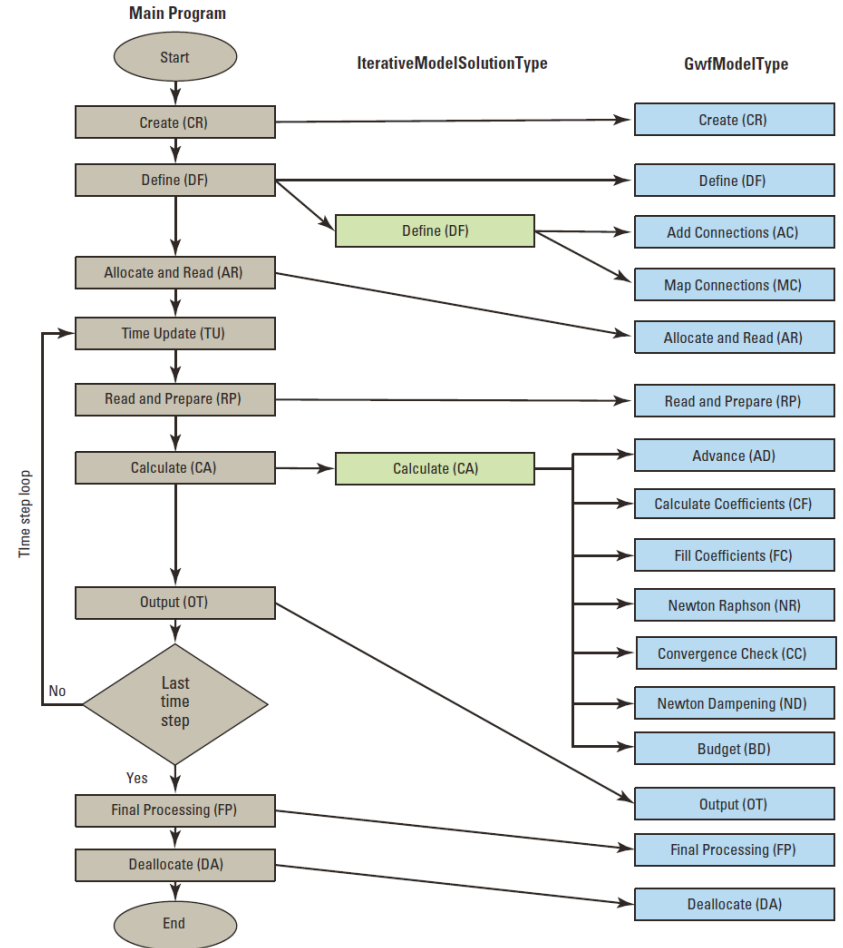
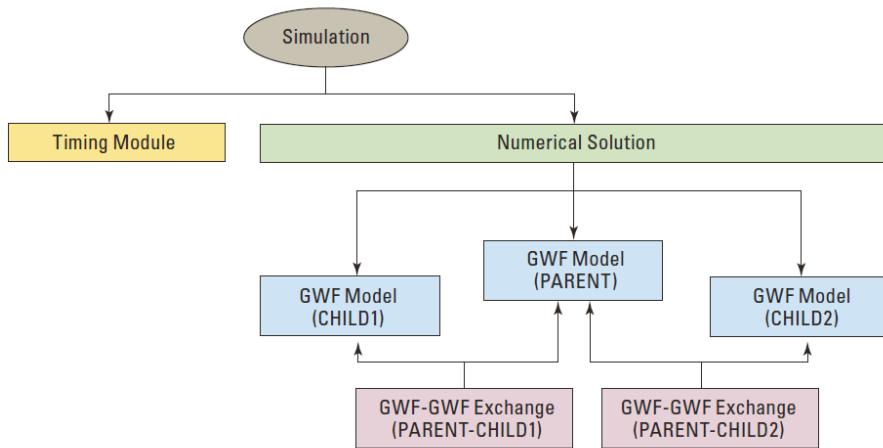
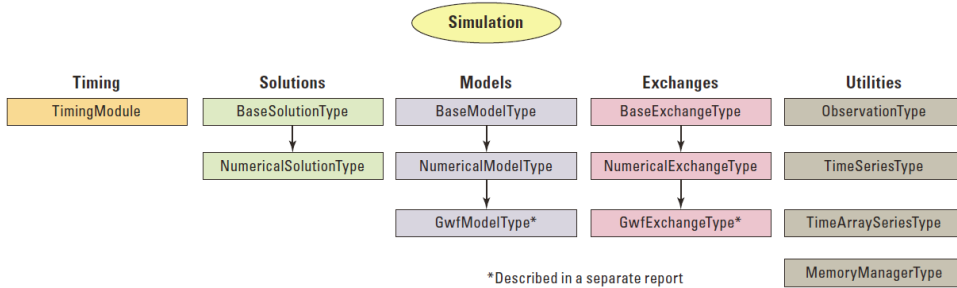


