An Introduction to Groundwater Modeling in Arizona

ARIZONA HYDROLOGICAL **SOCIETY**

PHOENIX CHAPTER

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BIOS

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OVERVIEW

Workshop Sections

Modeling Overview

-Learning Outcomes
-Modeling Terms
-Usage Justification
-MODFLOW Versions
-MODFLOW Models in AZ
-Guidance for MODFLOW

MODFLOW Examples

-Example1, 2D Coarse Model
-Example2, 2D Refined Model

General Knowledge

Class participants will learn what a Numerical Groundwater Model is used for and when it is needed. Participants will also gain hands-on experience using MODFLOW to model groundwater on different scales.

ARIZONA HYDROLOGICAL SOCIETY

MODELING TERMS

Primary Types of Models

Process-based

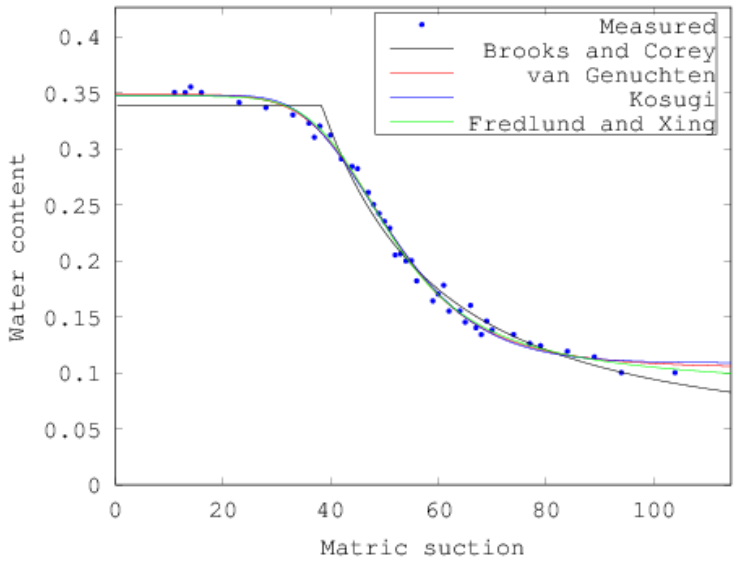
Physical processes and principles approximated to evaluate the modeled system.

- MODFLOW
- SWAT
- Most Environmental Models

Data-driven or Empirical

Empirical or statistical equations derived from available data are used to calculate an unknown variable.

- Brooks-Corey



From Haverkamp and Parlange, 1986

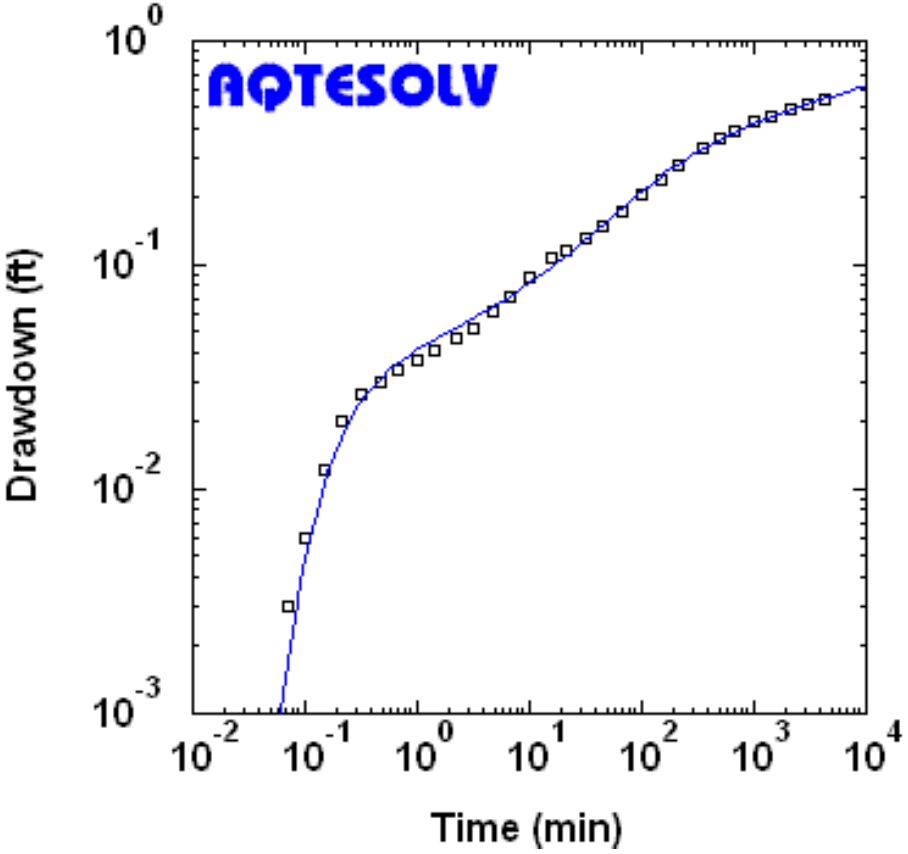
MODELING TERMS

Process-Based Models

Conceptual
A hypothesis that relates the behavior of the system to its internal processes.

Analytical
A math based description of groundwater flow through governing equation(s) and a solution algorithm.

- TH_Wells
- Aquifer Win 32
- MLAEM



Analysis of a constant-rate pumping (Tartakovsky and Neuman 2007). From AQTESOLV.com (HydroSOLVE, Inc).

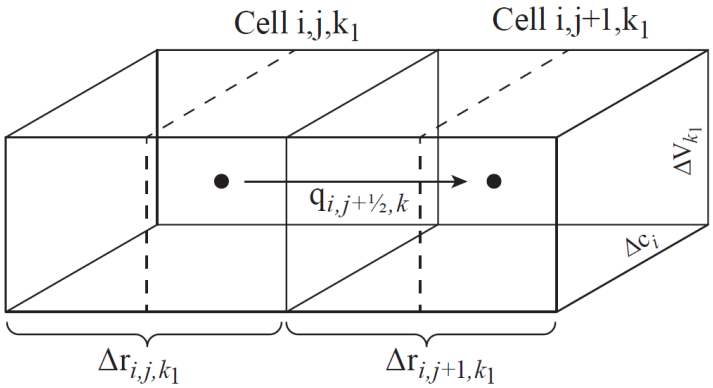
MODELING TERMS

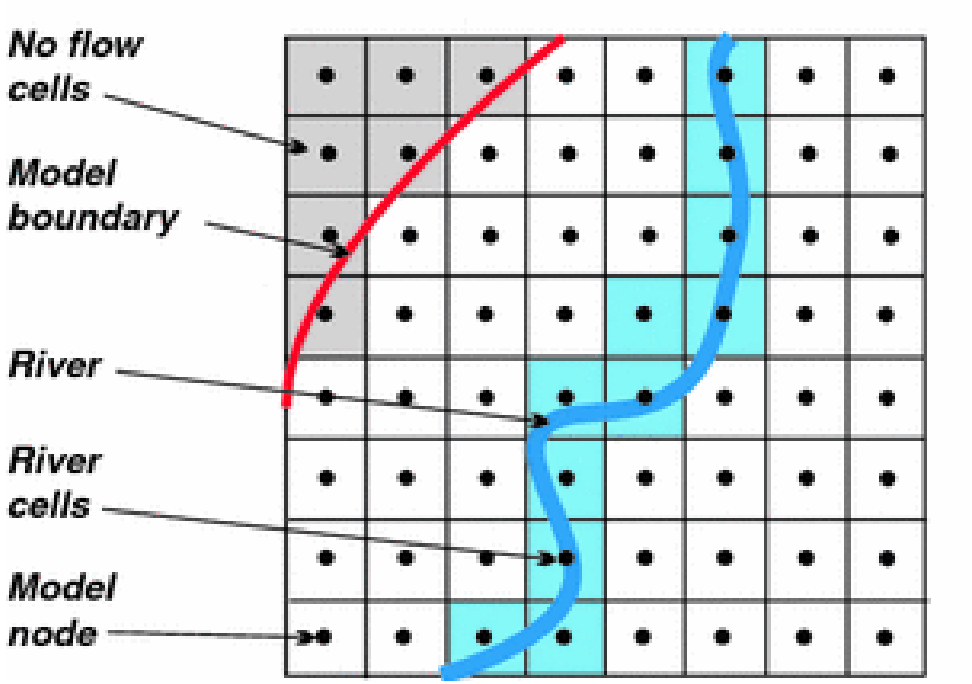
Process-Based Models

Numerical

Discretized system of partial differential equations approximated by algebraic equations at point locations.

