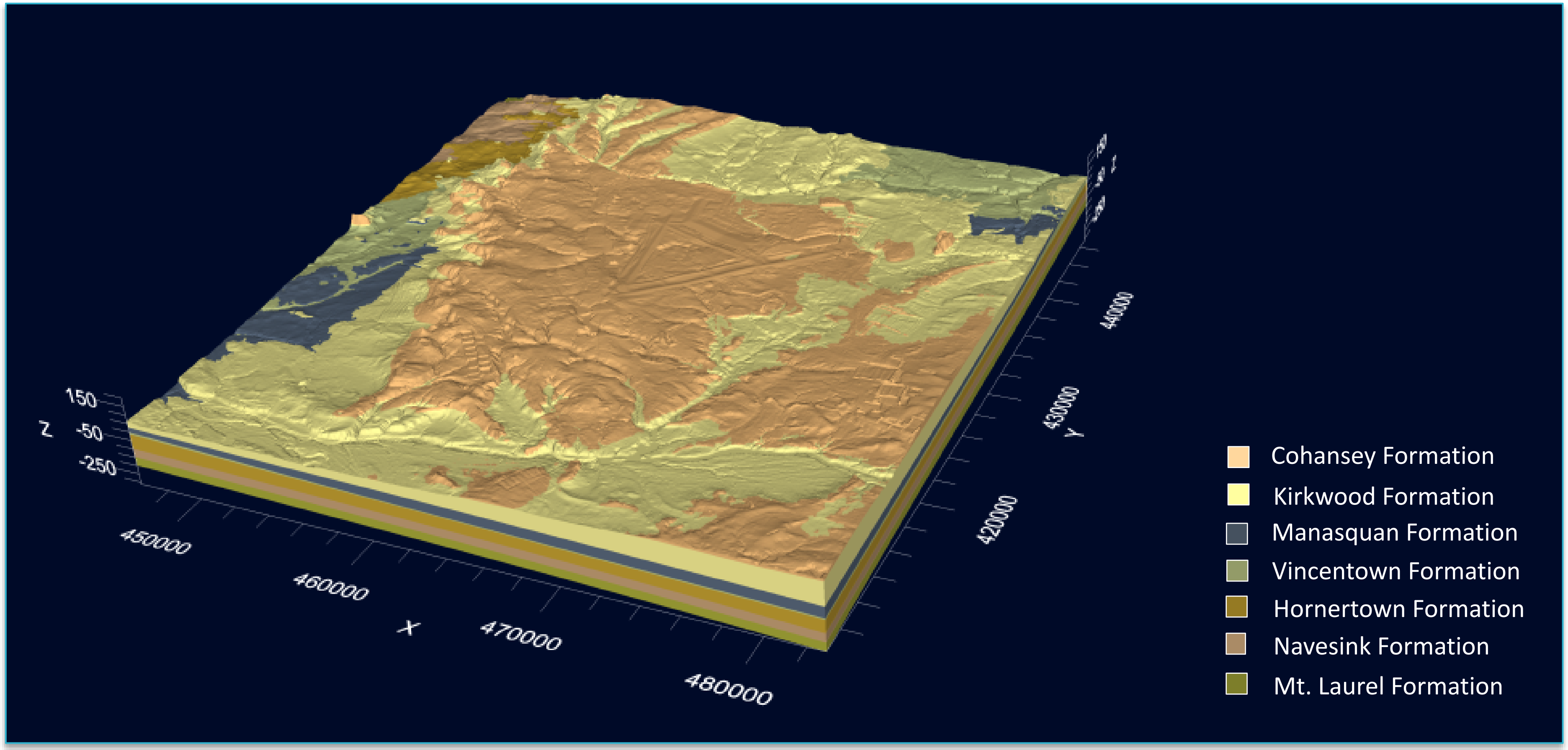
2. Create portable structural contours (Surfer Grids)



JBMDL: Framework Modeling

3D Model Framework

Visual Modflow FLEX



JBMDL: Boundary Conditions

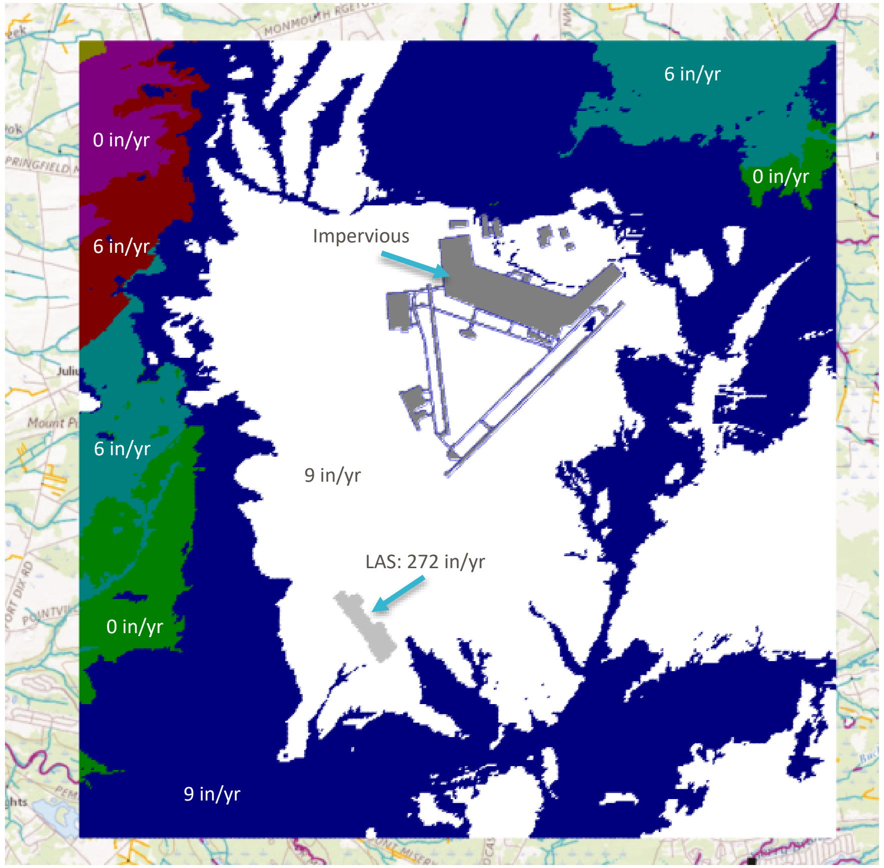
Finite Difference Modflow Model

Visual Modflow FLEX

Streams and Rivers:

Digitized from USGS National Map Hydrography
Mostly gaining streams: modeled as DRN boundary condition
DRN elevation = high resolution Digital Elevation Model value
Conductance per unit area = 100 1/day; Actual conductance proportional to cell area intersected by stream (assigned algorithmically by Visual Modflow)

Recharge



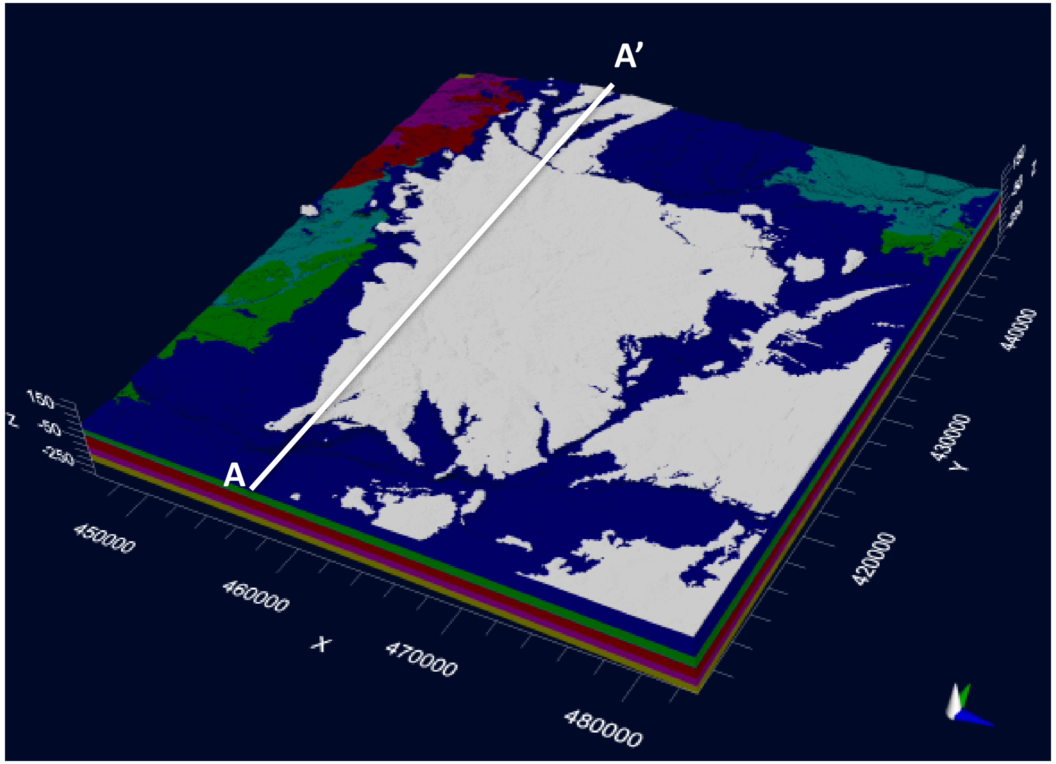
Assigned based on which formation is outcropping except for:
(1) Impervious areas
(2) LAS project – treated wastewater recharge

