Groundwater Availability Modeling (GAM) for the Queen City and Sparta Aquifers

GAM Stakeholder Training

Austin, Texas

October 19, 2004

Workshop Agenda

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

Workshop Goals

- Provide an introduction to groundwater modeling, MODFLOW, and PMWIN
- Review the development of the Queen City and Sparta GAMs
- 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

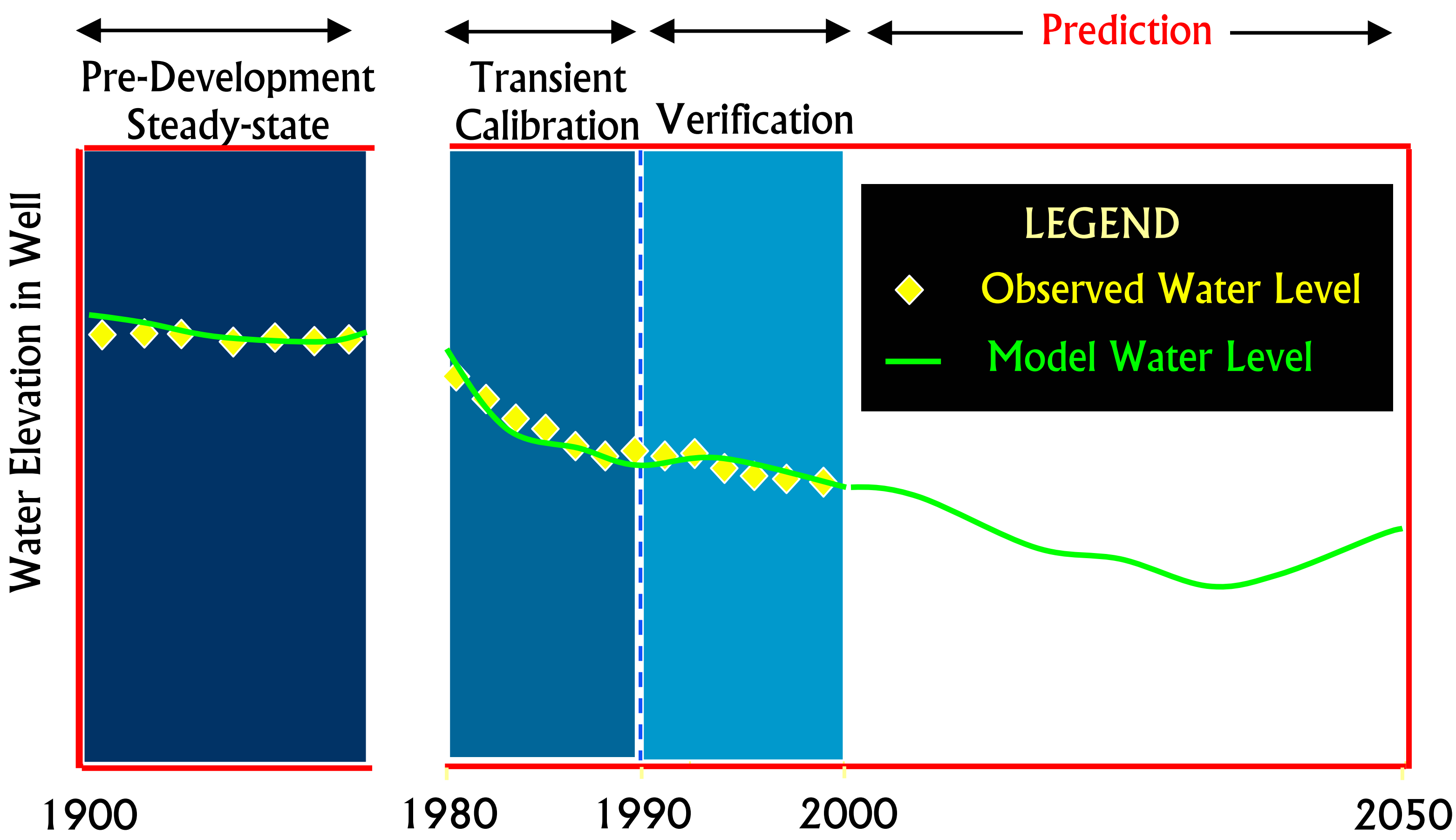
GAM Model Specifications

- Three dimensional (MODFLOW-96)
- Regional scale (1000's of mi^2)
- Grid spacing of 1 square mile
- Include Groundwater/surface water interaction (Stream routing, Prudic 1988)
- Physically-based implementation of recharge
- Stress periods as small as 1 month
- Calibrate to within 10% of head drop

Queen City-Sparta GAM Specifications

- **In addition to the generic GAM specifications, the Queen City and Sparta GAMs have additional specifications:**
  - The Queen City and Sparta aquifer GAMs have been incorporated into the current Carrizo-Wilcox GAMs
  - The product will be delivered as three models (southern, central, and northern regions) at the end of this month
  - One modeling report will be produced

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

Bankes (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.)

Bredehoeft 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

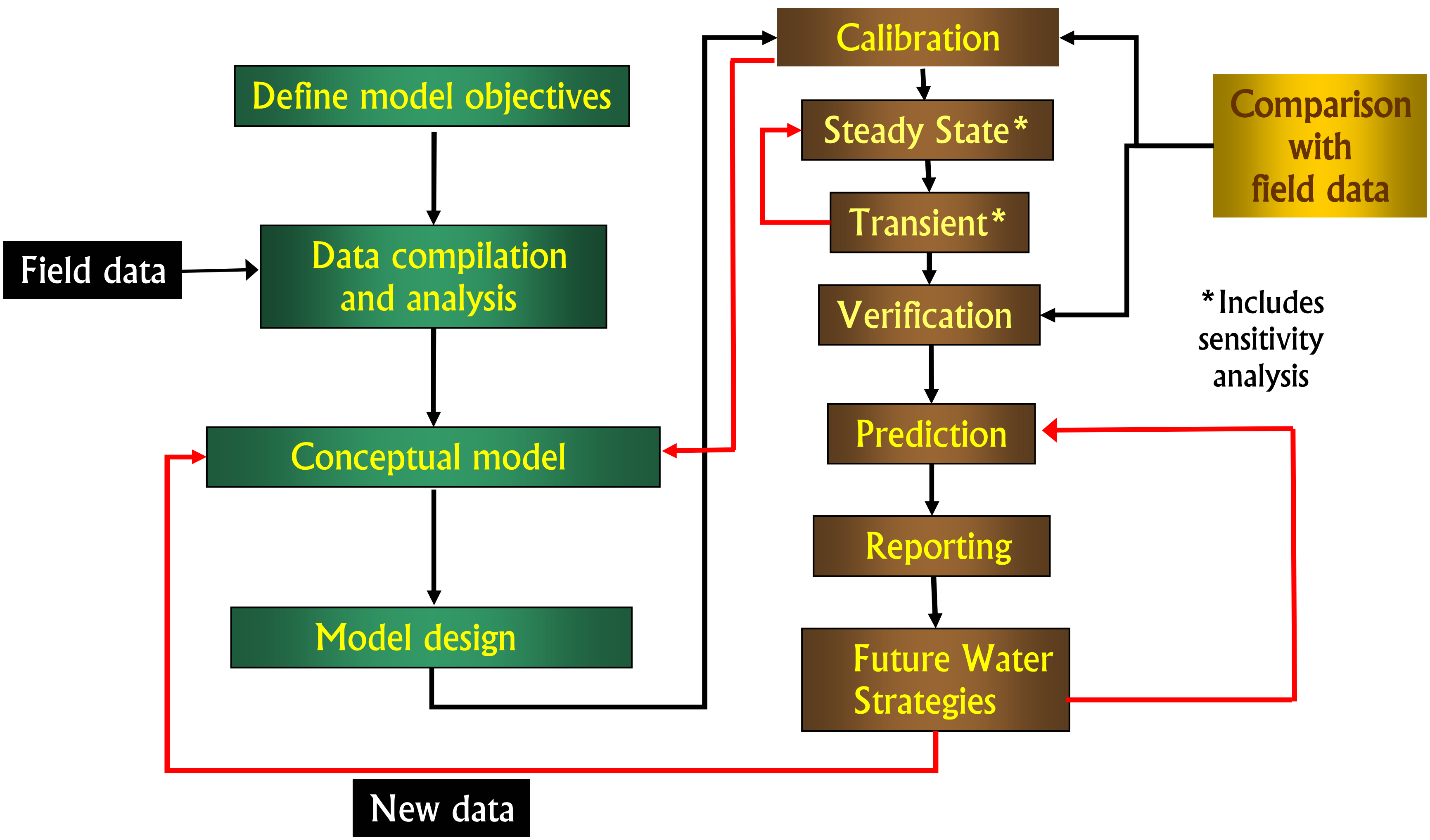
GW Models have been used in water resources in response to 4 basic issues.

