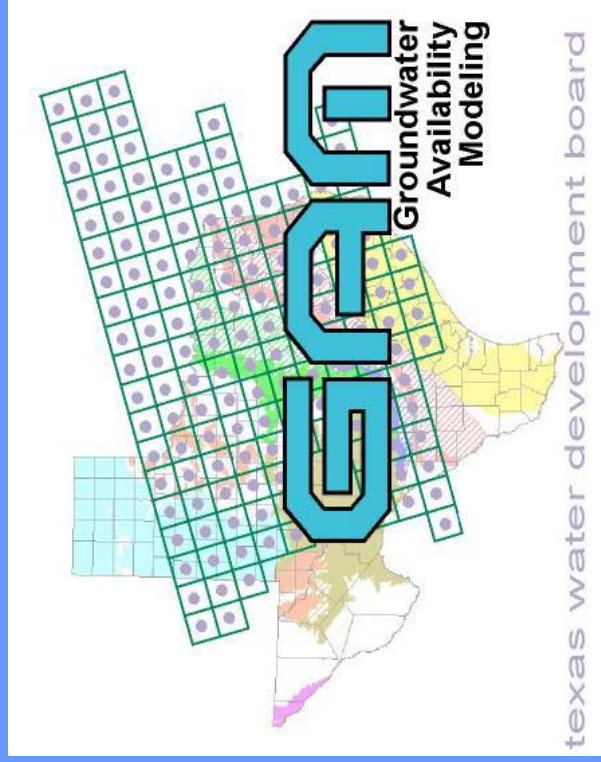


Central Carrizo-Wilcox Aquifer GAM Model Model Training Seminar February 12, 2003



Presented by

Alan R. Dutton

Jean-Philippe Nicot

Bureau of Economic Geology

John A. & Katherine G. Jackson

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

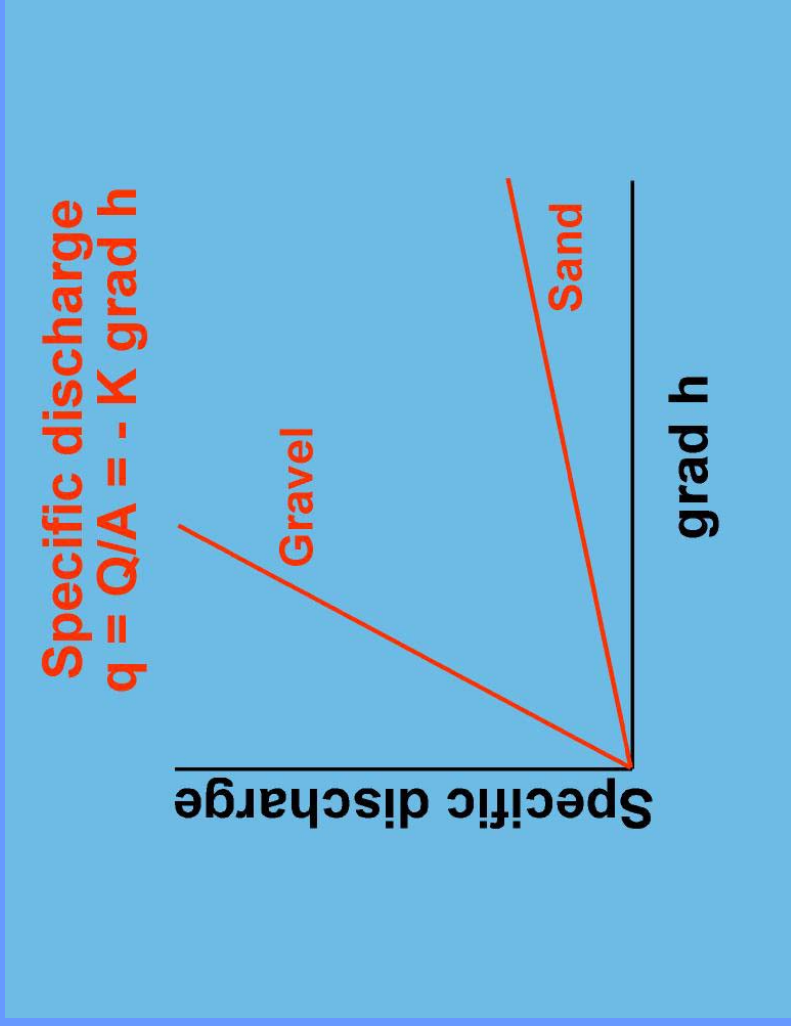
- 1856 Darcy's Law
- 1898 Physical model (sand model)
- 1935 Theis' equation for groundwater flow
- 1940s Electrical analog models
- 1960s Computer or numerical models
- 1971 PLASM – 1st widely used computer code
 - Simple and short
 - User modified for each model
- 1984 MODFLOW released by U.S. Geological 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:

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

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

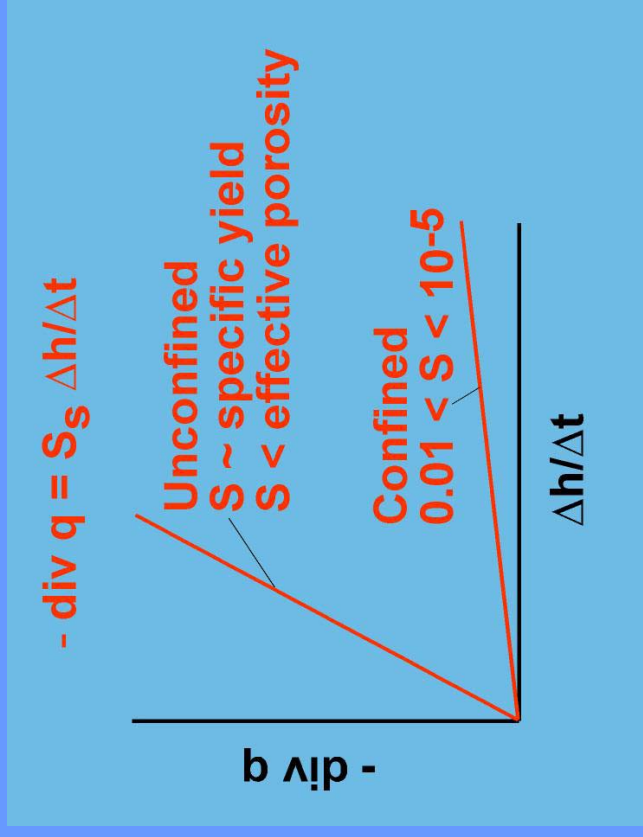
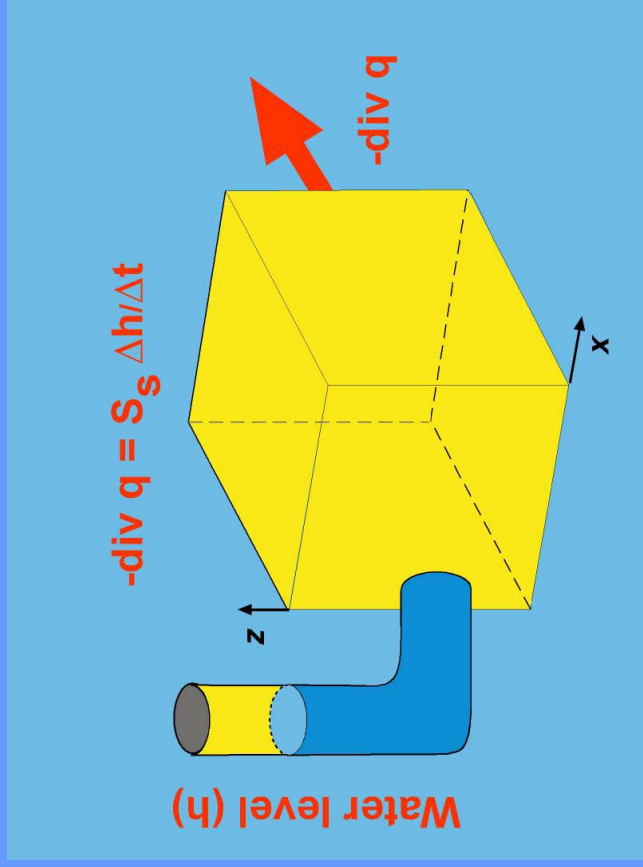


Mathematical operator:

$$\text{grad} = \partial/\partial x + \partial/\partial y + \partial/\partial z \quad \text{applied to scalar property}$$

Continuity Equation

$$\text{Inflow} - \text{Outflow} = -\text{div } \mathbf{q} = S_s \frac{\partial h}{\partial t}$$



Mathematical operator:

$$\text{div} = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \quad \text{applied to vector property}$$

General Equation of Groundwater Flow

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

$$T = K b \quad S = S_s b$$

Darcy's Law for flow in porous media:

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

Continuity equation:

$$\text{Inflow} - \text{Outflow} = -\text{div } q = S_s \frac{\partial h}{\partial t}$$

Solution requires initial conditions: $h(\text{time} = 0)$

$$Kh = K_x = K_y \text{ (no horizontal anisotropy)}$$
$$K_z$$

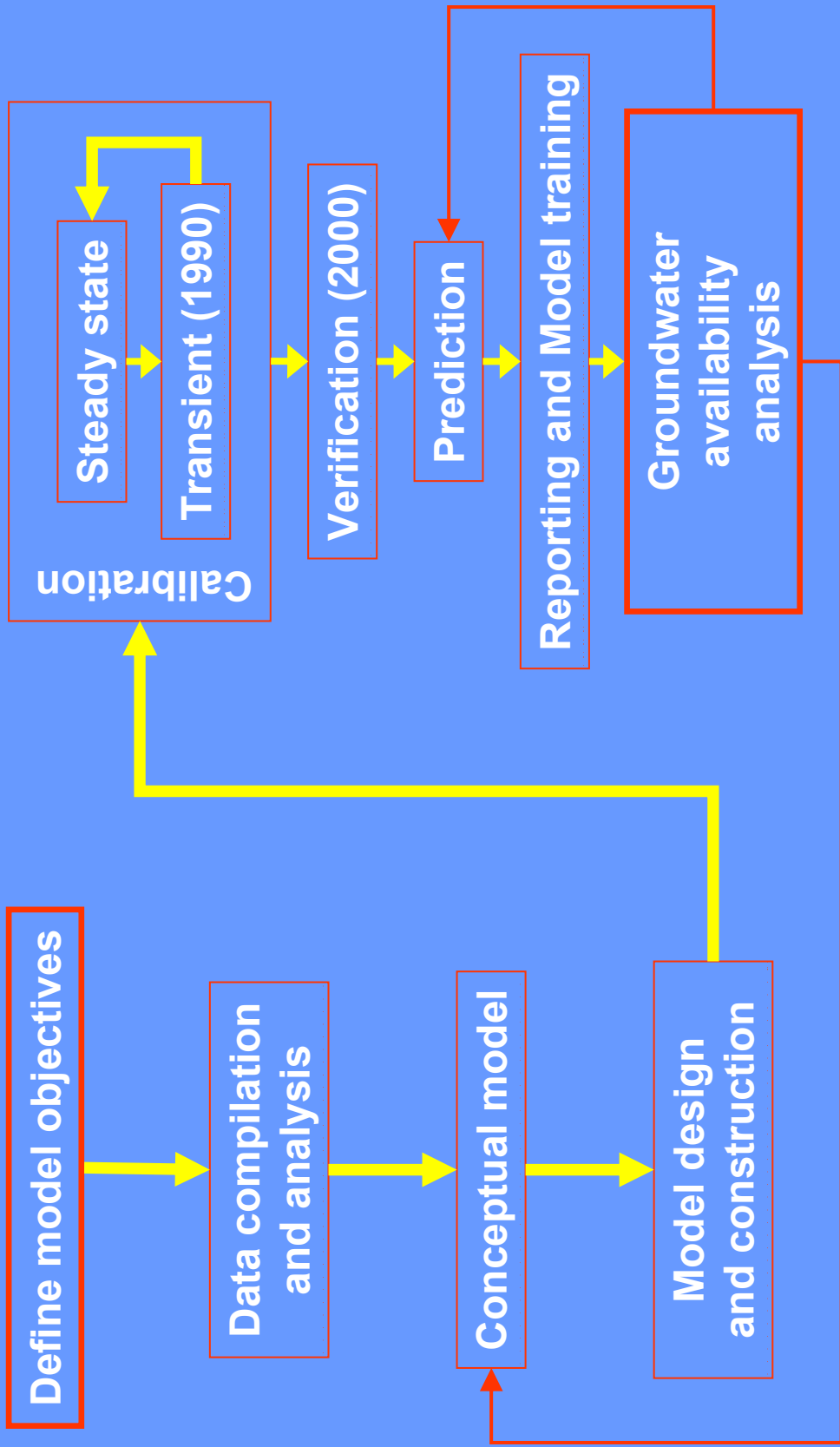
S (storativity)

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)

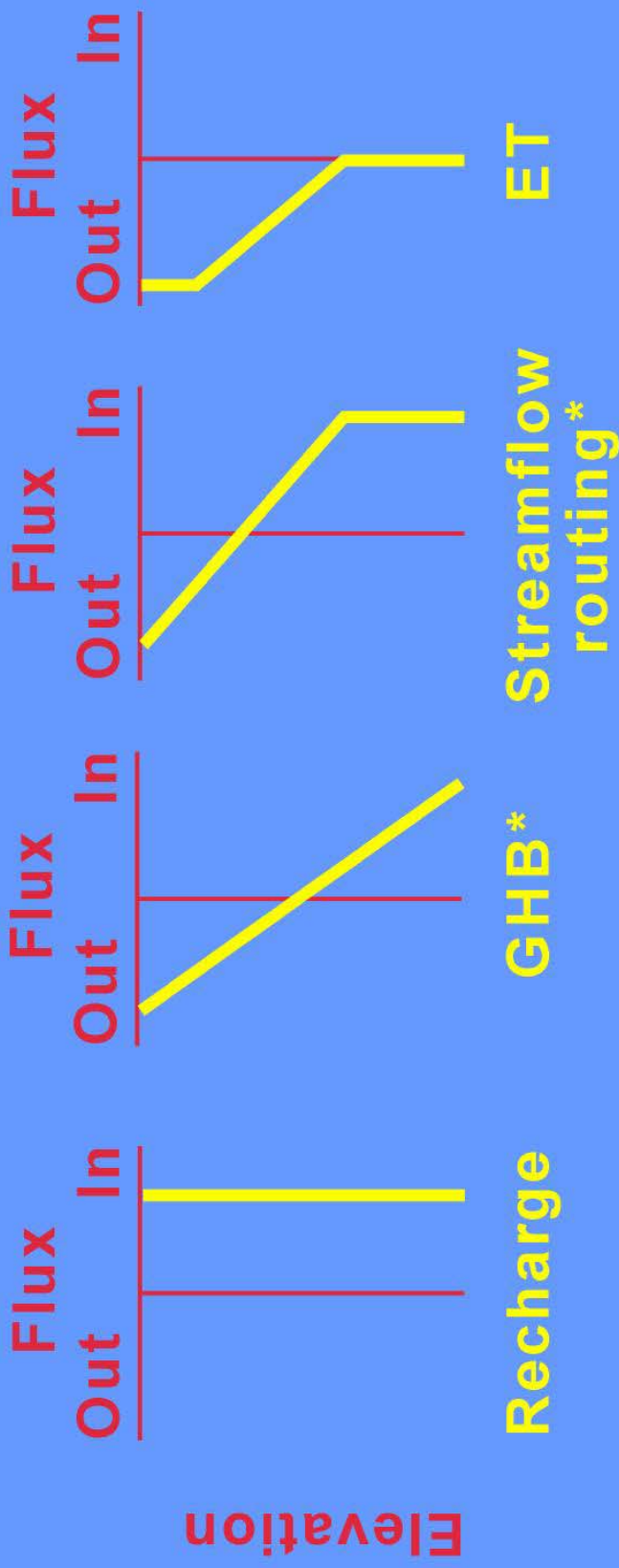
Reservoir (RES)

Horizontal Flow Barrier (HFB)

Solver (SIP)

Output Control (OC)

MODFLOW BOUNDARY PACKAGES

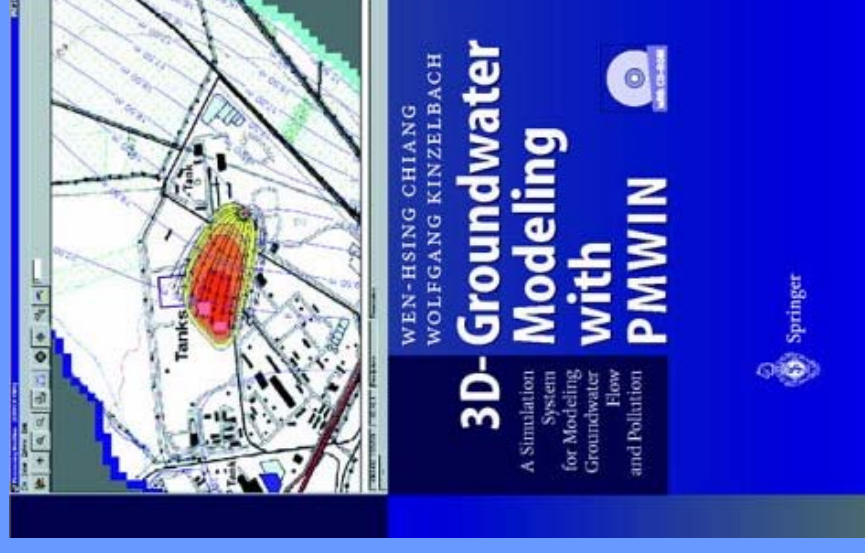
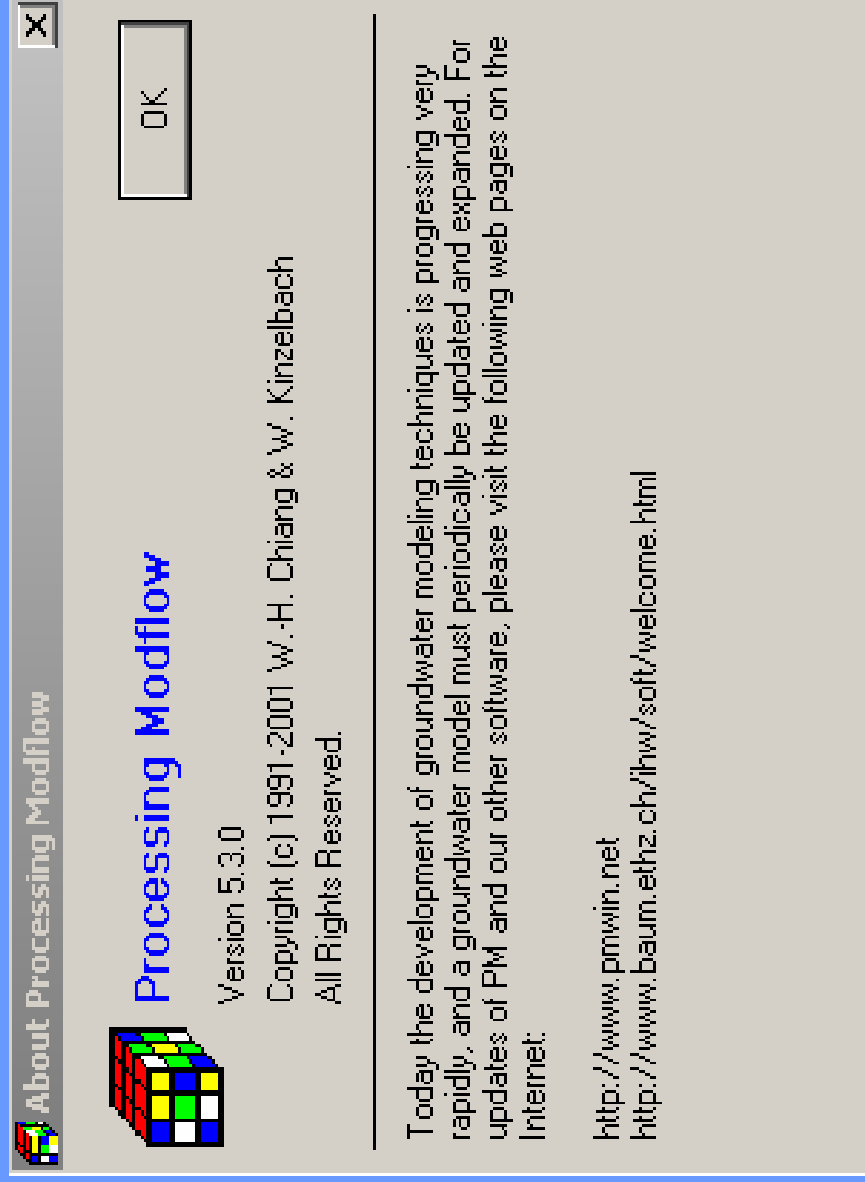


