GAM Stakeholder Training

Groundwater Availability Modeling (GAM) for the Northern Carrizo-Wilcox Aquifer

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Workshop Agenda

1. Introduction
2. Modeling Overview
   - Modeling Protocol and Practice
   - MODFLOW
   - PMWIN
3. Northern GAM Review
   - Technical Overview
   - Data and Model Inputs
4. LUNCH
5. Hands-On Modeling Lab
   - The PMWIN Interface
   - Steady-State Model
   - Transient Model Exercise(s)

Workshop Goals

- Provide an introduction to groundwater modeling, MODFLOW, and PMWIN
- Review the development of the Northern Carrizo-Wilcox GAM
- Provide information on model input and associated data sources
- Provide insight into the utility and applicability of the GAM

Workshop Expectations

- To gain an appreciation of the expertise required to use the GAM
- To gain an understanding as to the potential applicability of the GAM
- To gain some understanding of the limitations of the GAM
- To acquire the ability to make minor modifications to the model via PMWIN

The GAM Truth

- If you want to run these models – seek professional help
- "It is very easy for me to calculate the positions of Sun, Moon and any planet, but I cannot calculate the positions of water particles as they move through the earth." Galileo

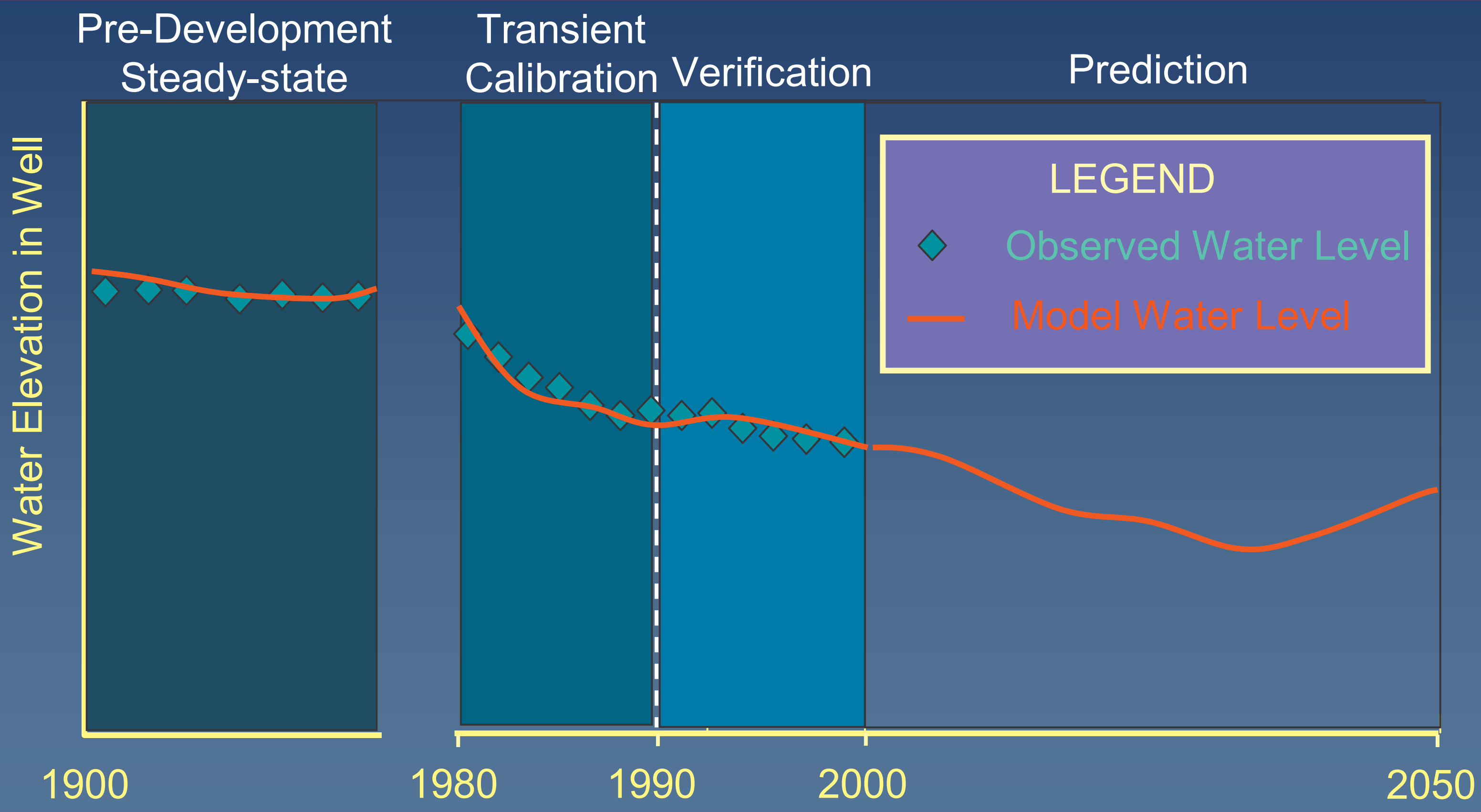
GAM Objectives

- Develop realistic and scientifically accurate GW flow models representing the physical characteristics of the aquifer and incorporating the relevant processes
- The models are designed as tools to help GWCD, RWPGs, and individuals assess groundwater availability
- Stakeholder participation is important to ensure that the model is accepted as a valid model of the aquifer

GAM Model Specifications

- Three dimensional (MODFLOW-96)
- Regional scale (1000's of mi2)
- Grid spacing of 1 square mile
- Include Groundwater/surface water interaction (Stream routing, Prudic 1988)
- Properly implement recharge
- Stress periods as small as 1 month
- Calibrate to within 10% of head drop

GAM Model Periods



Pre-development and transient calibration periods represent different hydrologic conditions

Modeling Overview

- Modeling Protocol & Practice
- MODFLOW
- PMWIN – Processing MODFLOW

Definition of a Model

Domenico (1972) defined a model as a representation of reality that attempts to explain the behavior of some aspect of it and is always less complex than the system it represents

Wang & Anderson (1982) defined a model as a tool designed to represent a simplified version of reality

Types of Models

Banks (1993) defines two types of models

1. Consolidative

consolidates facts regarding the system into a single model used as a surrogate to the real system

2. Exploratory

a series of computational experiments to explore cause & effect

Types of Models (cont.)

Bredehoft et al. (1996) further subdivided GW models

1. Data driven exploratory models “history matching”
2. Policy question driven models
3. Conceptually driven models

Historical Perspective

- Modeling of groundwater flow began with Darcy's Law published in 1856.
- Advances in numerical groundwater modeling were driven by the need to solve water supply problems in the 1960's.
- The first numerical model applications occurred around 1964 - 1965
- The first-widely used code was PLASM by Prickett & Lonnquist (1971)

GW Models in Water Resources

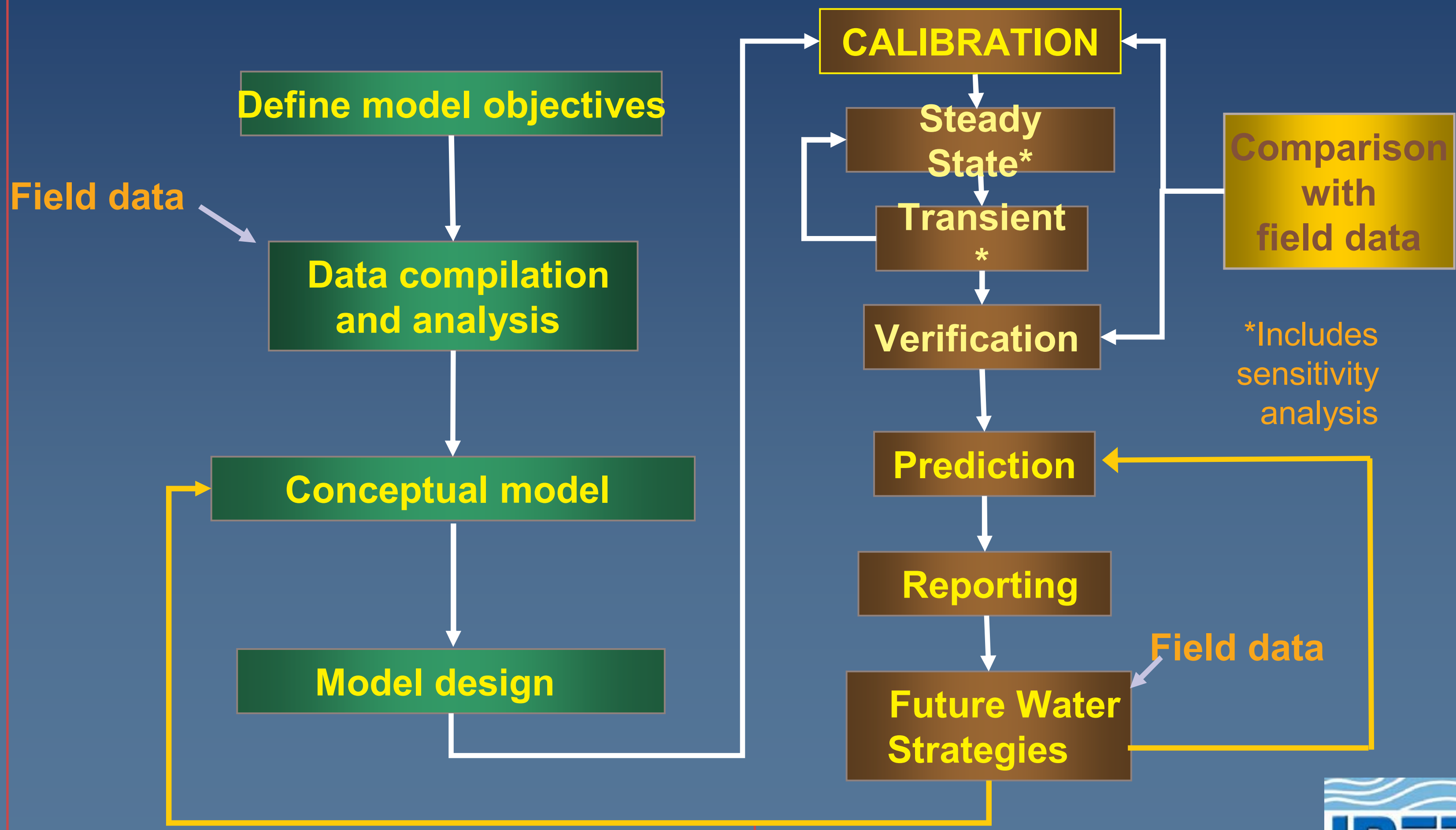
GW Models have been used in water resources in response to 4 basic issues:

- Impact on neighboring resources
- Conjunctive use issues (SW-GW)
- GW mining & resource depletion on practical time scales (regional resource issues)
- Water quality issues

GW Models in Water Resources

- Regional-scale models typically are used to address management as an institutional issue
- Local-scale models typically are used to address management as an operational issue

Modeling Protocol



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Modeling References

- Anderson & Woessner "Applied GW Modeling"
- ASTM D5447 "Standard Guide for Application of a Ground-Water Model to a Site-Specific Problem"
- "Fundamentals of Ground-Water Modeling", U.S. EPA
- Faust & Mercer: "GW Modeling: Numerical Models"
- Mercer & Faust: "GW Modeling: An Overview"

Conceptual Model

- Identify relevant processes and physical elements controlling GW flow in the aquifer:
  - Geologic Framework
  - Hydrologic Framework
  - Hydraulic Properties
  - Sources & Sinks (Water Budget)
- Determine Data Deficiencies
- Conceptual model dictates how you translate "real world" to Mathematical Model

To be Considered in Code Selection

- Simulates Relevant Physical/Chemical Processes
- Public-Domain vs. Proprietary
- Thorough Testing for Intended Use
- Complete Documentation

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Model Design

- Translate Conceptual Model to Mathematical Counterparts
- Procedure
  - Grid Design (Numerical)
  - Define Hydraulic Properties
  - Boundary & Initial Conditions

Grid Design – Typical Drivers

- Dimensionality (1D,2D,3D)
  - Vertical Gradients
  - Multiple Aquifers
  - Partially Penetrating Wells
- Number of Nodes
  - Run Time
  - Computer Memory
- Regular vs. Irregular Node Spacings
  - Design Time
  - Accuracy in Areas of Interest

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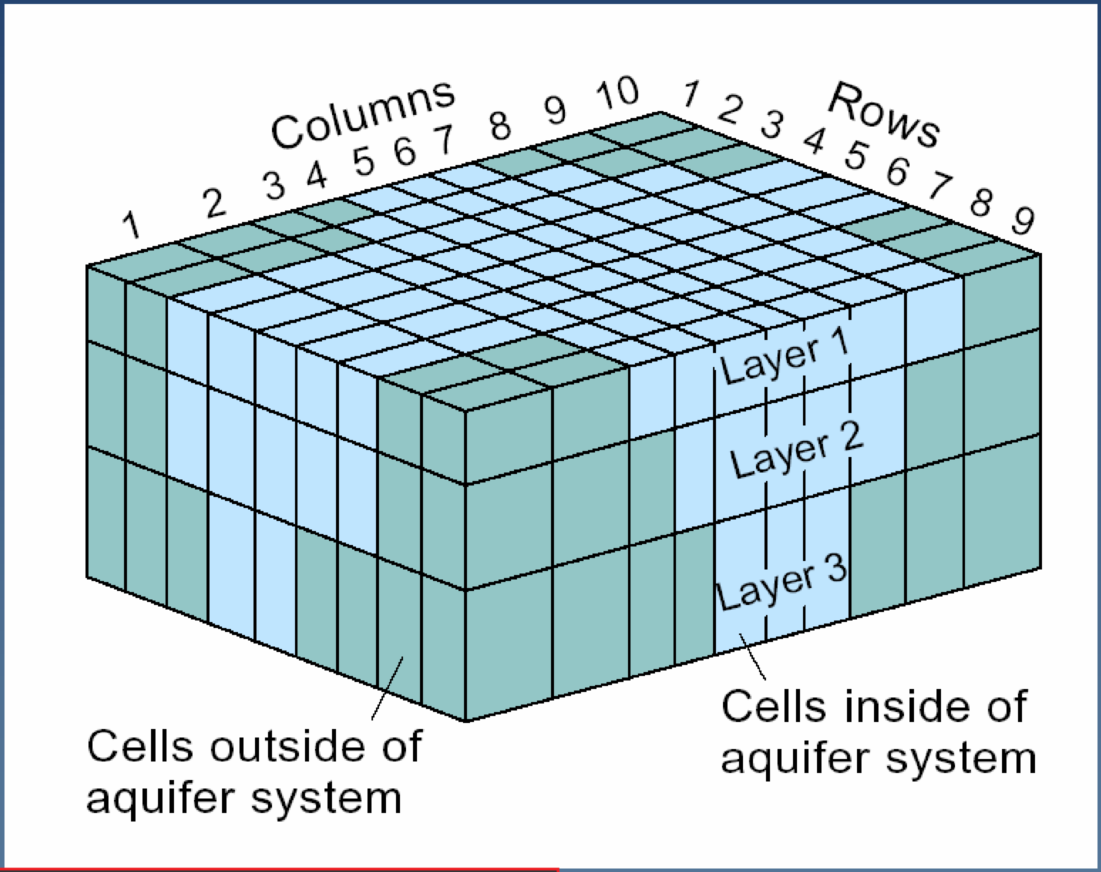
Grid Design – When to use a Regular (constant dimension) Grid

- Regional Studies (e.g. USGS RASA, GAM)
- Preliminary Analyses
- Models Where Area of Interest May Change
- High Resolution Models Where Memory is Not a Concern
- GAM grid defined to be 1 mile square

Model Grid Example



Source: USGS Fact Sheet FS-127-97

Model Inputs

- Hydrostratigraphic Surfaces for each Layer
- Hydraulic Properties:
  - Sand Thickness
  - Hydraulic Conductivity
  - Storativity (transient)
- Hydraulic heads
- Recharge
- Stream Flow (headwater flows, initial Cond.)
- Pumpage

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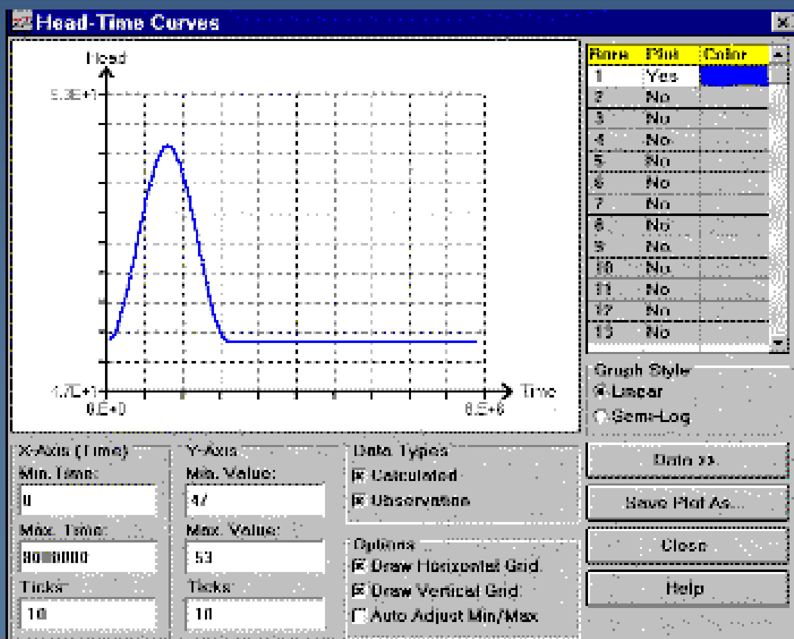
Boundary Conditions

- Boundary Condition is a constraint put on the active grid to characterize interaction between the modeled area and its environment
- Types:
  - Specified Head (Dirichlet – Type 1)
  - Specified Flux (Neumann – Type 2)
  - Head-Dependent Flux or Mixed (Cauchy- Type 3)
- Determination:
  - Based on Natural Hydrogeologic Boundaries
  - Analyze Impact of Artificial Boundaries

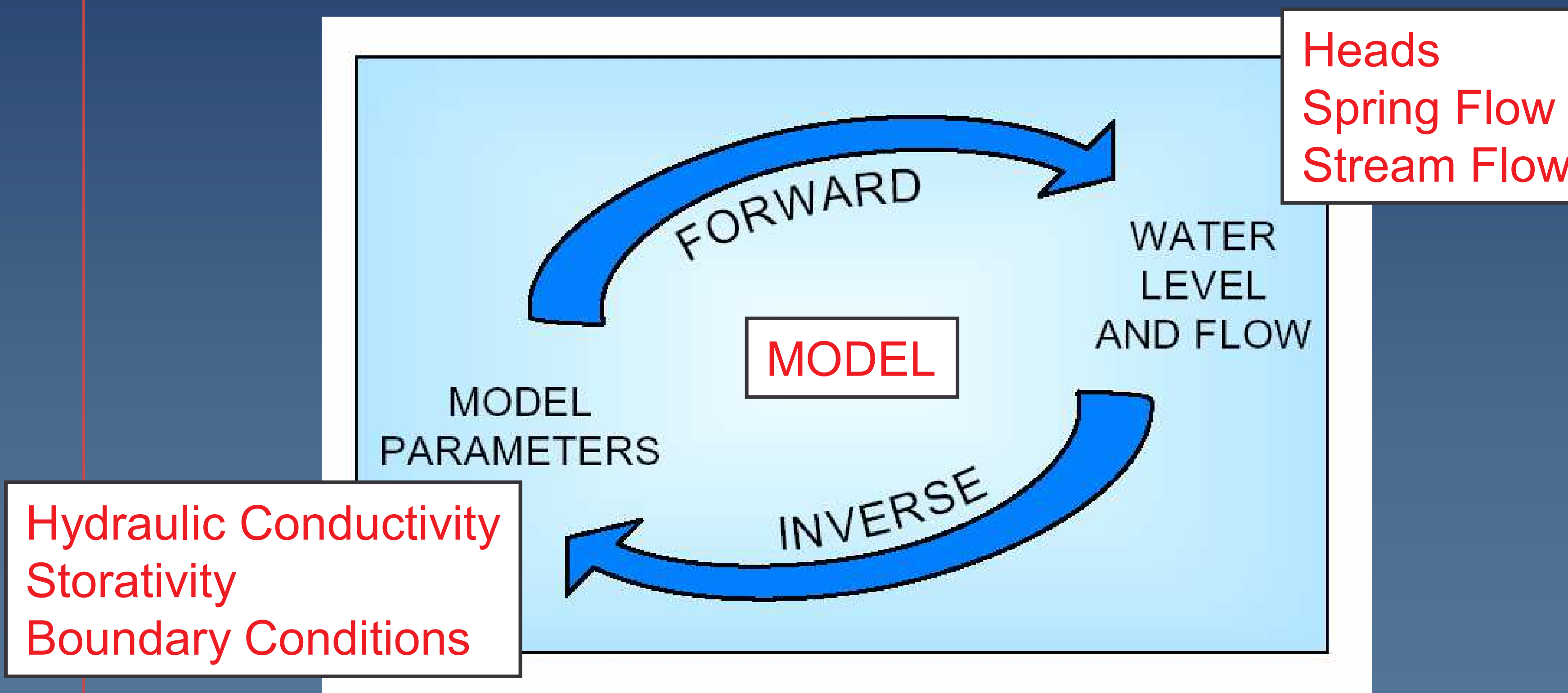
Boundary Conditions

- Boundary conditions may be static or transient



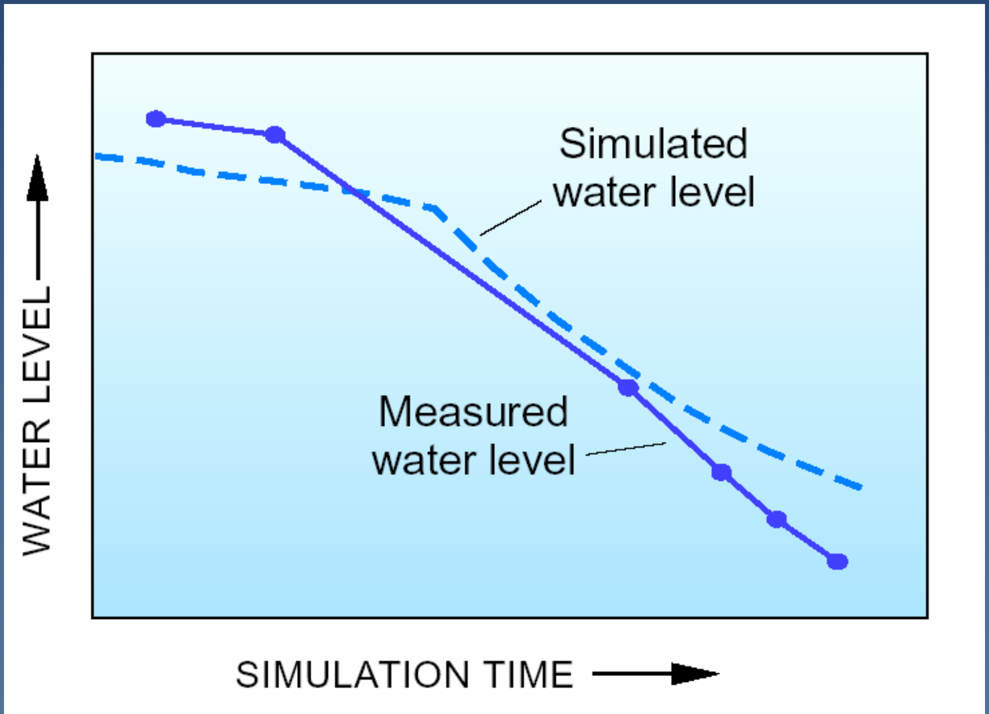
- Recharge or wells – Specified flow
- GHB, Reservoir, Stream – Head dependent flow
- Vertical or lower boundaries – specified flow @ zero = no flow

Modeling Approaches



Model Calibration

- Process used to produce agreement between observed and simulated data through adjustment of independent variables
- Typical variables adjusted are hydraulic conductivity, storativity, and recharge



Source: USGS Fact Sheet FS-127-97

Model Calibration

- Types:
  - Trial-and-Error
  - Automated or inverse
  - Stochastic
- Procedures:
  - Select Calibration Targets
  - Select Calibration Metrics
  - Adjust Boundary Conditions/Properties
  - Analyze Errors

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Model Calibration

- Steady-state calibration
  - Assumes that the hydrologic system is static over the time frame of interest
  - Q in = Q out ; No storage effects
- Transient calibration
  - Assumes that dependent variables change with time in response to changing stresses (recharge, pumping, stage, boundaries)

Sensitivity Analysis

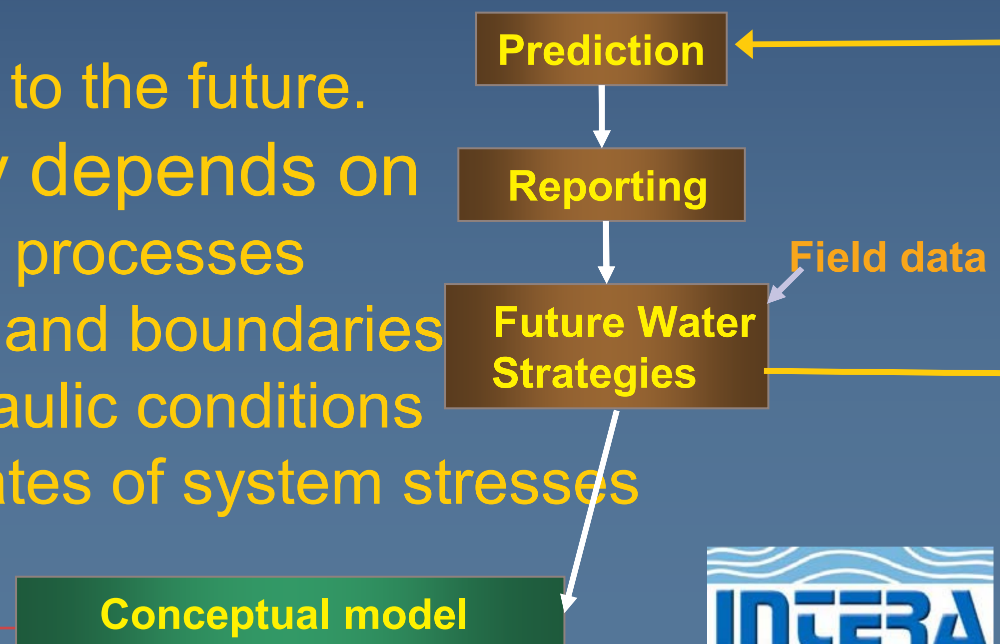
- A sensitivity analysis is a formal means of quantifying the effect of changes in model inputs on model outputs
- Provides a means of identifying parameters which are:
  - Important
  - Correlated
- Most common method is the one-of-method

Verification

- Simulation period where the model is run in a forward mode (ie without adjustment of parameters) to see how the model agrees with observations
- The more variable stresses the better the verification period
- Acceptable verification doesn't insure accuracy; does enhance model validity

Prediction

- Once the model meets the calibration metrics, it can be used for prediction.
- The basis behind model predictions is the assumption that:
  - The past is the key to the future.
- Predictive accuracy depends on
  - Validity of modeled processes
  - Accuracy of props. and boundaries
  - Knowledge of hydraulic conditions
  - Reliability of estimates of system stresses



Prediction – Post Audits

- Post-audits have demonstrated that models are moderately reliable and are uncertain
- As approximations to reality, models can, and should, always be improved – (updated)
- A primary value of a model, regardless of the predictive accuracy, is it allows for a disciplined format for the improvement of the understanding of an aquifer (Konikow, 1995)

Calibration Challenges

- Uniqueness of calibration
- Over-Calibration

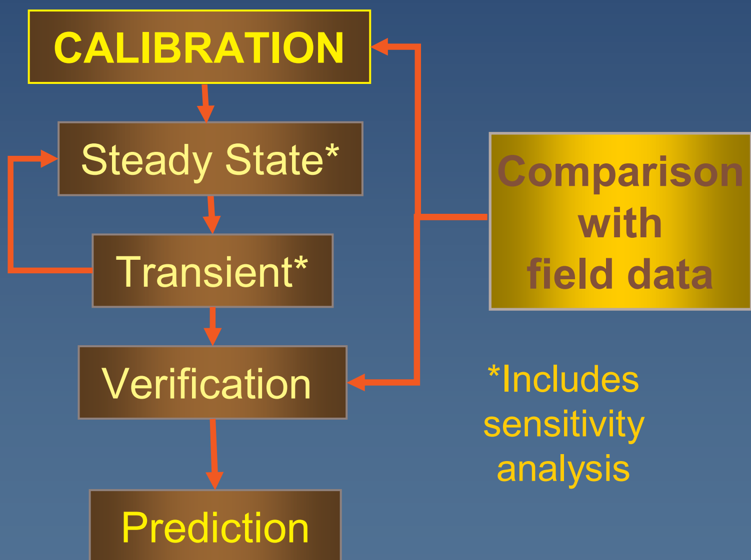
Model Uniqueness (Similarity Solutions)

- Models are inherently non-unique, that is multiple combinations of parameters and stresses can produce similar aquifer conditions.
- The ramification of this is:
  - A good match to observed data does not guarantee an accurate model

Modeling Approach to Deal with Uniqueness

- To reduce the impact of non-uniqueness:
  a) Calibrate to multiple hydrologic conditions
  b) Calibrate with parameters consistent with measured values
  c) Calibrate to multiple performance measures

(a) Calibrate to Multiple Hydrologic Conditions



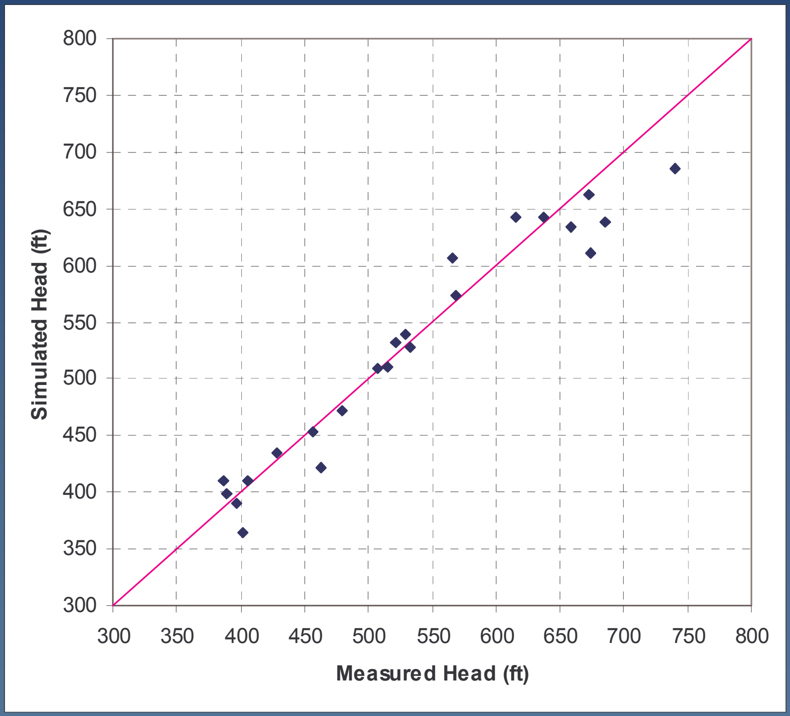
The calibration approach iterates between the steady-state (predevelopment) and the transient calibrations to reach a consistent set of physical parameters that match both sets of observation.