- HydroGeoSphere
- MODFLOW
- FEFLOW
- ParFlow





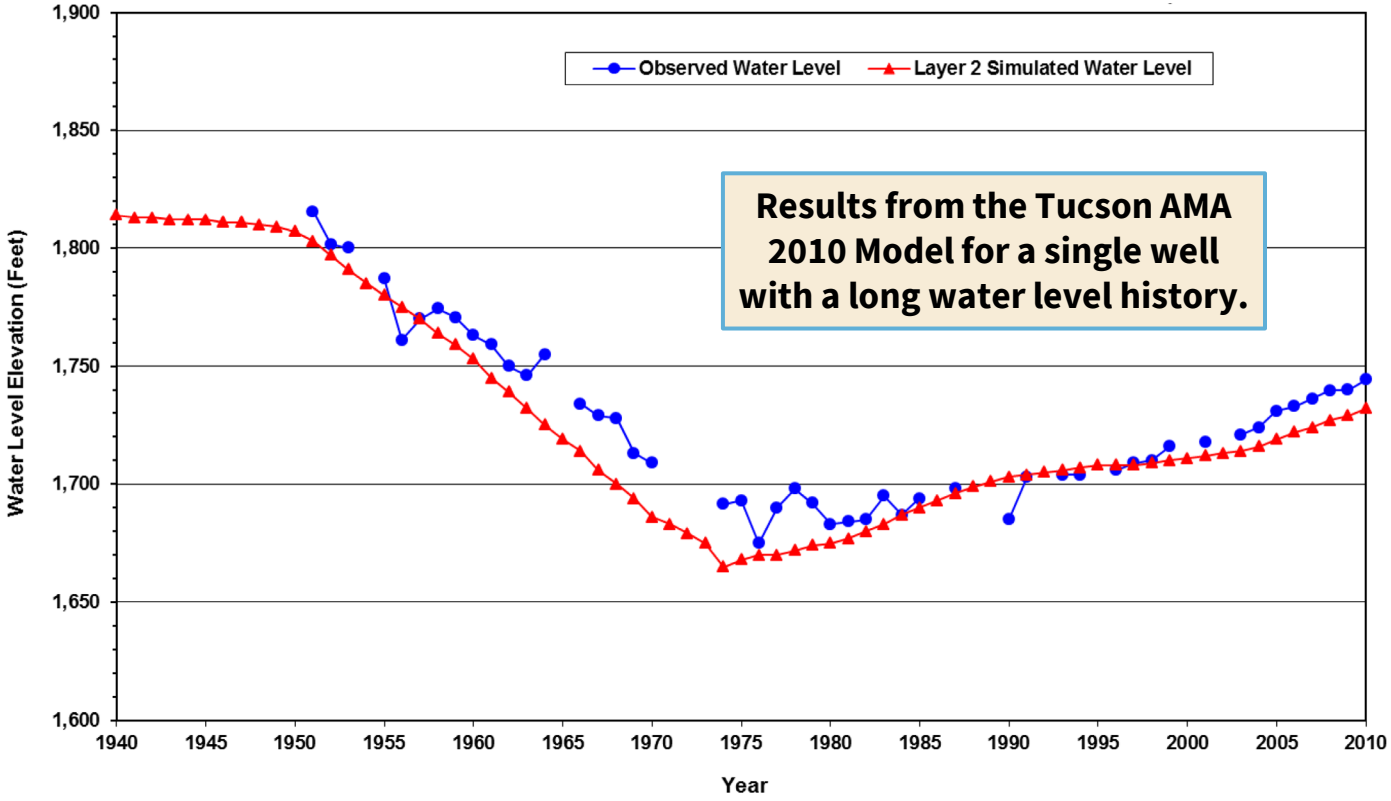
MODELING TERMS

Numerical Models

Deterministic

A model that makes a singular prediction or has a single outcome based on purpose of the model.

- Most Predictive Groundwater Models



ADWR 2013

MODELING TERMS

Numerical Models

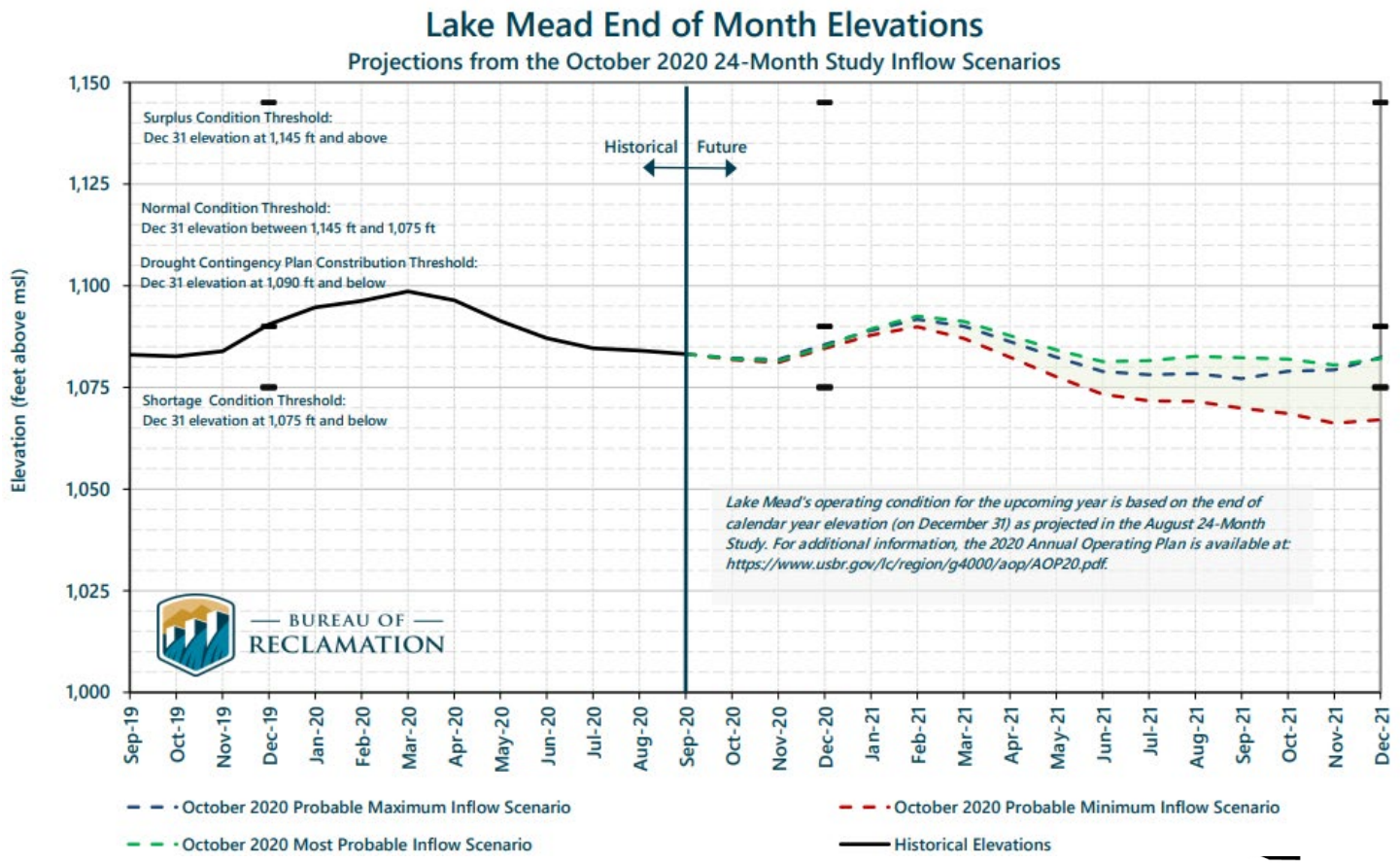
Probabilistic

A model that uses many parameter combinations based on statistical distributions and literature values.

