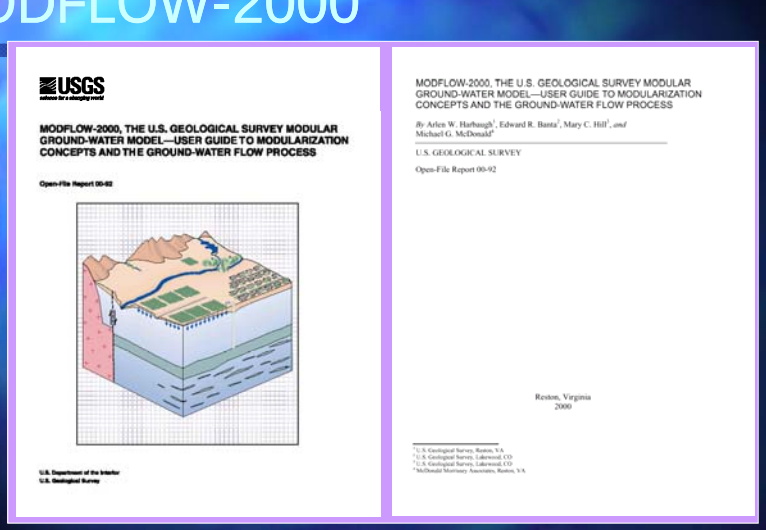
Presentation 6

MODFLOW-2000

MODFLOW-2000


USGS

MODFLOW-2000, THE U.S. GEOLOGICAL SURVEY MODULAR GROUND-WATER MODEL—USER GUIDE TO MODULARIZATION CONCEPTS AND THE GROUND-WATER FLOW PROCESS

Open-File Report 00-92

U.S. Department of the Interior
U.S. Geological Survey

MODFLOW-2000, THE U.S. GEOLOGICAL SURVEY MODULAR GROUND-WATER MODEL—USER GUIDE TO MODULARIZATION CONCEPTS AND THE GROUND-WATER FLOW PROCESS

By Arlen W. Harbaugh[1], Edward R. Banta[2], Mary C. Hill[3], and Michael G. McDonald[4]

U.S. GEOLOGICAL SURVEY

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Reston, Virginia
2000

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[3] U.S. Geological Survey, Lakewood, CO
[4] McDonald Morrissey Associates, Reston, VA

http://water.usgs.gov/software/modflow.html

History of MODFLOW

- 1970's: Trescott and Pinder 3D, transient
- 1983: modular model, 7,000 lines
- 1980's: MODFLOW escapes USGS. Commercial use exceeds use by USGS
- 1992: MODFLOWP, 17,000 lines
- 1996: MODFLOW96
- 2000: MODFLOW2000
- 1999-2000: 23,000 copies downloaded from USGS

Reasons For MODFLOW-2000

- Facilitate solving more than just the flow equation
  - Parameter estimation
  - Transport

Courtesy Arlen Harbaugh

Obvious Changes in MODFLOW-2000

- New Terminology
  - Processes
  - Parameters
- Discretization file
- Two listing files
- Input
  - Parameter definition
  - Discretization file
  - BAS and BCF changes
- Layer-Property Flow Package

Courtesy Arlen Harbaugh

Structure of MODFLOW2000

- Processes
- Packages
- Procedures

Processes

MODFLOW2000

- Global (GLO)
- Ground-Water Flow (GWF)
- Observation (OBS)
- Sensitivity (SEN)
- Parameter Estimation (PES)
- Ground-Water Transport (GWT) –Based on MOC3D code (*separate distribution*)

SEAWAT2000

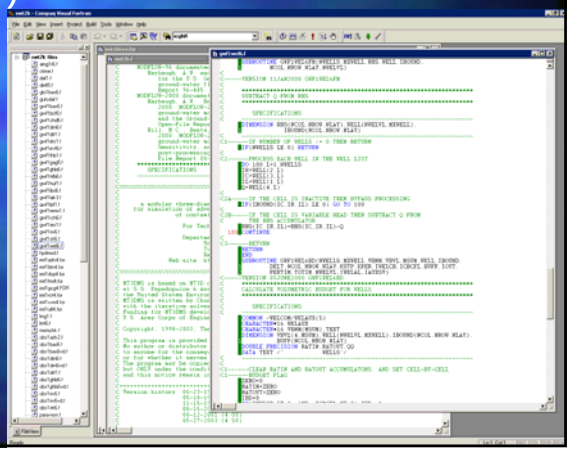
- Variable-Density Flow (VDF)
- Integrated MT3DMS (IMT)

Packages

- Typically one for each feature
- New packages in MODFLOW-2000
  - Layer Property Flow (LPF)
  - Hydrogeologic Unit Flow (HUF)
  - LMG Solver
  - Etc.