$$* Q (\text{flux}) = \text{COND} (h_b - h_{\text{cell}})$$

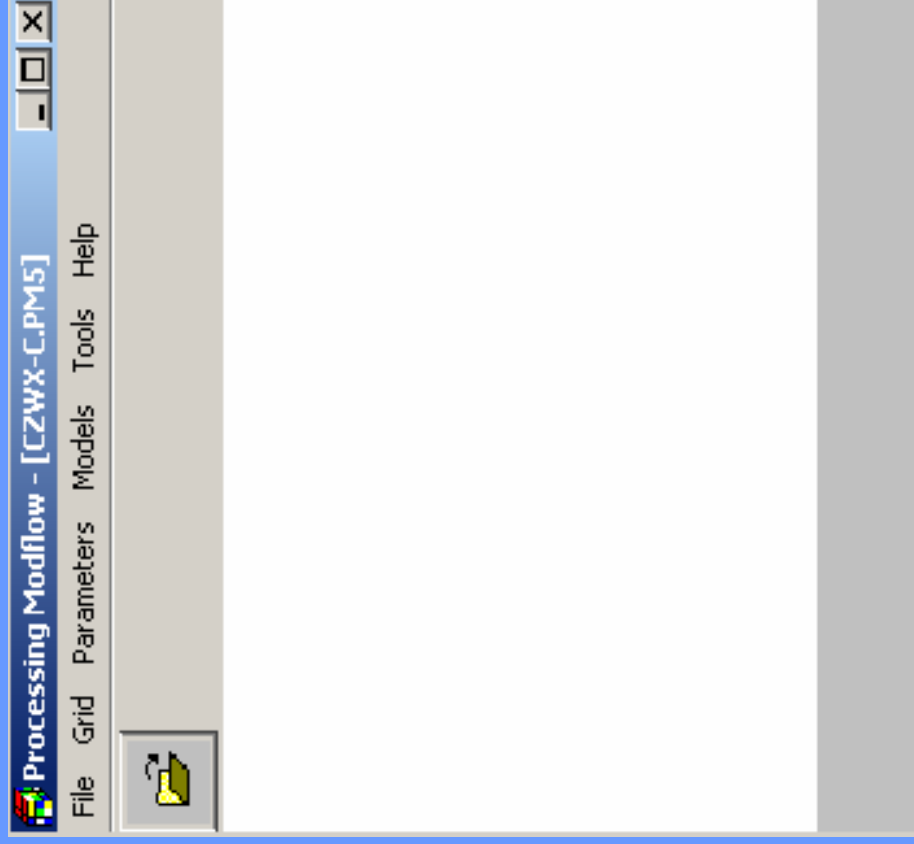
MODFLOW Interfaces

- **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

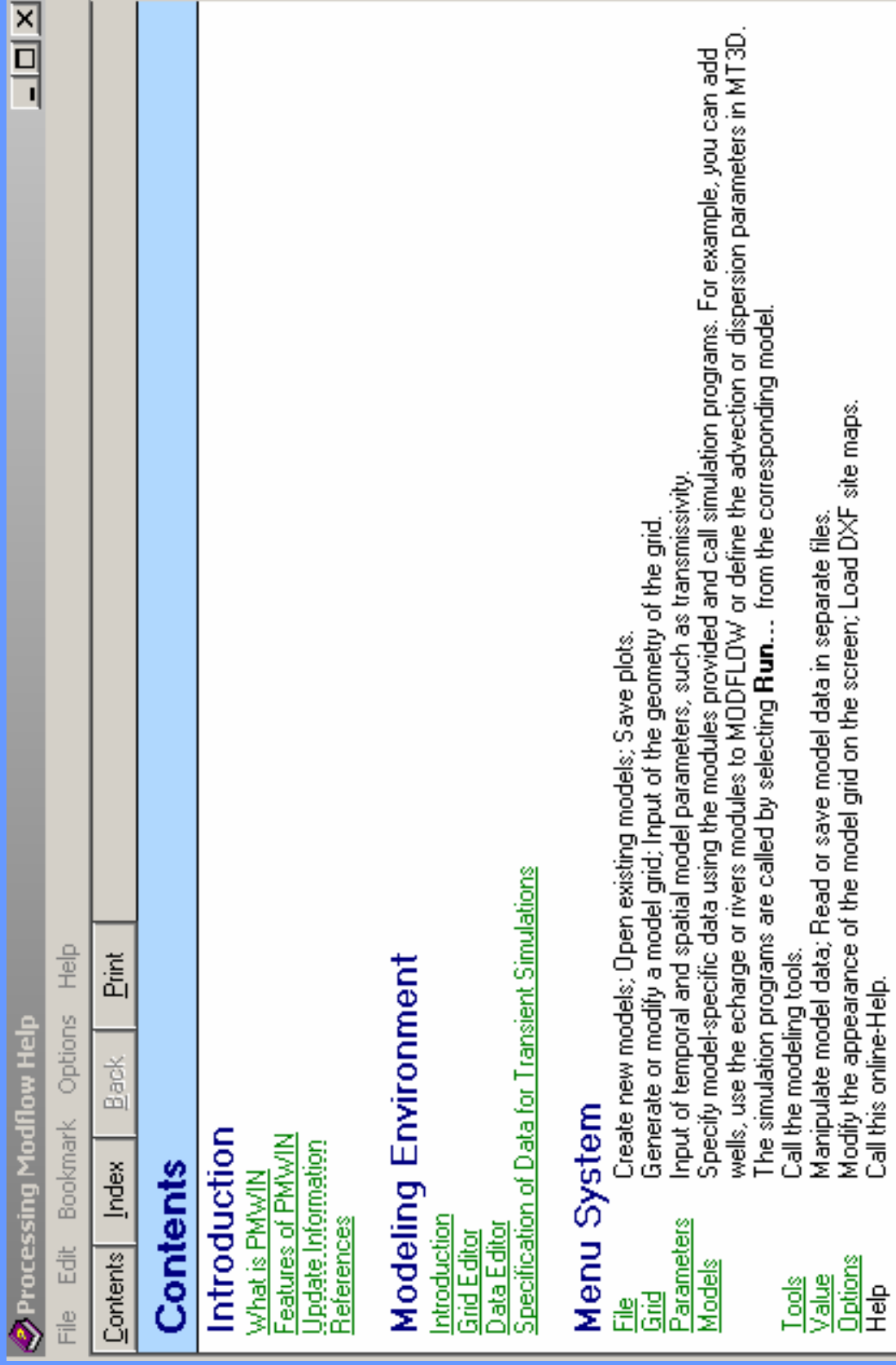


PMWIN Menu Bar



File
Grid
Parameters
Models
Tools
Help

Help Menu



The screenshot shows a web browser window titled "Processing Modflow Help". The address bar is empty. The menu bar contains "File", "Edit", "Bookmark", "Options", and "Help". Below the menu bar is a navigation bar with buttons for "Contents", "Index", "Back", and "Print". The main content area has a light blue header with the word "Contents" in bold. Below this, there are several sections of links:

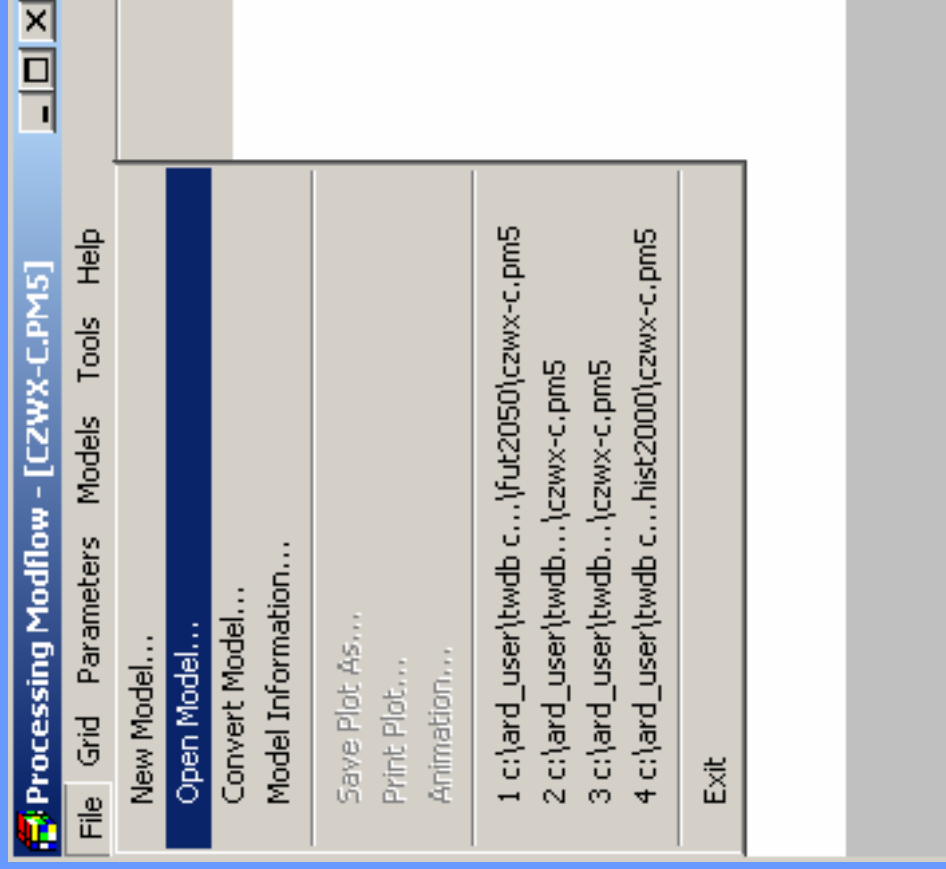
- Introduction**
 - [What is PMwWIN](#)
 - [Features of PMwWIN](#)
 - [Update Information](#)
 - [References](#)
- Modeling Environment**
 - [Introduction](#)
 - [Grid Editor](#)
 - [Data Editor](#)
 - [Specification of Data for Transient Simulations](#)
- Menu System**
 - [File](#)
 - [Grid](#)
 - [Parameters](#)
 - [Models](#)
 - [Tools](#)
 - [Value](#)
 - [Options](#)
 - [Help](#)

The "Menu System" section contains the following text:

Create new models; Open existing models; Save plots.
Generate or modify a model grid; Input of the geometry of the grid.
Input of temporal and spatial model parameters, such as transmissivity.
Specify model-specific data using the modules provided and call simulation programs. For example, you can add wells, use the recharge 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.
Call the modeling tools.
Manipulate model data; Read or save model data in separate files.
Modify the appearance of the model grid on the screen; Load DXF site maps.
Call this online-Help.

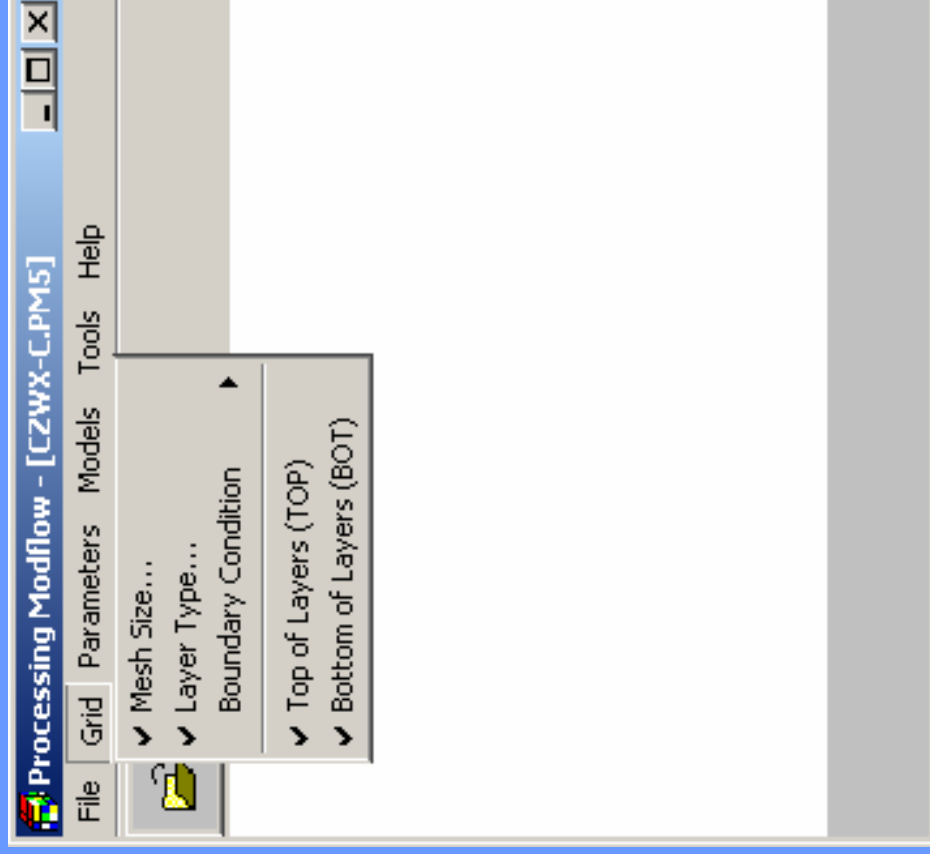
File > Open Model

Browse to CW-c GAM Model



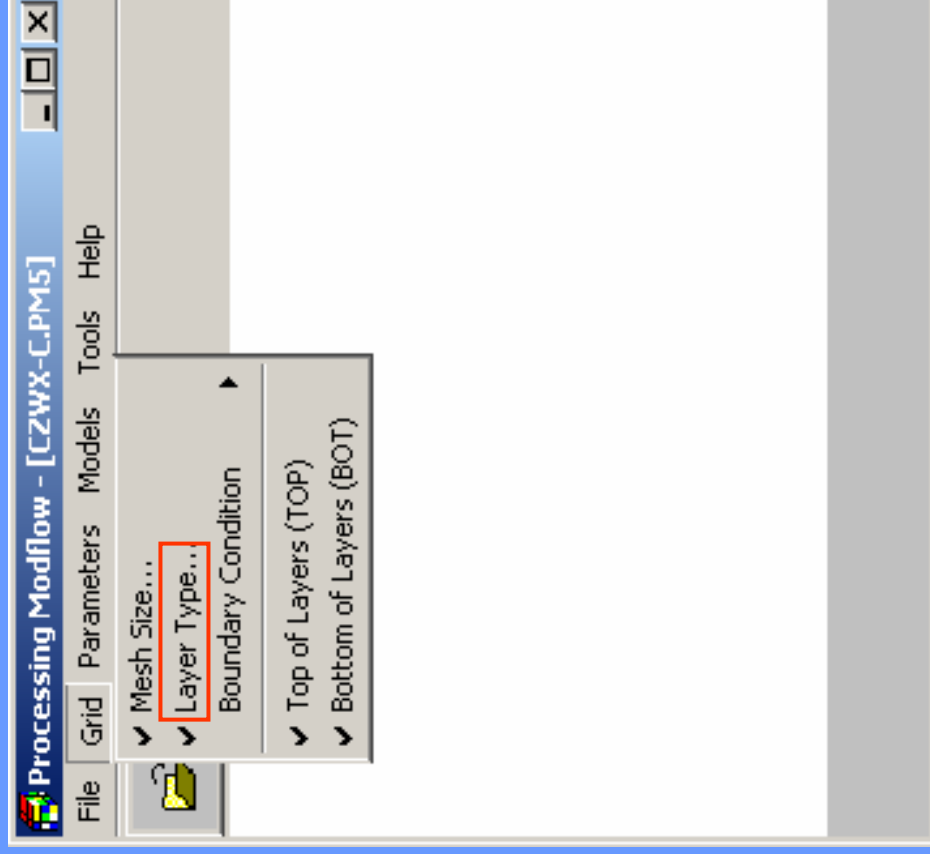
New Model
Open Model
Convert Model
Model Information

Grid Menu List



Mesh Size
Layer Type
Boundary Condition
TOP
BOT

Grid Menu List



Mesh Size
Layer Type
Boundary Condition
TOP
BOT

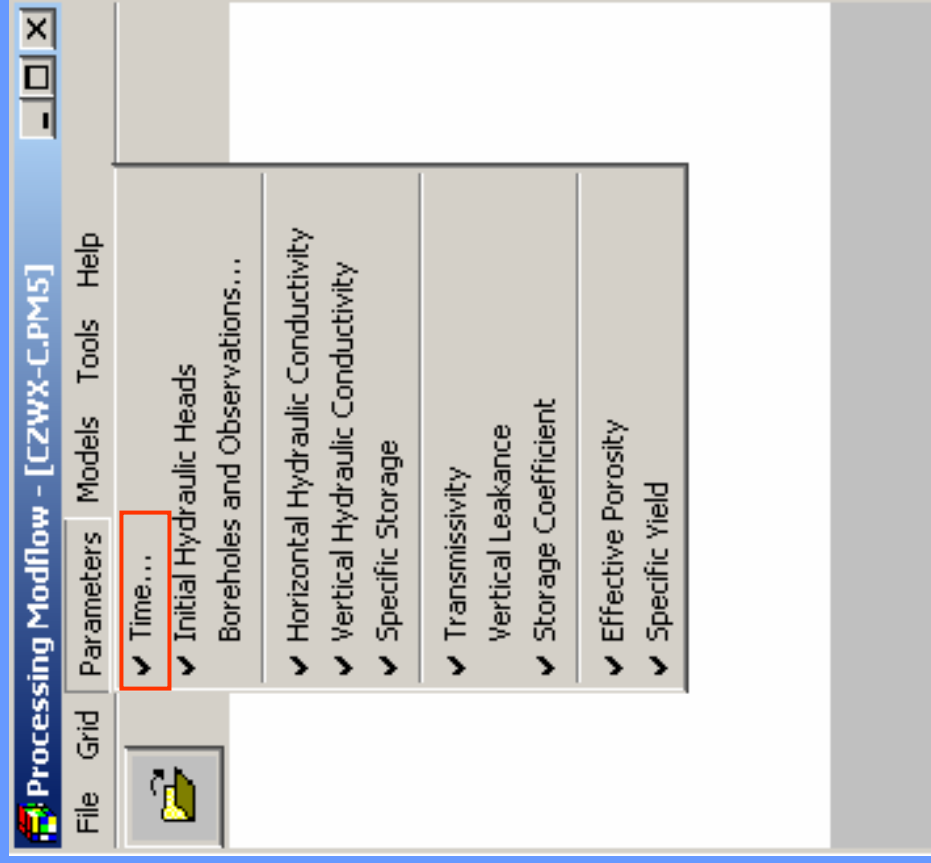
Grid > Layer type Layer Options

Layer Options

Type	Anisotropy Factor	Transmissivity	Leakance	Storage Coefficient	Interbed Storage	Density
1: Unconfined	1 Alluvium	Calculated	Calculated	User Specified	<input type="checkbox"/>	<input type="checkbox"/>
3: Confined/Unconfined (Transmissivity varies)	1 Reklaw	Calculated	Calculated	User Specified	<input type="checkbox"/>	<input type="checkbox"/>
3: Confined/Unconfined (Transmissivity varies)	1 Carrizo	Calculated	Calculated	User Specified	<input type="checkbox"/>	<input type="checkbox"/>
3: Confined/Unconfined (Transmissivity varies)	1 Calvert Bluff	Calculated	Calculated	User Specified	<input type="checkbox"/>	<input type="checkbox"/>
3: Confined/Unconfined (Transmissivity varies)	1 Simsboro	Calculated	Calculated	User Specified	<input type="checkbox"/>	<input type="checkbox"/>
3: Confined/Unconfined (Transmissivity varies)	1 Hooper	Calculated	Calculated	User Specified	<input type="checkbox"/>	<input type="checkbox"/>

OK Cancel Help

Parameters List



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

Time (Transient Model 1951-2000)

Time Parameters

Period	Active	Length	Time Steps	Multiplier (Flow)	Transport Step Size	T ₁
1	<input checked="" type="checkbox"/>	36525	200	1	0	
2	<input checked="" type="checkbox"/>	365.25	5	1	0	
3	<input checked="" type="checkbox"/>	365.25	1	1	0	
4	<input checked="" type="checkbox"/>	365.25	1	1	0	
5	<input checked="" type="checkbox"/>	365.25	5	1	0	
6	<input checked="" type="checkbox"/>	365.25	1	1	0	
7	<input checked="" type="checkbox"/>	365.25	1	1	0	
8	<input checked="" type="checkbox"/>	365.25	5	1	0	

Simulation Time Unit days Auto Update Period Length

Simulation Flow Type
 Steady-State
 Transient

Total Period Number = 117
Total Time Steps = 386
Total Simulation Time = 5.47875E+4 days

Save > *.tpr
Edit in Notepad

Load... Save... OK Cancel Help

Time (Predictive Model 2001-2050)

Time Parameters

Period	Active	Length	Time Steps	Multiplier (Flow)	Transport Stepsize	T ₀
1	<input checked="" type="checkbox"/>	365.25	1	1	0	
2	<input checked="" type="checkbox"/>	365.25	1	1	0	
3	<input checked="" type="checkbox"/>	365.25	1	1	0	
4	<input checked="" type="checkbox"/>	365.25	1	1	0	
5	<input checked="" type="checkbox"/>	365.25	1	1	0	
6	<input checked="" type="checkbox"/>	365.25	1	1	0	
7	<input checked="" type="checkbox"/>	365.25	1	1	0	
8	<input checked="" type="checkbox"/>	365.25	1	1	0	