Finite Difference Modflow Model: JBMDL

Finite Difference Modflow Model

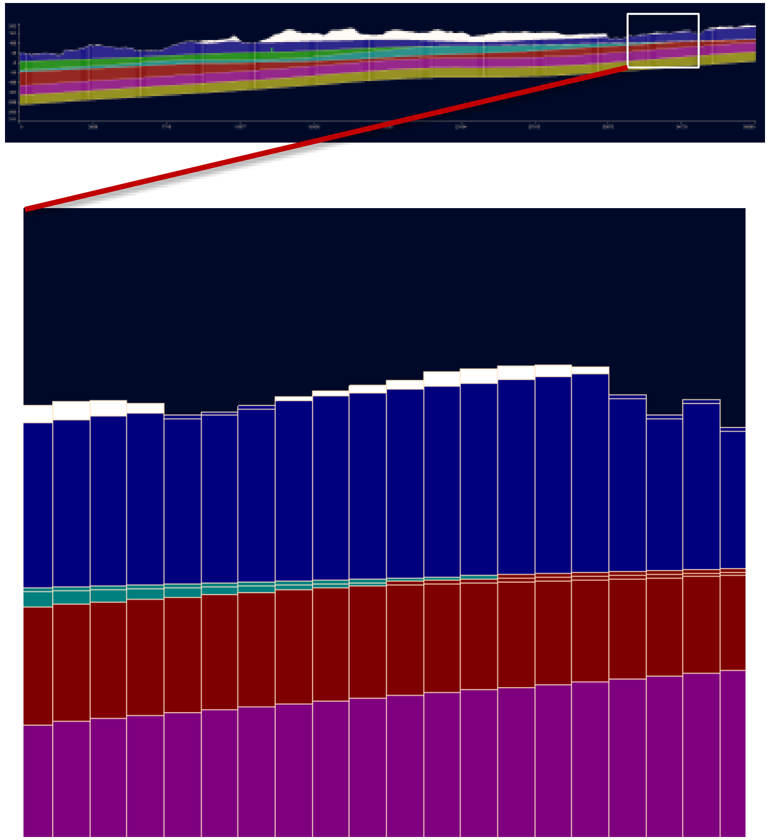
Visual Modflow FLEX

3. Use structural contours to build finite difference MODFLOW model



☐ Cohansey Formation
■ Kirkwood Formation
■ Manasquan Formation
■ Vincentown Formation
■ Hornertown Formation
■ Navesink Formation
■ Mt. Laurel Formation

A A'