(b) Calibrate with Parameters Consistent with Measured Values

- Because of the uniqueness issues, you must consider some parameters known
- On super-regional models such as the GAM, scale issues related to measured data and how they relate to the model is a difficult issue

(c) Calibrate using Multiple Targets and Performance Measures

- Heads (SS and transient)
  - Distributions
  - Time series
  - Scatter plots
  - Statistics (RMS, ME)
- Stream aquifer interaction
  - Stream flow rates
  - Gain loss estimates
- Flow balance (qualitative)
- Don't calibrate better than target error (see next slide)



$$RMS = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s\right)_i^2 \right]^{0.5}$$

Over Calibration

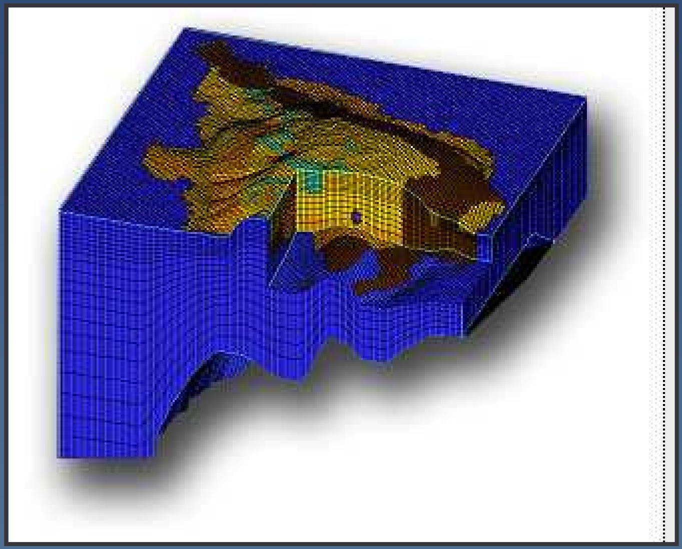
- One must strive to not over-calibrate (tweak) a model; that is:
  - Over parameterize lacking data support
  - Adjust parameters to bring model agreement below performance measure uncertainty
  - In the GAM model, head is the primary performance measure and we have estimated errors associated with heads to be on the order of at least 30 feet

Calibration and Prediction

- Freyberg published a study on calibration and prediction (GW, 1988, Vol. 26, No. 3)
- Nine modeling teams using same data
- Best model prediction came from the model with the least estimated parameters and with inferior local fits
- Good calibration may not equal good prediction
- Best calibrated model yielded poorest prediction

MODFLOW (is a Code)

- Developed by the United States Geological Survey
- Three-dimensional, finite difference groundwater flow CODE



MODFLOW Version History

- Various USGS research codes; Trescott (1975), and others
- MODFLOW (1984)
  - McDonald and Harbaugh, 1986 (Fortran 66)
- MODFLOW (1988)
  - McDonald and Harbaugh, 1988 (Fortran 77)
- MODFLOW96 (1996)
  - Harbaugh and McDonald, 1996
- MODFLOW2000 (2000)
  - Harbaugh et al (2000)

MODFLOW Packages

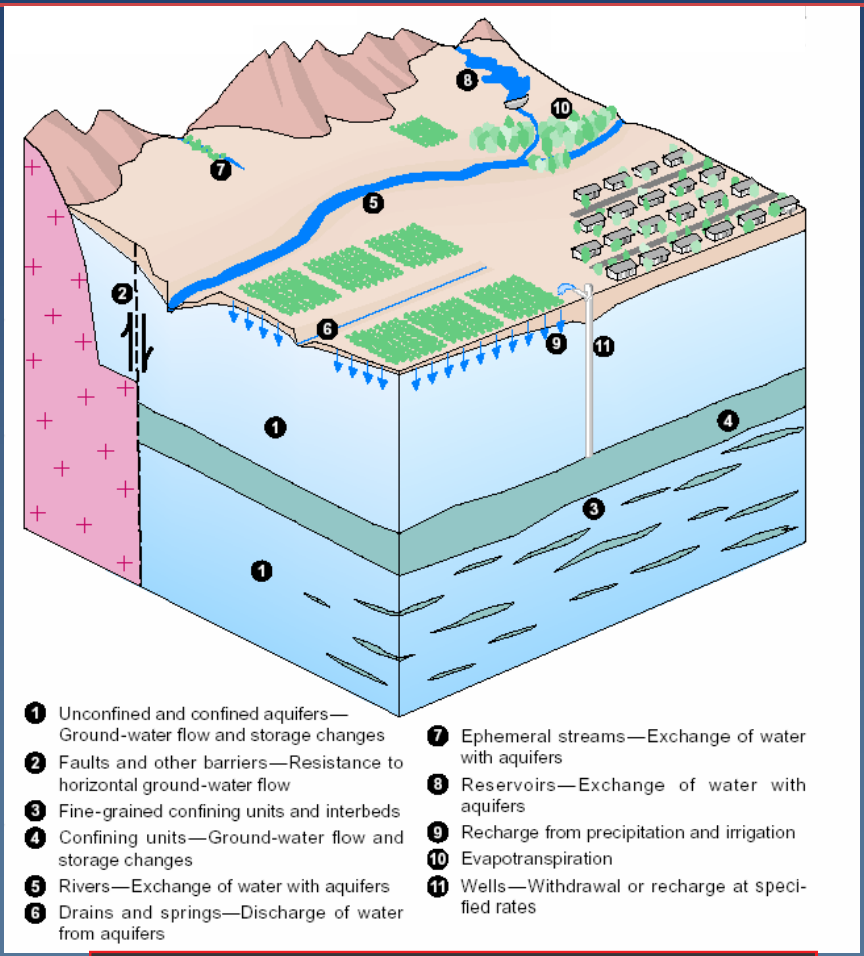
- Original Packages (88)
  - Basic
  - Block-Centered Flow
  - Recharge
  - Evapotranspiration
  - River
  - Well
  - Drain
  - General Head Boundary
  - Output Control
  - SIP/SOR Solvers
- Add on Packages (96..)
  - Block-Centered Flow 2,3
  - PCG/PCG2 Solvers
  - Horizontal Flow Barrier (HFB)
  - Compaction (IBS)
  - Time-variant C.H. (CHD)
  - Stream Routing (STR)
  - Transient Leakage (TLK)
  - Direct solver (DE4)
  - Various user add-ons

Subroutines are called modules
Groups of subroutines representing a “process” are packages

MODFLOW Advantage

- Handles the basic processes
- Well documented
- Testing is documented – courts accept
- Public domain – non-proprietary
- Most widely used model
  - USGS had 12,261 downloads of MODFLOW in 2000
- Multiple utility programs and Graphical User Interfaces (GUIs) available

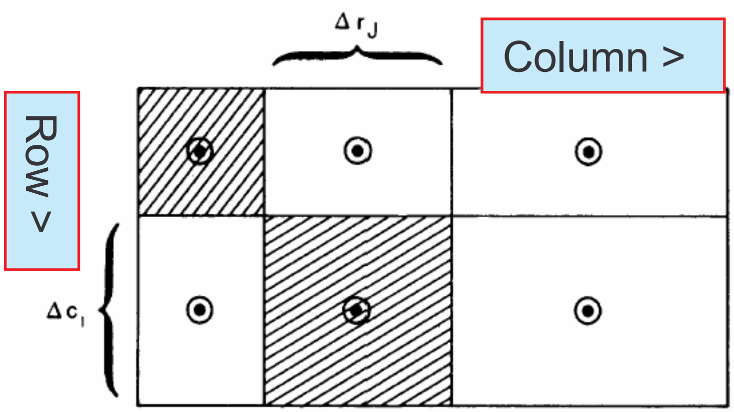
MODFLOW Processes



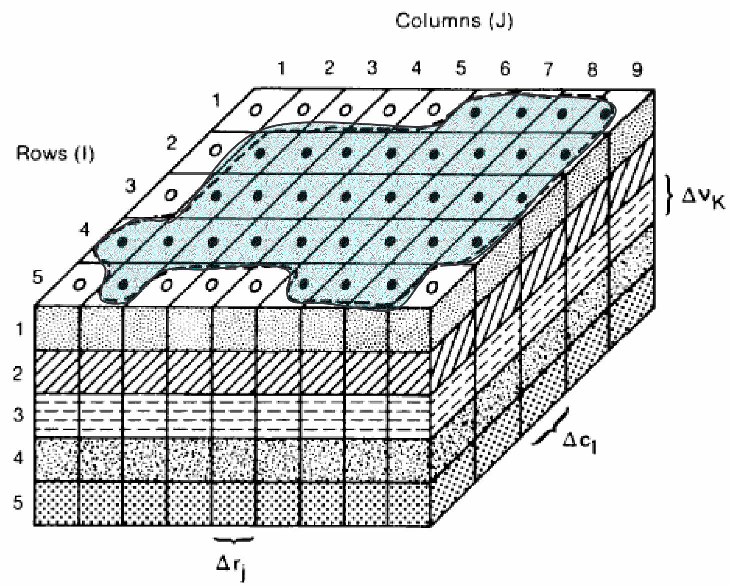
Source: USGS Fact Sheet FS-127-97

- Important for GAM
  - Confined/unconfined GW flow
  - Recharge/ET
  - Horizontal flow barriers
  - Wells
  - Streams
  - Drains (springs)
  - Reservoirs

Example of a MODFLOW Grid
Note – Regular Grid



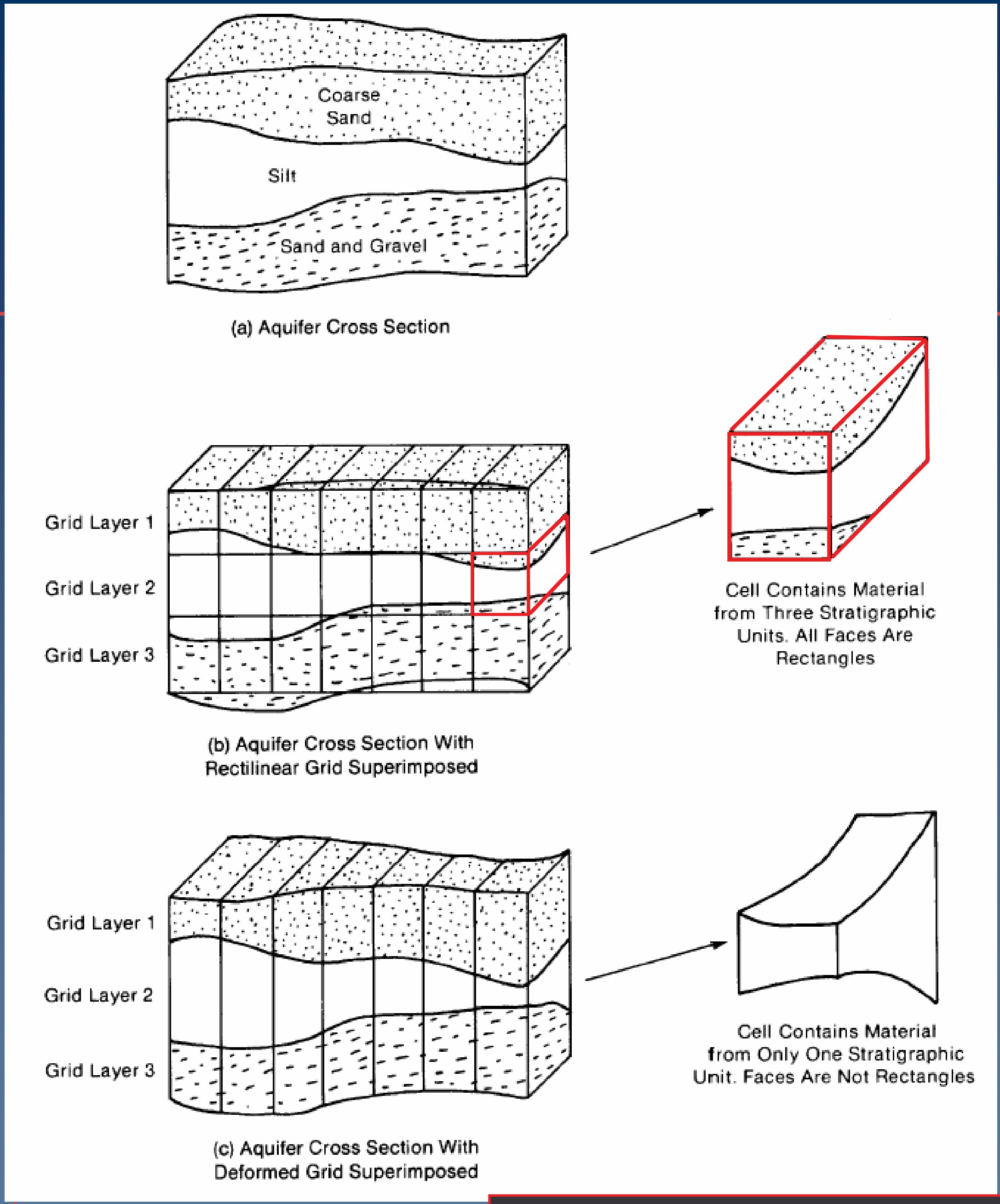
Block-Centered Grid System



Explanation

----	Aquifer Boundary
•	Active Cell
o	Inactive Cell
Δr_J	Dimension of Cell Along the Row Direction. Subscript (J) Indicates the Number of the Column
Δc_I	Dimension of Cell Along the Column Direction. Subscript (I) Indicates the Number of the Row
Δv_K	Dimension of the Cell Along the Vertical Direction. Subscript (K) Indicates the Number of the Layer

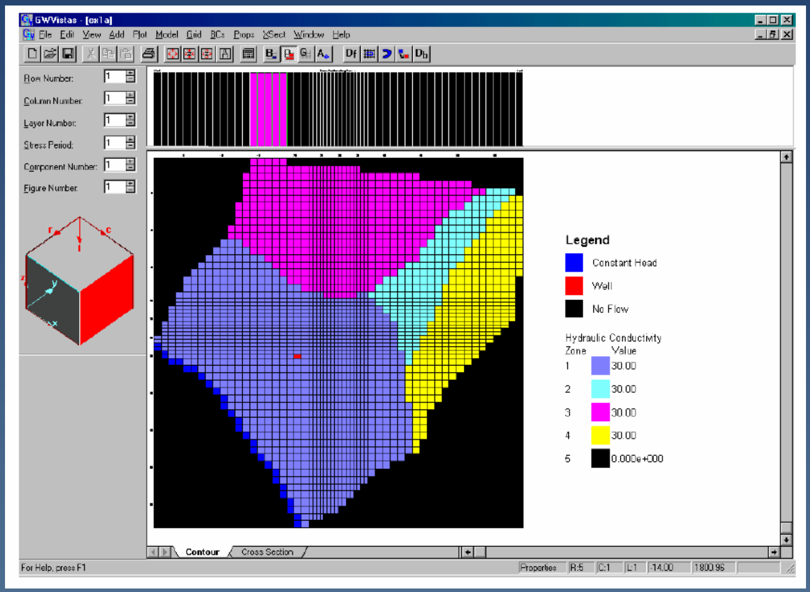
After McDonald & Harbaugh, 1988



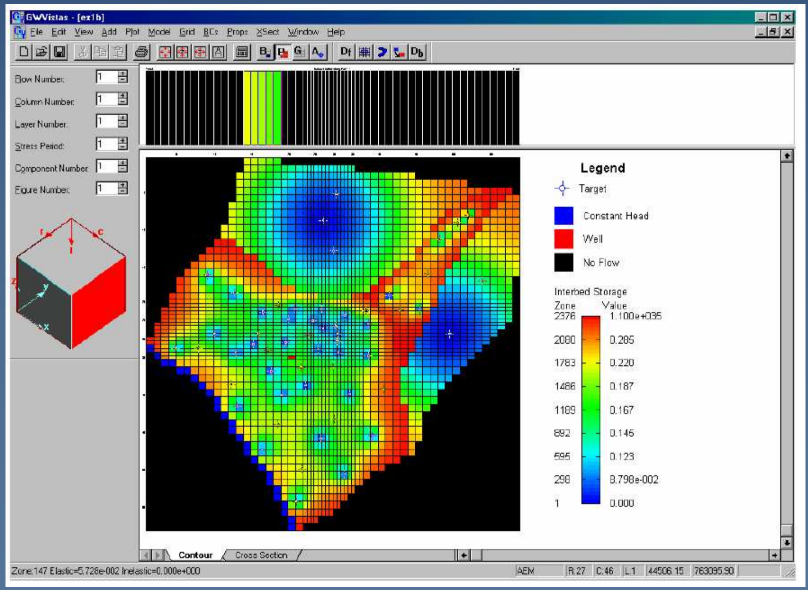
Vertical Discretization Should have physical significance

After McDonald & Harbaugh, 1988

Assignment of Properties

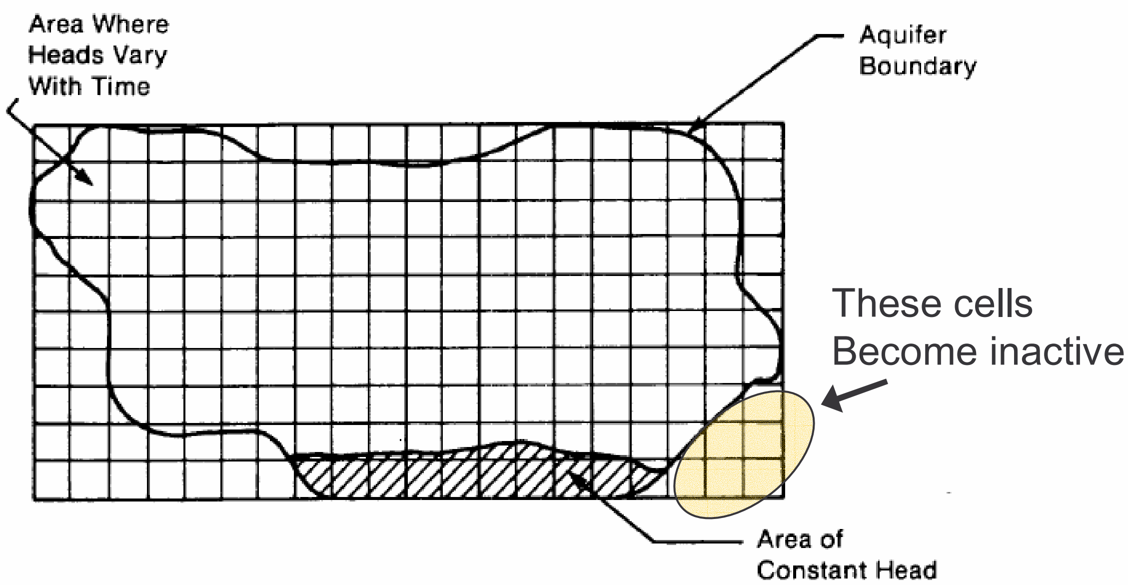


Properties can be assigned on a grid Cell basis as below



Properties can be assigned in zones as above

Single Layer example of conceptualizing a Model grid and assigning boundary conditions



Example of an IBOUND Array (Basic package) for a Single Layer

0	1	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	0

IBOUND Codes

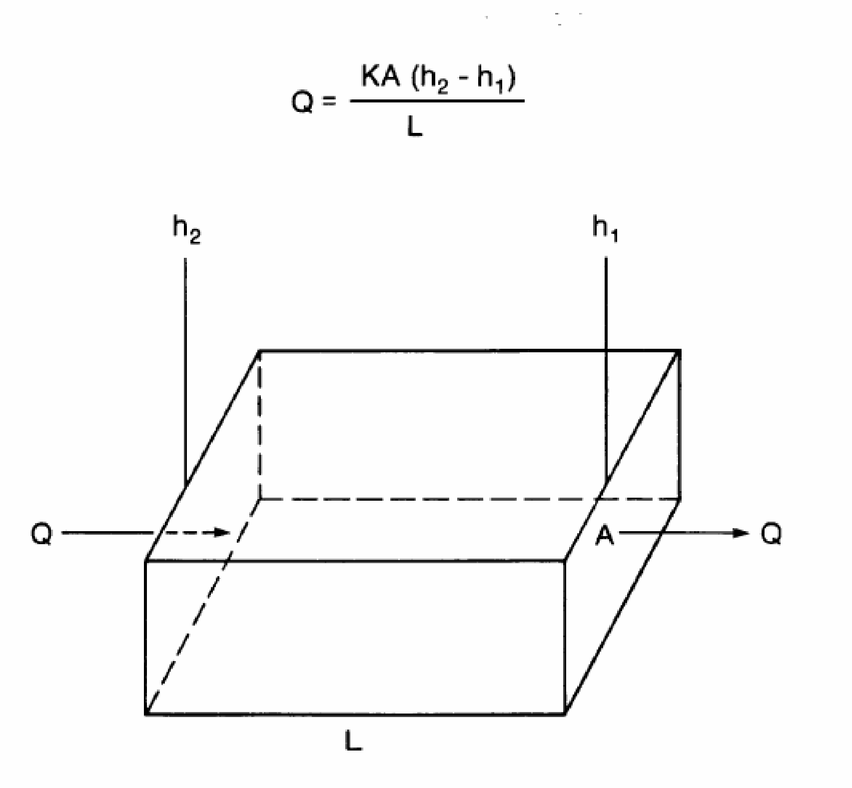
< 0 Constant Head
= 0 No Flow
> 0 Variable Head

After McDonald & Harbaugh, 1988

MODFLOW in simplest terms

- MODFLOW calculates flow in 3 dimensions using a finite difference (FD) approach
- The GW flow FD equation form follows from the the application of the continuity equation which stipulates that:
  - The sum of all flows into and out of a cell at a given time step must equal the rate of change of storage within the cell

Steady-state, One Dimensional Flow
Darcy's Law – One cell



- Where:
  - K = hydraulic conductivity
  - A = area normal to Flow
  - h = head
  - L = length

Darcy's Law Can be Rewritten

$$Q = C\,(h2 - h1)$$

Where C is equal to the hydraulic conductance (L3/T L)

$$C = K\,A\,/\,L$$

MODFLOW uses hydraulic conductance to calculate flow rates using Darcy's Law

Vertical Conductance - Vcont

- Simply stated – Vcont is the interval conductance divided by the area (plan view)
- MODFLOW uses Vcont (also known as leakance) to calculate vertical flow

$$\frac{C_{i,j,k+1/2}}{DELR_j\,DELC_i} = \frac{1}{\sum_{g=1}^{n} \frac{\Delta z_g}{K_g}}$$

$$Vcont_{i,j,k+1/2} = \frac{1}{\sum_{g=1}^{n} \frac{\Delta z_g}{K_g}}$$

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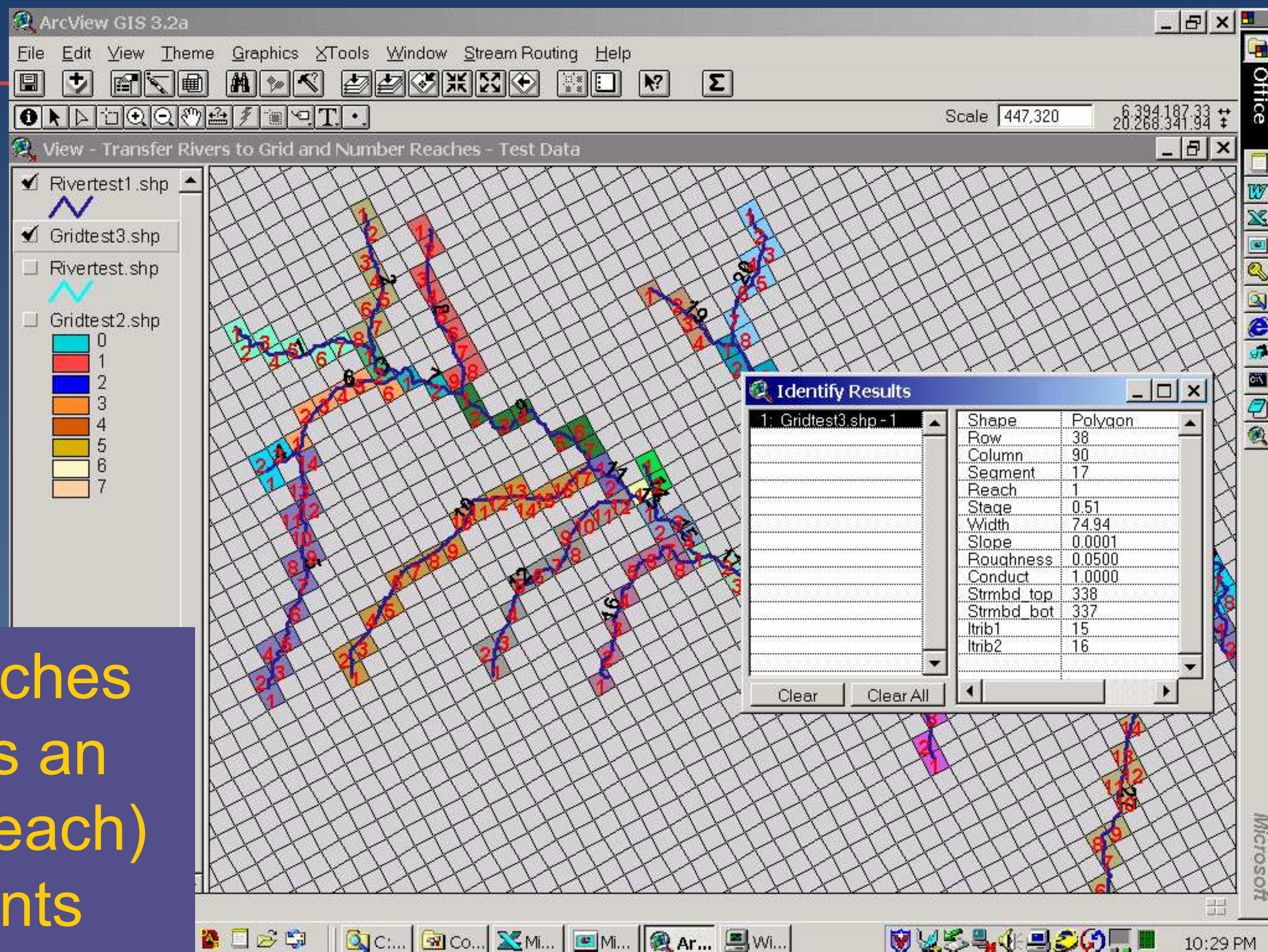
Wells in MODFLOW96

- MODFLOW96 does not have a wellbore submodel
  - Therefore, simulated heads are representative of the grid volume
- Well rates are specified by row, column, layer (r,c,l)
- Multiple wells can be assigned one grid cell
- Wells are specified in the well package (.wel)

Stream Routing

- Use MODFLOW Stream Routing Package (Prudic, 1988)
- Stream stages are calculated using Manning’s equation
- Stream-routing package routes surface water and calculates stream/aquifer interaction (gaining/losing)
- Input headwater flow rate, stream conductance, stream dimensions, and Manning’s n parameter

Stream Routing Package



Stream reaches (each cell is an individual reach) and segments must be numbered

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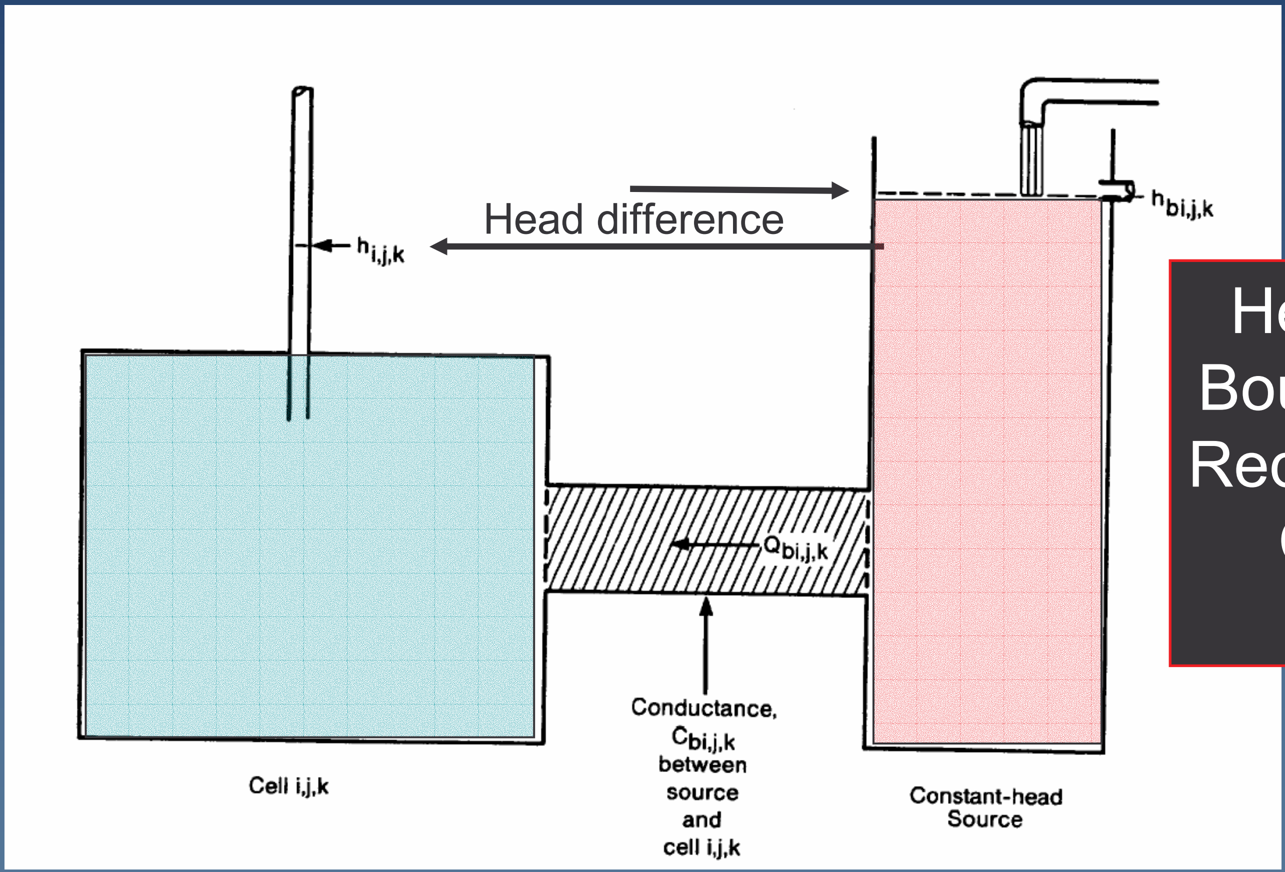
Head Dependent Flow Boundaries

- General head boundaries
- Reservoirs
- River cells
- Stream cells
- Drains

Head-dependent Boundaries



Head dependent Boundaries always Require input of the Conductance

$C = K A / L$

Specified-flow Boundaries

- Wells
- Recharge
- Evapotranspiration ET (hybrid – head dependent)

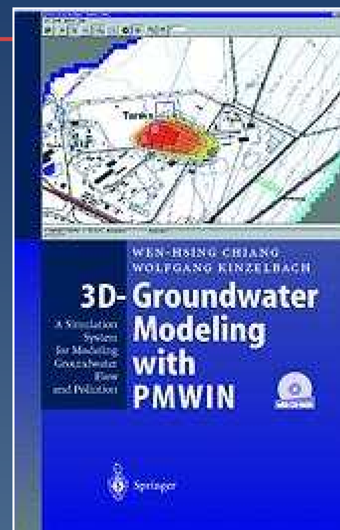
MODFLOW Interfaces

- PMWIN
  - Academic, commercially available
- Groundwater Modeling System (GMS)
  - DOD, commercially available
- GWVistas
  - Private, commercially available
- Visual MODFLOW
  - Private, commercially available

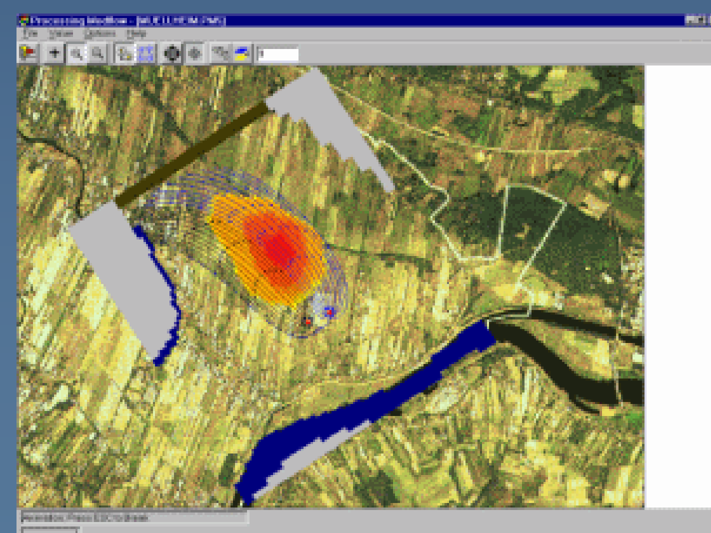
PMWIN – Processing MODFLOW

- Developed at the Institute of Hydromechanics and Water Resources Management, Swiss Federal Institute of Technology in Zurich
- Authors:

  Wen-Hsing Chiang and Wolfgang Kinzelbach



http://www.ihw.ethz.ch/soft/PMWIN.html



PMWIN

- Offers a Windows based interface for developing MODFLOW models and for using the family of MODFLOW codes
- Imports existing standard MODFLOW models
- Supports all standard packages
- Allows many options for data input through raster graphics (bitmap), vector graphics (DXF)
- Imports Surfer grid files, exports Surfer data files
- Allows for telescopic grid refinement
- Some degree of checking of input prior to execution

PMWIN Requirements

- Pentium or better
- Windows 95/98/2000/NT 4.0/XP
- 16 MB RAM (32 Recommended)
- GAM model
  - Requires at least 128 MB RAM
  - 2 GIGs or better disk space