Procedures

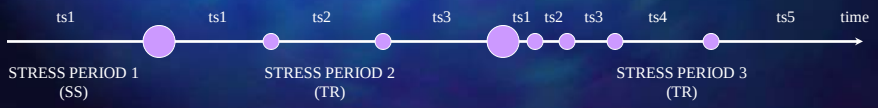
- One for each type of programming calculation
  - Read and Prepare (RP)
  - Formulate (RP)
  - Etc.
- Typical procedure name
  - GWF1WEL6FM



Temporal Discretization

- Stress periods
- Time steps

- In MODFLOW2000, stress periods may be either steady-state or transient



Program Structure

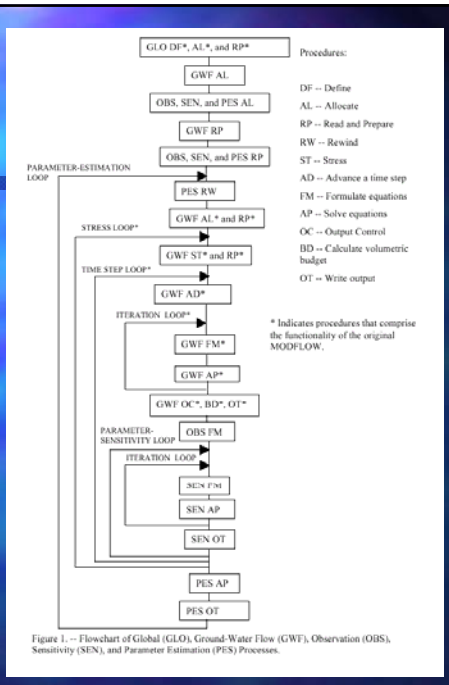


Figure 1. -- Flowchart of Global (GLO), Ground-Water Flow (GWF), Observation (OBS), Sensitivity (SEN), and Parameter Estimation (PES) Processes.

Harbaugh and others (2000)

Flow Equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

Finite-Difference Approximation

$$CC\left(h^m_{i+1,j,k} - h^m_{i,j,k}\right) + CC\left(h^m_{i-1,j,k} - h^m_{i,j,k}\right) + CR\left(h^m_{i,j+1,k} - h^m_{f,i,j,k}\right) + CR\left(h^m_{i,j-1,k} - h^m_{i,j,k}\right)$$
$$+ CV\left(h^m_{i,j,k+1} - h^m_{i,j,k}\right) + CV\left(h^m_{i,j,k-1} - h^m_{i,j,k}\right) + P_{i,j,k}h^m_{i,j,k} + Q_{i,j,k} = S_{i,j,k}V_{i,j,k}\frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t^m - t^{m-1}}$$

CR, CC, and CV are hydraulic conductances in the row, column, and layer directions;
h is head;
m is timestep;
P is the sum of head coefficients;
Q is the sum of discharges;
S is the storativity; and
V is the saturated cell volume

$$CV_{i,j,k-1/2}h^m_{i,j,k-1} + CC_{i-1/2,j,k}h^m_{i-1,j,k} + CR_{i,j-1/2,k}h^m_{i,j-1,k}$$
$$+\left(-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k} - CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k}\right)h^m_{i,j,k}$$
$$+ CR_{i,j+1/2,k}h^m_{i,j+1,k} + CC_{i+1/2,j,k}h^m_{i+1,j,k} + CV_{i,j,k+1/2}h^m_{i,j,k+1} = RHS_{i,j,k}$$