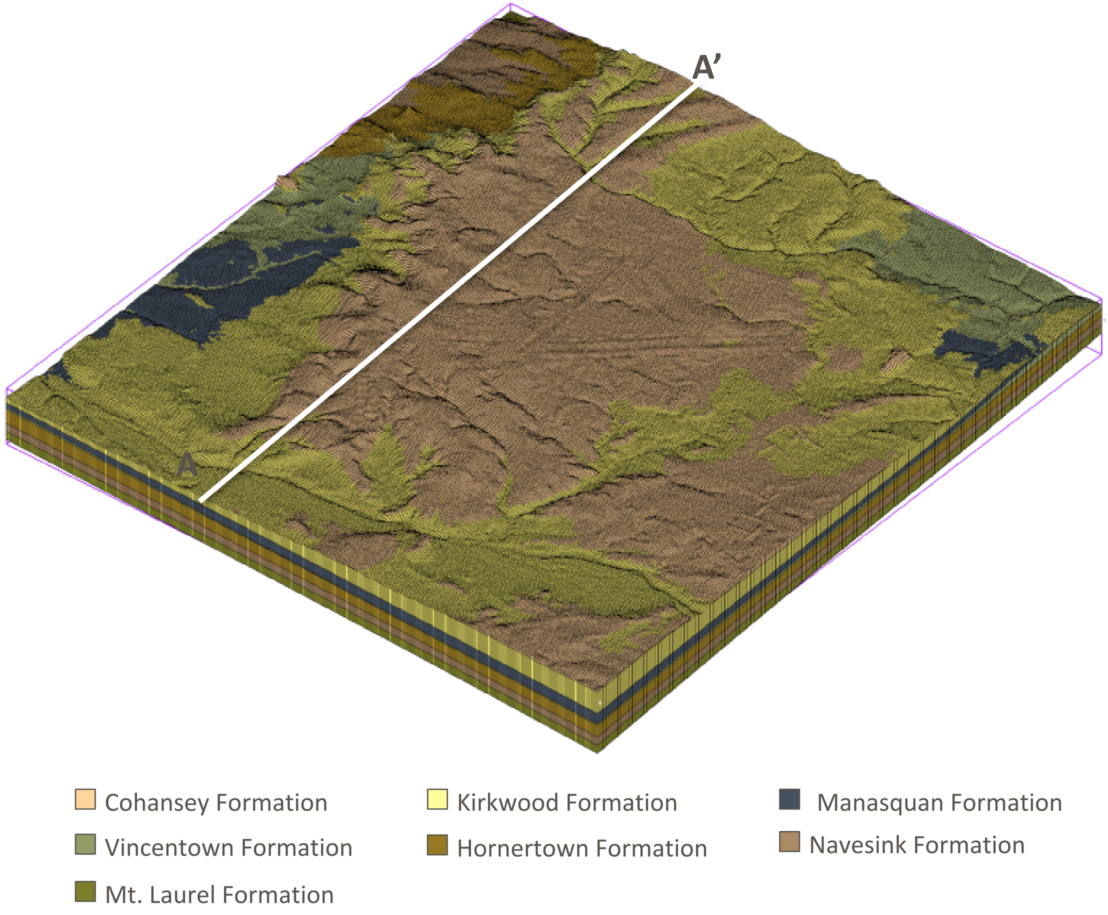
HALEY ALDRICH

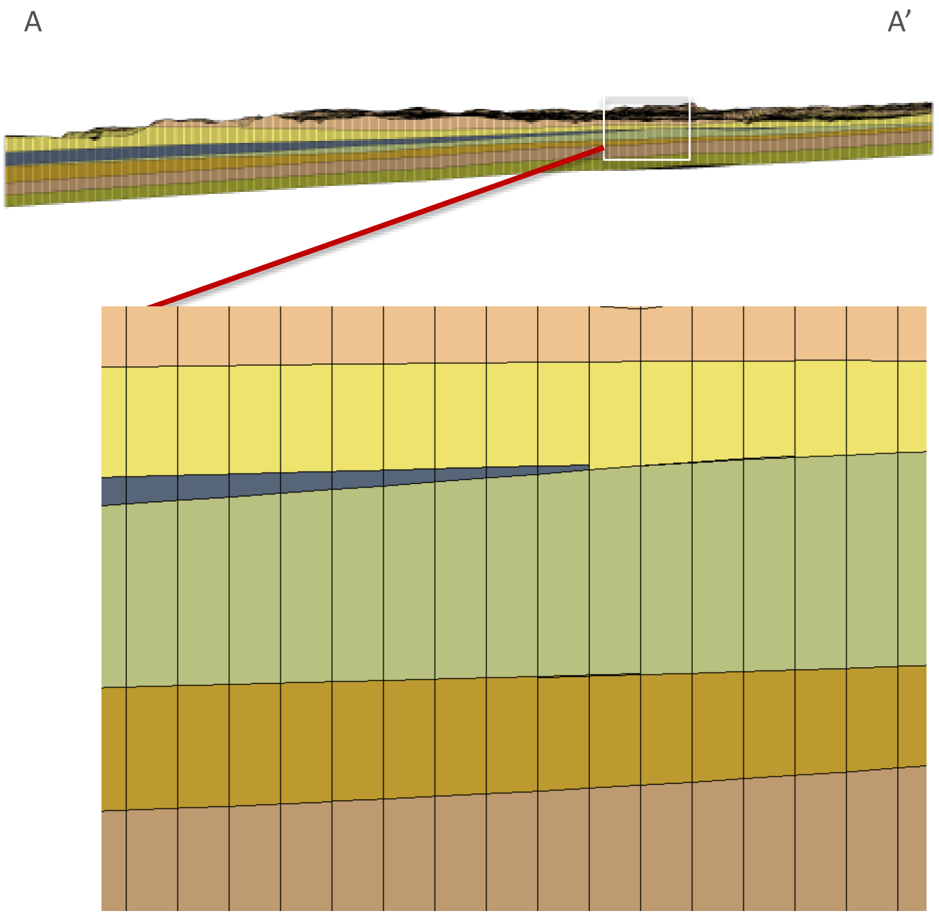
Unstructured Grid Model: JBMDL

Modflow USG Model

GMS

Same grid size, but using USG explicit pinch-outs



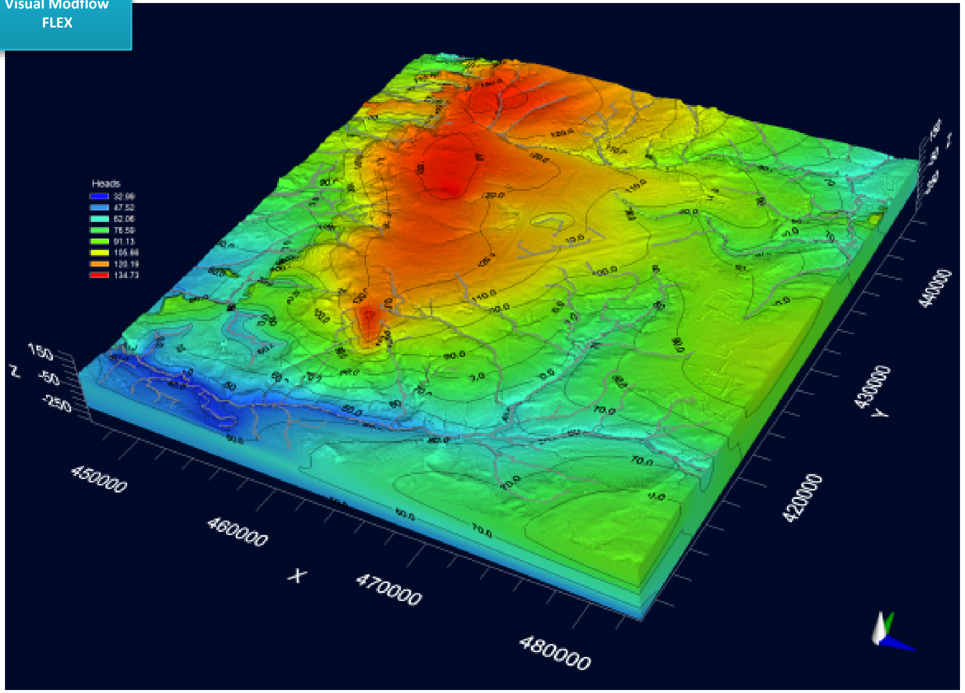


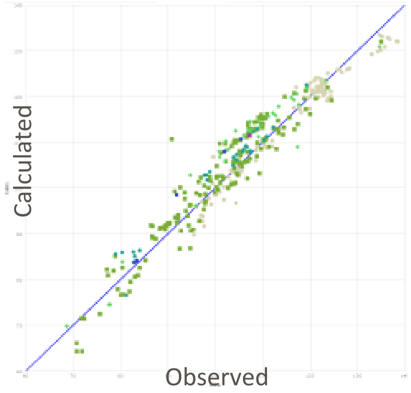
HALEY ALDRICH

JBMDL: Preliminary Calibration

Finite Difference Modflow Model

Visual Modflow FLEX



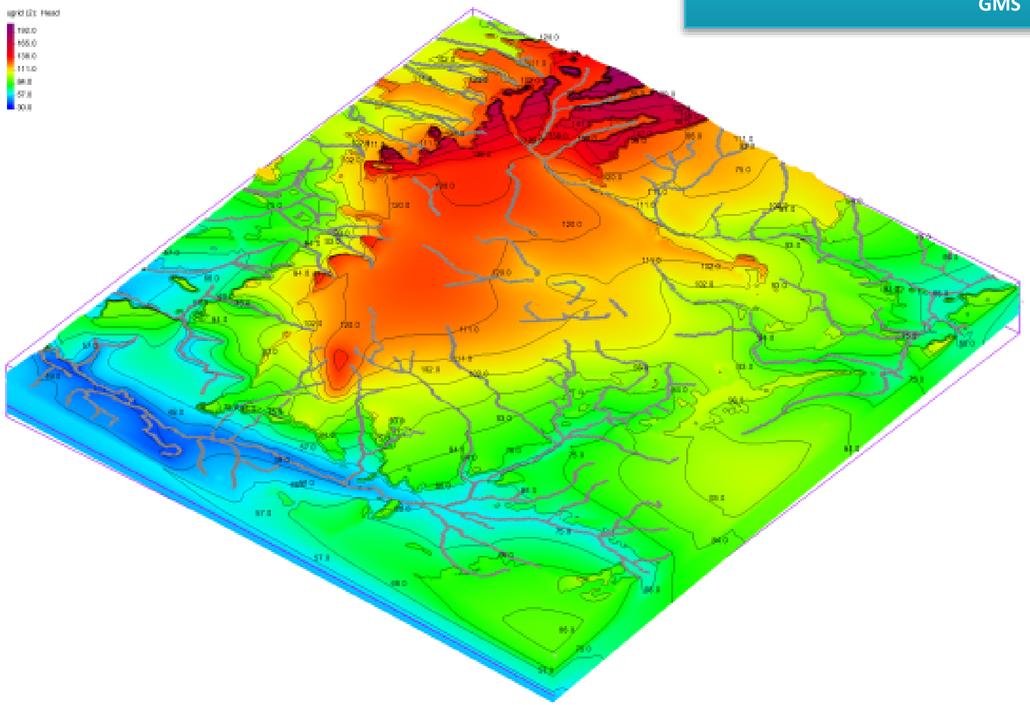


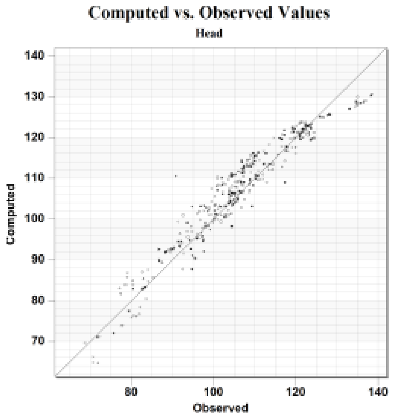
RMSE = 5.25%

Correlation Coefficient = 0.97

Modflow USG Model

GMS



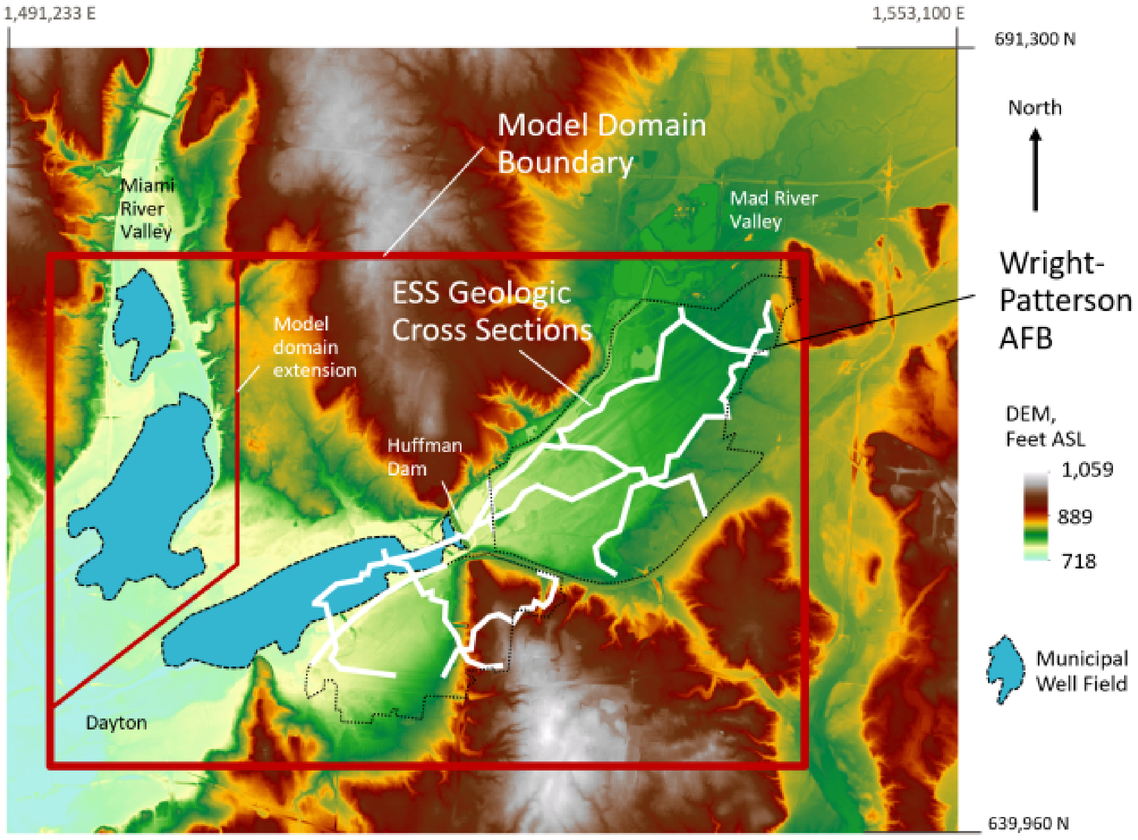


RMSE = 5.55%

Correlation Coefficient = 0.96

HALEY ALDRICH

Modeling for Wright-Patterson AFB

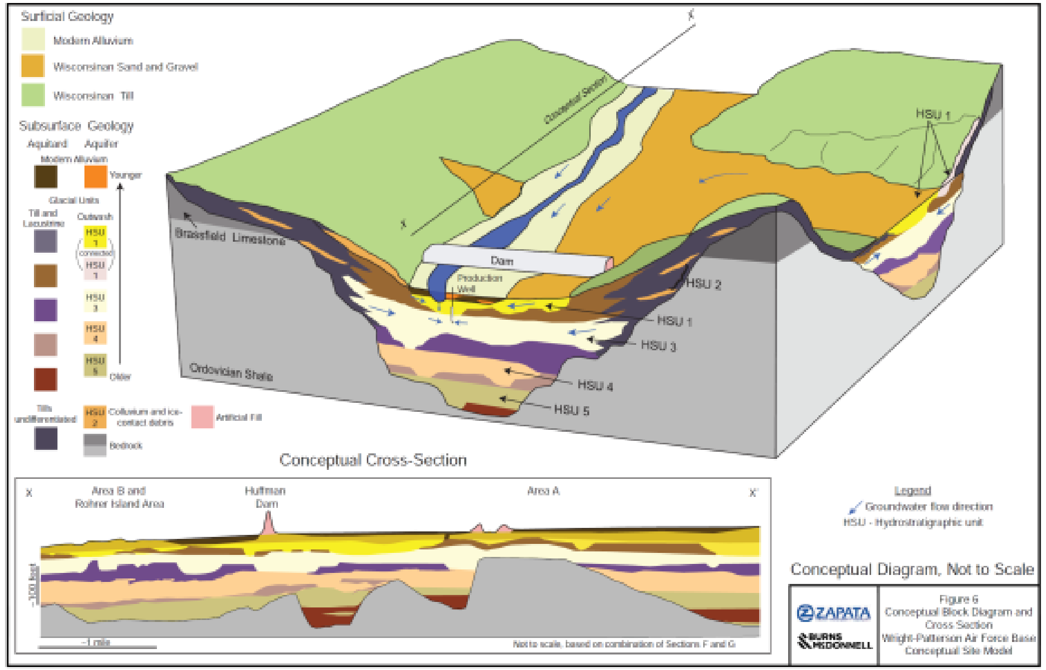


Digital Elevation Model from USGS 3DEP

- Moderately complex geology:

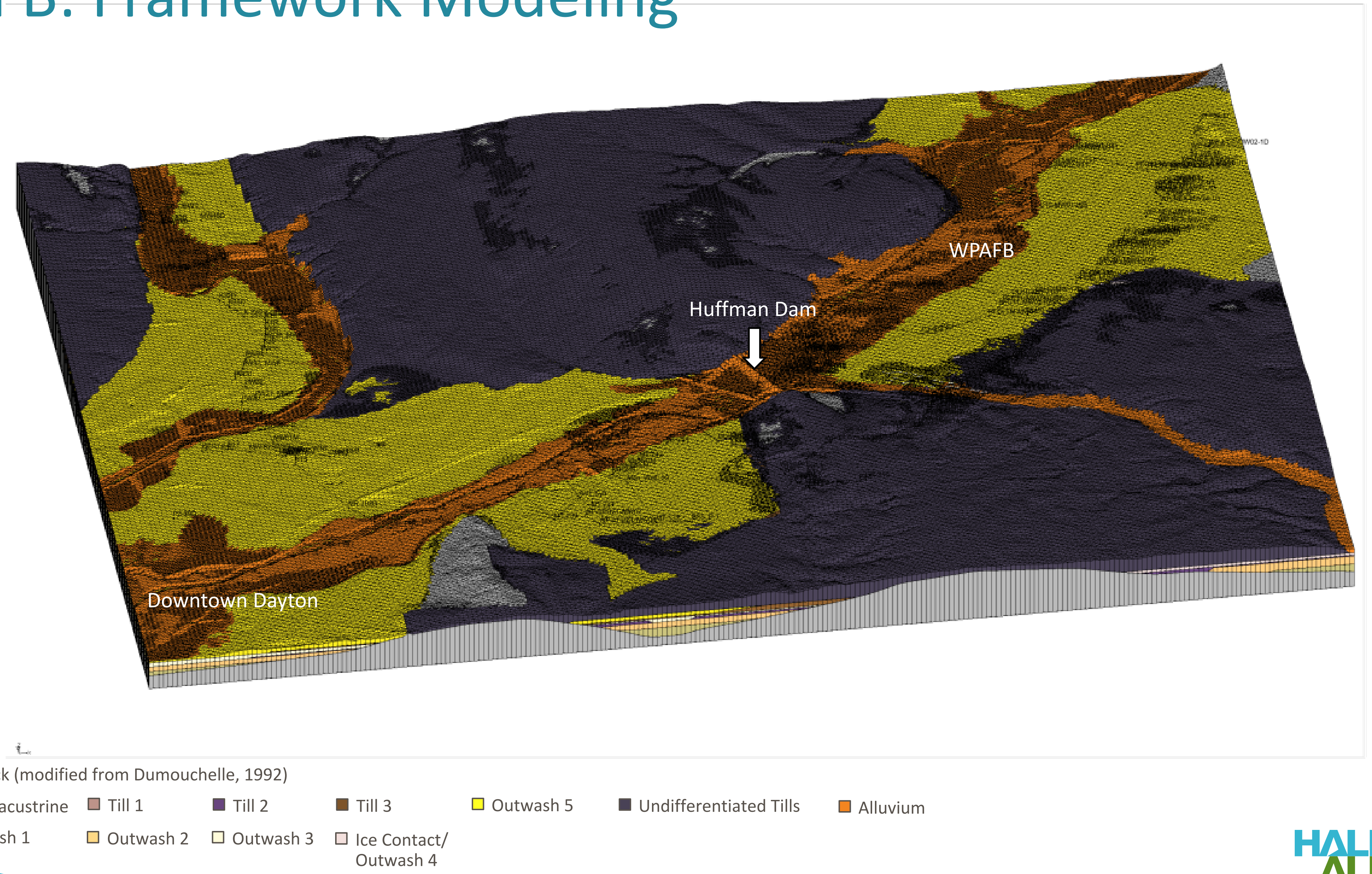
Glacial valley incised into Paleozoic platform carbonates.

Glacial valley filled with diamictons interbedded with lacustrine / other water lain sediments.



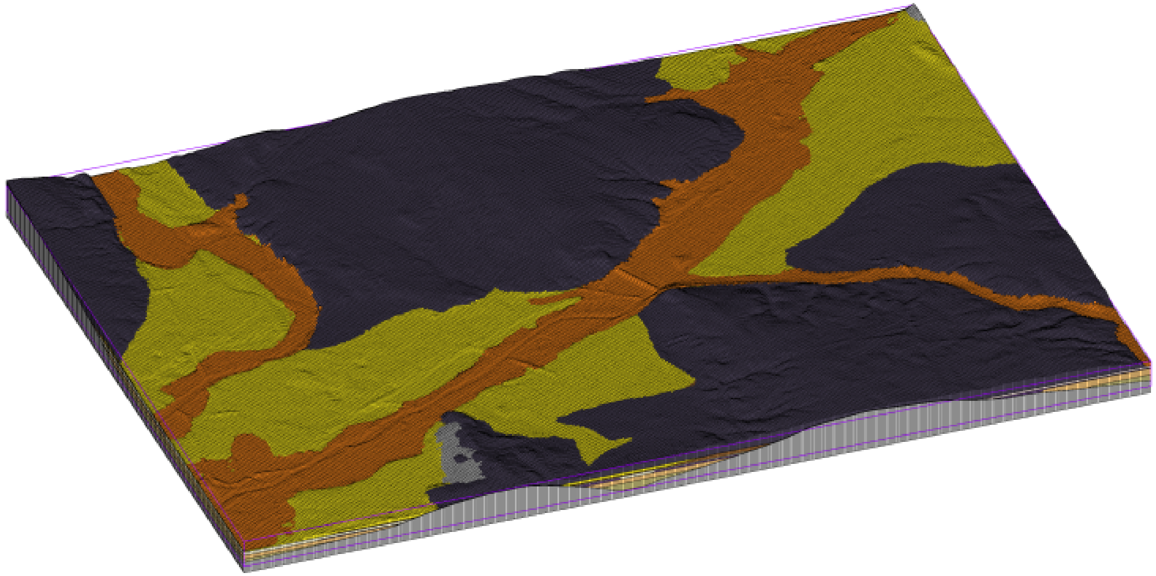
ESS-based CSM from Colin Plank, Burns & McDonnell