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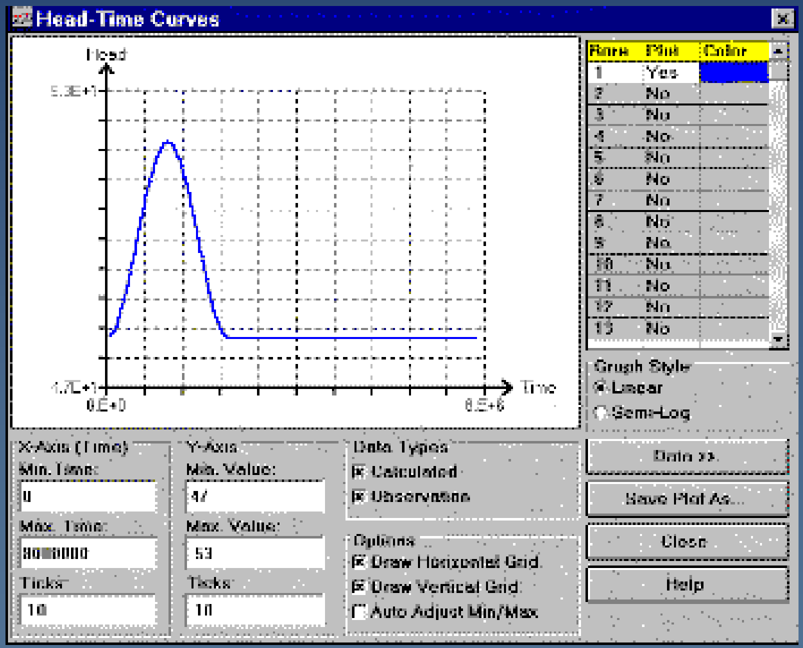
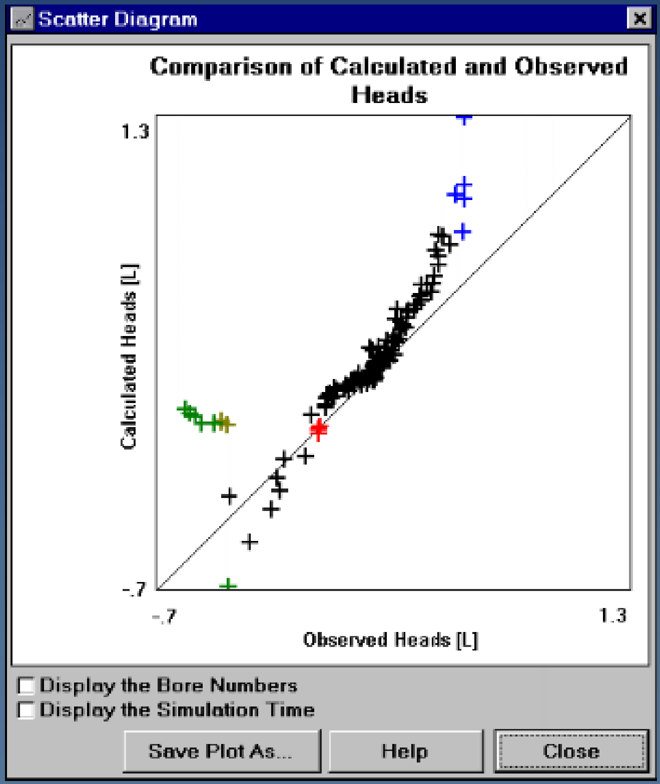
PMWIN Interface





Data Models background

- Consistent methodology for storage of GAM data
- Facilitates future improvements or modifications of current work
- Available to the general public as an addition to the final reports

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Data Models basic structure

- **srcdata** – contains the source and some derived data used to generate the model input data sets
- **grddata** – contains all of the model input parameter and stress data by (r,c,l,sp)
- **modflow** – contains all of the actual model input and output data files

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Data Models srcdata - examples

- **geol** – faults, subsurface geology, outcrop delineation, net sand maps
- **soil** – STATSGO data, runoff numbers
- **subhyd** – pumping rates, hydraulic conductivities, water levels, hydrographs
- **surhyd** – streamflows, stream/aquifer interaction, springflows

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Data Models grddata - examples

- **hydraul** – hydraulic properties such as horizontal and vertical conductivities
- **storage** – specific yield, storativity
- **stress** – pumping rates, recharge, et, streamflows
- **struct** – structure information (layer tops and bottoms)

Data Models modflow

- **modfl_96**
  - Input -- ASCII input data sets for running modflow from the command line
  - Output – All output data sets for ststate, trans, 2010, 2020, 2030, 2040, 2050 models
- **pmwin_50**
  - Input -- Data sets for running the models from pmwin interface
  - Output – All output data sets

3. Southern GAM Review

Northern GAM Review

- Technical Overview
  - Emphasis on Data and Model Inputs

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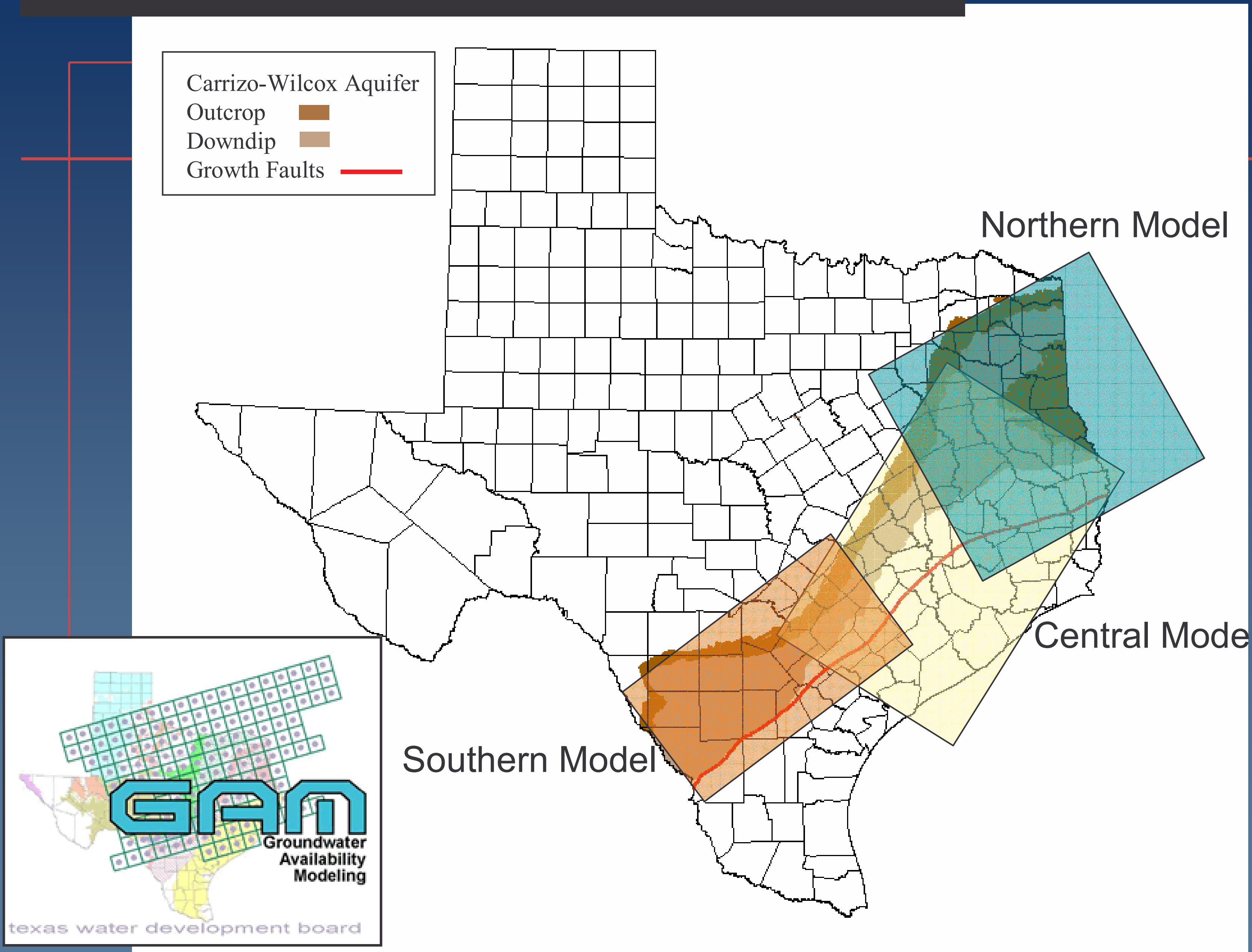
PARSONS

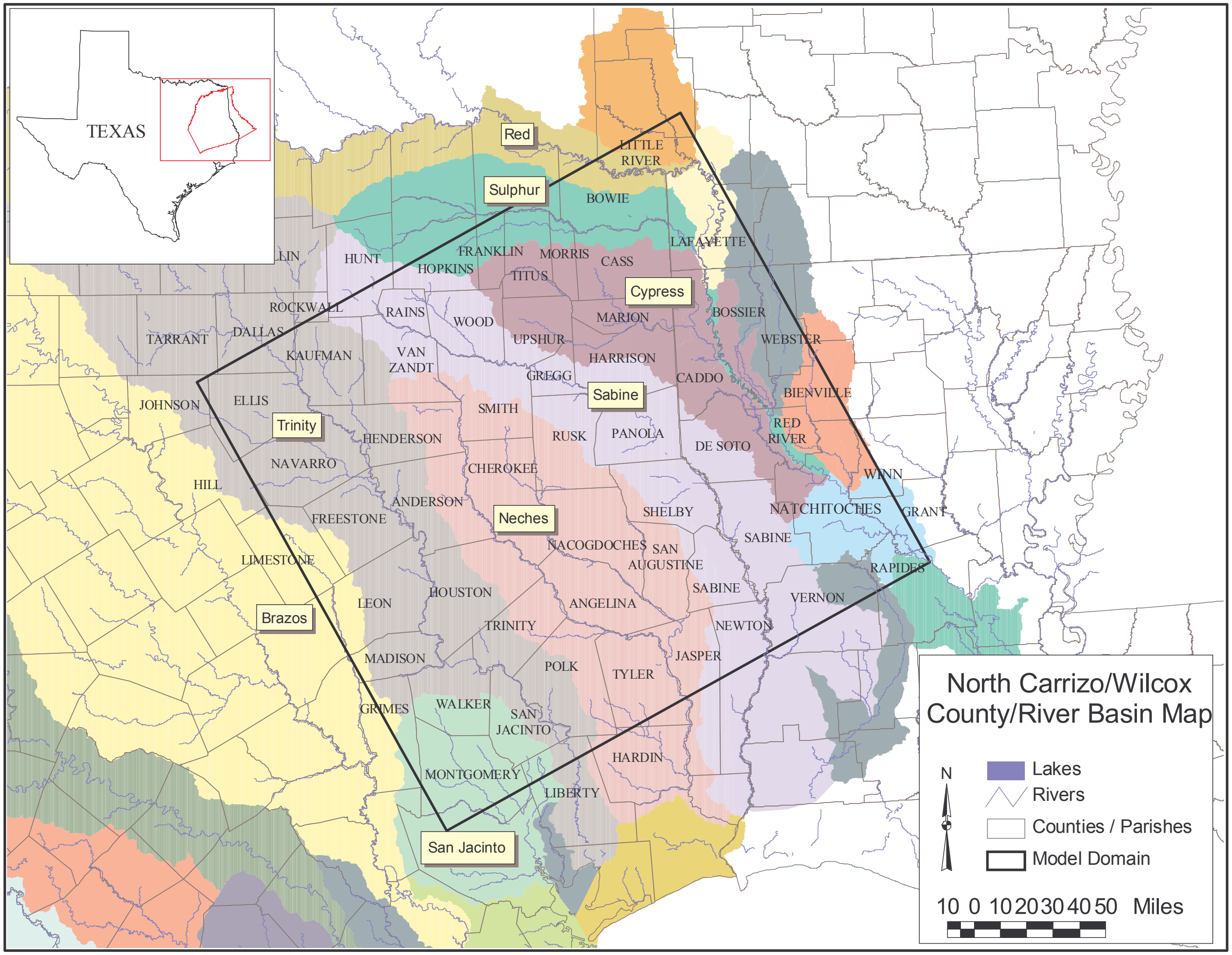
WATERSTONE
Environmental Hydrology and Engineering, Inc.

Carrizo-Wilcox GAM Model Domains

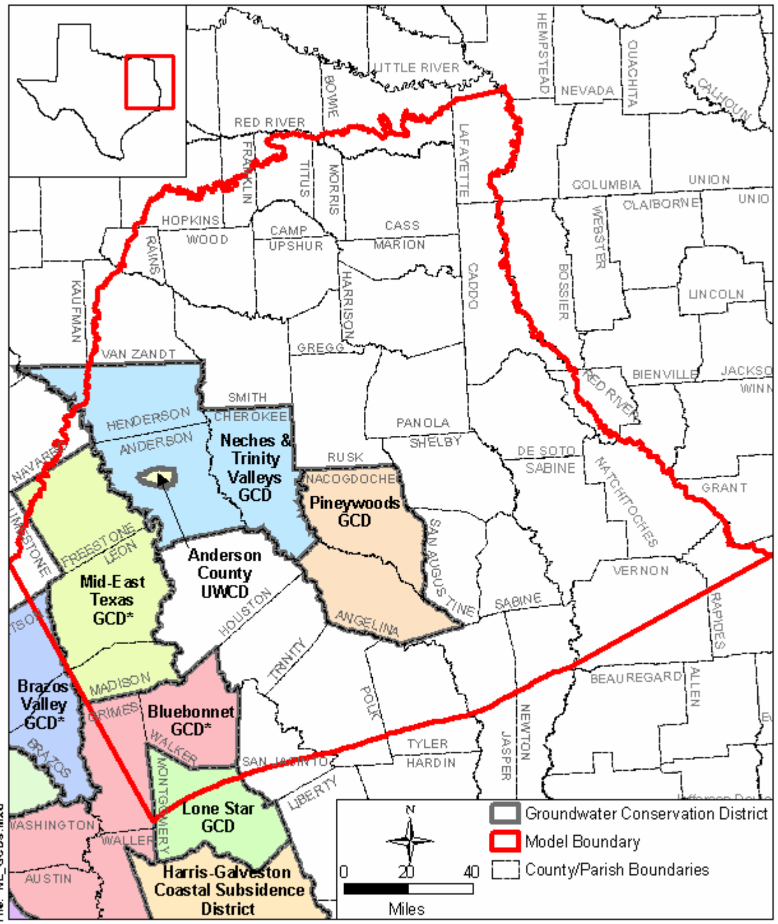
3. Southern GAM Review



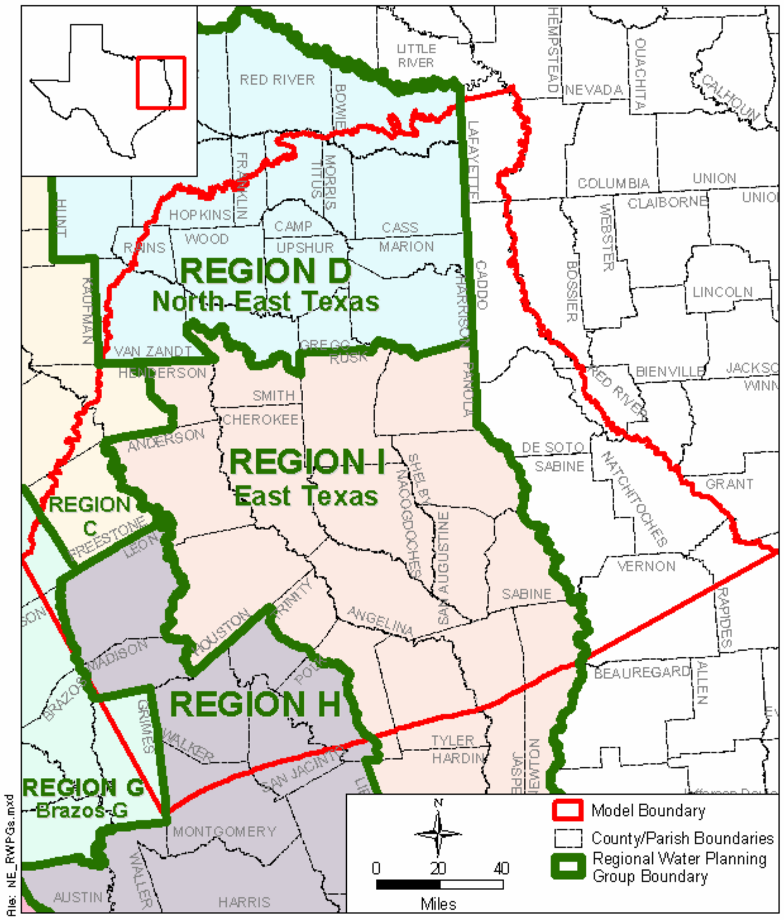
Northern Carrizo-Wilcox GAM



GWCDs & RWPGs

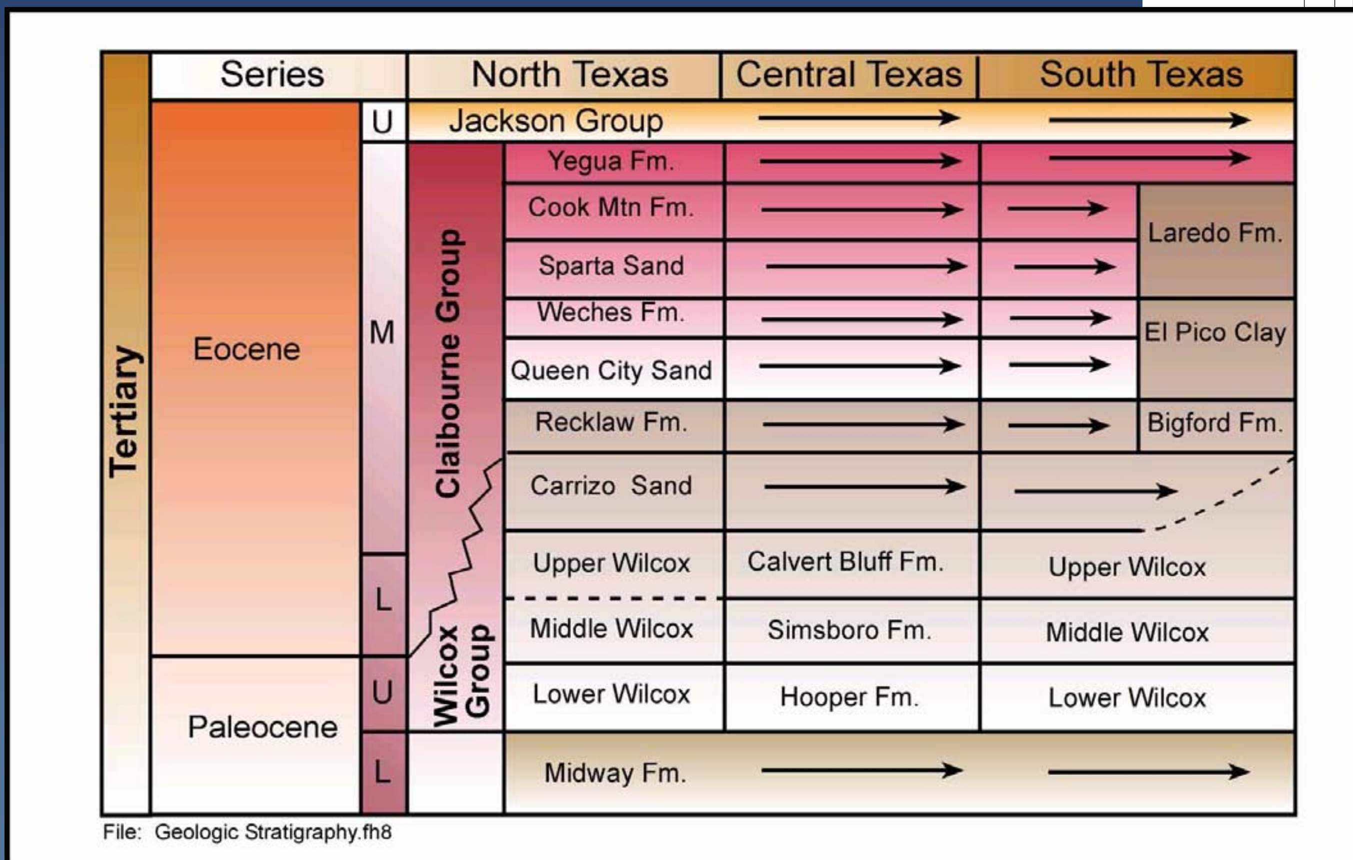


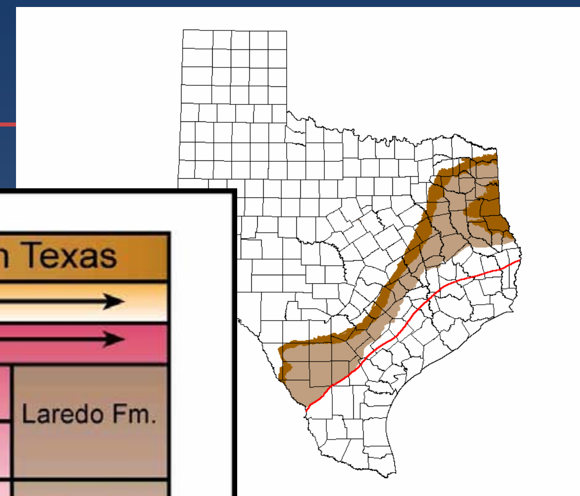
*=Pending Confirmation
UWCD=Underground Water Conservation District
GCD=Groundwater Conservation District
Source: Online: Texas Water Development Board, August 2002



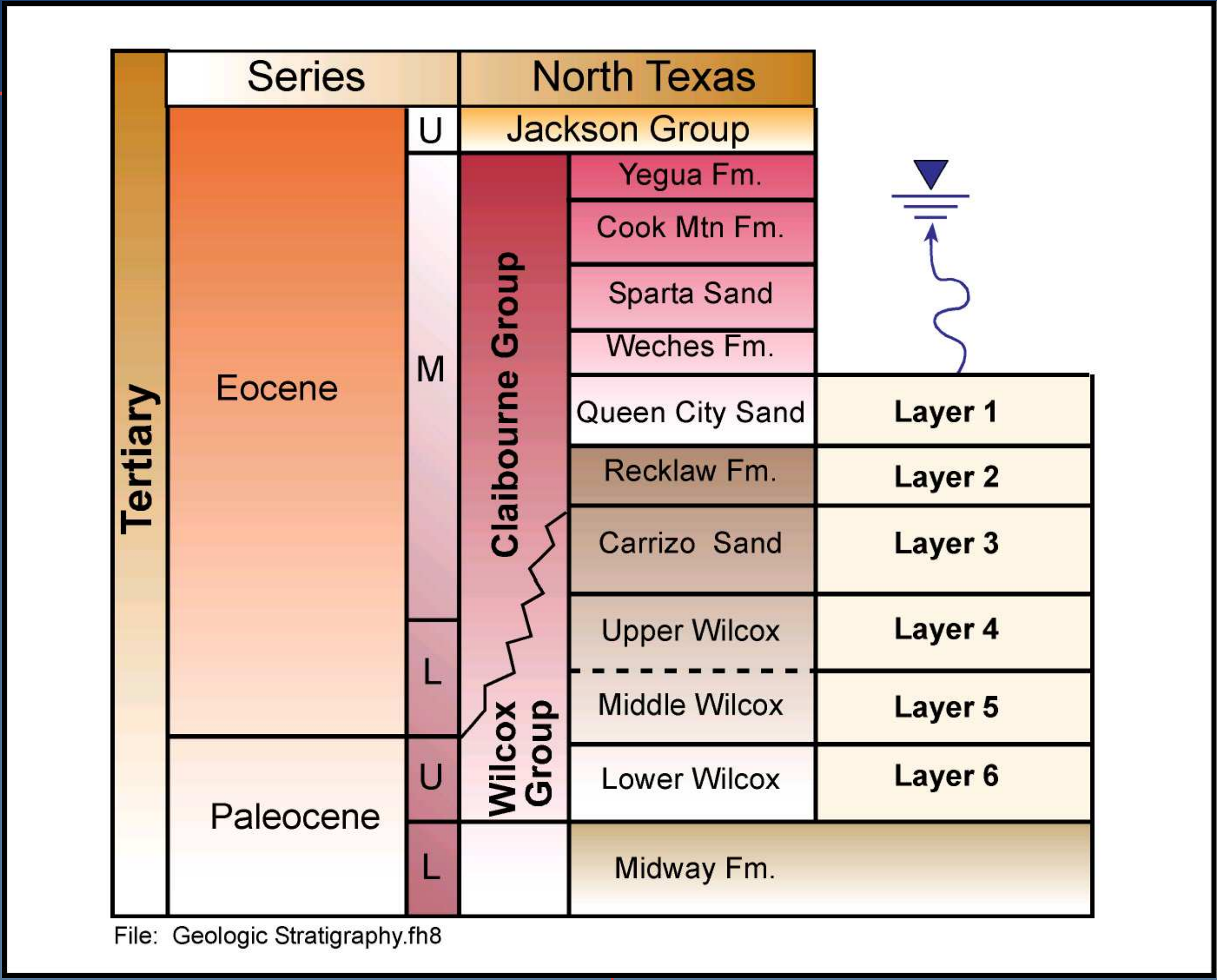
Source: Online: Texas Water Development Board, September 2002

Geologic Framework — Stratigraphy

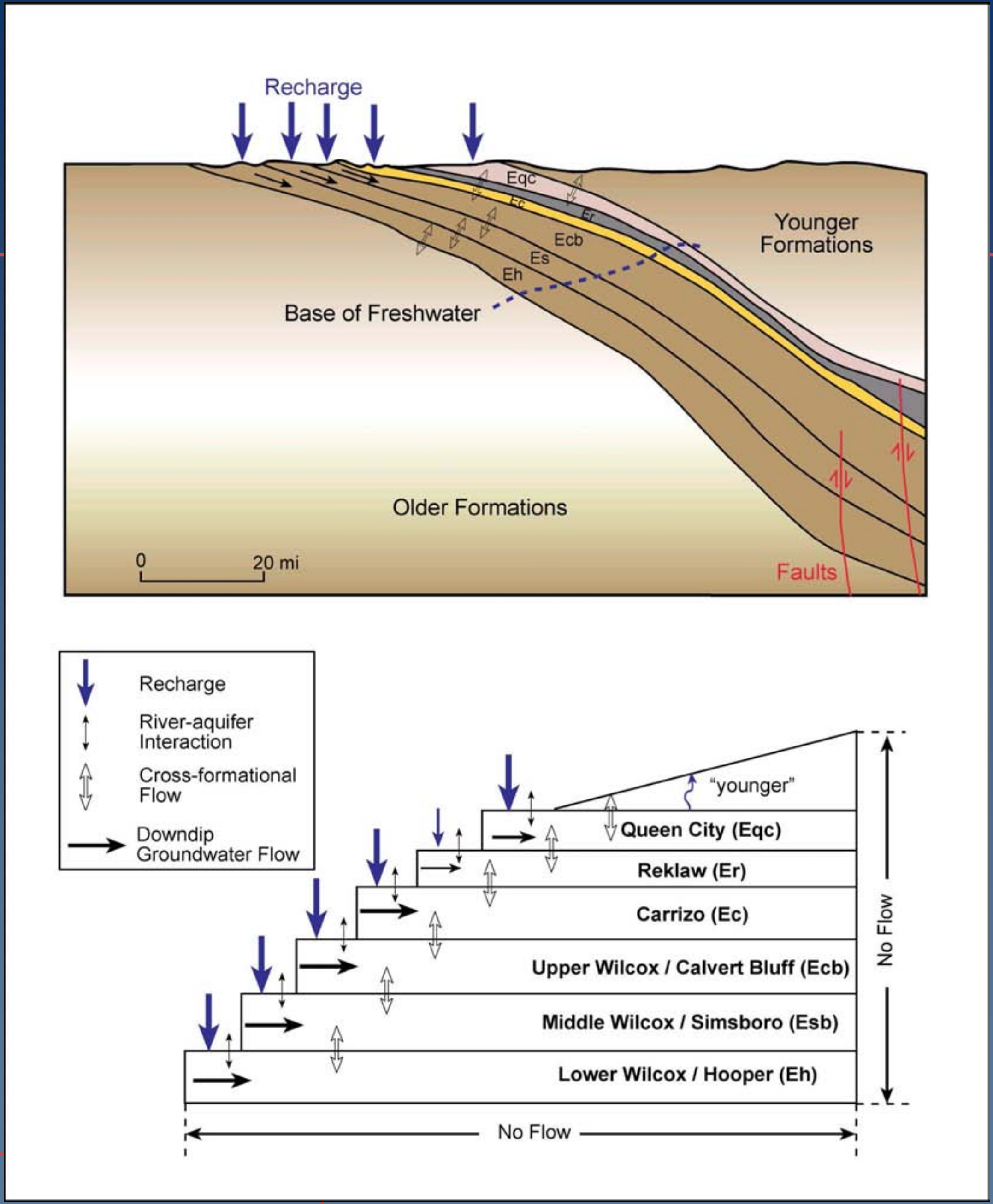




Hydrostratigraphy and Model Layers

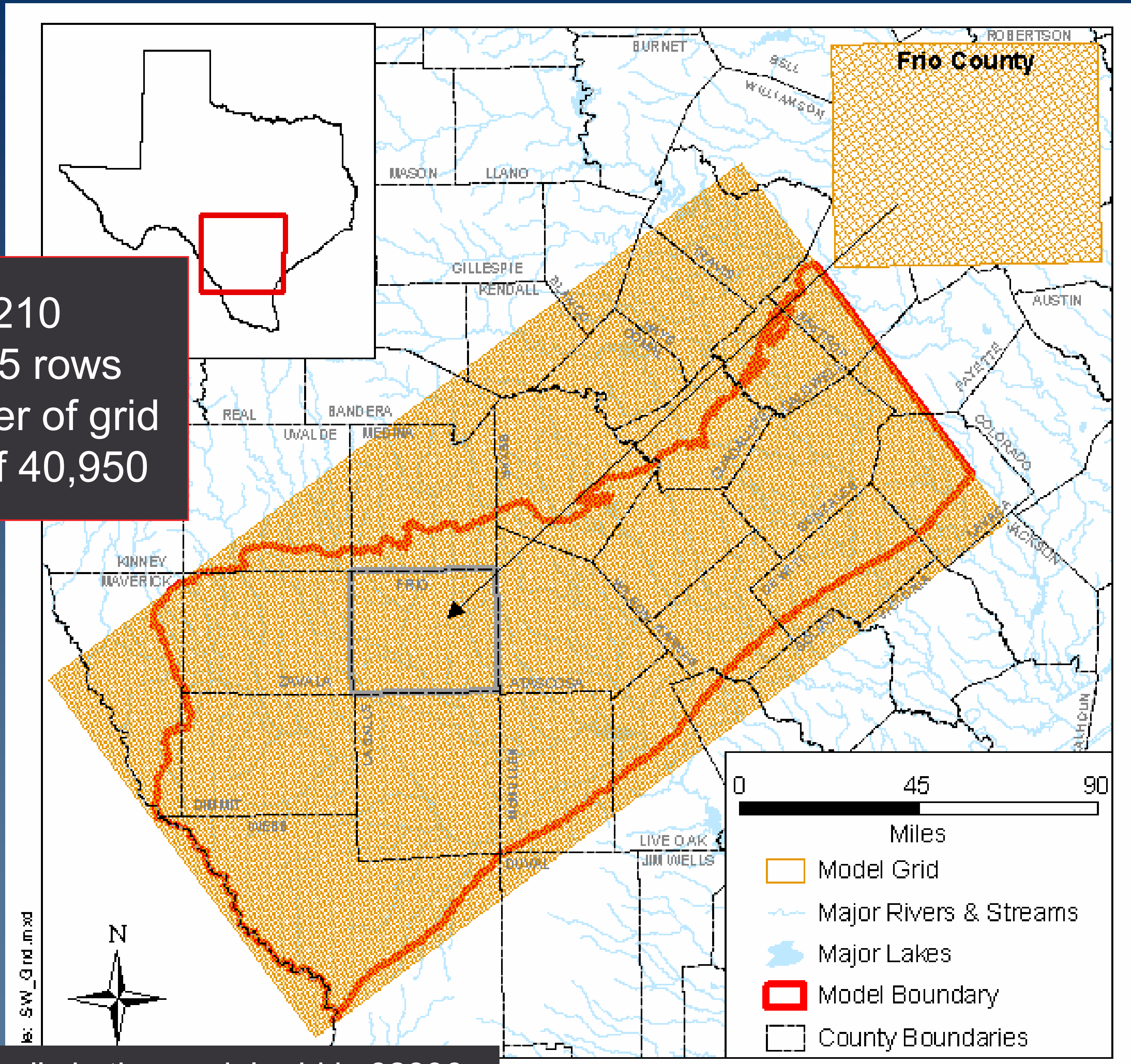


Conceptual GW Flow Model



Model Grid

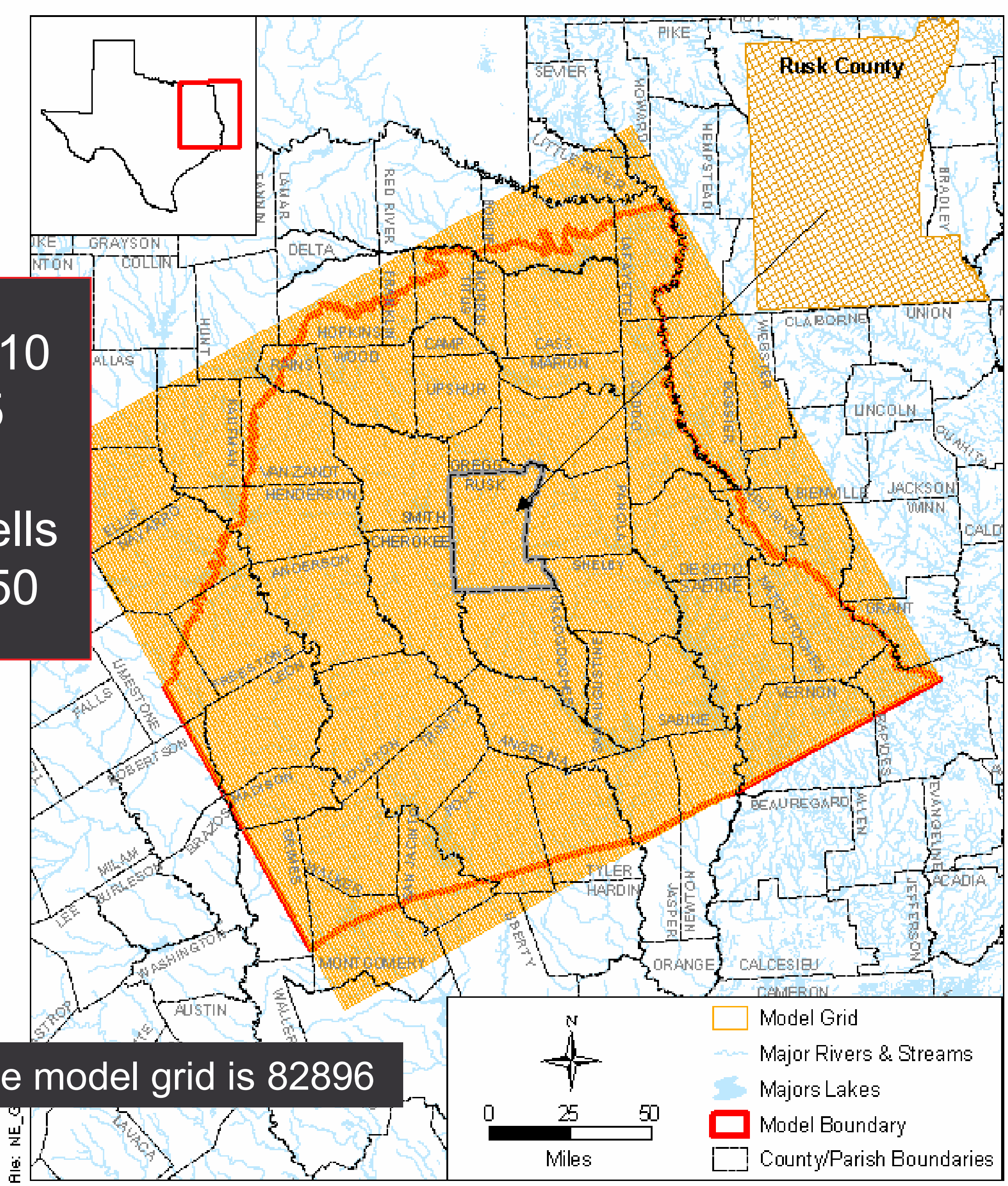
The model has 210 columns and 195 rows for a total number of grid cells per layer of 40,950