Simulation Time Unit
days

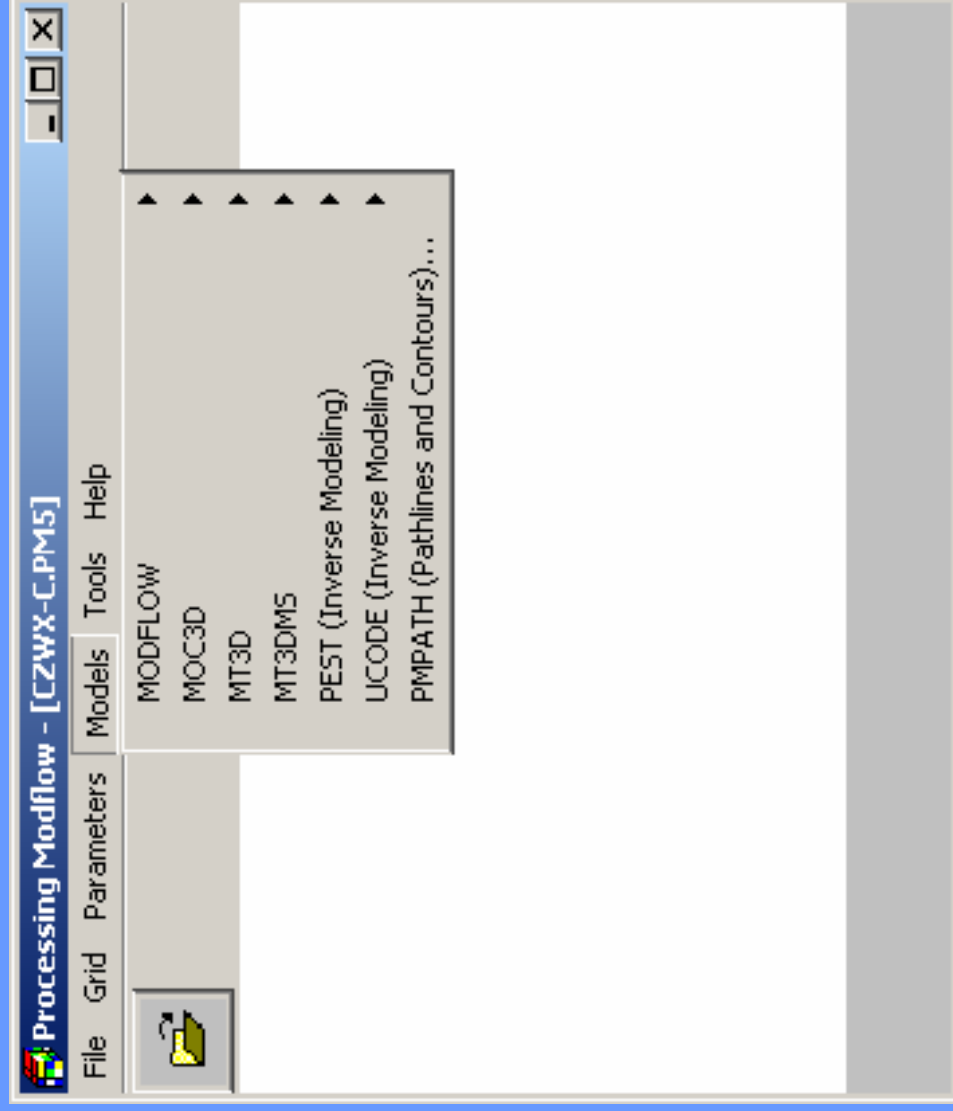
Auto Update Period Length

Simulation Flow Type
 Steady-State
 Transient

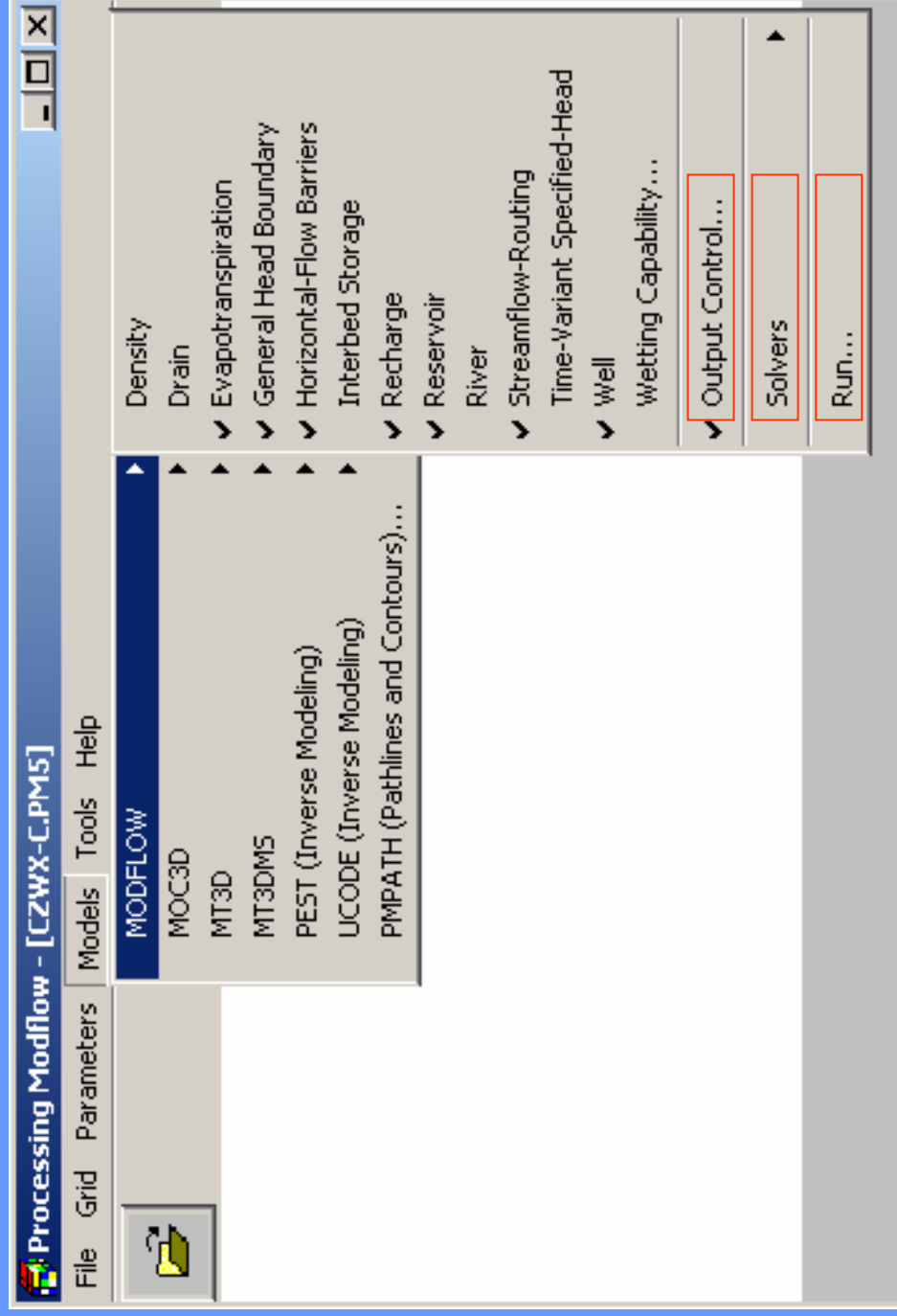
Total Period Number = 160
Total Time Steps = 160
Total Simulation Time = 1.82625E+4 days

Load... Save... OK Cancel Help

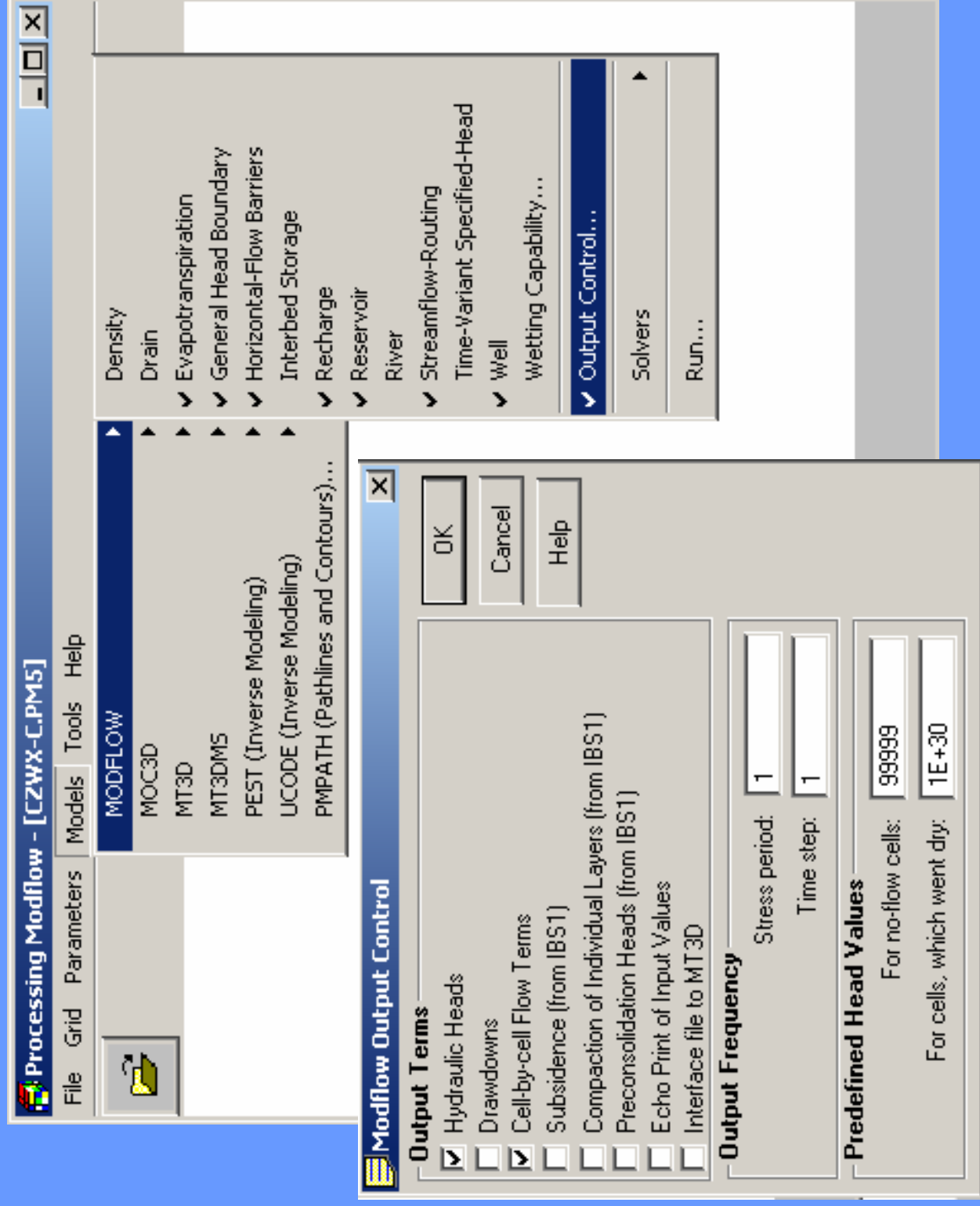
Models List



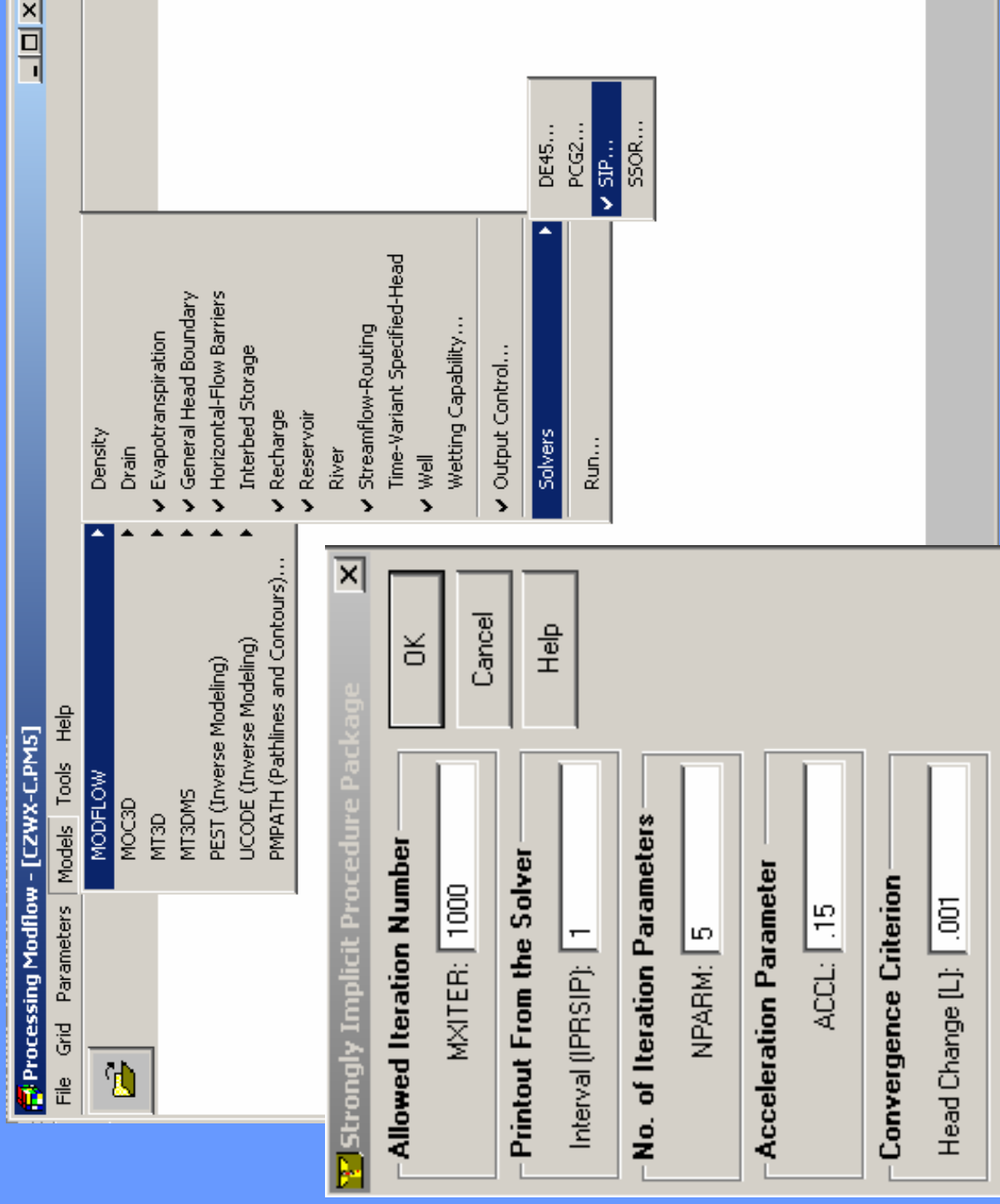
Models > MODFLOW Packages and Run Command



Models > MODFLOW > Output Control



Models > MODFLOW > Solvers > SIP



Models > MODFLOW > Run

Processing Modflow - [CZWX-C.PMS]

File Grid Parameters Models Tools Help

MODFLOW

- MOC3D
- MT3D
- MT3DMS
- PEST (Inverse Modeling)
- UCODE (Inverse Modeling)
- PMPATH (Pathlines and Contours),...

Run Modflow

Modflow Version: MODFLOW96

Modflow Program: c:\.....\modflow96_czwx-c.exe

Generate	Description	Destination File
<input checked="" type="checkbox"/>	Basic Package	c:\low-c_gam\bas.dat
<input checked="" type="checkbox"/>	Block-Centered Flow (BCF1,2)	c:\low-c_gam\bcf.dat
<input checked="" type="checkbox"/>	Output Control	c:\low-c_gam\oc.dat
<input checked="" type="checkbox"/>	General-Head Boundary	c:\low-c_gam\ghb.dat
<input type="checkbox"/>	Stream Flow	c:\low-c_gam\str1.dat
<input checked="" type="checkbox"/>	Well	c:\low-c_gam\wel.dat
<input checked="" type="checkbox"/>	Evapotranspiration	c:\low-c_gam\evt.dat
<input checked="" type="checkbox"/>	Horizontal-Flow Barrier	c:\low-c_gam\hfb1.dat
<input checked="" type="checkbox"/>	Recharge	c:\low-c_gam\rch.dat
<input checked="" type="checkbox"/>	Reservoir	c:\low-c_gam\res1.dat
<input checked="" type="checkbox"/>	Solver - SIP1	c:\low-c_gam\sip.dat
<input type="checkbox"/>	Modpath (Vers. 1.x)	c:\low-c_gam\main.dat
<input type="checkbox"/>	Modpath (Vers. 3.x)	c:\low-c_gam\main30.dat

Options

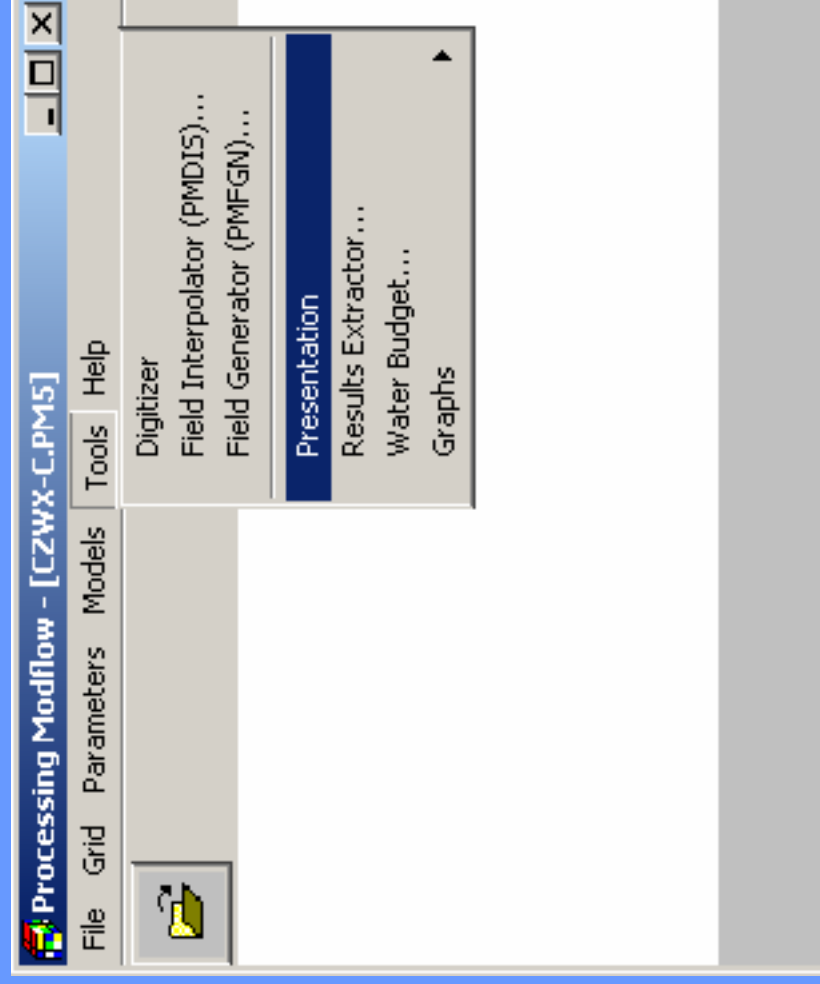
- Regenerate all input files for MODFLOW
- Check the model data
- Generate input files only, don't start MODFLOW
- Don't generate MODPATH files anyway.

OK Cancel Help

Do NOT select Stream Flow!

