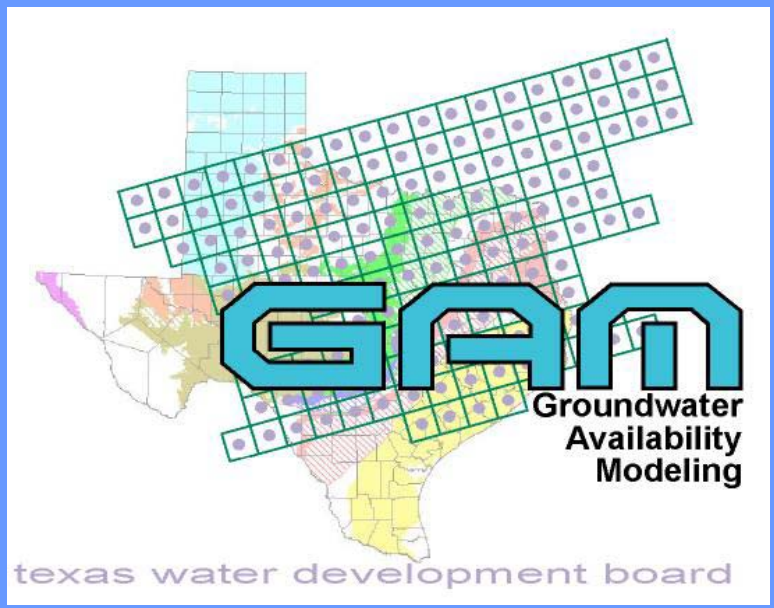
Central Carrizo-Wilcox Aquifer GAM Model
Model Training Seminar
February 12, 2003



Presented by
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Jean-Philippe Nicot
Bureau of Economic Geology
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School of Geosciences
The University of Texas at Austin

Agenda

9:30	Welcome and introductions Goals, expectations, objectives
10:00	Introduction to modeling, MODFLOW, and PMWIN
11:00	Technical review of the CW-c GAM model Focus on input data and their derivation Visualize data in PMWIN environment
12:00	Lunch
1:30	Computer lab and exercises

Part 1.
Goals, Expectations, Objectives

Seminar Goals

- Get acquainted with MODFLOW and the PMWIN modeling environment
- Review the data and development of the CW-c GAM model
  - Model complexity
  - Data quality
  - Inherent limitations for model applicability
- Successfully run the model
- Appreciate the level of professional expertise required

Seminar Prerequisites

- Familiarity with the science of geology, including groundwater hydrogeology
- Fluency with management of files and directories in PC Windows
- Familiarity with the development of the CW-c GAM model through the SAF meetings and website documents

GAM Objectives

- Develop a scientifically accurate and realistic computer model capable of use as a predictive tool
- Model will be used by groundwater conservation districts, RWPGs, TWDB, and individuals
- Stakeholder participation is important to ensure the model is accepted as a valid representation of the aquifer
- Once the model is developed, it can be used to assess availability of groundwater

GAM Model Characteristics

- Three dimensional and multi-layered
- Regional scale (CW-c: >26,000 sq. miles)
- Grid cell size of 1 sq. mile
- Properly and accurately represent recharge, discharge, water levels, interaction of groundwater and surface water, and the water budget
- Stress periods of 1 month to 1 yr
- Calibrated to within 10% of data range, and other criteria (hydrograph matching, base flow, residuals)

Part 2.
Introduction to Modeling, MODFLOW, and PMWIN

Definition of a Groundwater Model

- A groundwater ***model*** is…
  - a representation or accounting of the occurrence and movement of groundwater
  - a simplification and approximation of a real and complex groundwater-flow system
- A ***code*** is the software that solves the groundwater flow equation

Selected History of Groundwater Modeling

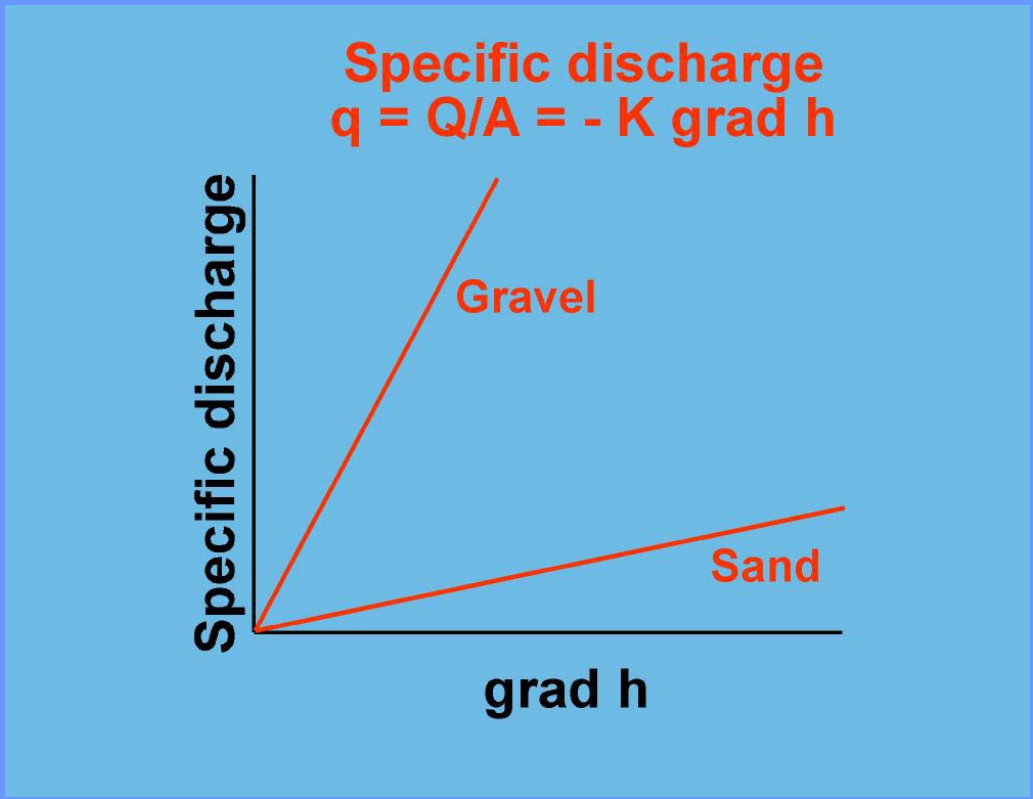
- 1856 Darcy's Law
- 1898 Physical model (sand model)
- 1935 Theis' equation for groundwater flow
- 1940s Electrical analog models
- 1960s Computer or numerical models
- 1971 PLASM – 1st widely used computer code
  - Simple and short
  - User modified for each model
- 1984 MODFLOW released by U.S. Geological Survey
  - Modular code
  - Widely used and well documented
  - Public domain - nonproprietary
  - Upgrades (1984, 1988, 1996, 2000)
  - Multiple add-on packages developed

Darcy's Law

- **Darcy's Law for flow in porous media:**

  $Q = -K A \text{ grad } h$

  $q = Q/A = -K \text{ grad } h$

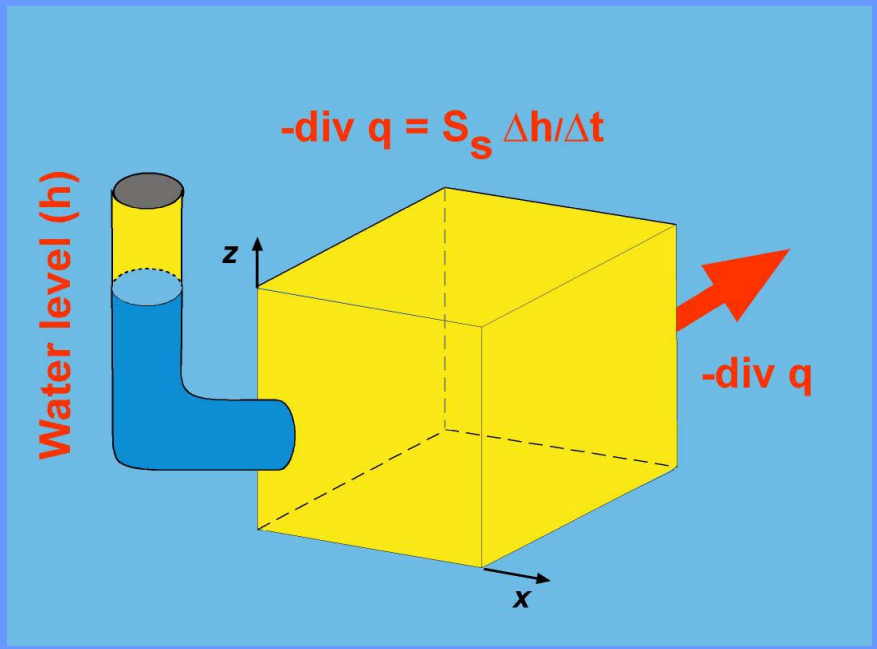


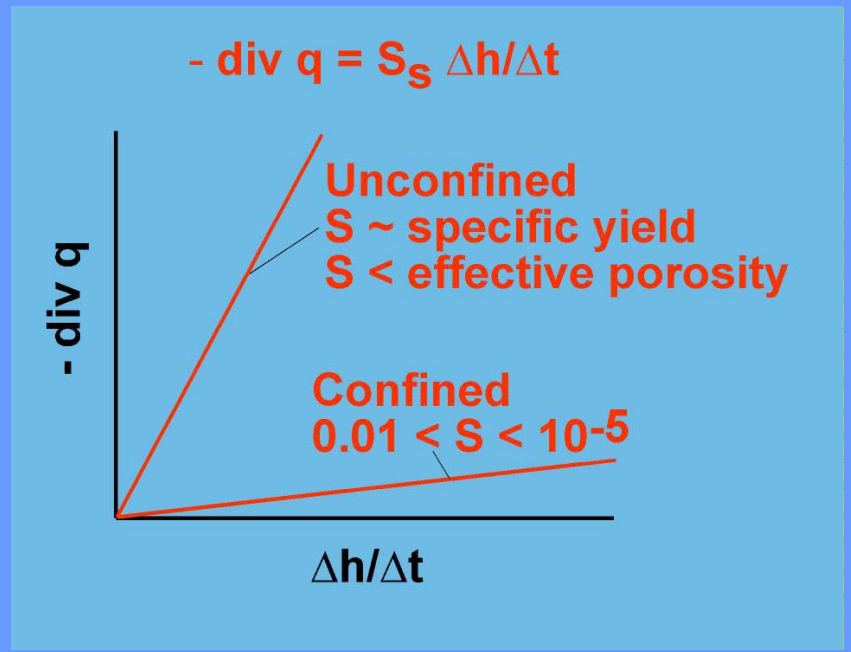
Mathematical operator:

grad = $\partial/\partial x + \partial/\partial y + \partial/\partial z$ applied to scalar property

Continuity Equation

Inflow – Outflow = –div q = S_s ∂h/∂t





Mathematical operator:

div = ∂/∂x + ∂/∂y + ∂/∂z applied to vector property

General Equation of Groundwater Flow

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(T_z \frac{\partial h}{\partial z}\right) - W = S \frac{\partial h}{\partial t}$$

T = K b *S = Ss b*

Darcy's Law for flow in porous media:

Q = –K A grad h q = Q/A = –K grad h

Continuity equation:

Inflow – Outflow = –div q = S_s ∂h/∂t

Solution requires initial conditions: ***h(time = 0)***

Kh = Kx = Ky (no horizontal anisotropy)

Kz

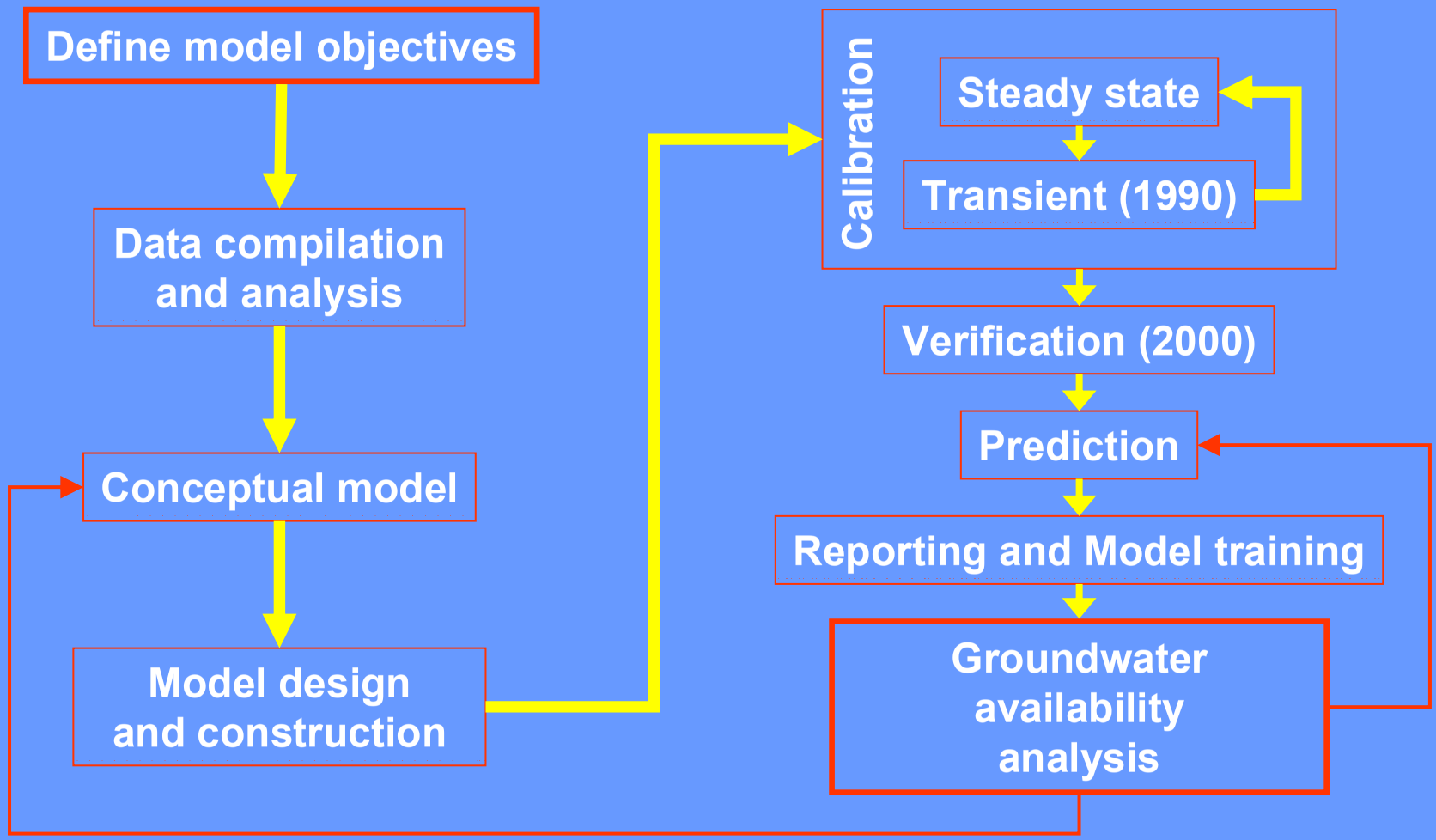
S (storativity)

b (cell thickness), Top, Bottom

W = accounting of all boundary and internal sources and sinks of water

MODELING PROTOCOL

(Modified from Anderson and Woessner, 1992)



MODFLOW

Modular Three-Dimensional Finite-Difference Groundwater Flow Model

Original packages*

- Basic (BAS)
- Block Centered Flow (BCF)
- Well (WEL)
- Drain (DRN)
- River (RIV)
- ET (ET)
- General Head Boundary (GHB)
- Recharge (RCH)
- Solvers (SIP/SOR)
- Output Control (OC)

Add on packages*

- Streamflow Routing (STR)
- Horizontal Flow Barrier (HFB)
- Reservoir (RES)
- Compaction (IBS)
- Time-variant Constant Head (CHD)
- Interbed Storage (IBS)
- Solvers (PCG)
- Transient Leakage (TLK)
- Density (DEN)

*Packages consist of groups of modular subroutines

MODFLOW
Packages Used in CW-c GAM Model

Basic (BAS)

Block Centered Flow (BCF)

Well (WEL)

ET (ET)

General Head Boundary (GHB)

Recharge (RCH)

Stream flow Routing (STR)

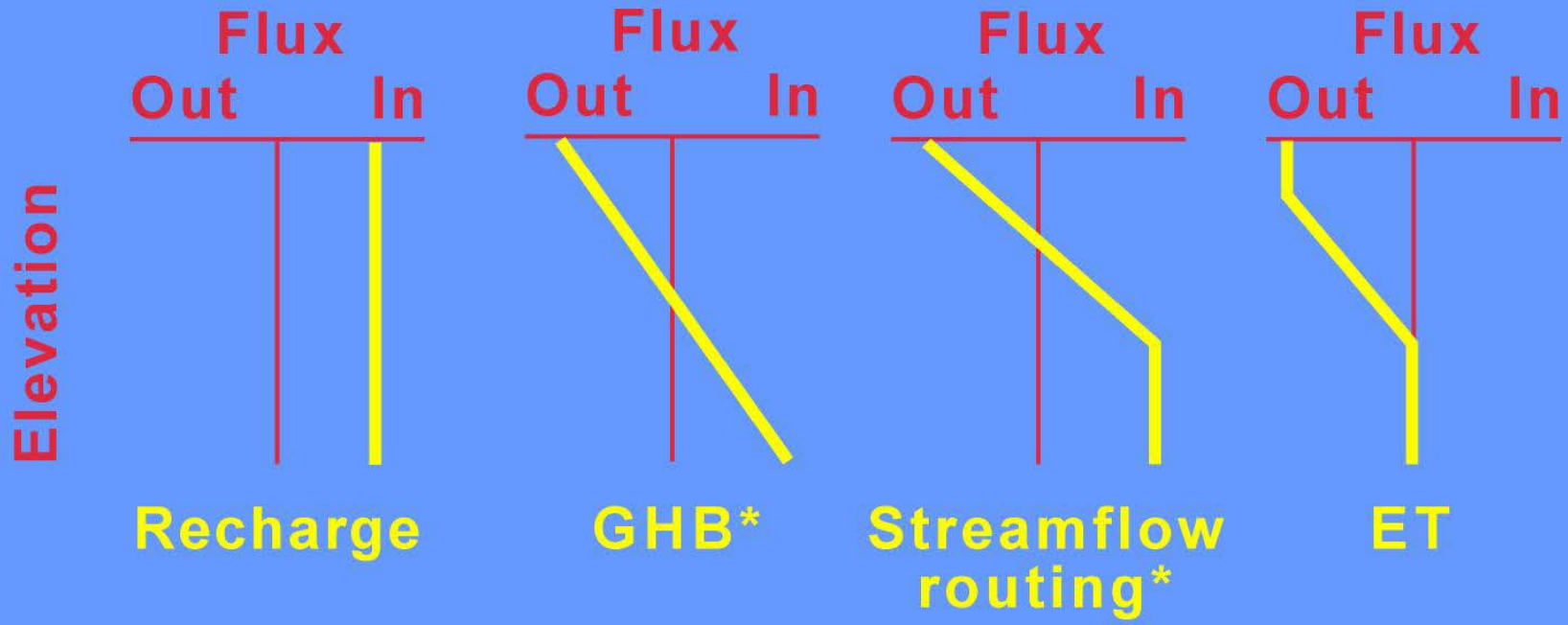
Reservoir (RES)

Horizontal Flow Barrier (HFB)

Solver (SIP)

Output Control (OC)

MODFLOW BOUNDARY PACKAGES

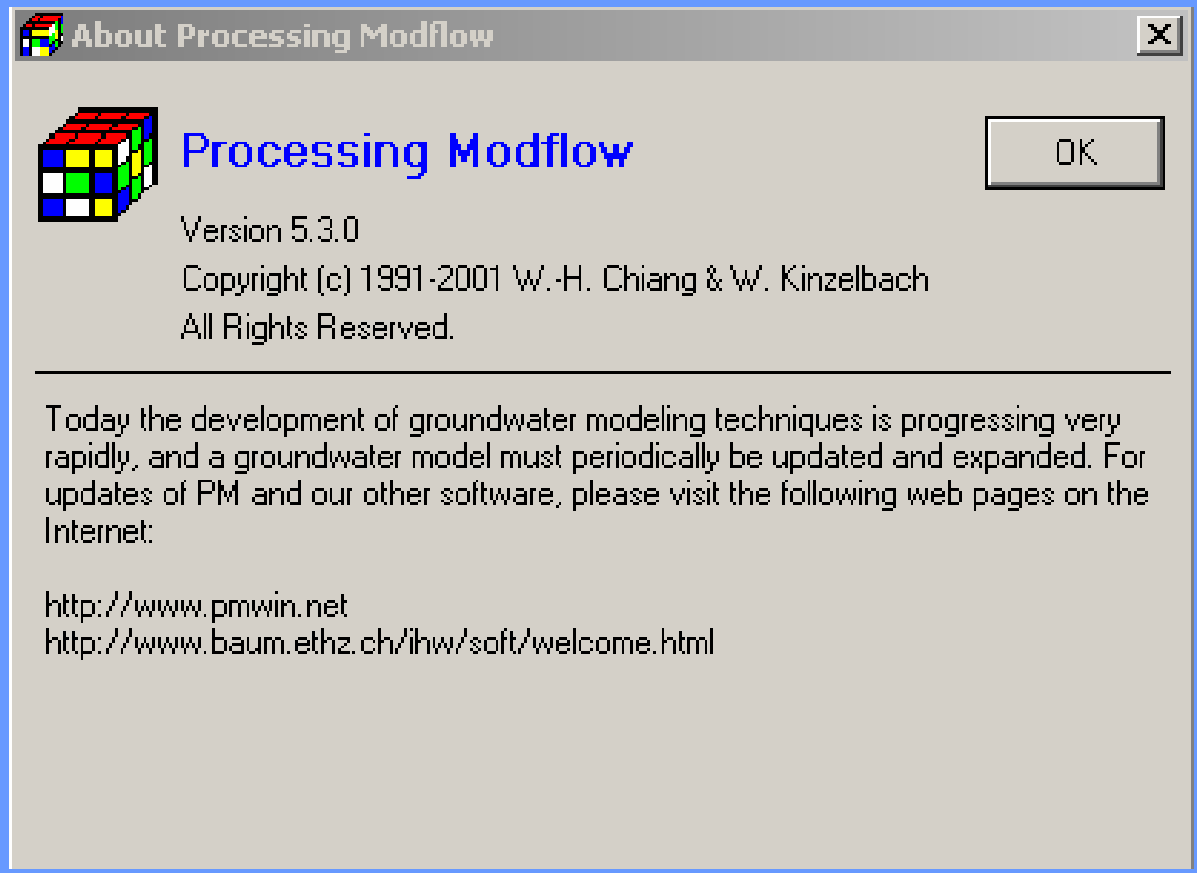


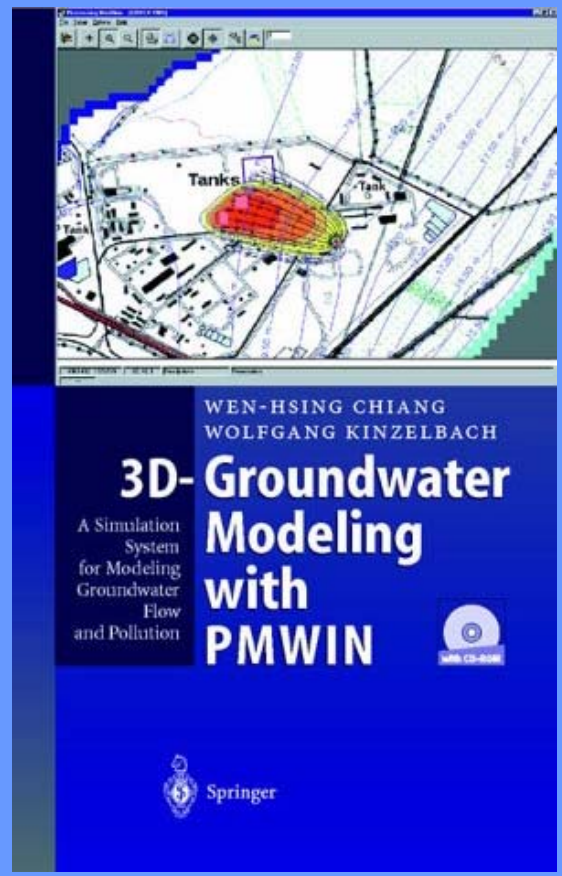
* Q (flux) = COND (h_b - h_{cell})

MODFLOW Interfaces

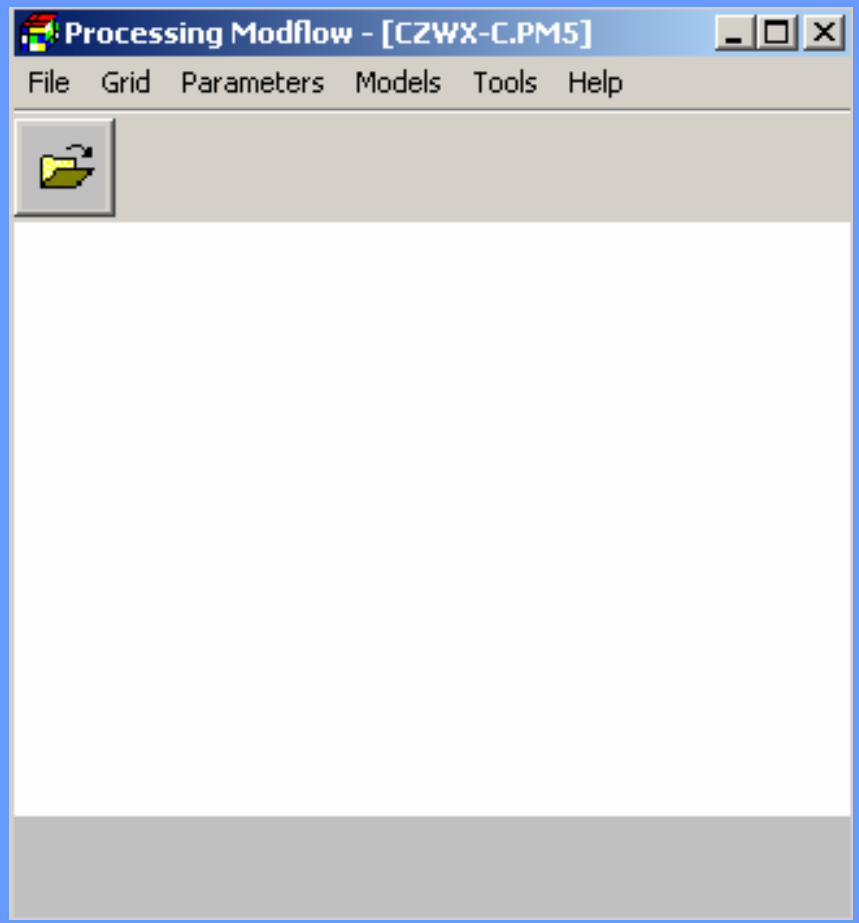
- **User interfaces facilitate the tasks of setting up, running, and looking at results of a model**
  - **PMWIN (Processing MODFLOW for Windows)**
  - **Groundwater Vistas**
  - **Visual MODFLOW**
  - **Groundwater Modeling System (GMS)**