Active grid cells in the model grid is 82896

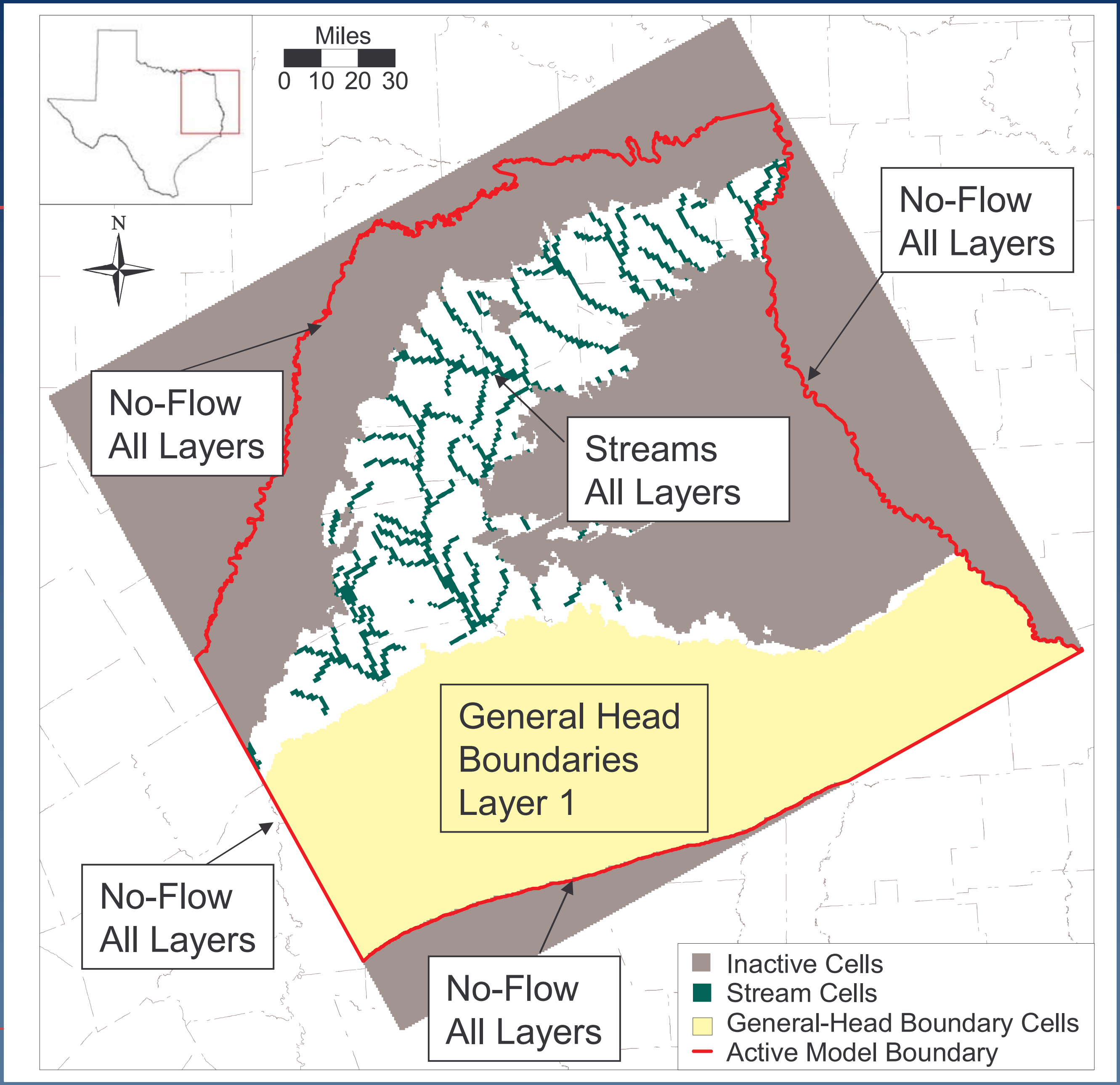
Model Grid

The model has 210 columns and 195 rows for a total number of grid cells per layer of 40,950

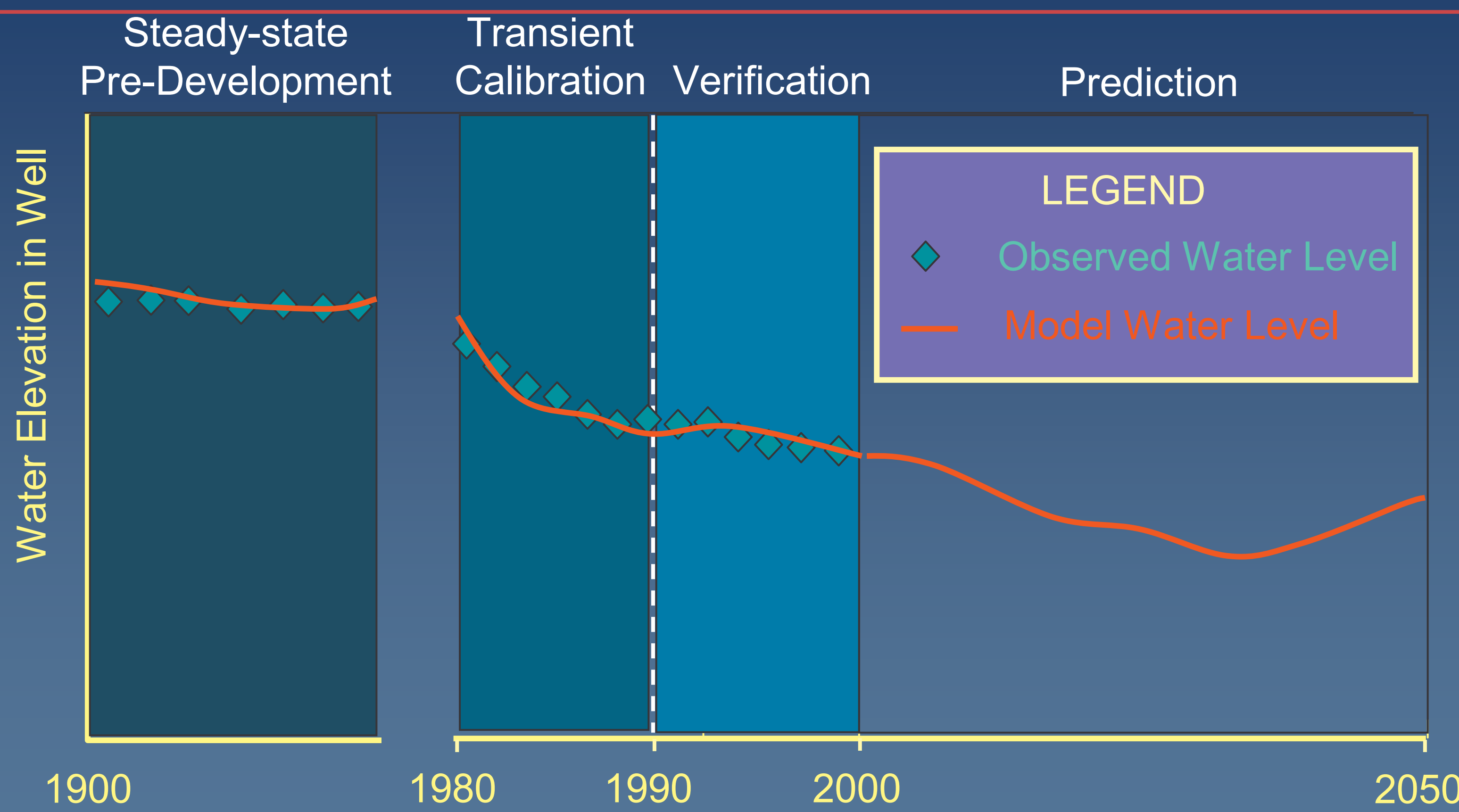


Active grid cells in the model grid is 82896

Model Boundaries



Calibration and Prediction Periods



Pre-development and transient calibration periods represent different hydrologic conditions

Model Input – Supporting Data

- Hydrostratigraphic Surfaces for each Layer
- Hydraulic Properties:
  - Sand Thickness
  - Hydraulic Conductivity
  - Storativity (transient)
- Recharge
- Stream Flow
- Pumpage (transient)
- Reservoir Stages

All model data, source, and derived data was delivered to the TWDB and will be available to the public

INTERA

Assessment of Supporting Data

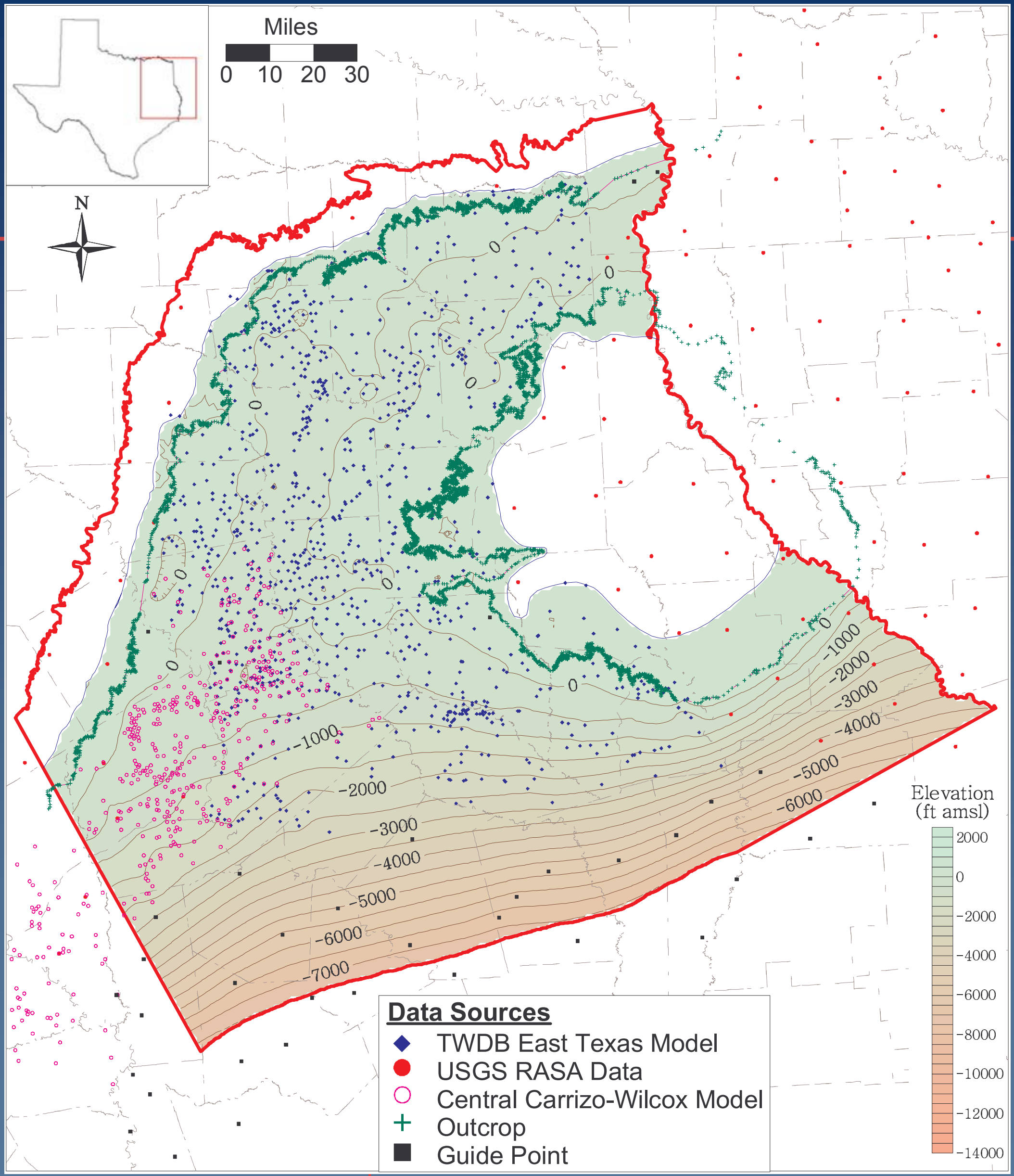
Hydraulic Parameter	Supporting Data
Horizontal Hyd. Cond.	Measured values
Vertical Hyd. Cond.	Model estimates
Recharge	Field and model
Storage	Limited measurements
Stream flow rates	Limited
Gain loss estimates	Limited

INTERA

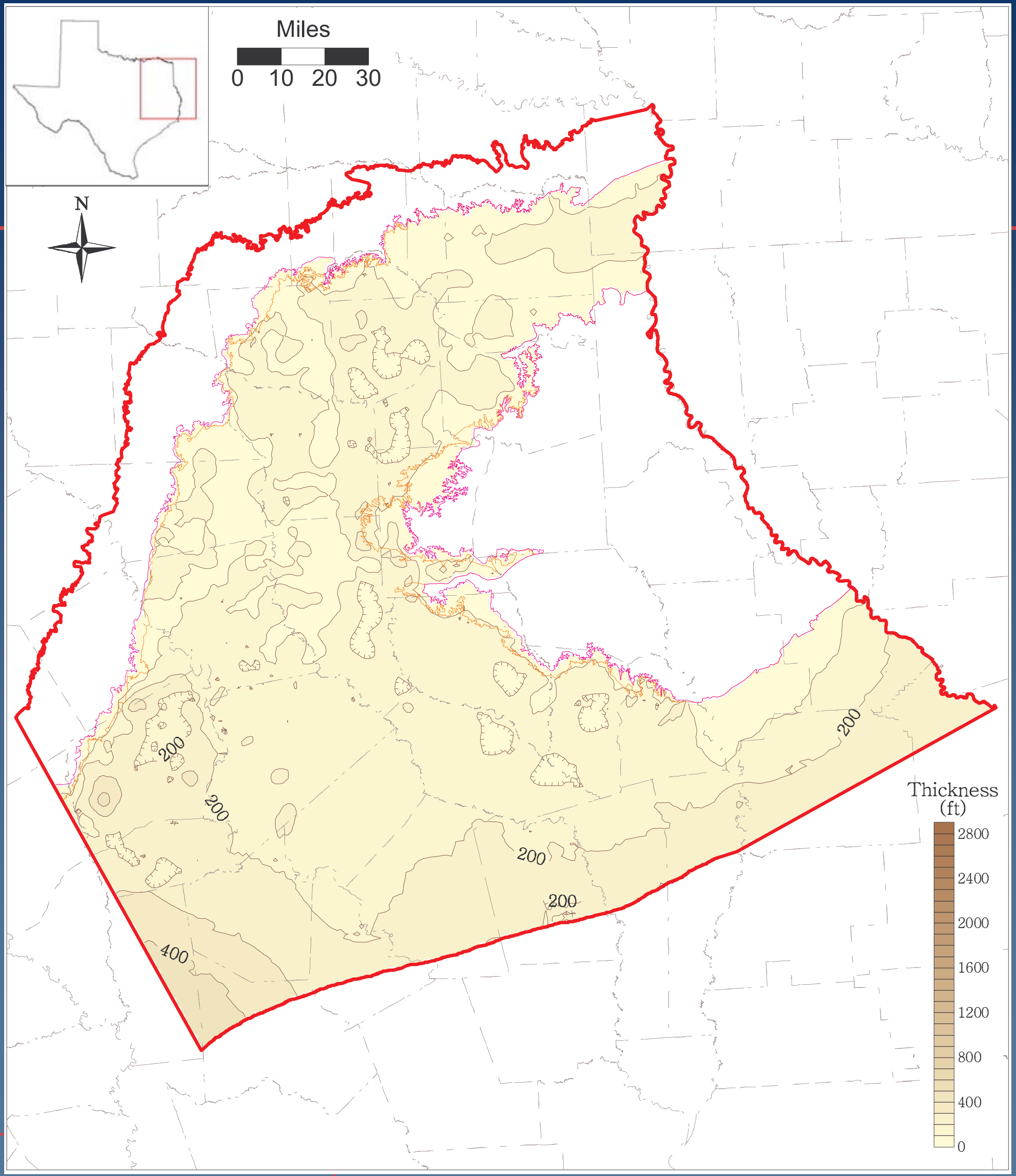
Structure Data Manipulation

- Blank kriged data.
- Merge kriged data with outcrop elevation grid.
- Insure that no elevations are above surface.
- Calculate layer thicknesses.
- Insure that layer thicknesses are no less than 20 ft throughout.

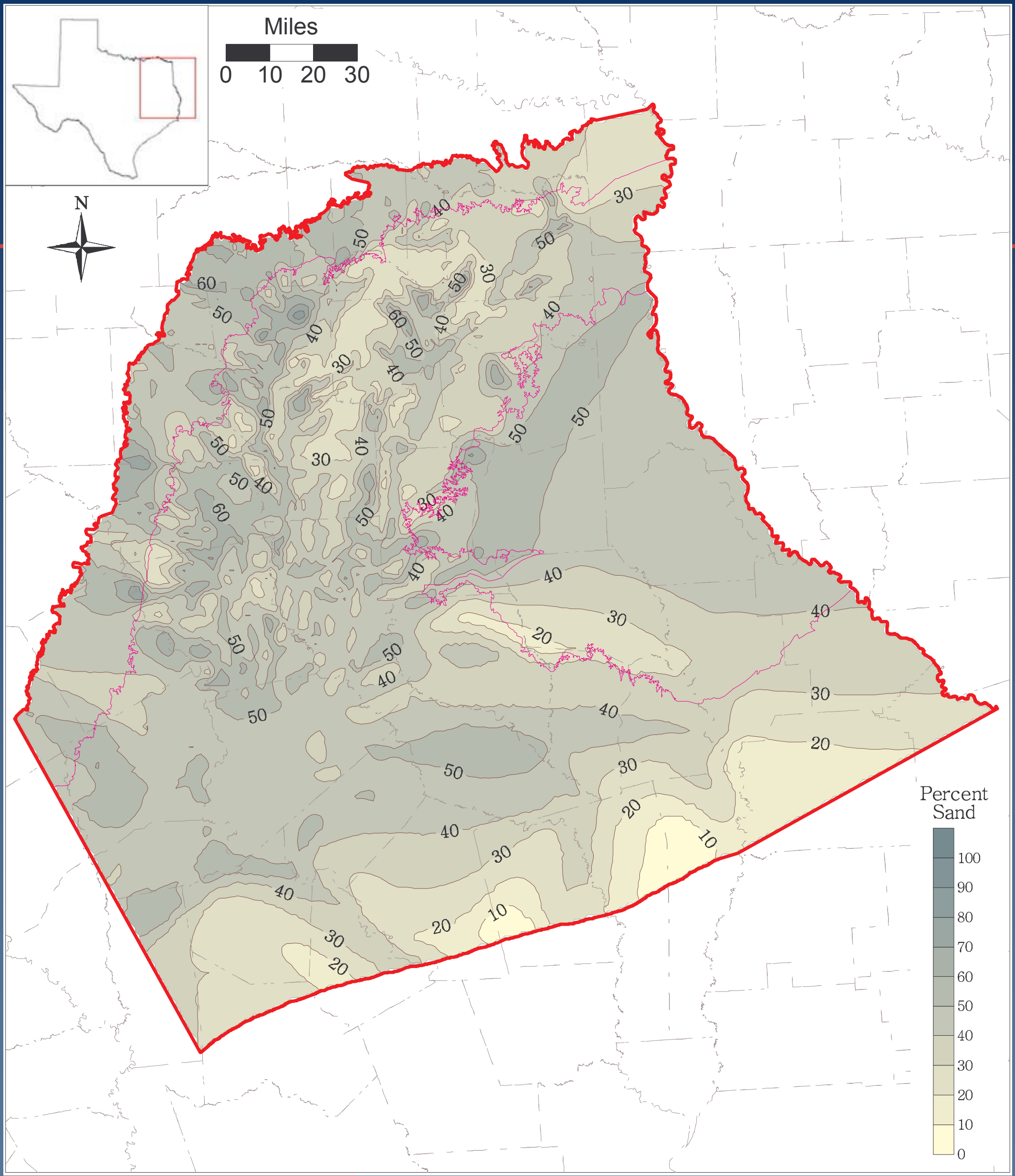
Structure Top of Wilcox



Thickness: Carrizo Sand



Sand Percent: Wilcox



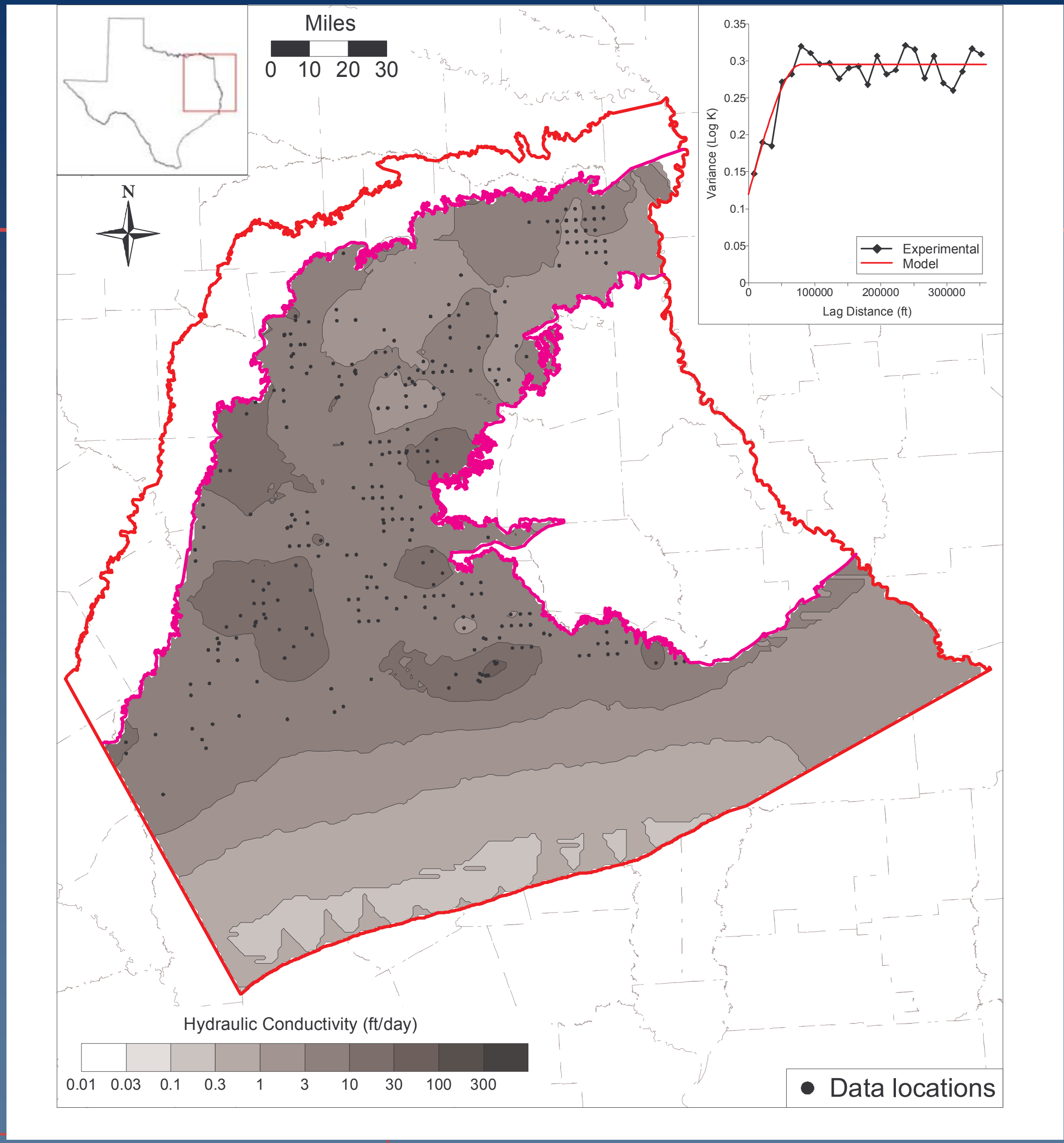
Hydraulic Conductivity

- Horizontal hydraulic conductivity point measurements are available (Mace et al, 2000) MS Access Database (file: cw_97_xp.mdb)
- Poor correlation between measured values and estimated sand patterns
- Must scale K_h and K_v to regional grid scale
- Vertical hydraulic conductivity is not measurable at the grid scale.