Parameters

- Generic meaning of “PARAMETER”
  - Any input data for a model
- Meaning of “PARAMETER” in MODFLOW-2000
  - A specially designated value that can define many input values for a model
  - Changing the parameter value changes all of the associated input values
- Necessary for parameter estimation because we don’t have enough data to estimate values for all input data
- Parameters are a convenient way to specify input data even if not using parameter estimation

Courtesy Arlen Harbaugh

Example of Array Parameters

Define Parameters HKA and HKB:

Make hydraulic conductivity equal to the value of HKA times the multiplier array at cells where zone array = 2

Make the hydraulic conductivity equal to the value of HKB times the multiplier array at cells where zone array = 5

If HKA=10.0 and HKB=30.0, the resulting hydraulic conductivity is:

Zone Array

2	2	2	5	5
2	2	2	5	5
2	2	5	5	5
2	2	5	5	5

Multiplier Array

0.7	0.8	0.9	1.0	1.0
0.8	0.9	1.0	1.0	1.0
0.9	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0

7.0	8.0	9.0	30.0	30.0
8.0	9.0	10.0	30.0	30.0
9.0	10.0	30.0	30.0	30.0
10.0	10.0	30.0	30.0	30.0

Courtesy Arlen Harbaugh

Example of List Parameters

Define Parameters RIVA and RIVB:

Make the Riverbed Conductance equal to the value of RIVA times the Factor in the corresponding list of river locations

Make the Riverbed Conductance equal to the value of RIVB times the Factor in the corresponding list of river locations

List for Parameter RIVA

Layer	Row	Col.	Factor
1	10	11	14.0
1	11	12	15.0
1	11	13	16.0

List for Parameter RIVB

Layer	Row	Col.	Factor
1	12	13	18.0
1	13	14	20.0

Thus, if RIVA=10.0 and RIVB=20.0, the riverbed conductance list is:

Layer	Row	Col.	Conductance
1	10	11	140.0
1	11	12	150.0
1	11	13	160.0
1	12	13	360.0
1	13	14	400.0

Courtesy Arlen Harbaugh

Parameter Definition

- Parameters can only be specified for part of the input data: LPF, CHD, GHB, RIV, DRN, WEL, RCH, EVT, HFB allow parameters
- Array parameters
  - For each layer, specify multiplier and zone arrays
  - NONE is a special multiplier array
  - ALL is a special zone array
  - If an array is defined using parameters, values for all cells in all layers must be defined by the parameters – i.e. cannot define values for some cells using parameters and some without using parameters
  - Additive parameters
- List parameters
  - Can mix parameters with non-parameter data
  - Additive parameters

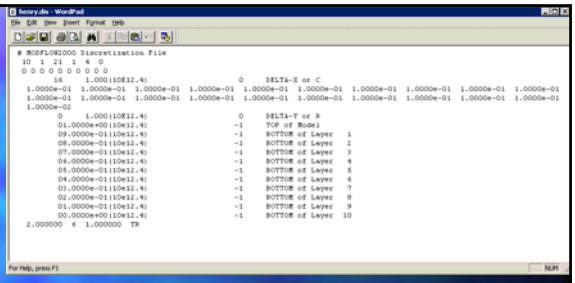
Courtesy Arlen Harbaugh

Global Process

- Discretization Data
  - All discretization data in one place
  - Elevations always included even if GWF does not need because there is a good chance other processes will need
    - Not always included originally in order to save memory

Courtesy Arlen Harbaugh

Discretization



- NLAY, NROW, NCOL, NPER, ITMUNI, LENUNI
- Existence of Quasi-3D Confining Units
- DELR
- DELC
- TOP elevation of system
- Bottom elevation of each model layer and Quasi-3D Confining Unit
- PERLEN, NSTP, TSMULT, SS/TR for each stress period
  - Mixed steady-state and transient simulations