- 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



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

Code Selection

- **Things to be considered:**
  - Simulates Relevant Physical/Chemical Processes
  - Public-Domain vs. Proprietary
  - Thorough Testing for Intended Use
  - Complete Documentation

Model Design

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

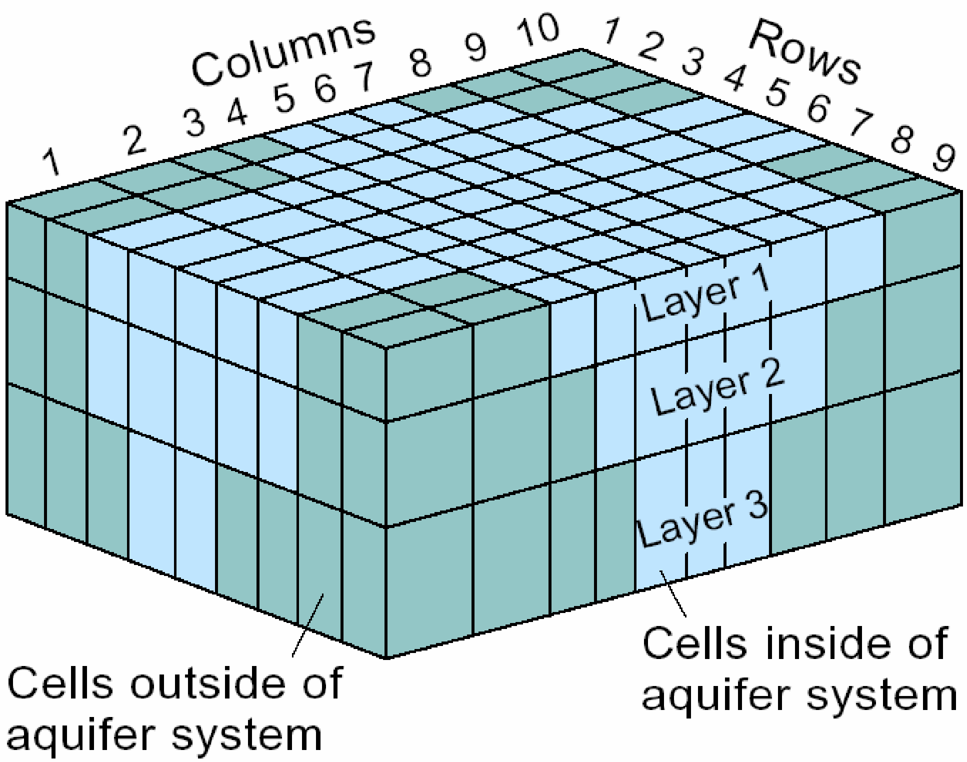
Grid Design – Typical Drivers

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

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 up to 1 mile square

Model Grid Example



Source: USGS Fact Sheet FS-127-97

Model Inputs

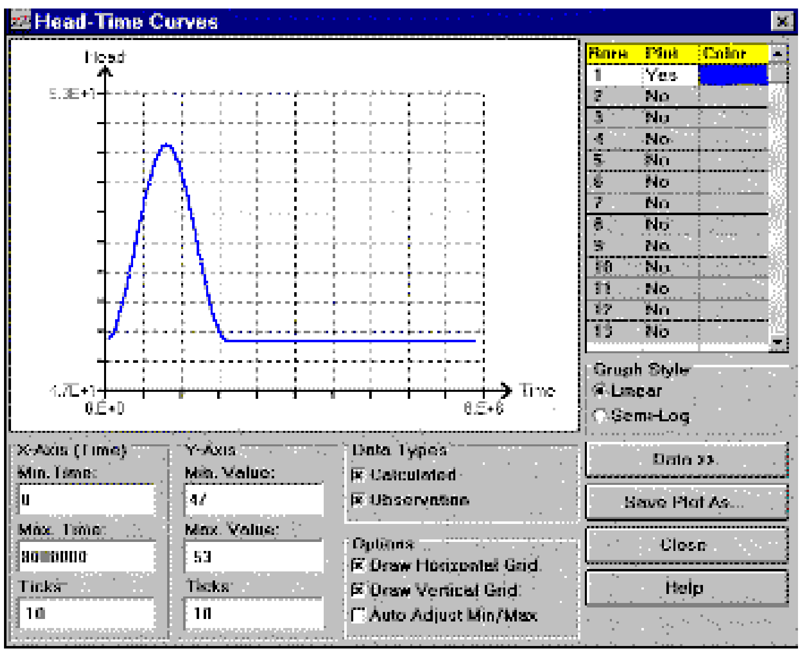
- Hydrostratigraphic Surfaces for each Layer
- Hydraulic Properties:
  - Hydraulic Conductivity
  - Storativity (transient)
- Hydraulic heads
- Recharge
- Stream Flow (headwater flows, initial C)
- Pumpage