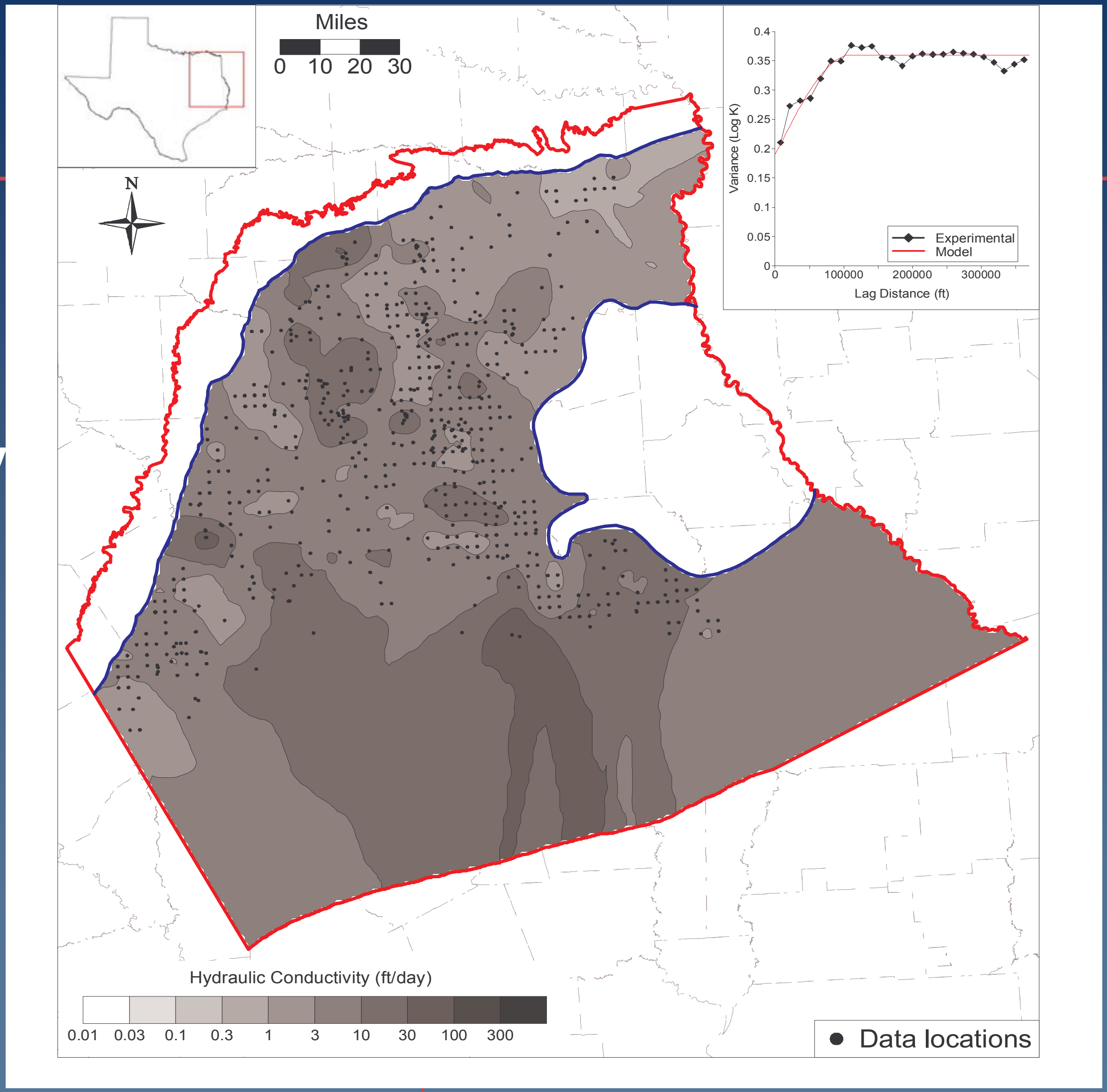
Effective Horizontal Conductivity

- Estimate block center K through kriging
- Estimate block center net sand thickness (b_{sand})
- Effective K calculated based upon $b_{sand}/b_{aquifer}$
- Horizontal K interpolated or zonal when data density is less than the correlation length

Carrizo: Hydraulic Conductivity



Upper Wilcox: Hydraulic Conductivity



Effective Vertical Conductivity

- No measurements at model scale
- Kh/Kv will be a calibrated parameter based on:
  - Observed drawdowns (vertical gradients)
  - Cross-formational flow at 10,000 ppm
  - Specification of recharge
  - Depositional environments/sand distributions

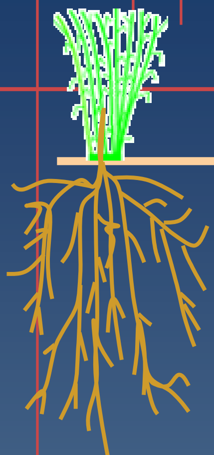
Storativity Estimates

- Mace et al. (2000a) compiled 107 estimates of storativity and calculated 64 estimates of specific storage
  - Storativity (geometric mean): 3×10^{-4}
  - Specific storage: 4.6×10^{-6} 1/m
- Unconfined storativity: 0.20
- Specific storage: 4.5×10^{-6} 1/m

Recharge Estimation: SWAT (Soil and Water Assessment Tool)

- SWAT developed by Blacklands Research Center
- Physically based (primarily) watershed scale model
- Infiltration/runoff based on SCS Curve Number method (daily timestep)
  - Land use
  - Soil type
  - Antecedent soil condition
- Recharge = Infiltration – Evapotranspiration

SWAT-MODFLOW one-way coupled



Run on a daily timestep

SWAT

Daily Estimates of
- Precipitation,
- Temperature,
- Land use/cover,
- Soil type,
- Curve number
- Solar radiation

Daily Calculation of:
(1) The recharge rate for the recharge package,
(2) Groundwater ET for the ET package,
(3) the extinction depth for the ET package

Recharge Package

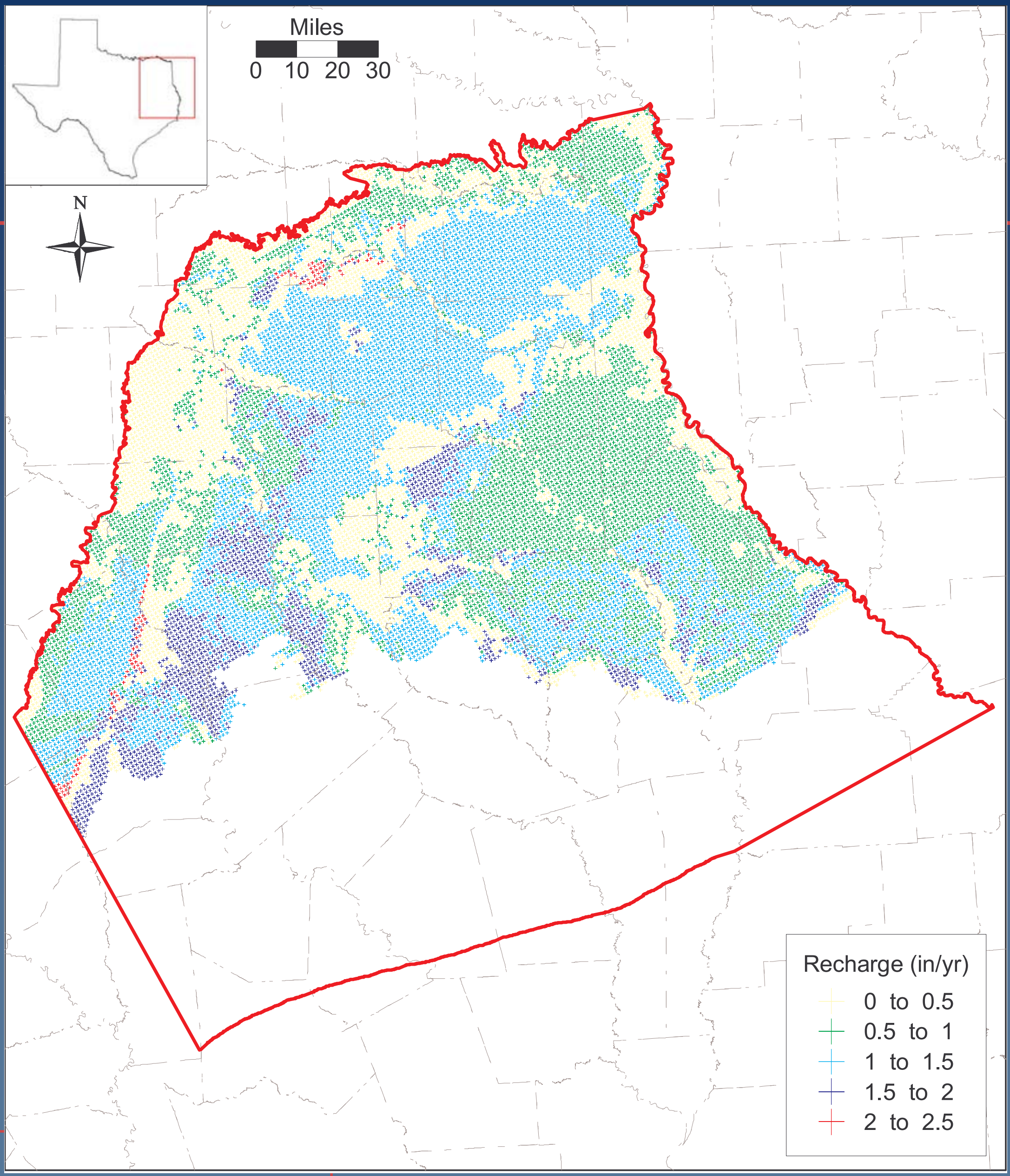
ET Package

MODFLOW

Run on a monthly stress period

INTERA

SWAT Recharge Distribution, Calibrated for Steady-State Conditions

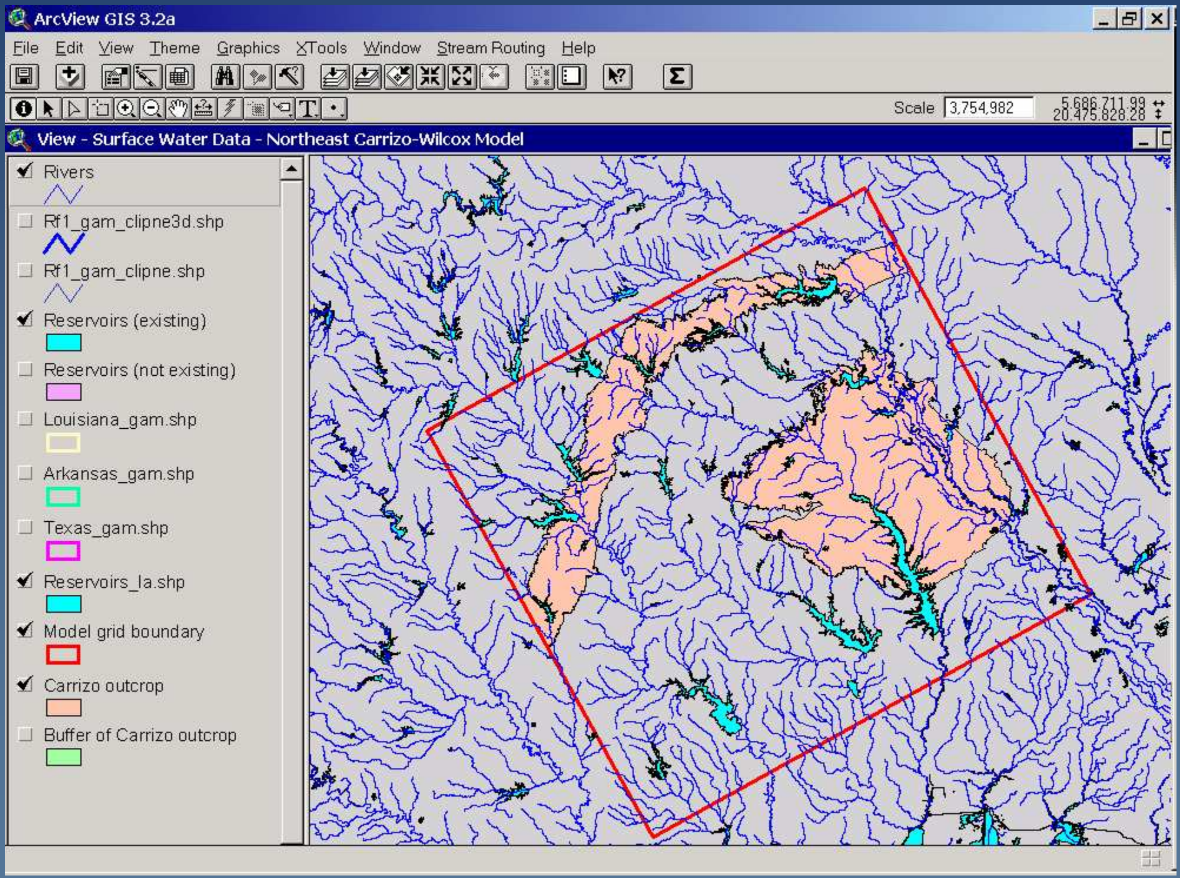


Stream Routing

- Initial stream conductance estimated from EPA RF1 reach file parameters
- (http://www.epa.gov/region02/gis/atlas/rf1.htm)
- Variation in modeled conductance primarily due to stream width
- Relative bed conductivity scaled during calibration

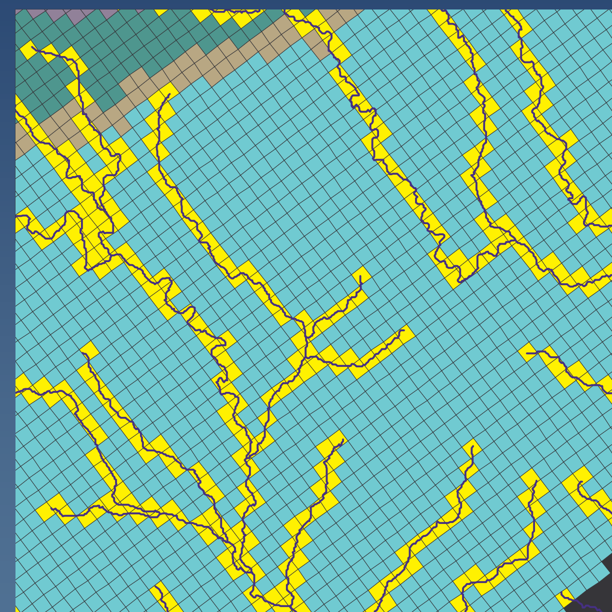
EPA River Reach Data

- EPA river reach data include many attributes needed for the Prudic package: width, depth, stage, roughness, etc.

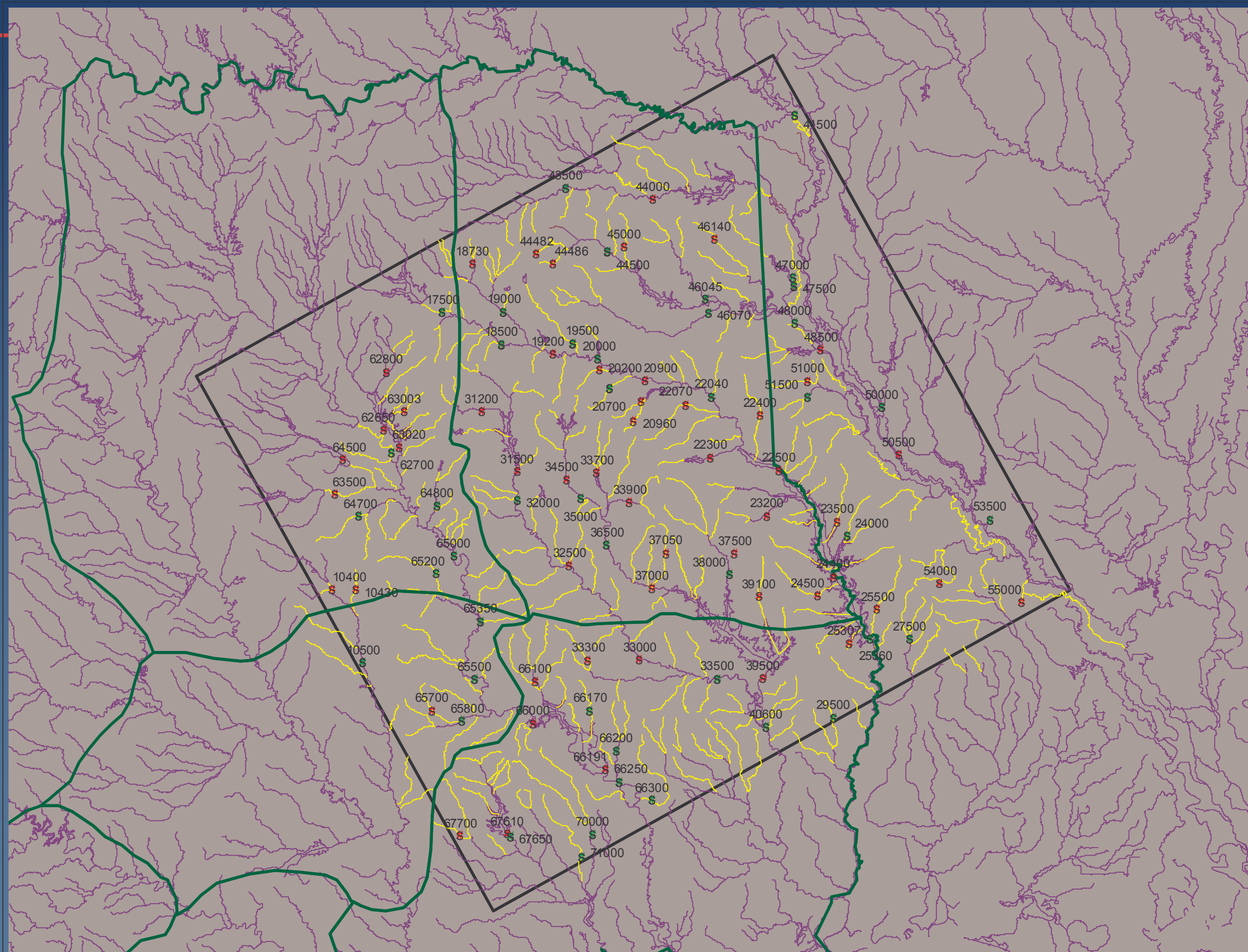


Phased Approach to Stream Routing

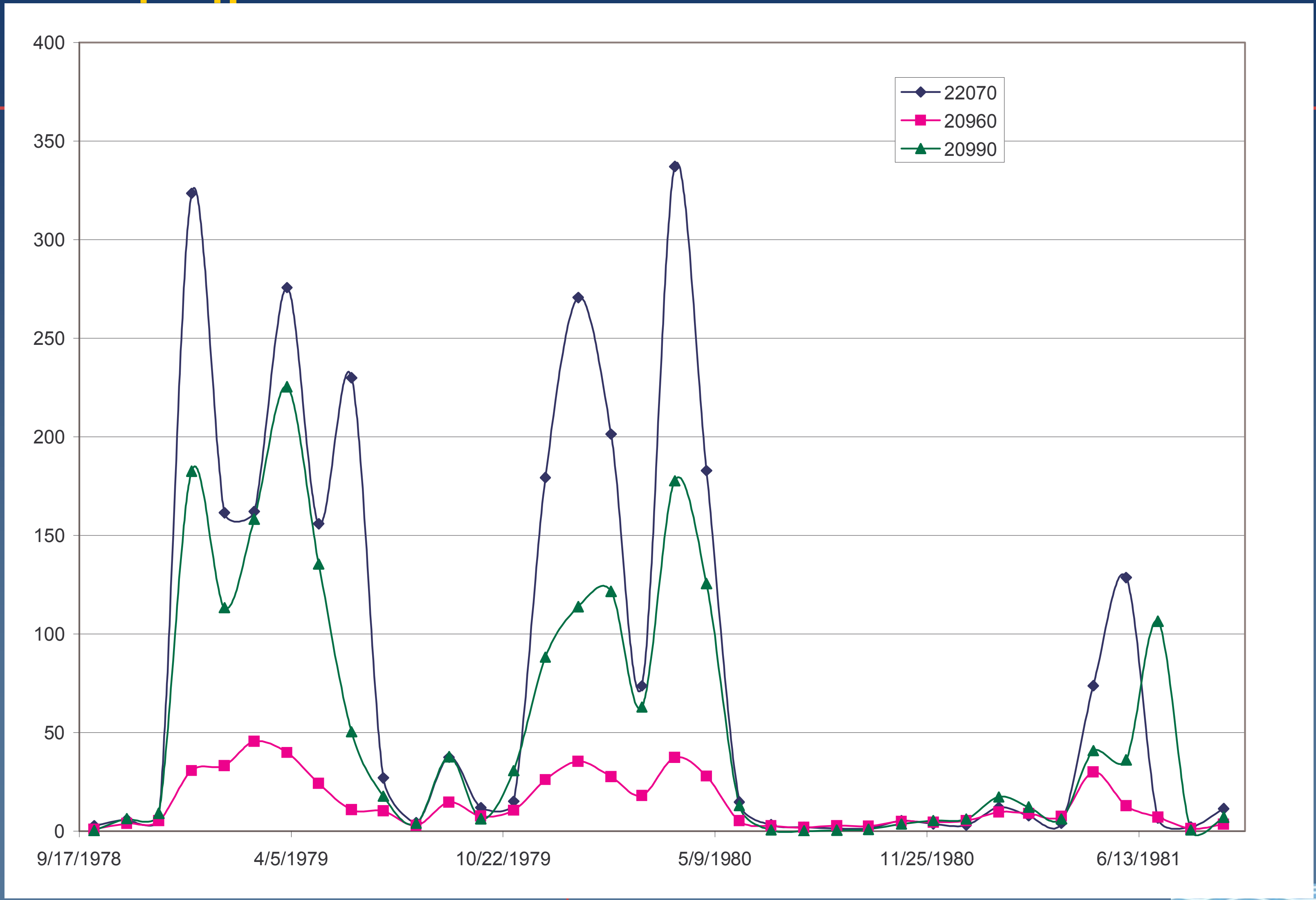
- First, we used average streamflows in the MODFLOW stream-routing package for the steady-state model
  - Average flows from the EPA RF1 data set
- Second, we use transient streamflows to perform the full stream-routing in the transient model
  - Transient streamflow data from USGS stream gages



USGS gages with complete record (1975 – 1998)

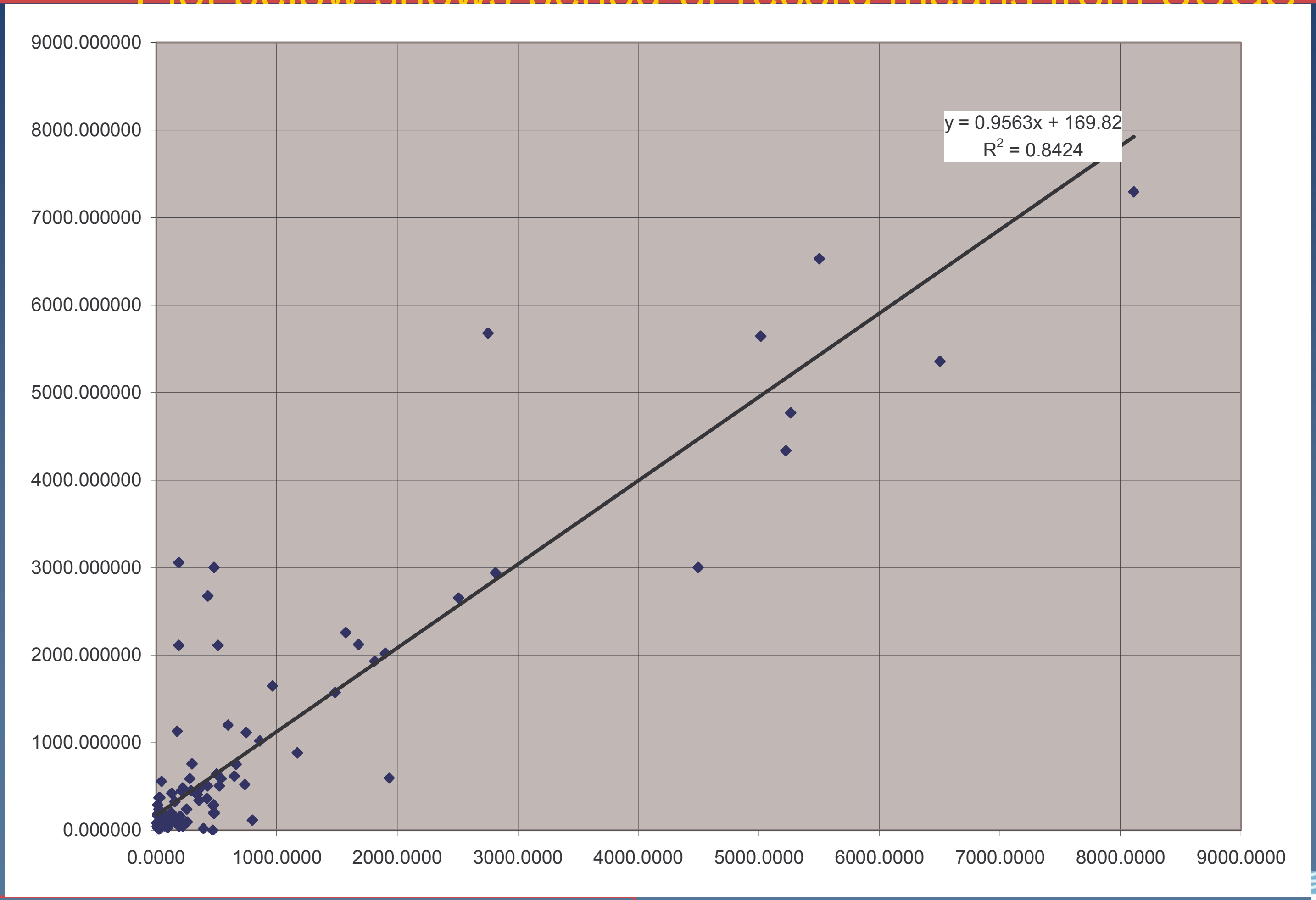


Response of nearby streams is



Mean flows were generated from USGS gage data, and a graphical/regression technique

– Plot below shows period-of-record means from USGS

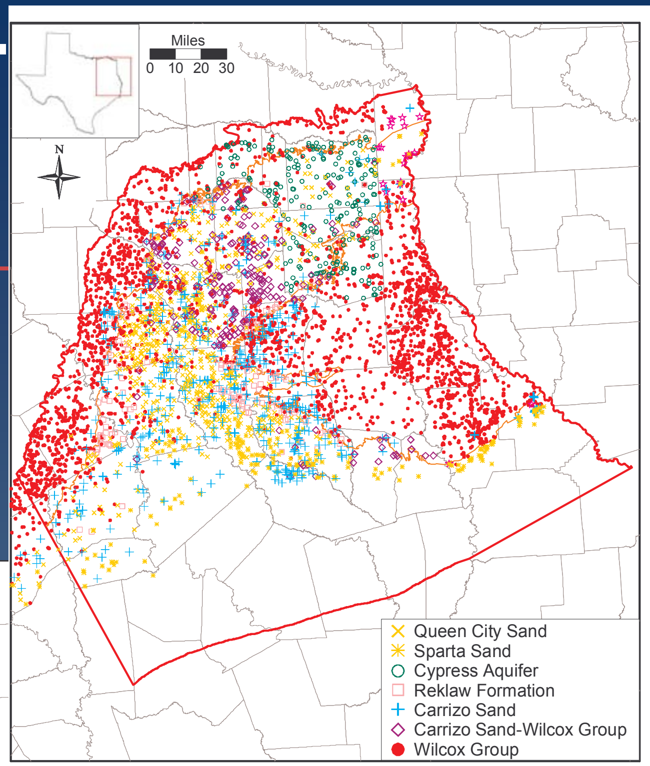


Hydraulic Heads: Predevelopment Conditions

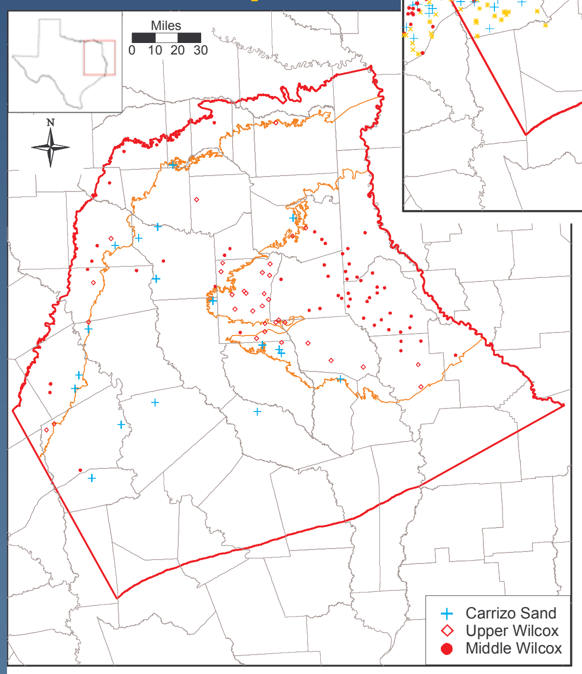
- Evaluated water-level data on a county by county basis
- For each county, determination the hydraulic connectiveness of the Carrizo and Wilcox based on a literature review
- Conducted a literature review on the historical development of the Carrizo and Wilcox in each county
- Used maximum water-level elevations (regardless of date measured) in each area of the county