Processing Modflow for Windows
PMWIN v. 5.3.0



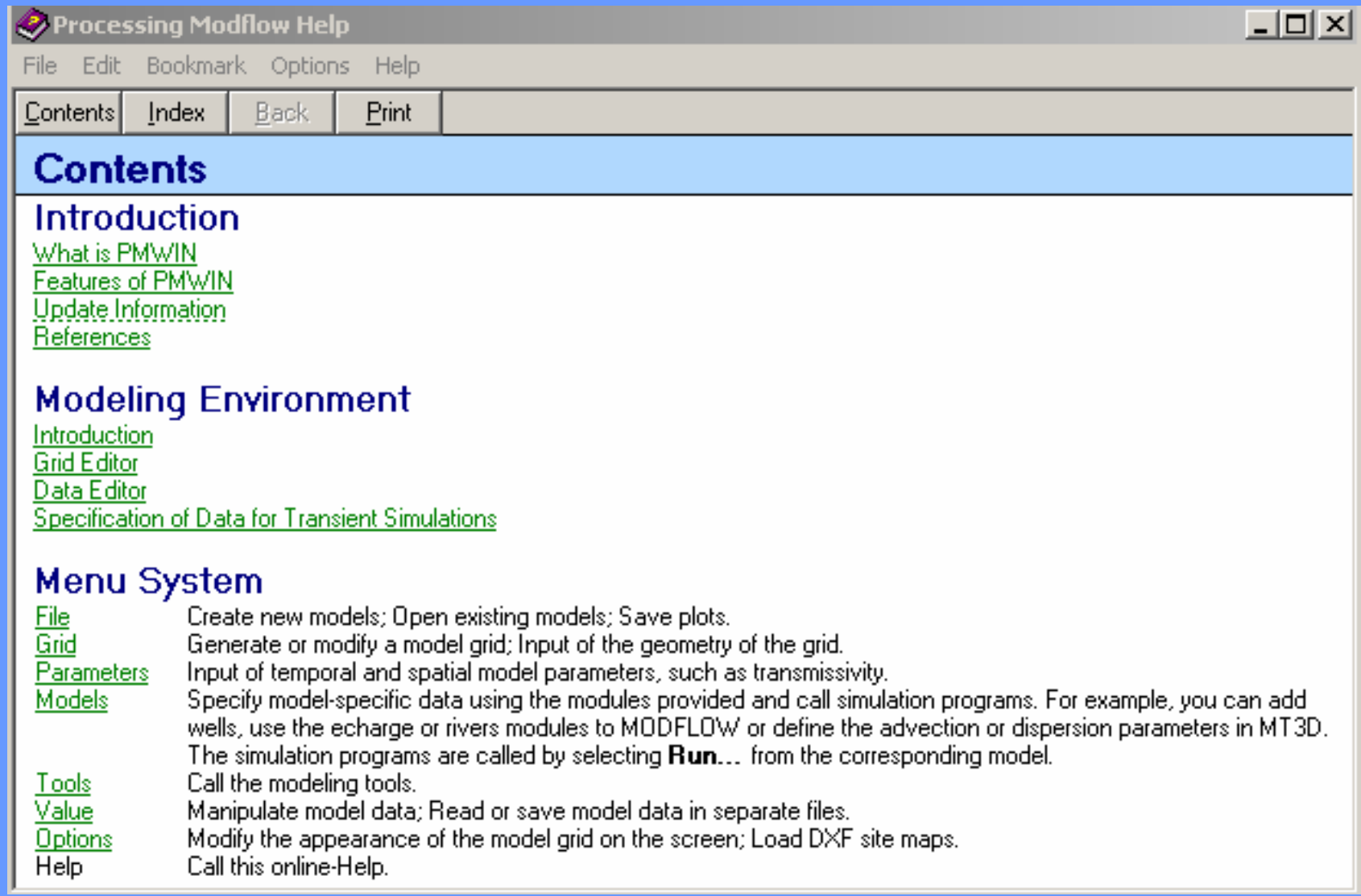


PMWIN Menu Bar



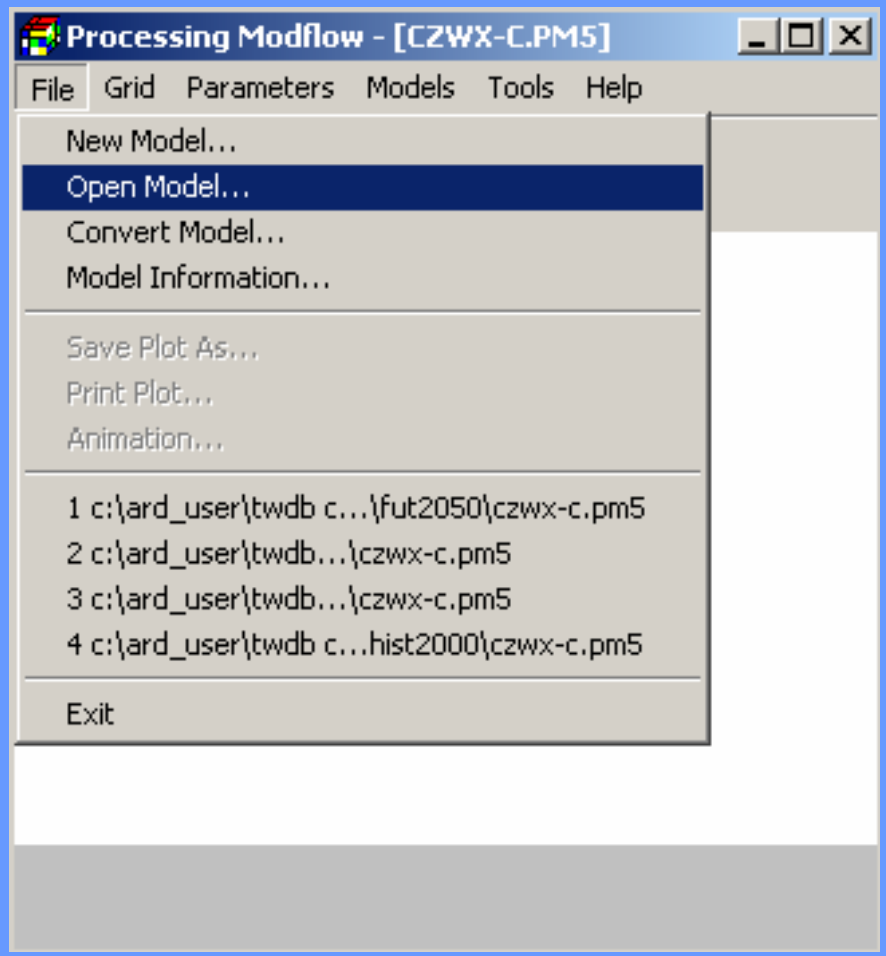
File
Grid
Parameters
Models
Tools
Help

Help Menu


Processing Modflow Help
File Edit Bookmark Options Help
Contents Index Back Print
Contents
Introduction
What is PMWIN
Features of PMWIN
Update Information
References
Modeling Environment
Introduction
Grid Editor
Data Editor
Specification of Data for Transient Simulations
Menu System
File Create new models; Open existing models; Save plots.
Grid Generate or modify a model grid; Input of the geometry of the grid.
Parameters Input of temporal and spatial model parameters, such as transmissivity.
Models Specify model-specific data using the modules provided and call simulation programs. For example, you can add wells, use the echarge or rivers modules to MODFLOW or define the advection or dispersion parameters in MT3D. The simulation programs are called by selecting Run... from the corresponding model.
Tools Call the modeling tools.
Value Manipulate model data; Read or save model data in separate files.
Options Modify the appearance of the model grid on the screen; Load DXF site maps.
Help Call this online-Help.

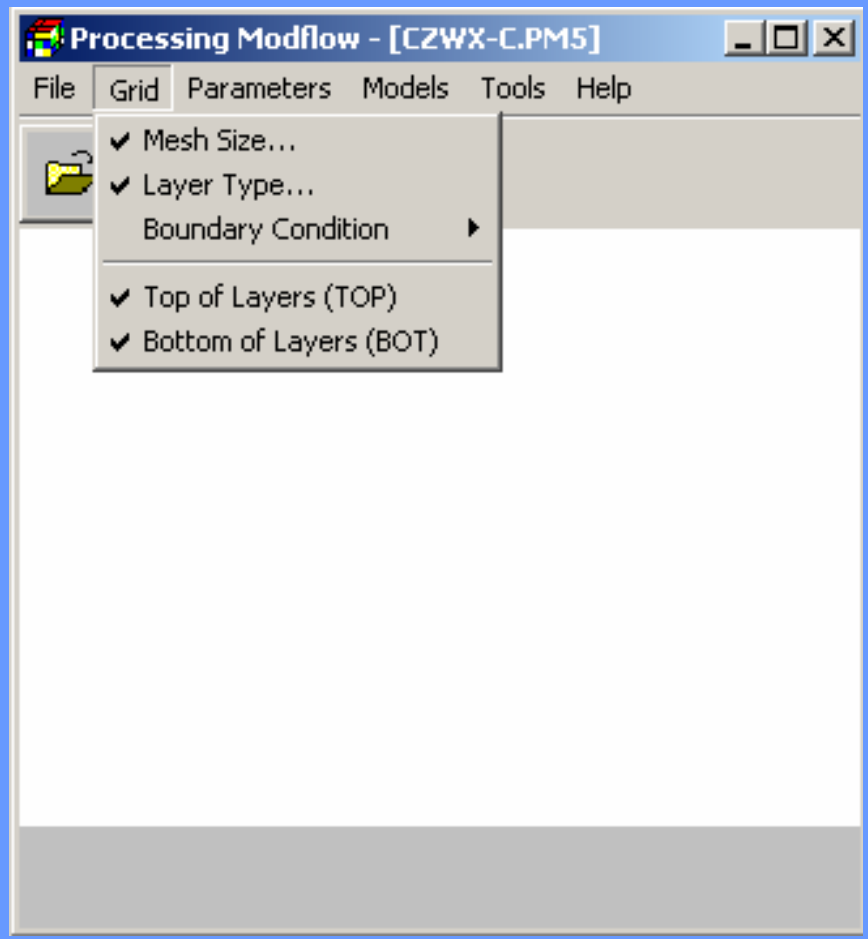
File > Open Model

Browse to CW-c GAM Model



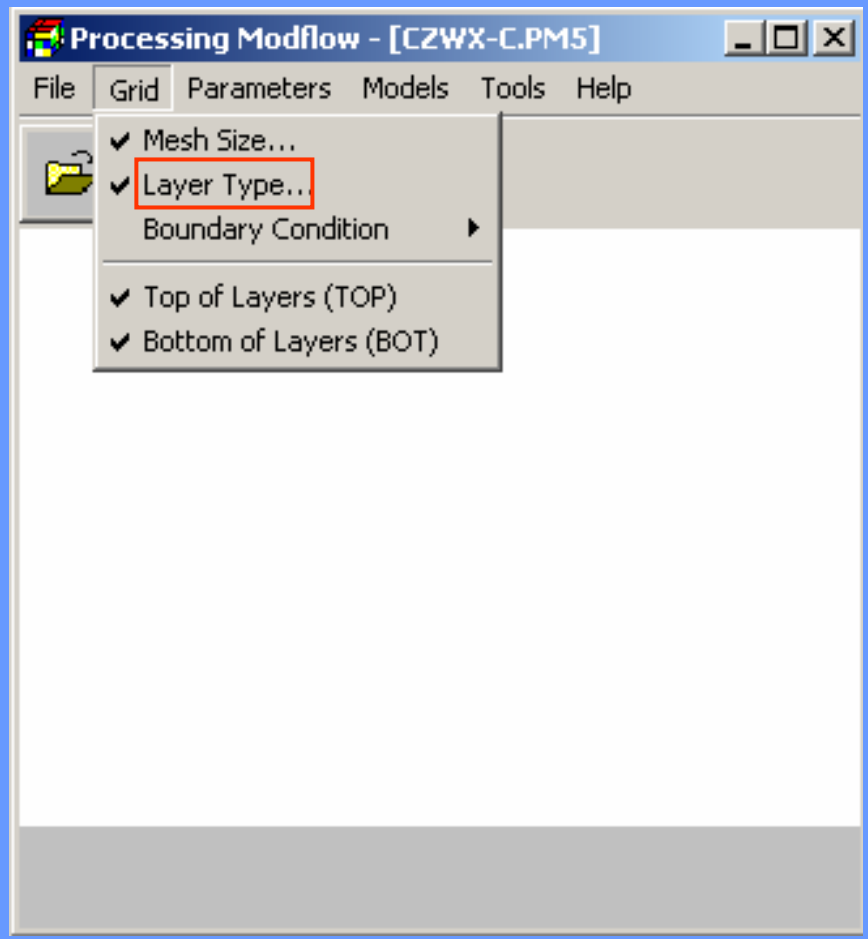
New Model
Open Model
Convert Model
Model Information

Grid Menu List



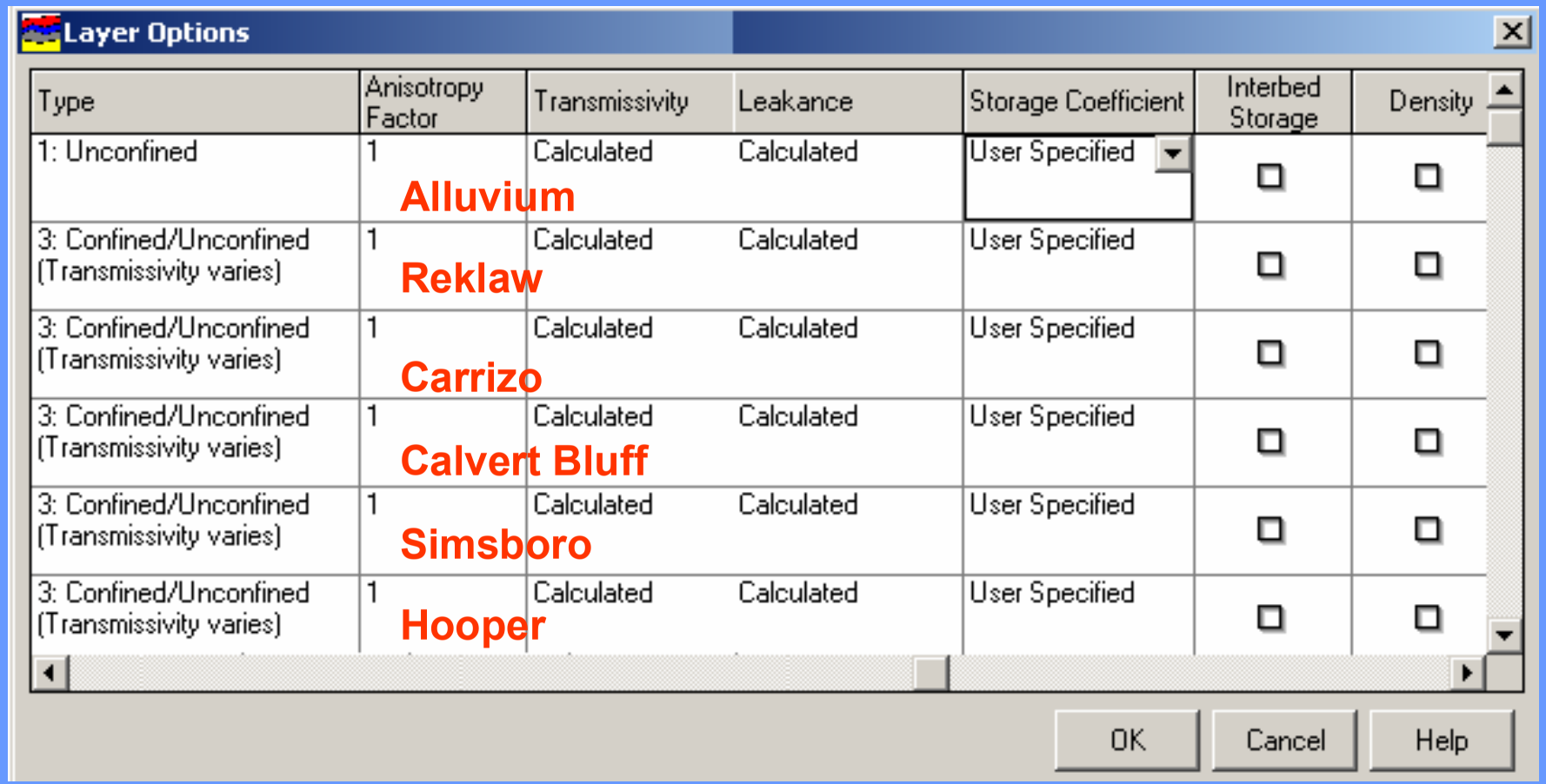
Mesh Size
Layer Type
Boundary Condition
TOP
BOT