Modeling Code: Introduction to MODFLOW 6



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 U.S. Geological Survey
 Idaho Water Science Center
 September 7, 2017



Goals

Introduce MODFLOW 6

Selection criteria

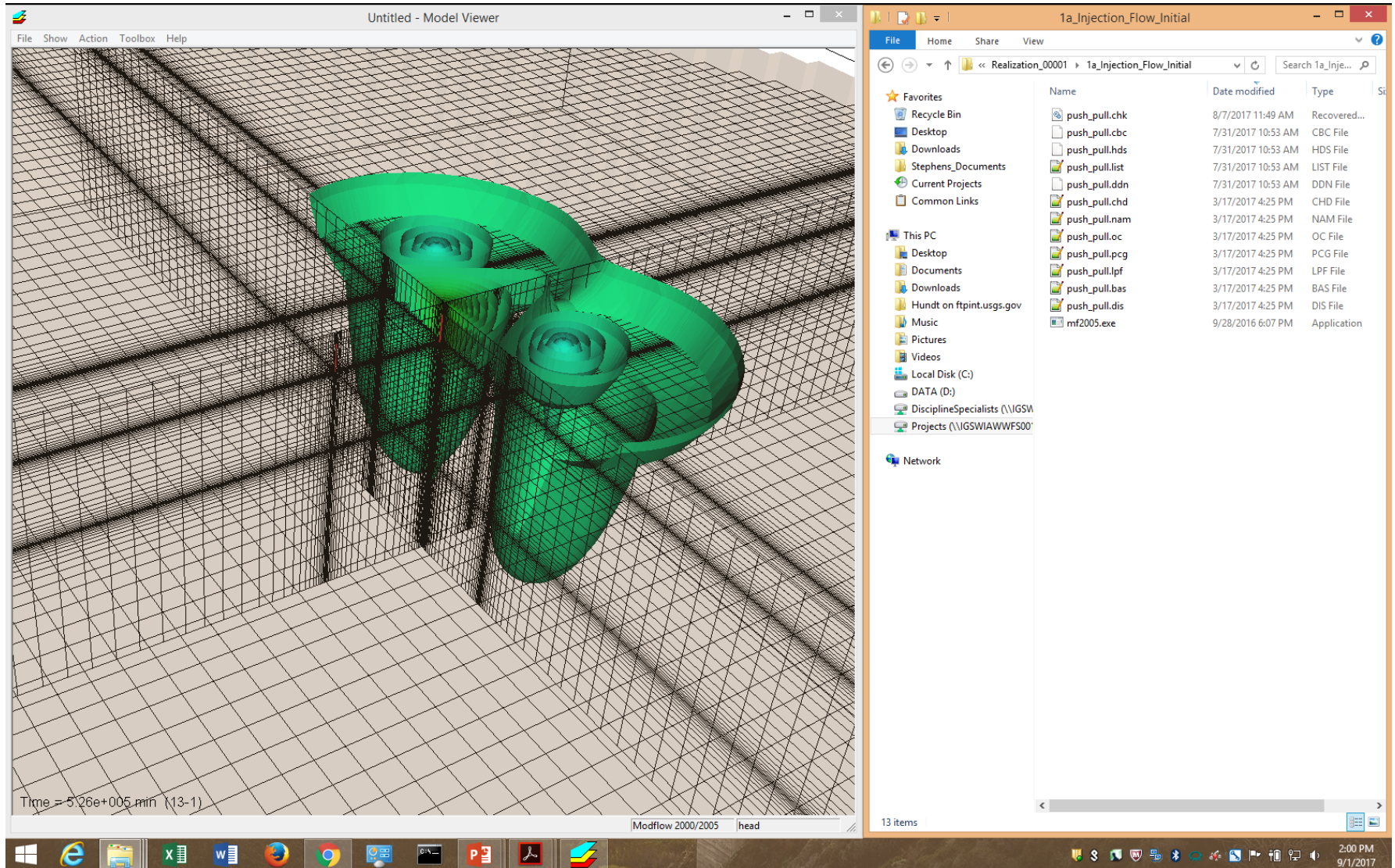
Some thoughts

Real System



Michael Gordon [CC BY 3.0 (<http://creativecommons.org/licenses/by/3.0/>)], via Wikimedia Commons

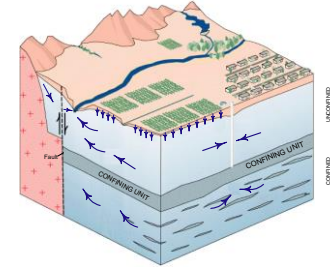
Model



Model, Model, Model...

Conceptual Model

- properties, geometry, boundaries
- important physical processes (process models)



Mathematical Model

- governing equations

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + Q'_s = SS \frac{\partial h}{\partial t}$$

Numerical Approximation

- Discretize time, space
- Linear system -> solver
- *Numerical Model*