- Most Climate Models

- CRSS: Colorado River Simulation System

USBR 2020



MODELING TERMS

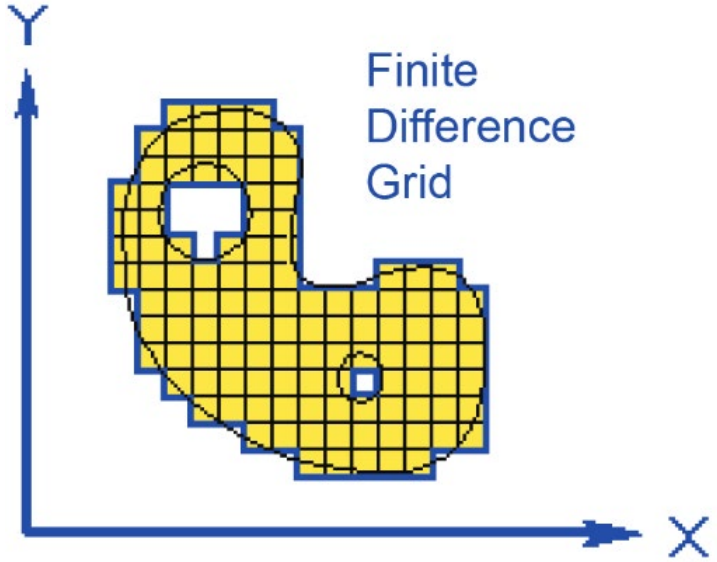
Numerical Models

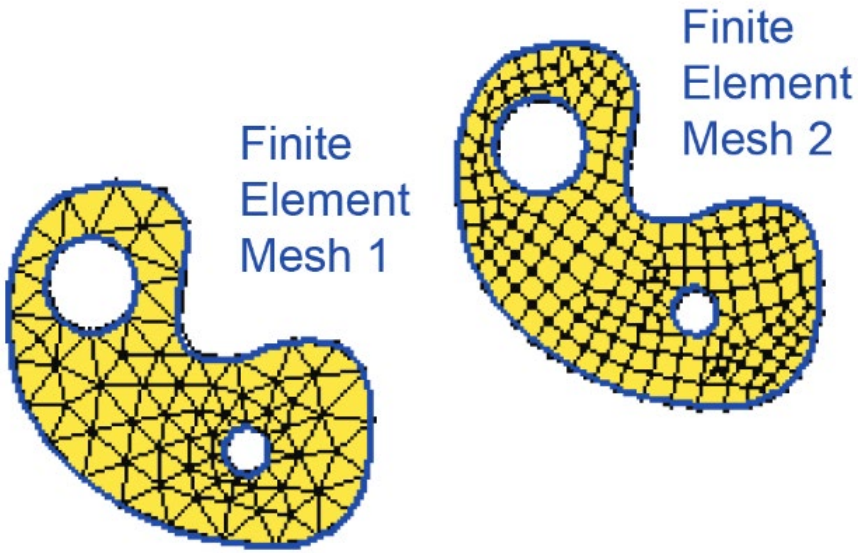
Finite Difference
Nodes in rectangular grid using layer, row, column index (i,j,k).

- Most MODFLOW Releases

Finite Element
Nodes in mesh with defined connections and spatial coordinates (x,y,z).

- FEFLOW
- HydroGeoSphere





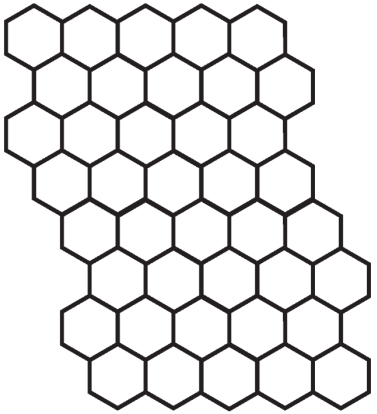
MODELING TERMS

Numerical Models

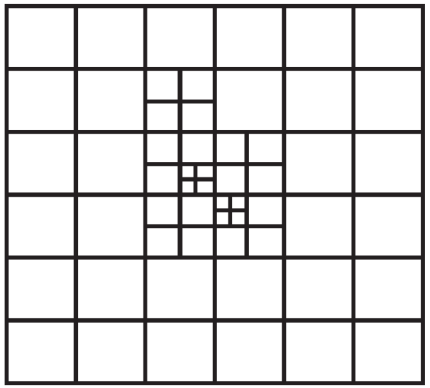
Finite Volume

Cutting-edge method developed Sorab Panday (GSI, USGS) allowing more complex grid options.

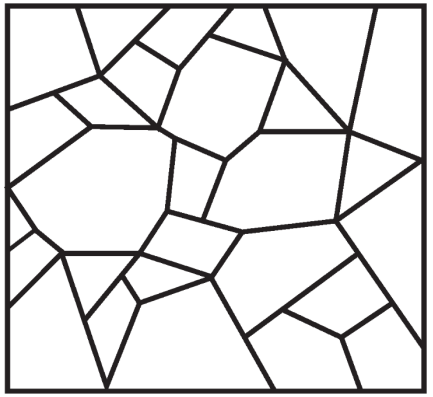
Hexagonal grid



Rectangular, quadtree grid, with smoothing



Irregular polygon grid



USAGE JUSTIFICATION

Why Do We Model?

Usage

-Basic understanding of groundwater system
-Estimation of aquifer properties
-Understanding the present

→ **Interpretive**

-Understanding the past
-Estimating future conditions

→ **Hindcasting**
Forecasting

Common Applications

-Predicting the effects of groundwater pumping on future availability.

-Predicting the effects of recharge on local groundwater levels.

-Determining the direction of transport in a groundwater system to avoid potential risk.

USAGE JUSTIFICATION

When Do We Model?

When to Use a Model
A model should be used when estimating the response of an aquifer system to stresses or significant physical changes.

Cautionary Notes
All models are inexact and expressing the degree of uncertainty is necessary. Models can be expensive and in some cases are not justified due to cost estimates and desired outcomes.

MODFLOW VERSIONS

MODFLOW Versions

Outdated

-MODFLOW 88
-MODFLOW 96

→ **No Longer Used**

-MODFLOW 2000
-MODFLOW 2005
-MODFLOW NWT
-MODFLOW LGR

→ **Still Used Commonly**

Actively Being Developed

-MODFLOW One Water
-MODFLOW USG
-MODFLOW 6
-MODFLOW-SURFACT

→ **Proprietary Version**

MODFLOW VERSIONS

MODFLOW One Water

Release Info

MODFLOW-OWHM: One Water Hydrologic Flow Model

V1.0.0 Released in 2014

V1.0.12 Released in 2016

V2.0.2 Recently Released

Features

Ideal version for integrated and coupled hydrologic flow modeling.