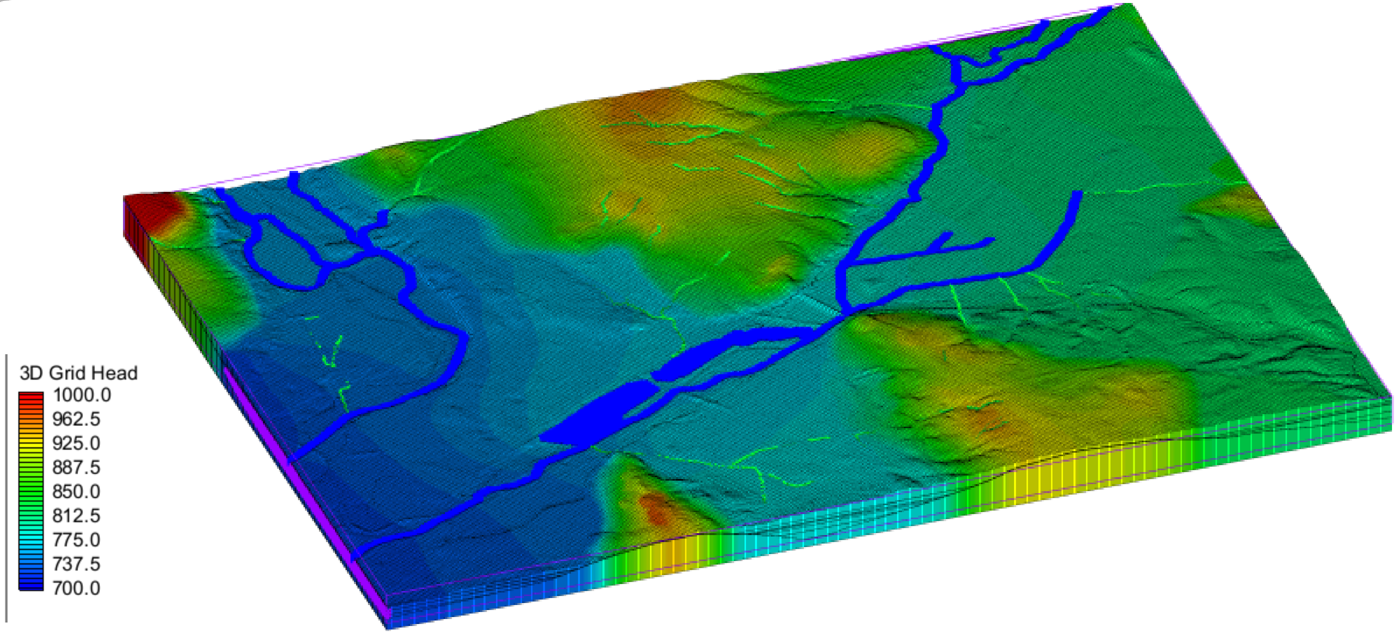
WPAFB: Framework Modeling



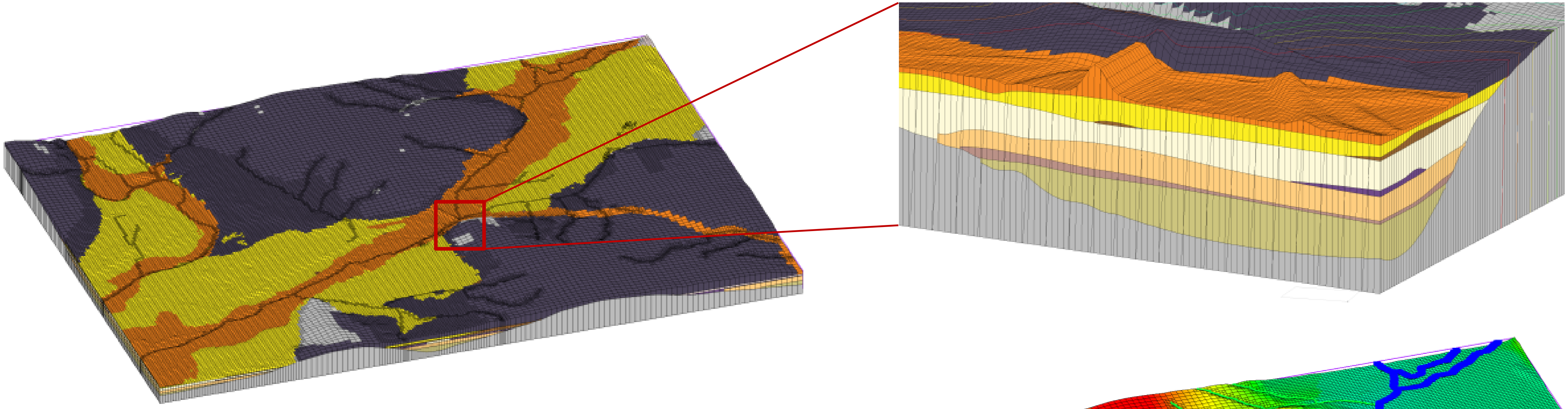
HALEY ALDRICH

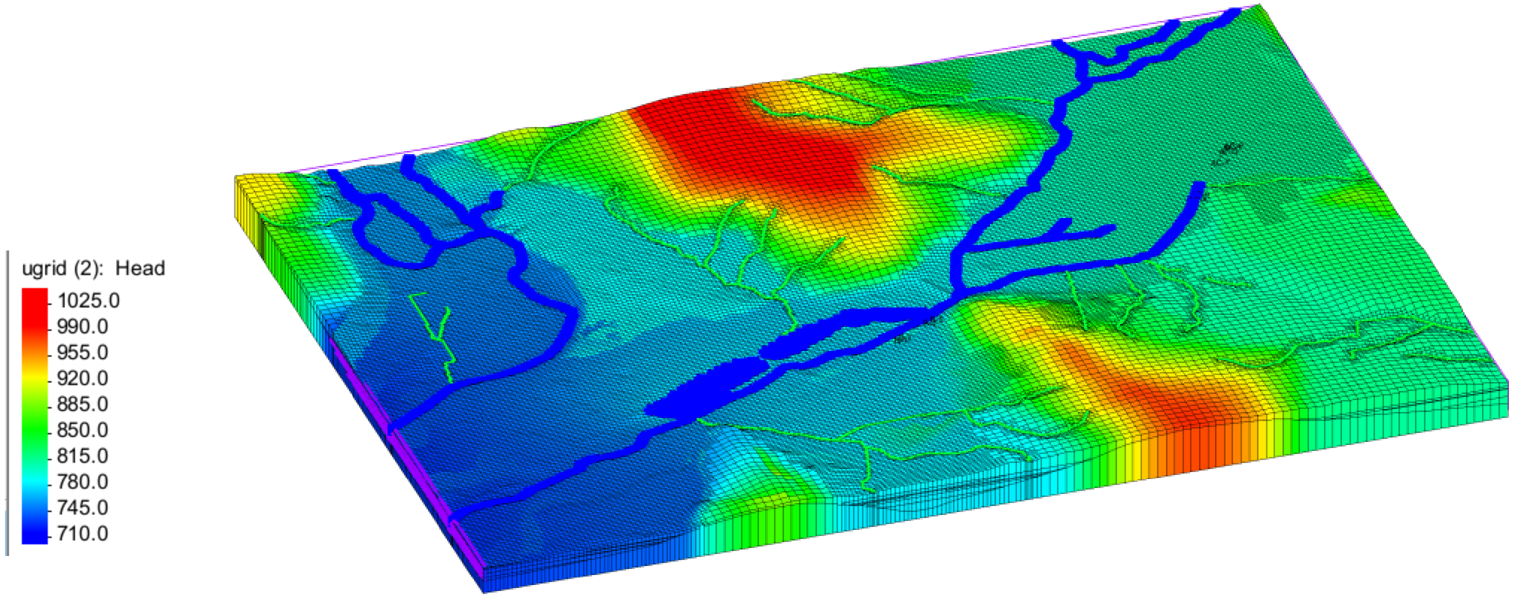
Finite Difference Modflow Model:



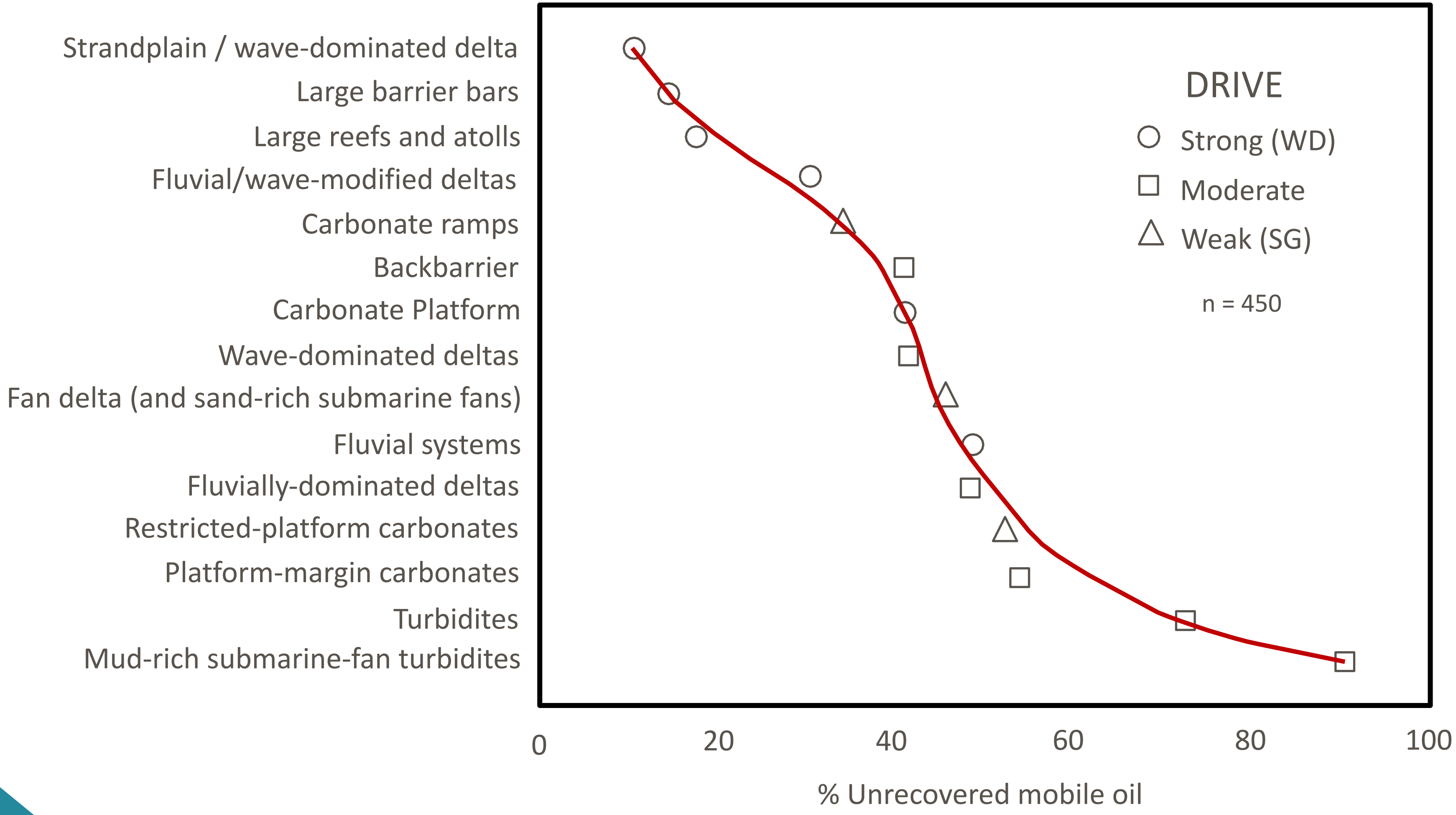


Unstructured Grid Modflow Model:



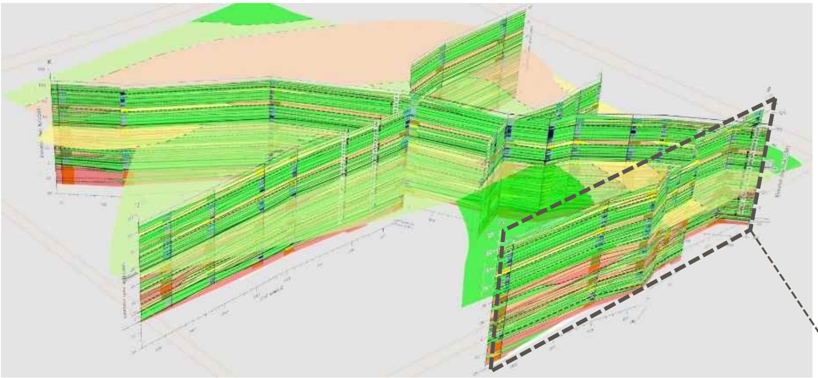


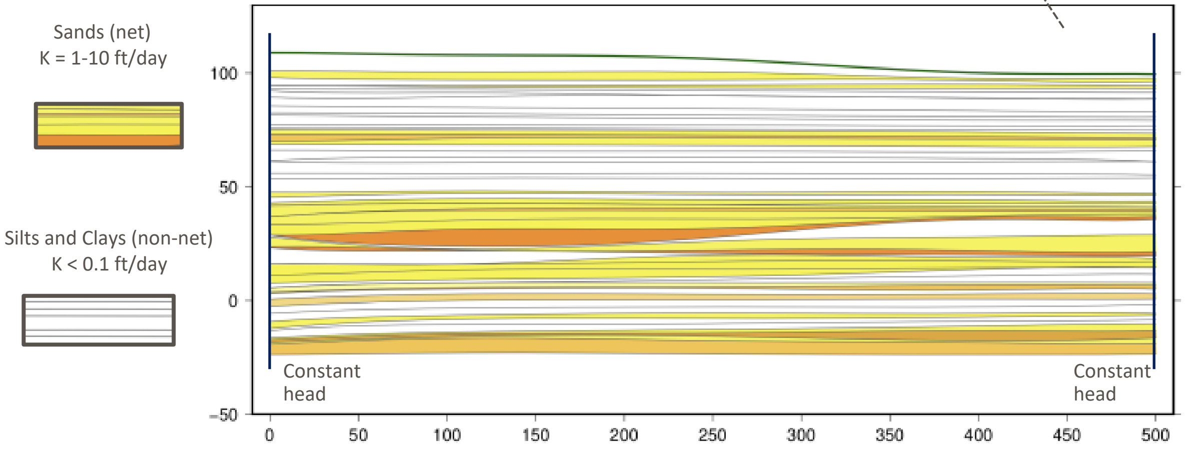
Relationship between “NAPL” recoverability and geologic facies (Petroleum industry)



From Tyler and Finley, 1992.

Numerical experiment: contaminant transport

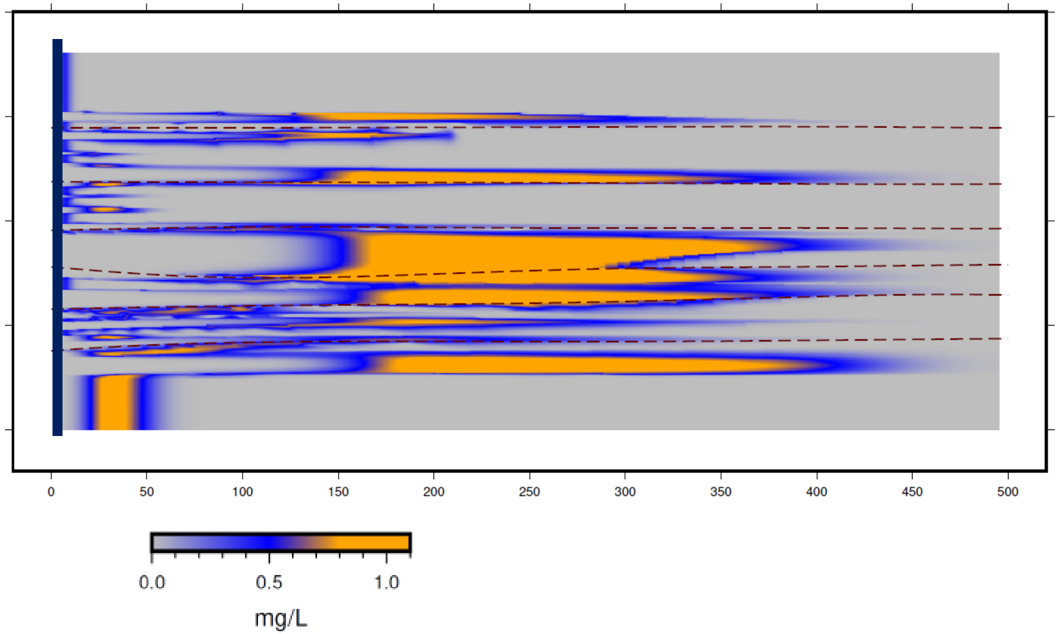




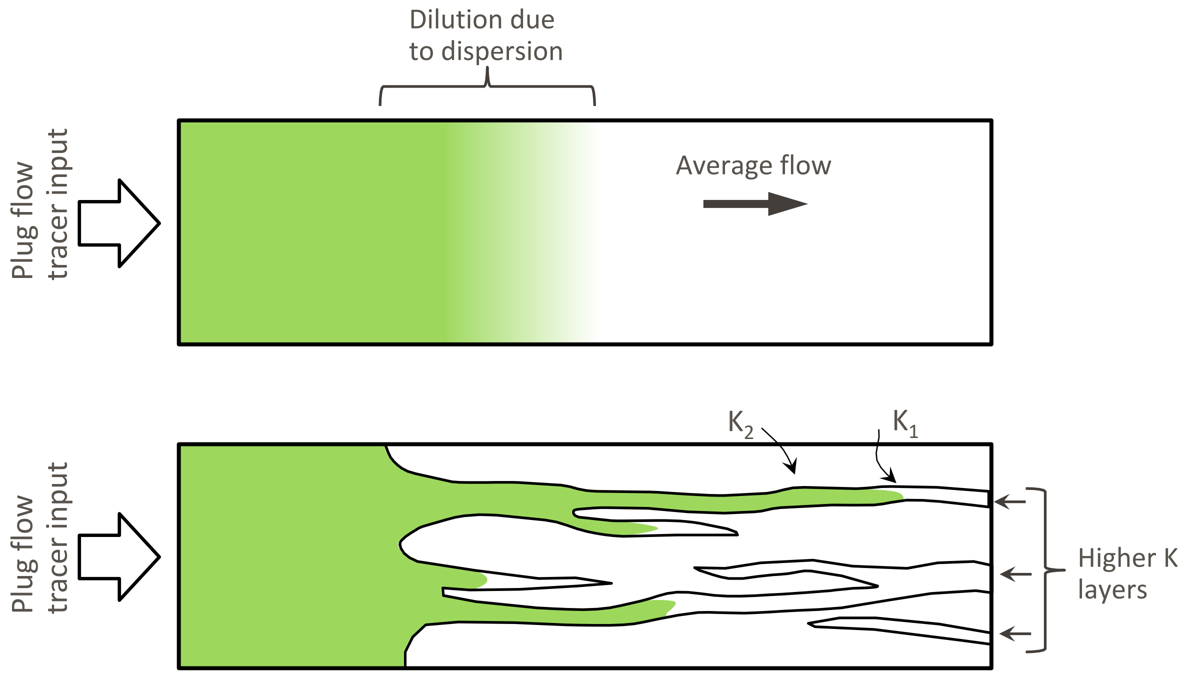
From Brandenburg et al., 2019.