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

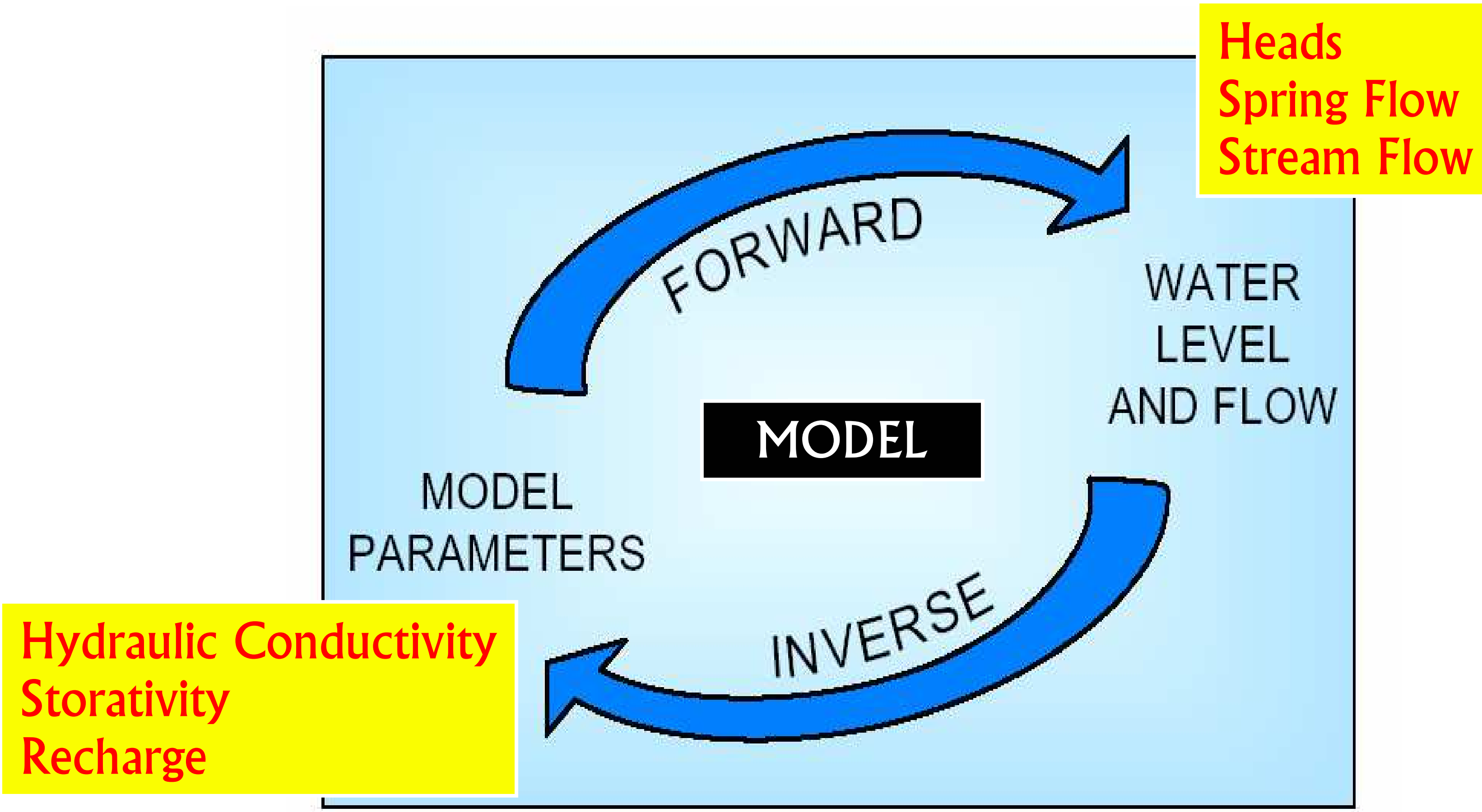
Boundary Conditions

- **Boundary conditions may be static or transient**



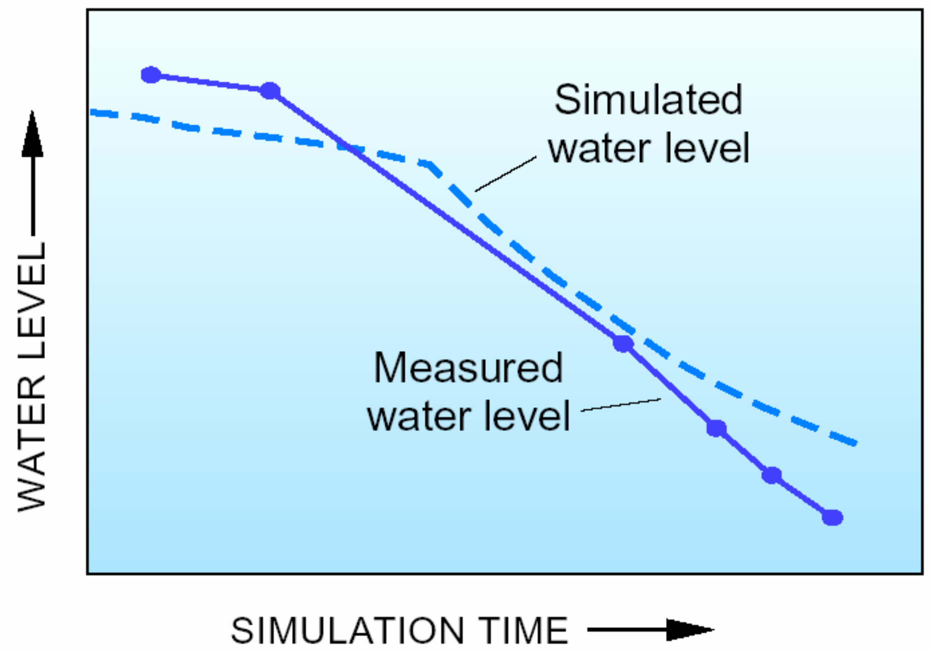
- **Recharge or wells – Specified flow**
- **GHB, Reservoir, Stream – Head dependent flow**
- **Vertical or lower boundaries – specified flow @ zero = no flow**

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 (heads, stream flows, spring flows)
  - Select Calibration Metrics
  - Adjust Boundary Conditions/Properties
  - Analyze Errors (ME, RMS)

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

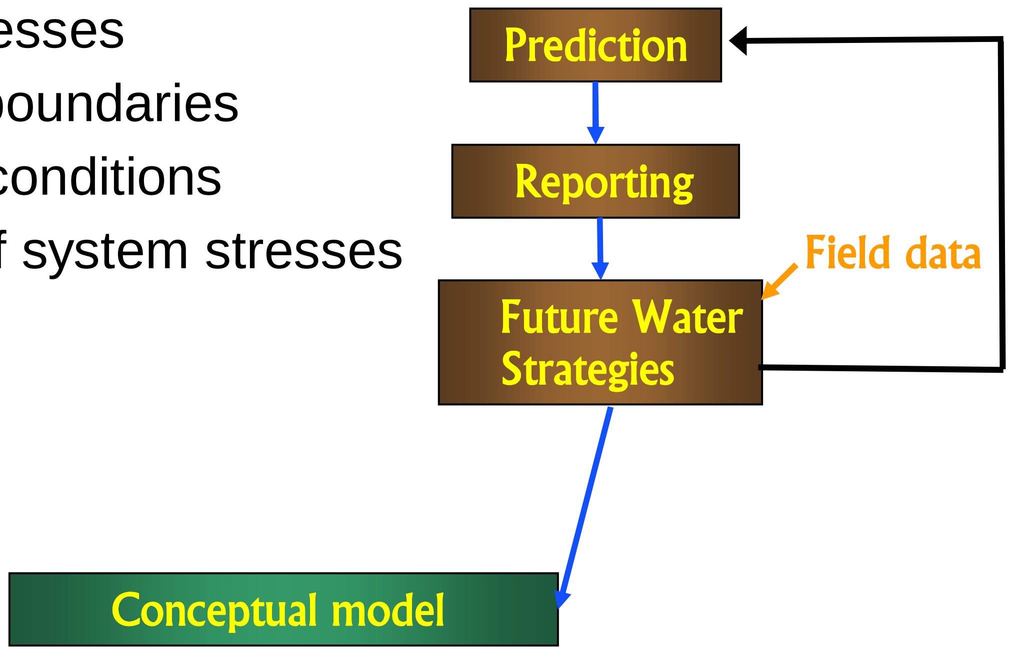
- **A sensitivity analysis is a formal means of quantifying the effect of changes in model inputs on model outputs**
- **Provides a means of identifying parameters which are:**
  - Important to model response
  - Correlated - identifiable
- **Most common method is the one-off-method**

Verification (Validation)

- **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**

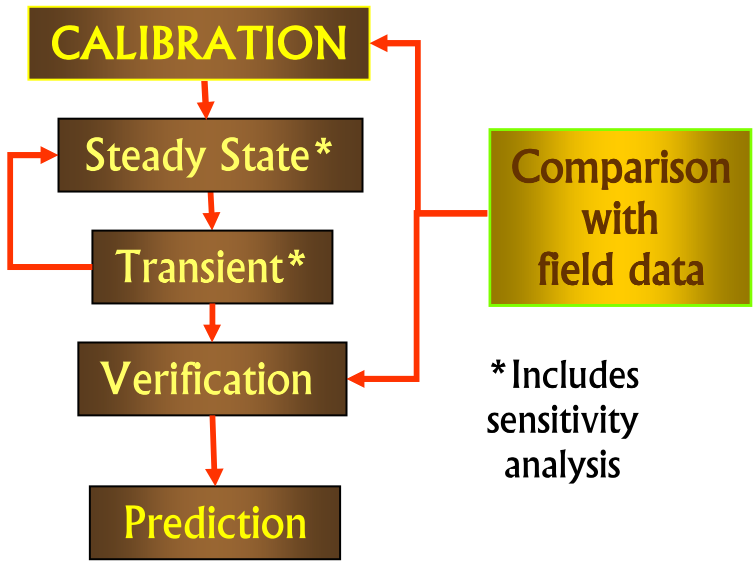
Model Uniqueness (Similarity Solutions)

- **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



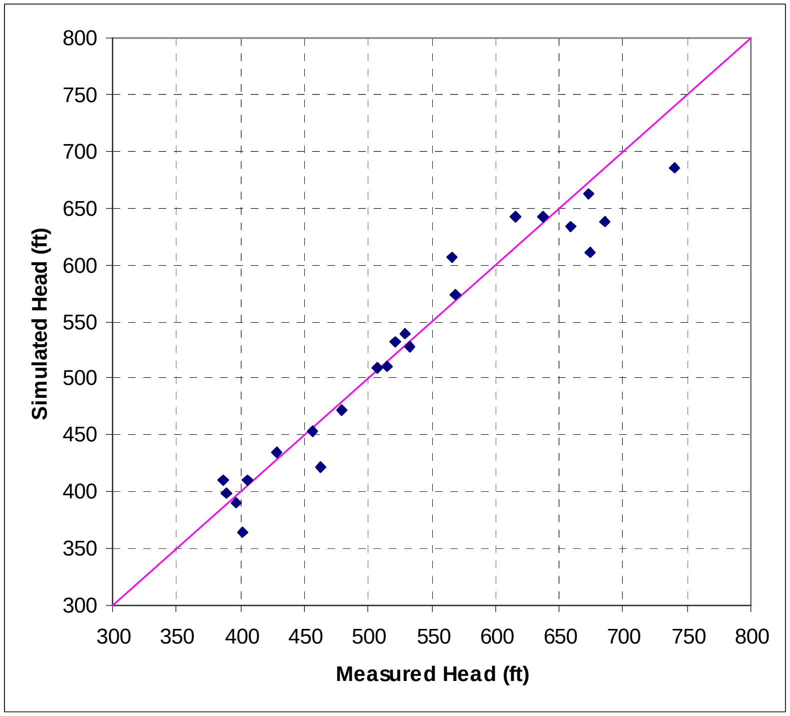
The calibration approach iterates between the steady-state and the transient calibrations to reach a consistent set of physical parameters that match both sets of observation.