$$\begin{aligned} & CR_{i,j-1/2,k} (h_{i,j-1,k}^m - h_{i,j,k}^m) + CR_{i,j+1/2,k} (h_{i,j+1,k}^m - h_{i,j,k}^m) \\ & + CC_{i-1/2,j,k} (h_{i-1,j,k}^m - h_{i,j,k}^m) + CC_{i+1/2,j,k} (h_{i+1,j,k}^m - h_{i,j,k}^m) \\ & + CV_{i,j,k-1/2} (h_{i,j,k-1}^m - h_{i,j,k}^m) + CV_{i,j,k+1/2} (h_{i,j,k+1}^m - h_{i,j,k}^m) \\ & + P_{i,j,k} h_{i,j,k}^m + Q_{i,j,k} = SS_{i,j,k} (\Delta T_j \Delta C_i \Delta V_k) \frac{h_{i,j,k}^m - h_{i,j,k}^{m-1}}{t^m - t^{m-1}} \end{aligned}$$

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} x \end{bmatrix} = \begin{bmatrix} B \end{bmatrix}$$

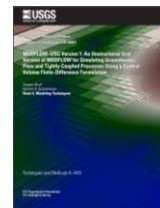
Analytical Solution

- Exact, closed form
- *Analytical Model*

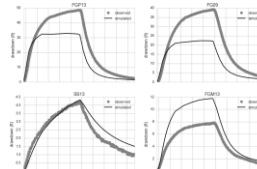
$$s = \frac{Q}{4\pi T} W(u) = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{4T \Delta t}\right)$$



Modeling Code



Model Scenario

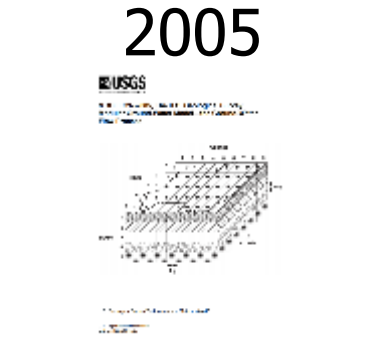
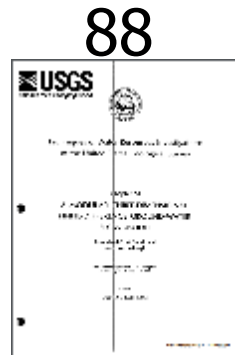
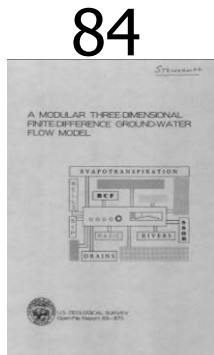