Grid Menu List

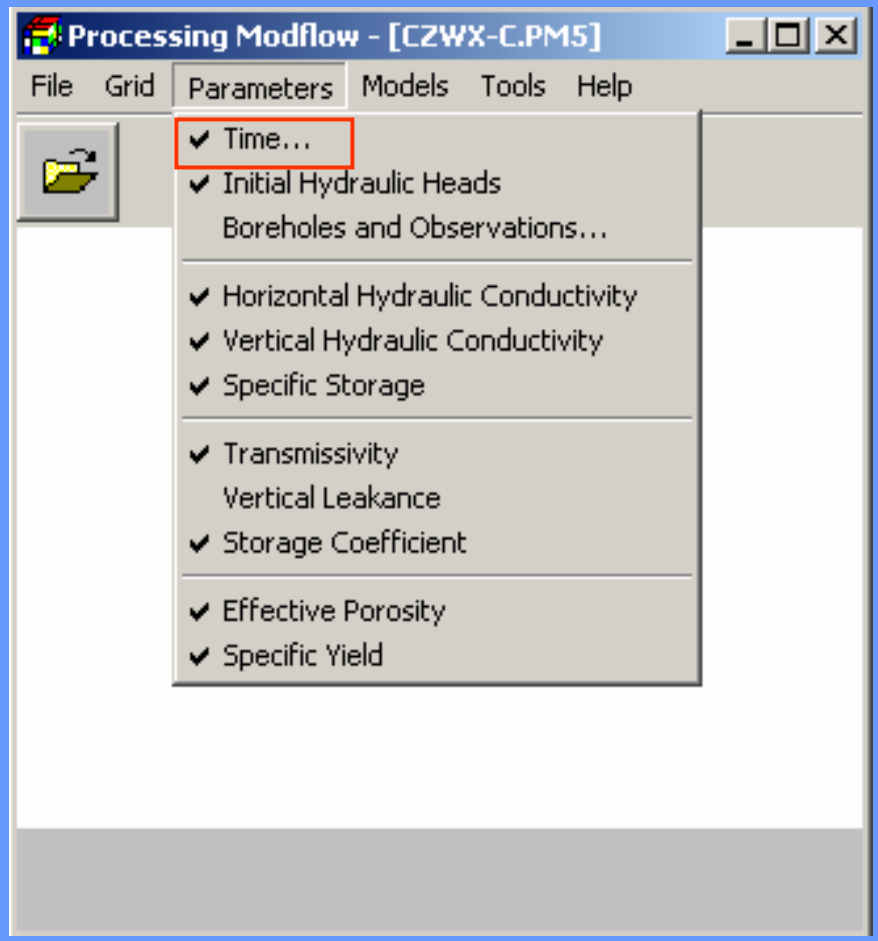


Mesh Size
Layer Type
Boundary Condition
TOP
BOT

Grid > Layer type
Layer Options

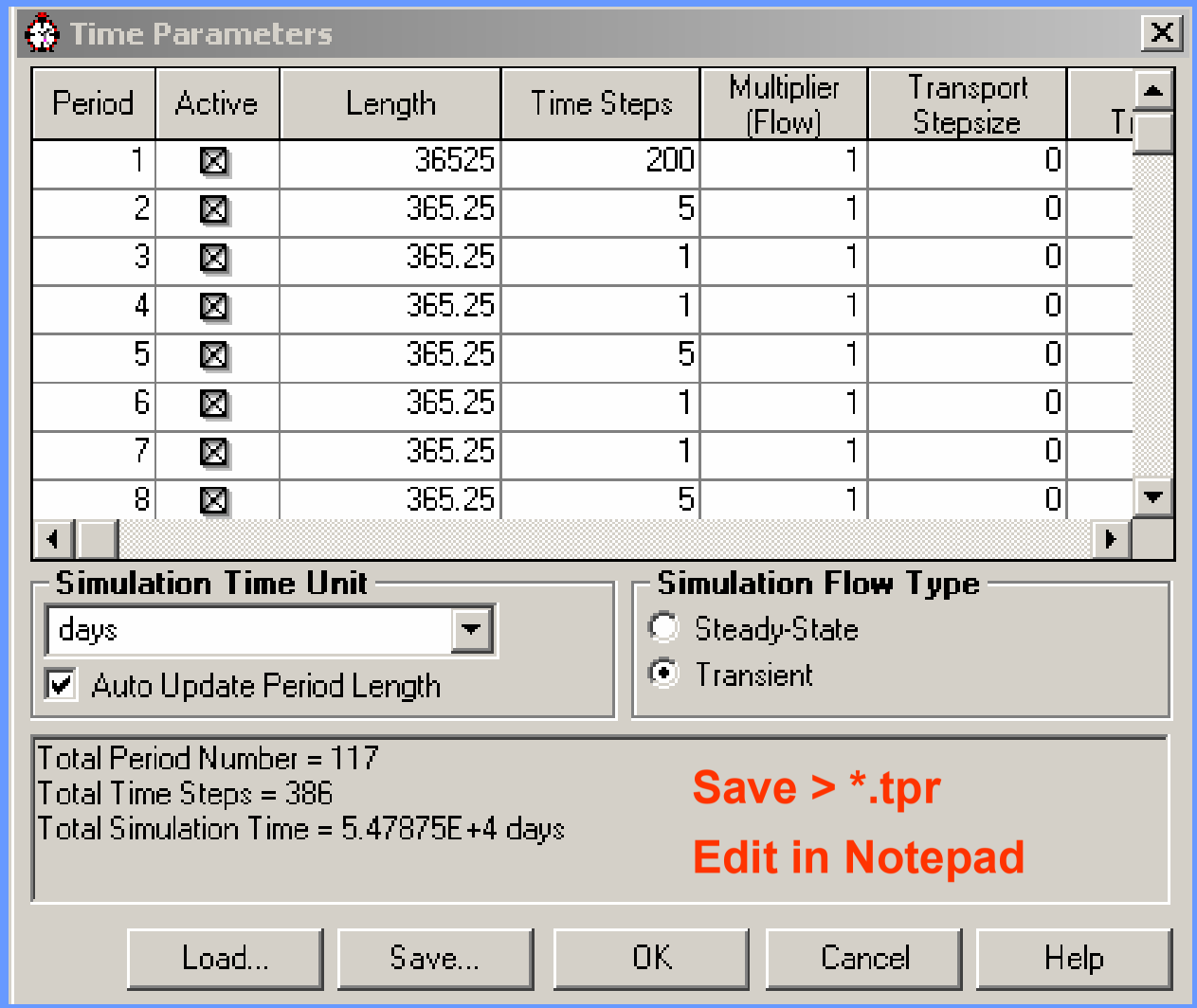


Parameters List

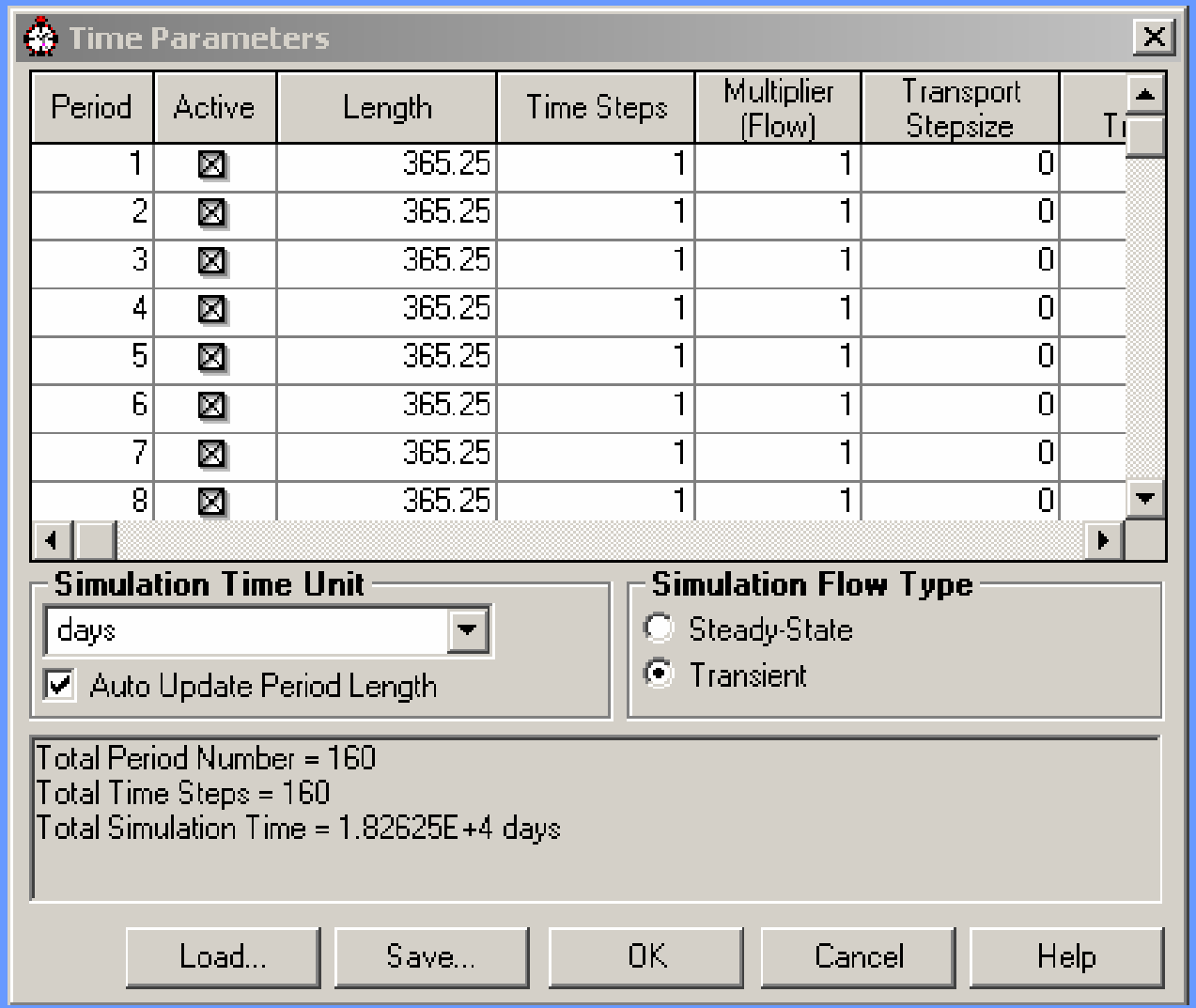


Time (*.tpr file)
For transient and predictive runs

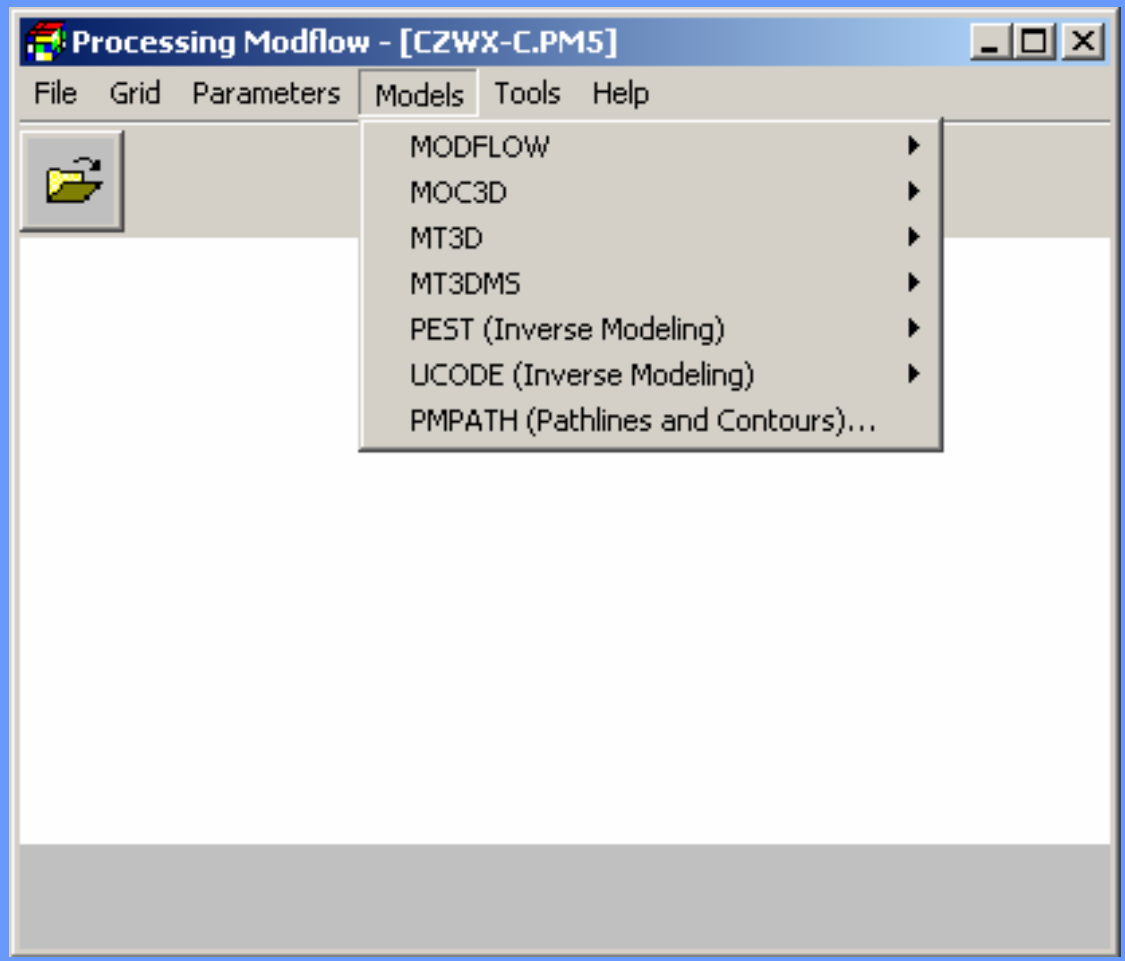
Time
(Transient Model 1951-2000)



Time
(Predictive Model 2001-2050)

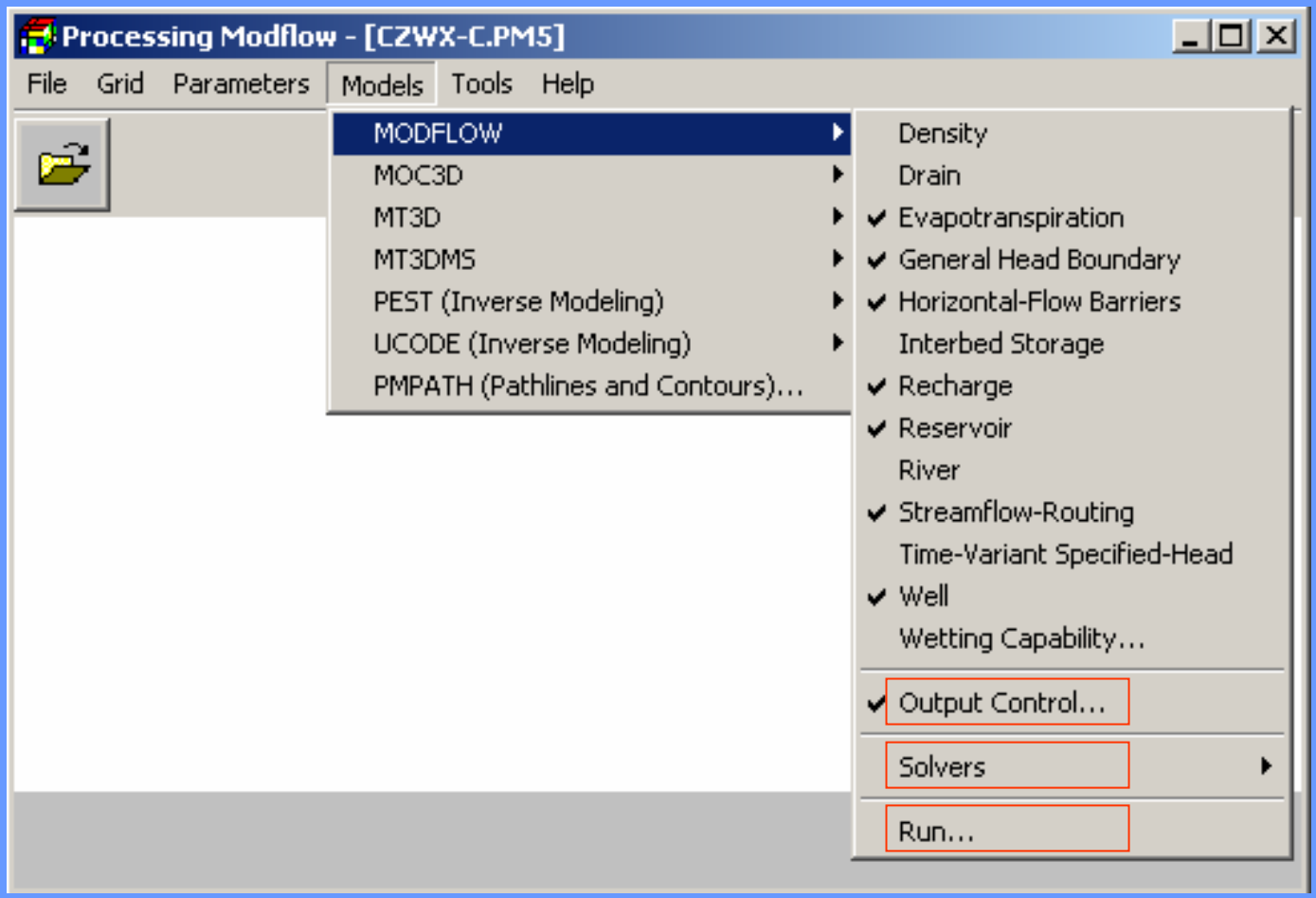


Models List

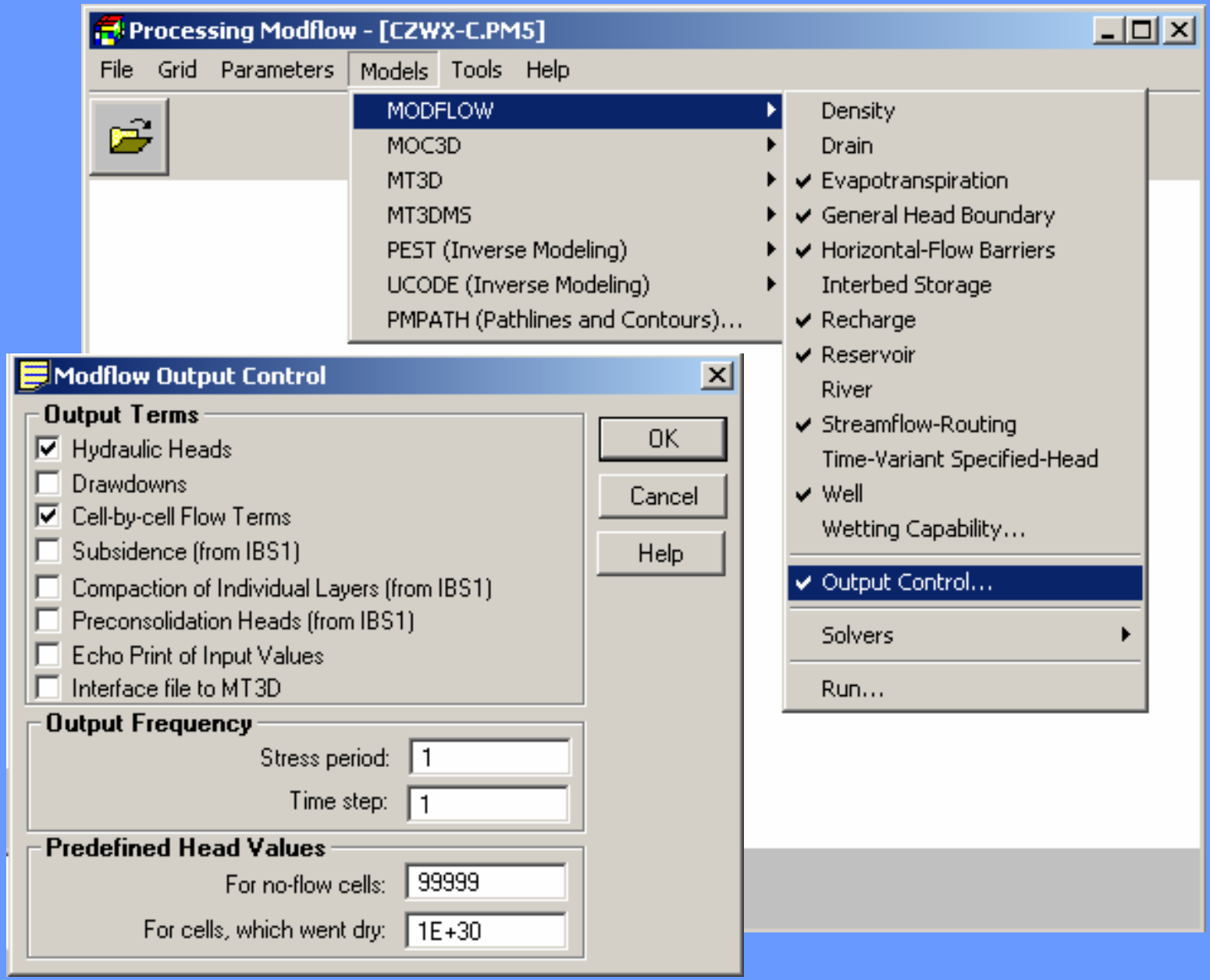

Processing Modflow - [CZWX-C.PM5]
File
Grid
Parameters
Models
Tools
Help
MODFLOW
MOC3D
MT3D
MT3DMS
PEST (Inverse Modeling)
UCODE (Inverse Modeling)
PMPATH (Pathlines and Contours)...