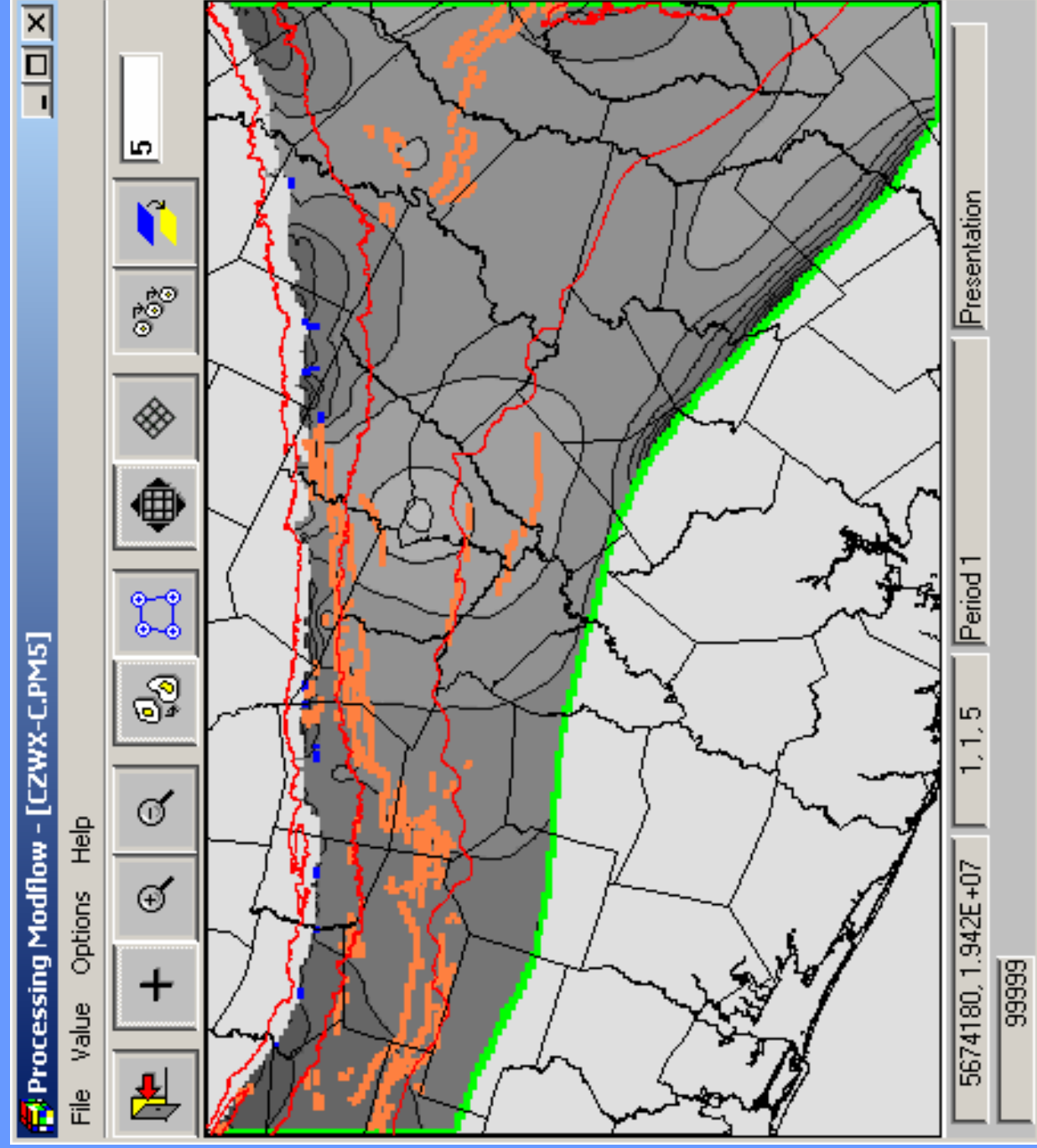
Tools

Tools > Presentation

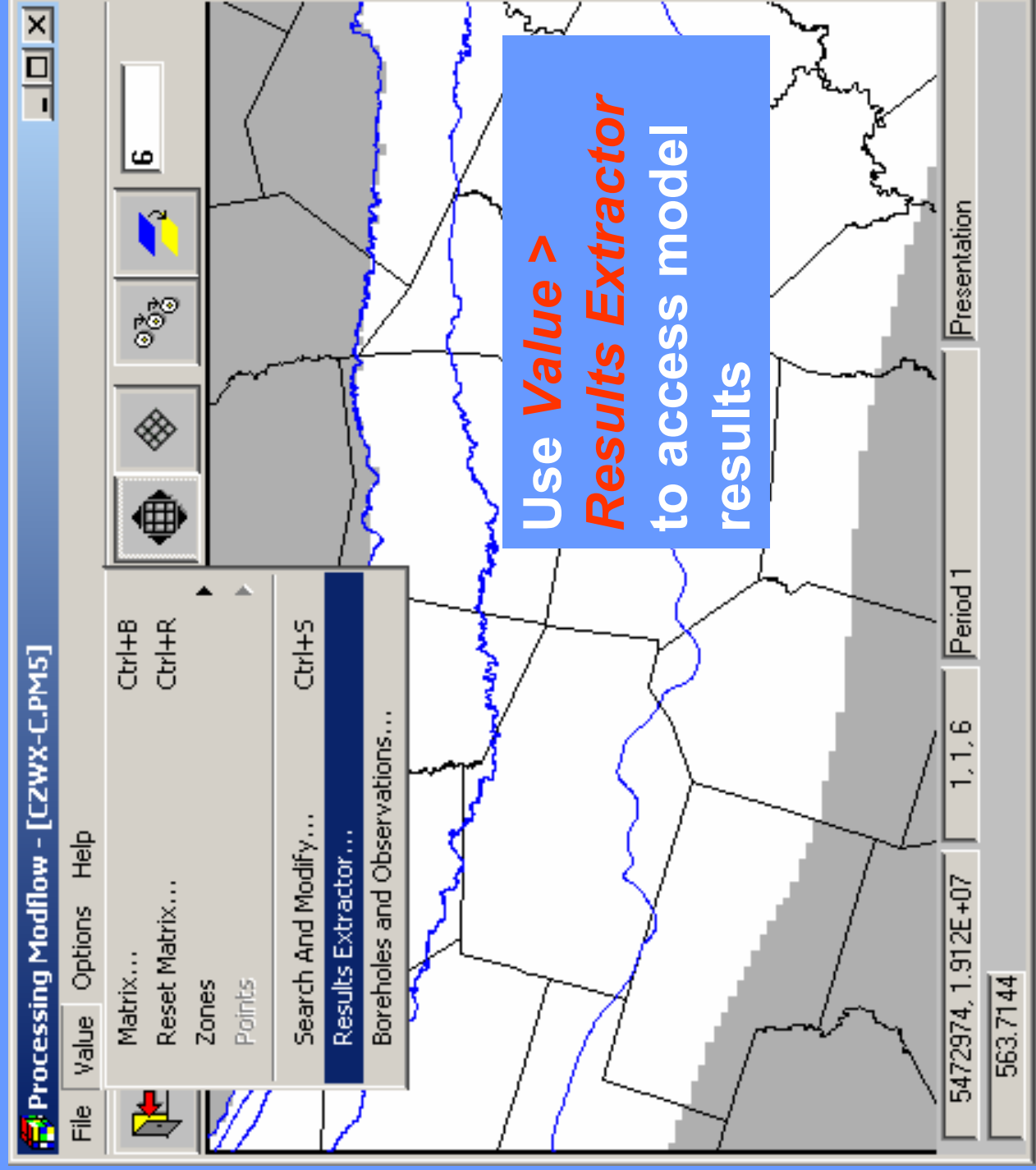


Use **Tools** >
Presentation to
(a) access model
results, and
(b) use graphics

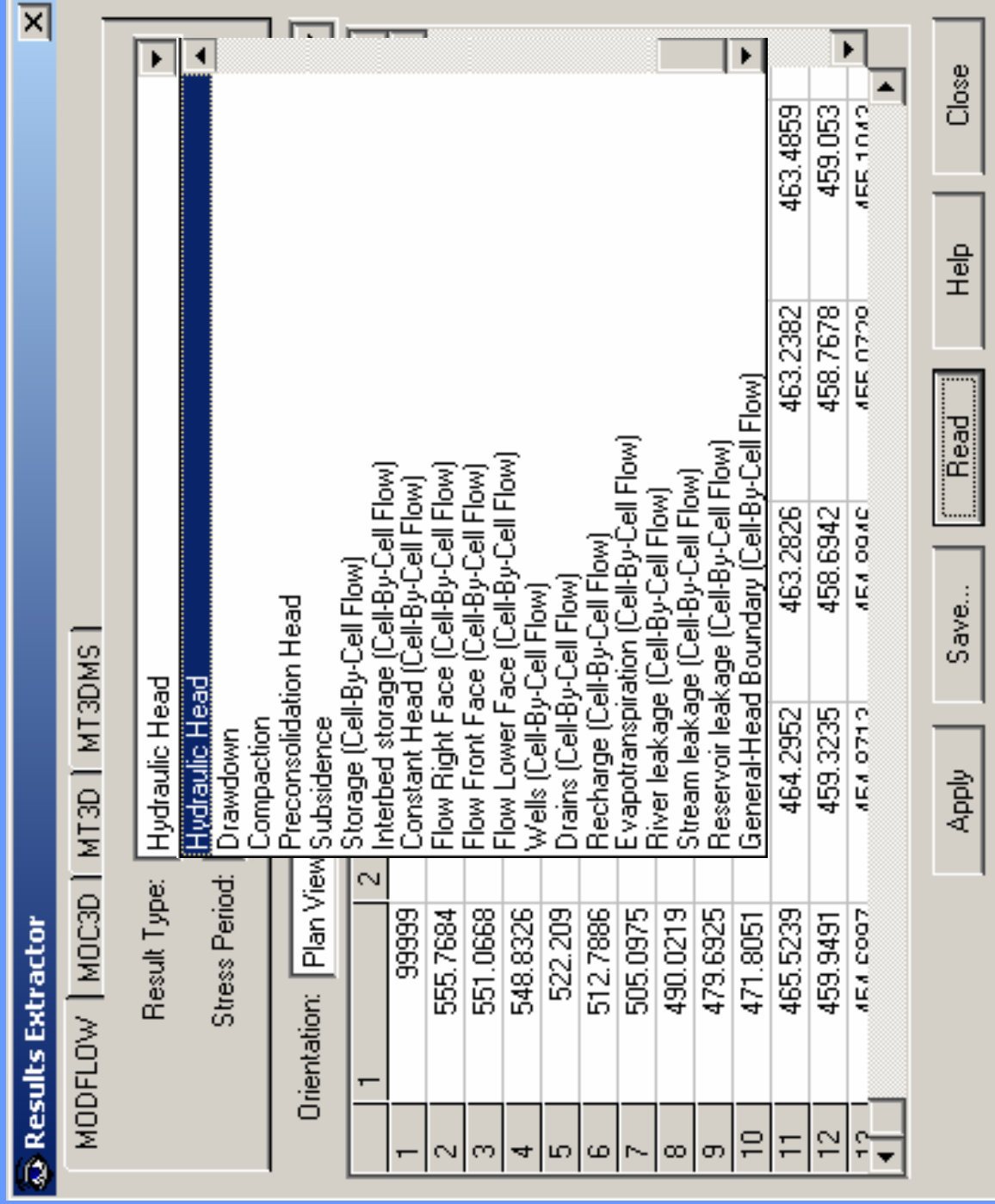
Graphical Data Editor



Value > Results Extractor



Value > Results Extractor



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

Value > Results Extractor

Results Extractor

MODFLOW | MOD3D | MT3D | MT3DMS

Result Type:

Stress Period: Time Step:

Orientation: Layer: ColumnWidth:

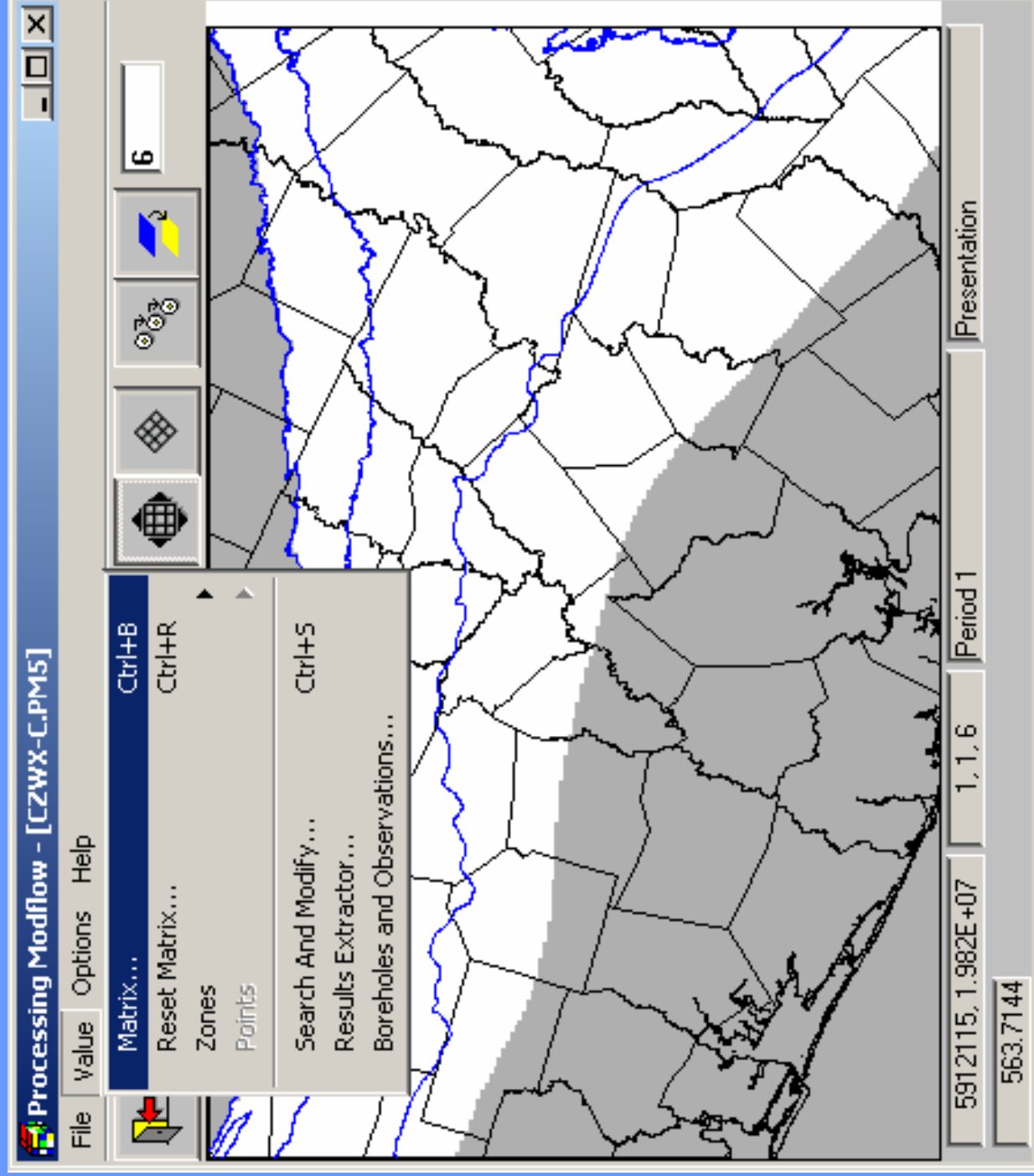
	1	2	3	4	5	6
1	999.999	999.999	999.999	999.999	999.999	999.999
2	555.7684	999.999	999.999	999.999	999.999	999.999
3	551.0668	518.1408	999.999	999.999	999.999	999.999
4	548.8326	532.4772	530.5089	517.8479	999.999	999.999
5	522.209	509.3212	515.7987	505.5062	495.4899	999.999
6	512.7886	501.1007	492.9125	495.8729	499.5307	999.999
7	505.0975	493.947	487.5611	487.101	489.9981	999.999
8	490.0219	485.0163	481.0656	480.607	482.2628	999.999
9	479.6925	476.845	474.5504	474.1469	474.9113	999.999
10	471.8051	470.099	468.612	468.3824	468.6378	999.999
11	465.5239	464.2952	463.2826	463.2382	463.4859	999.999
12	459.9491	459.3235	458.6942	458.7678	459.053	999.999
13	454.0007	454.0712	454.0046	454.0770	454.1042	999.999

Apply Save... Read Help Close

Specify:
Result Type
Period
Time Step
Layer

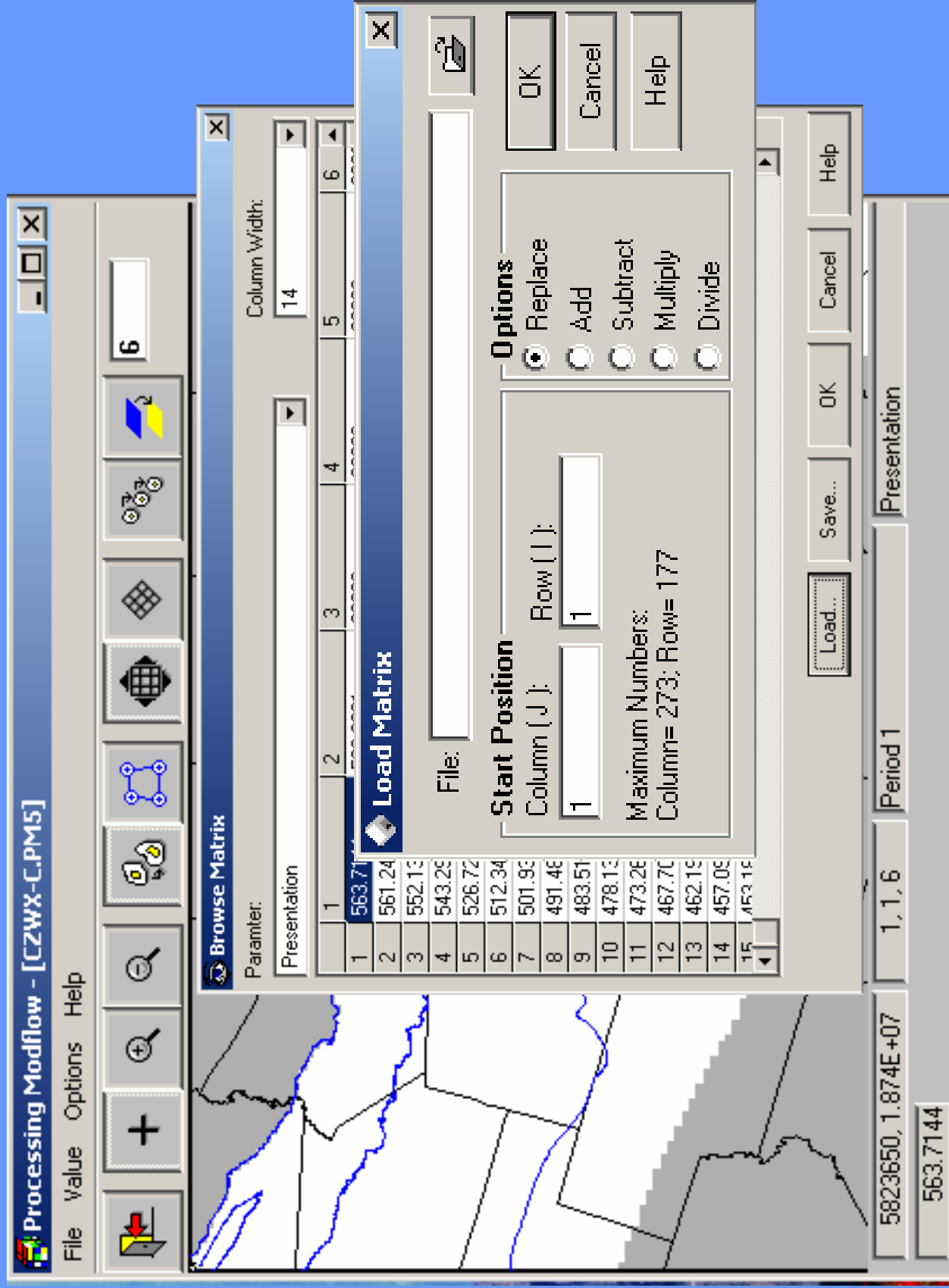
Apply or
Save

Value > Matrix



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

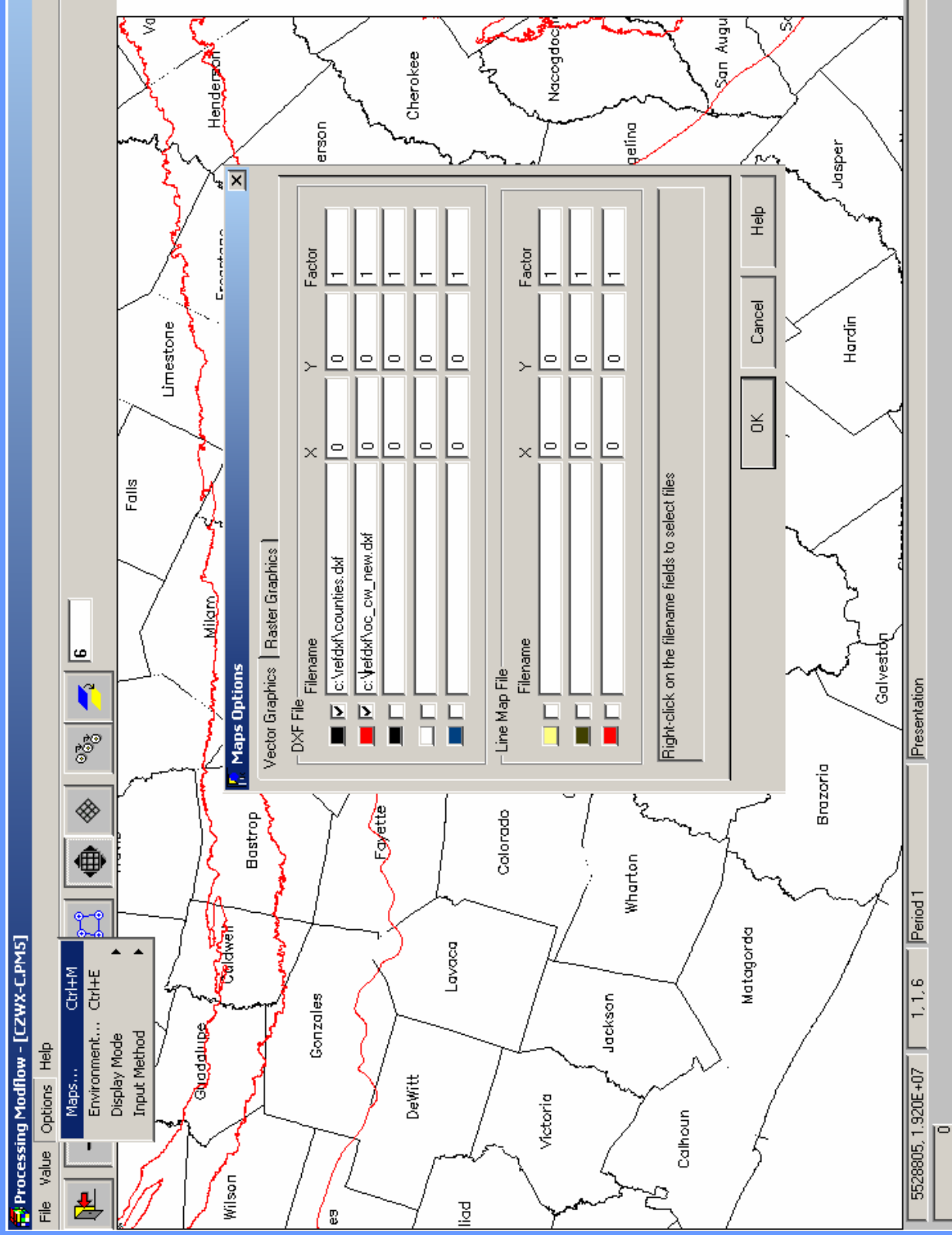
Value > Matrix > Load



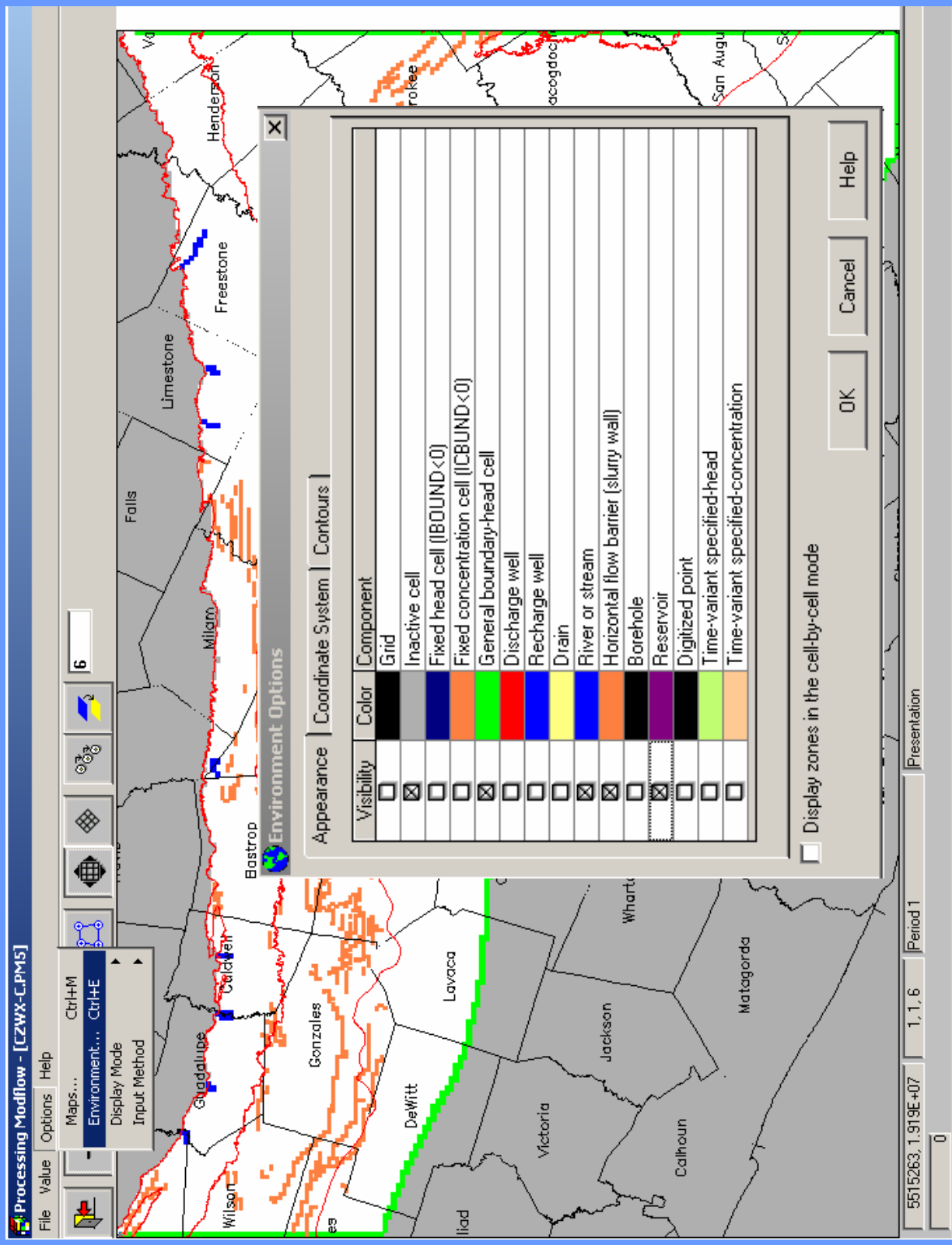
Value > Matrix > Save Save Matrix As



Options > Maps > Vector Graphics



Options > Environment.. > Appearance



Options > Environment > Contours

Processing Modflow - [CZWX-C.PM5]