MODFLOW

- ❖ Groundwater modeling software from USGS
- ❖ Free and open-source
- ❖ Long history
- ❖ Used in Idaho
- ❖ Well-documented
- ❖ Commercial interfaces & other tools

MODFLOW History

Core Versions



Variants



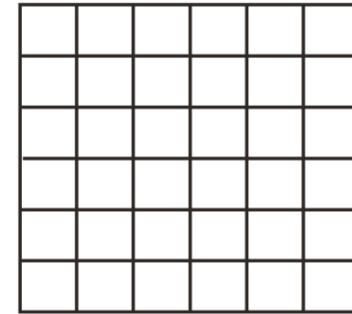
Modflow 6

- ❖ New core version
- ❖ Cleans-up
- ❖ Brings features from alternate versions together
- ❖ New framework for future extensions
- ❖ New I/O options

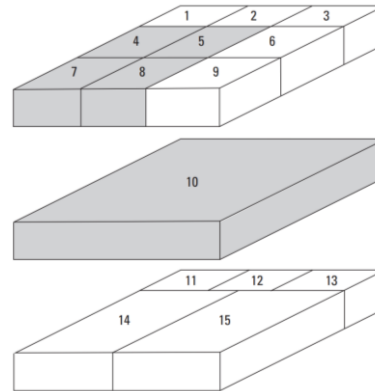


Modflow 6: Spatial Discretization

❖ Regular, fully structured

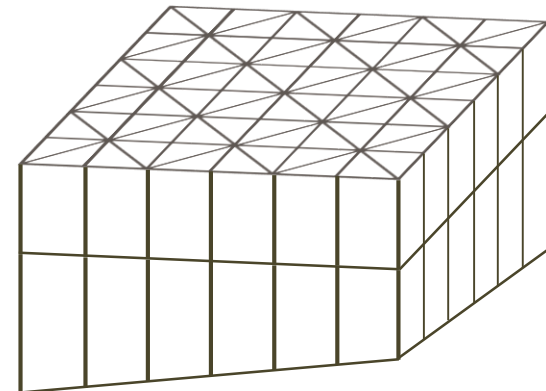


❖ Fully unstructured



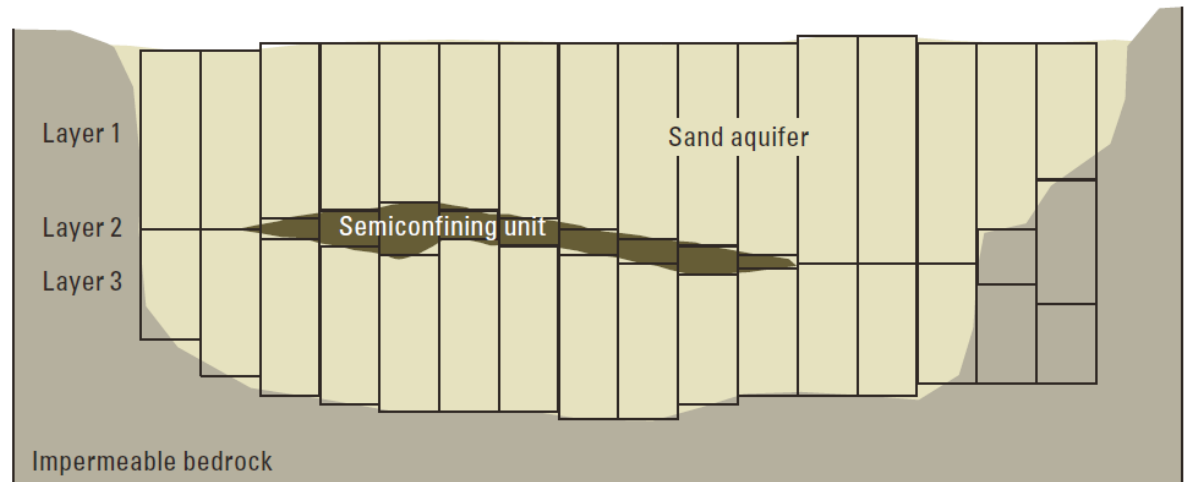
❖ Layered mesh

- Flexible cell shapes, all layers the same



Modflow 6: Grids

- ❖ Pinched cells in structured grid
- ❖ Connect cells through inactive cell
- ❖ IBOUND replaced by IDOMAIN