-Newtonian Solver (NWT)
-Local Grid Refinement (LGR)
-Surface-Water Routing (SWR)
-Farm Process (FMP2)
-Subsidence w/Compaction (SWT)
-Riparian Evapotranspiration (RIP-ET)

-Groundwater Flow (GWF)
-Connected Linear Networks (CLN)

MODFLOW VERSIONS

MODFLOW USG

Release Info

MODFLOW-USG: An Unstructured Grid Version of MODFLOW

1.0 Released in 2013

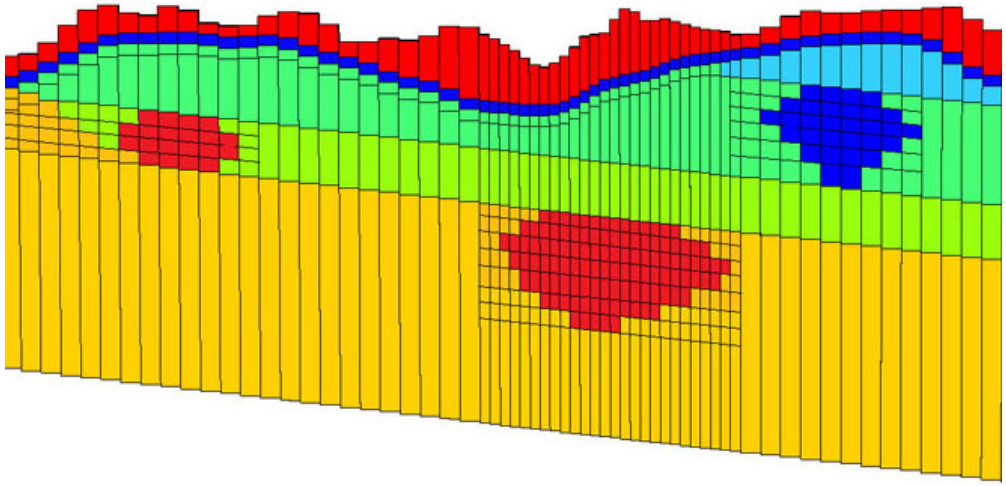
1.5 Released in 2019

Features

Control Volume Finite-Difference derivation allowing for complex grids

Ideal version for coupling with geochemical models

-Groundwater Flow (GWF)
-Connected Linear Networks (CLN)

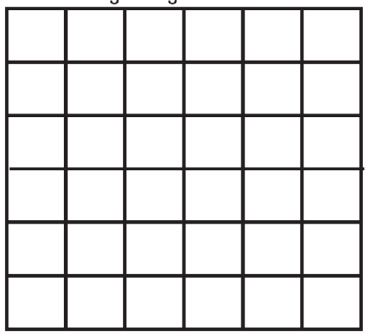


MODFLOW VERSIONS

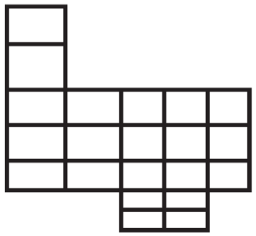
MODFLOW USG

Structured Grids

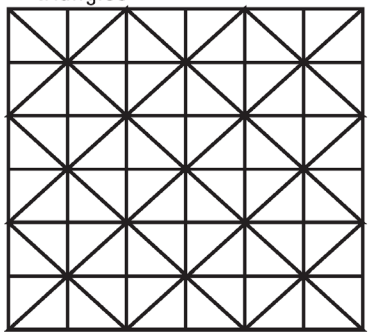
A. Rectangular grid



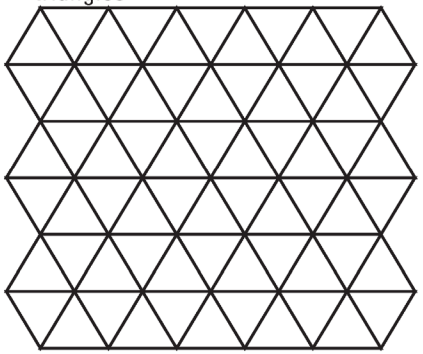
B. Rectangular grid, irregular domain



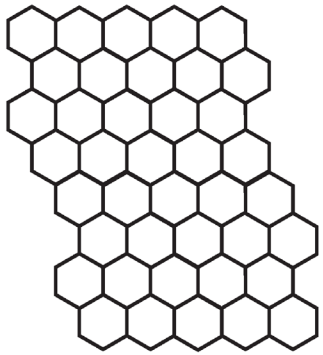
C. Triangular grid, isosceles triangles



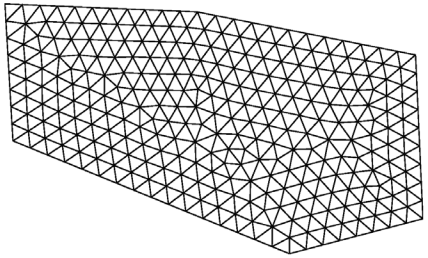
D. Triangular grid, equilateral triangles



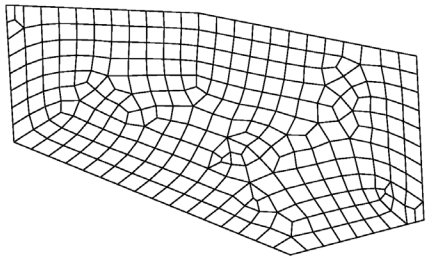
D. Hexagonal grid



F. Warped triangular grid



G. Warped quadrilateral grid

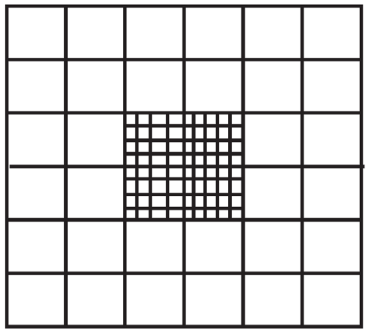


MODFLOW VERSIONS

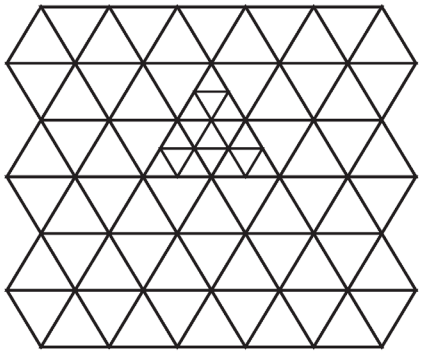
MODFLOW USG

Unstructured Grids

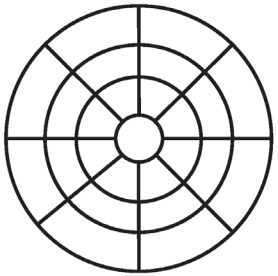
H. Rectangular, nested grid



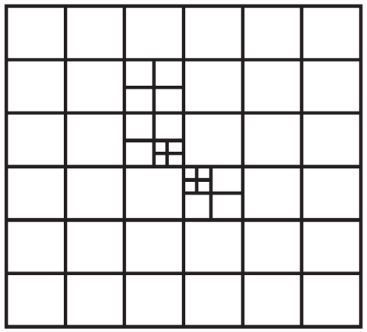
I. Triangular, nested grid



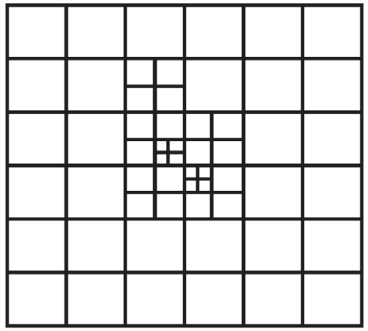
J. Radial grid



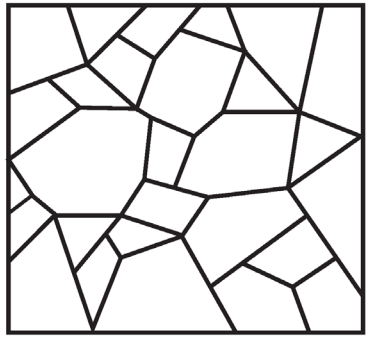
K. Rectangular, quadtree grid, no smoothing