File Value Options Help

Environment Options

Appearance | Coordinate System: [Contours]

Visible Display contour lines Fill contours

Orient labels uphill Ignore inactive cells

Parameter: Presentation

Level...	Line...	Fill...	Label...	Label Height...	Label Spacing...
-300			<input type="checkbox"/>	9000	171789.2
-250			<input type="checkbox"/>	9000	171789.2
-200			<input type="checkbox"/>	9000	171789.2
-150			<input type="checkbox"/>	9000	171789.2
-100			<input type="checkbox"/>	9000	171789.2
-50			<input type="checkbox"/>	9000	171789.2
0			<input type="checkbox"/>	9000	171789.2
50			<input type="checkbox"/>	9000	171789.2
100			<input type="checkbox"/>	9000	171789.2
150			<input type="checkbox"/>	9000	171789.2

Display zones in the cell-by-cell mode

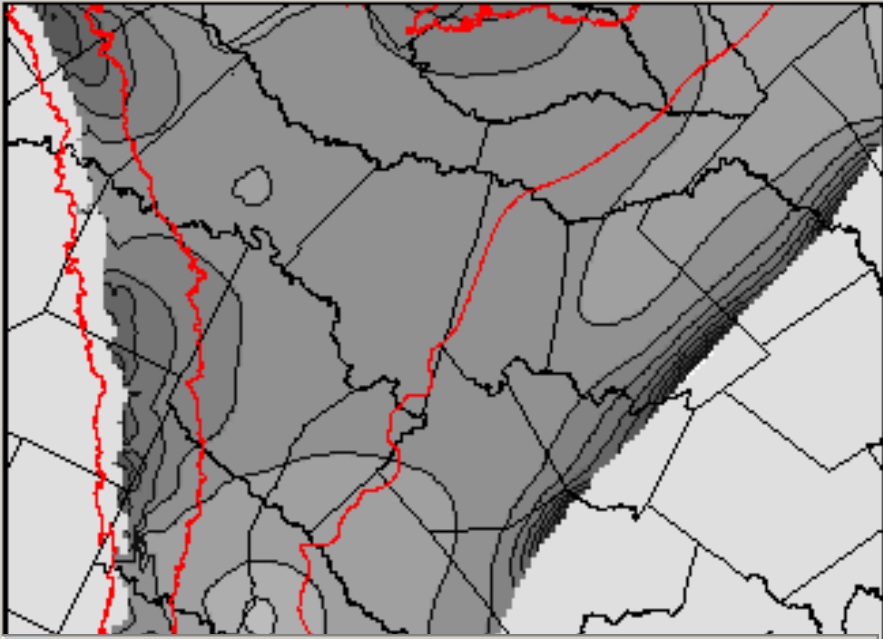
Label Format Restore Defaults Load Save

OK Cancel Help

5570522, 1.923E+07 1, 1, 5 Period 1

999999

Presentation



Options > Environment.. > Coordinate System

Processing Modflow - [CZWX-C.PM5]

File Value Options Help

Environment Options

Appearance Coordinate System Contours

Grid Position

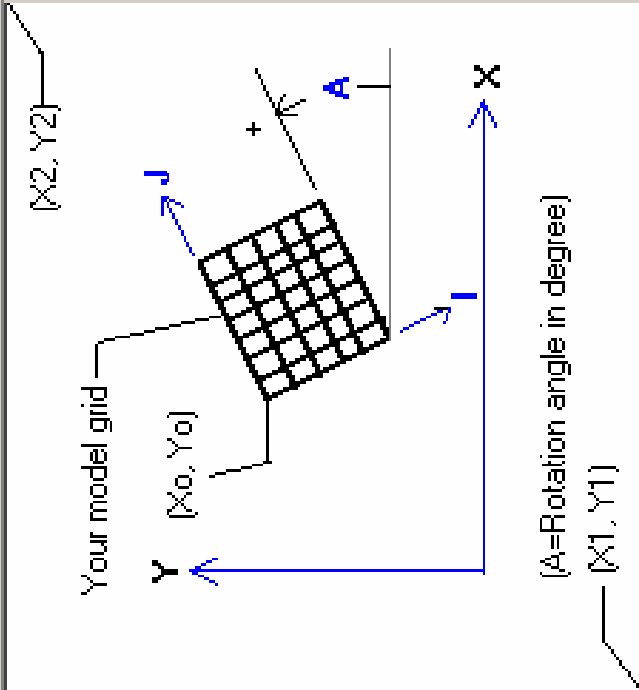
X₀= 5382716
Y₀= 1.897722E+07
A= 58

Worksheet Size

X₁= 5214290
Y₁= 1.843445E+07
X₂= 7095534
Y₂= 2.024206E+07

Display zones in the cell-by-cell mode

Worksheet / Coordinate System



(A=Rotation angle in degree)
(X₁, Y₁)

5

sentation

OK Cancel Help

99999

Specification of Data for Transient Simulations

The screenshot displays a software interface for a transient simulation. The main window, titled "Processing Modflow - [CZWX-C.PM5]", shows a map of a region with a red boundary. A "Temporal Data" dialog box is open, allowing the user to specify data for different stress periods. The dialog includes a table with columns for "Period", "Data", and "Use". Below the table are buttons for "Edit Data", "Copy Data", "Leave Editor", "Cancel", and "Help".

Temporal Data

To edit the model data for a specific stress period, select a period from the table below then press "Edit Data".

Period	Data	Use
1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
2	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
3	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
4	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
5	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
6	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
7	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
8	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
9	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
10	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
11	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
12	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
...	<input type="checkbox"/>	<input type="checkbox"/>

Buttons: Edit Data, Copy Data, Leave Editor, Cancel, Help

Main window controls: 5584435, 1.917E+07, 1.1, 1.5, Wells [L^3/T], Period 1, 0, 0

Part 3.