Layer 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Layer 2	-1	-1	1	1	1	1	1	1	1	1	-1	-1	-1	0	0
Layer 3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0

EXPLANATION

IDOMAIN codes

- >0 Included cell
- =0 Excluded cell
- <0 Excluded pass-through cell

Modflow 6: Packages

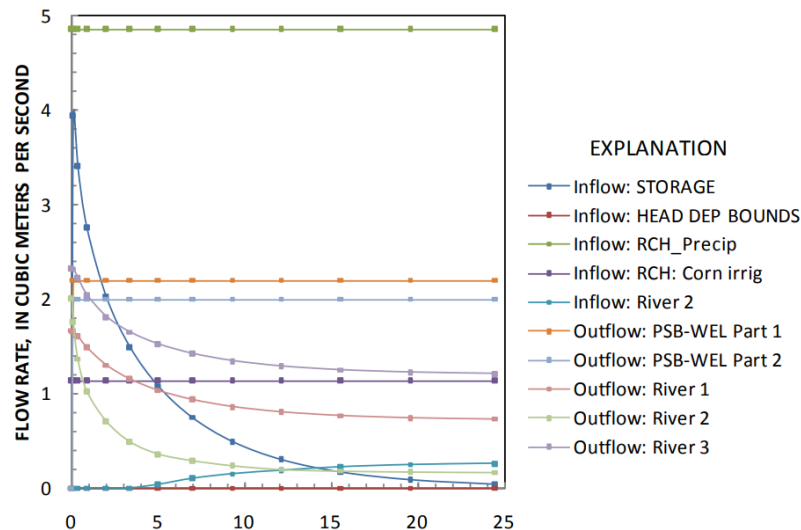
- ❖ *Most* options from 2005, LGR, USG, NWT
- ❖ Some reorganization
- ❖ Some simplifications
 - MAW (from MNW)
 - SFR
- ❖ New features

Package Name	Abbreviation	Package Category
Discretization	DIS, DISV, or DISU	Hydrologic/Internal
Initial Conditions	IC	Hydrologic/Internal
Node Property Flow	NPF	Hydrologic/Internal
Horizontal Flow Barrier	HFB	Hydrologic/Internal
Ghost-Node Correction	GNC	Hydrologic/Internal
Storage	STO	Hydrologic/Internal
Specified Head	CHD	Hydrologic/Stress
Well	WEL	Hydrologic/Stress
Recharge	RCH	Hydrologic/Stress
River	RIV	Hydrologic/Stress
General-Head Boundary	GHB	Hydrologic/Stress
Drain	DRN	Hydrologic/Stress
Evapotranspiration	EVT	Hydrologic/Stress
Stream-Flow Routing	SFR	Hydrologic/Advanced Stress
Lake	LAK	Hydrologic/Advanced Stress
Multi-Aquifer Well	MAW	Hydrologic/Advanced Stress
Unsaturated Zone Flow	UZF	Hydrologic/Advanced Stress
Water Mover	MVR	Hydrologic/Advanced Stress
Model Observations	OBS	Output
Output Control	OC	Output