Courtesy Arlen Harbaugh

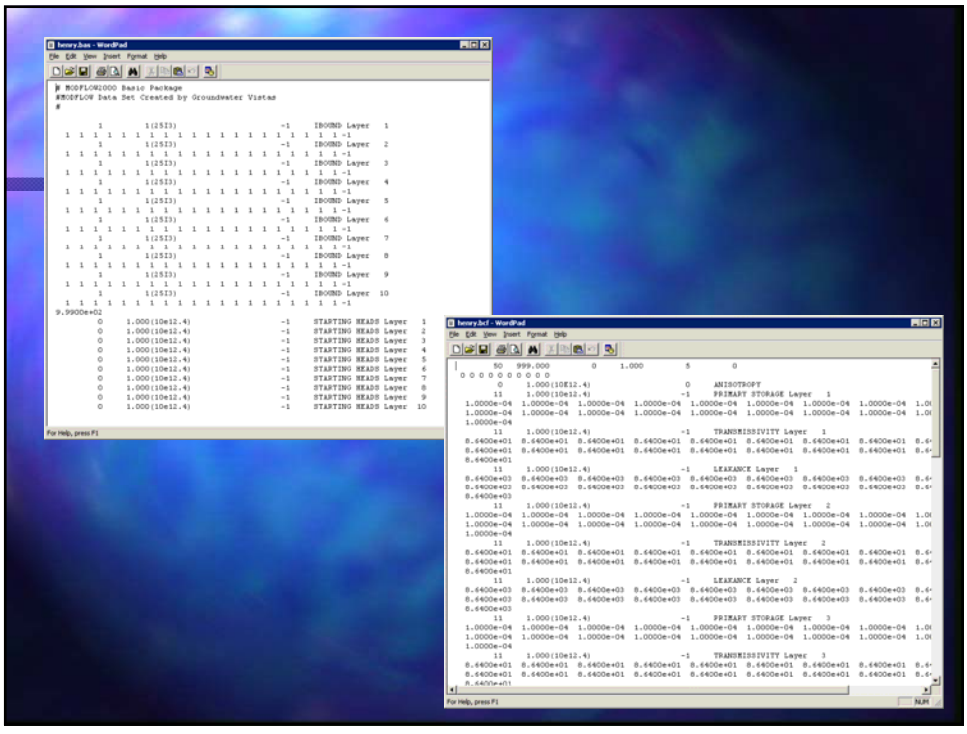
List of Packages (included with MF2K version 1.17)

- BAS6 -- Basic Package
- BCF6 -- Block-Centered Flow Package
- LPF1 -- Layer-Property Flow Package
- RIV6 -- River Package
- DRN6 -- Drain Package
- WEL6 -- Well Package
- GHB6 -- General Head Boundary Package
- RCH6 -- Recharge Package
- EVT6 -- Evapotranspiration Package
- CHD6 -- Time-Variant Specified-Head Package
- HFB6 -- Horizontal Flow Barrier Package
- SIP5 -- Strongly Implicit Procedure Package
- SOR5 -- Slice Successive Over-Relaxation Package
- PCG2 -- Version 2 of Preconditioned Conjugate Gradient Package
- DE45 -- Direct solver
- LMG1 -- Multigrid solver (for USGS use only)
- **STR6 -- Streamflow-Routing Package**
- **ADV2 -- Advective-Transport Observation Package**
- **RES1 -- Reservoir Package (RES is the file type in the MODFLOW name file)**
- FHB1 -- Flow and Head Boundary Package (FHB is the file type in the MODFLOW name file)
- IBS6 -- Interbed Storage (subsidence) Package (IBS is the file type in the name file)
- HUF2 -- Hydrogeologic-Unit Flow Package
- **LAK3 -- Lake Package**
- ETS1 -- Evapotranspiration with a Segmented Function Package
- DRT1 -- Drains with Return Flow Package
- LMT6 -- Link to MT3DMS contaminant-transport model
- MNW1 -- Multi-Node Well Package
- **DAF1 -- Diffusion Analogy Surface-Water Flow Package**
- **SUB1 -- Subsidence and Aquifer-System Compaction Package**
- **SFR2 -- Stream-Flow Routing Package, version 2**
- GMG1 -- Geometric MultiGrid Solver Package

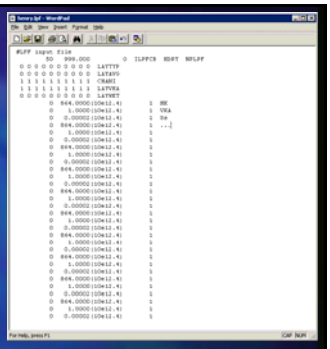
Bold indicates package not compatible with SEAWAT-2000