L. Rectangular, quadtree grid, with smoothing



M. Irregular polygon grid



MODFLOW VERSIONS

MODFLOW 6

Release Info

MODFLOW 6: USGS Modular Hydrologic Model

6.0.1 Released in 2017

6.0.4 Released in 2019

6.2.0 Released Oct. 2020

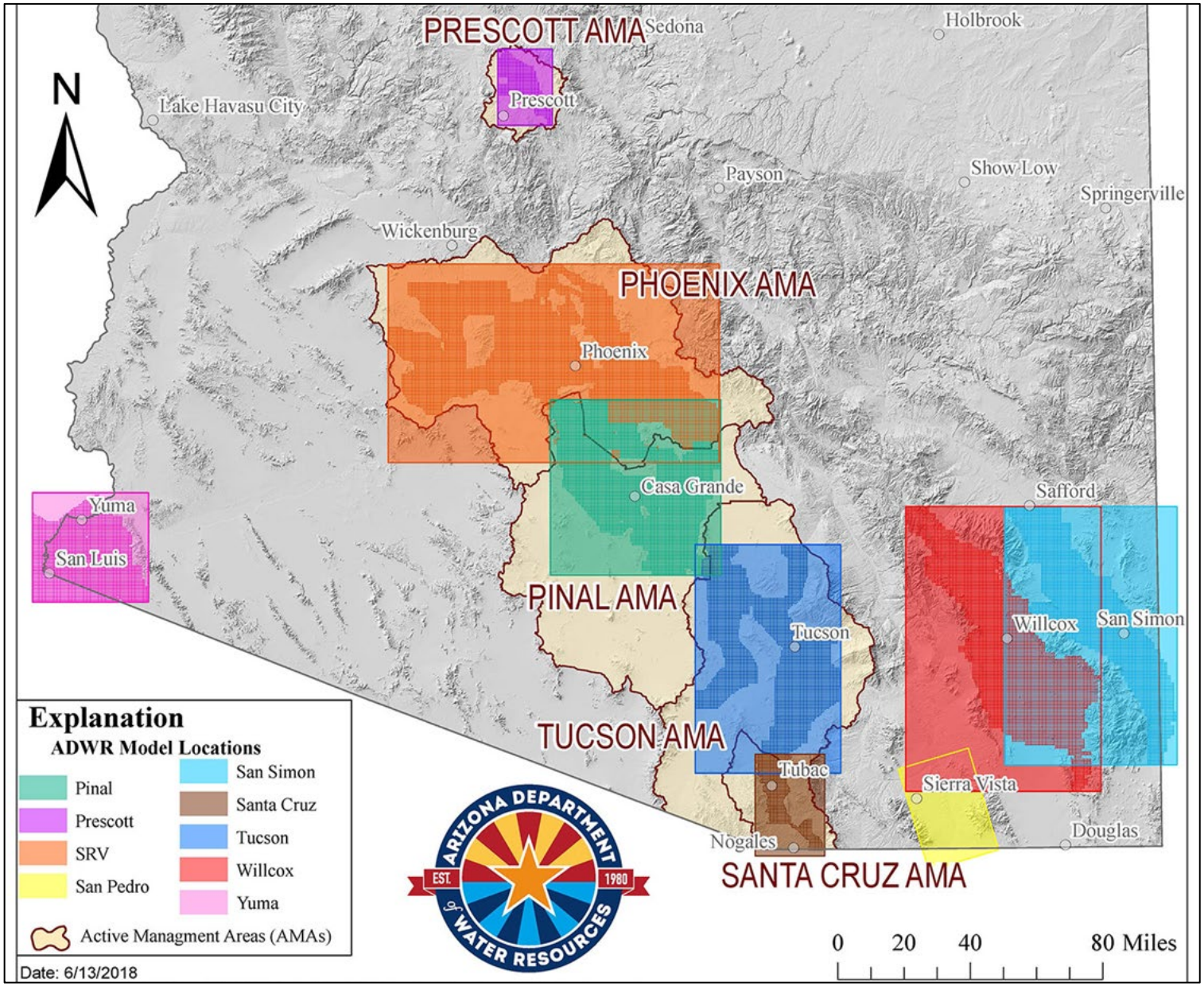
Features

-Object-Oriented Framework
-Complex Grids Allowed
-Control Volume Finite-Difference
-Direct Internal Coupling of Models

-Groundwater Flow (GWF)
-Groundwater Transport (GWT)

The next major iteration of MODFLOW. Great for coupling hydrologic models, but not commonly used.