Models > MODFLOW

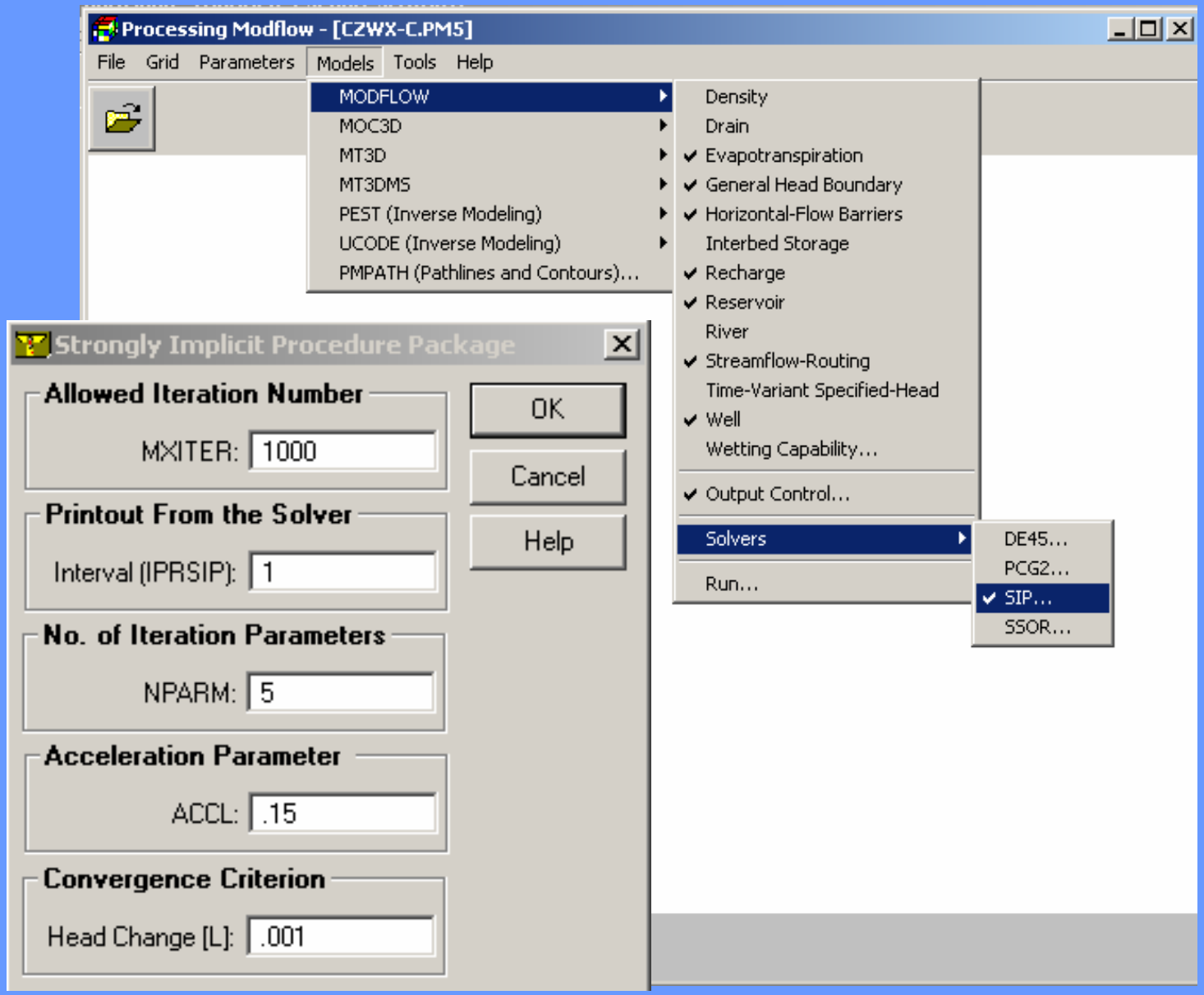
Packages and Run Command



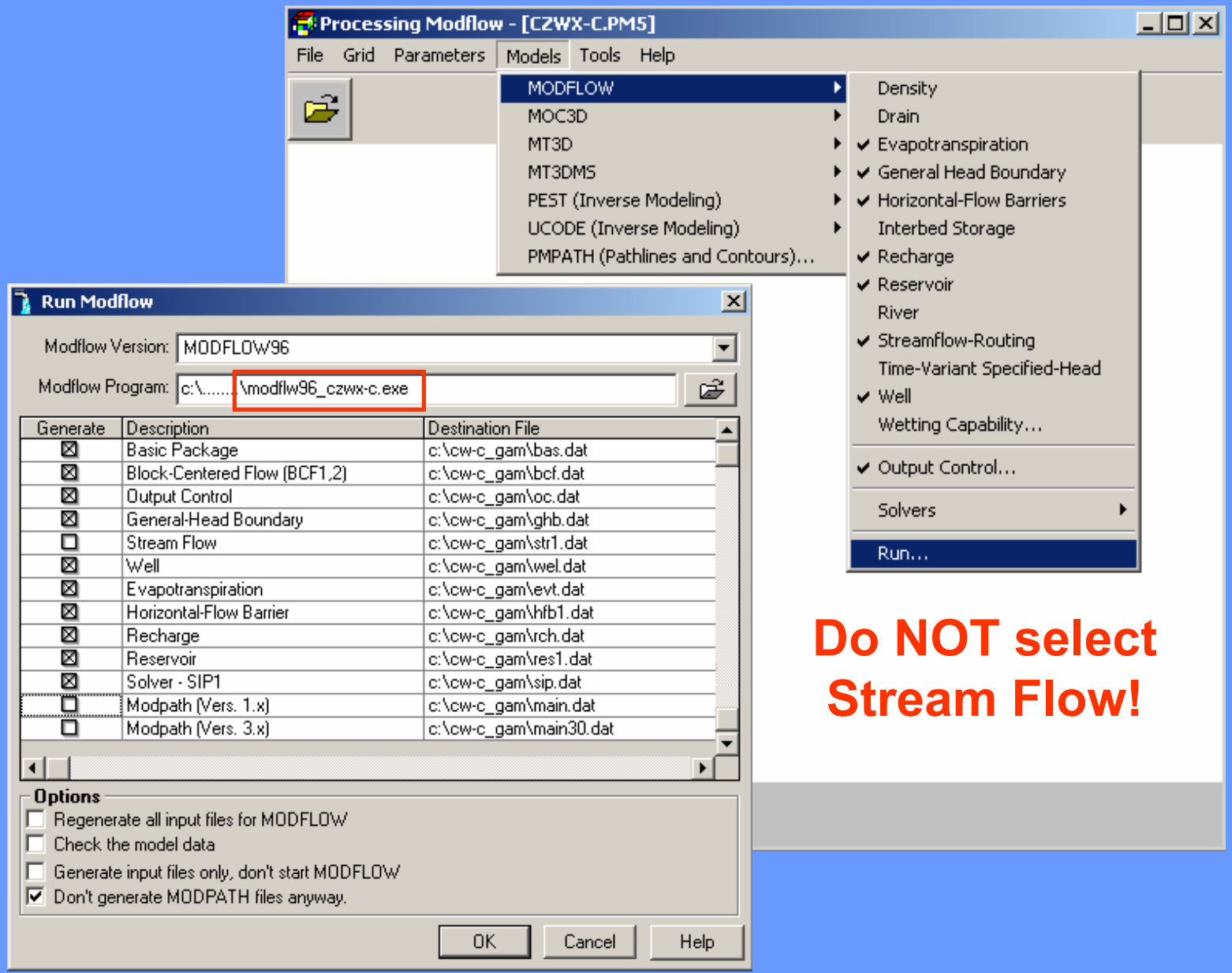
Models > MODFLOW > Output Control



Models > MODFLOW > Solvers > SIP

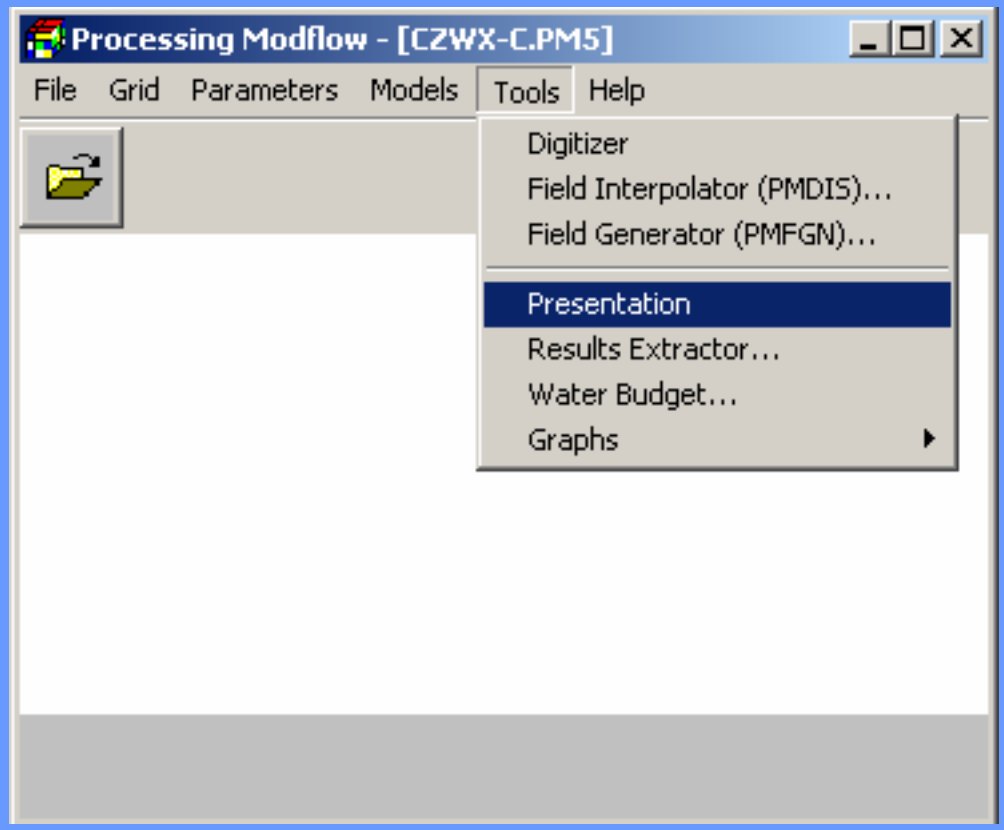


Models > MODFLOW > Run



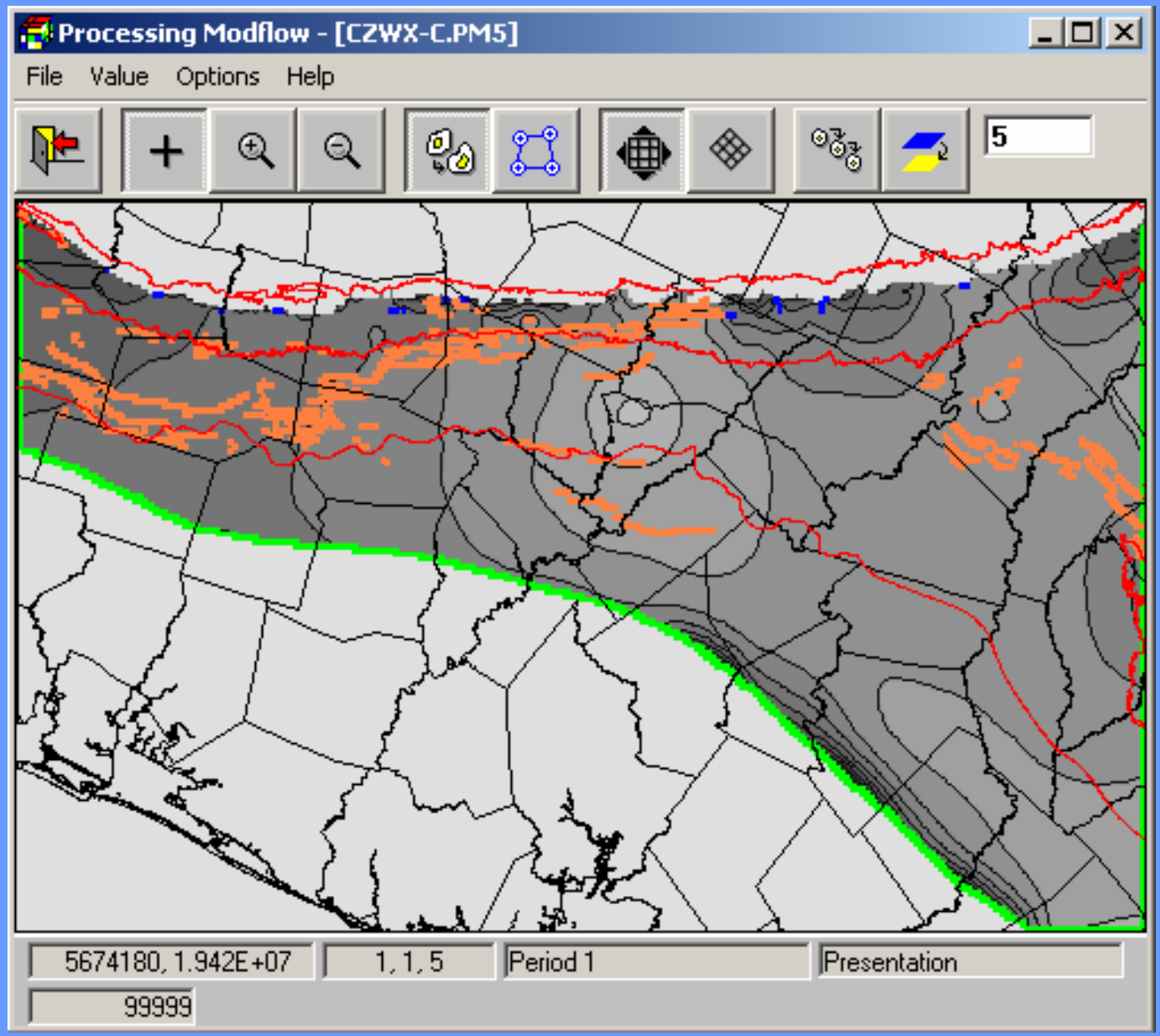
Tools

Tools > Presentation

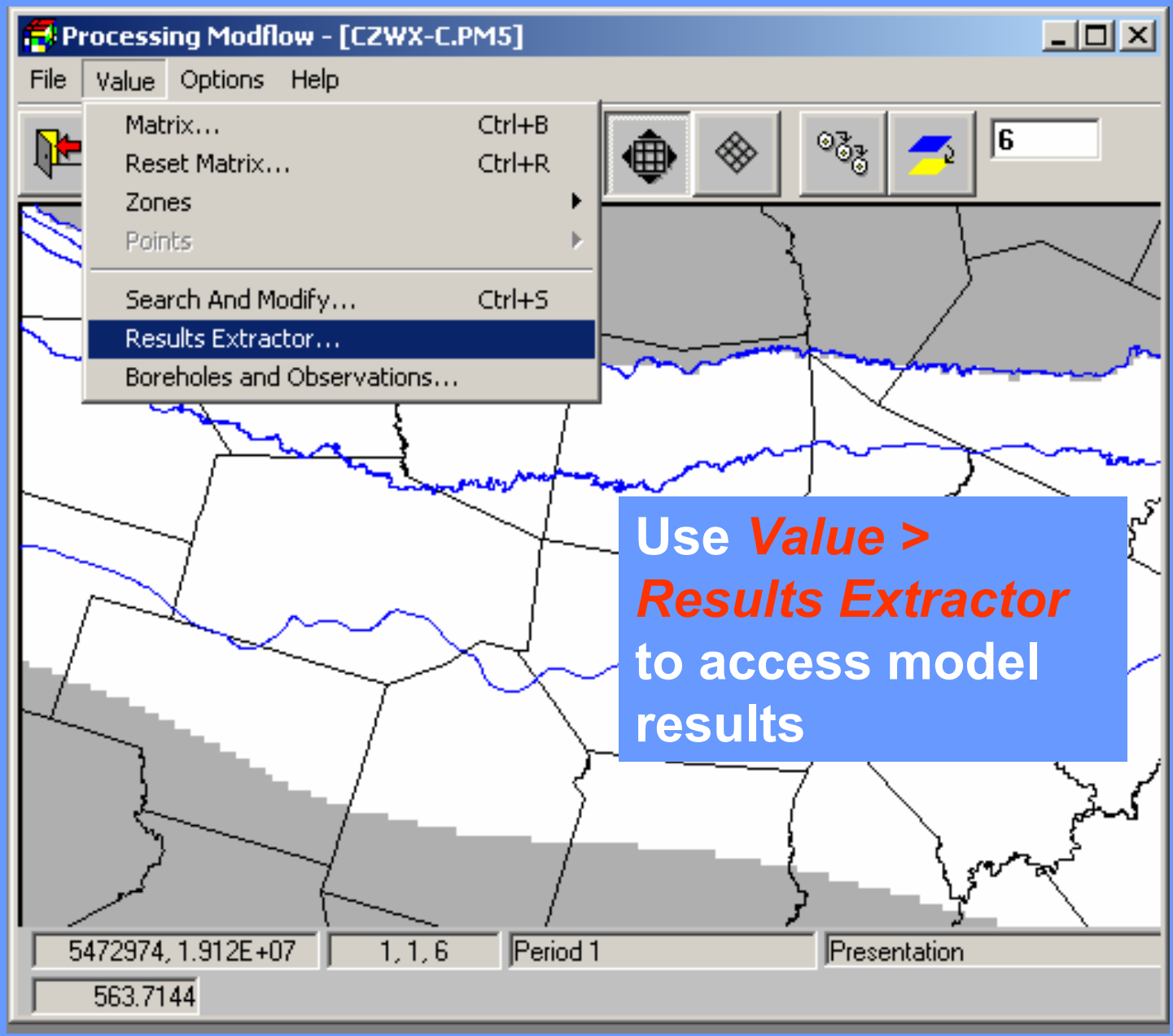


Use *Tools > Presentation* to (a) access model results, and (b) use graphics

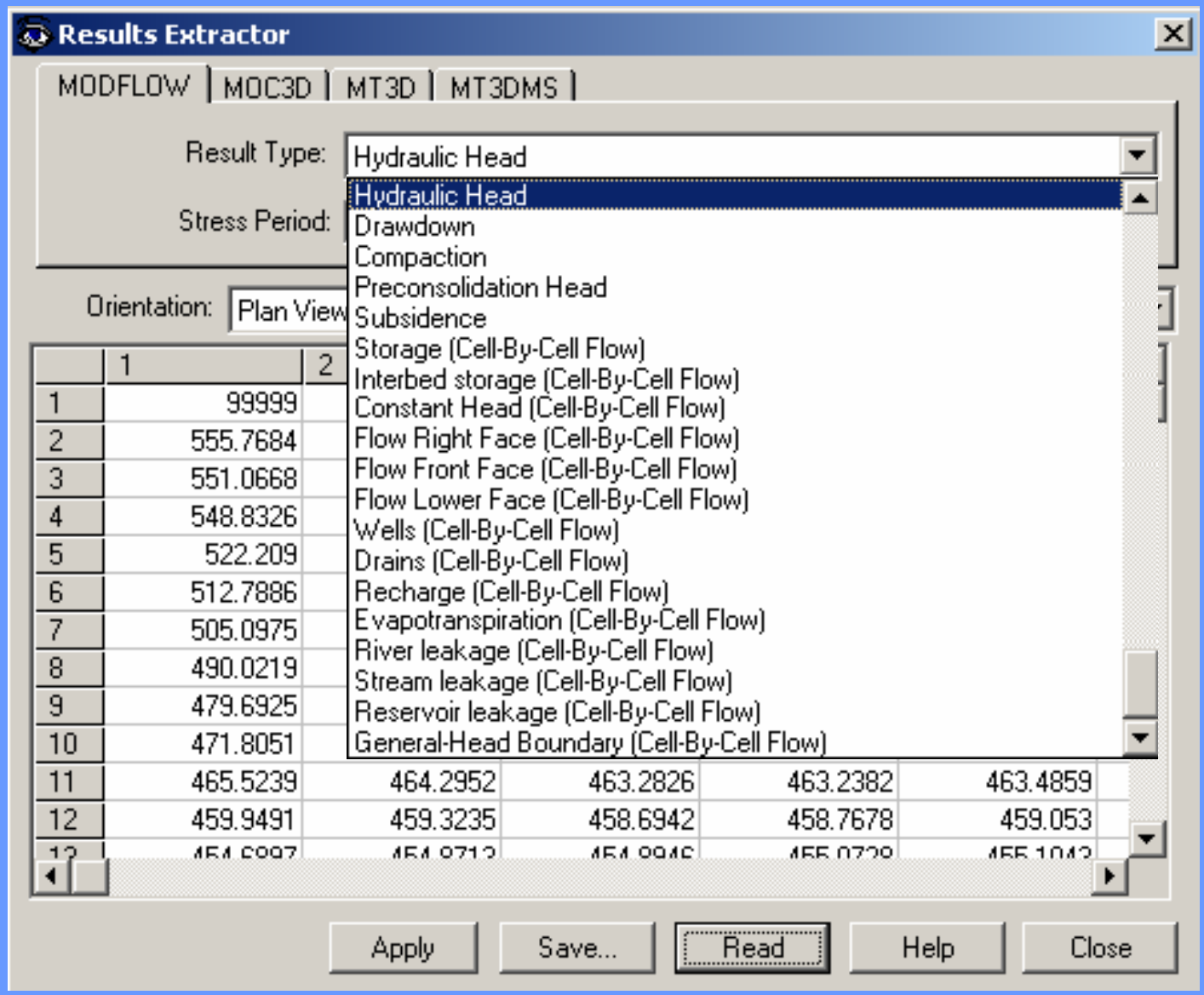
Graphical Data Editor



Value > Results Extractor

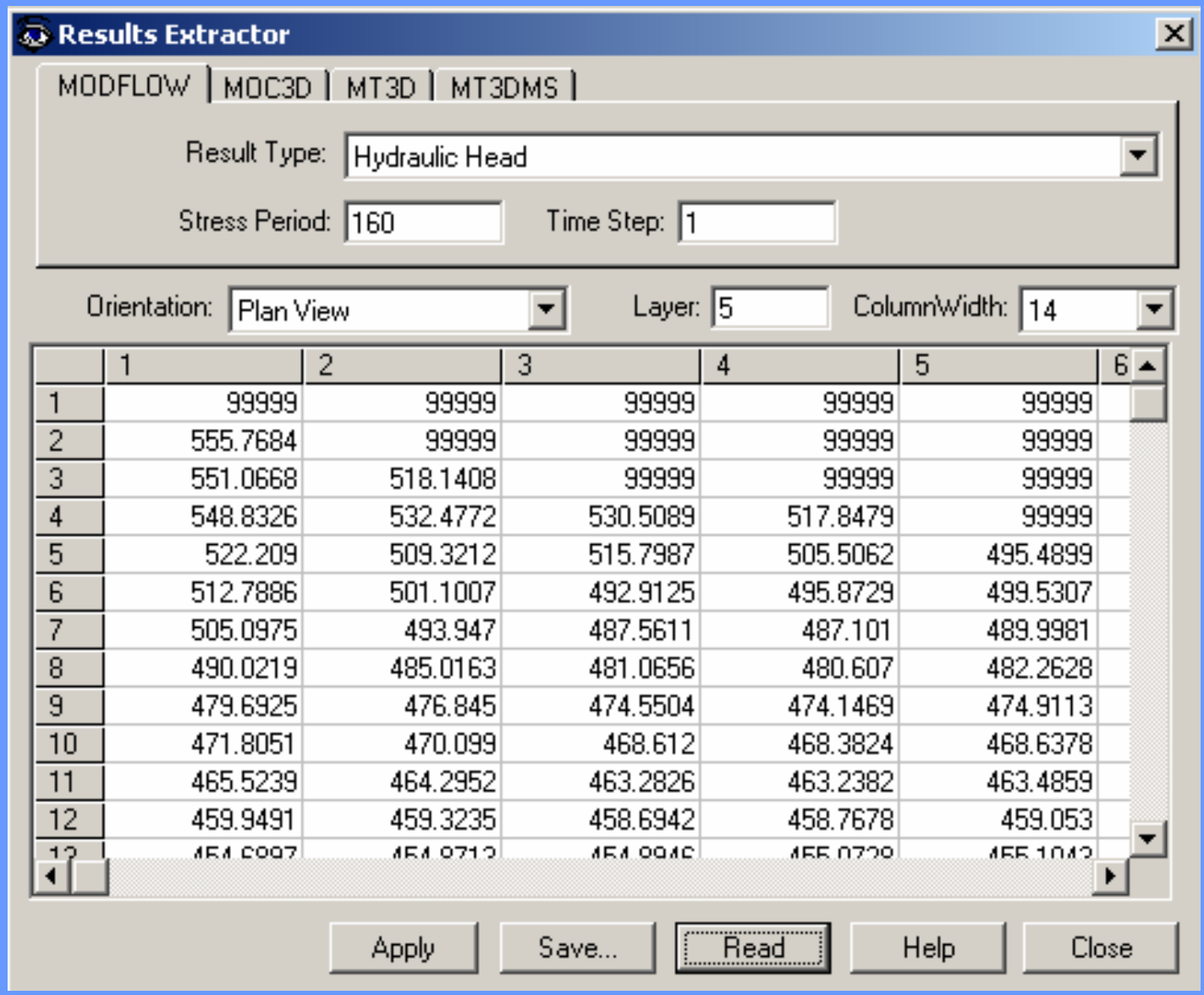


Value > Results Extractor



Results Extractor: ***Read results from simulations for given Result Type***

Value > Results Extractor

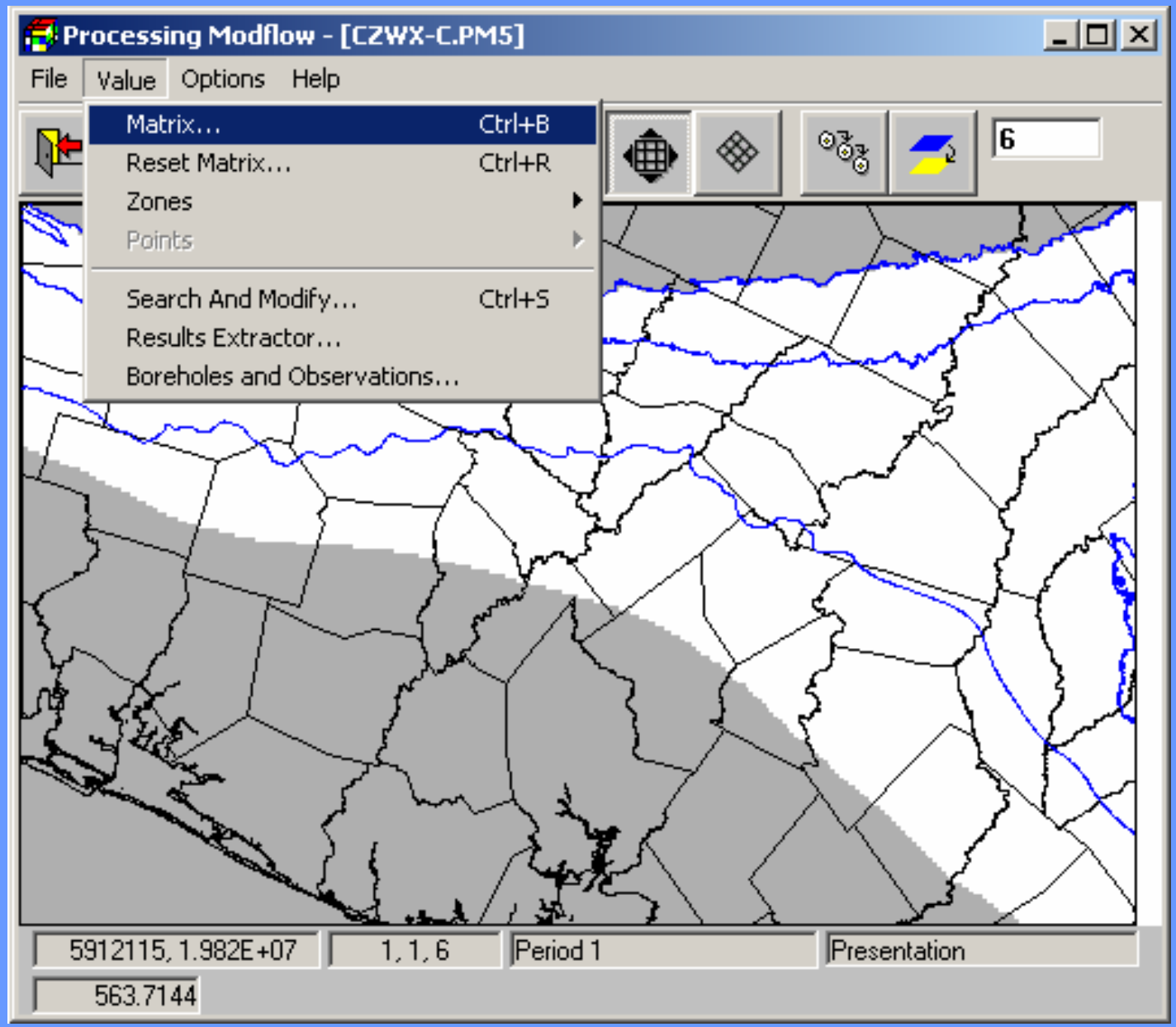


	1	2	3	4	5	6
1	99999	99999	99999	99999	99999	
2	555.7684	99999	99999	99999	99999	
3	551.0668	518.1408	99999	99999	99999	
4	548.8326	532.4772	530.5089	517.8479	99999	
5	522.209	509.3212	515.7987	505.5062	495.4899	
6	512.7886	501.1007	492.9125	495.8729	499.5307	
7	505.0975	493.947	487.5611	487.101	489.9981	
8	490.0219	485.0163	481.0656	480.607	482.2628	
9	479.6925	476.845	474.5504	474.1469	474.9113	
10	471.8051	470.099	468.612	468.3824	468.6378	
11	465.5239	464.2952	463.2826	463.2382	463.4859	
12	459.9491	459.3235	458.6942	458.7678	459.053	

Specify:
Result Type
Period
Time Step
Layer

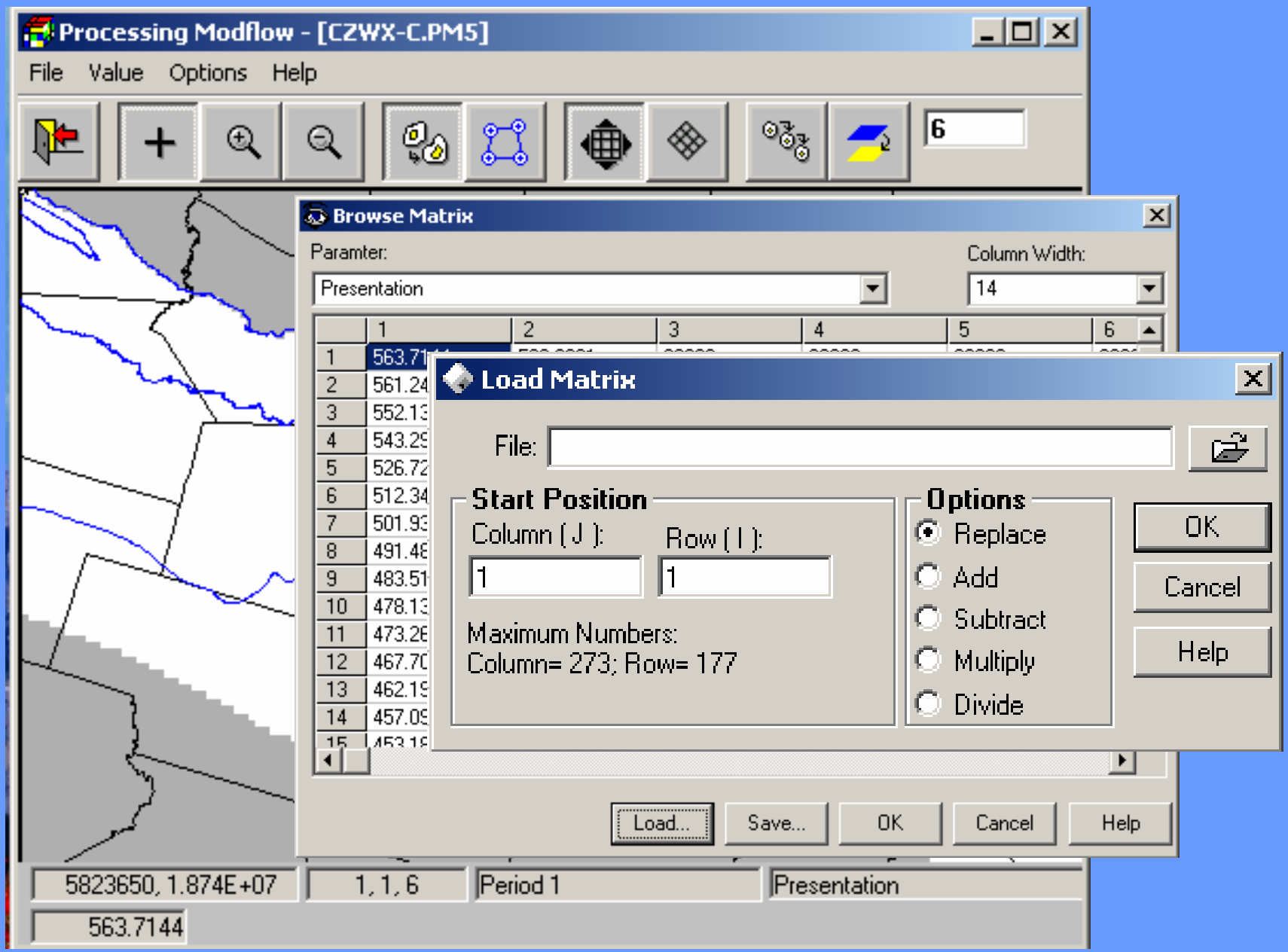
Apply or Save

Value > Matrix



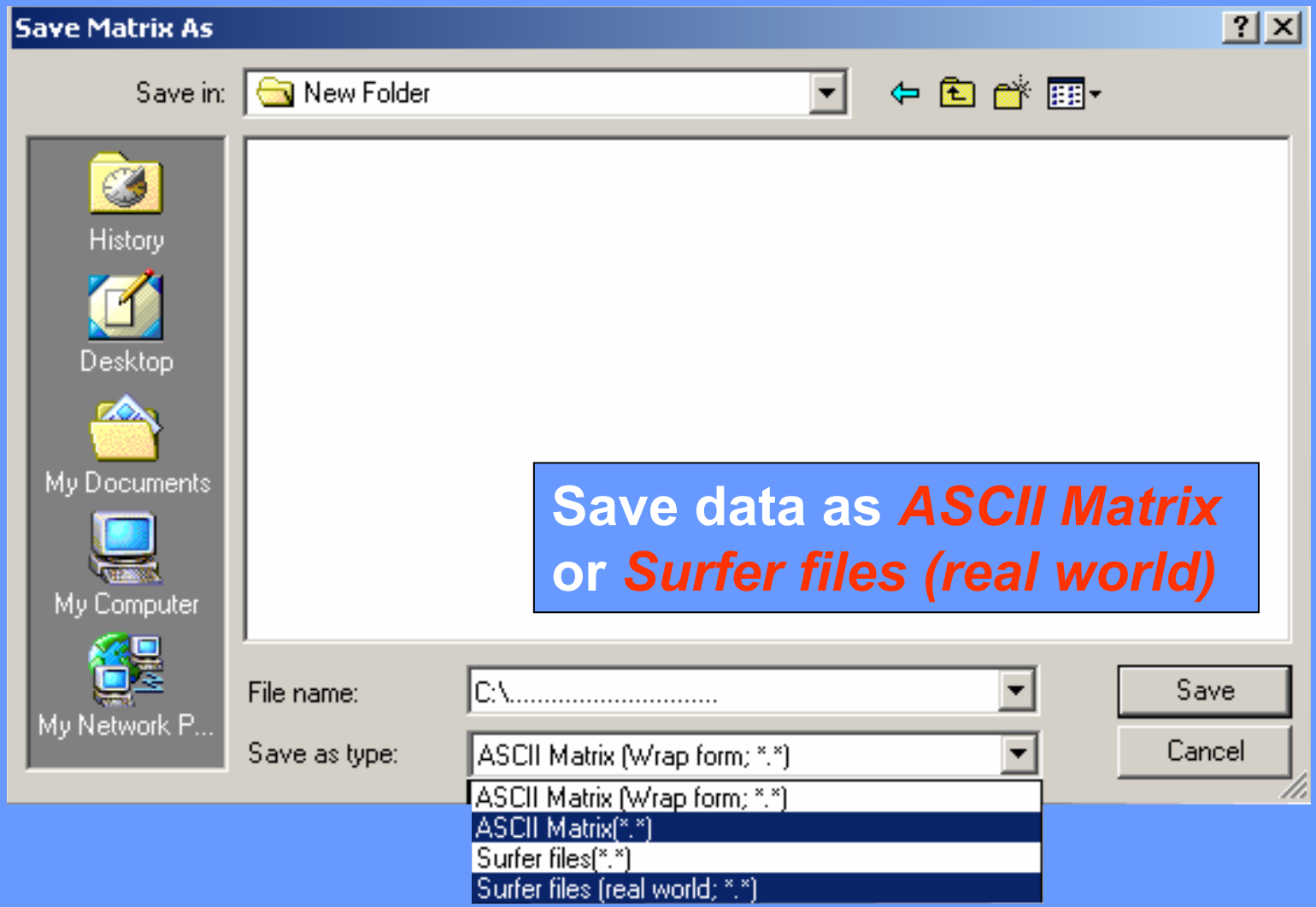
Matrix: ***Load or save data in matrix or x-y format***