Changes to BAS and BCF (MF96 TO MF2K)

- BAS
  - Removed NLAY, NROW, NCOL, NPER, ITMUNI
  - Removed PERLEN, NSTP, TSMULT
- BCF
  - Removed DELR and DELC
  - Removed TOP and BOT for convertible and water-table layers
  - Removed steady-state flag
- MF96TO2K can convert MODFLOW-96 data sets

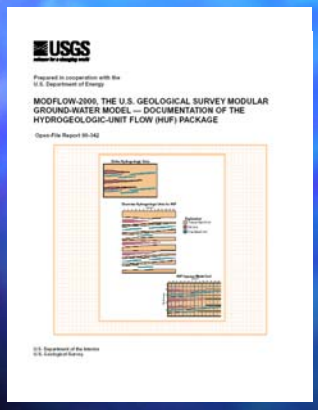


LPF Package



- Substitute for Block-Centered Flow (BCF)
- Internally LPF works like BCF
  - Layers are confined or convertible
  - Transmissivity, storage, and vertical leakage are based on saturation for convertible layers
  - Wetting and drying
- Grid independent hydraulic properties
  - Specific storage when confined
  - Horizontal K even for confined layers
  - Vertical K or horizontal to vertical anisotropy ratio
  - Vertical K of quasi 3-D confining beds
    - NO MORE VCONT

HUF Package



Anderman, E.R., and Hill, M.C., 2000, MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model - Documentation of the Hydrogeologic-Unit Flow (HUF) Package: U.S. Geological Survey Open-File Report 00-342, 89 p.

HUF (cont.)

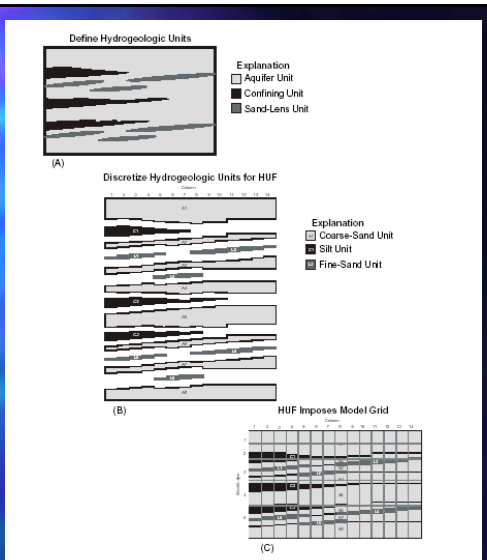
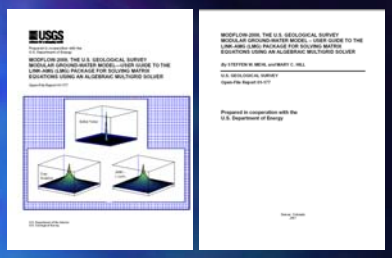


Figure 1. Hypothetical situation involving definition of hydrogeologic units. (A) Definition of hydrogeologic units, which is part of the data preparation step of ground-water model development (the data can be organized using some of the software listed for (B)); (B) Horizontal discretization of hydrogeologic units used to construct the HUF Package input file (the discretization can be performed by software such as Stratamodel, Earthvision, Arcview, and Voxel Analyst, and by some MODFLOW-2000 graphical user interfaces), with the 17 hydrogeologic units shown exploded; (C) Assignment of hydrogeologic units to model layers (performed by the Hydrogeologic-Unit Flow Package).

Source: Anderman and Hill (2000)

HUF (cont.)