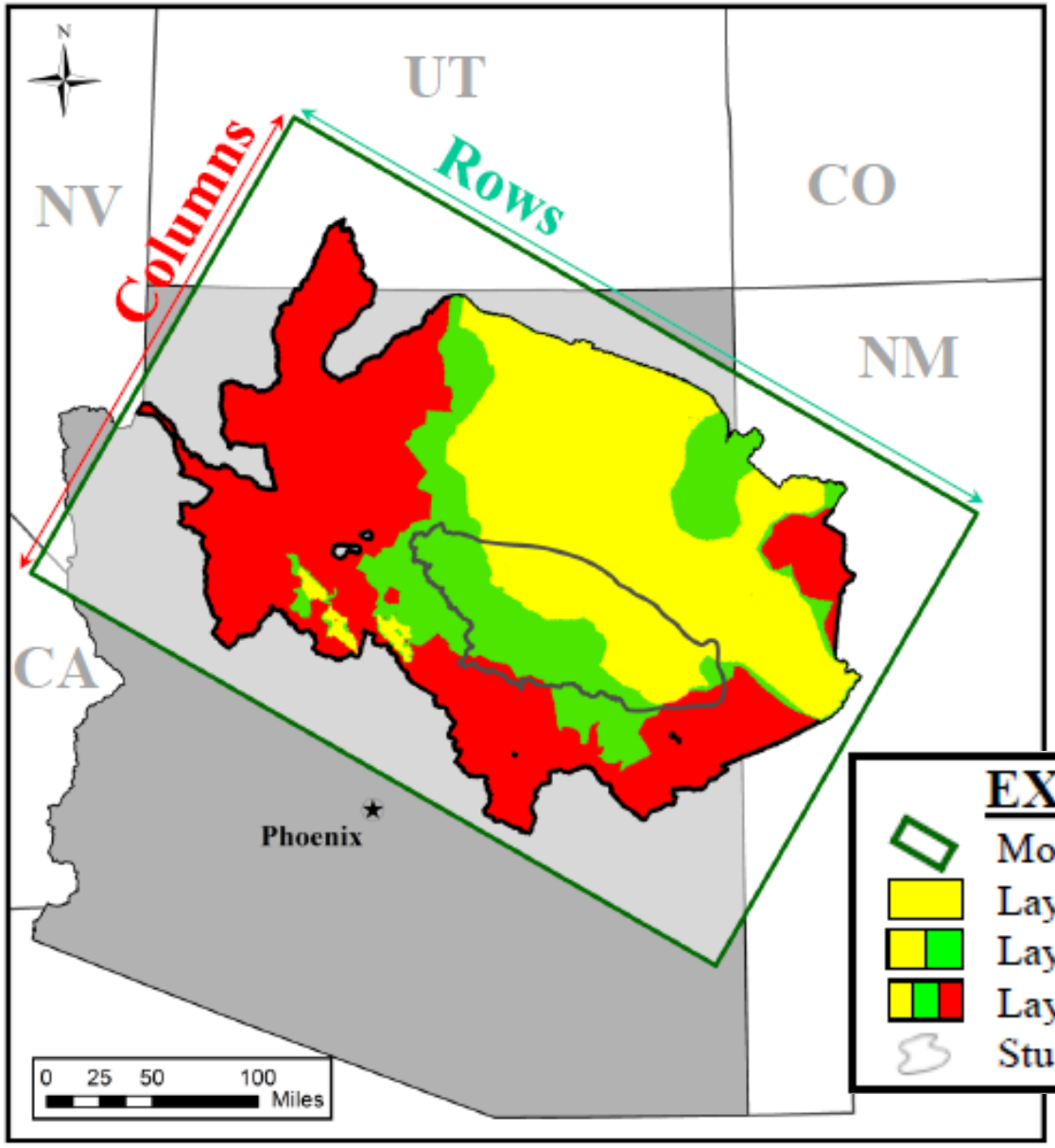
ARIZONA MODELS



Developed Groundwater Models Map

ADWR 2018

ARIZONA MODELS



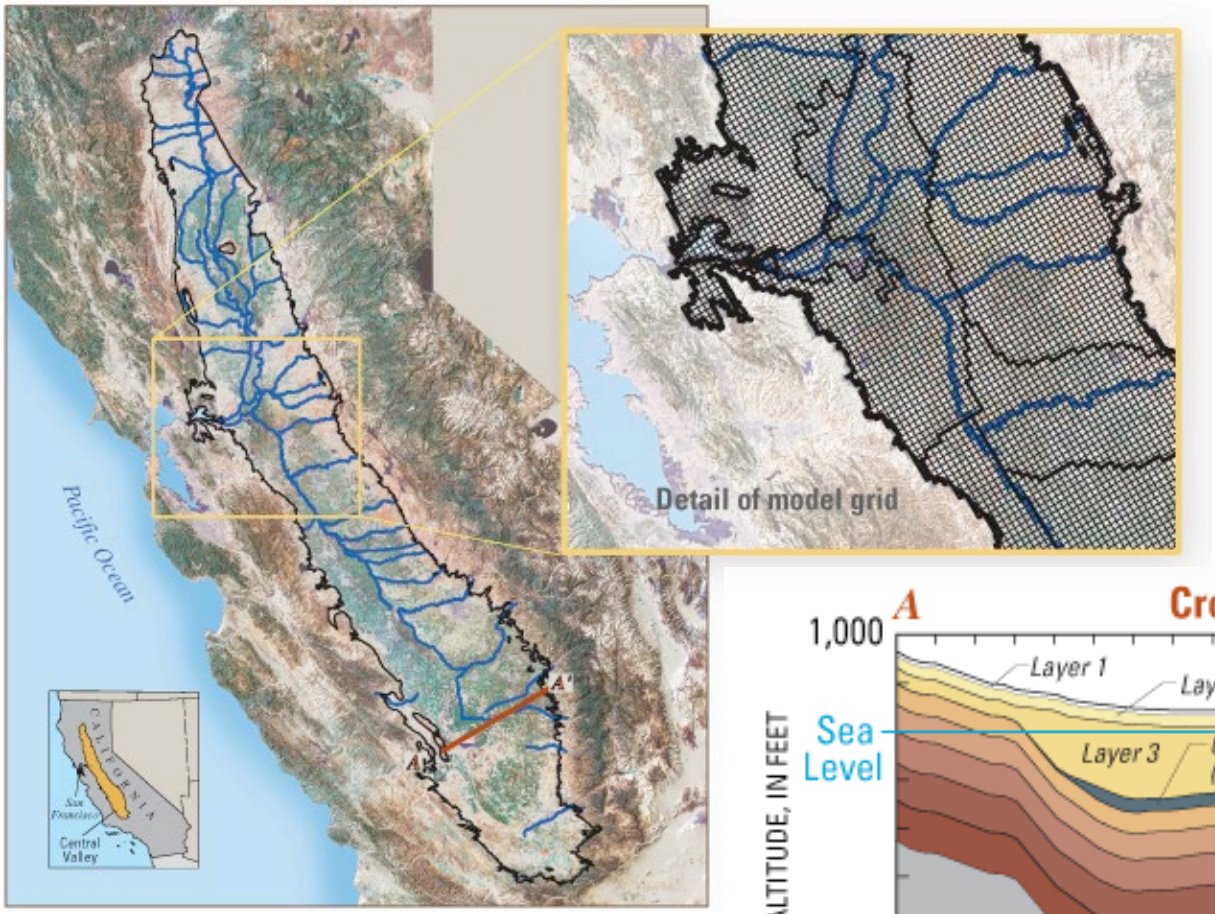
Northern Arizona Groundwater Flow Model – NARGFM & RGRLGFM

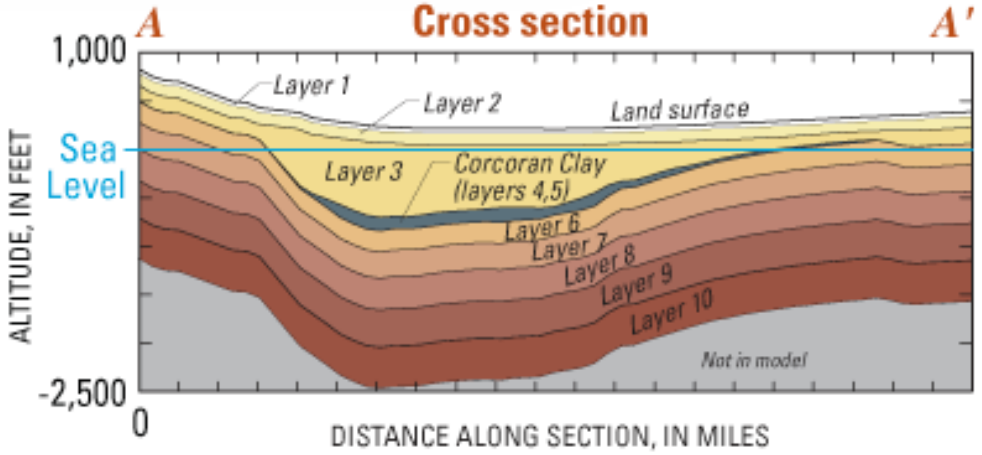
Source: Coconino Plateau Water Advisory Council and Watershed Partnership