Value > Matrix > Load

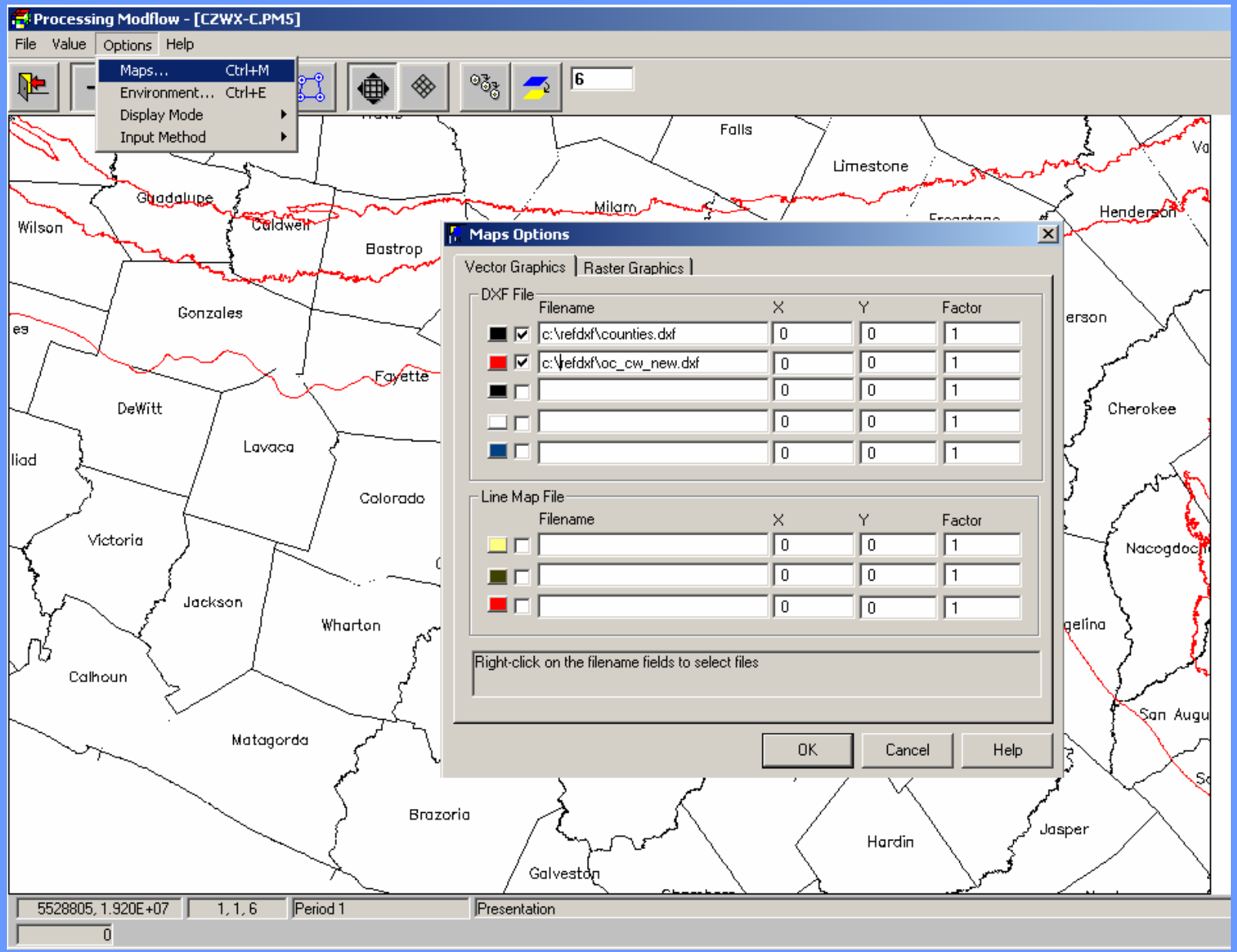


Value > Matrix > Save

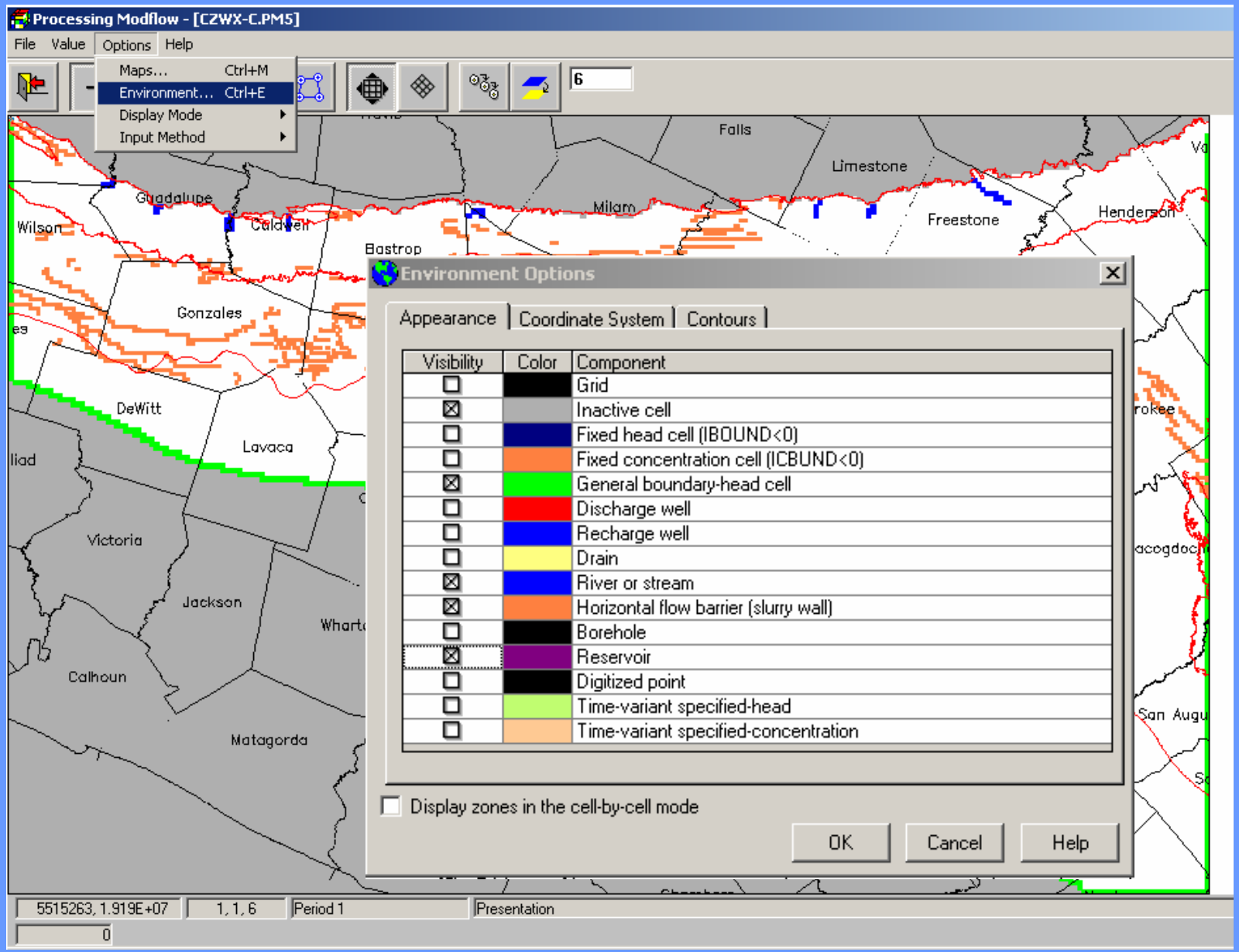
Save Matrix As



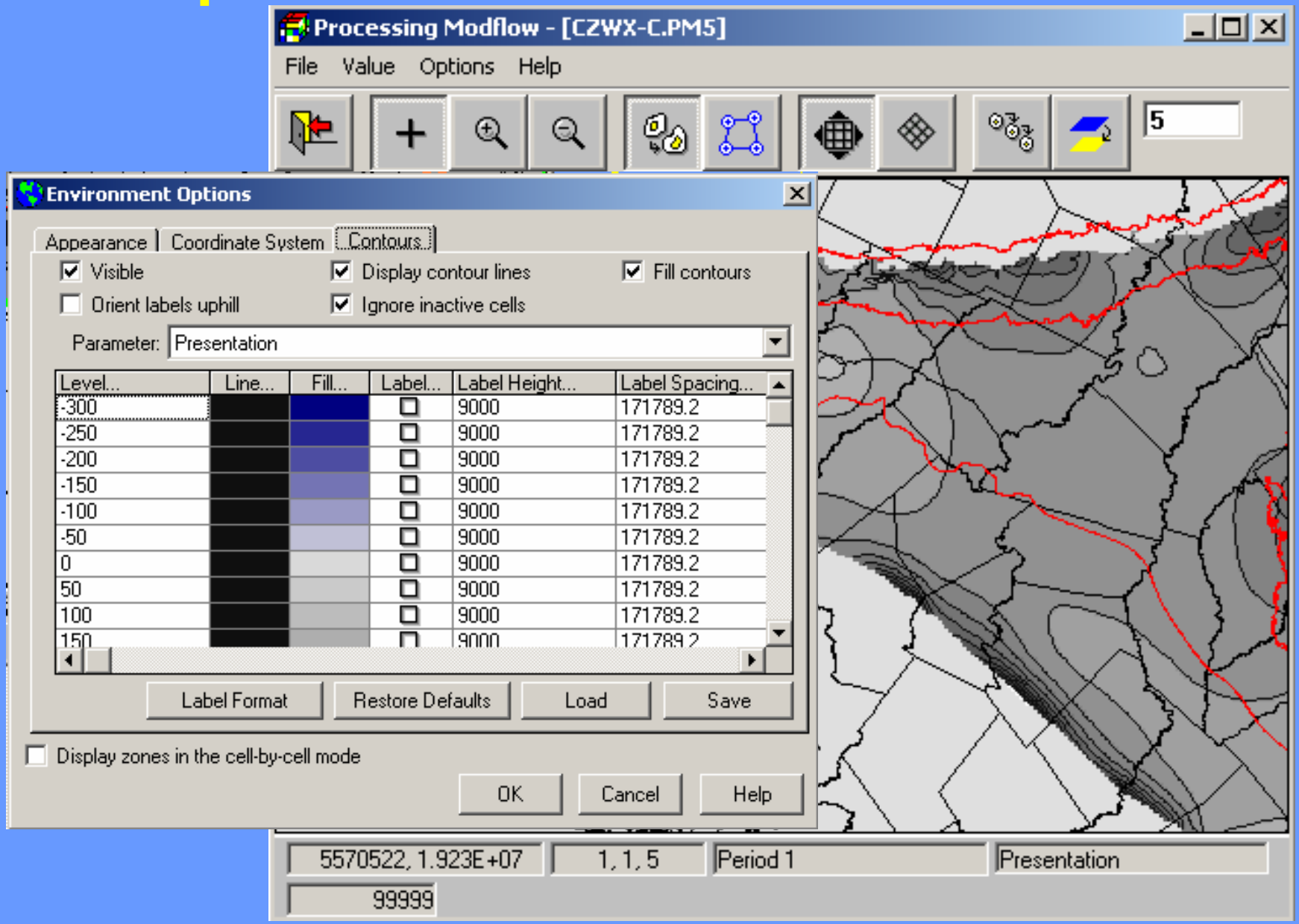
Options > Maps > Vector Graphics



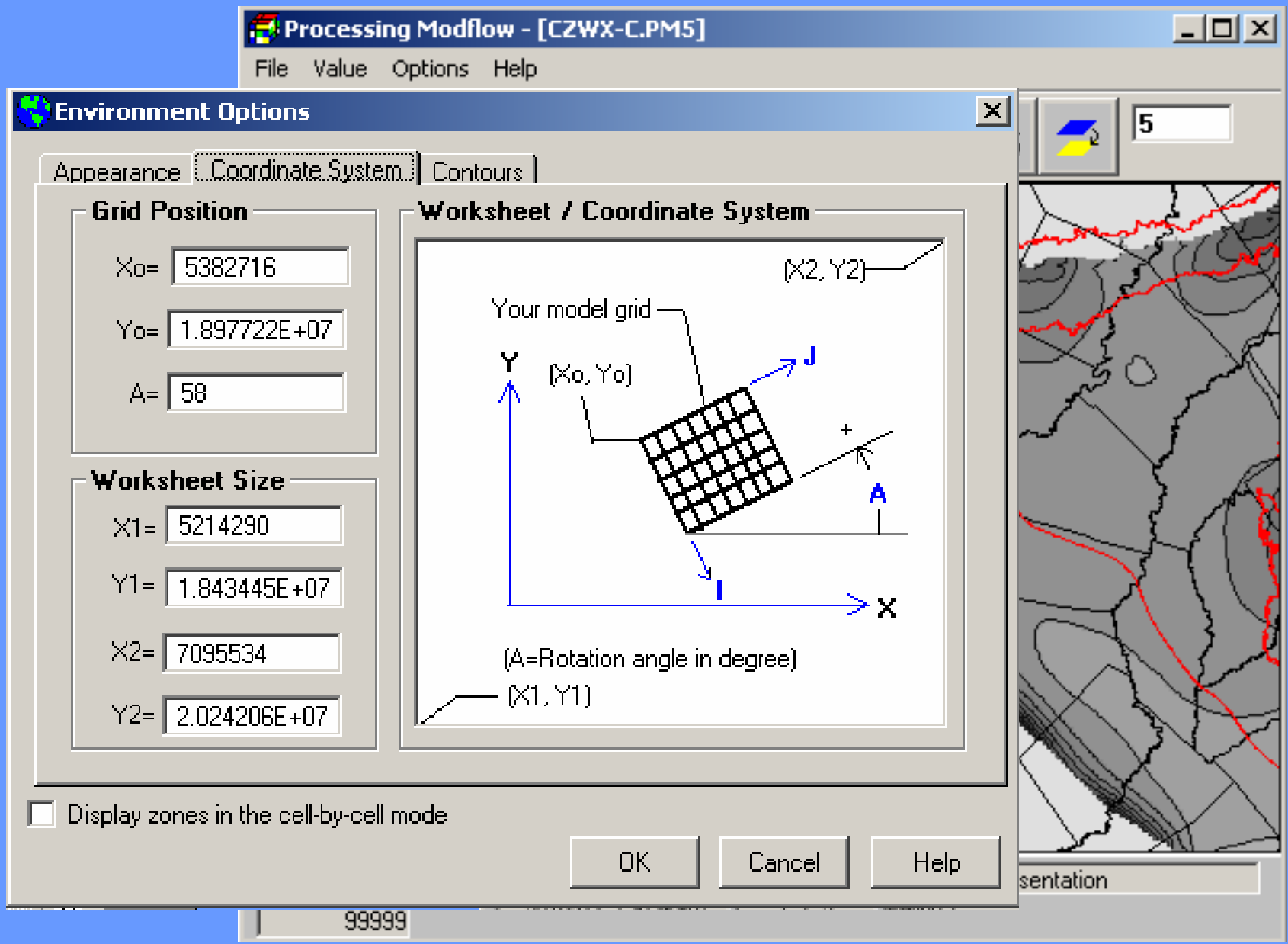
Options > Environment.. > Appearance



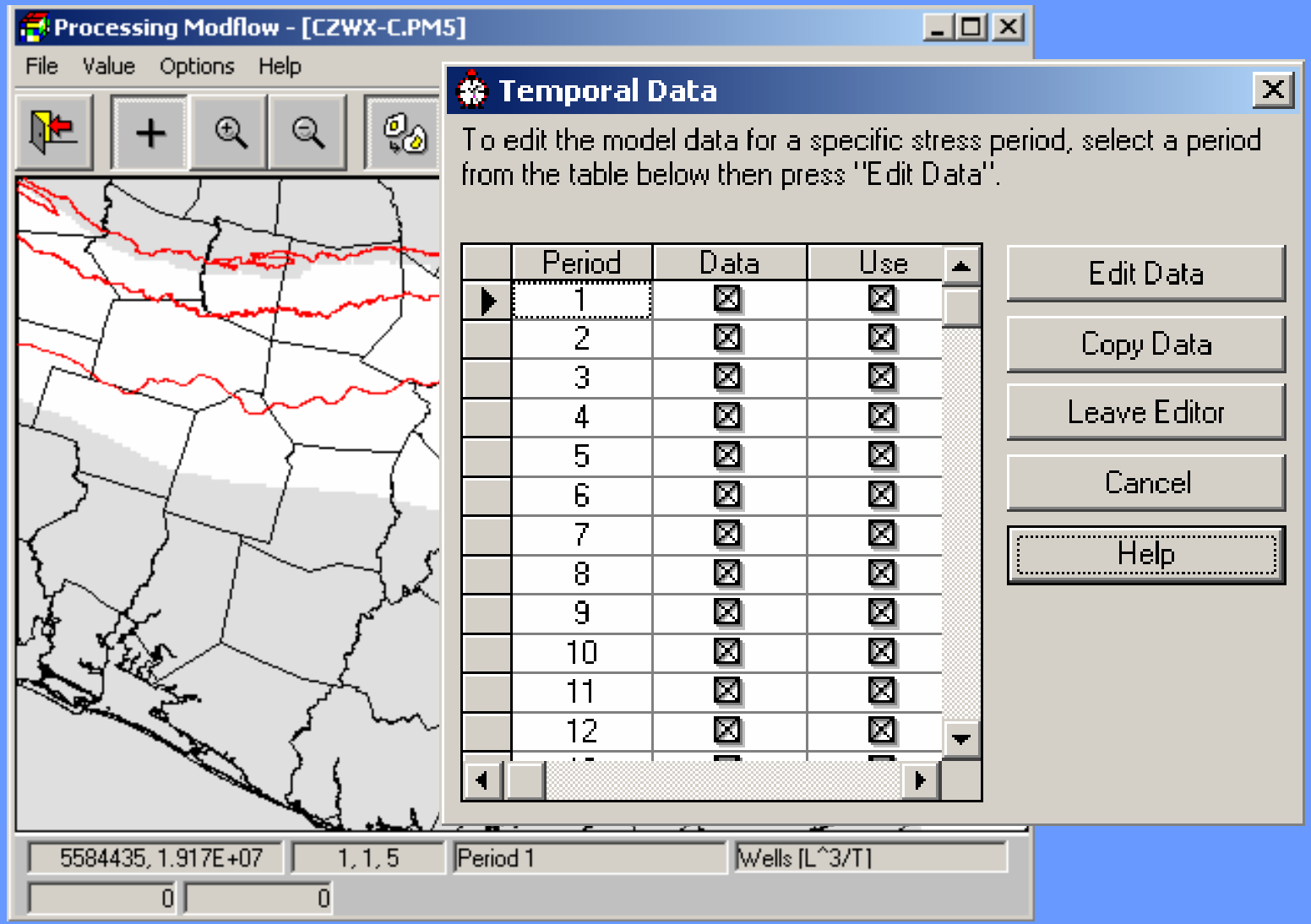
Options > Environment > Contours



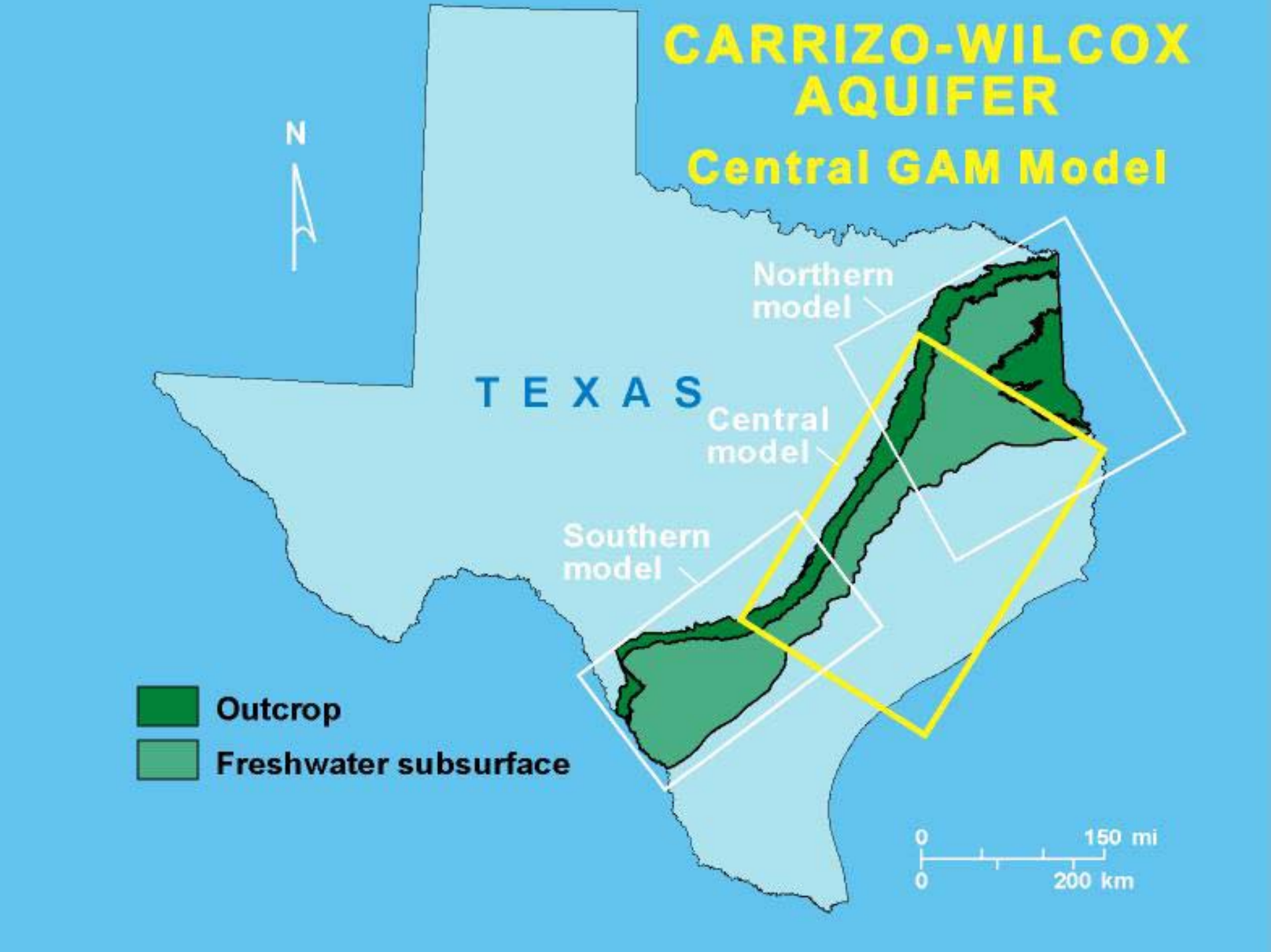
Options > Environment.. > Coordinate System



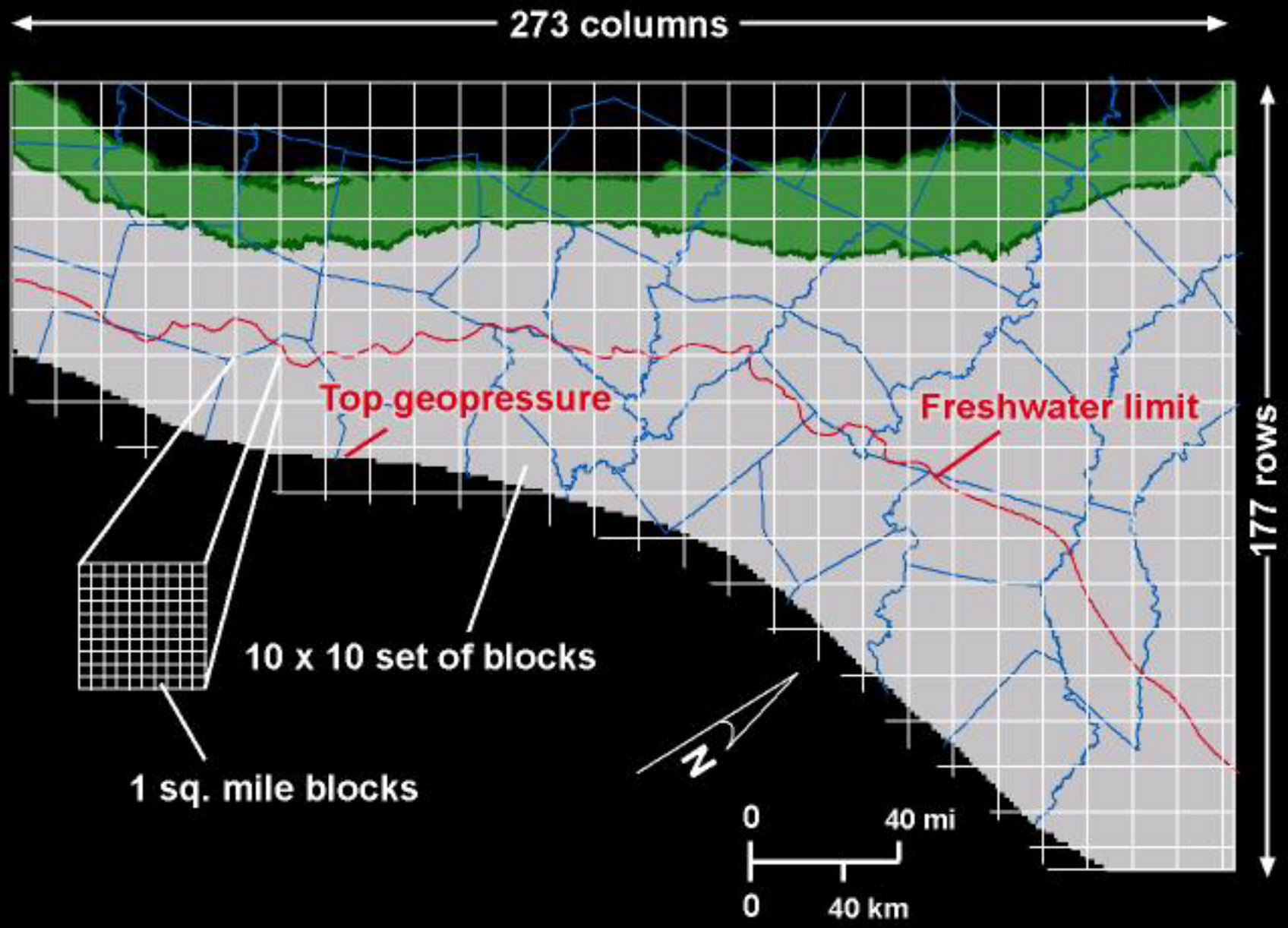
Specification of Data for Transient Simulations



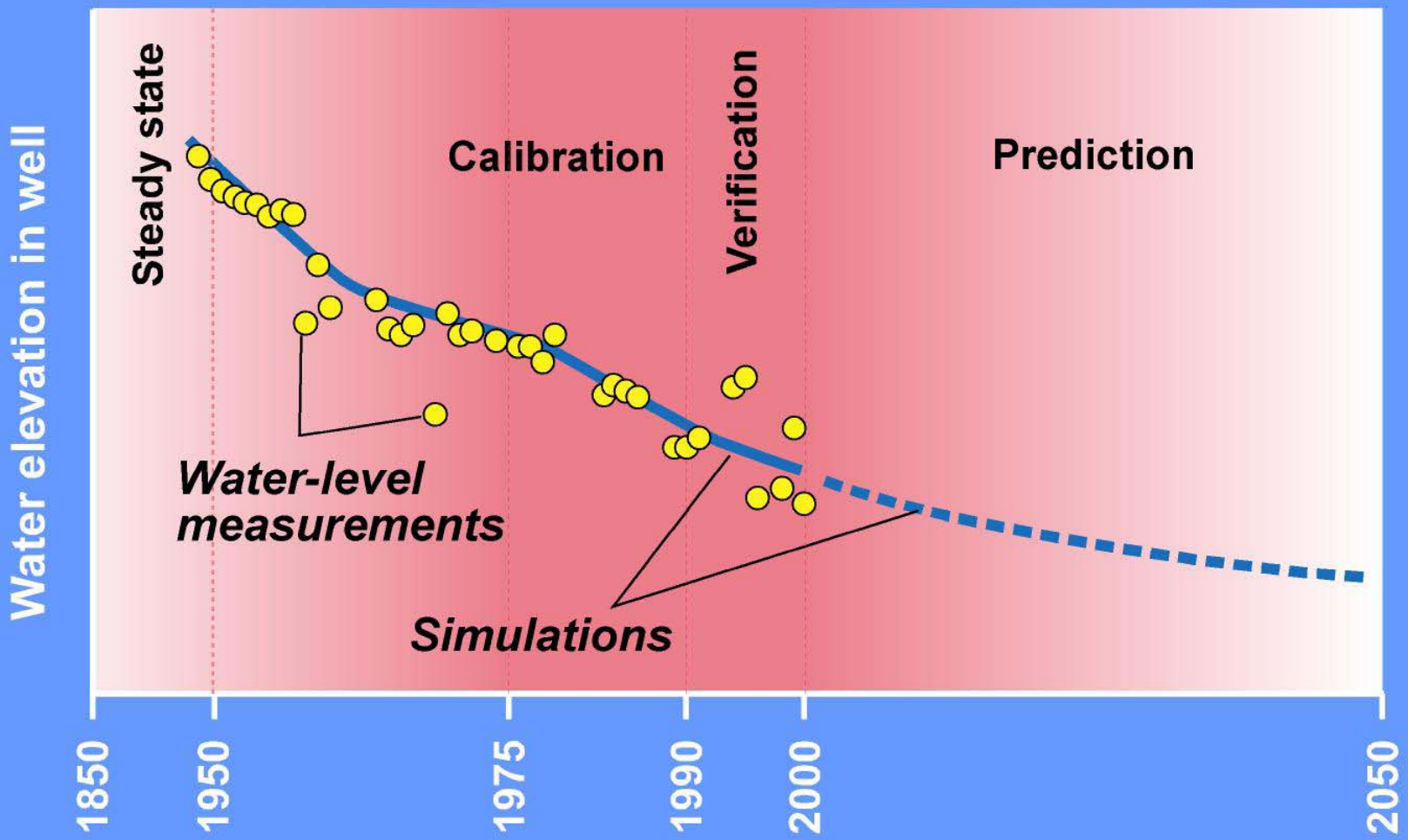
Part 3.
Technical Review of the CW-c GAM model