Technical Review of the CW-c GAM model

CARRIZO-WILCOX AQUIFER

Central GAM Model



- Outcrop**
- Freshwater subsurface**

Northern
model

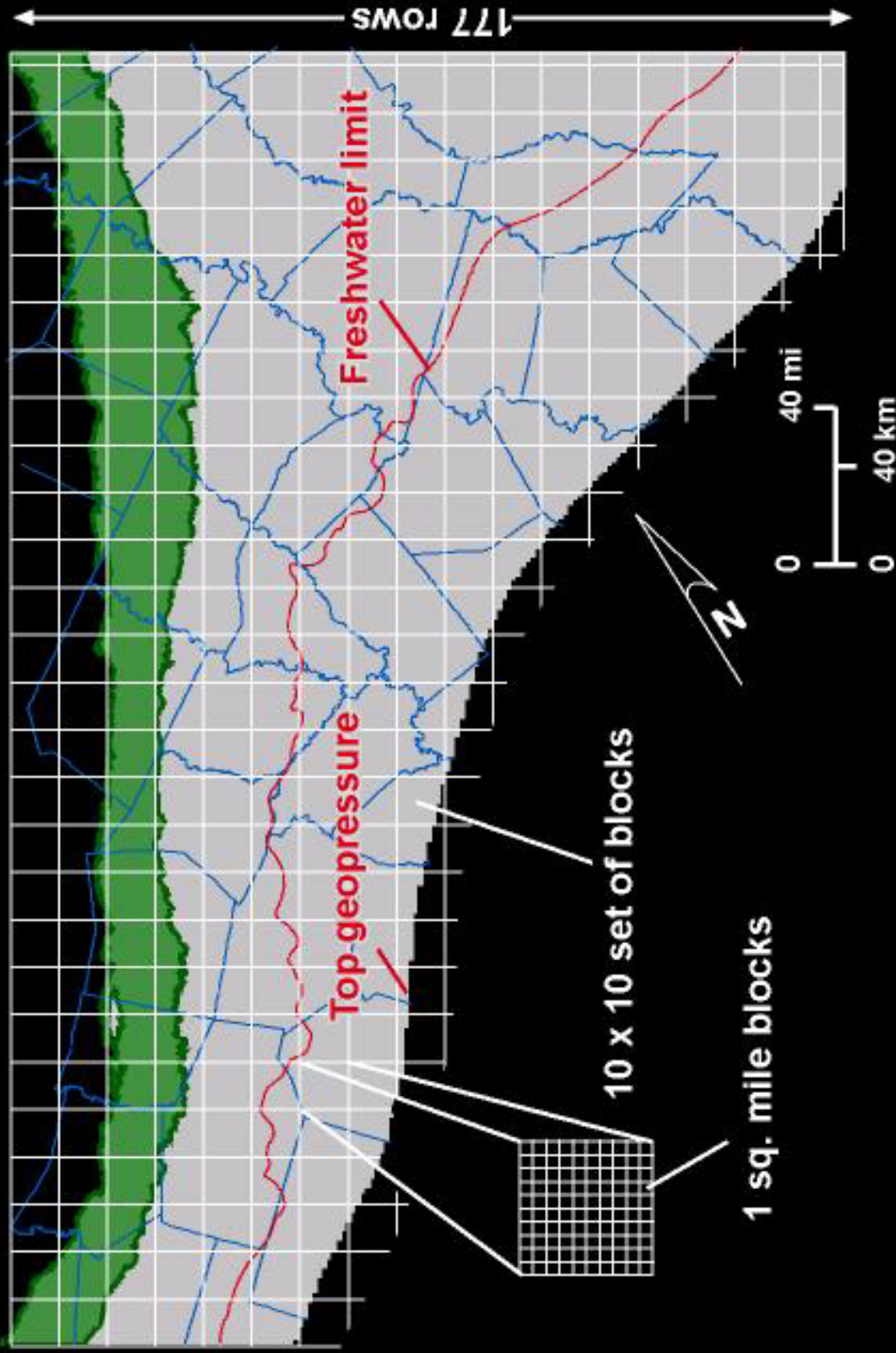
Central
model

Southern
model

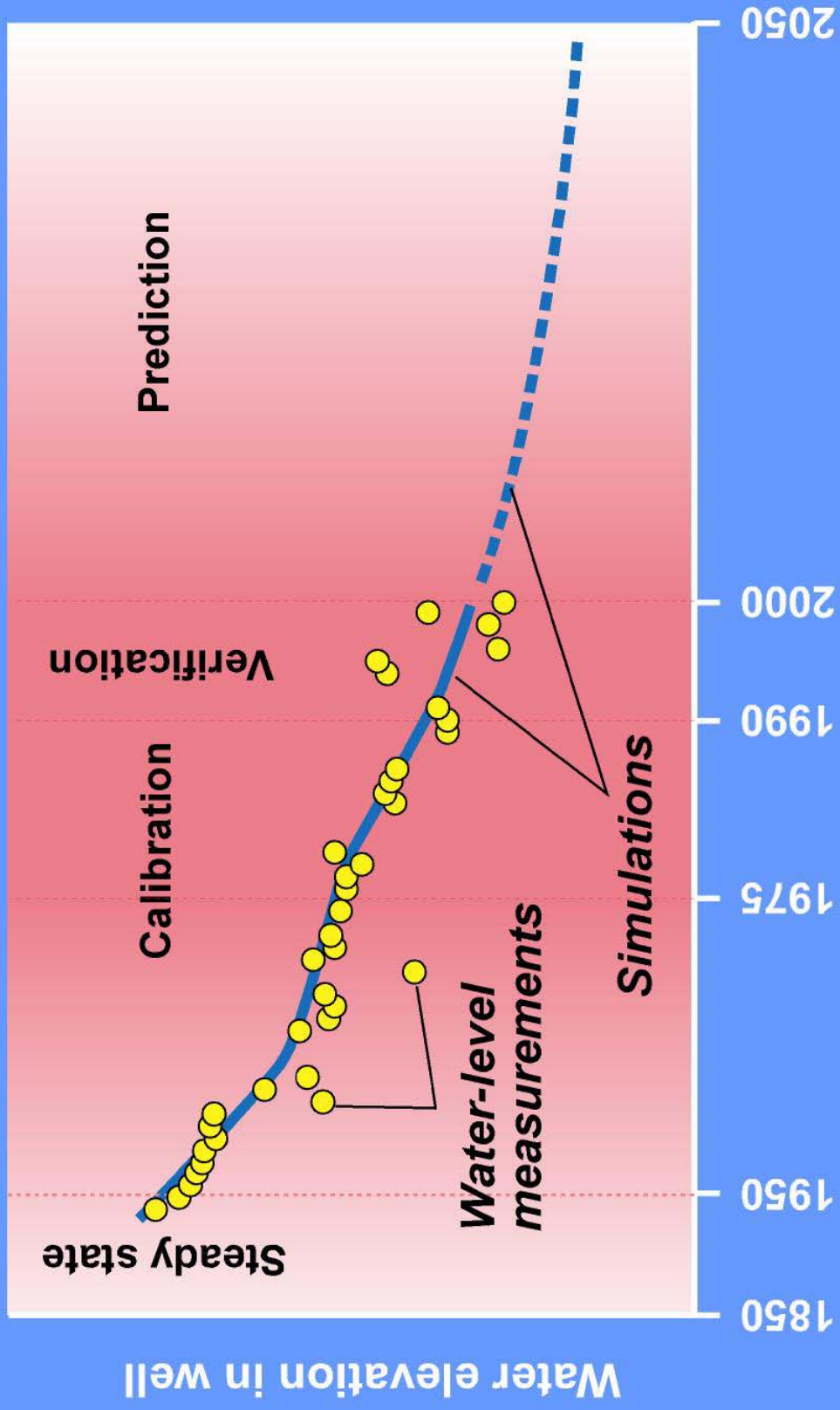
0 150 mi
0 200 km

MODEL GRID

273 columns

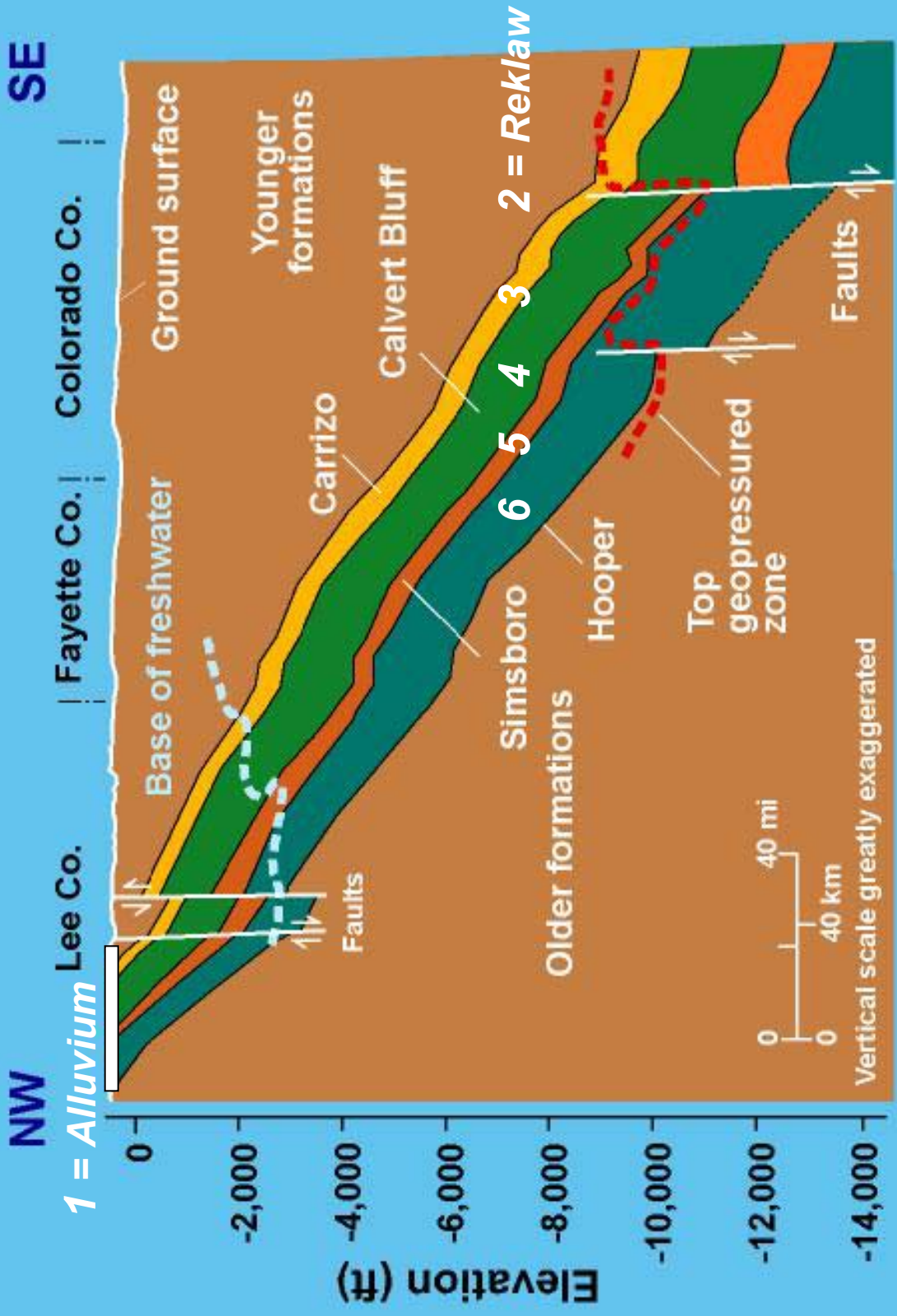


MODELING PERIODS



CARRIZO-WILCOX HYDROGEOLOGY

Central Part of Model Area

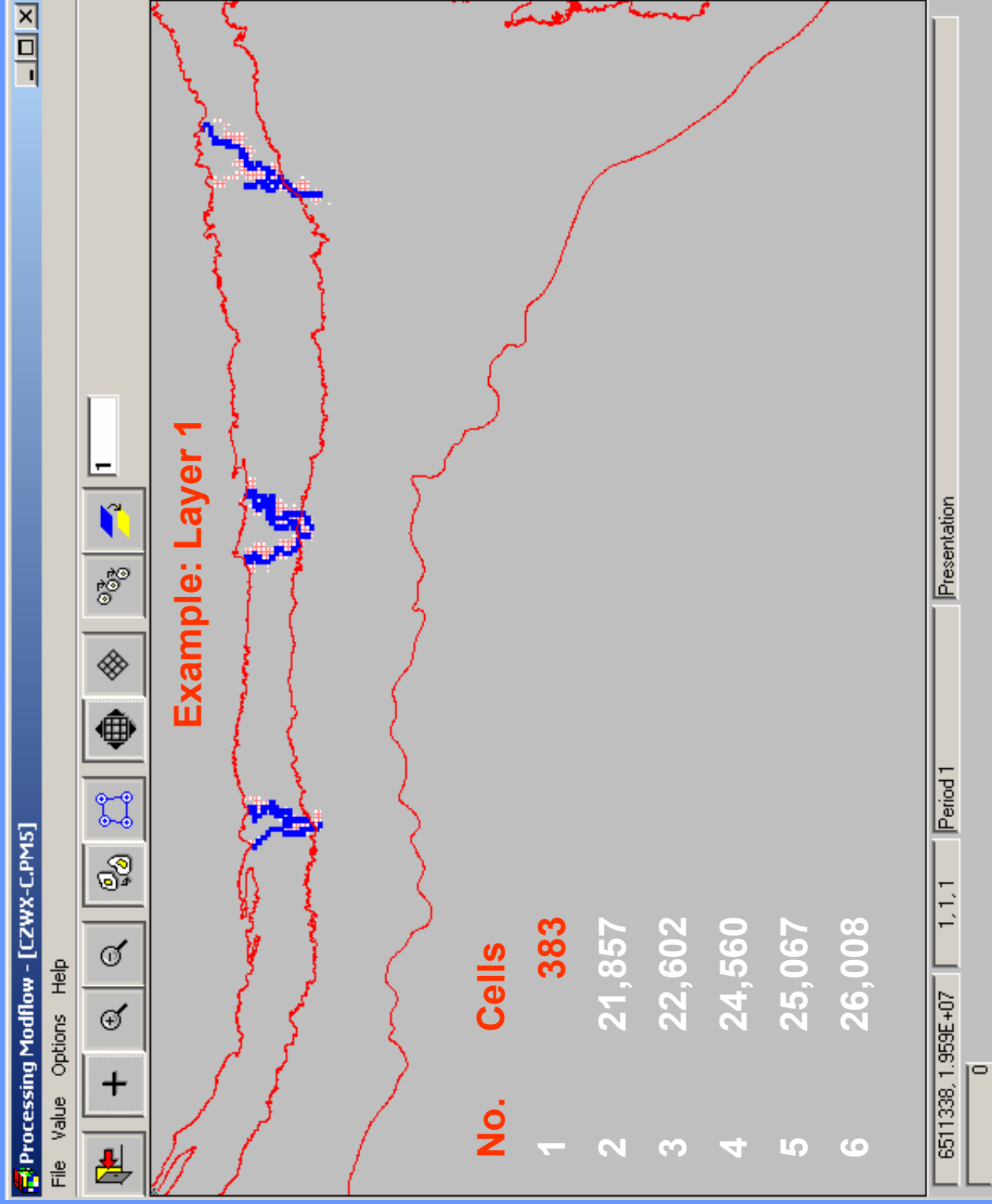


GAM MODEL INFORMATION REQUIREMENTS

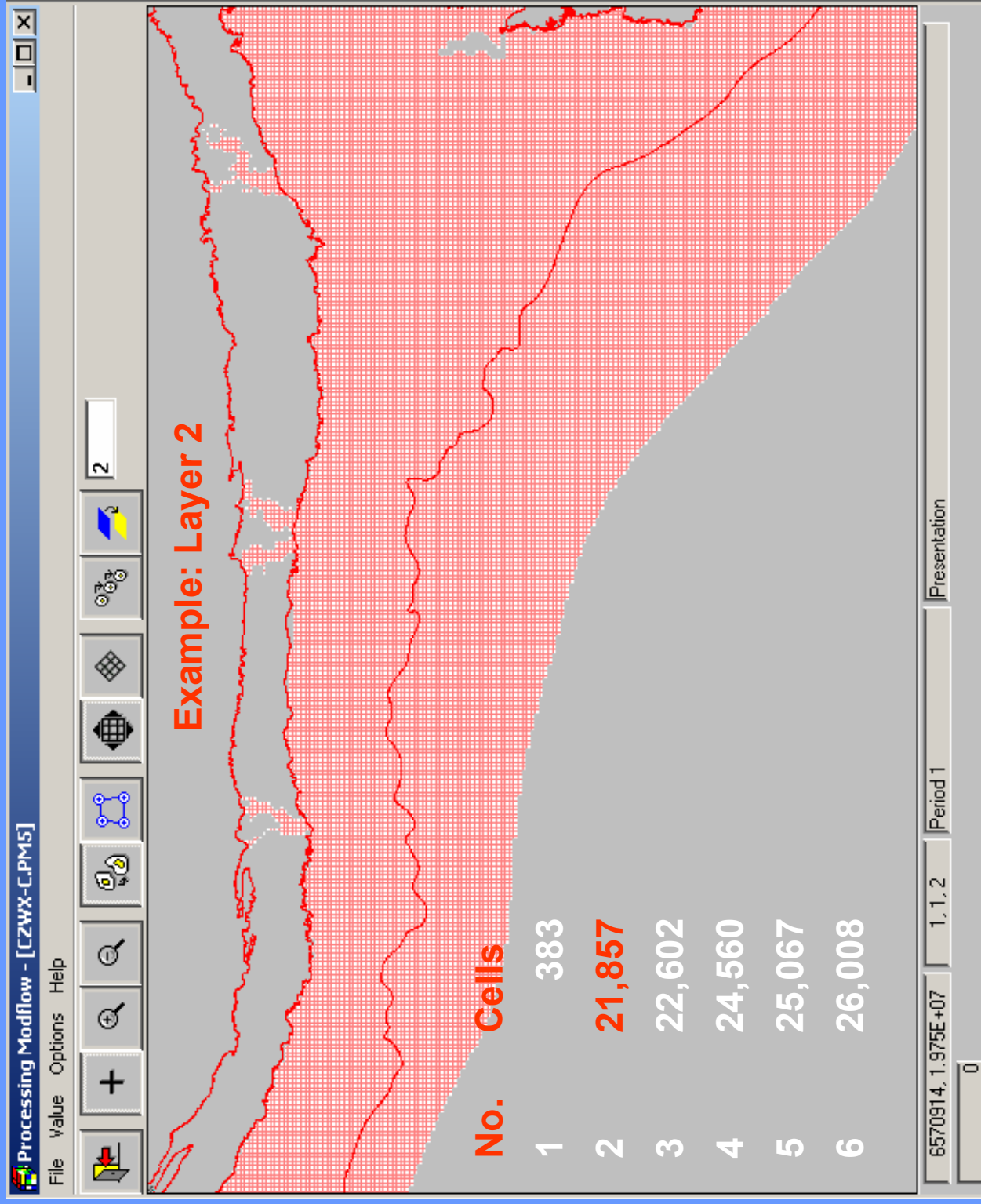
$$\frac{\partial}{\partial x} \left(T_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(T_z \frac{\partial h}{\partial z} \right) + W = S \frac{\partial h}{\partial t}$$

- **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**

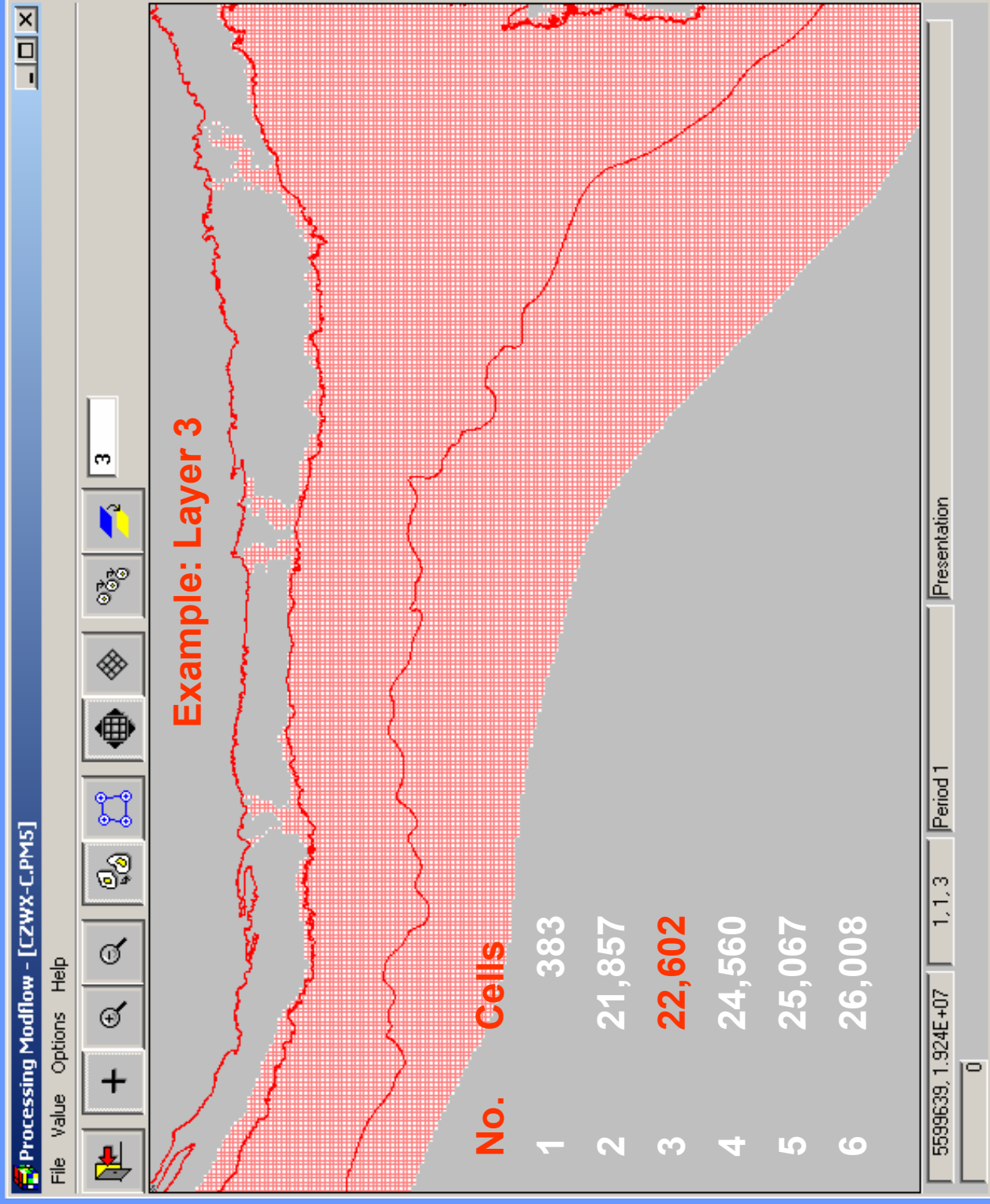
MODEL GRID



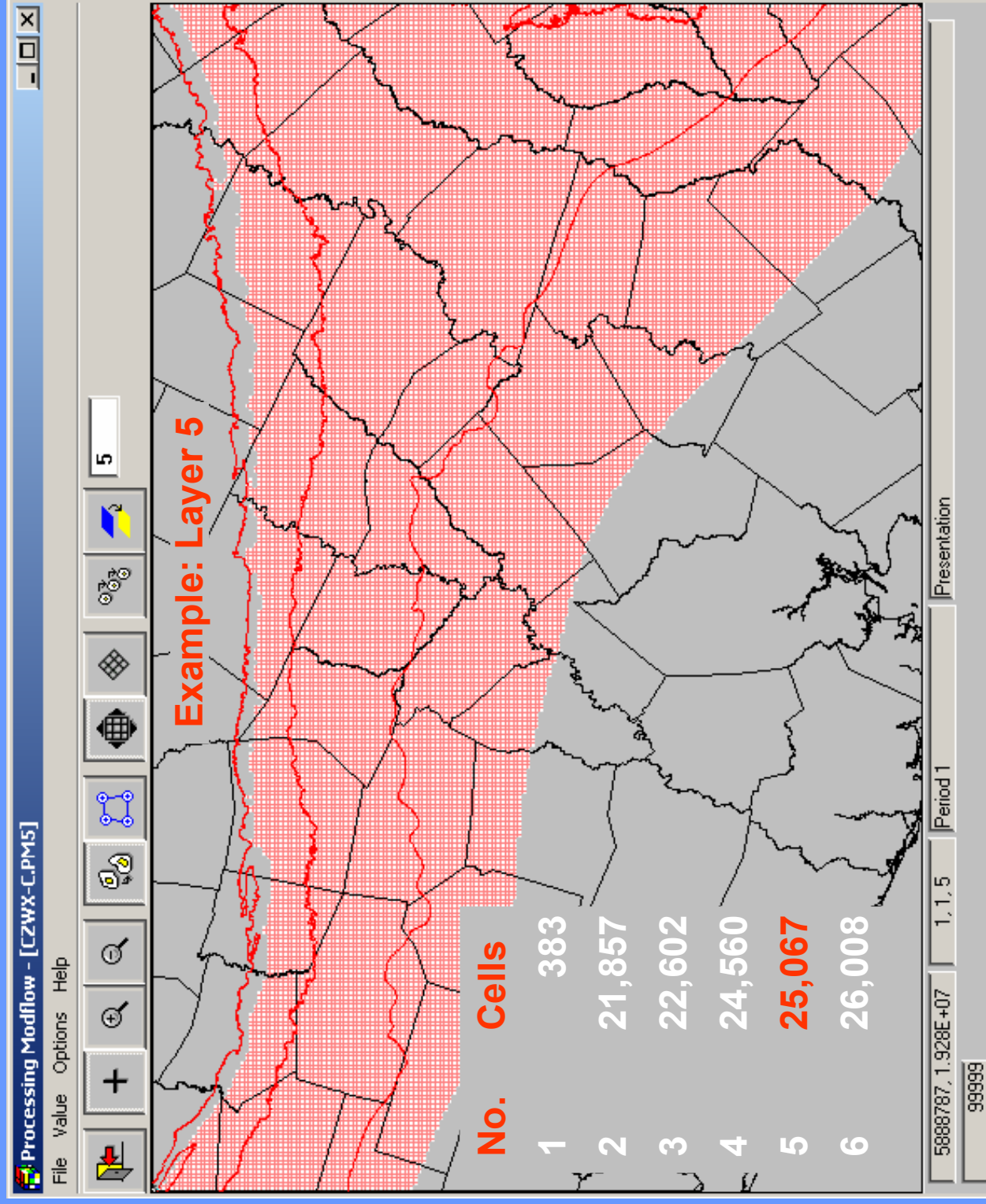
MODEL GRID



MODEL GRID



MODEL GRID



Supporting Data

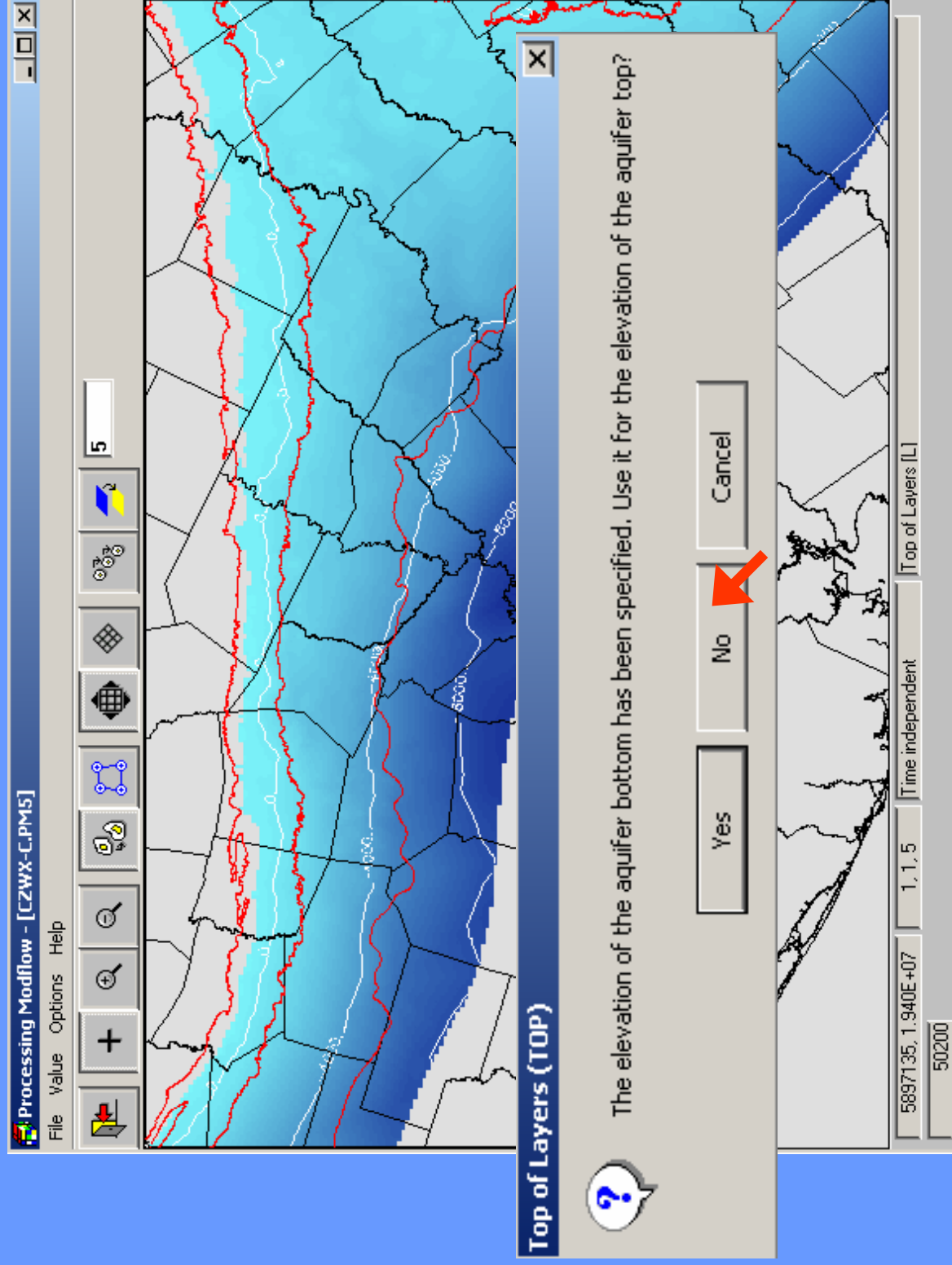
Model parameter	Data
Structure	Geophysical well logs, DEM for outcrop
Hydraulic properties (Kh, Kv), (S)	Field data, previous models, net sand maps, structure
Recharge	Field data, previous model results, Model calibrated
Base flow to streams	Outcrop watershed statistics
Reservoirs	Calibration target 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

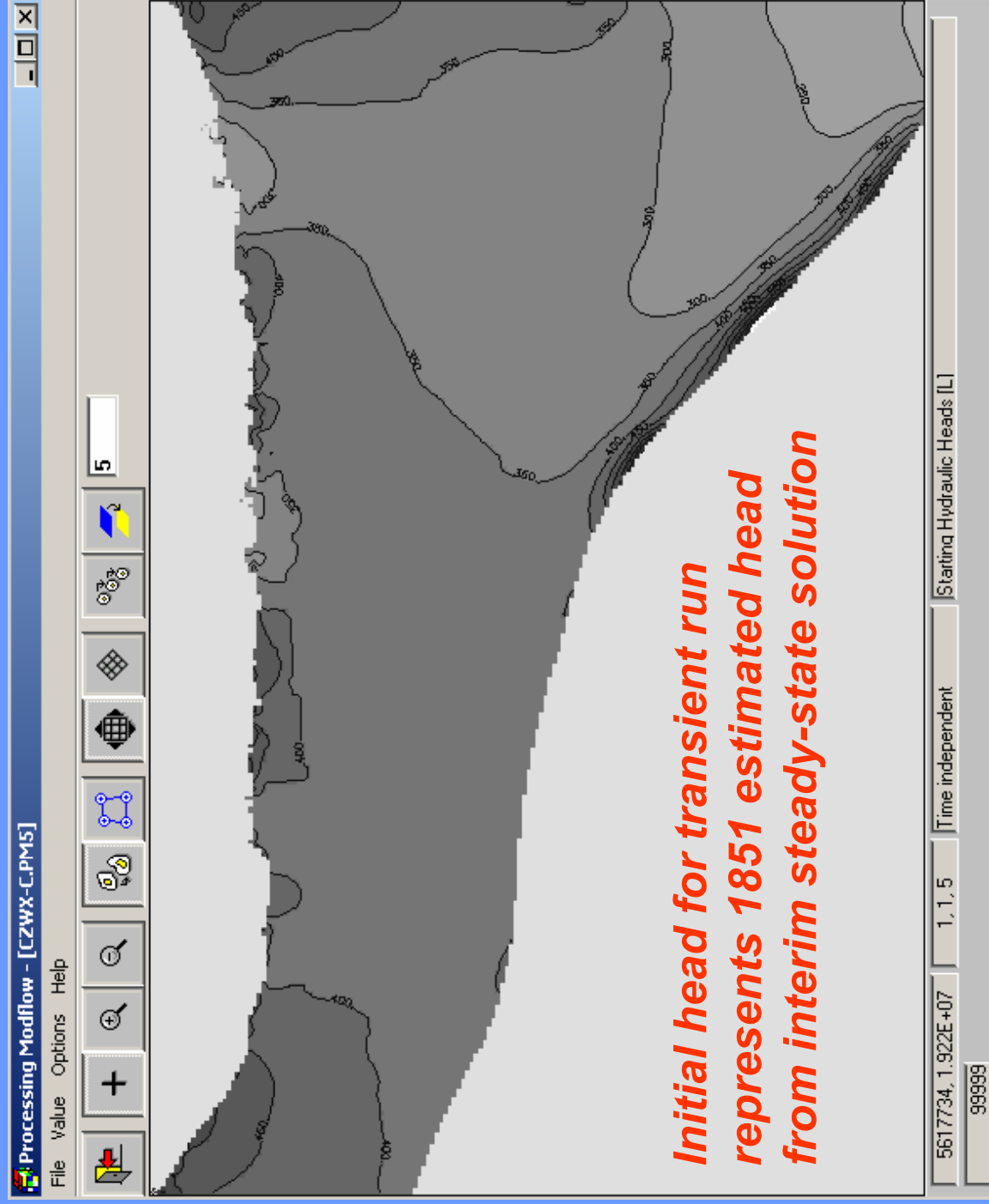
Mapping of structure data was coordinated between **CW-n**, **CW-c**, and **CW-s** models