Water-Level Data

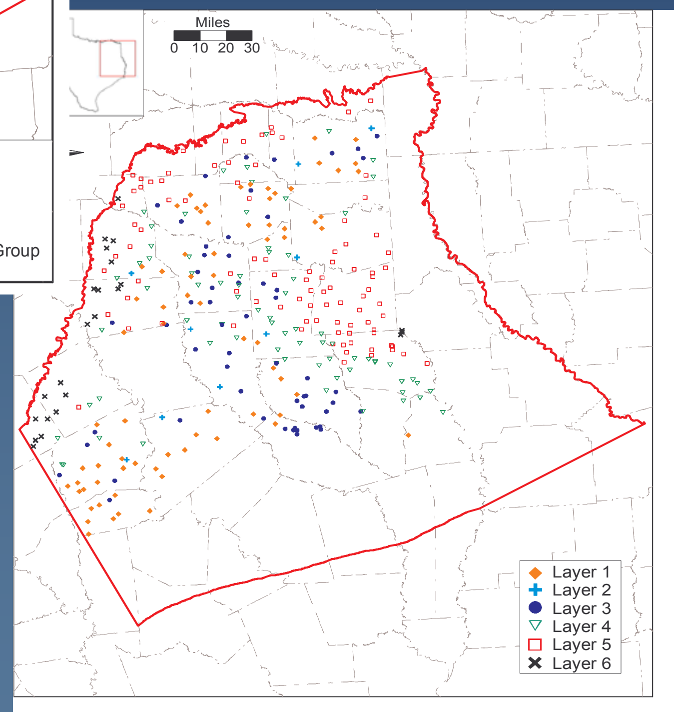
All data



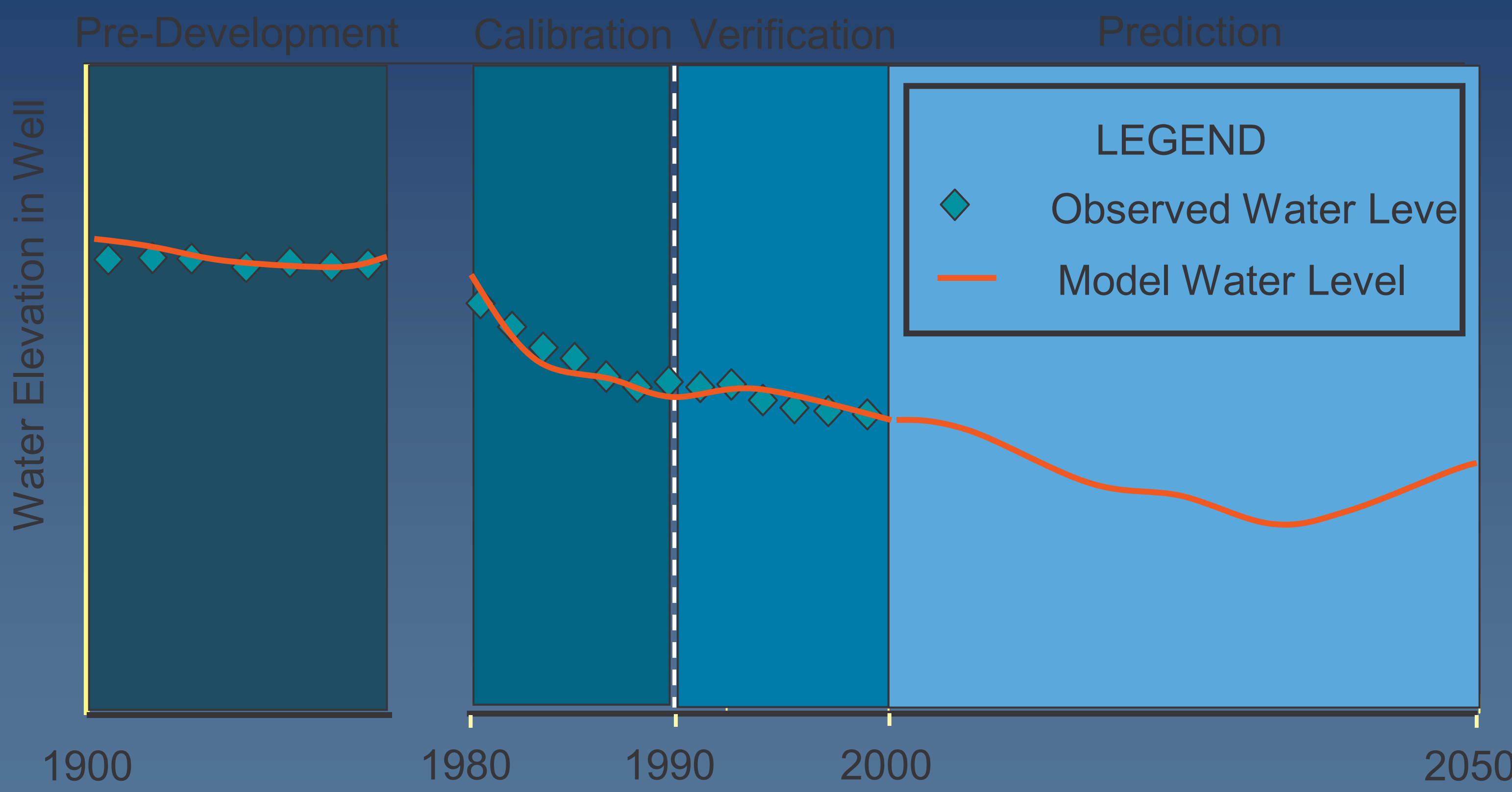
Pre-Development



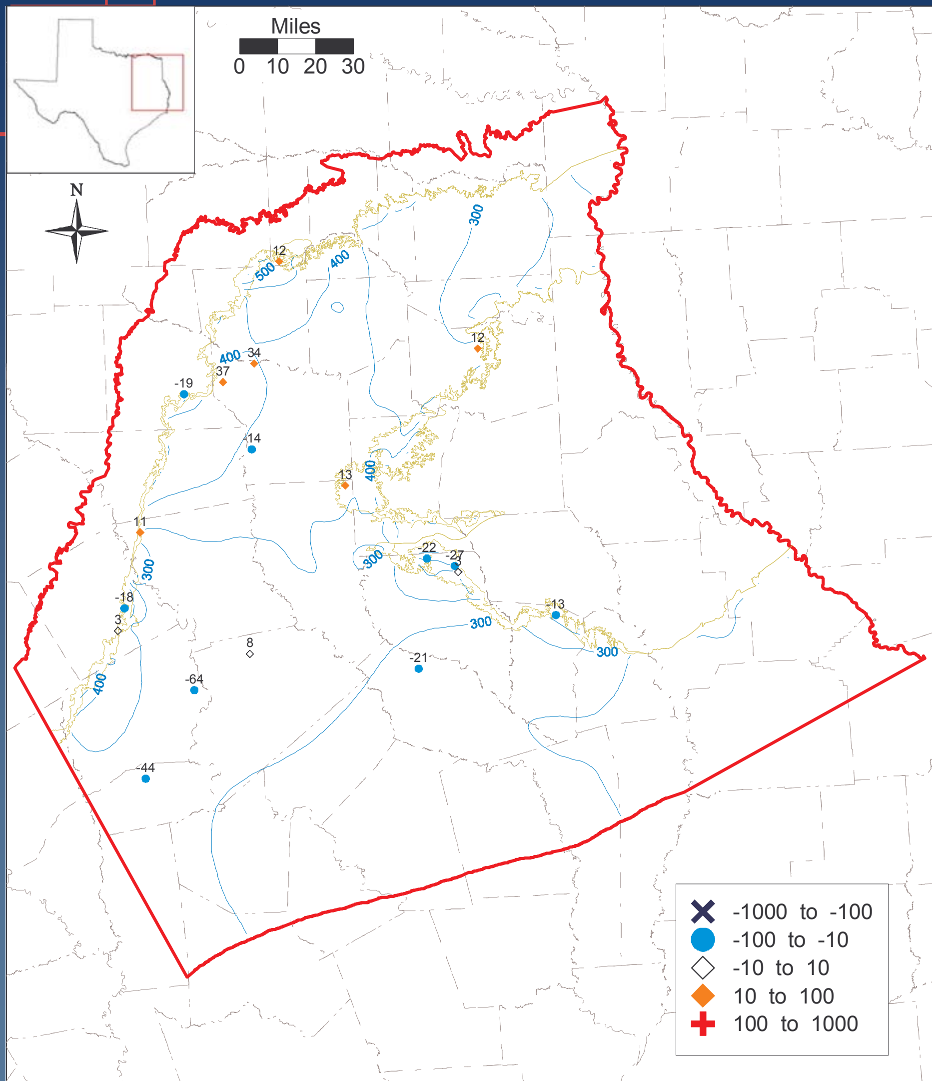
Transient Calibration

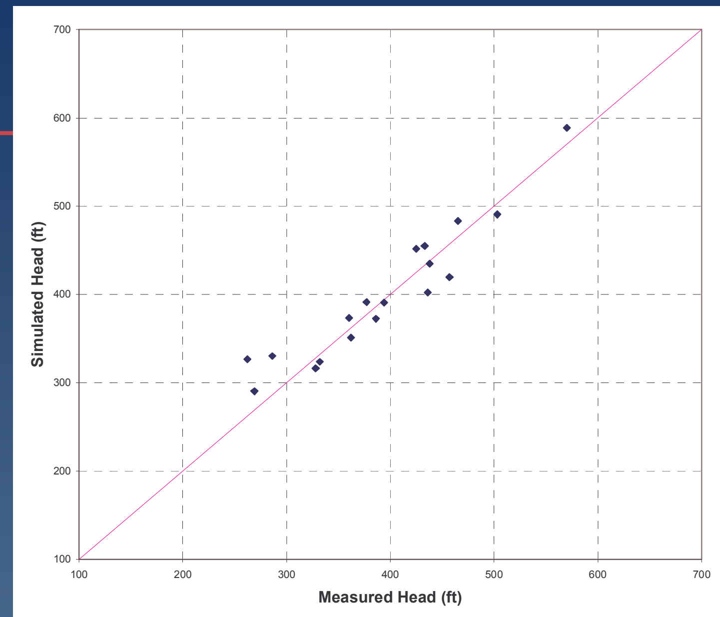


Modeling Periods



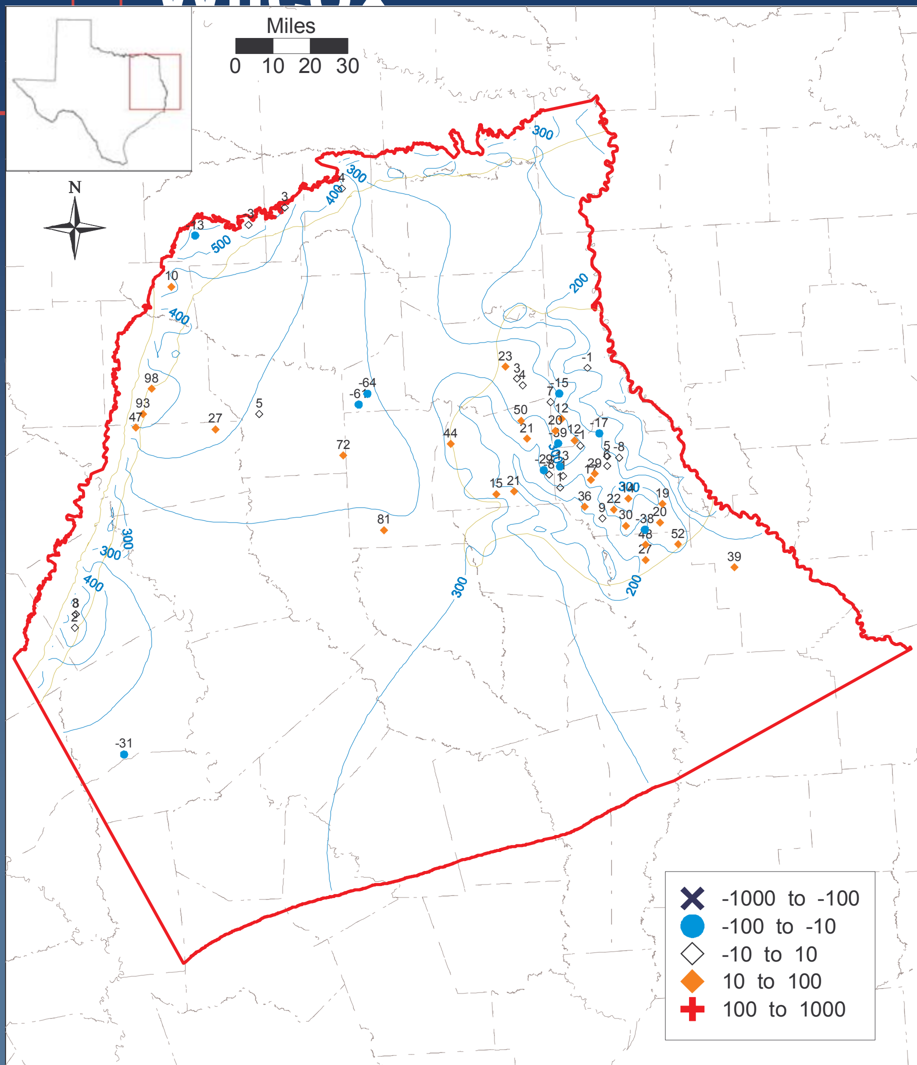
Pre-development Calibration: Carrizo

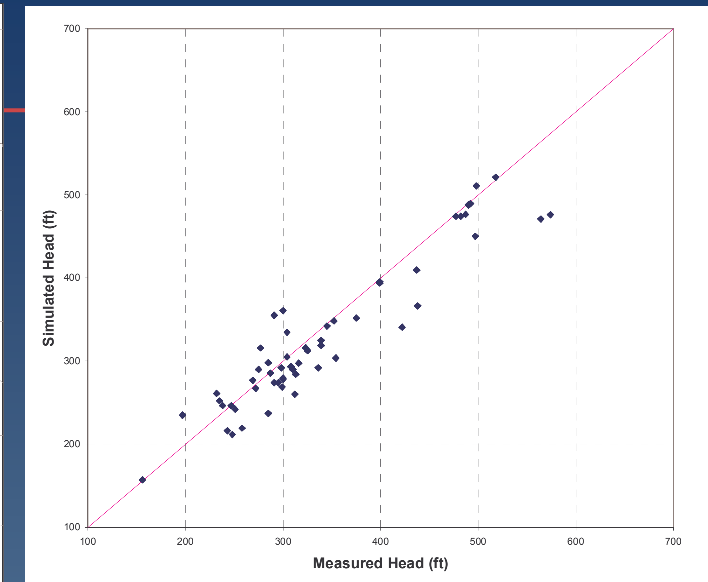




Layer	Total RMS (ft)	Range (ft)	Adj. RMS
Layer 1	45.8	366	0.13
Layer 3	25.9	308	0.08
Layer 4	38.5	257	0.15
Layer 5	33.9	418	0.08

Pre-development Calibration: Middle Wilcox





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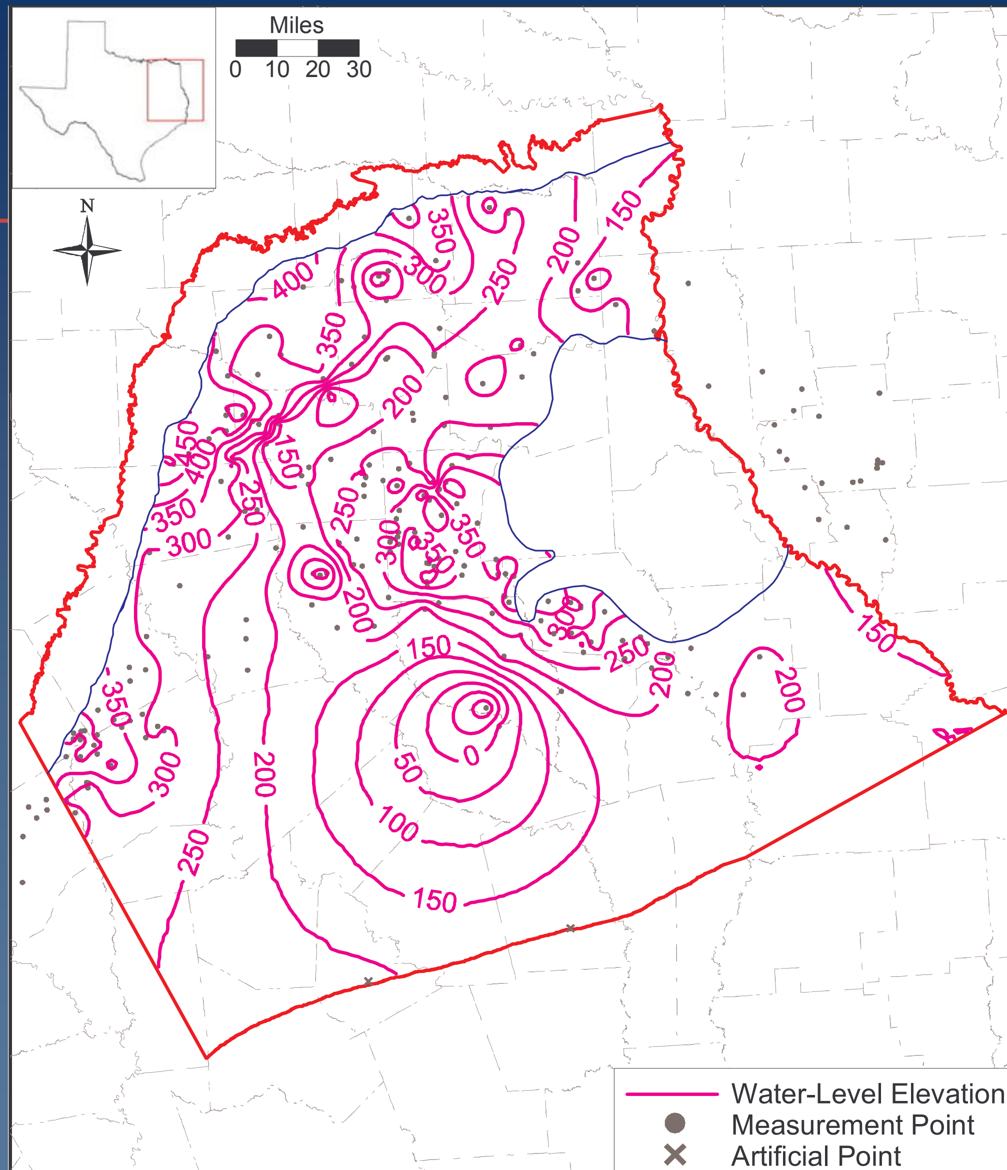
Layer 5	33.9	418	0.08

INTERA

Hydraulic Heads: Transient Calibration/Verification

- Used the TWDB head database
- Developed head surfaces for Carrizo
- 1980, 1990, 2000
- Developed hydrographs (time series) for transient calibration

Hydraulic Heads 1980: Upper Wilcox



Evaluation of Historic Pumping Demand

- TWDB Technical Memo on Pumping allocation and distribution (see www.twdb.state.tx.us/GAM)
- Standard Operating Procedure (SOP) developed for historical (1980-1999) Pumping
- Standard Operating Procedure (SOP) developed for predictive simulations (2000-2050)
  - **Based on TWBD predictive data found in GAMPredictivePumpage_2002SWP.xls**

PARSONS

INTERA

Pumping - Data Sources for Groundwater Use Provided by the TWDB (1980-1999)

- Annual water use summary by major aquifer
- Annual water use summary by individual county and river basin
- Monthly water use summary for municipal users
- Monthly water use summary for manufacturing users

Categories of Groundwater Use

Point Source Data

- Municipal
- Manufacturing
- Power
- Mining

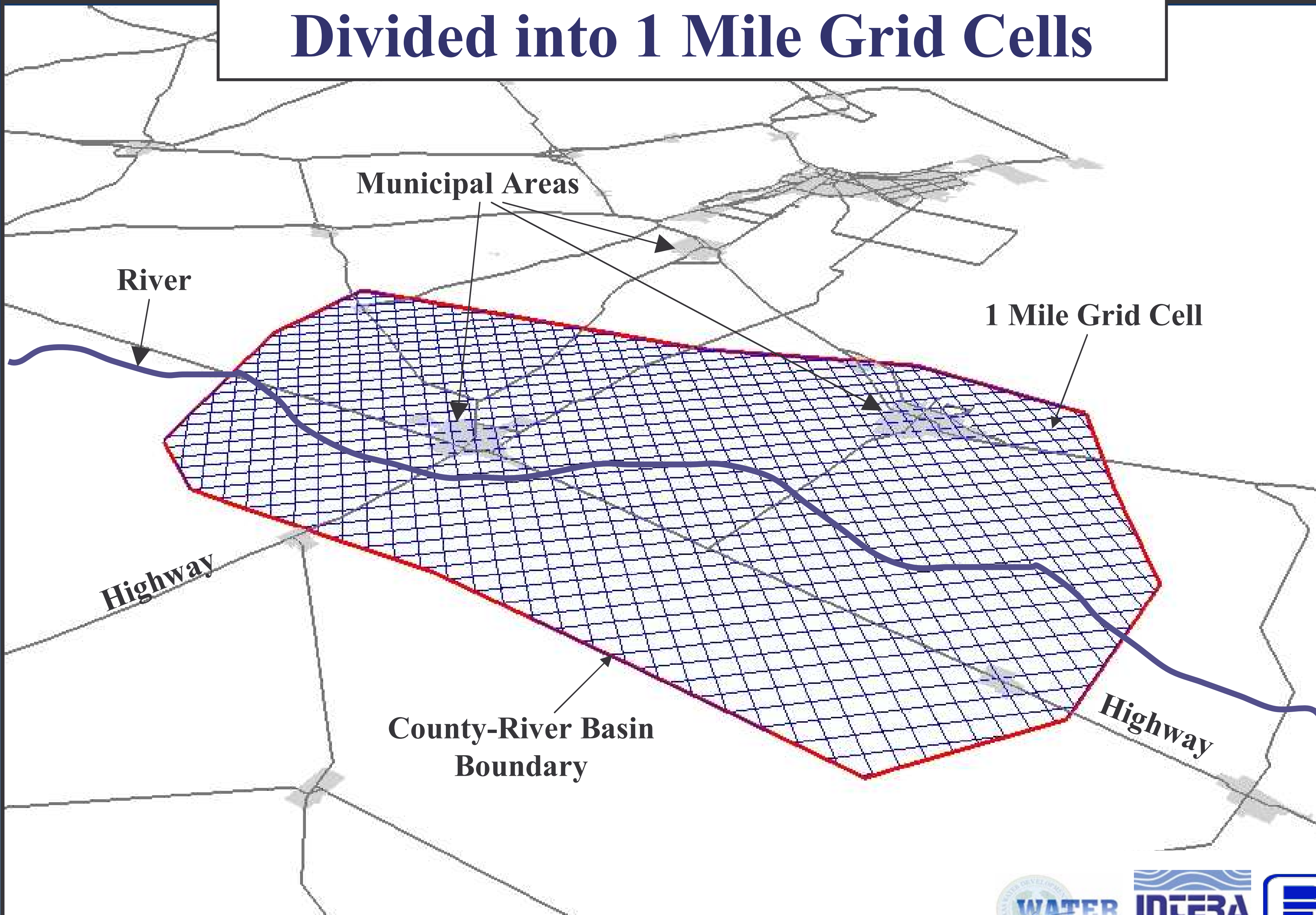
Non-Point Source Data

- Irrigation
- Livestock
- Rural Domestic

Database Processing

- Utilize TWDB Technical Memorandums
- Prepare 1 mile by 1 mile grid cells using GIS (Geographic Information Systems) computer programs
- Separate point source municipal wells from non-point source rural domestic wells
- Distribute monthly pumpage for each of the 7 groundwater uses across each grid cell

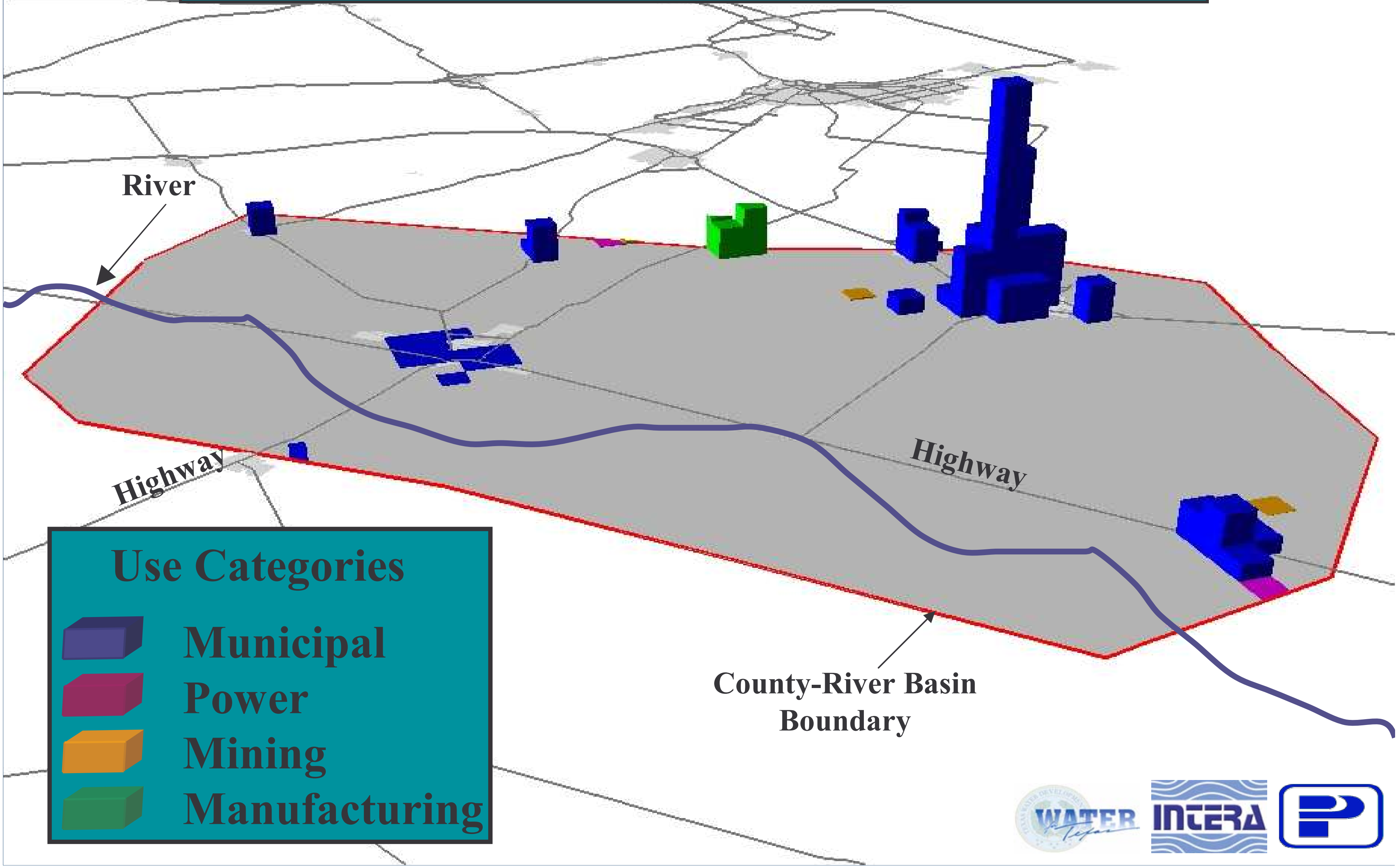
Conceptual County & River Basin Divided into 1 Mile Grid Cells



Locate Pumpage Using Point Source Data

- Applicable for municipal, manufacturing, power and mining uses
- Utilize TWDB water use survey and TWDB well database
- Assign well screened intervals (top and bottom) to specific groundwater flow layers within the model
- Label each pumping record with the appropriate grid cell identifier

Conceptual County & River Basin Point Source Data for February, 1980



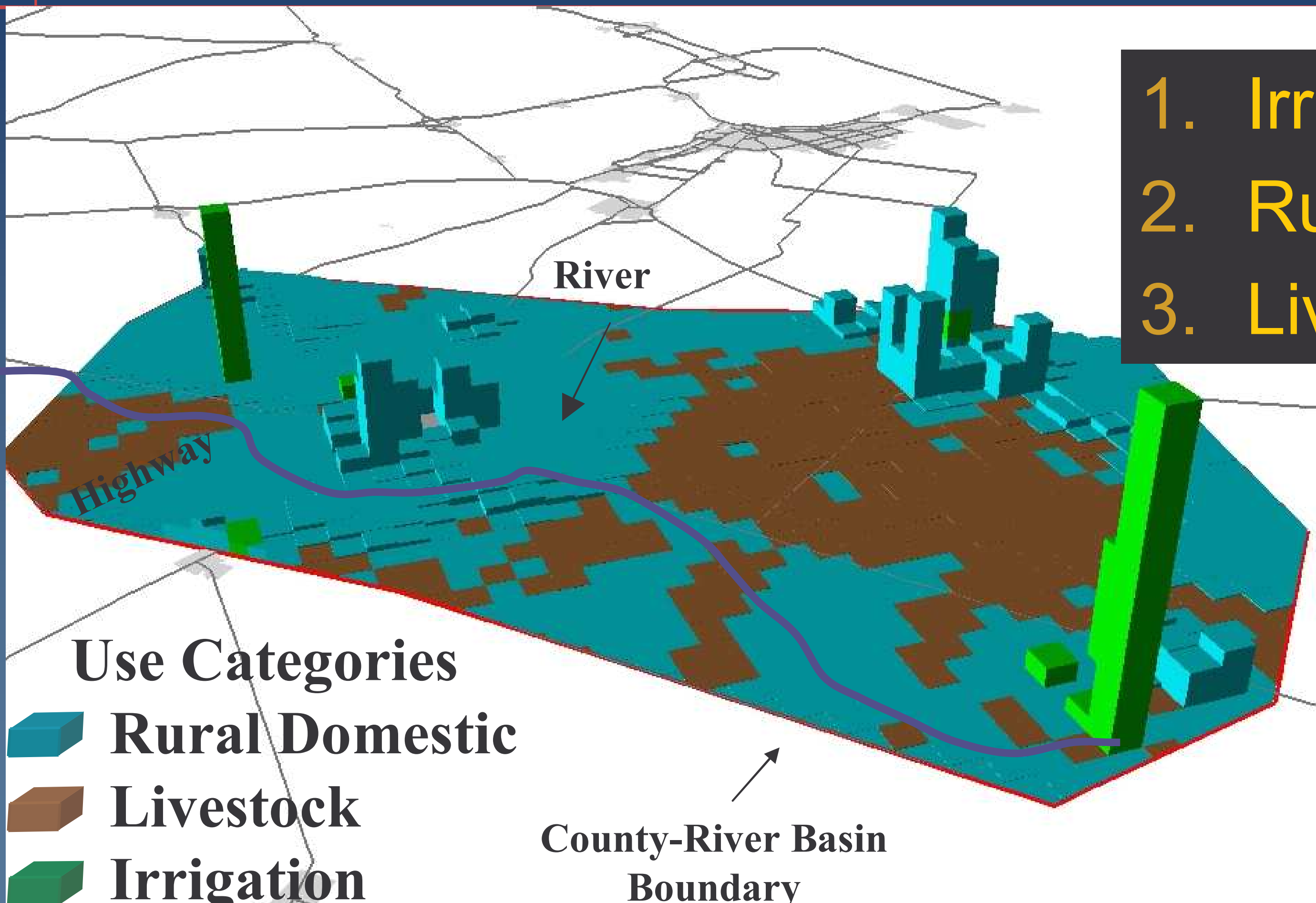
Locate Pumpage Using Non-Point Source Data

Rural Domestic Pumpage:

- Distribute pumpage data based on population density, excluding municipalities with a Public Water Supply
- Distribute annual pumpage into monthly increments in proportion to nearby larger municipalities
- Well depths assigned from nearby wells in TWDB well database

Locate Pumpage Using Non-Point Source Data

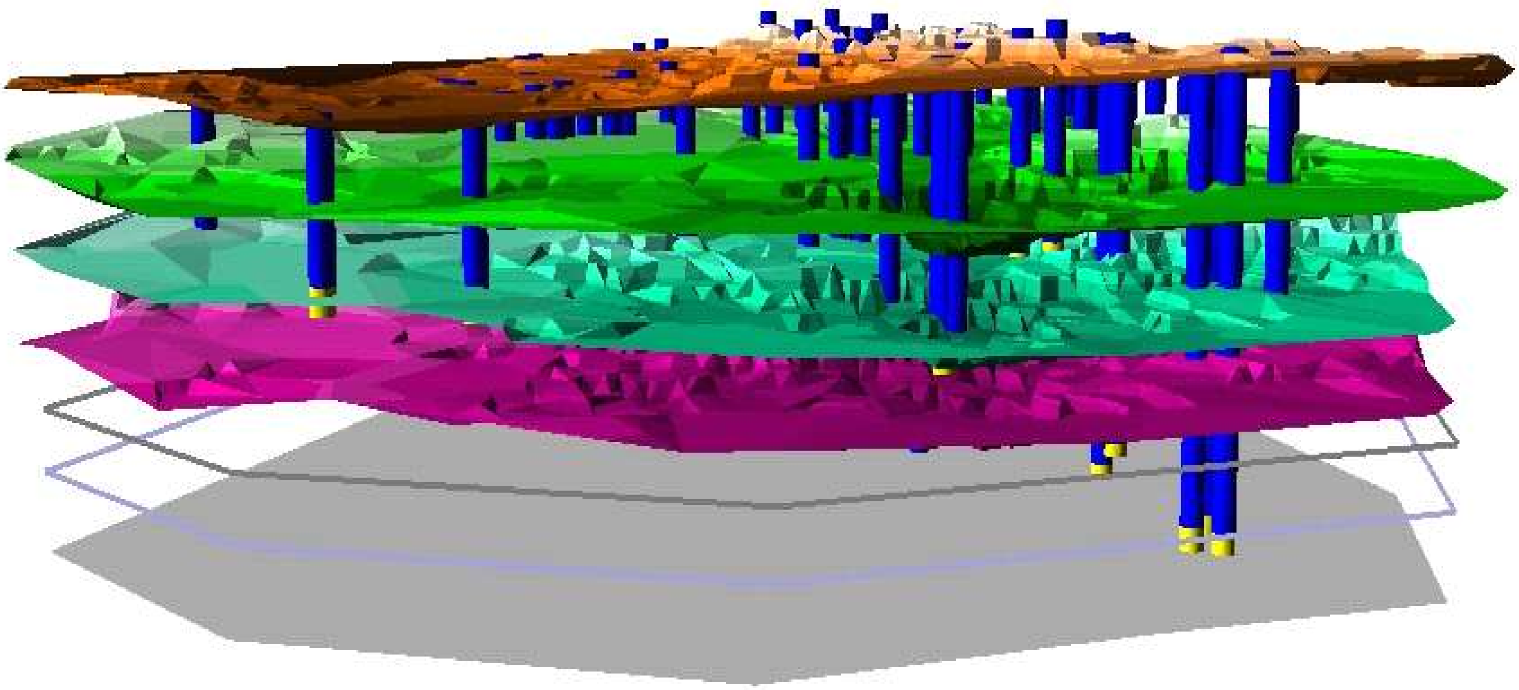
1. Irrigation
2. Rural/Domestic
3. Livestock



Pumping Implementation

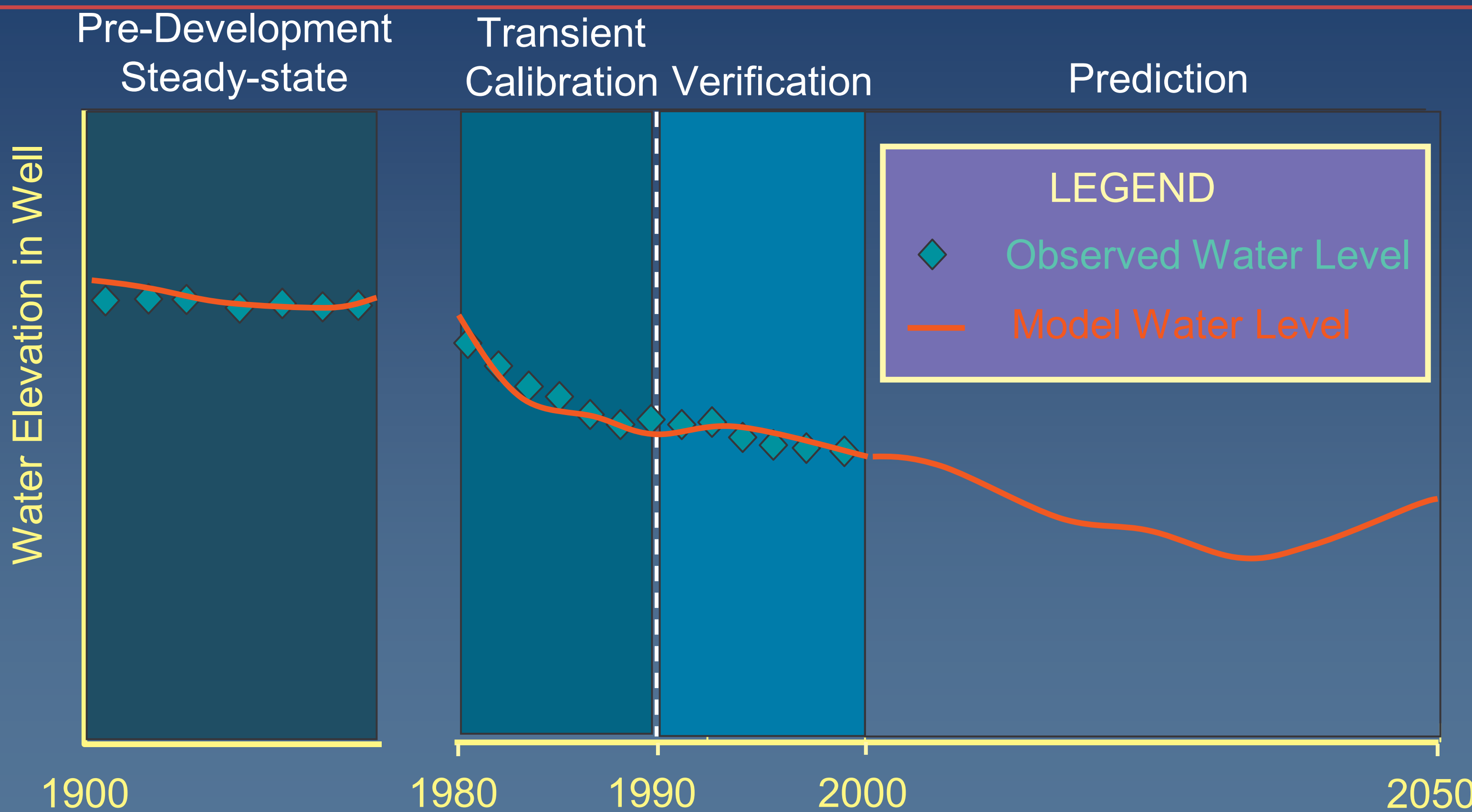
- Once the pumping has been estimated for each of the seven user groups;
  - It is summed across all user groups for a given model cell (row, column) and a given model layer
  - This process is repeated for all active model cells in the model domain for each transient stress period.
  - The stress period used in the transient simulations is 1 month.
- A well package is written for each stress period

Conceptual County & River Basin Wells with Various Depths in Multiple Aquifer Layers



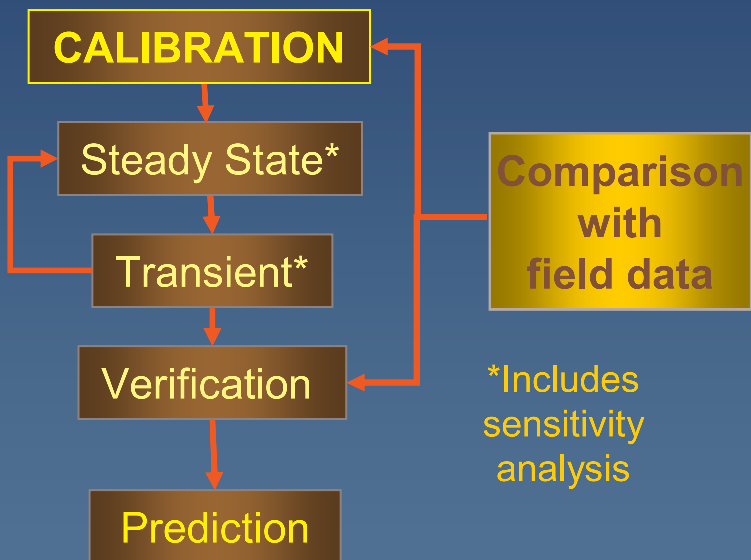
PARSONS INTERA

Calibration and Prediction Periods



Pre-development and transient calibration periods represent different hydrologic conditions