CARRIZO-WILCOX AQUIFER
Central GAM Model
N
TEXAS
Northern model
Central model
Southern model
Outcrop
Freshwater subsurface
0
150 mi
0
200 km

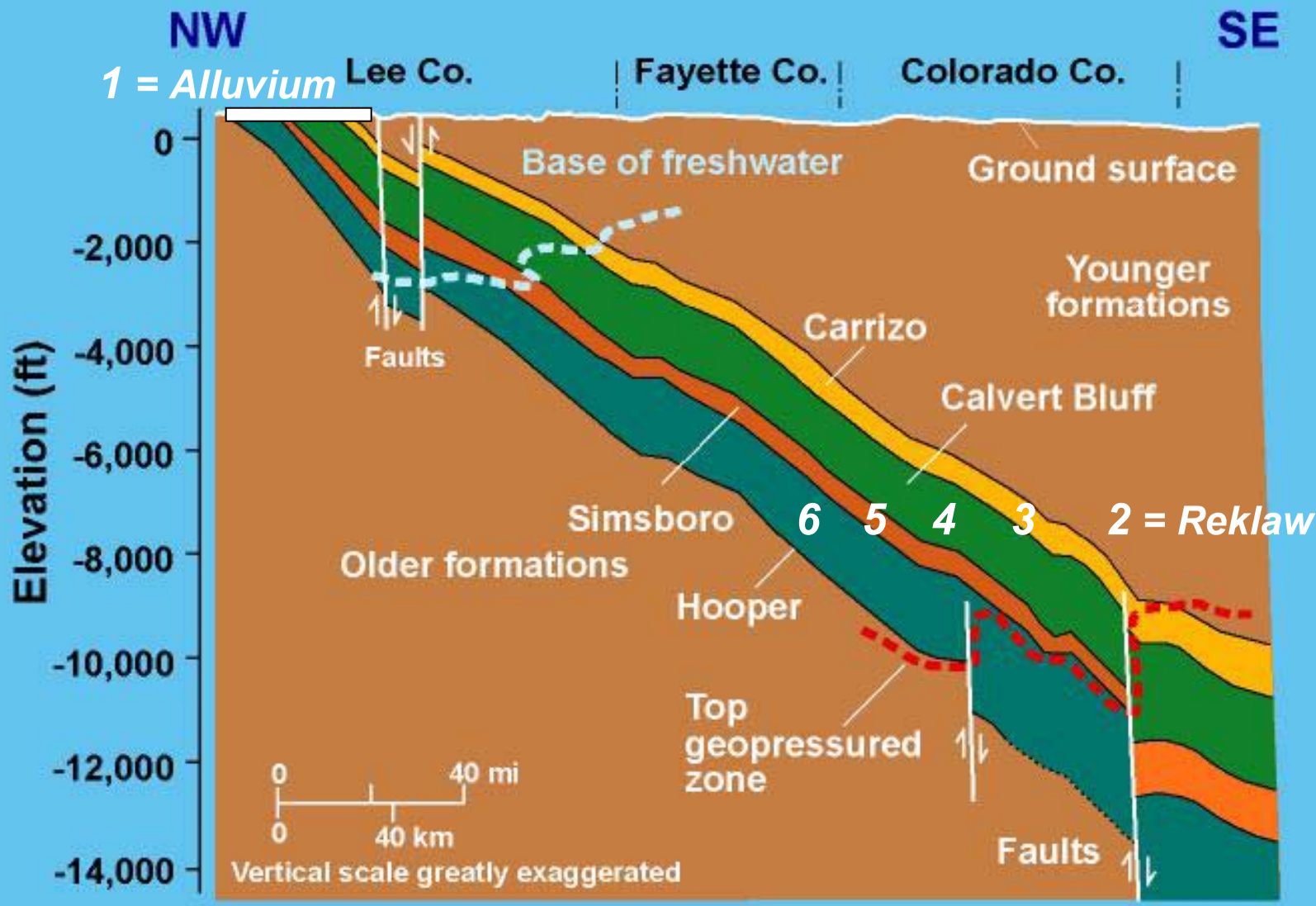
MODEL GRID


273 columns
177 rows
Top geopressure
Freshwater limit
10 x 10 set of blocks
1 sq. mile blocks
N
0
40 mi
0
40 km

MODELING PERIODS



CARRIZO-WILCOX HYDROGEOLOGY
Central Part of Model Area

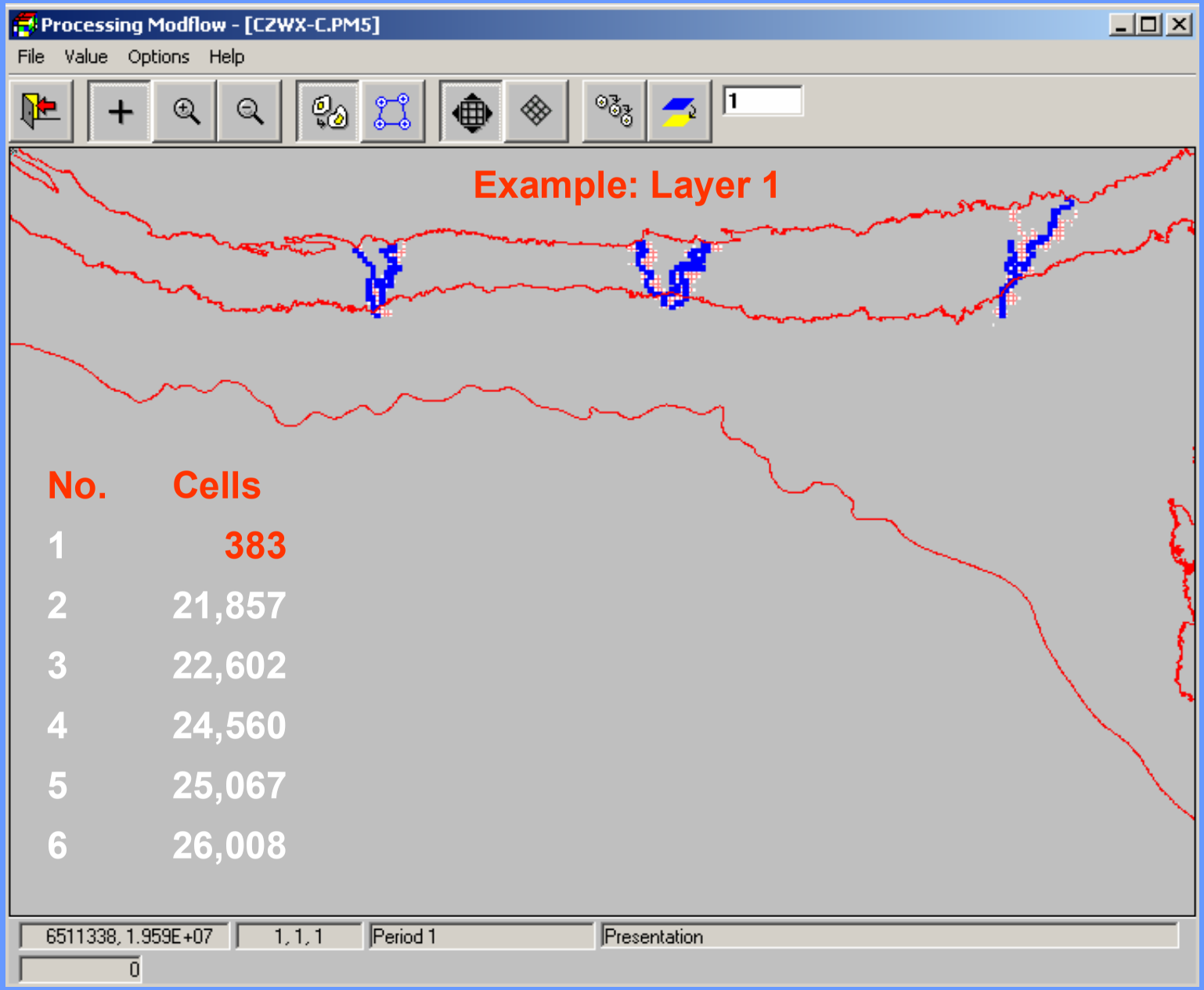


GAM MODEL INFORMATION REQUIREMENTS

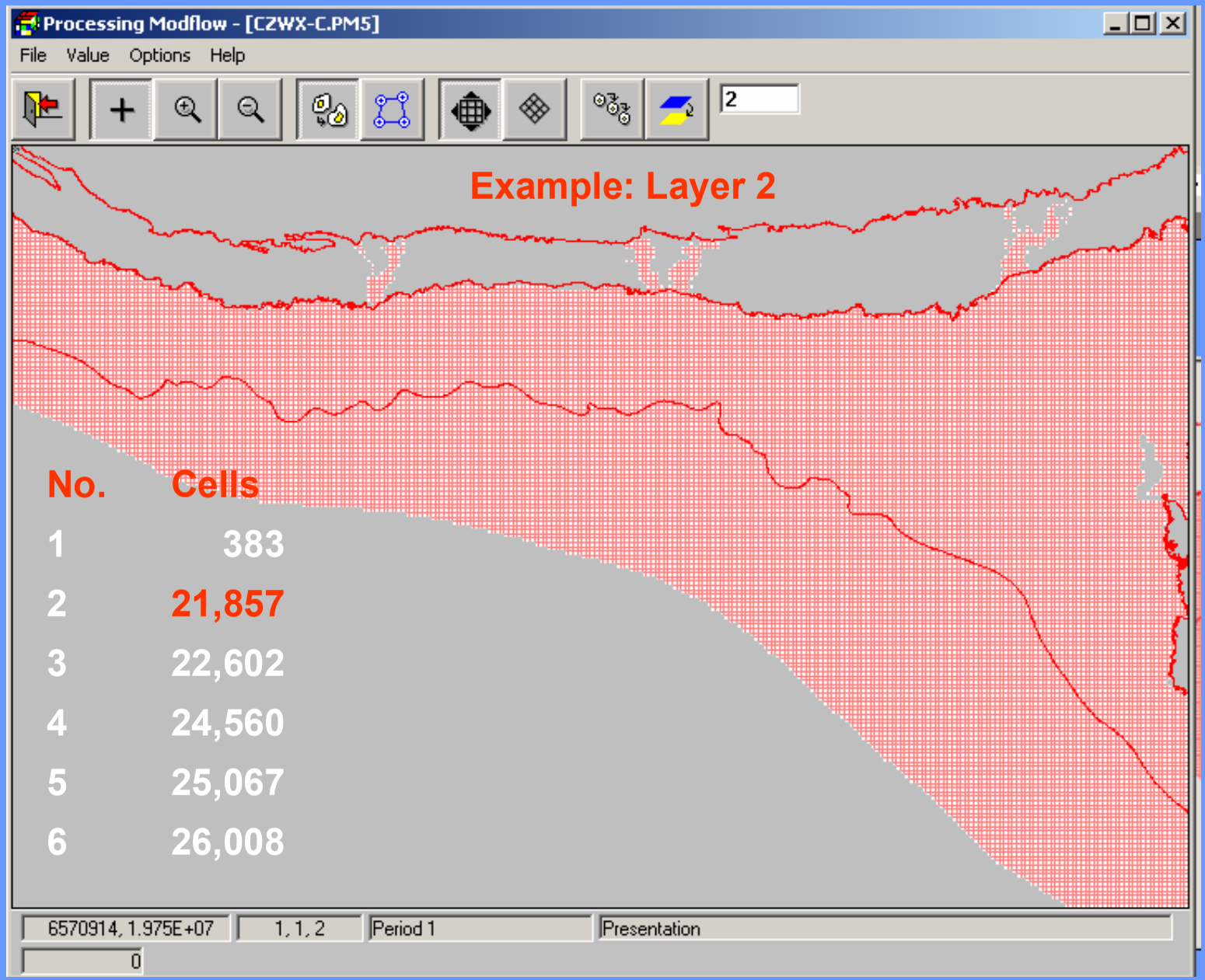
$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(T_z \frac{\partial h}{\partial z}\right) + W = S \frac{\partial h}{\partial t}$$

- **Aquifer geometry**
  - Model grid
  - Model perimeter and extent (active and inactive cells)
  - Top elevation of layers
  - Bottom elevation of layers
  - Water levels (initial and calibration)
- **Aquifer properties**
  - Hydraulic conductivity (horizontal and vertical)
  - Storage coefficient and specific yield
  - Horizontal flow barrier
- **Boundary conditions and fluxes**
  - Recharge
  - Surface water interaction (Stream flow routing, Reservoirs)
  - Groundwater ET
  - Pumping
  - Top, bottom, and lateral boundaries (e.g., GHB)
- **Solver**

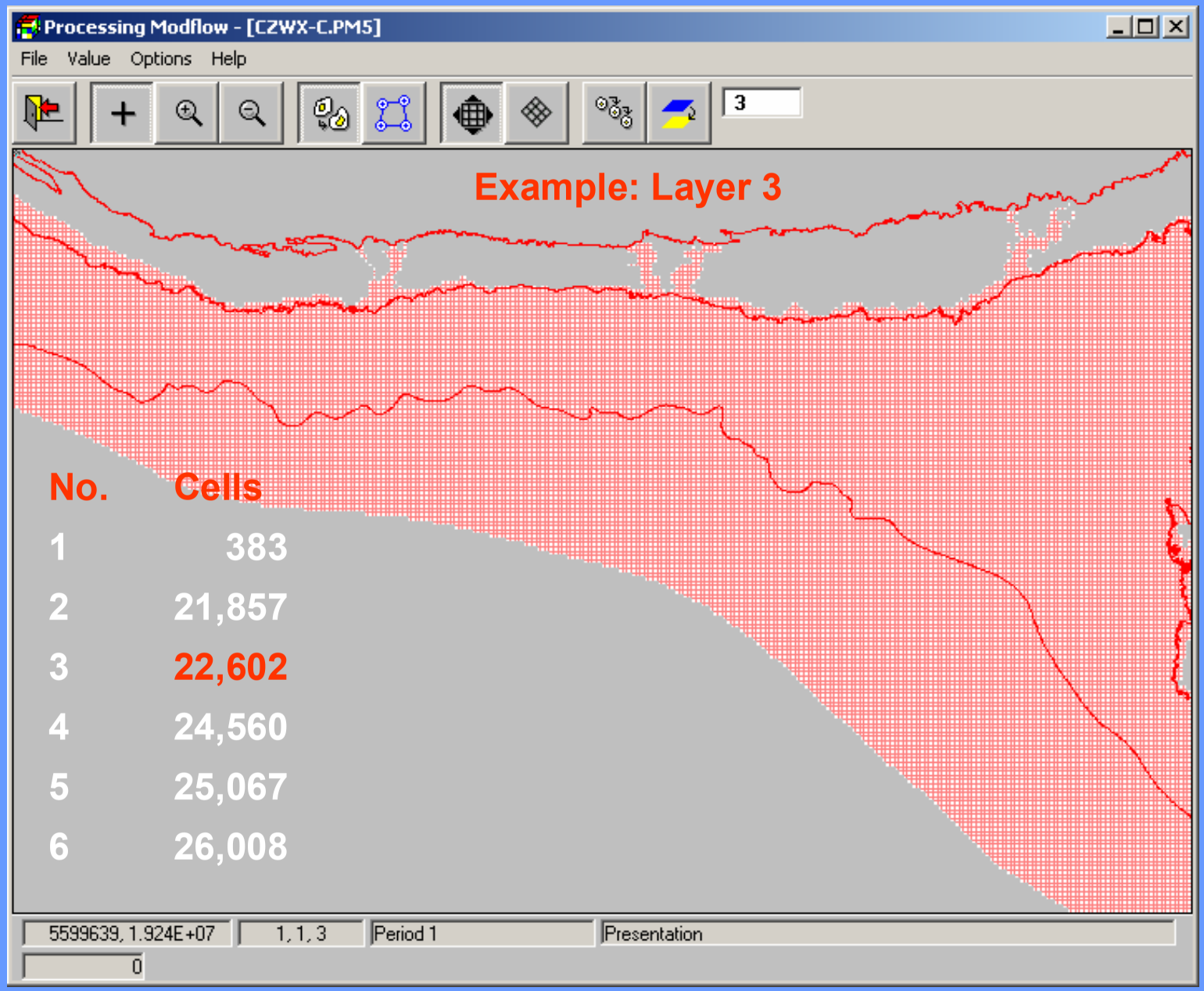
MODEL GRID


Processing Modflow - [CZWX-C.PM5]
File Value Options Help
1
Example: Layer 1
No. Cells
1 383
2 21,857
3 22,602
4 24,560
5 25,067
6 26,008
6511338, 1.959E+07
1, 1, 1
Period 1
Presentation
0

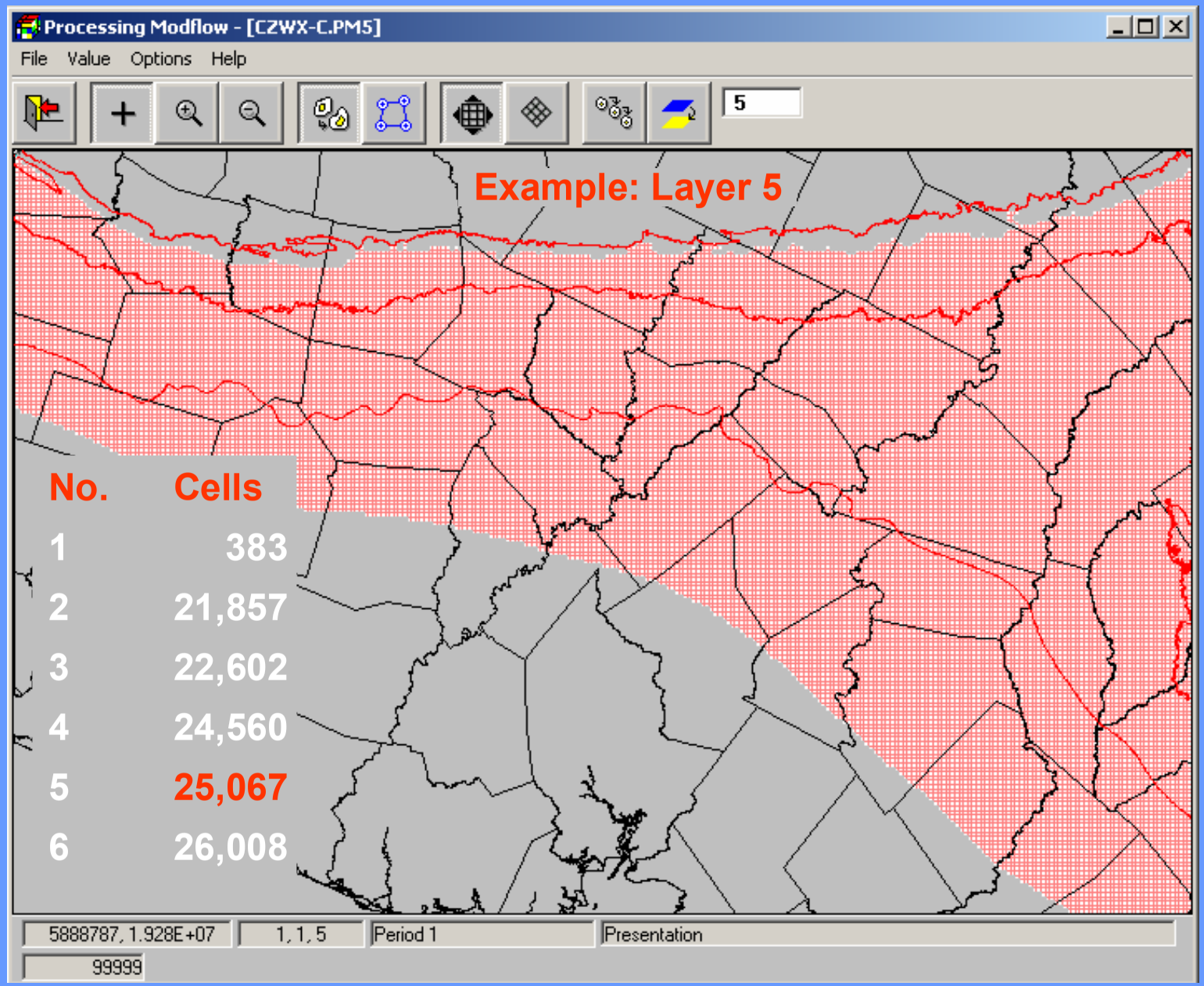
MODEL GRID


Processing Modflow - [CZWX-C.PM5]
File Value Options Help
2
Example: Layer 2
No. Cells
1 383
2 21,857
3 22,602
4 24,560
5 25,067
6 26,008
6570914, 1.975E+07
1, 1, 2
Period 1
Presentation
0

MODEL GRID


Processing Modflow - [CZWX-C.PM5]
File Value Options Help
3
Example: Layer 3
No. Cells
1 383
2 21,857
3 22,602
4 24,560
5 25,067
6 26,008
5599639, 1.924E+07
1, 1, 3
Period 1
Presentation
0

MODEL GRID


Processing Modflow - [CZWX-C.PM5]
File Value Options Help
5
Example: Layer 5
No. Cells
1 383
2 21,857
3 22,602
4 24,560
5 25,067
6 26,008
5888787, 1.928E+07
1, 1, 5
Period 1
Presentation
99999

Supporting Data

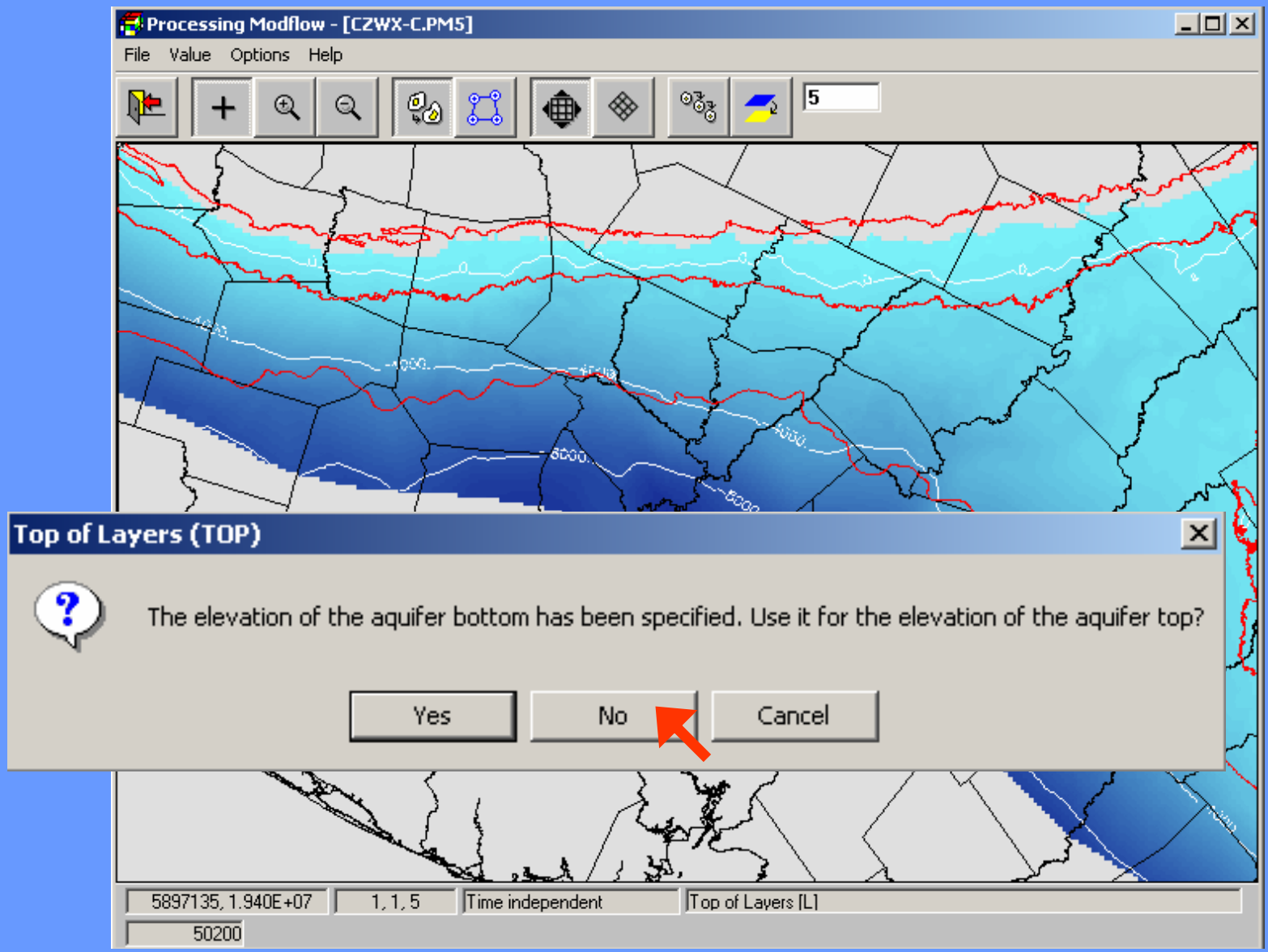
Model parameter	Data
Structure	Geophysical well logs, DEM for outcrop
Hydraulic properties (Kh, Kv), (S)	Field data, previous models, net sand maps, structure
Recharge	Field data, previous model results, Model calibrated
Base flow to streams	Outcrop watershed statistics
Reservoirs	Calibration target is poorly constrained
Initial and calibration water-level elevations	Field data from TWDB http://www.twdb.state.tx.us/data/waterwell/well_info.html
Groundwater ET	Average net lake evaporation Other terms calibrated
Pumping	Water use surveys, RWPG projections