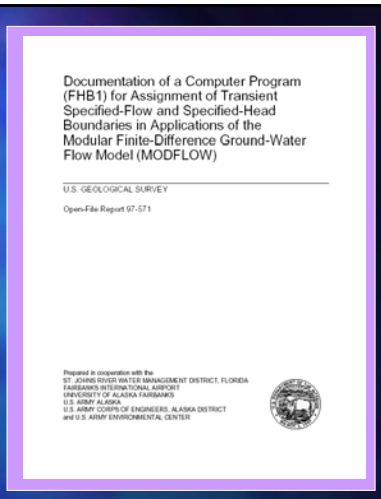


- Substitute for BCF and LPF
- Internally, HUF works like BCF, LPF
  - Layers are confined or convertible
  - Transmissivity and storage are based on saturation for convertible layers
  - Wetting and drying
- New: Vertical leakage changes gradually with saturated thickness
- New: specify hydraulic properties by hydrogeologic units (HGU's) that are independent of model layers
  - Within each cell, HGU's are assumed to be layered horizontally
  - Hydrogeologic units can pinch out

Source: *Calibration and uncertainty of models*, course notes, USGS, 2002

FHB

- Flows and heads that vary at times other than starting and ending of stress periods
- Now compatible with SEAWAT-2000


Documentation of a Computer Program (FHB1) for Assignment of Transient Specified-Flow and Specified-Head Boundaries in Applications of the Modular Finite-Difference Ground-Water Flow Model (MODFLOW)

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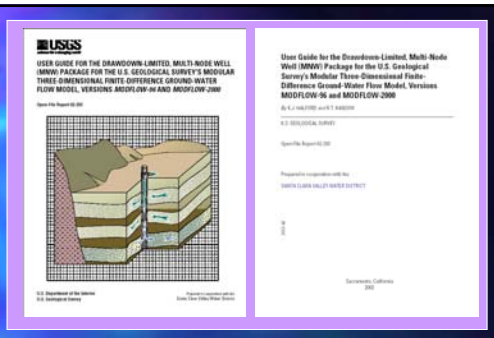
Open-File Report 97-571

MNW


USGS

USER GUIDE FOR THE DRAWDOWN-LIMITED, MULTI-NODE WELL (MNW) PACKAGE FOR THE U.S. GEOLOGICAL SURVEY'S MODULAR THREE-DIMENSIONAL FINITE-DIFFERENCE GROUND-WATER FLOW MODEL, VERSIONS *MODFLOW-96* AND *MODFLOW-2000*

User Guide for the Drawdown-Limited, Multi-Node Well (MNW) Package for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Versions MODFLOW-96 and MODFLOW-2000

- Represent wells that span several aquifers (or multiple model cells)
- Represent leaking wells?
- MNW2 not included in SEAWAT-2000

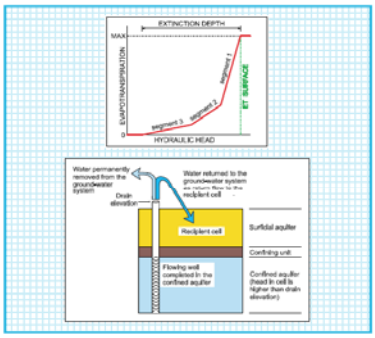
ETS and DRT

USGS
science for a changing world

Prepared in cooperation with the Colorado Water Conservation Board
and the Colorado Division of Water Resources

MODFLOW-2000, THE U.S. GEOLOGICAL SURVEY
MODULAR GROUND-WATER MODEL—DOCUMENTATION
OF PACKAGES FOR SIMULATING EVAPOTRANSPIRATION
WITH A SEGMENTED FUNCTION (ETS1) AND DRAINS WITH
RETURN FLOW (DRT1)

Open-File Report 00-466



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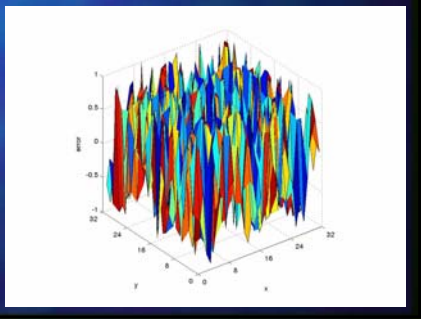
LMG Solver

- Link to algebraic multi-grid
- Can be very fast for big problems (more than about 50,000 cells)
  - 2 to 30 times faster than PCG2 in tests
- Uses a lot of RAM
  - 3 times as much as PCG2, or more