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

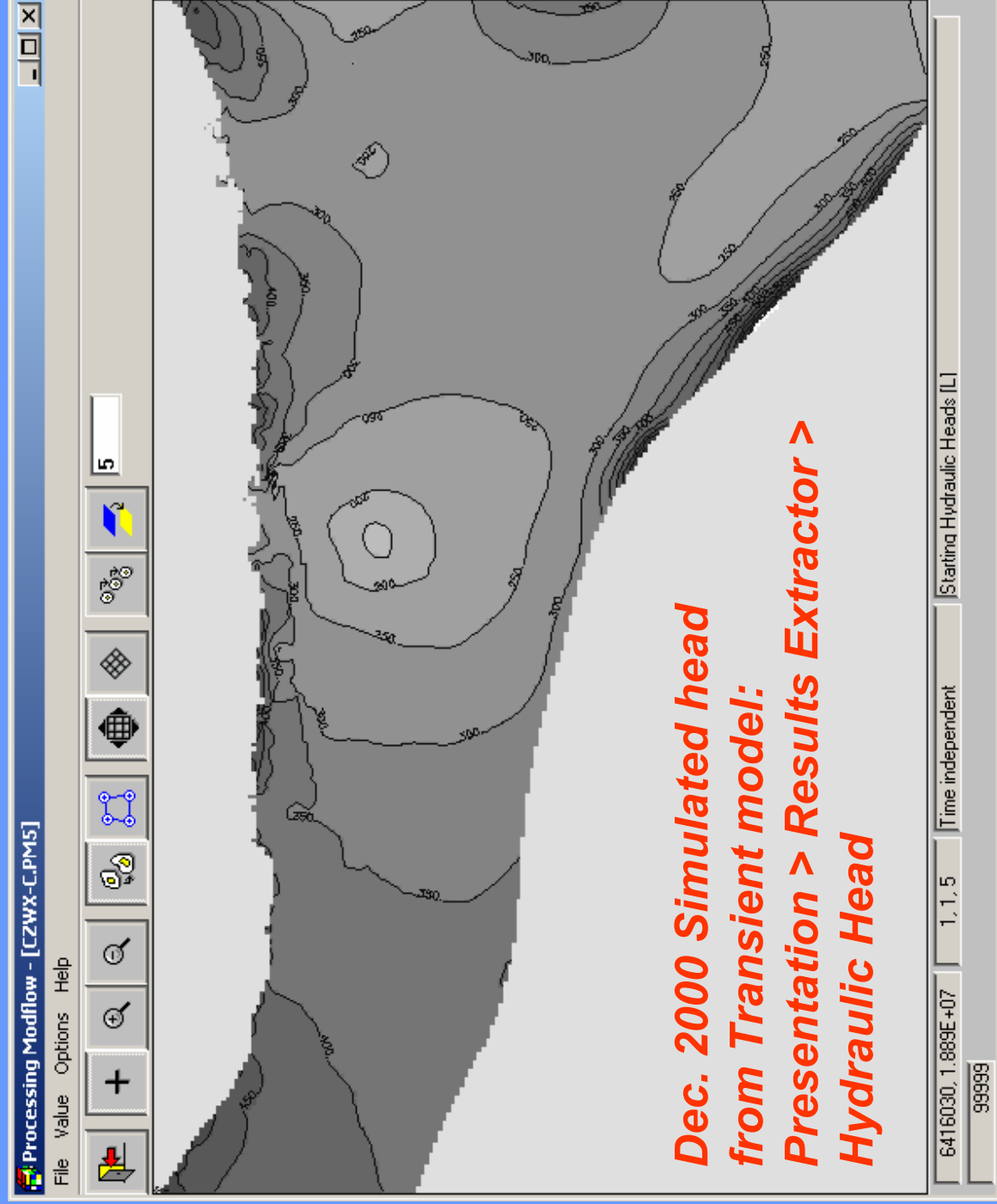
Structure Data Mapping



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

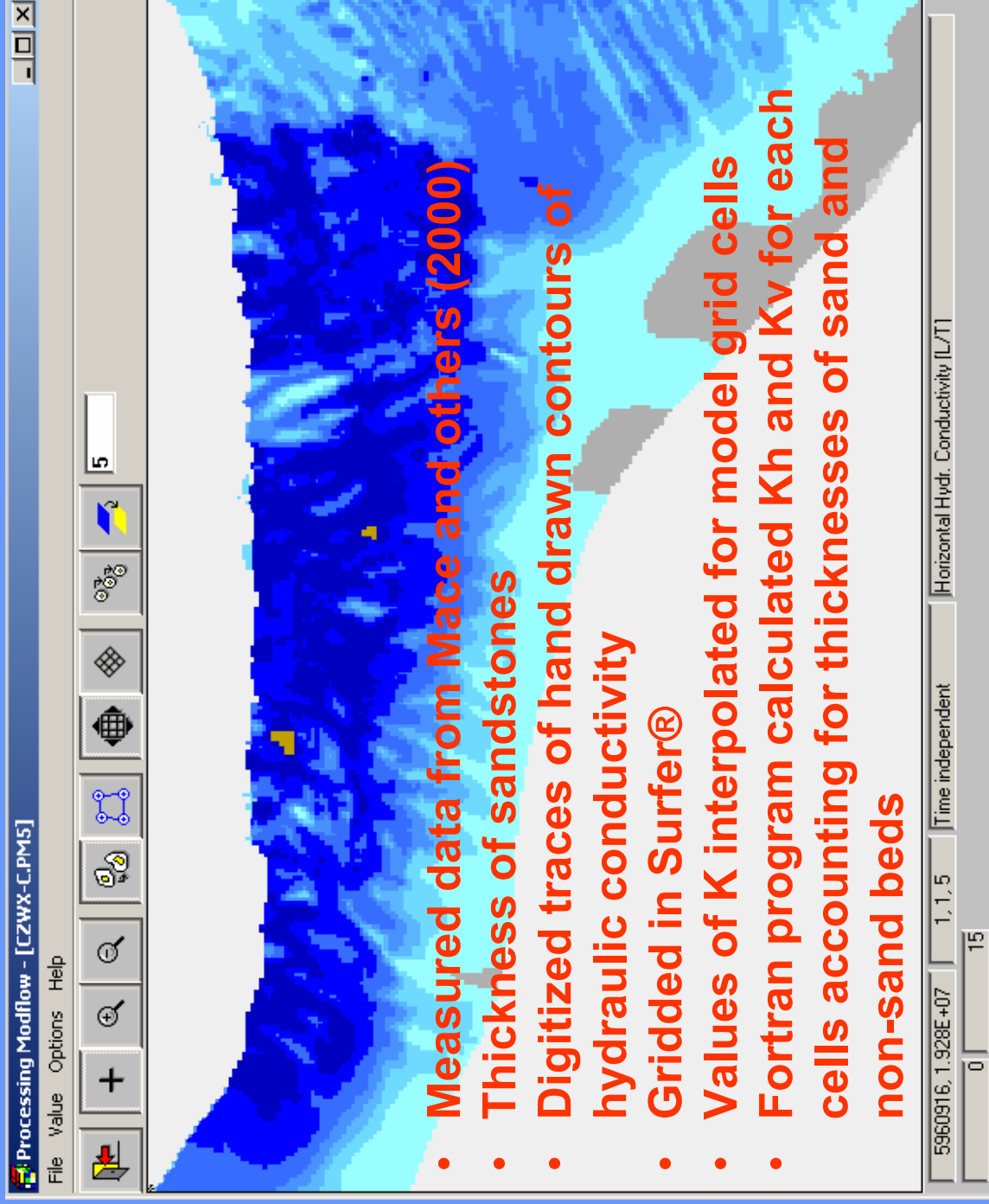


Initial Hydraulic Heads (Predictive Run)

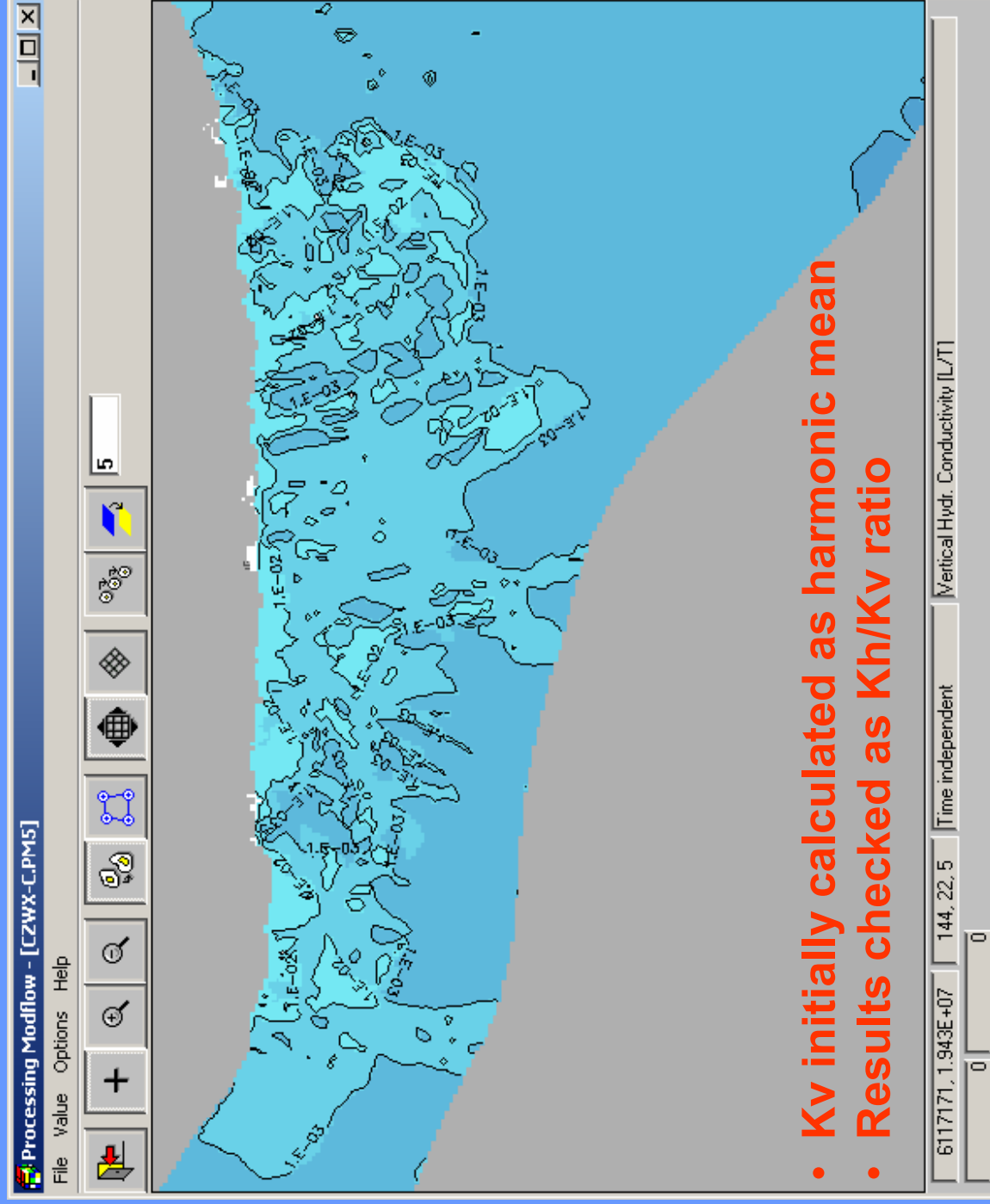


***Dec. 2000 Simulated head
from Transient model:
Presentation > Results Extractor >
Hydraulic Head***

Horizontal Hydraulic Conductivity (Kh)



Vertical Hydraulic Conductivity (Kv)

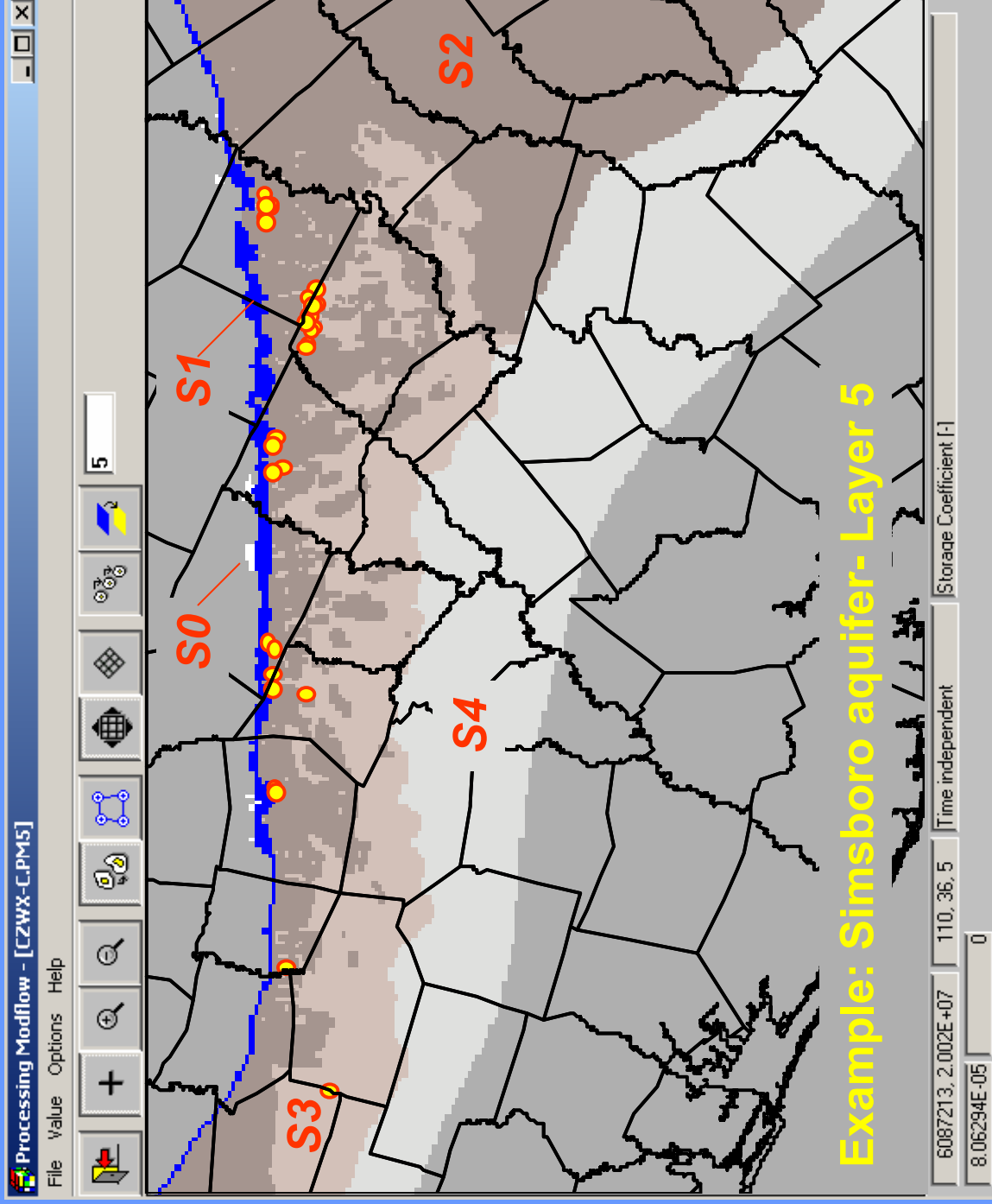


- Kv initially calculated as harmonic mean
- Results checked as K_h/K_v ratio

Storativity (S)

● All C-W field S data
S varied with depth and sand content

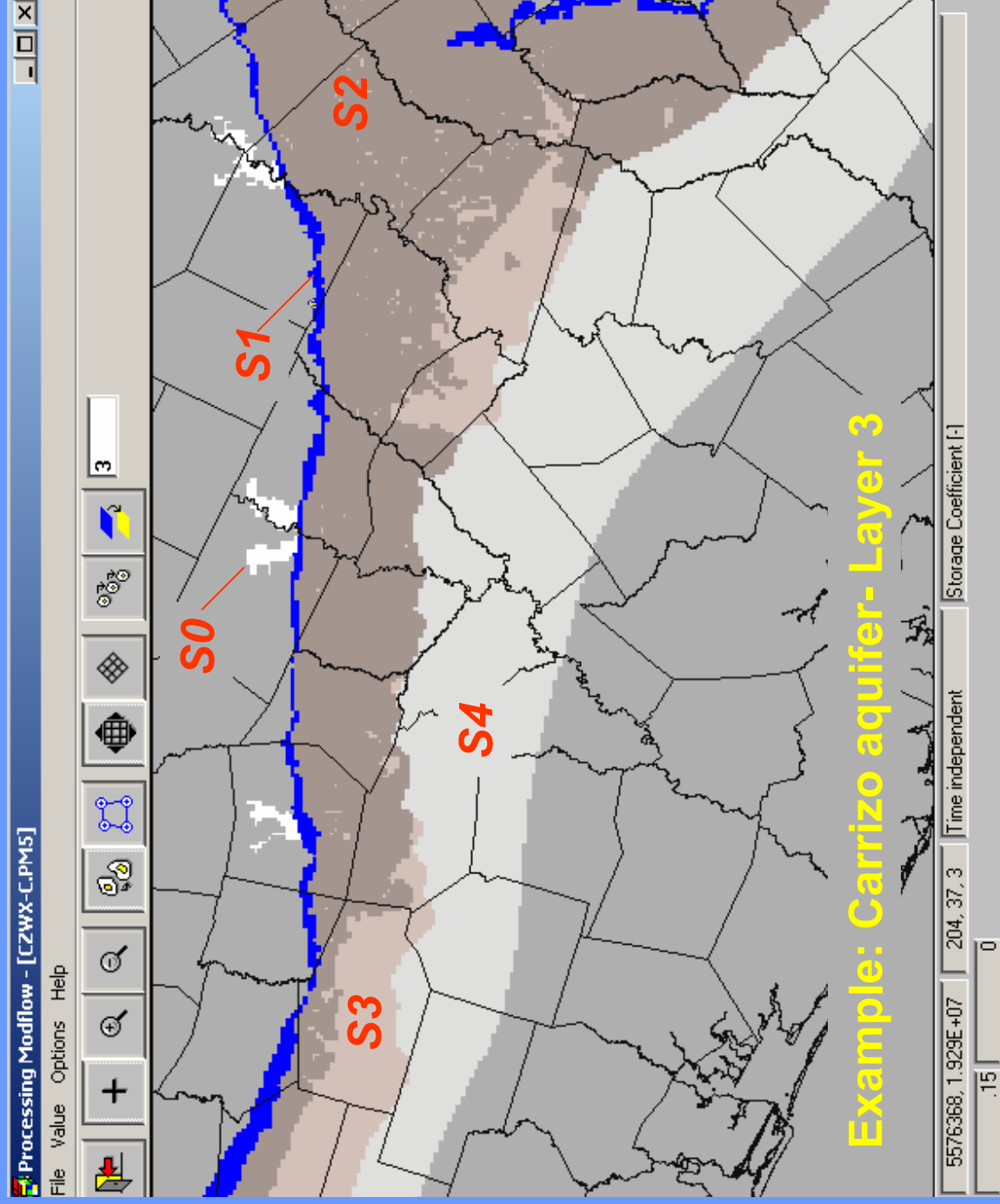
S0: 0.25 (Additional cells)
S1: 0.15 (Outcrop cells)
S2: $10^{-3.5}$ to 10^{-4}
S3: 10^{-4} to $10^{-4.5}$
S4: $10^{-4.5}$



Storativity (S)