Structure Data Mapping

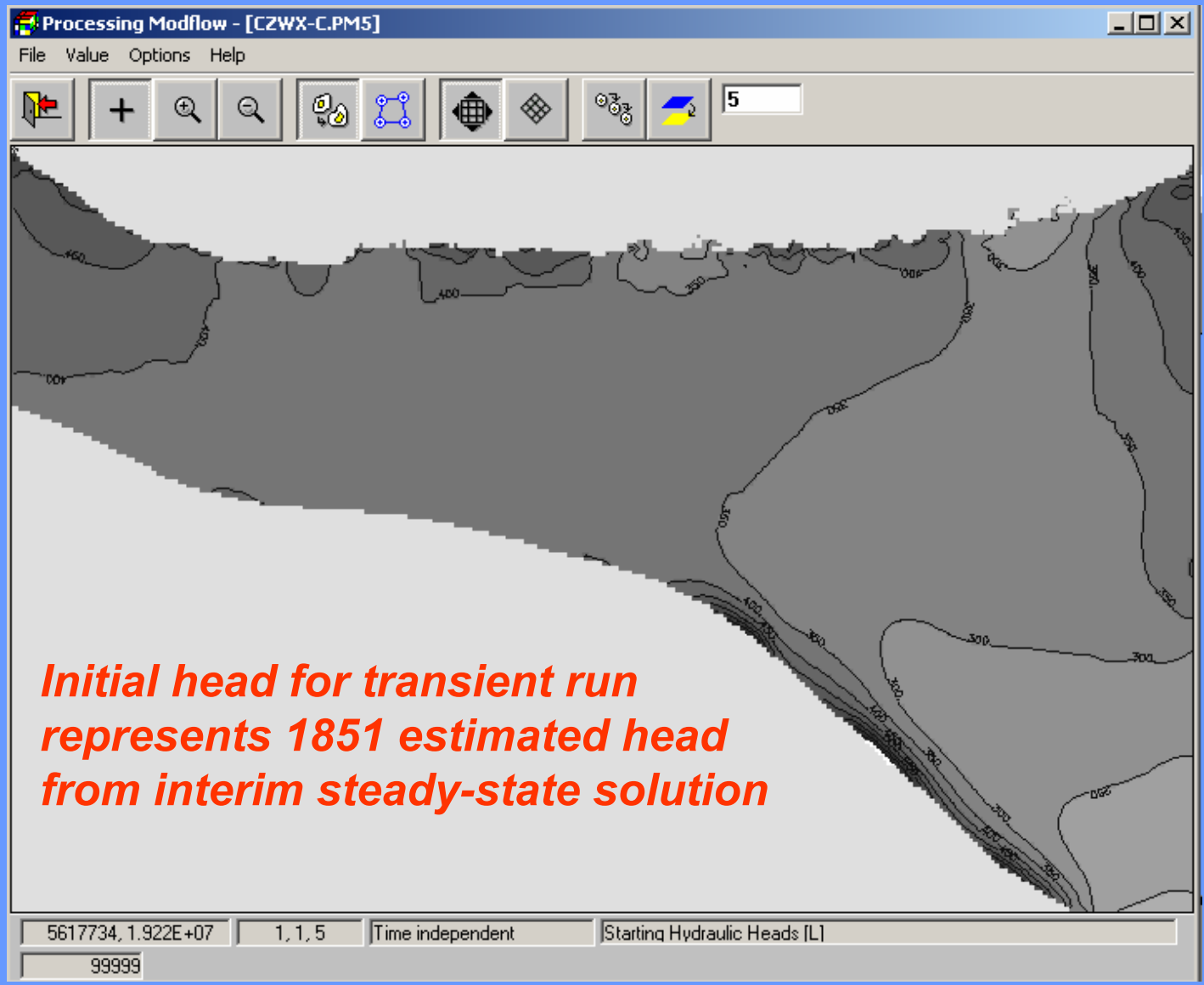
	Ayers and Lewis (1985)	Thorkildsen (unpublished)	Hosman and Weiss (1991)	Kaiser (1990)	DEM	Well data
Alluvium					×	×
Reklaw	×	×			×	
Carrizo	×	×	×		×	
Calvert Bluff	×	×			×	
Simsboro	×	×		×	×	
Hooper	×	×	×		×	

Mapping of structure data was coordinated between *CW-n*, *CW-c*, and *CW-s* models

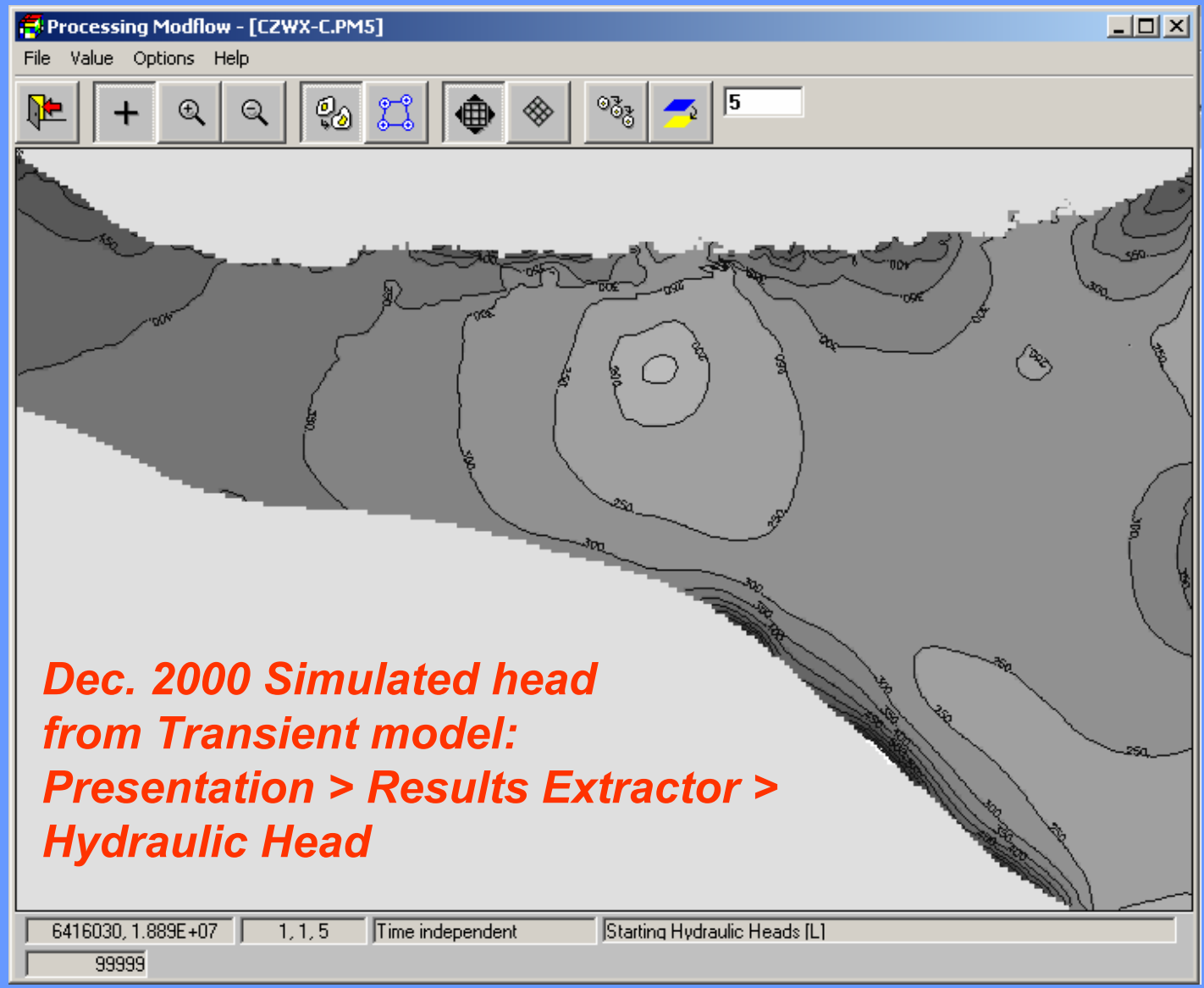
Structure Data Mapping



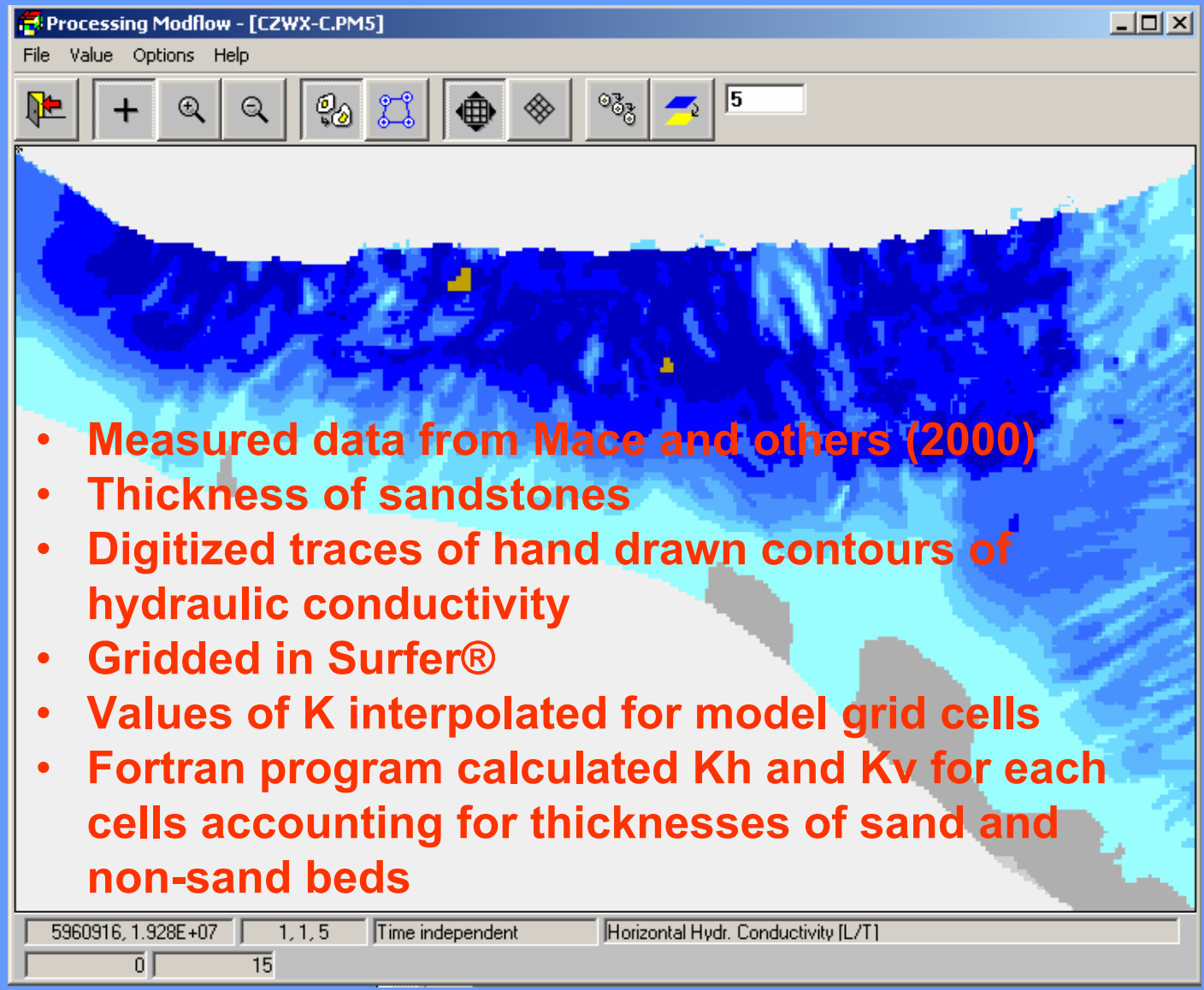
Initial Hydraulic Heads
(Steady-state and Transient Model Run)



Initial Hydraulic Heads
(Predictive Run)

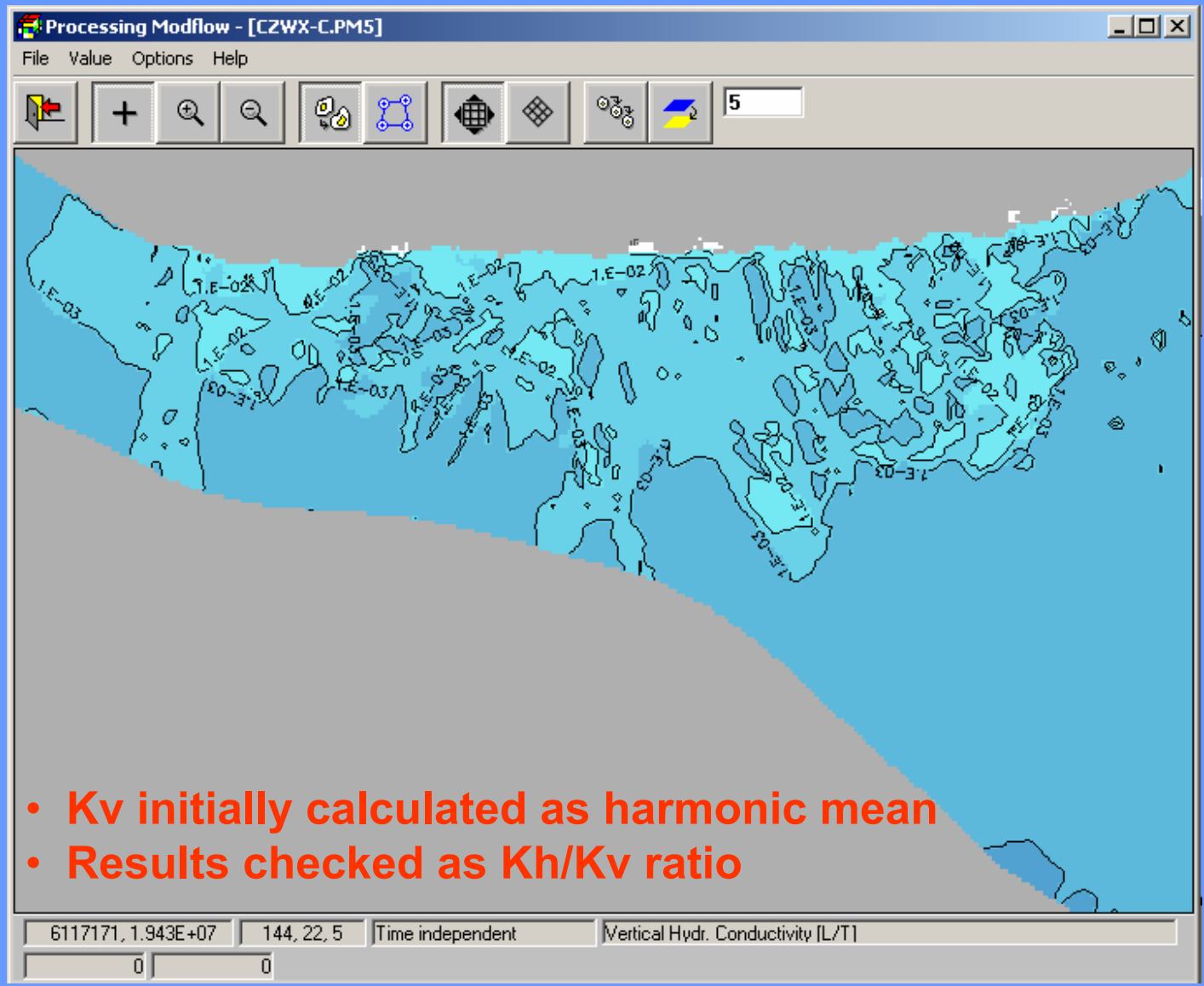


Horizontal Hydraulic Conductivity (Kh)

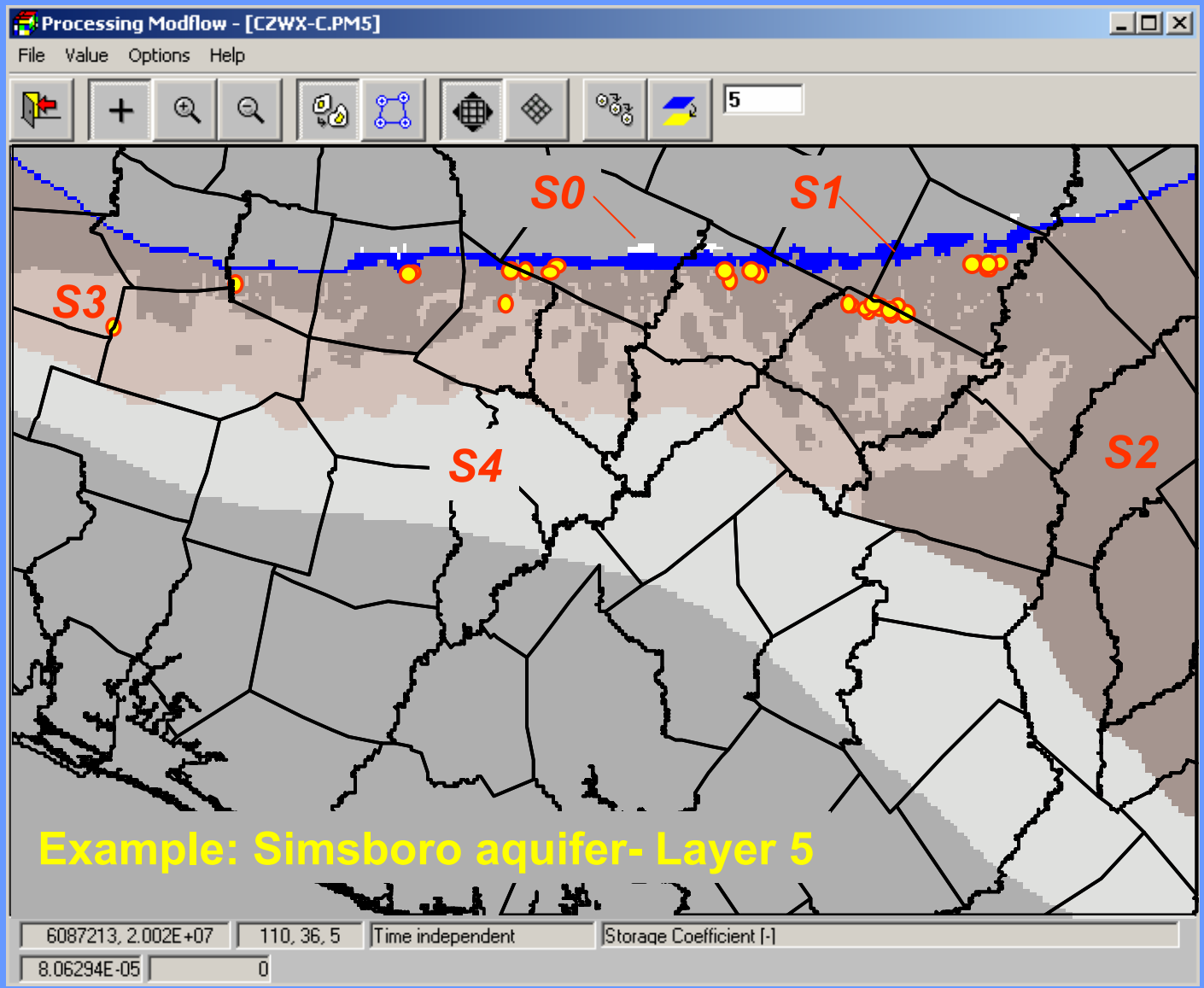


- Measured data from Mace and others (2000)
- Thickness of sandstones
- Digitized traces of hand drawn contours of hydraulic conductivity
- Gridded in Surfer®
- Values of K interpolated for model grid cells
- Fortran program calculated Kh and Kv for each cells accounting for thicknesses of sand and non-sand beds

Vertical Hydraulic Conductivity (Kv)



Storativity (S)



- All C-W field S data

S varied with depth and sand content

S0: 0.25 (Additional cells)

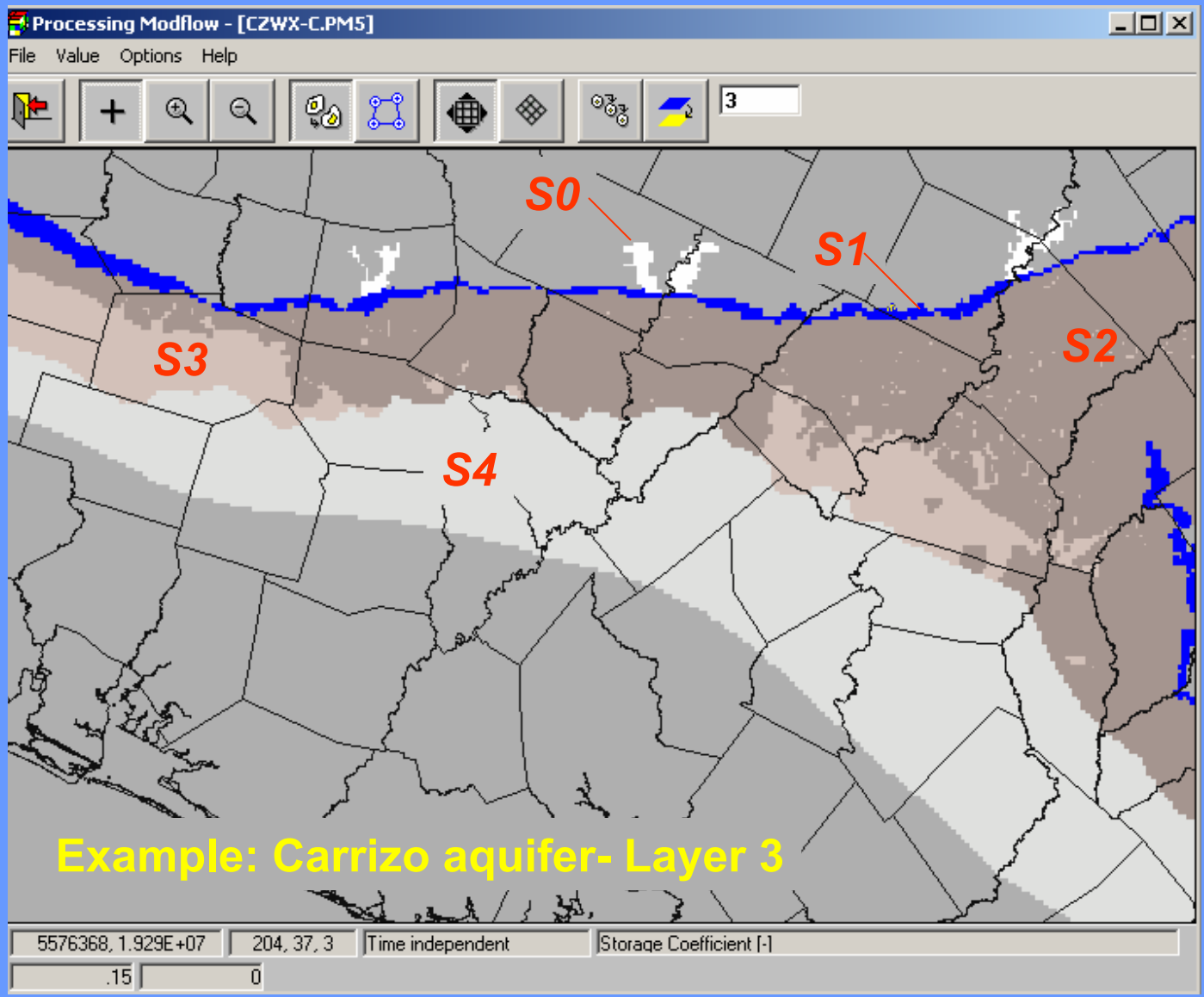
S1: 0.15 (Outcrop cells)

S2: $10^{-3.5}$ to 10^{-4}

S3: 10^{-4} to $10^{-4.5}$

S4: $10^{-4.5}$

Storativity (S)



S varied with depth and sand content

S0: 0.25 (Additional cells)

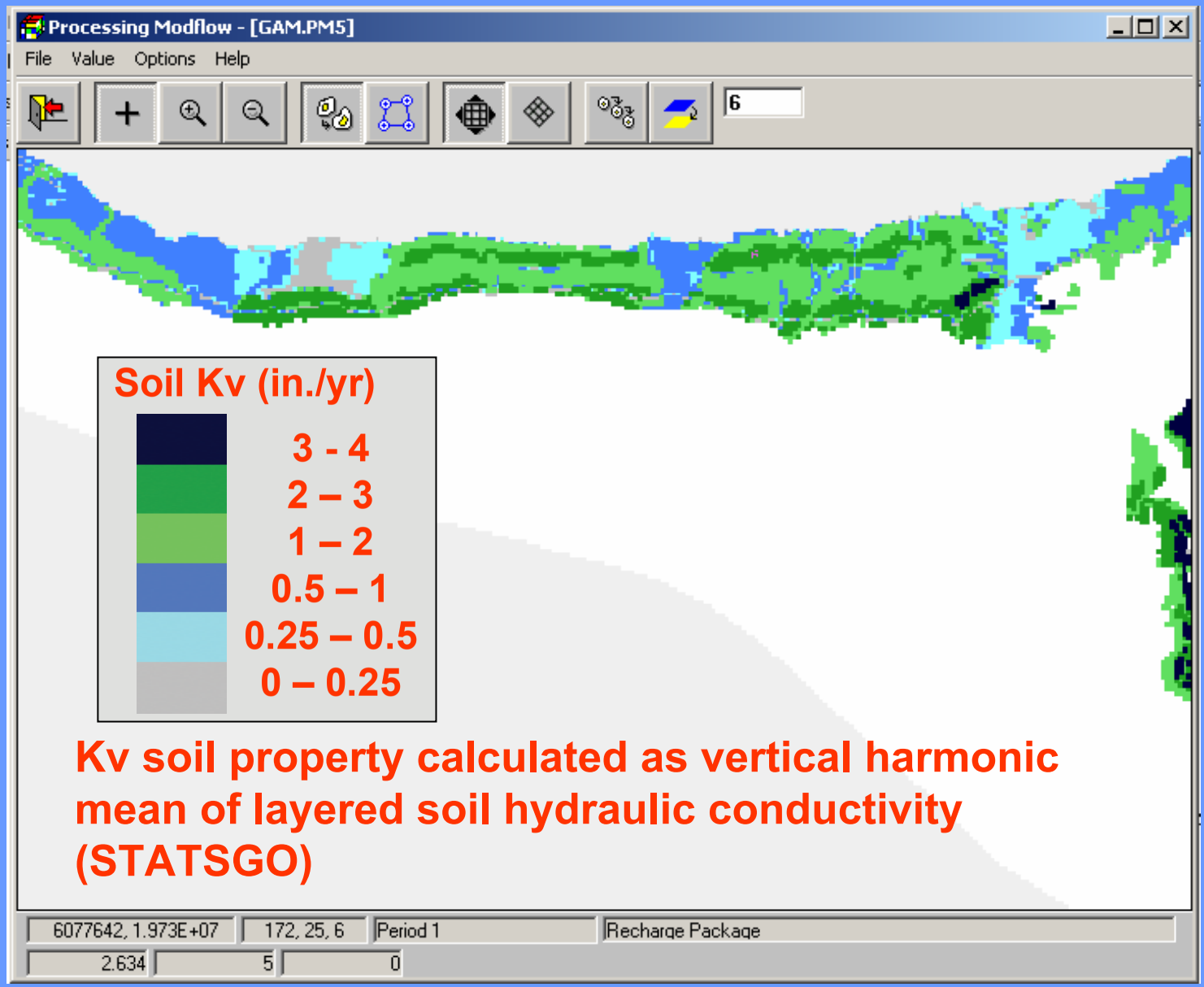
S1: 0.15 (Outcrop cells)