- Discretize an ESS panel to Regular 2D Grid, with 6-inch cell size
- Apply basic constant head boundary conditions
- Apply constant upgradient source, 1 mg/L PCE for 5 years; clean water for 3 years
- Model section (transect) is orthogonal to plume axis

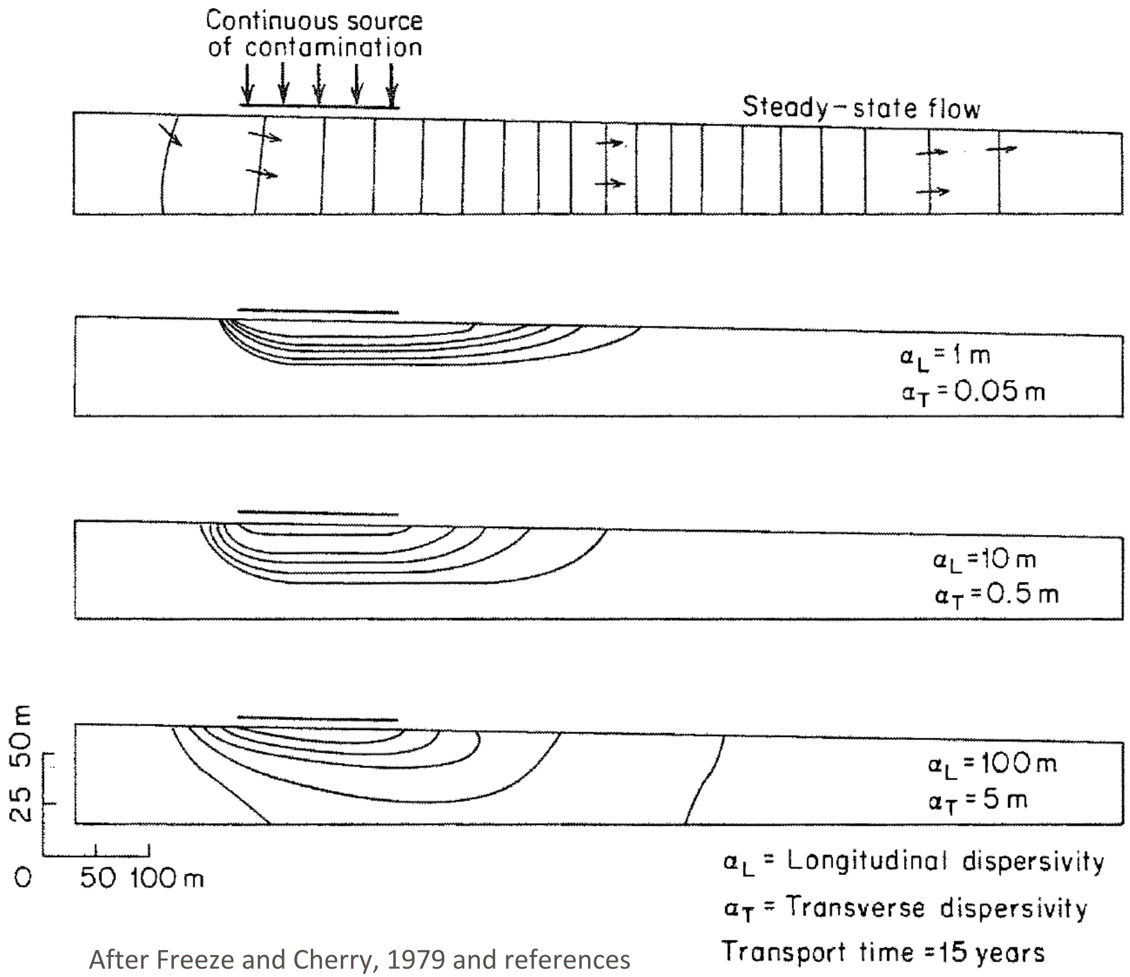
PCE plume after 8 years:



Hydrodynamic dispersion



After Freeze and Cherry, 1979.



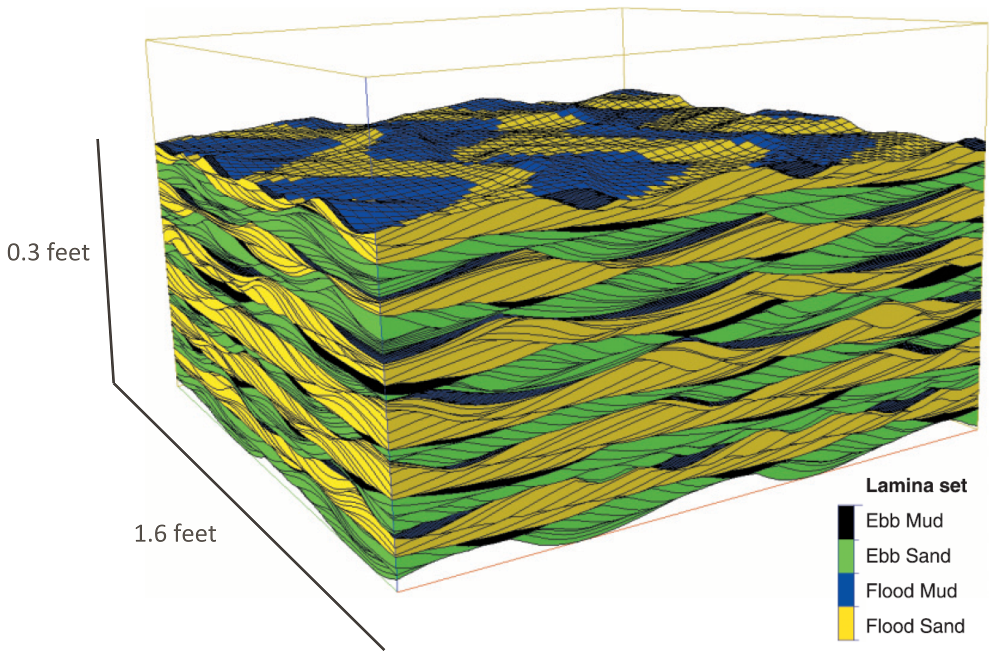
After Freeze and Cherry, 1979 and references therein.

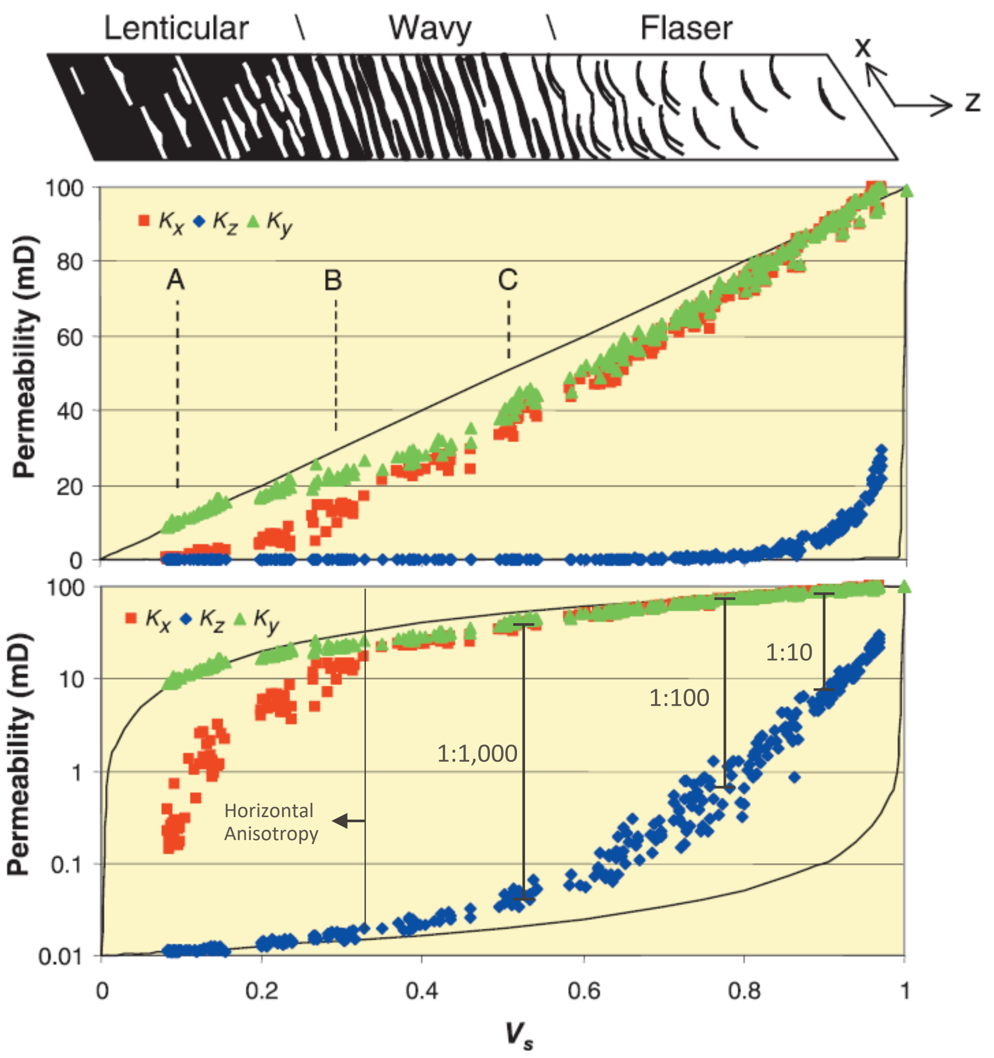
Dispersion of a contaminant during transport in a shallow groundwater flow system. Porosity 30%; hydraulic conductivity 0.5 m/day; $\alpha_l/\alpha_t = 20$; transport time 15 years; concentration contours at $C/C_0 = 0.9, 0.7, 0.5, 0.3$, and 0.1 (after Pickens and Lennox, 1976).