(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 result in difficulties**

(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

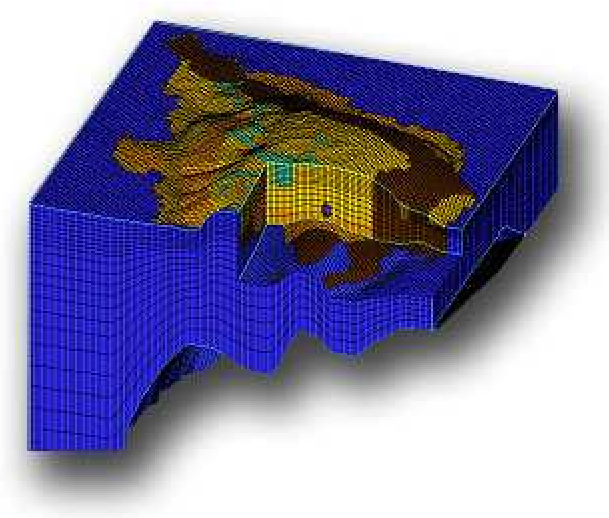
- **One must strive to not over-calibrate (tweak) a model; that is:**
  - Over parameterize lacking data support
  - Adjust parameters to bring model agreement below performance measure uncertainty
  - In the GAM model, head is the primary performance measure and we have estimated errors associated with heads to be on the order of 30-40 feet
    - Therefore, happy with RMS between 30 and 40 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

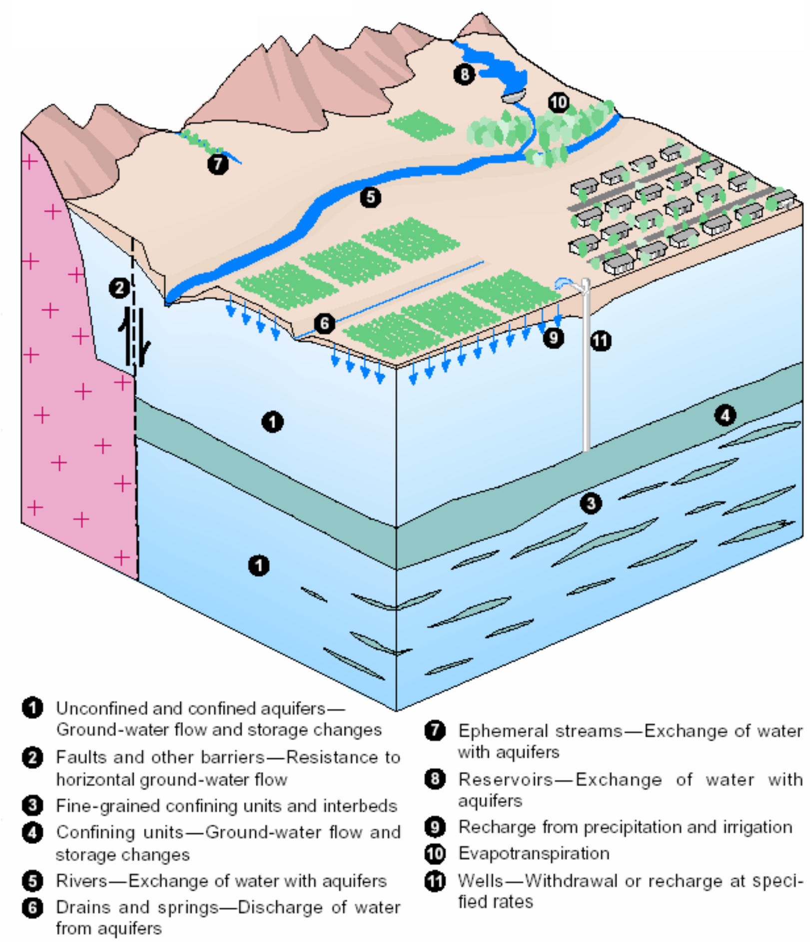
- **Original Packages (88)**
  - Basic
  - Block-Centered Flow
  - Recharge
  - Evapotranspiration
  - River
  - Well
  - Drain
  - General Head Boundary
  - Output Control
  - SIP/SOR Solvers
- **Add on Packages (96..)**
  - Block-Centered Flow 2 .. 6
  - PCG/PCG2 Solvers
  - Horizontal Flow Barrier (HFB)
  - Compaction (IBS)
  - Time-variant C.H. (CHD)
  - Stream Routing (STR)
  - Transient Leakage (TLK)
  - Direct solver (DE4)
  - GMG Solver (2000)
  - 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**