Modflow 6: Stress Packages

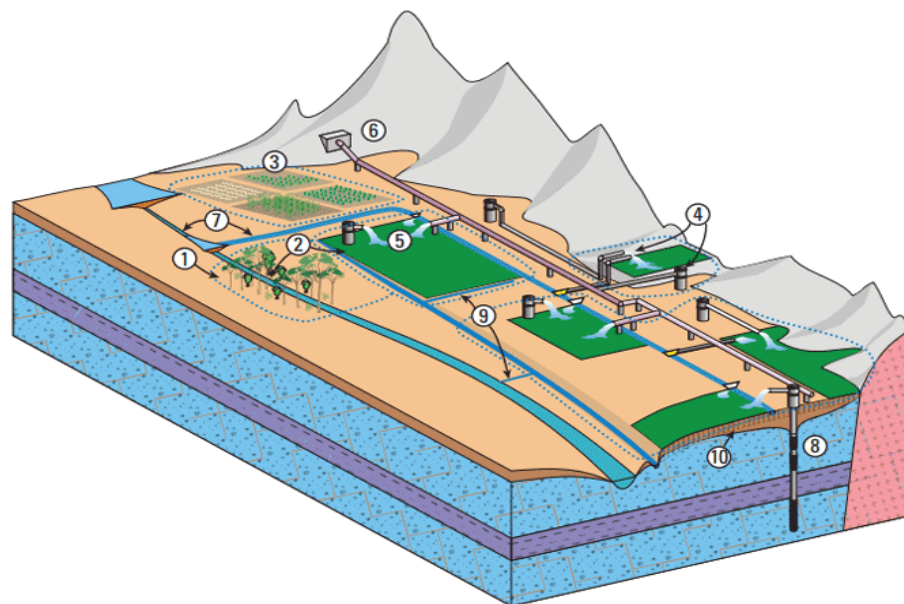
❖ Multiple stress packages of same type in a model

- E.g. rch_pppt & rch_irrig
- Organization; accounting



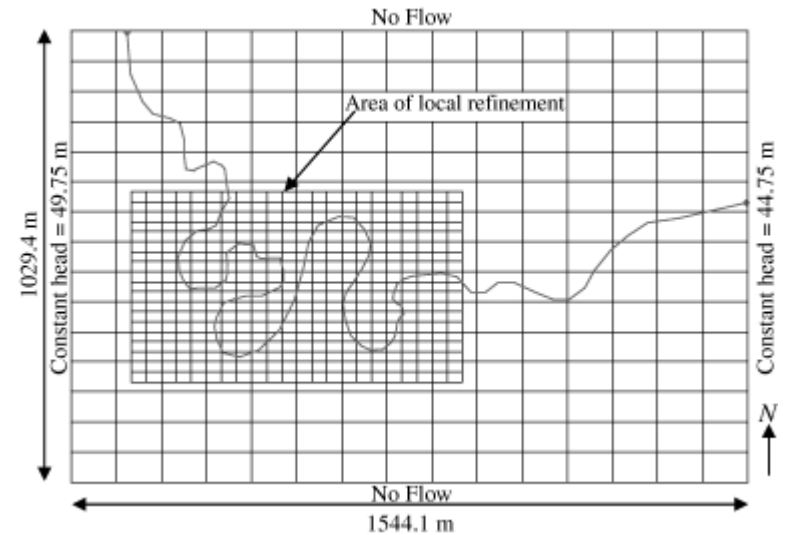
❖ *Water mover* to transfer between packages

- Tracks and reports flows
- Rules and priorities

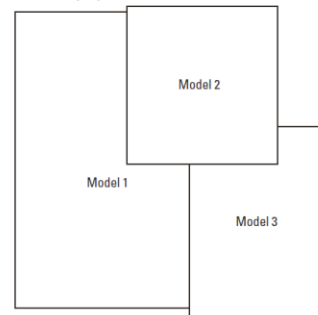


Modflow 6: Multiple Models

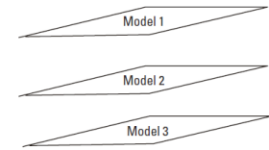
- ❖ Multiple models can be coupled together
- ❖ Child models, or adjacent models can run as one model