Calibration Approach

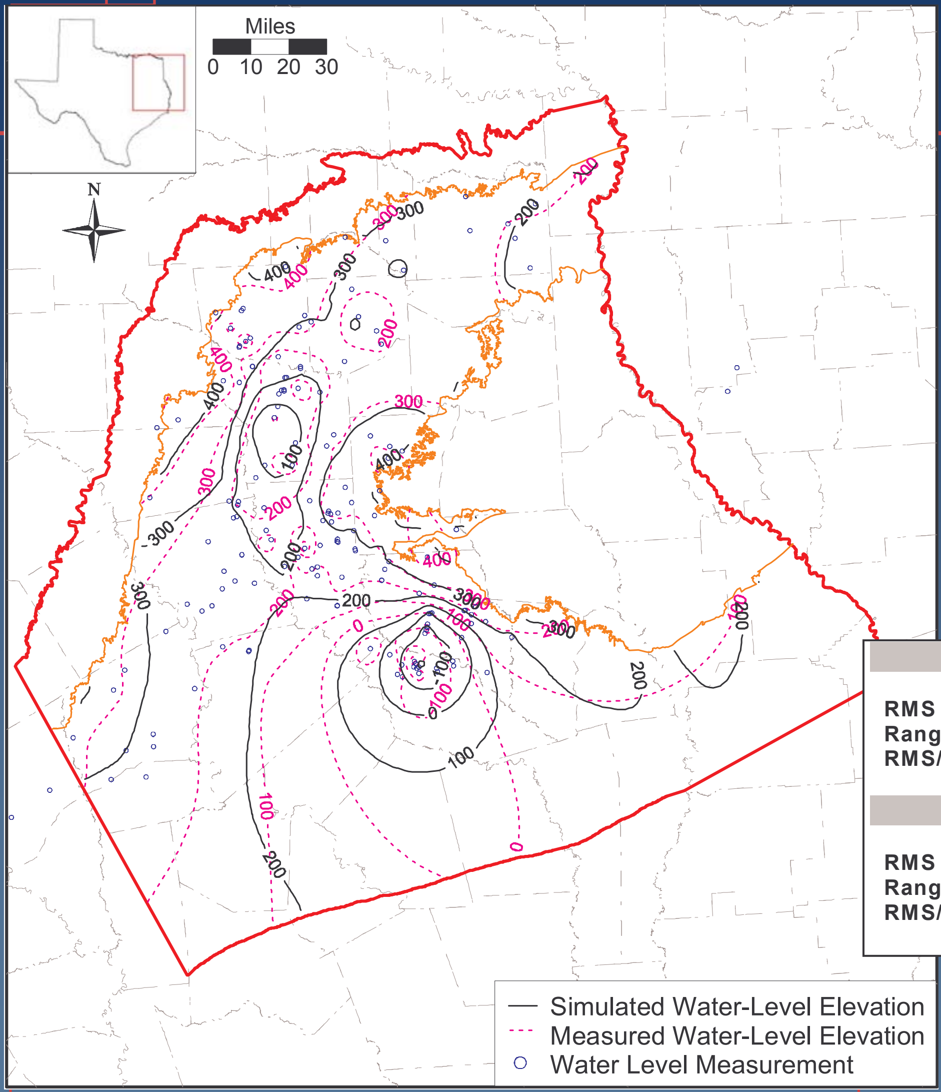


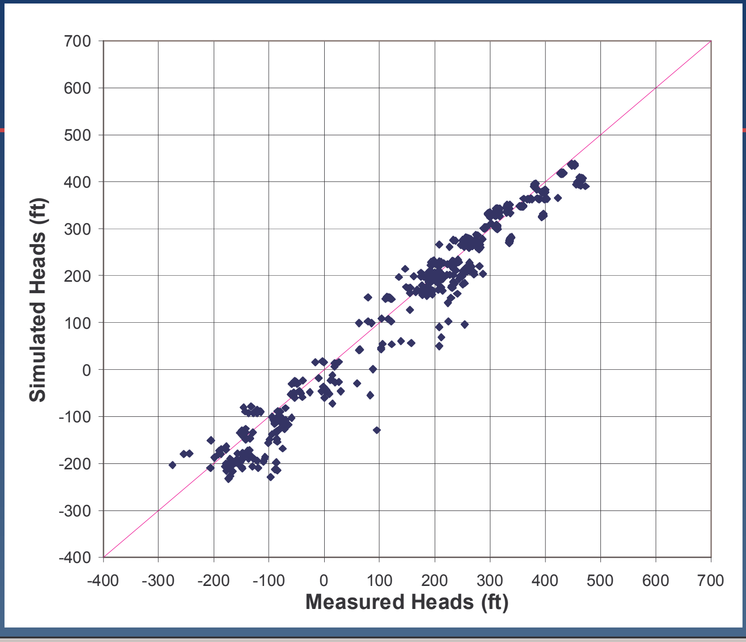
The calibration approach iterates between the steady-state (predevelopment) and the transient calibrations to reach a consistent set of physical parameters that match both sets of observation.

Transient Model Calibration

- Transient calibration required:
  - Reduced K_v of the Reklaw
  - Reduced K_v of the Wilcox layers
  - Adjusted conductivity of the GHBs attached to the Queen City

Transient Calibration: Carrizo

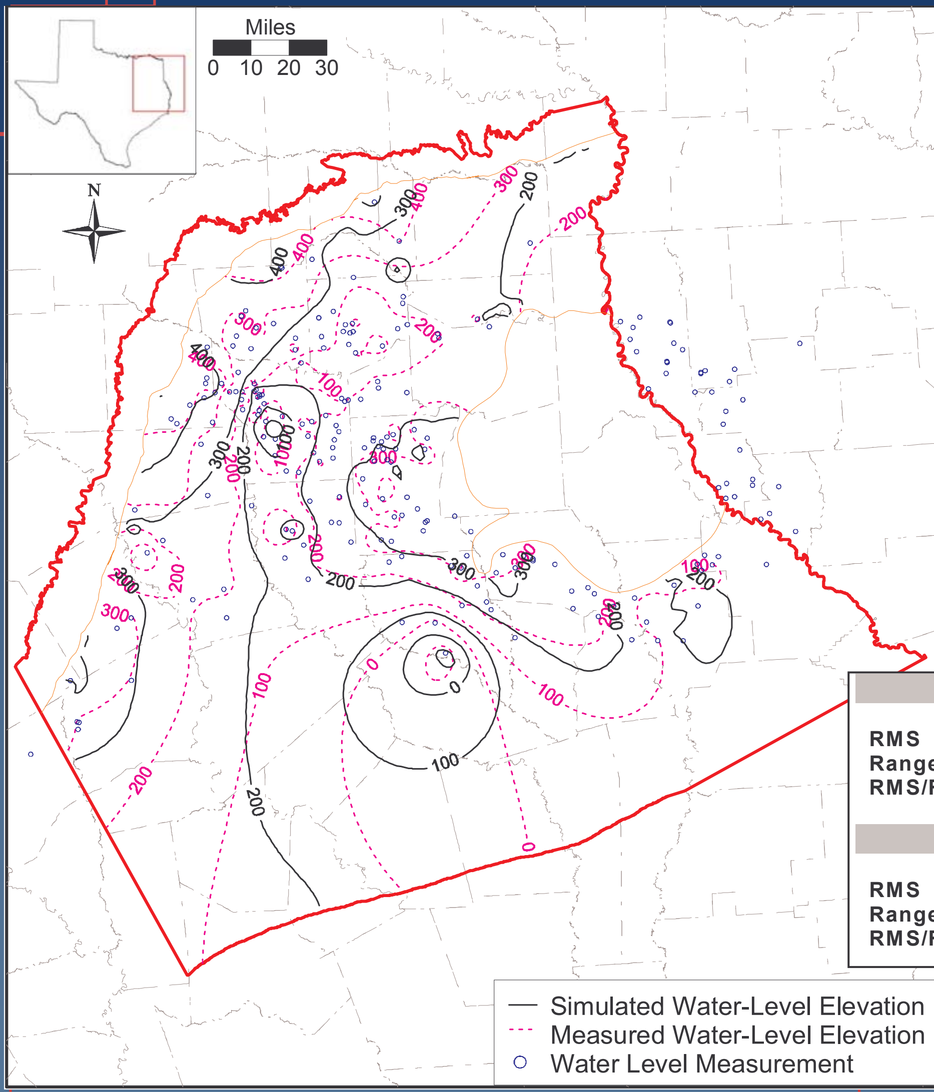


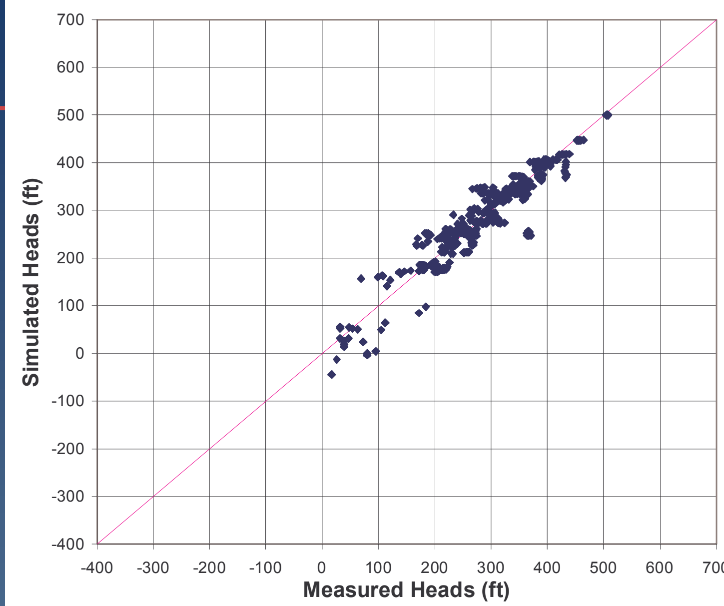


Calibration period (1980-1989)					
	Layer 1	Layer 3	Layer 4	Layer 5	Layer 6
RMS	40.87	35.14	26.57	31.74	24.70
Range	433	743	491	523	310
RMS/Range	0.094	0.047	0.054	0.061	0.080

Verification period (1990-1999)					
	Layer 1	Layer 3	Layer 4	Layer 5	Layer 6
RMS	41.08	42.10	34.37	38.44	31.01
Range	459	821	660	523	300
RMS/Range	0.090	0.051	0.052	0.073	0.103

Transient Calibration: Upper Wilcox





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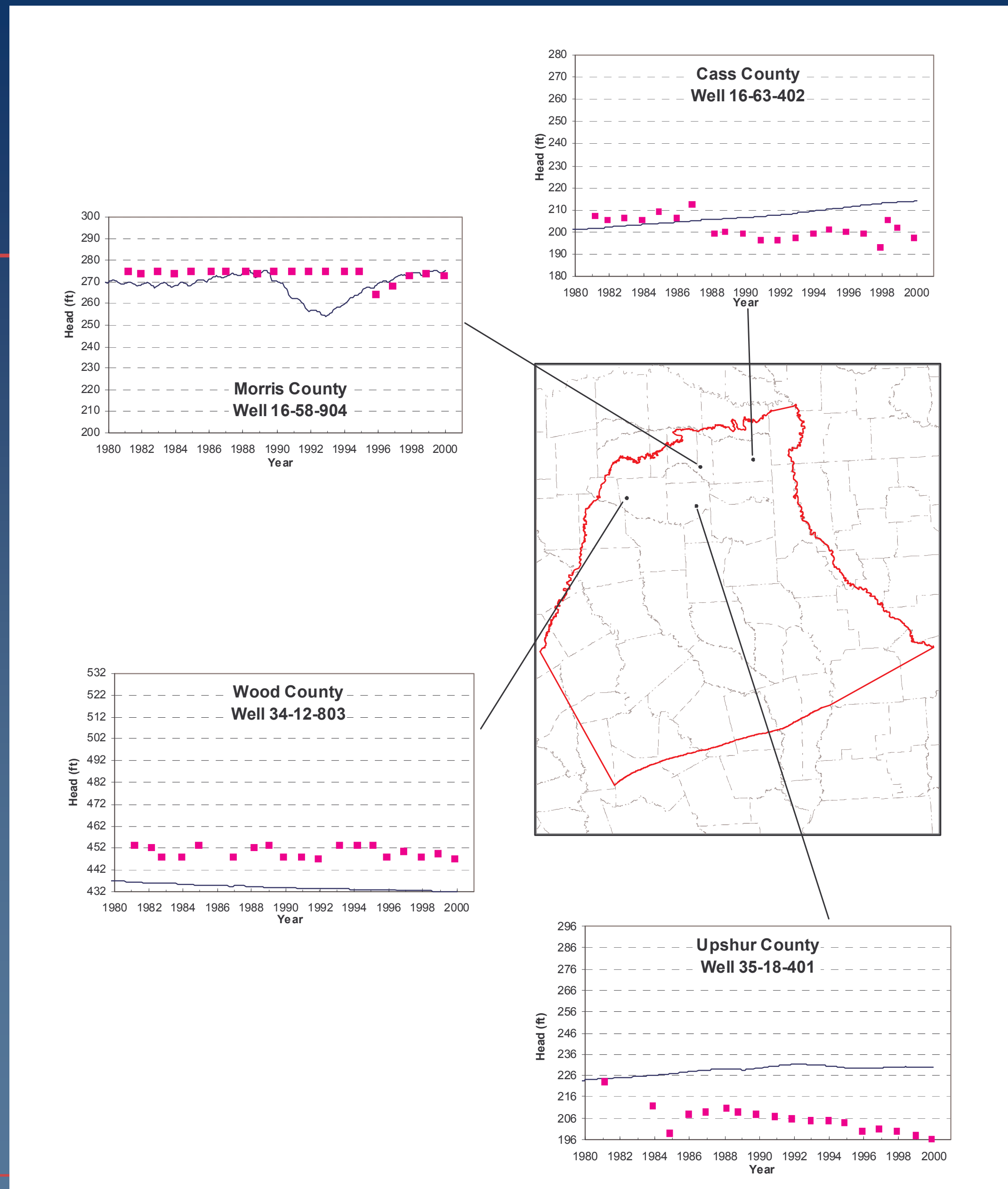
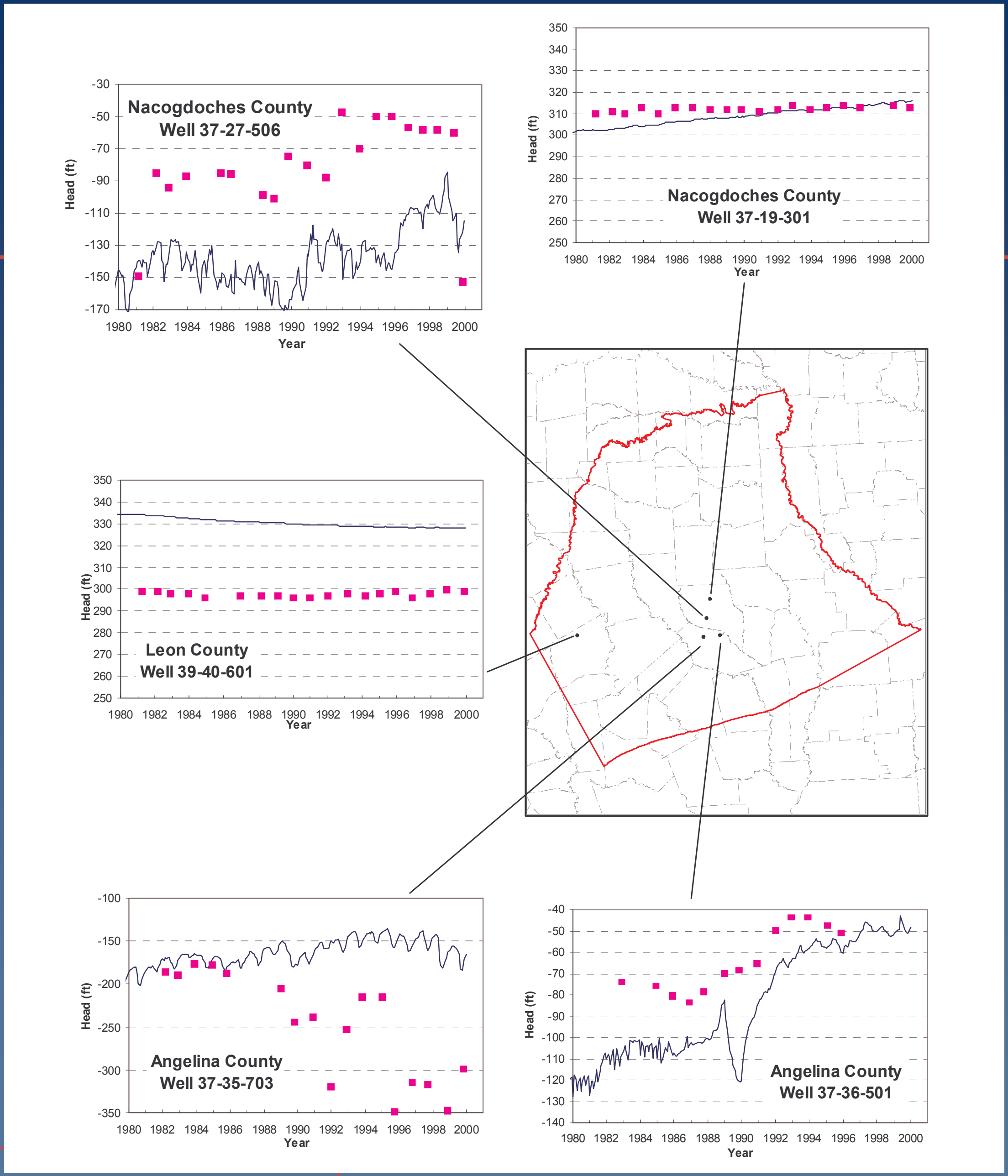
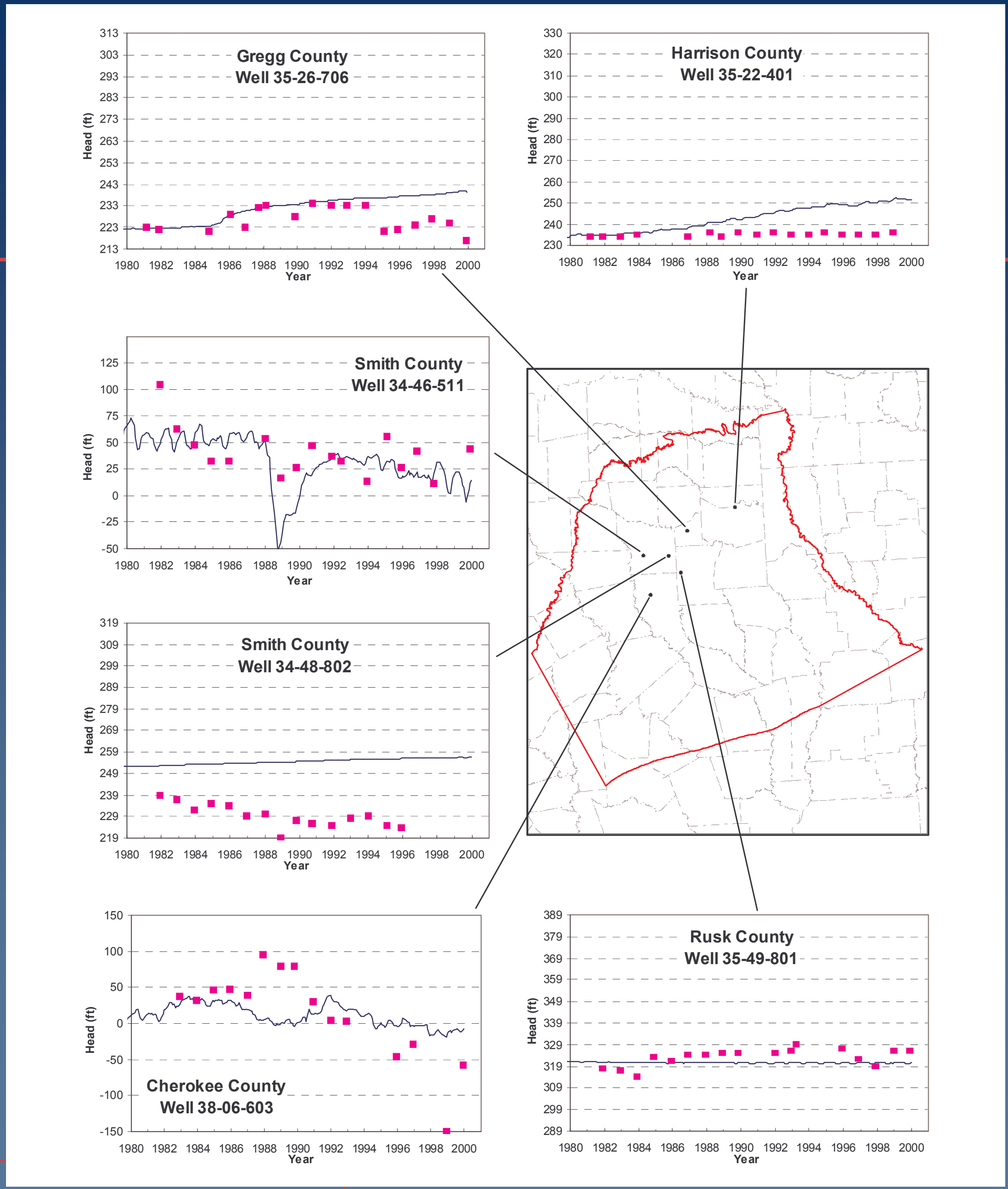
Hydrographs: Carrizo