S2: $10^{-3.5}$ to 10^{-4}

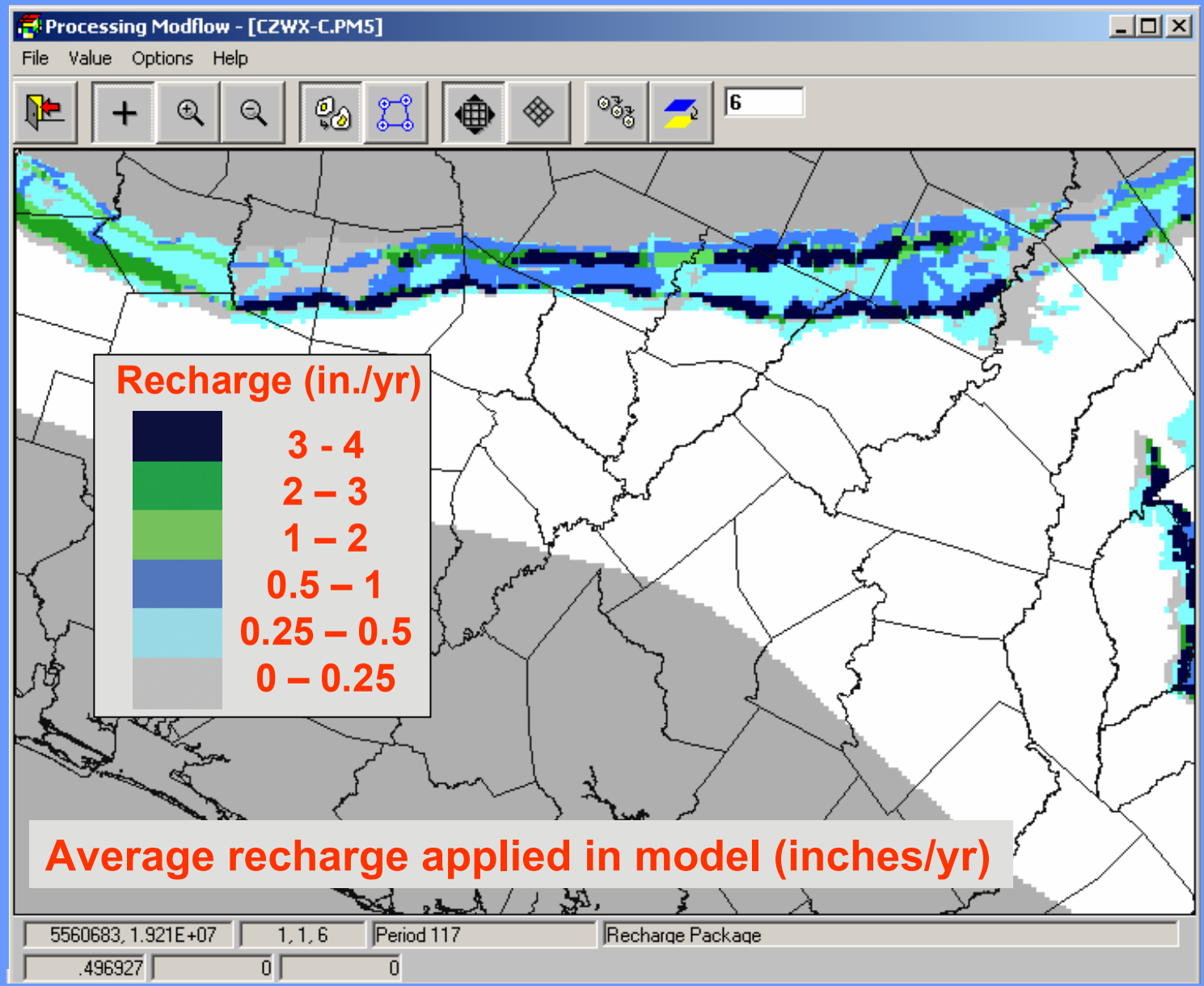
S3: 10^{-4} to $10^{-4.5}$

S4: $10^{-4.5}$

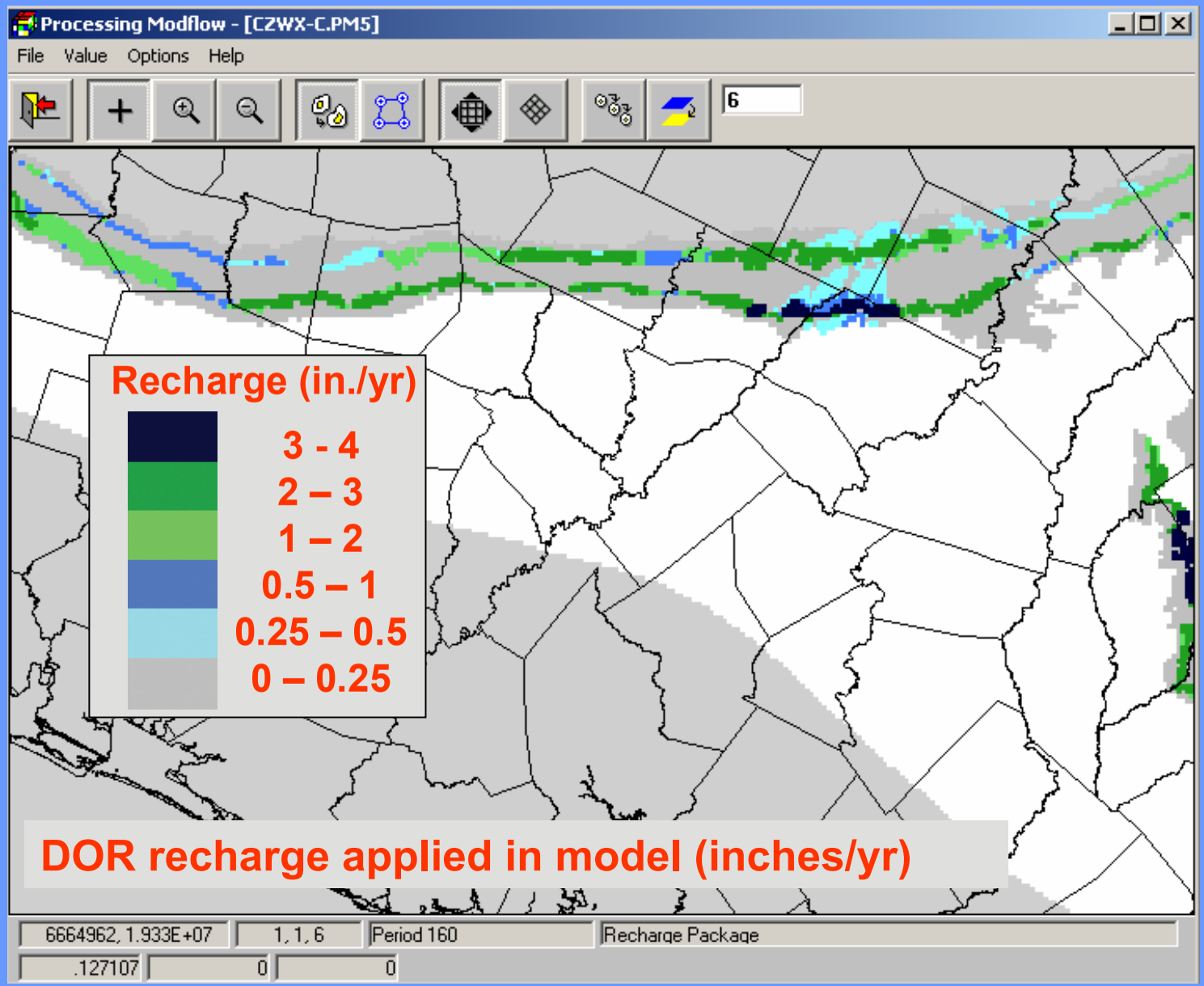
Soil Kv for Map of Recharge



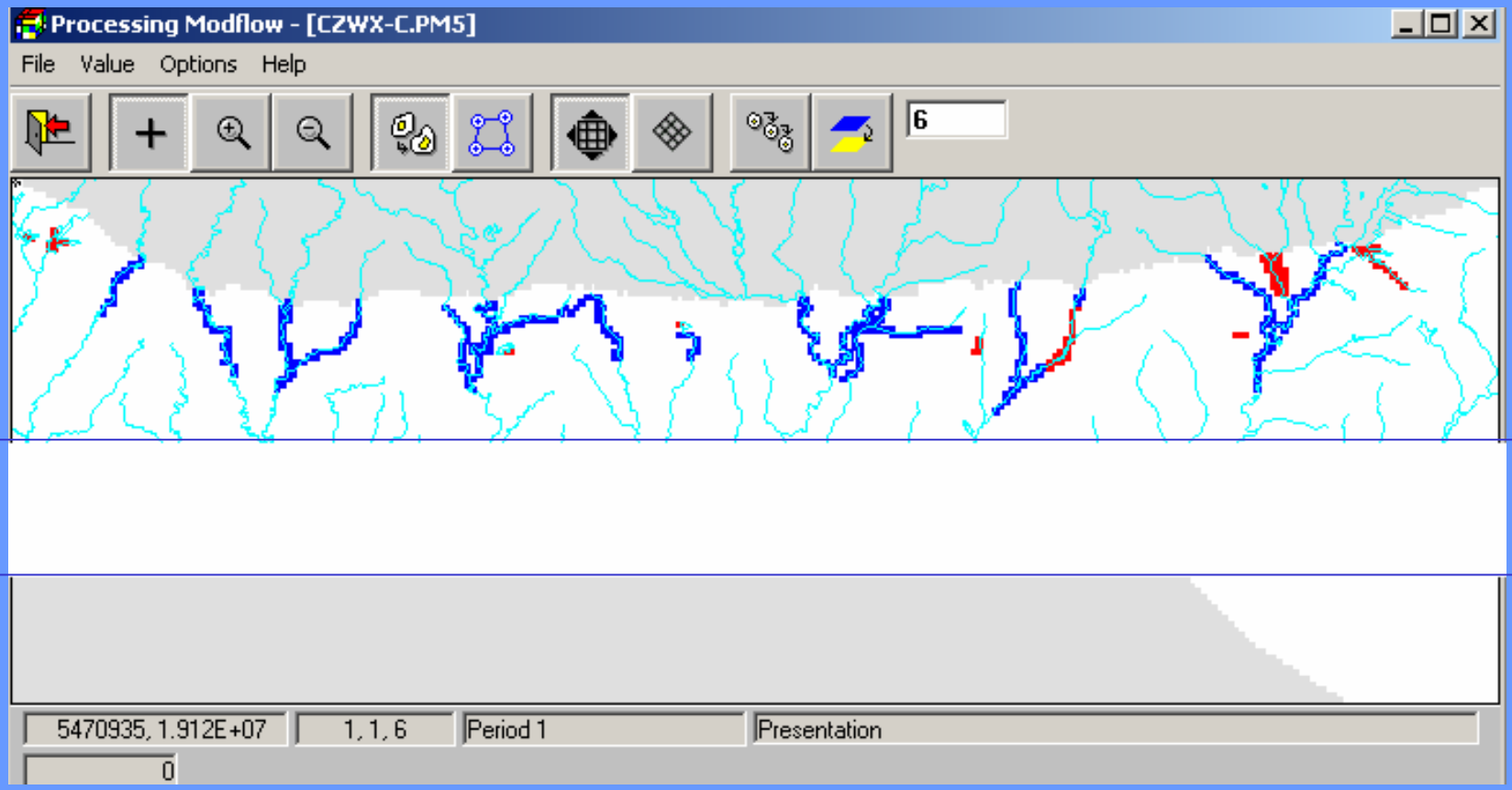
Recharge (2000)



Recharge (DOR)



Stream Flow Routing & Reservoirs



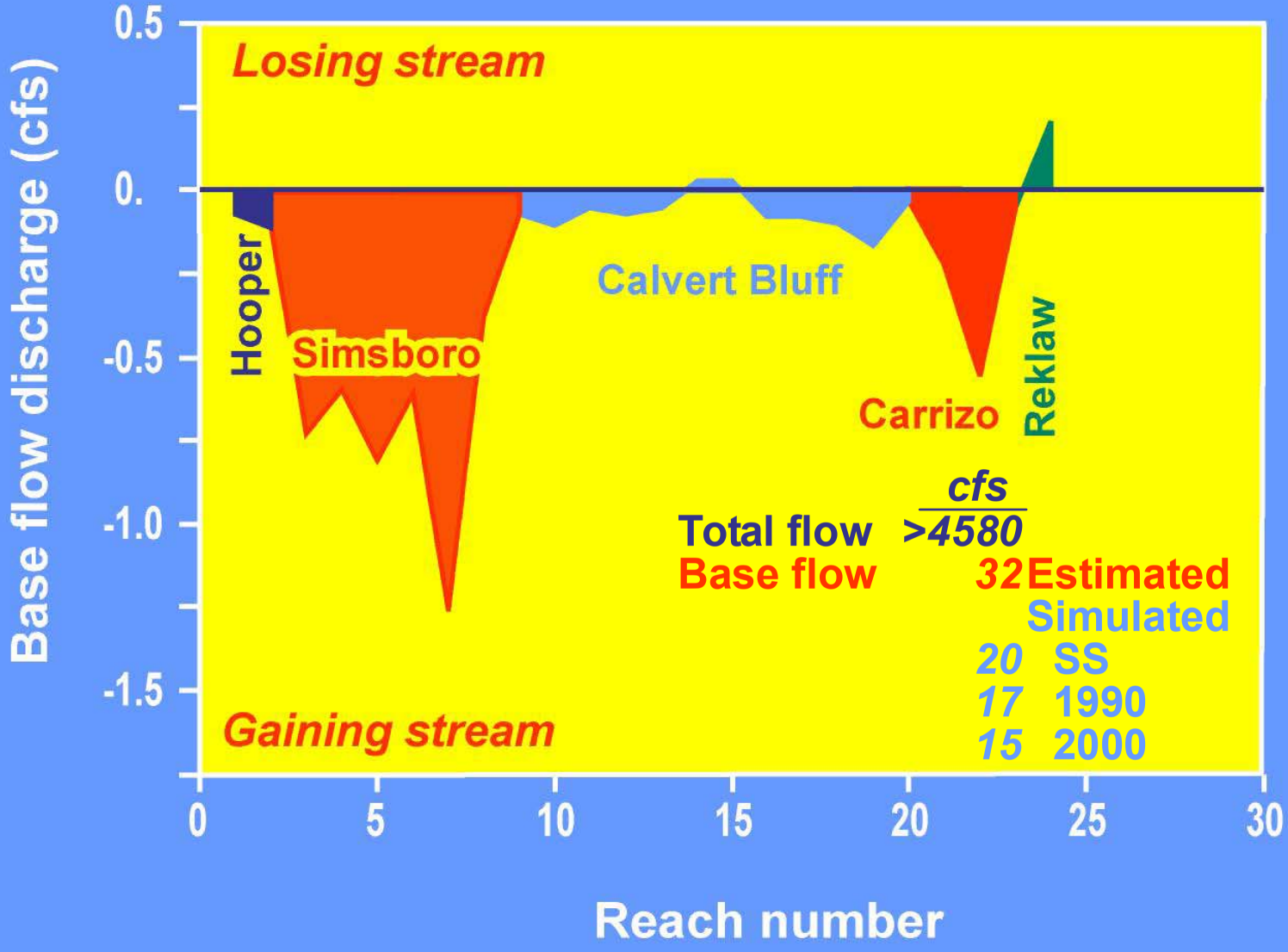
MODEL

Reservoirs

Rivers

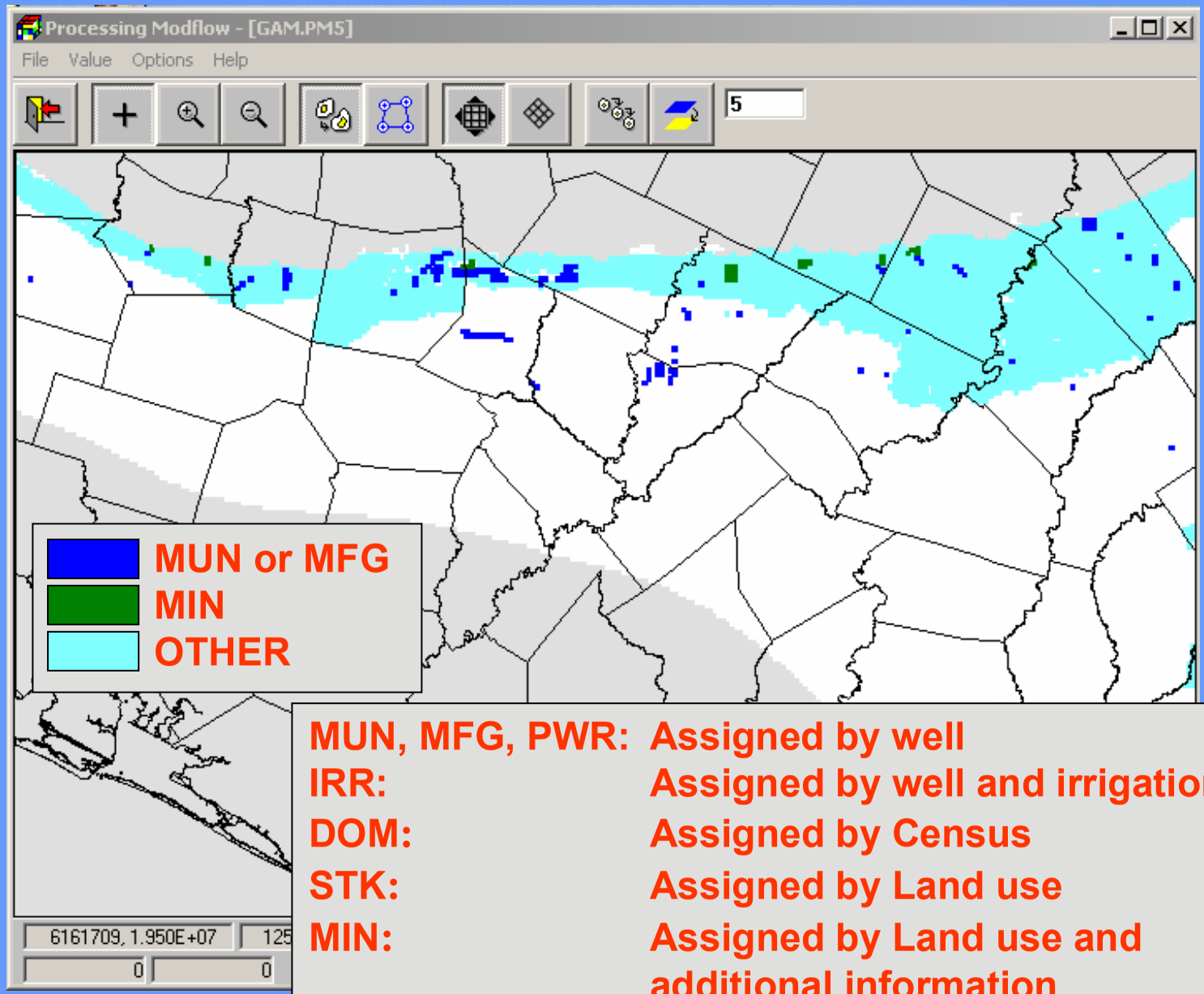
Base Flow from Aquifers

Brazos River



Pumping 2010

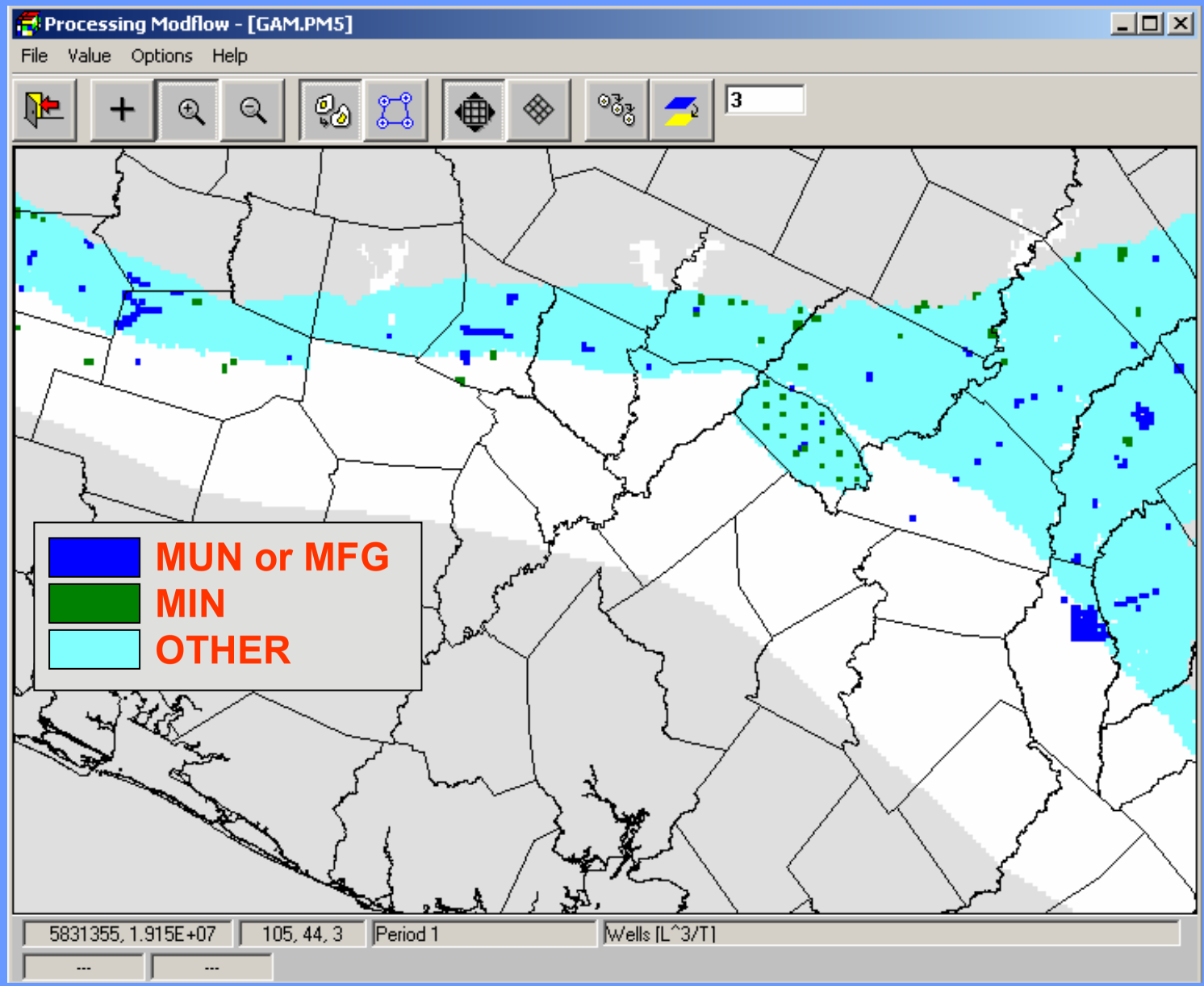
Simsboro (Layer 5)

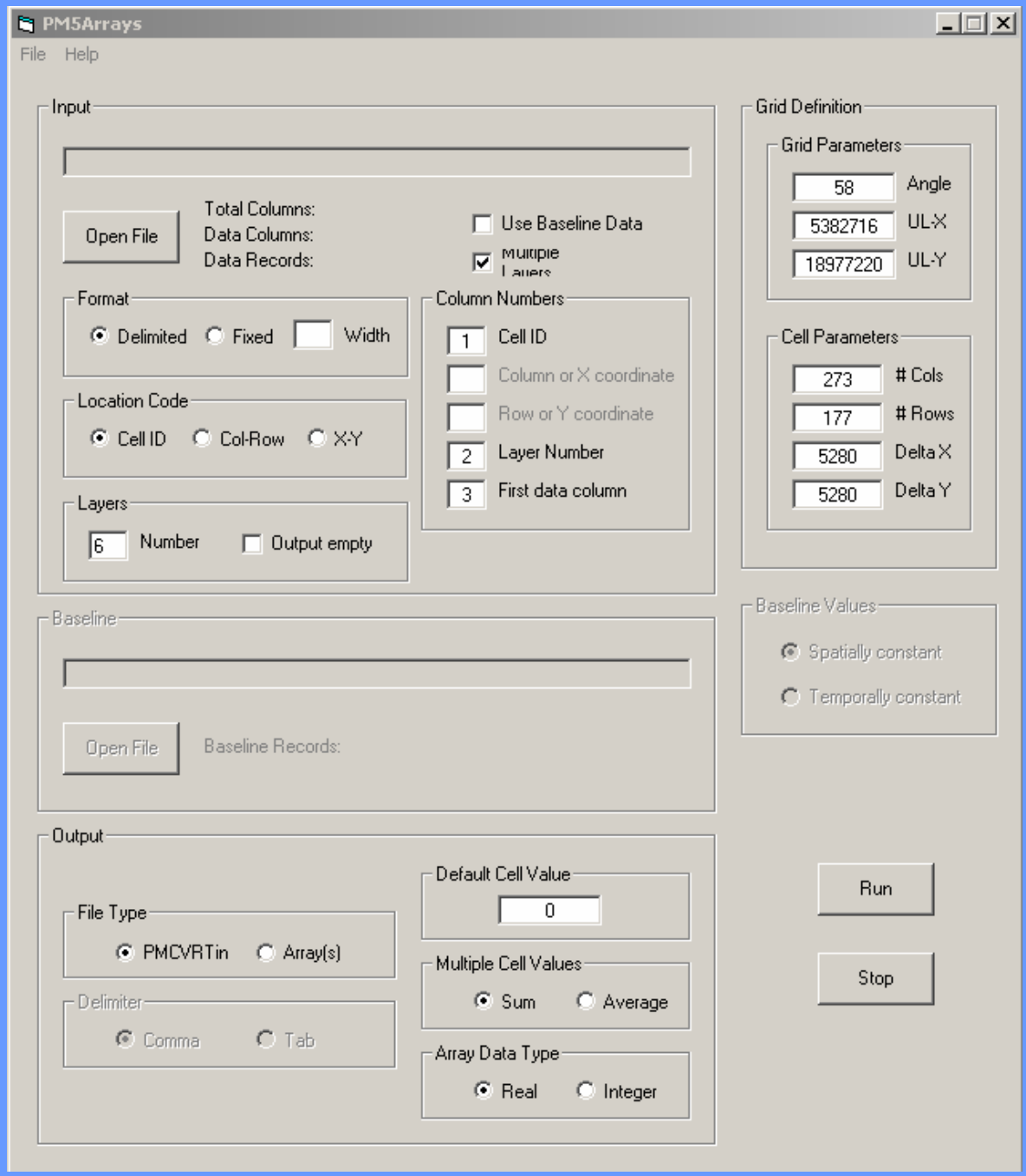


MUN, MFG, PWR:	Assigned by well
IRR:	Assigned by well and irrigation survey
DOM:	Assigned by Census
STK:	Assigned by Land use
MIN:	Assigned by Land use and additional information

Pumping 2010

Carrizo (Layer 3)





PM5Arrays3.0

Visual Basic program for preparing data by layer

PMCVRT.exe

PM5 File Converter (ASCII > Binary PM5 file)