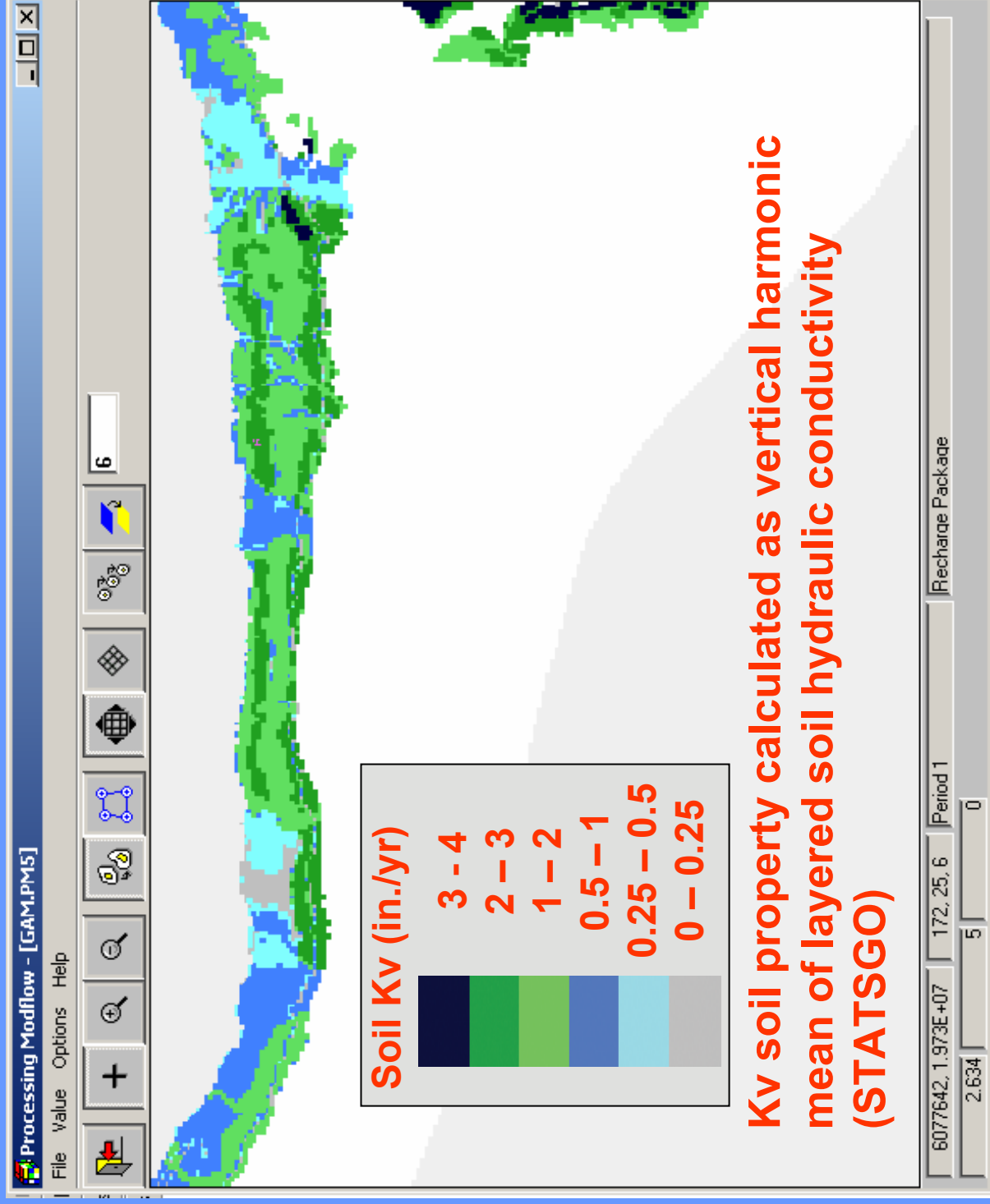
S varied with
depth and
sand content

- 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: $10^{-4.5}$

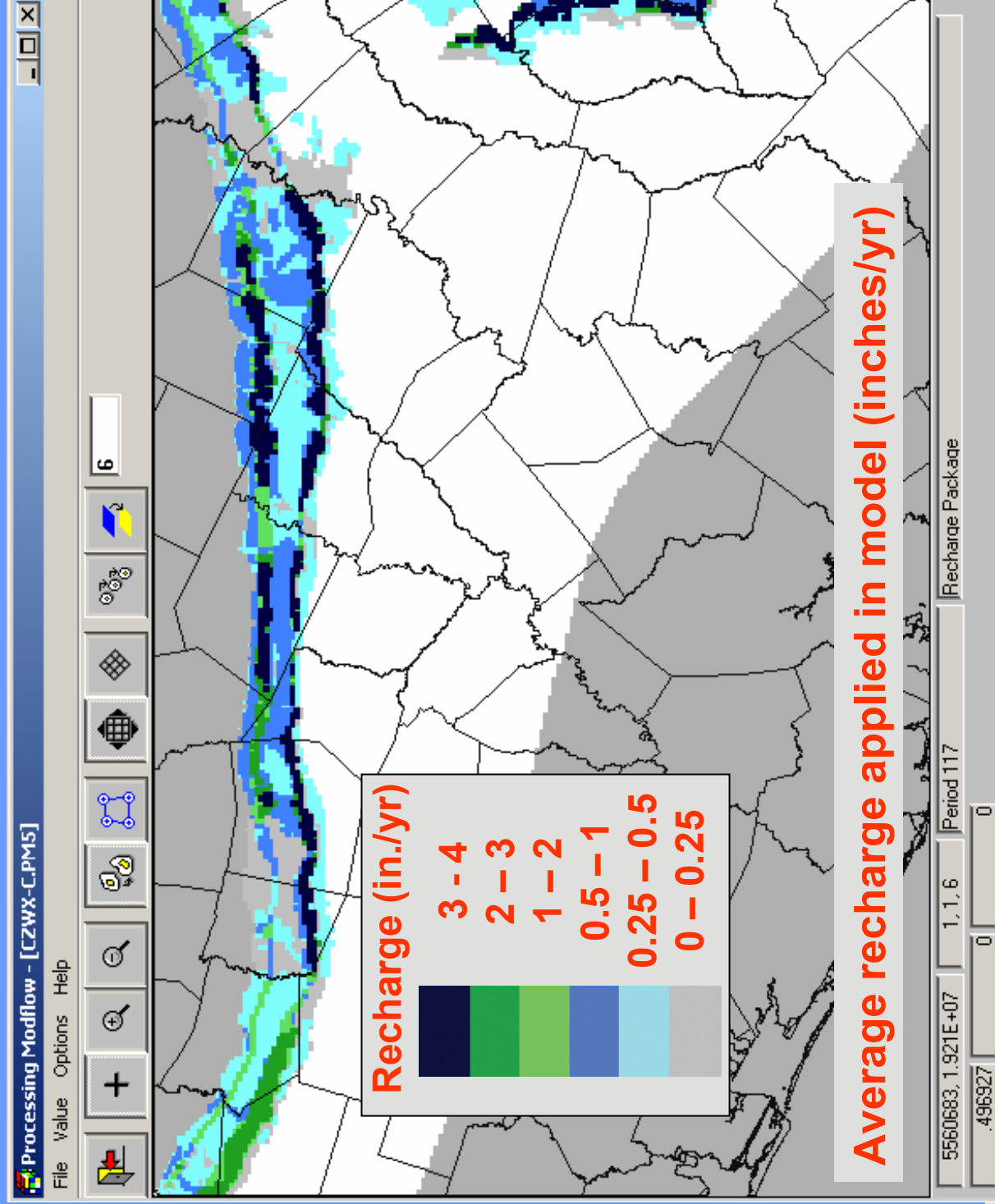


Example: Carrizo aquifer- Layer 3

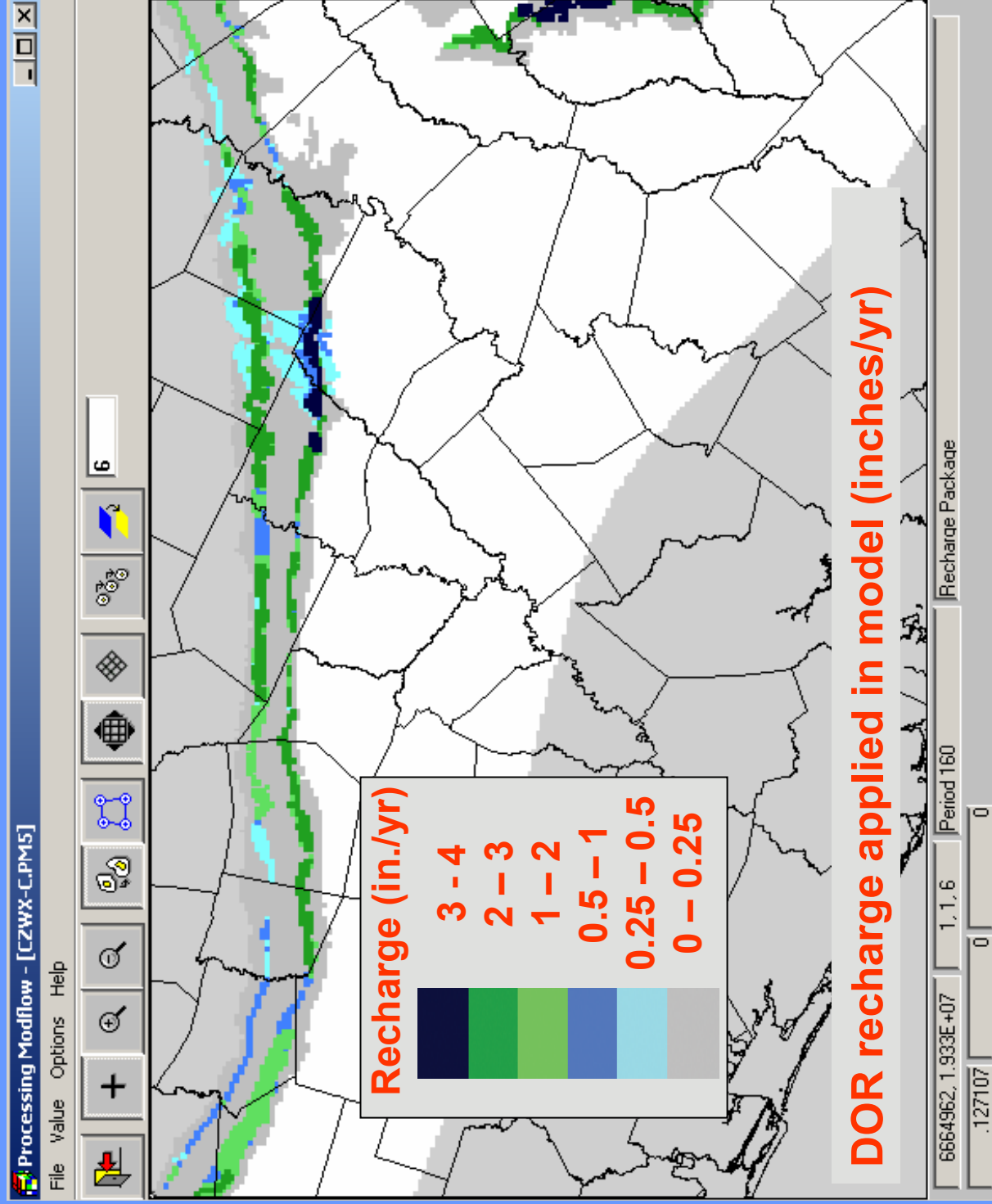
Soil Kv for Map of Recharge



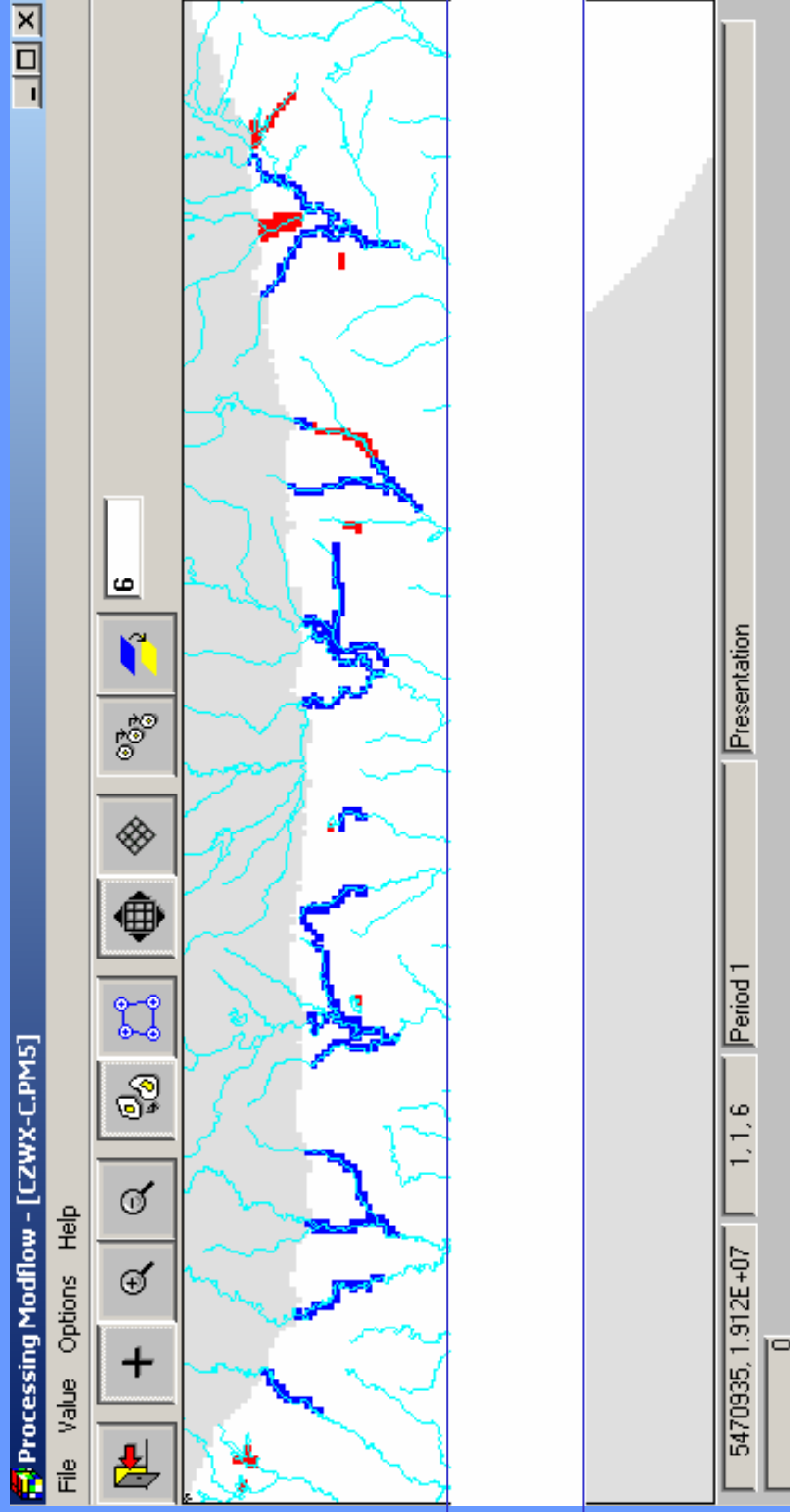
Recharge (2000)



Recharge (DOR)



Stream Flow Routing & Reservoirs

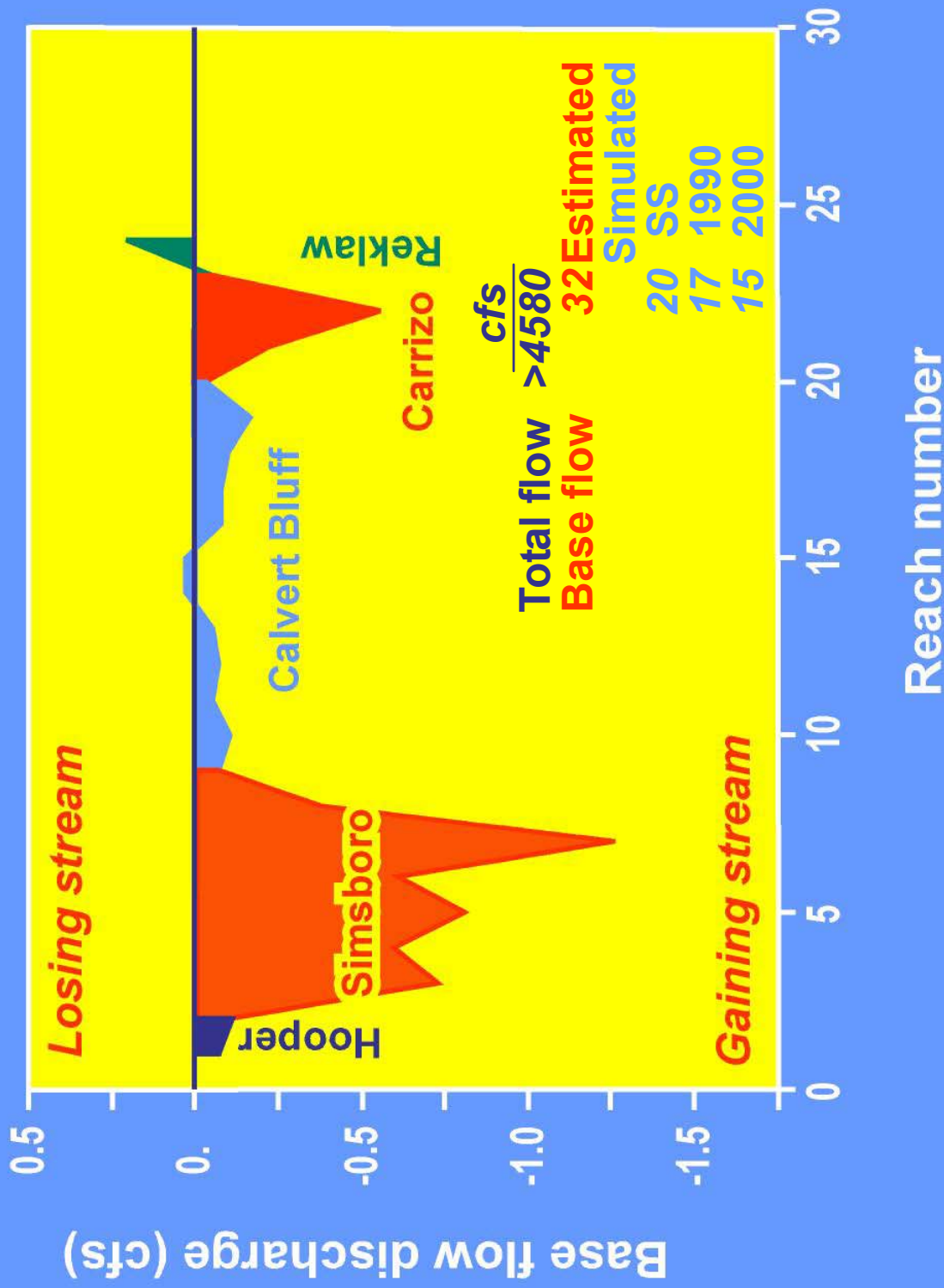


MODEL

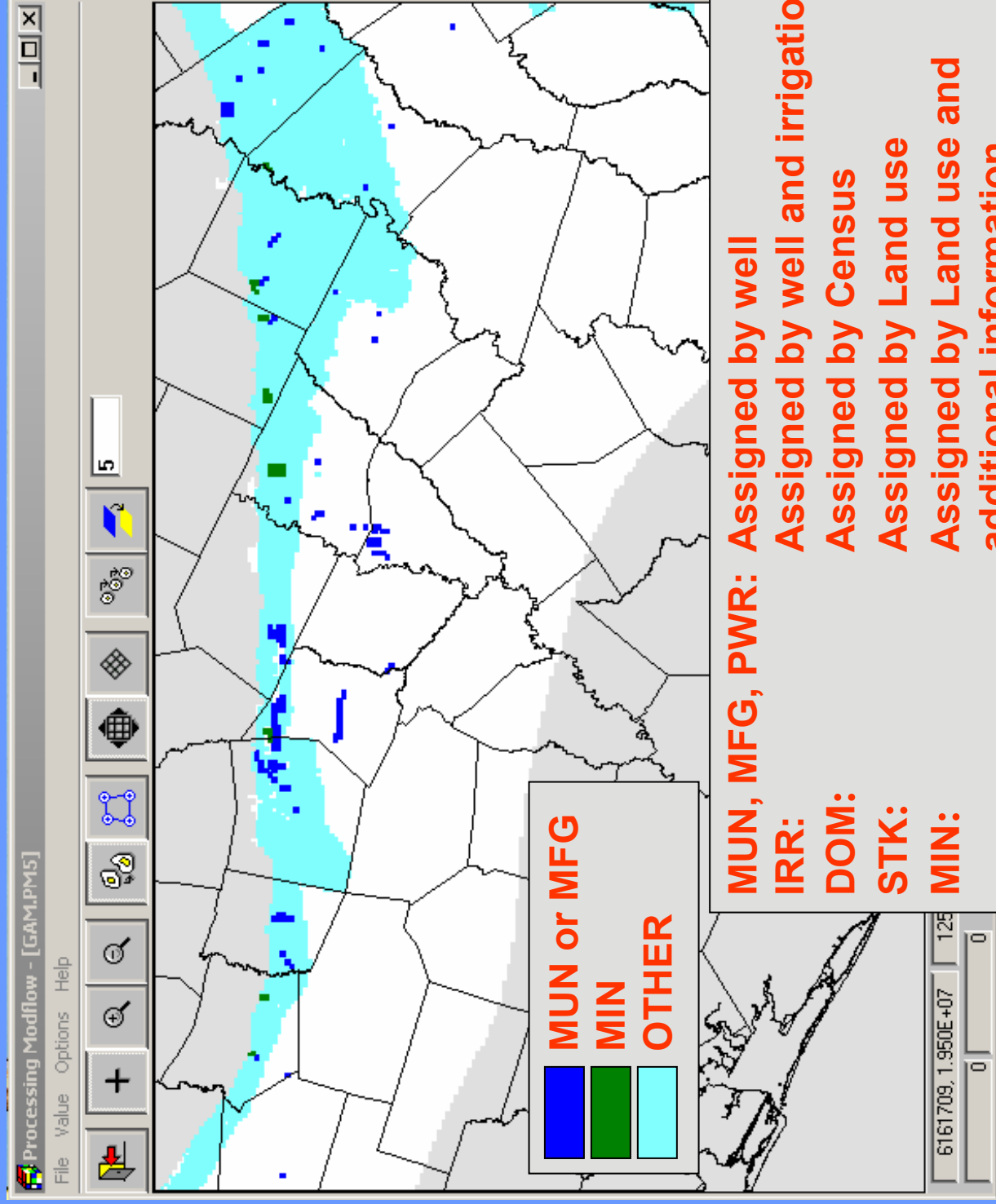
- Reservoirs
- Rivers

Base Flow from Aquifers

Brazos River

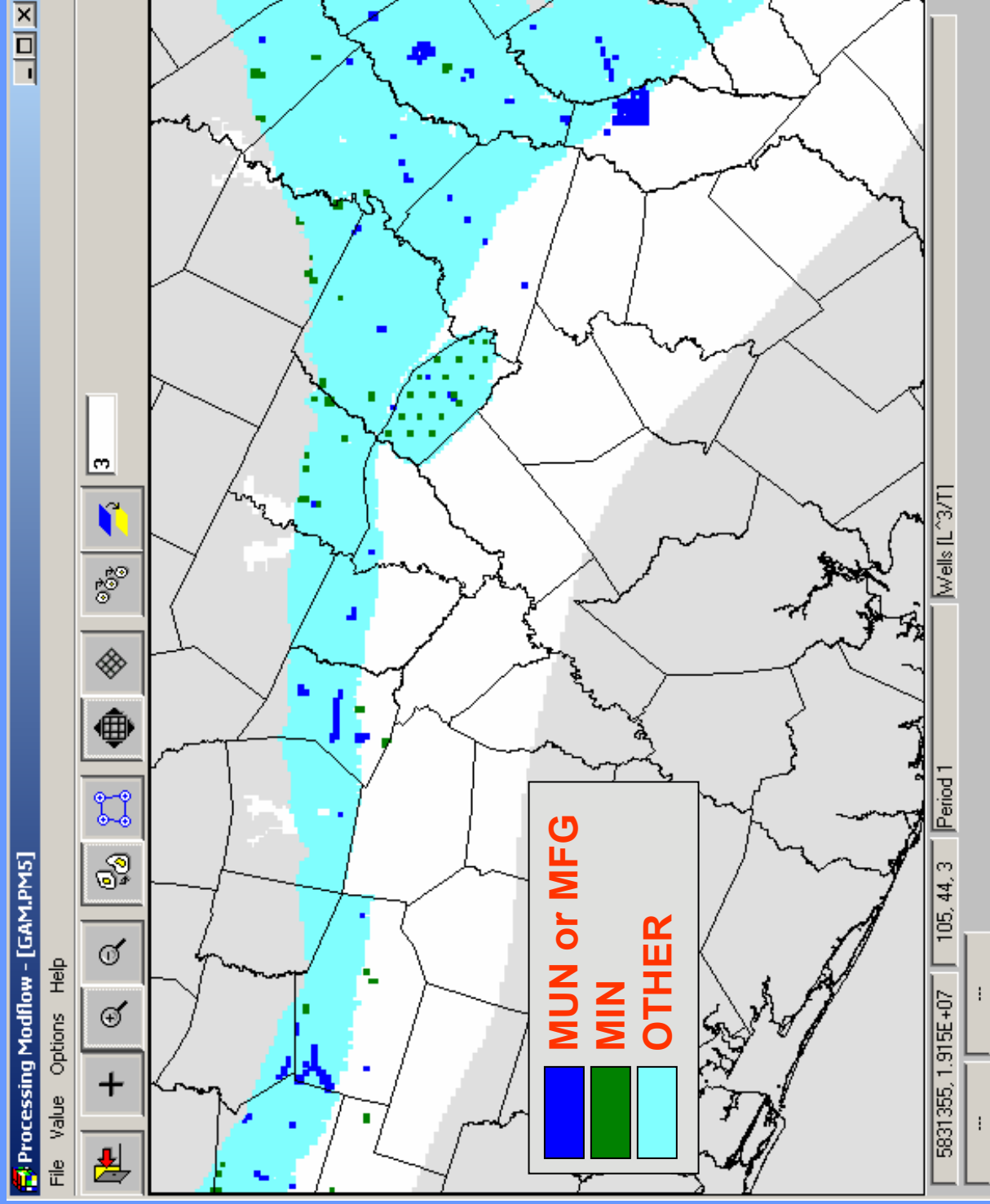


Pumping 2010



Simsboro (Layer 5)

Pumping 2010



Carrizo (Layer 3)

Input

Open File

Total Columns: _____

Data Columns: _____

Data Records: _____

Format: Delimited Fixed Width

Location Code: Cell ID Col-Row X-Y

Layers: Number Output empty

Grid Definition

Grid Parameters: Angle: UL-X: UL-Y:

Cell Parameters: # Cols: # Rows: Delta X: Delta Y:

Use Baseline Data

Use Baseline Data

Multiple Layers

Column Numbers: Cell ID Column or X coordinate Row or Y coordinate Layer Number First data column

Baseline Values

Spatially constant

Temporally constant

Baseline

Open File

Baseline Records: _____

Output

File Type: PMCVRTin Array(s)

Delimiter: Comma Tab

Default Cell Value:

Multiple Cell Values: Sum Average

Array Data Type: Real Integer

Run

Stop

PM5Arrays3.0

Visual Basic

program

for preparing data

by layer

PMCVRT.exe

PM5 File Converter (ASCII > Binary PM5 file)