http://www.cpwac.org/generalfiles/RGRL%20Groundwater%20Flow%20Model.pdf

OTHER MODELS

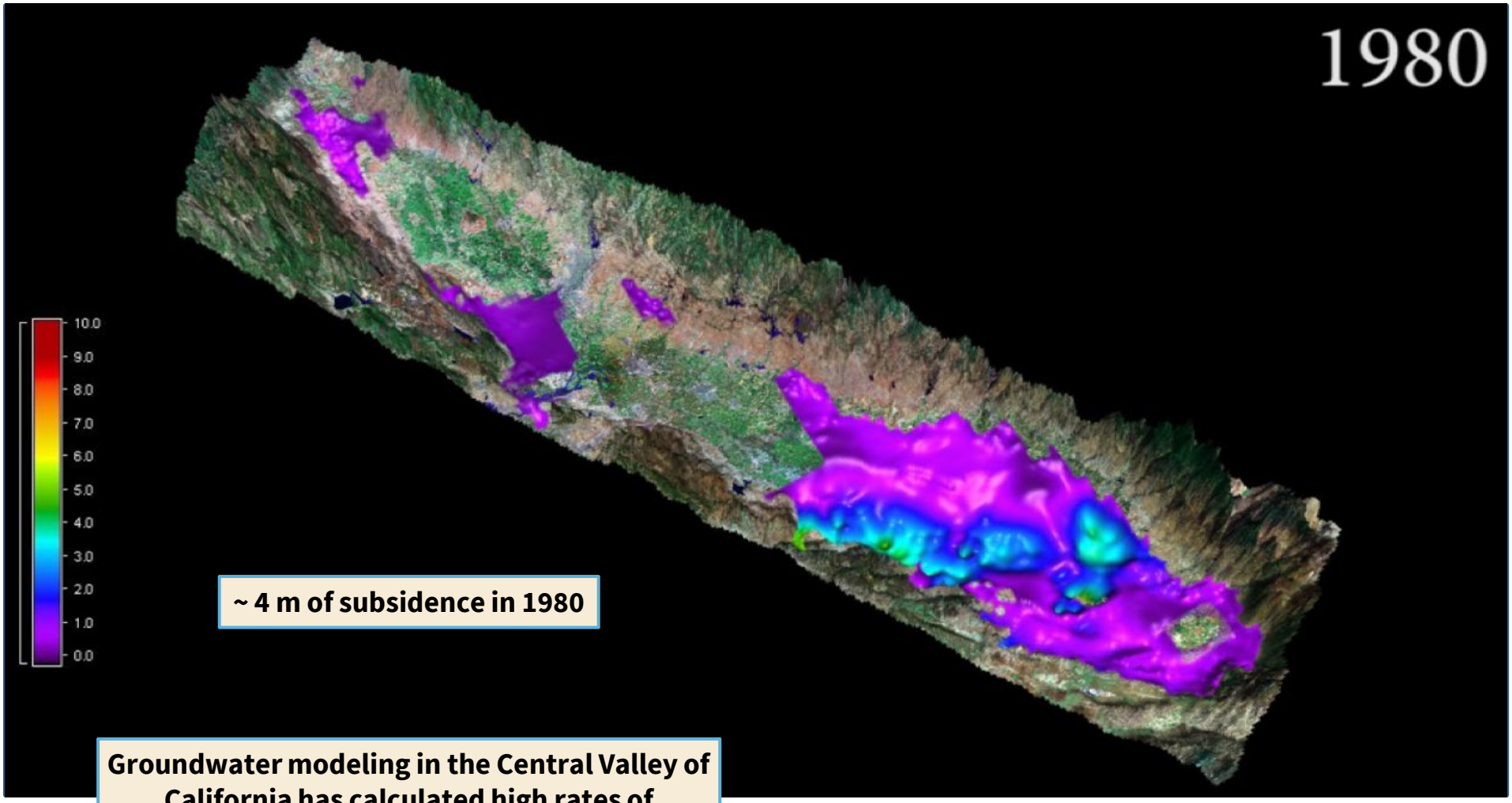
Central Valley - CVHM





OTHER MODELS

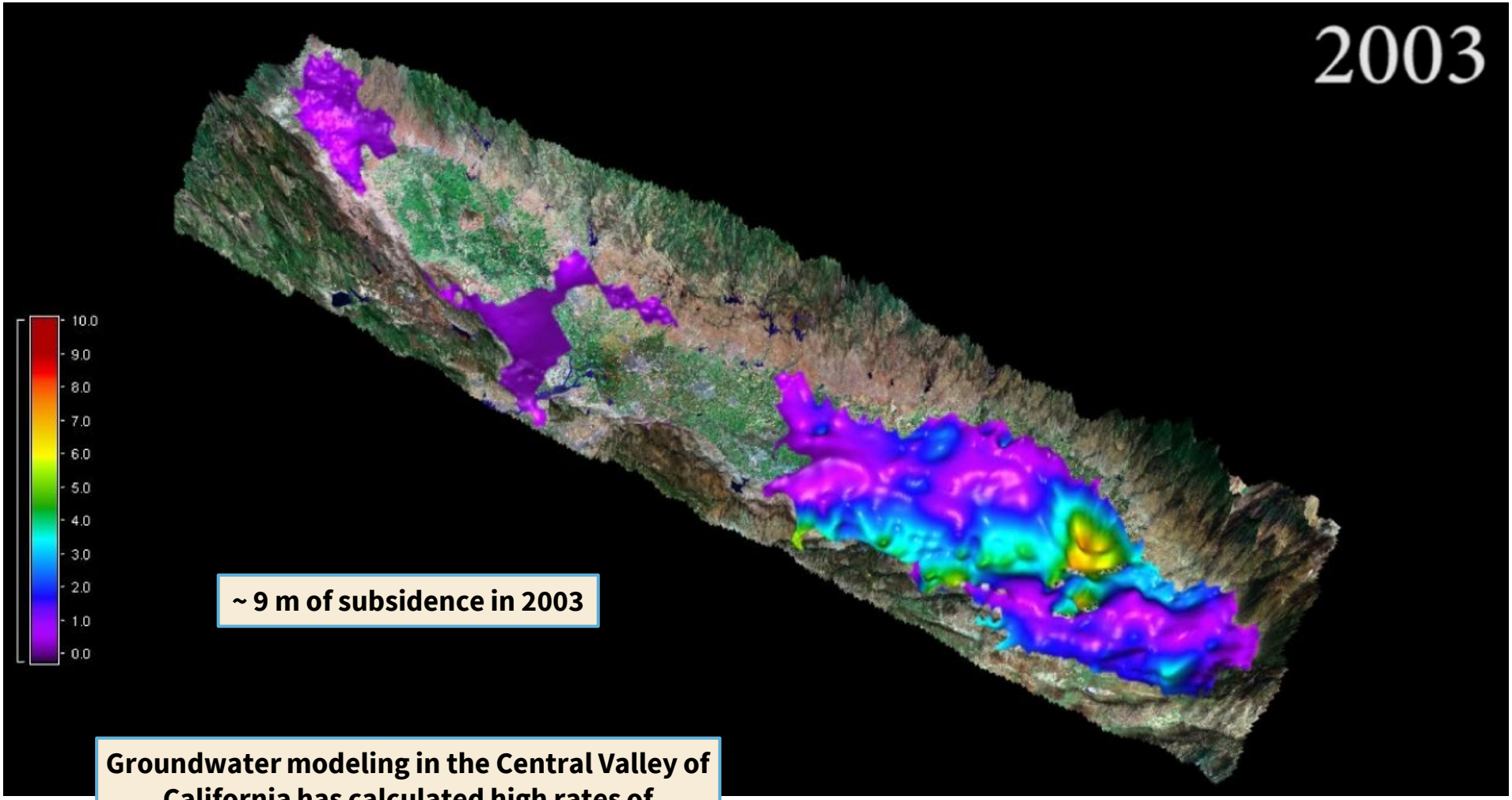
Central Valley - CVHM



Groundwater modeling in the Central Valley of California has calculated high rates of subsidence due to groundwater pumping.

OTHER MODELS

Central Valley - CVHM



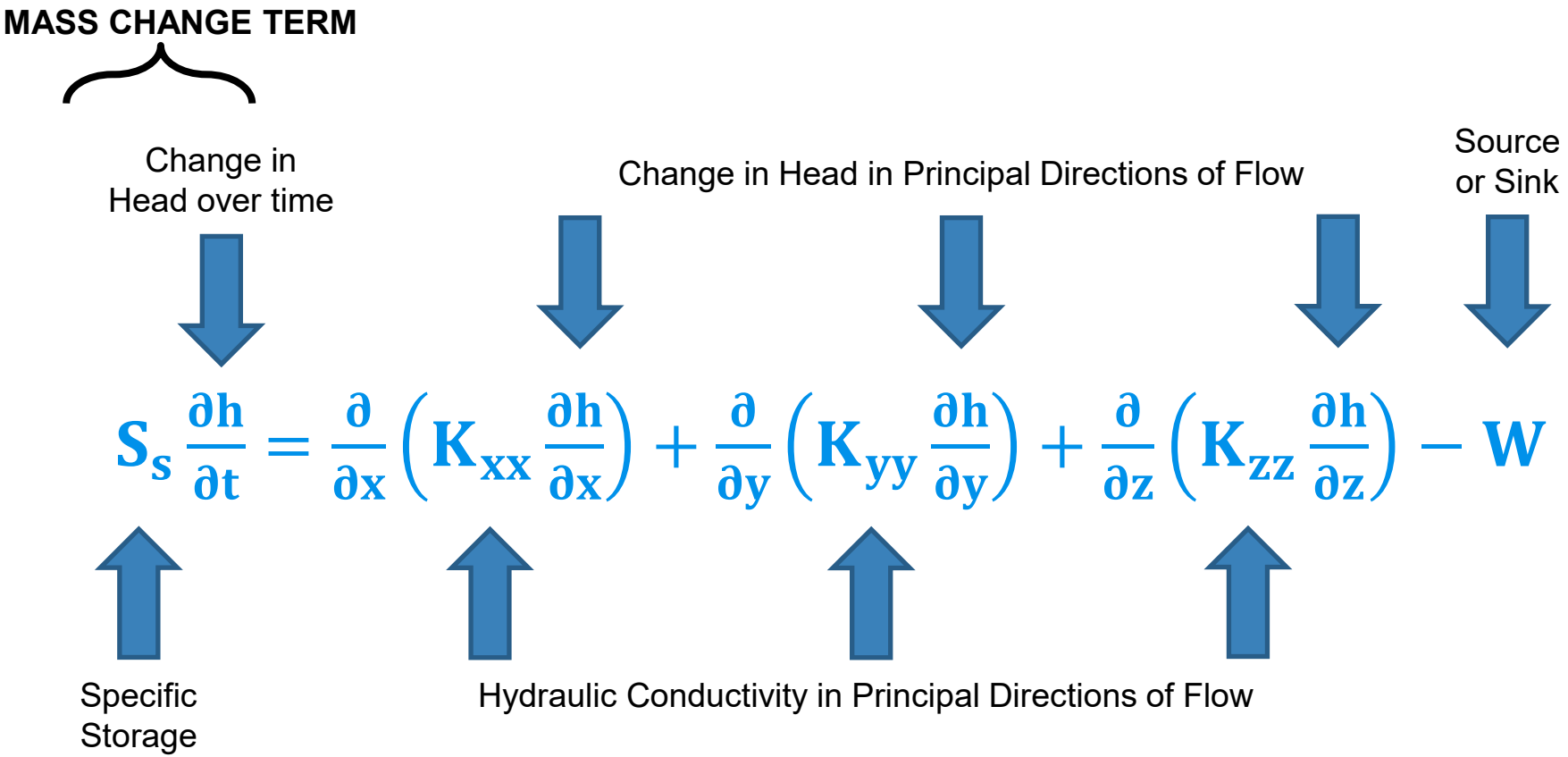
Groundwater modeling in the Central Valley of California has calculated high rates of subsidence due to groundwater pumping.