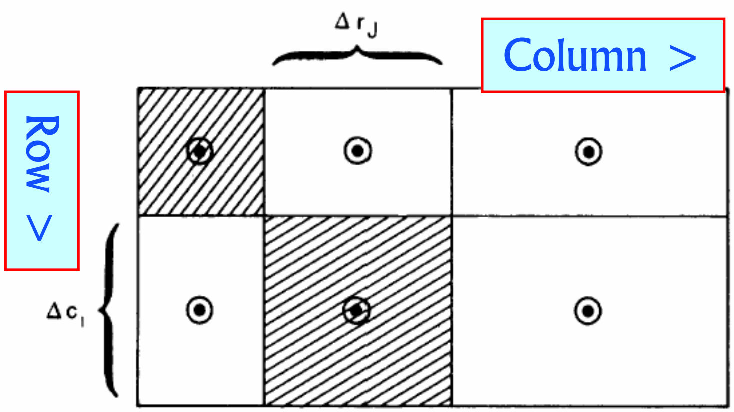
MODFLOW Processes



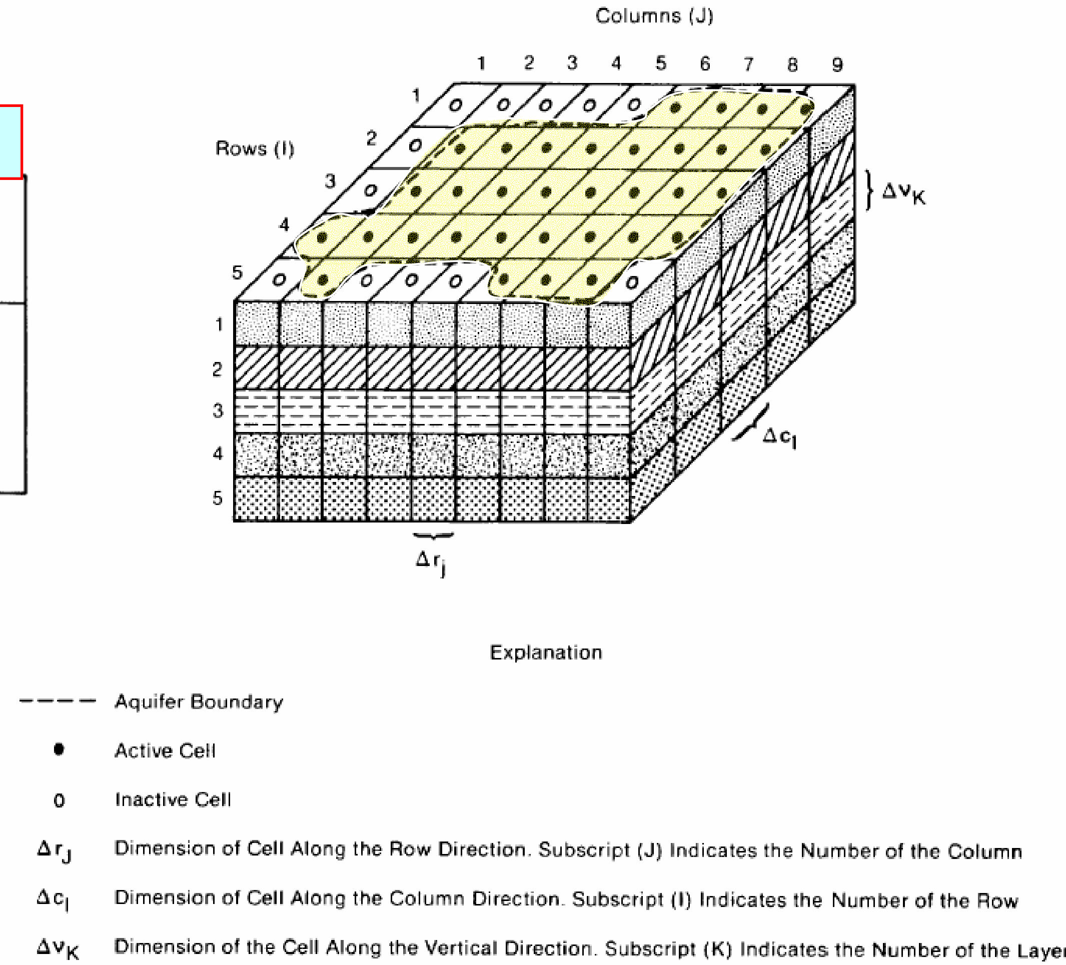
Source: USGS Fact Sheet FS-127-97

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

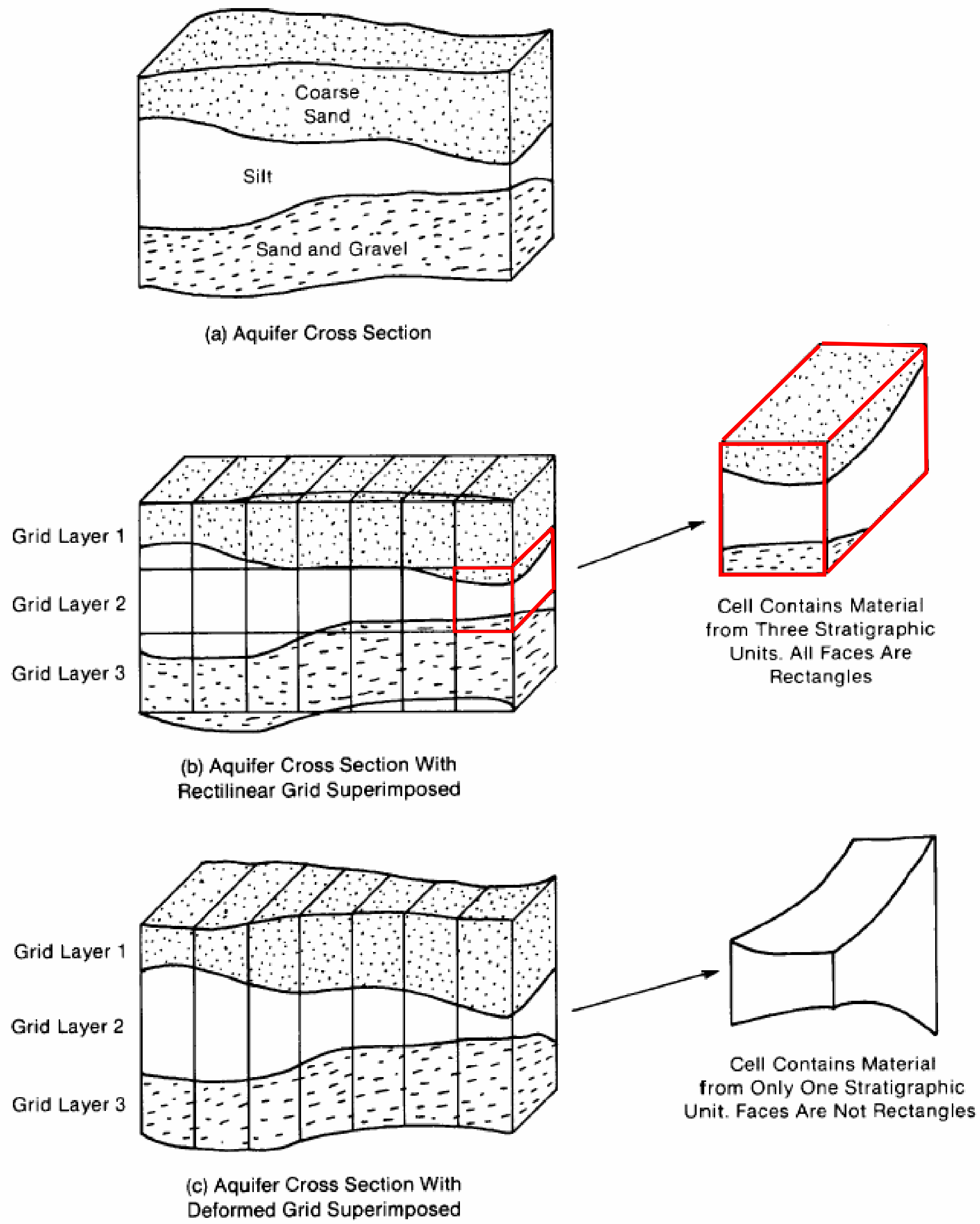
Example of a MODFLOW Grid
Note – Regular Grid