Flow-based upscaling

High resolution gridded model

Tidal/deltaic sands with Flaser bedding: generated in SBED



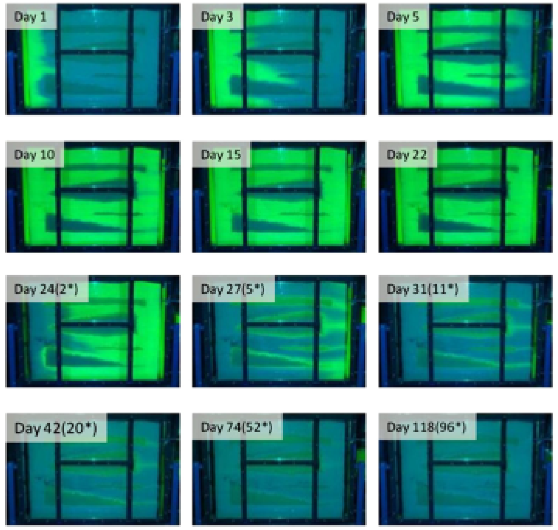


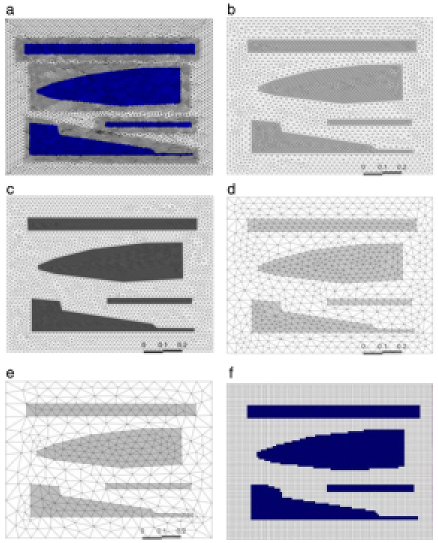
From Ringrose and Bentley, 2015

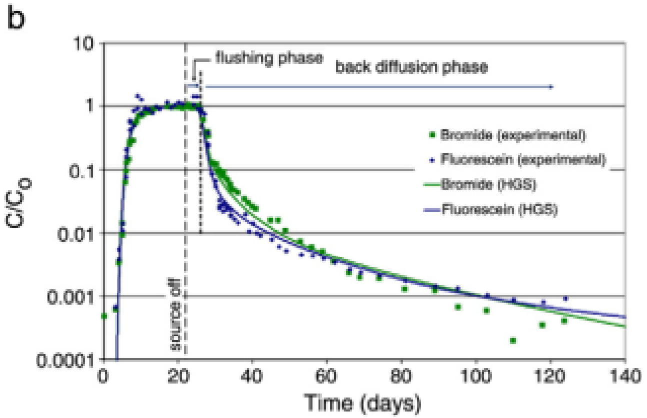
ESTCP project: G3 stratigraphic/groundwater flow models

Matrix Diffusion

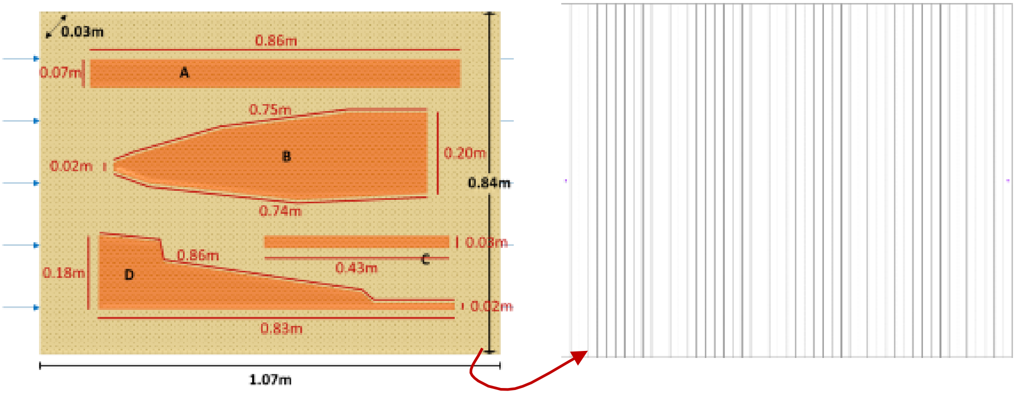
Tank and numerical models (Chapman et al., 2012)

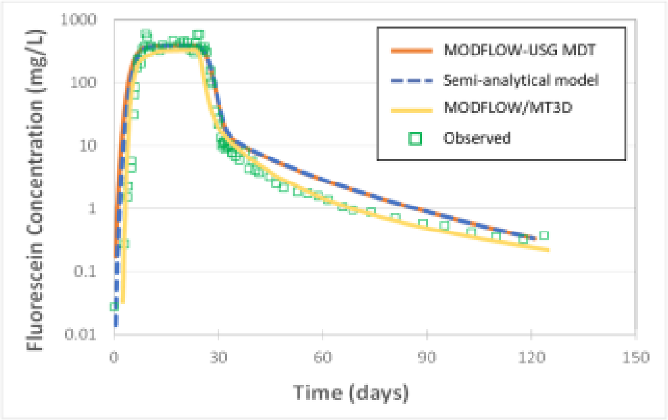






Semi-analytical method (Muskus and Falta, 2018)





Conclusions

1. Reviewed ESS methods and examples
2. Instructive to consider oil and gas origins of ESS
3. Scale of observations/interpretations/models: always a challenge
4. Key challenge: converting ESS details to parameters like dispersivity
5. Flow-based upscaling: one potential path forward

References

Alpak, Faruk O., Mark D. Barton, Frans F. van der Vlugt, Carlos Pirmez, Bradford E. Prather, and Steven H. Tennant. “Simplified Modeling of Turbidite Channel Reservoirs.” *SPE Journal* 15, no. 02 (2010): 480–94.

Alpak, Farouk O. and Mark D. Barton and Steve J. Naruk. “The impact of fine-scale turbidite channel architecture on deep-water reservoir performance.” AAPG Bulletin, v.97, no.2 (2013): 251-284.

Alpak, Farouk O. and Mark D. Barton. “Dynamic impact and flow-based upscaling of estuarine point bar stratigraphic architecture.” *Journal of Petroleum Science and Engineering*, 120 (2014): 18-38.

Brandenburg, JP, Murray Einarson and Farouk O. Alpak. “Capturing Uncertainty in Environmental Sequence Stratigraphy.” *AGU Fall Meeting 2019*, H43J-2153.

Chapman, Steven W., Beth L. Parker, Tom C. Sale, Lee Ann Doner. “Testing high resolution numerical models for analysis of contaminant storage and release from low permeability zones.” *Journal of Contaminant Hydrology*, 136-137 (2012): 106-116.

Chen, Tianhong. *New Methods for Accurate Upscaling with Full-Tensor Effects*. Stanford University, 2009.

Einarson, Murray, Adrian Fure, Randy St. Germain, Steve Chapman, and Beth Parker. “DyeLIF™: A new direct-push laser-induced fluorescence sensor system for chlorinated solvent DNAPL and other non-naturally fluorescing NAPLs.” Groundwater Monitoring & Remediation 38, no. 3 (2018): pp 28-42.

Freeze, R. Allen and John Cherry. “*Groundwater*.” Englewood Cliffs, NJ, Prentice-Hall. 604 pp.

Glover, Paul WJ, and Miao Luo. “The Porosity and Permeability of Binary Grain Mixtures.” *Transport in Porous Media* 132, no. 1 (2020): 1–37.

Hovadik, David K. and Joseph Larue. “Stratigraphic and Structural Connectivity.” *Geological Society of London Special Publication* 347 (2010): 219-242.

Mohrig, David, and Jeffrey G. Marr. “Constraining the Efficiency of Turbidity Current Generation from Submarine Debris Flows and Slides Using Laboratory Experiments.” *Marine and Petroleum Geology* 20, no. 6–8 (2003): 883–99.

Muskus, Noelia and Ronald W. Falta. “Semi-analytical method for matrix diffusion in heterogeneous and fractured systems with parent-daughter reactions.” *Journal of Contaminant Hydrology*, 218 (2018): 94-109.

Ringrose, Philip, and Mark Bentley. *Reservoir Model Design*. Springer, 2016.

Sandrea, Ivan, and Rafael Sandrea. “Recovery Factors Leave Vast Target for EOR Technologies.” *Oil & Gas Journal* 105, no. 41 (2007): 44–47.

Schultz, Mike, Rick Cramer, Herb Levine and Ken Ehman. “Best Practices for Environmental Site Management: A practical guide for applying environmental sequence stratigraphy to improve conceptual site models.” (2017) *USEPA Technical Report*, EPA/600/R17/293.

Shepherd, Mike. *Oil Field Production Geology: AAPG Memoir 91*. Vol. 91. AAPG, 2009.

Tyler, Noel, and Robert J. Finley. “Architectural Controls on the Recovery of Hydrocarbons From Sandstone Reservoirs,” 1991.

HALEY ALDRICH

Environmental Sequence Stratigraphy in Numerical Groundwater Models

Background/Objectives

Recent advances in borehole logging and visualization software combined with more rigorous evaluation of depositional environments have made sophisticated subsurface geologic interpretation and models accessible to the environmental consulting industry. However, in practice, conceptual site models are still very often based on generalized and often arbitrarily subdivided stratigraphy. Relationships between stratigraphy and non-stratigraphic features such as bedrock unconformities and anthropogenic construction fill are often conceptually challenging in this layer-based framework. Interpretation and model improvement are important in characterizing the geological controls of complex processes such as biological and abiotic degradation pathways. What is less defined is the added value for including detailed stratigraphy in numerical groundwater models.

Approach/Activities

Stratigraphic interpretations and related groundwater models for contaminated groundwater sites are reviewed in the context of informing remedial design and scope. The value of information is assessed by comparing the potential influence of using a more detailed stratigraphic model compared to a simpler layered geologic model. We evaluate performance of different numerical discretization schemes for representing complex stratigraphy and discuss efficient workflows for converting to scale-appropriate numerical models.

Results/Lessons Learned

Application of detailed stratigraphic analysis offers many benefits to contaminated site management. Of these, more accurate site conceptualization is arguably the most valuable. The ability to develop and communicate a geologically consistent interpretation at the correct resolution adds context for heterogeneous data and uncertainty inherent in standard environmental projects. An understanding of the maximum level of detail that is appropriate, and their representation in numerical models is critical to maximizing this value.