Running MODFLOW

DOS Execution (Windows CMD)
The simplest way to run MODFLOW.

Running MODFLOW With a GUI
Graphical User Interfaces often have a model execution option with on-screen progress reporting. Can be very helpful but take time to learn.

MODFLOW in Linux / Unix
The source code for most versions of MODFLOW is publicly available. The OS can be changed during compiling.



The Governing Equation: Richard's Law (MacDonald and Harbaugh, 1988)

Primary Control File

Name File

The file that stores the filenames and Fortran unit numbers for input files read by MODFLOW and output files created by MODFLOW.

```
#  Tuc4010.Nam
#Tucson Model 1940 - 2010
#
#  Parameter Input Files
DIS     10     Tuc4010.dis
BAS6    11     Tuc4010.bas
UPW     12     Tuc4010.upw
#  Solver & Output Control
NWT     13     Tuc4010.nwt
OC      14     Tuc4010.oc
#  Stress Files
WEL     15     Tuc4010.wel
EVT     16     Tuc4010.evt
CHD     17     Tuc4010.chd
RCH     18     Tuc4010.rch
#  Observation Files
HOB     19     Tuc4010.hob
HYD     20     Tuc4010.hyd
#  Output Files
LIST           30     Tuc4010.lst
DATA           31     Tuc4010.hds
DATA(BINARY)   32     Tuc4010.bgt
DATA           33     Tuc4010_hobs.dat
DATA(BINARY)   34     Tuc4010_graphs.out
```

Parameter Input Files

Upstream Spatial Weighting (.UPW) Package
The package that defines the Hydraulic Properties of the modeled cells (Kx, Ky, Kz, SS, SY). Previous versions of MODFLOW used the BCF or LPF Packages.

Basic Package (.BAS)
Package defining the active model grid cells and the initial head conditions.

Model Discretization (.DIS) Package
The package that defines the geometry of the model.
-Section 1: Horizontal Discretization
-Section 2: Vertical Discretization
-Section 3: Temporal Discretization

MODFLOW MODELING

Stress Files

Well (.WEL) or Multi-Node Well (.MNW) Package
Packages to model the process of pumping or recharging water through a groundwater well.

Stream (.STR) or Streamflow Routing (.SFR) Package
Packages that model the process of streamflow and groundwater interaction with streams (both in and out).

Recharge (.RCH) Package
A package designed to add water recharged to the surface to the uppermost groundwater layer, does not have internal lagging.

Stress Files (cont.)

Constant Head (.CHD) or Global Head (.GHB) Package
Packages designed to model boundary fluxes. The constant head package defines heads at boundary cells. The global head package defines the head at some distance away from the boundary location.

Evapotranspiration (.ET or .EVT) Package
A package designed to extract water from the groundwater system to simulate ET.

Drain (.DRN) Package
A MODFLOW package designed to simulate agricultural drains and ditches.

Observation Files

Head Observations (.HOB) Package
Allows for the extraction of modeled data at point locations in space and time. Built for comparing field head observations to model results.

Hydrograph Observations (.HYD) Package
A package that lets the user choose locations to extract modeled head data for every model timestep.

Gage (.GAGE) Package
A package that lets the user extract streamflow modeled results specific times, to compare with observation data.

Output Files

List (.LST or .LIST) Output
Run results log file. This file documents the reading of input files, shows model solver results and budget summaries. The best way to troubleshoot a program.

Heads (.HDS) Output
The output file containing cell specific head data by layer for specified times.

Budget Output
Calculated volumetric outflow/inflow rate between two connected cells output to a binary file. Also known as the cell-by-cell budget.

Observation File Outputs
HOB, HYD and GAGE packages each make output files.

LOOKING FORWARD

Methods Being Developed

Coupled Surface Water and Groundwater Models
Many recent examples and significant method development. USGS has developed GSFLOW (Precip. Runoff + MODFLOW).

Coupled Contaminant Transport and Groundwater Models
Many codes have been developed but the process is resource intensive. USGS has developed MT3D (Transport + MODFLOW) for models with geochemical interactions.

Flow and Transport Animations
Being accomplished through model GUIs, GIS Software and/or automation (Python). Can covey a lot of information.

3-D Map Views
Surprisingly uncommon, most data is presented in 2-D form. Some 3D platflorms include GIS Software (ESRI or QGIS), Paraview, Leapfrog.

MODELING RESOURCES

Websites

ADWR
Groundwater modeling reports, model datasets and GIS datasets are available.

USGS
- Primary USGS MODFLOW Repository
- USGS maintains Flopy, the Python wrapper for MODFLOW.
- USGS San Diego Science Center hosts MODFLOW One Water.

Hatari Labs
A training resource with amazing video tutorials for modeling and GIS methods, varying levels of difficulty. Test datasets and Python scripts are available.

S.S. Papadopolus and Associates (SSPA)
Free tools for particle trace analyses, a model GUI (Groundwater Desktop), free contaminant transport codes.

MODELING RESOURCES

Written Material

USGS Guidance Documents
The user manuals for specific versions of MODFLOW and advanced packages. Good input/output instructions at the end the guides. Publication library can inform models.

Applied Groundwater Modeling, Second Edition: Simulation of Flow and and Advective Transport
Anderson, Woessner, Hunt (2015). Rereleased classic book from 2002 has been expanded for the current digital world.

Effective Groundwater Model Calibration: With Analysis of Data, Sensitivities, Predictions, and Uncertainty
Hill and Tiedemen (2005). Reputable book about applied statistics for calibration of models.

ASTM Standards
A simple set of standard guidance documents that are useful and defensible.

MODELING RESOURCES

Training

Groundwater Resources Association (GRA)
Annual MODFLOW 4-day training course at UC Davis campus. Taught by Graham Fogg and Thomas Harter.

AHS Symposium
Potentially offering another training session on MODFLOW, not yet announced for 2021. We are taking suggestions.

USGS
The authors of MODFLOW offer training on using MODFLOW and Flopy.

GSI Environmental Inc. (Sorab Panday)
MODFLOW solvers class offered approximately every 6 months. This is an advanced level class.

The End

Questions?

ARIZONA
HYDROLOGICAL
SOCIETY

ASU

ARIZONA DEPARTMENT of WATER RESOURCES
EST. 1980