Block-Centered Grid System



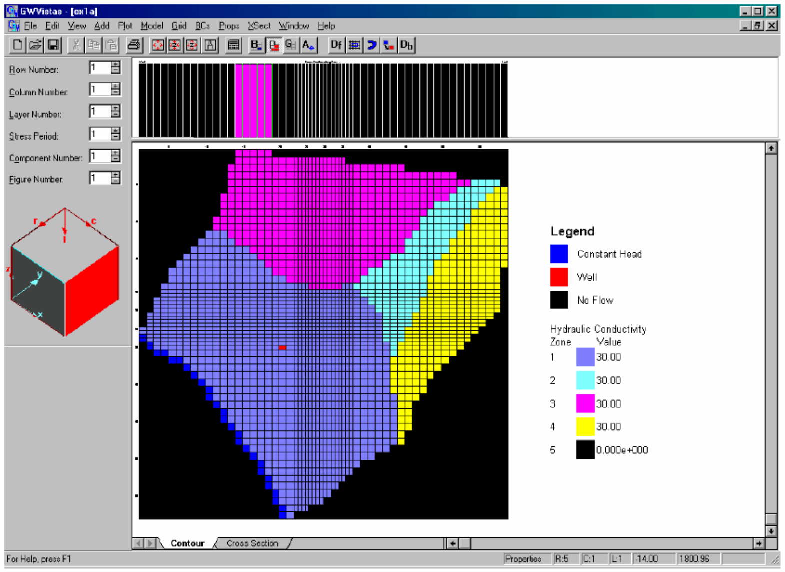
After McDonald & Harbaugh, 1988



Vertical Discretization
Should have physical significance

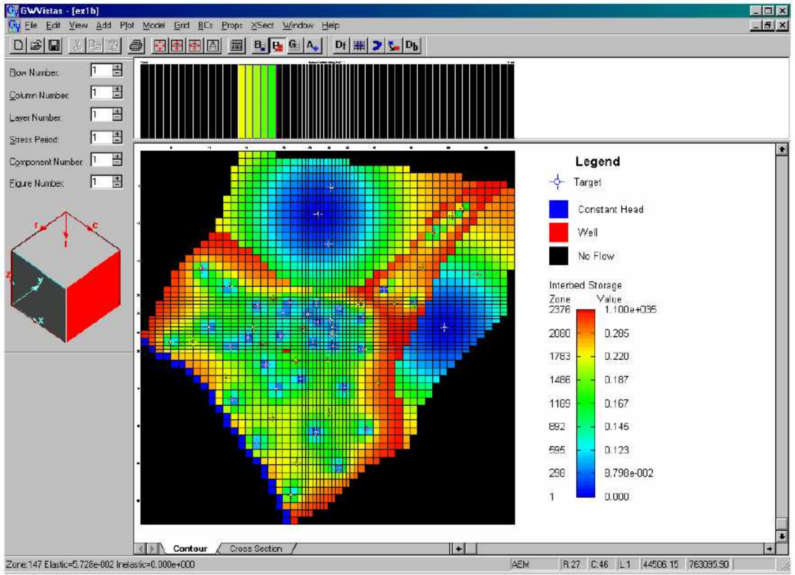
After McDonald & Harbaugh, 1988

Assignment of Properties

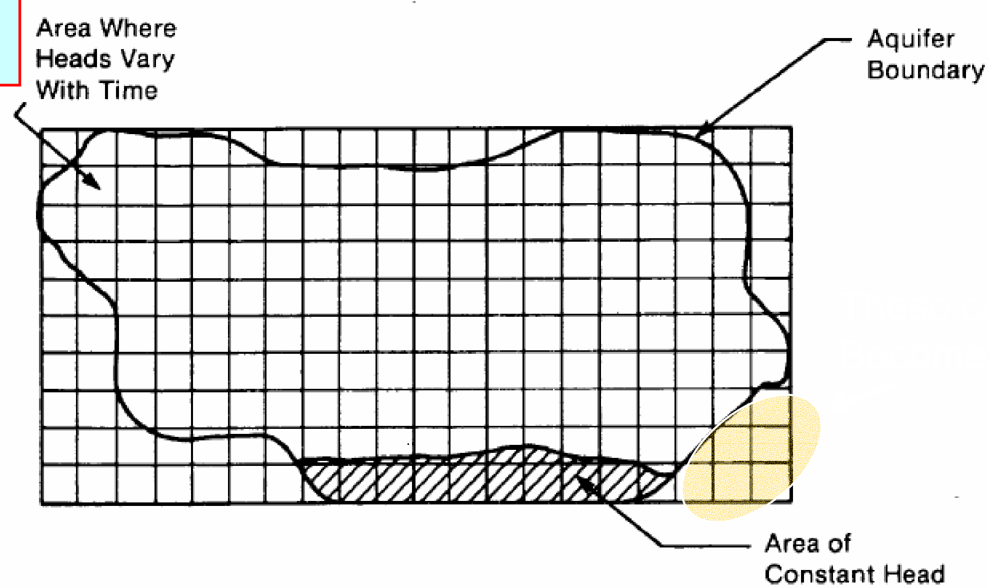


Properties can be assigned in zones as above

Properties can be assigned on a grid Cell basis as below



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

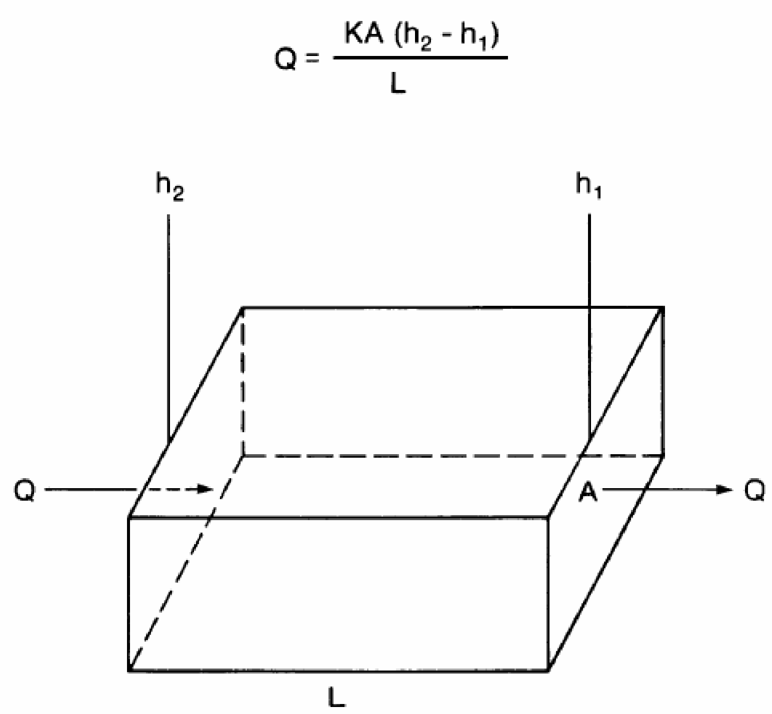
< 0 Constant Head
$= 0$ No Flow
> 0 Variable Head

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 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

$$\boxed{Q = C\,(h2 - h1)}$$

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

$$\boxed{C = K\,A\,/\,L}$$

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**

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

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

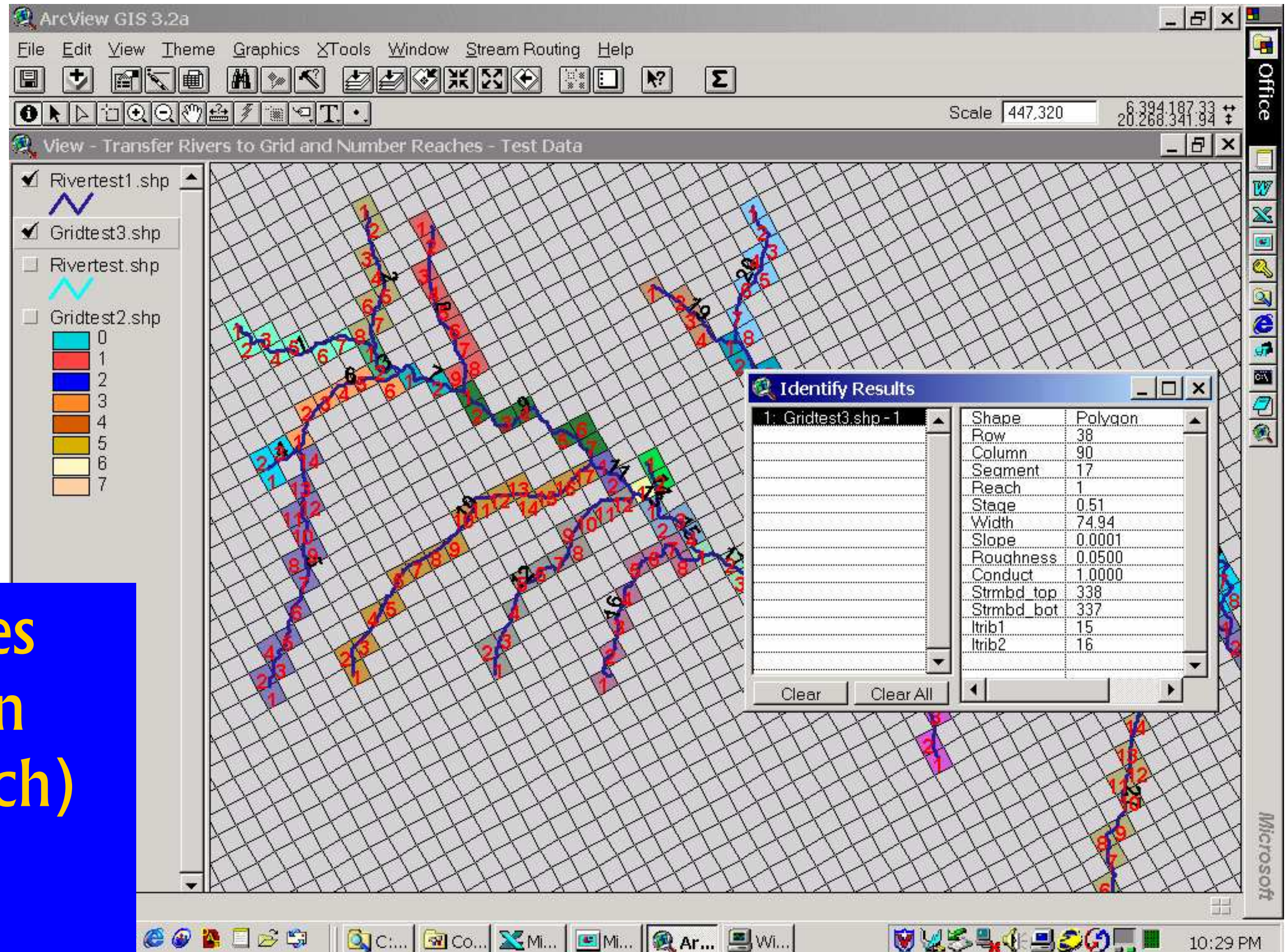
Wells in MODFLOW96

- **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 to 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