Source: *Calibration and uncertainty of models*, course notes, USGS, 2002

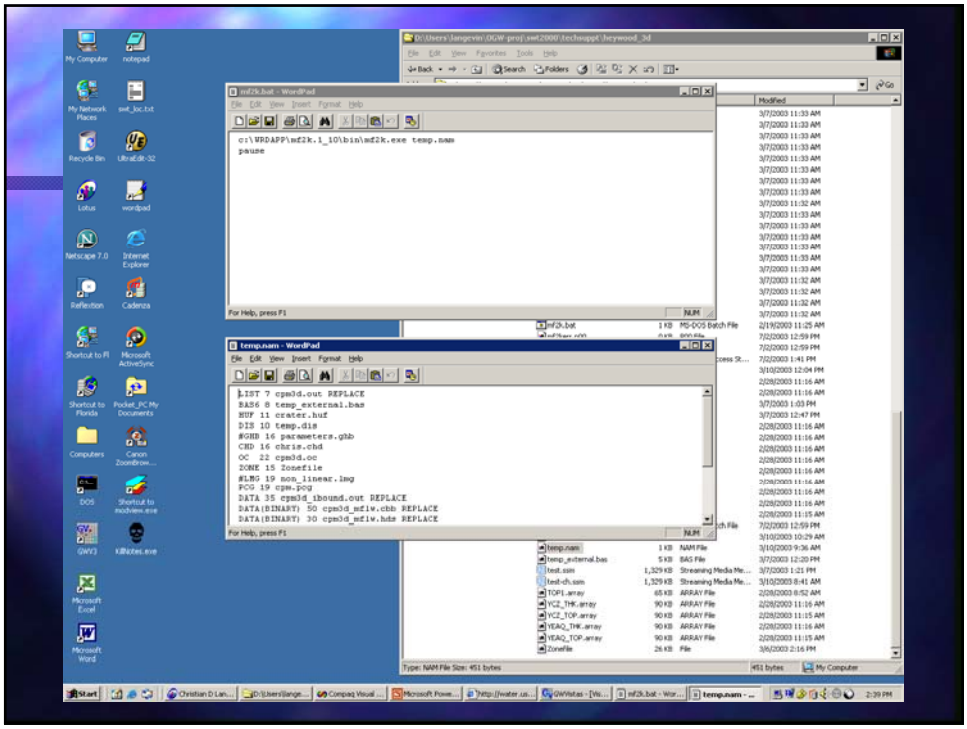
GMG Solver

- Geometric Multi-Grid
- May substantially improve runtimes for very large models
- RCLOSE and HCLOSE



Running MODFLOW-2000

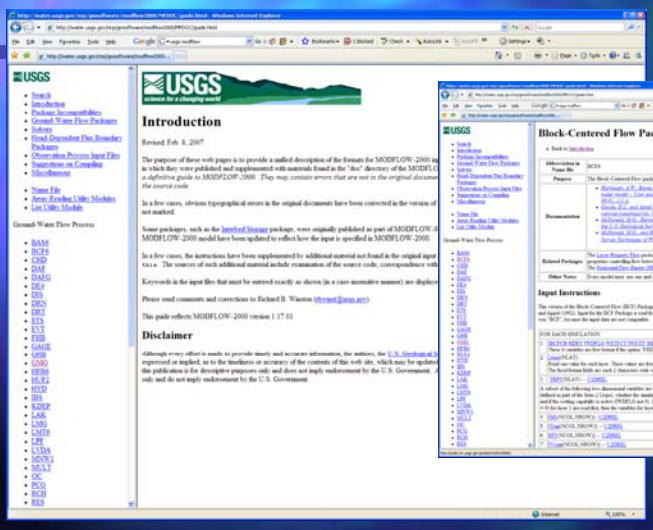
- Directly from Groundwater Vistas
  - Vistas includes Windows version of MODFLOW-2000
- Using a batch file
  - Create a batch file and run from Windows file manager



Two Listing Files

- LIST
  - Contains GWF output from the last parameter-estimation iteration
- GLOBAL
  - Contains PES output for each parameter-estimation iteration

Online MODFLOW Guide



http://water.usgs.gov/nrp/gwsoftware/modflow2000/MFDOC/guide.html