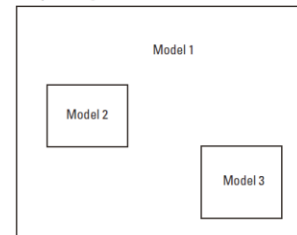
A. Horizontally adjacent models



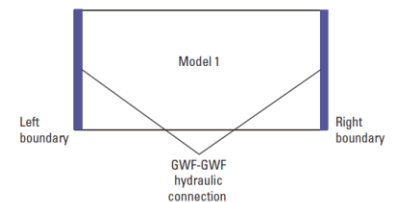
B. Vertically adjacent models



C. Locally refined grids

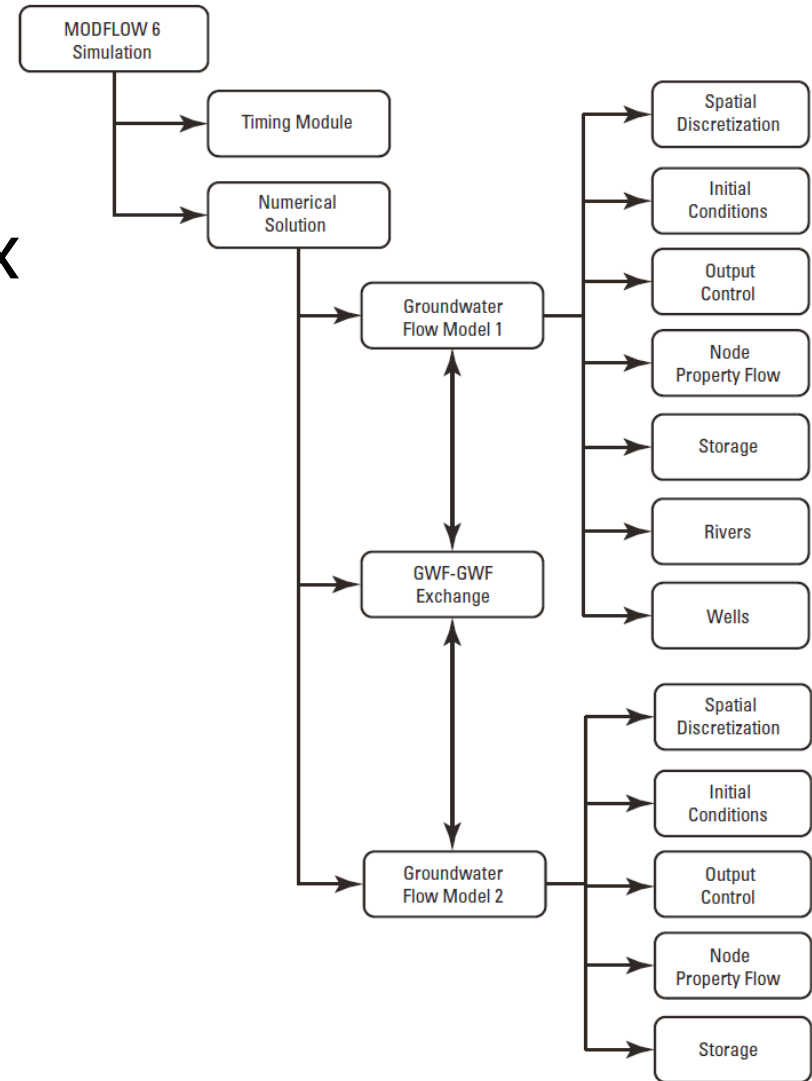
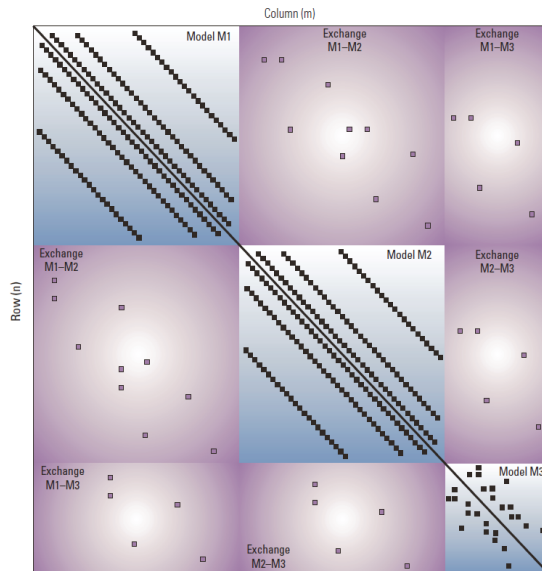


D. Periodic boundary conditions



Modflow 6: Multiple Models

- ❖ Define exchange between models
- ❖ Tightly-coupled at matrix level
 - Faster, more stable