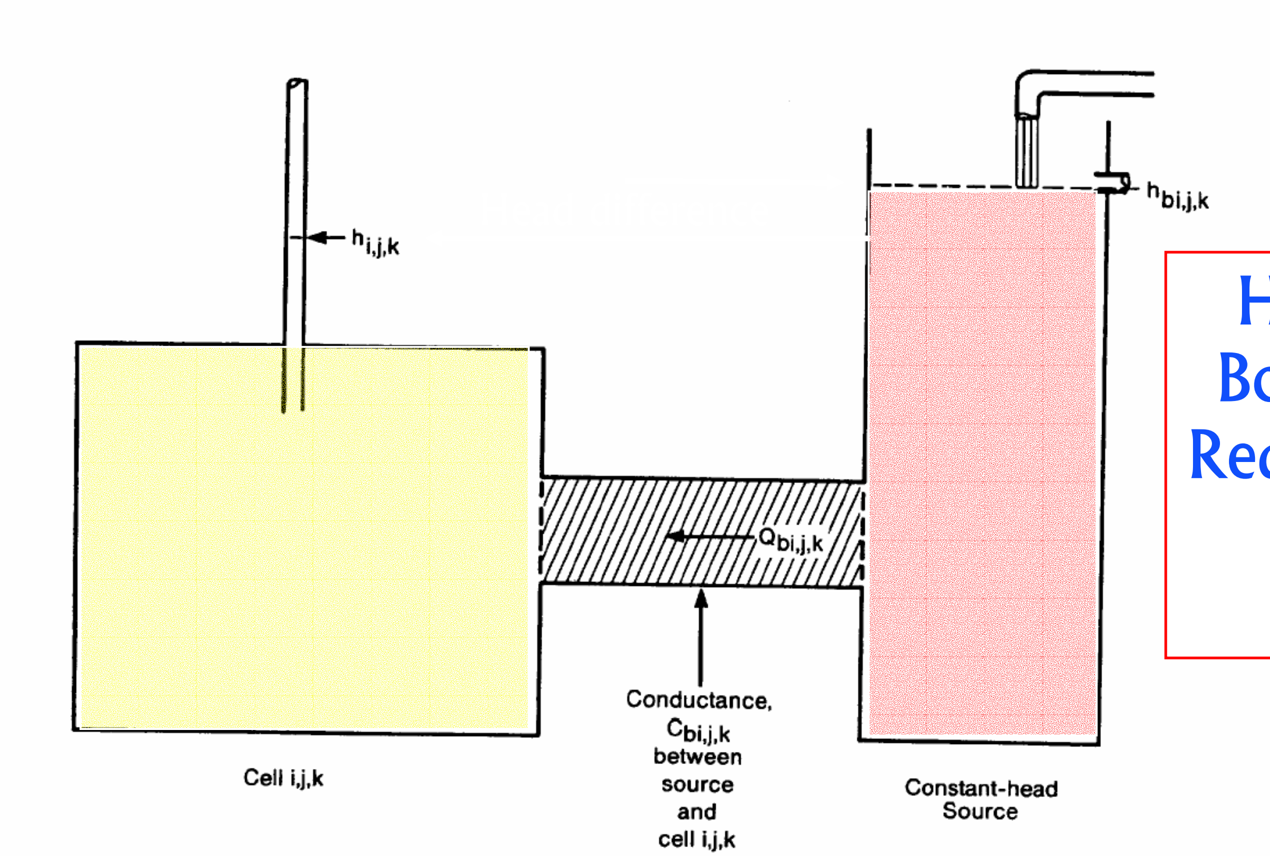


Stream reaches (each cell is an individual reach) and segments must be numbered

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)**

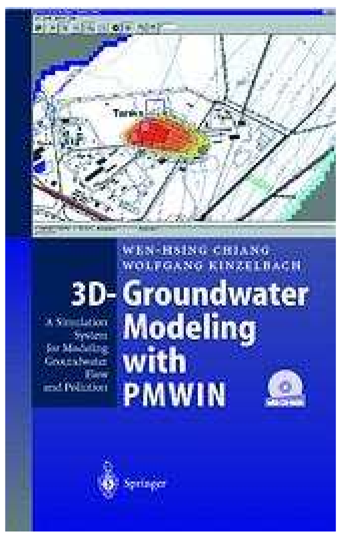
MODFLOW Interfaces

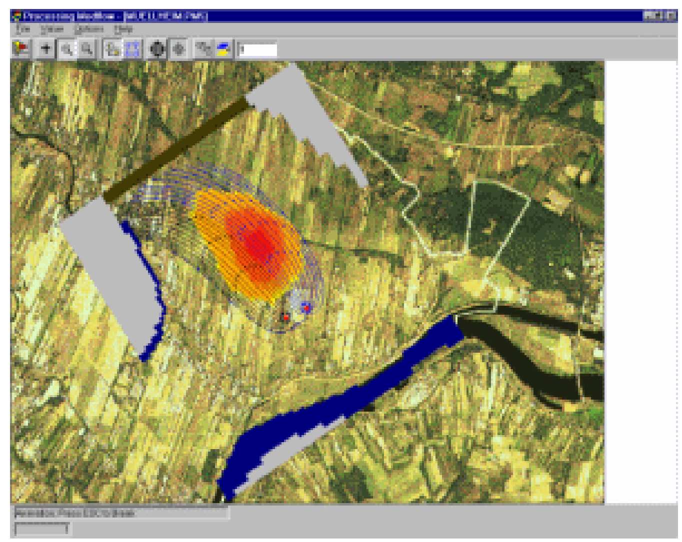
- **PMWIN**
  - Academic, commercially available
- **Groundwater Modeling System (GMS)**
  - DOD, commercially available
- **GWVistas**
  - Private, commercially available
- **Visual MODFLOW**
  - Private, commercially available

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/publications/software/pmwin/index_EN