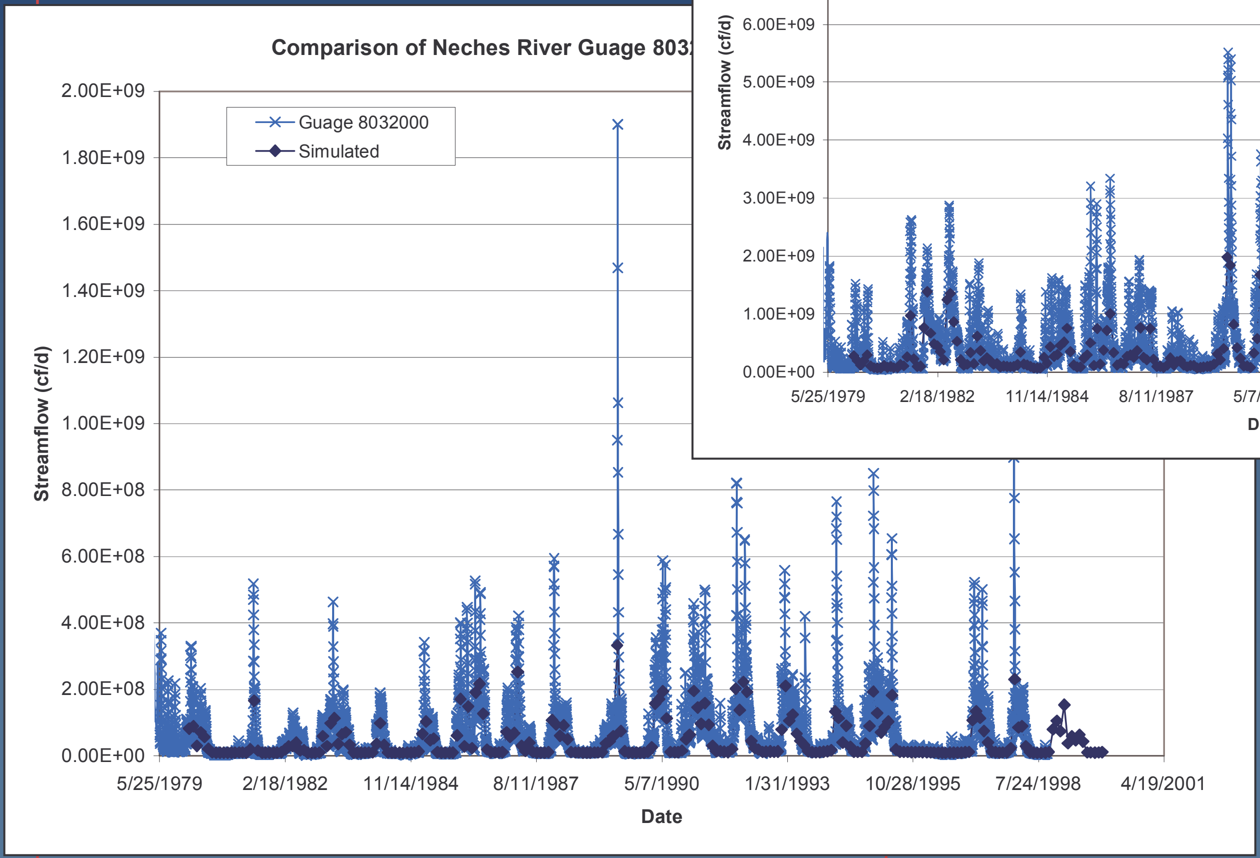
Hydrographs: Carrizo

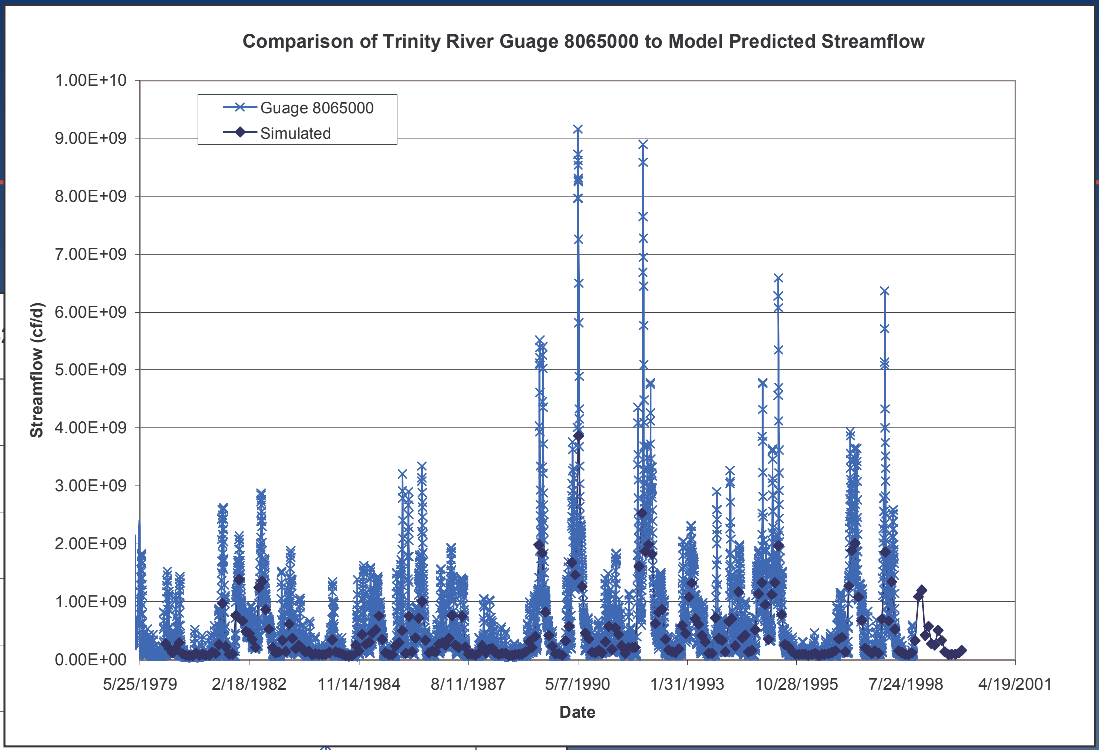


Hydrographs : Upper Wilcox

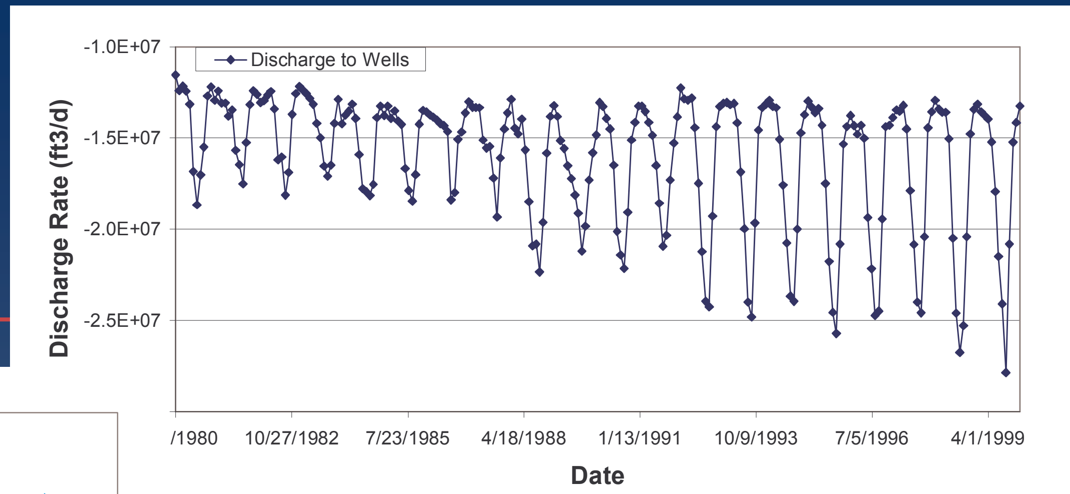


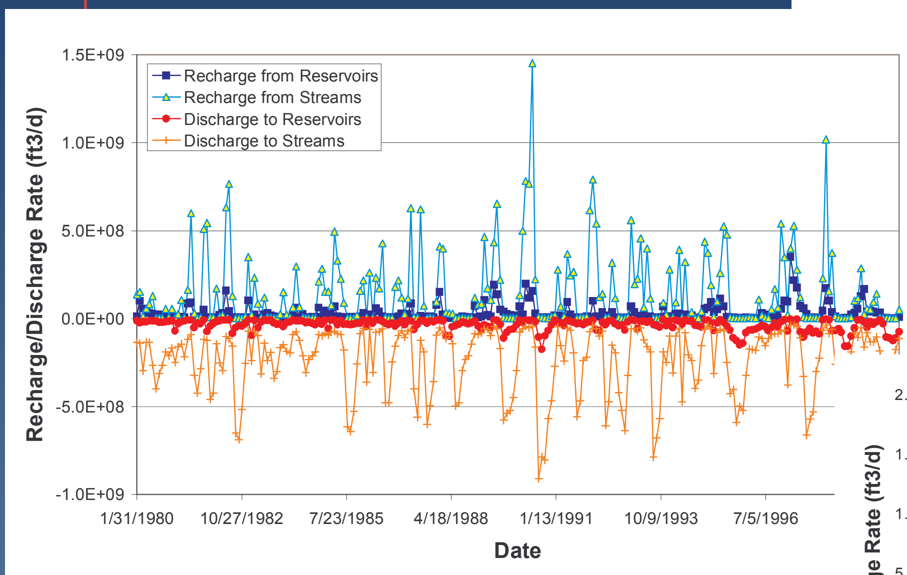
Stream Gage Comparison

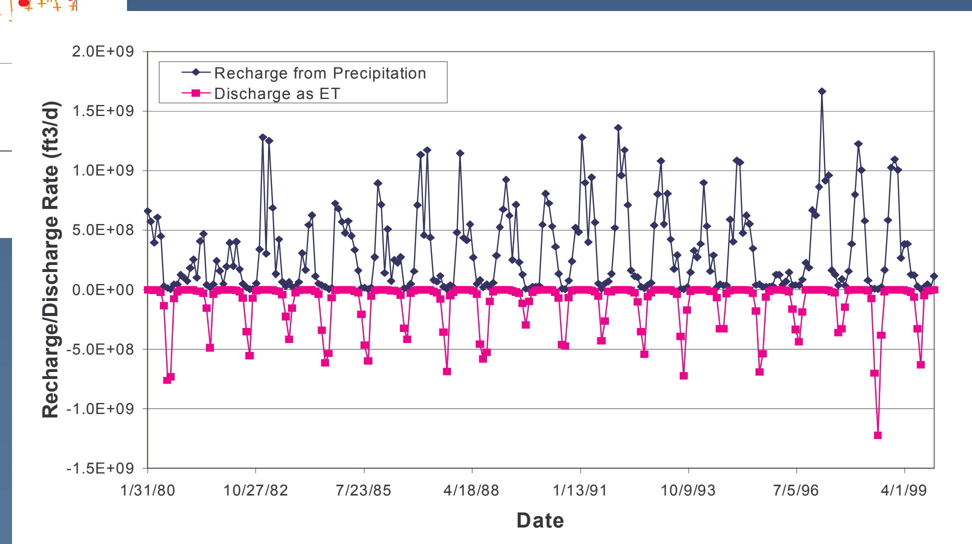




Recharge/ Discharge



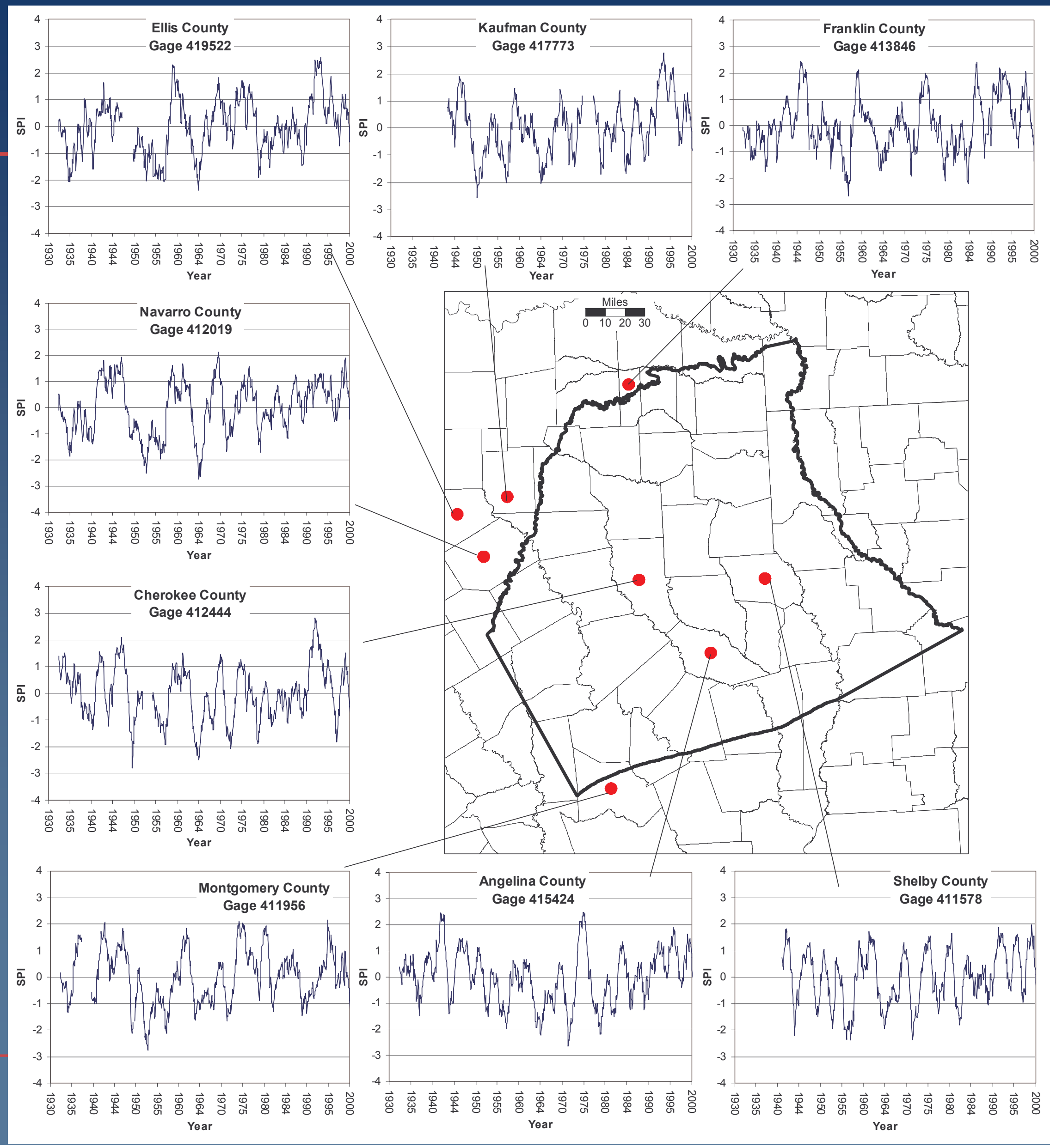




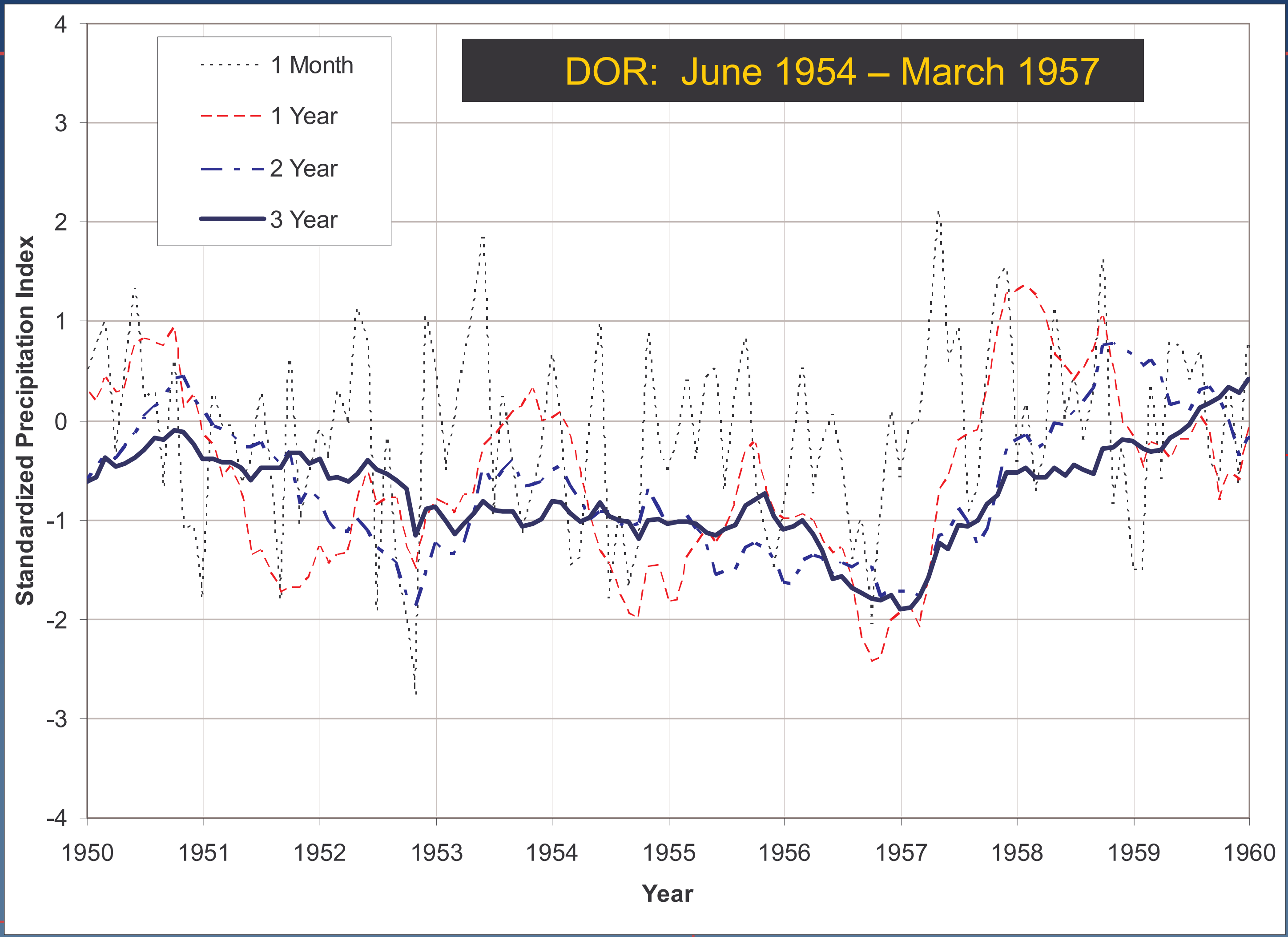
Predictive Simulation (2000-2050)

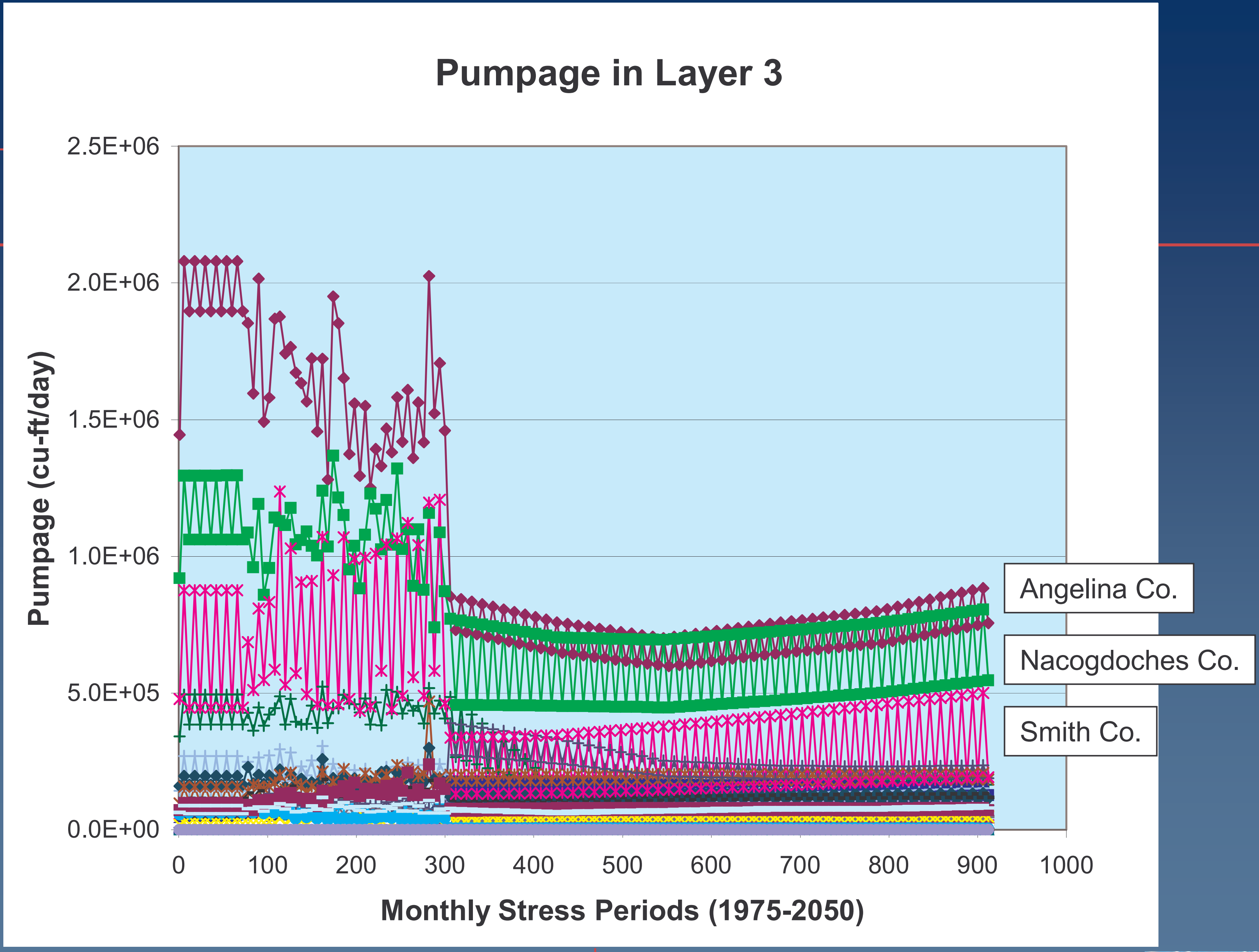
- Predictive Pumpage based on RWPGs
- Six Model Scenarios:
  - Average Recharge Conditions through 2050
  - Average Recharge Conditions ending with the drought of record (DOR) in 2010
  - Average Recharge ending w/ DOR in 2020.
  - Average Recharge ending w/ DOR in 2030.
  - Average Recharge ending w/ DOR in 2040.
  - Average Recharge ending w/ DOR in 2050.

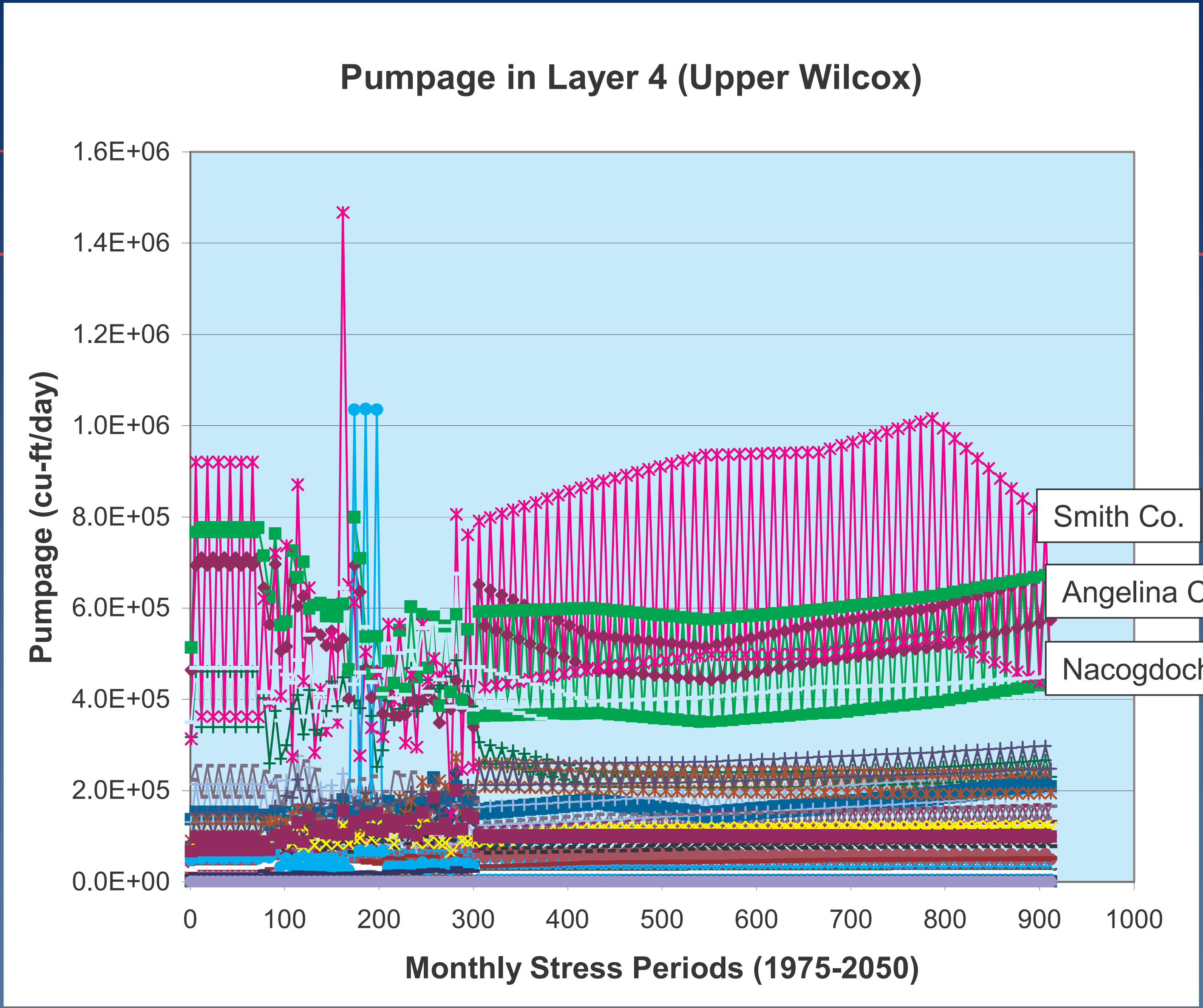
Drought of Record (DOR)



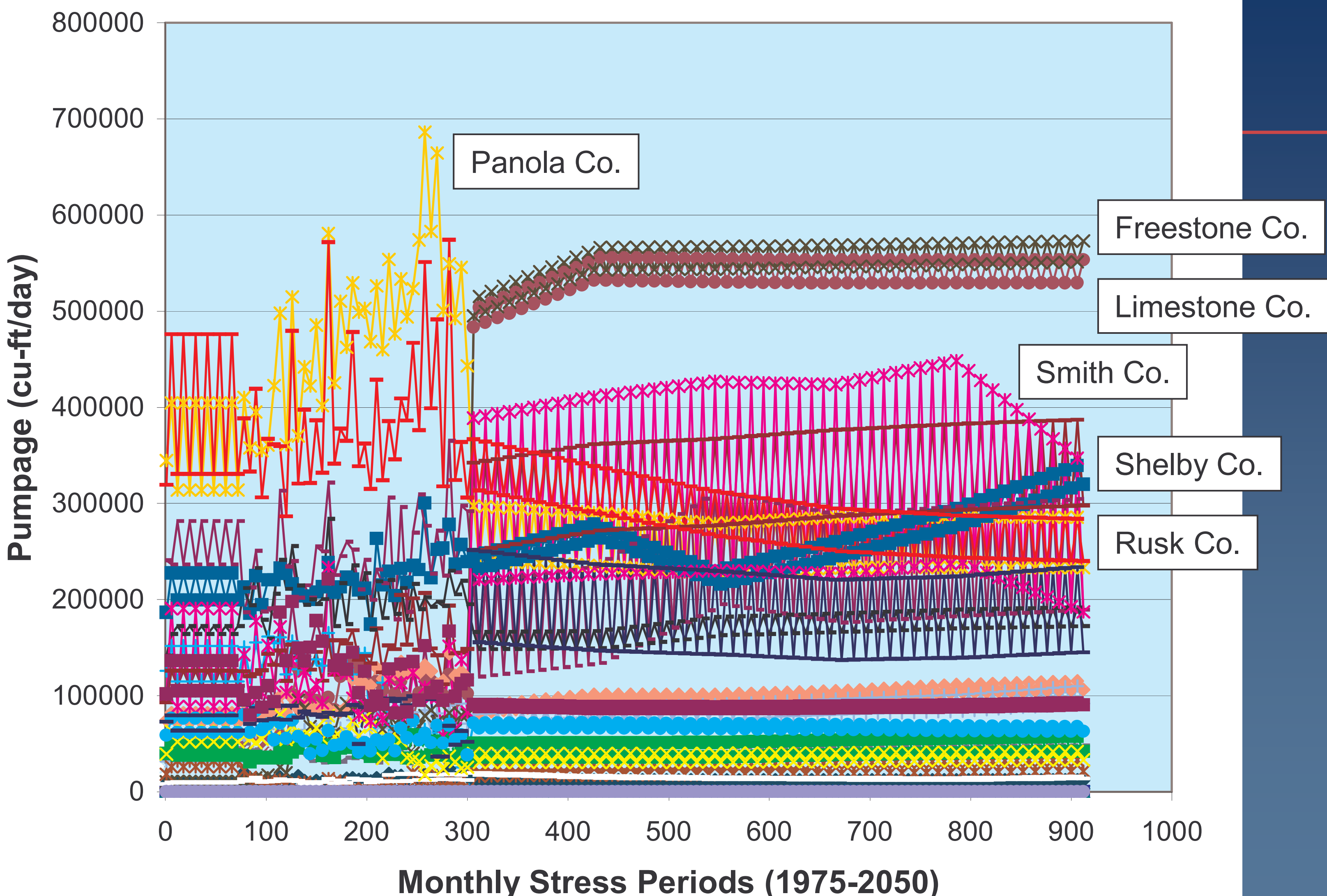
Drought of Record: 1950s



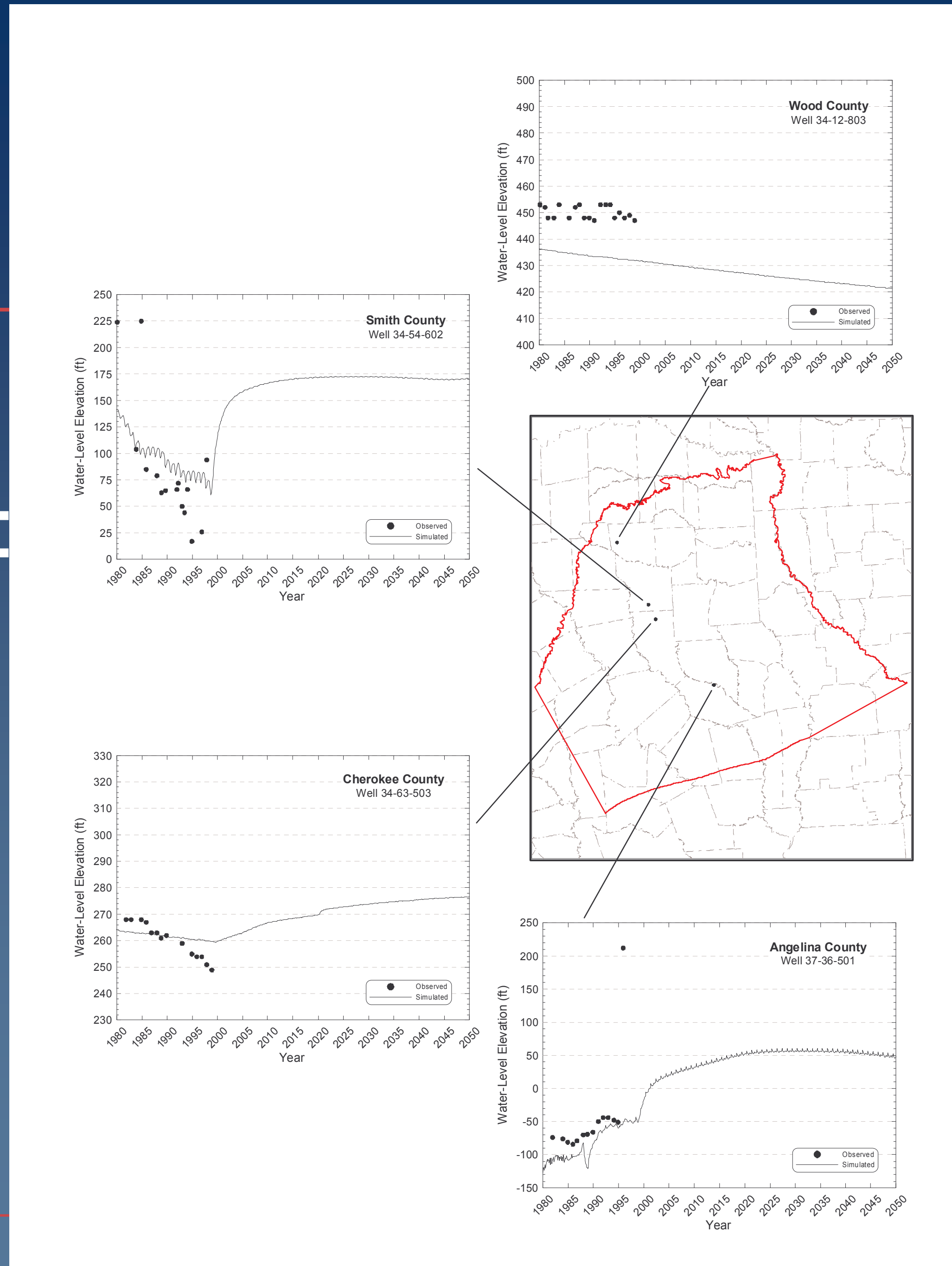

Pumpage in Layer 3
Pumpage (cu-ft/day)
2.5E+06
2.0E+06
1.5E+06
1.0E+06
5.0E+05
0.0E+00
0
100
200
300
400
500
600
700
800
900
1000
Monthly Stress Periods (1975-2050)
Angelina Co.
Nacogdoches Co.
Smith Co.
INTERA


Pumpage in Layer 4 (Upper Wilcox)
Pumpage (cu-ft/day)
1.6E+06
1.4E+06
1.2E+06
1.0E+06
8.0E+05
6.0E+05
4.0E+05
2.0E+05
0.0E+00
0
100
200
300
400
500
600
700
800
900
1000
Monthly Stress Periods (1975-2050)
Smith Co.
Angelina Co.
Nacogdoches Co.

Pumpage in Layer 5

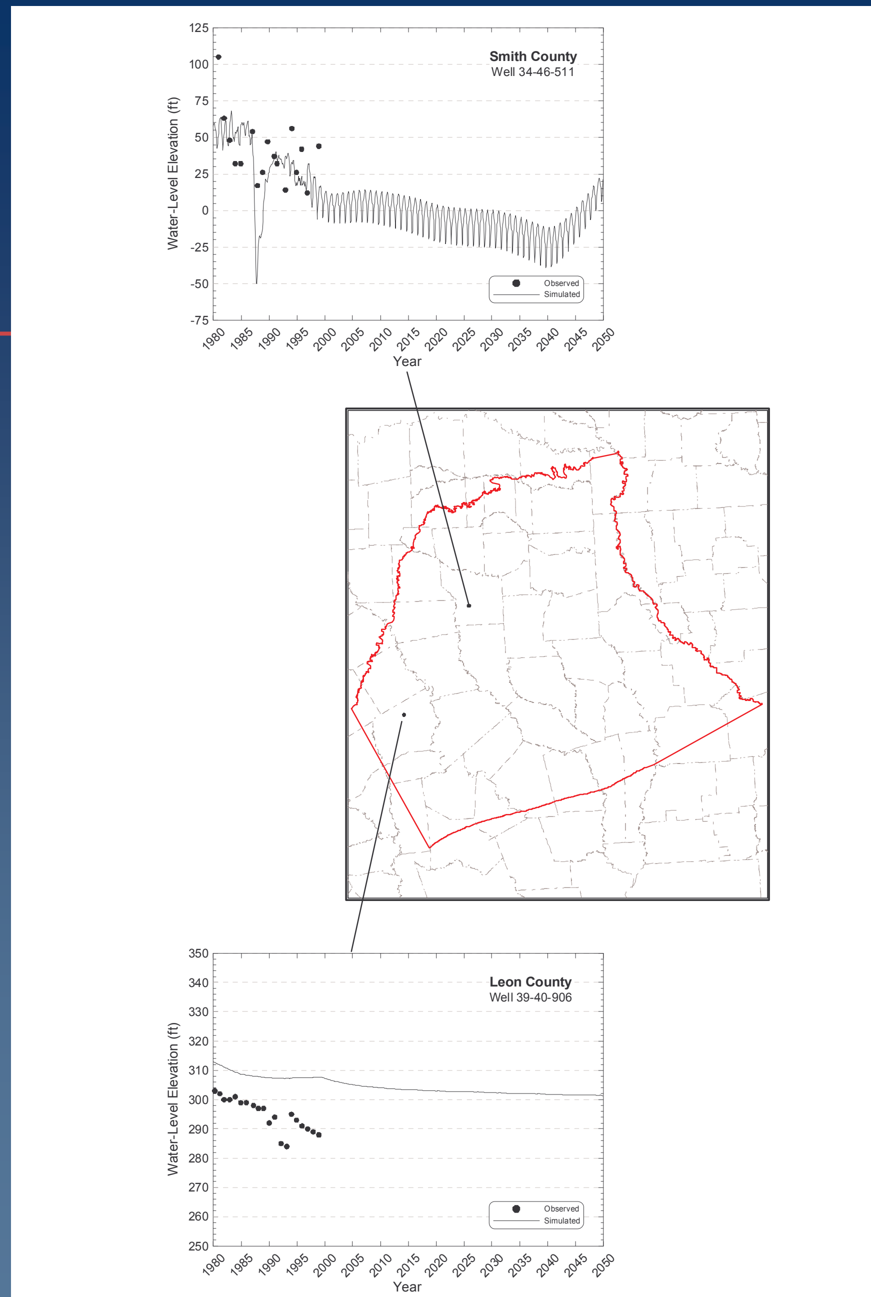


Predictive Simulations: Carrizo



INTERA

Predictive Simulations: Upper Wilcox



Conclusions

- GAM for Northern Carrizo-Wilcox Aquifer:
  - Incorporated all relevant features, data on aquifer properties, recharge estimates, and pumpage
  - Calibrated to specifications:
    - pre-development
    - transient conditions (1980-1989)
    - verified from (1990-1999)
  - Required some adjustment of properties during transient calibration (not beyond measured data)

Limitations & Applicability of the GAM

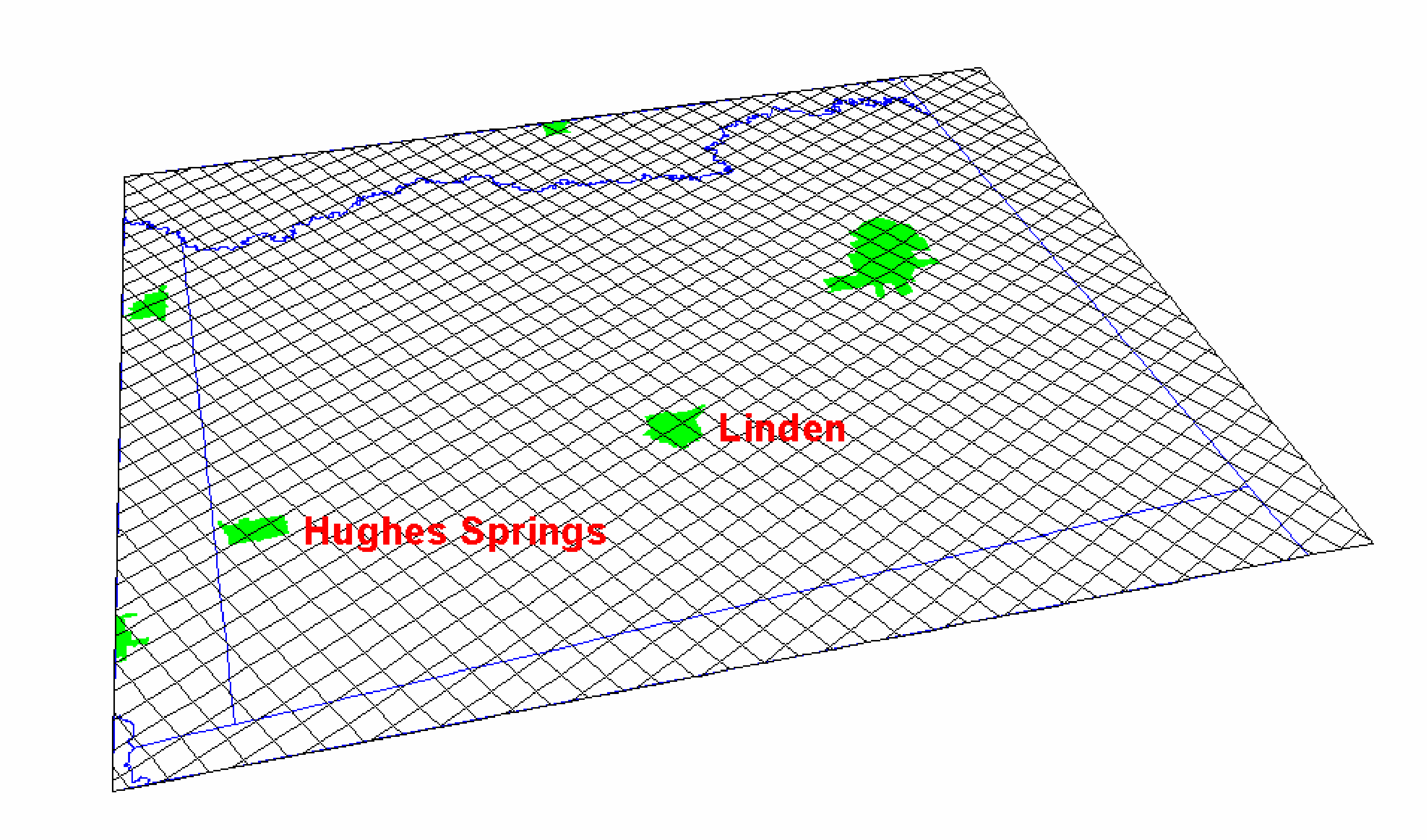
- The GAM is a tool capable of being used to make groundwater availability assessments on a regional scale
- The model is well suited for studying institutional water resource issues
- The model would likely require refinement to study operational issues for a specific project
- The GAM allows regional consideration of interference between resource strategies

Limitations & Applicability (cont.)

- The GAM scale of application is for areas of many square miles.
  - The GAM produces water levels representative of large volumes of aquifer (e.g., 5,280 ft X 5,280 ft X100 ft aquifer thickness)
- The GAM is not capable of predicting aquifer responses at particular point such as a particular well
  - The model is well suited for refinement to address local-scale, operational water resource questions.

INTERA

Model Grid Scale



Limitations & Applicability (cont.)

- The GAM model provides a first-order approach to coupling surface water to groundwater
  - The surface water portion of the GAM model is consistent with the GAM purpose and for the scale of application.
  - The GAM does not provide a rigorous solution to surface water flow and should not be used as a surface water modeling tool in isolation.