Modflow 6: Input Structure

❖ Blocks and keywords

- More readable
- Easier backward compatibility

❖ More commenting options

- More readable
- Include documentation in input files

```
# Comment for this TDIS input file
```

```
BEGIN OPTIONS  
  TIME_UNITS DAYS  
END OPTIONS
```

```
BEGIN DIMENSIONS  
  NPER 2  
END DIMENSIONS
```

```
BEGIN PERIODDATA  
  365.00 1 1.0  Items: PERLEN NSTP TSMULT  
  365.00 10 1.2 Items: PERLEN NSTP TSMULT  
END PERIODDATA
```

```
#This is an alternative options block
```

```
BEGIN OPTIONS  
  # Assign two auxiliary variables  
  AUXILIARY temperature salinity  
  # Specify the maximum iteration  
  MAXIMUM_ITERATION 10  
  #specify the print input option  
  PRINT_INPUT  
END OPTIONS
```

```
#done with the options block
```

Modflow 6: Input Structure

```
#The OPTIONS block is optional
BEGIN OPTIONS
  LENGTH_UNITS METERS
END OPTIONS

#The DIMENSIONS block is required
BEGIN DIMENSIONS
  NLAY 10
  NROW 1
  NCOL 21
END DIMENSIONS

#The GRIDDATA block is required
BEGIN GRIDDATA
  DELR
    INTERNAL FACTOR 1.
      .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 0.01
  DELC
    CONSTANT 1.0
  TOP LAYERED
    CONSTANT 1.
  BOTM LAYERED
    CONSTANT 0.9
    CONSTANT 0.8
    CONSTANT 0.7
    CONSTANT 0.6
    CONSTANT 0.5
    CONSTANT 0.4
    CONSTANT 0.3
    CONSTANT 0.2
    CONSTANT 0.1
    CONSTANT 0.0
END GRIDDATA
```

Modflow 6: Input Structure

❖ Time-series files

- External files
- Named columns
- Times independent of model periods
- Dates and times an option

Contents of file “well_pump_rates.ts”:

```
BEGIN ATTRIBUTES
  NAMES well-A-series well-B-series well-C-series
  METHODS stepwise linear stepwise
END ATTRIBUTES

BEGIN TIMESERIES
  # time well-A-series well-B-series well-C-series
  0.0      0.0          0.0          0.0
  1.0     -500.0        0.0         -400.0
  2.0     -500.0     -1000.0     -500.0
  5.0     -500.0     -1200.0     -200.0
  8.0     -500.0     -1100.0        0.0
END TIMESERIES
```

Contents of the Well Package input file:

```
BEGIN OPTIONS
  TS6 FILEIN well_pump_rates.ts
END OPTIONS

BEGIN DIMENSIONS
  MAXBOUND 4
END DIMENSIONS

BEGIN PERIOD 2
  #layer row col Q (or time series)
      9 192 44 well-A-series
     10  43 17 well-B-series
     11  12 17 well-C-series
END PERIOD
```

Modflow 6: Input Structure

- ❖ Same READARRAY options
 - External arrays used for things like PEST pilot point tools remain intact

Modflow 6: Misc. & Upcoming

- ❖ MF6 will be base model for future enhancements
 - Pipe-network model
 - Transport (non-MT3D)
 - Variable density flow
 - Surface water routing
 - Watershed model

Modflow 6: Accompanying Tools

❖ Commerical GUIs:

- MF6 developers have talked to major GUI developers, have intentions to support
 - GMS
 - GW Vistas
 - Visual MODFLOW

❖ TV Model won't be tied to GUI

Modflow 6: Accompanying Tools

❖ PEST

- PEST is model-independent
- Some GW Utilities won't currently work
 - Changed binary output format
 - MOD2OBS & MOD2SMP
- MF6 OBS package
 - can report any head or fluxes
 - won't interpolate in space or time

Selection Criteria

❖ MF6, USG, or 2005?

❖ Factors

- Needed features <- not limiting factor
- Familiarity <- older *may be* better
- Ease of learning model <- MF6
- Ease of updating & running scenarios <- MF6 *if* GUI support is good
- Support from existing tools <- older is better
- Execution (solver) speed <- MF6
- Proven reliability <- older *may be* better

My 2¢

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