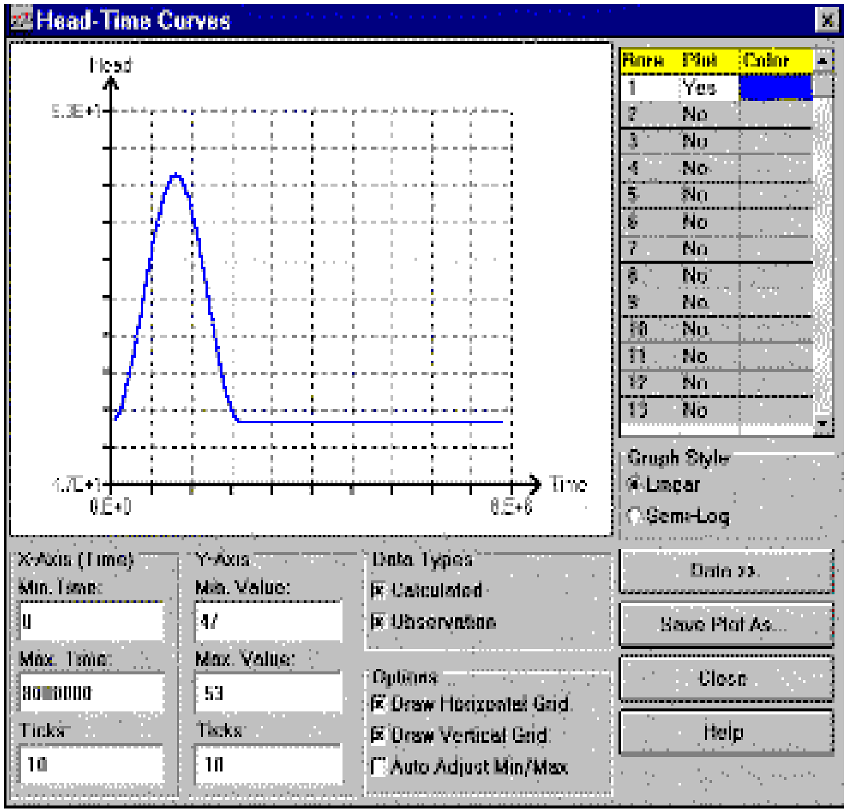
PMWIN

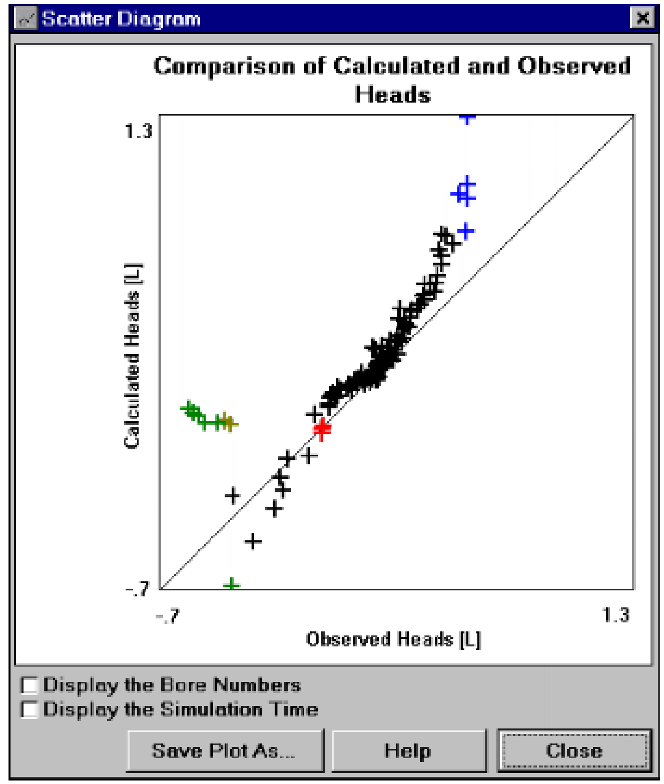
- **Offers a Windows based interface for developing MODFLOW models and for using the family of MODFLOW codes**
- **Imports existing standard MODFLOW models**
- **Supports all standard packages**
- **Allows many options for data input through raster graphics (bitmap), vector graphics (DXF)**
- **Imports 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

PMWIN Interface





Queen City and Sparta GAM Review

- Technical Overview
  - Emphasis on Data and Model Inputs

Queen City-Sparta GAM Specifications

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  - The Queen City and Sparta aquifer GAMs will be incorporated into the current Carrizo-Wilcox GAMs
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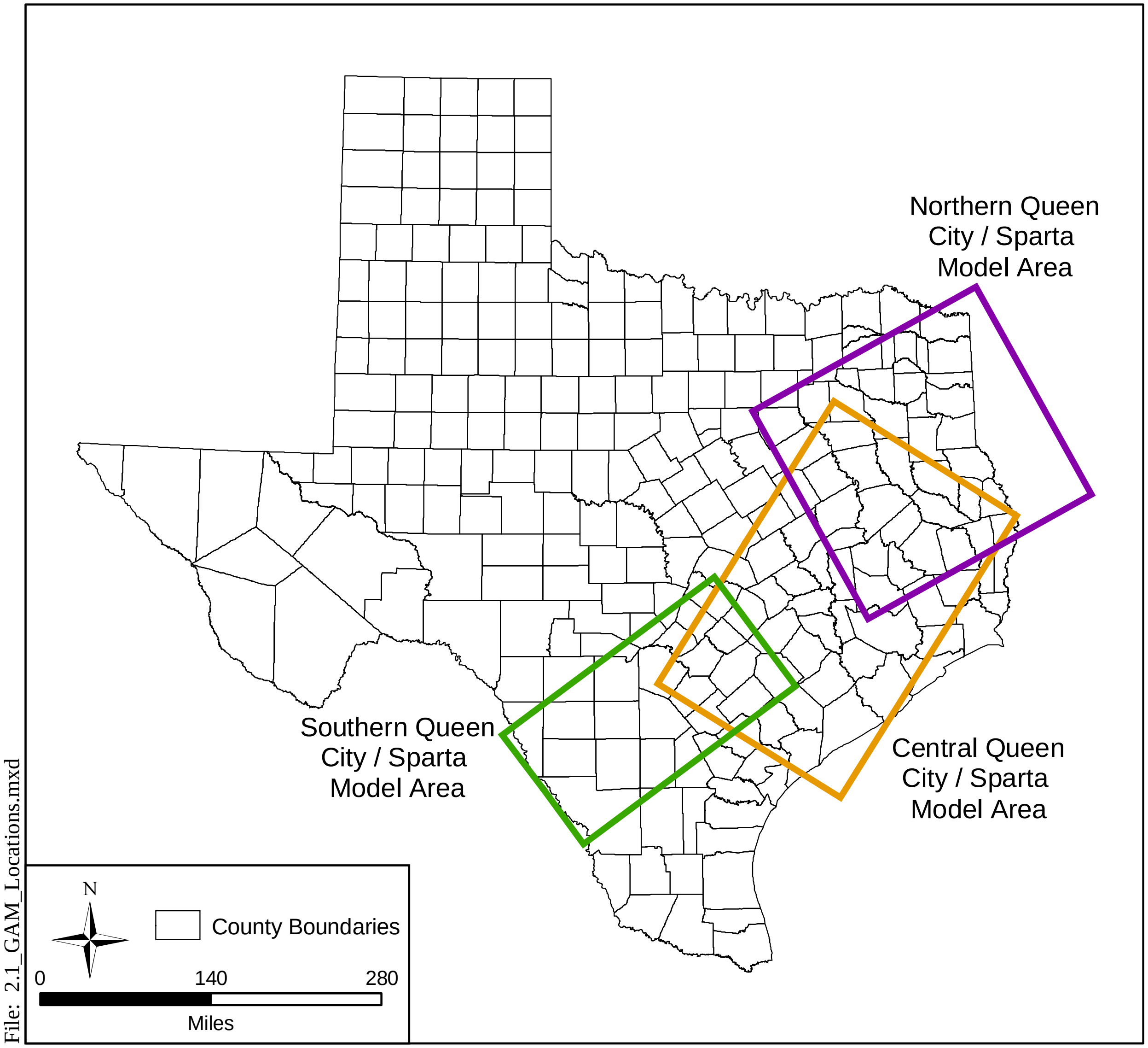
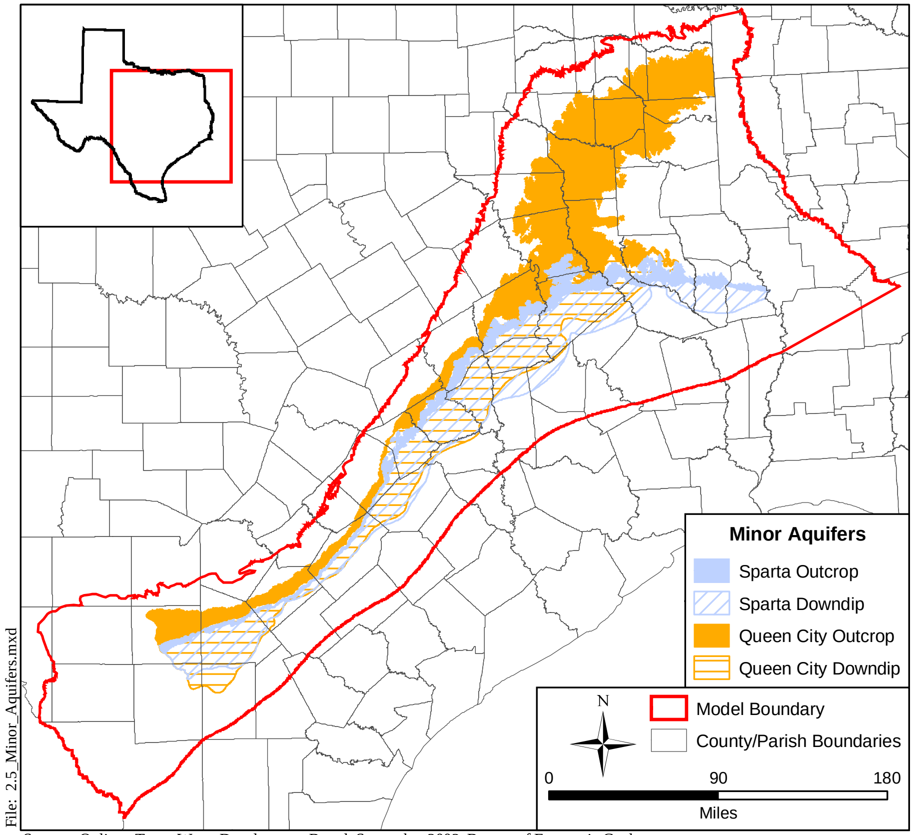
Model Area

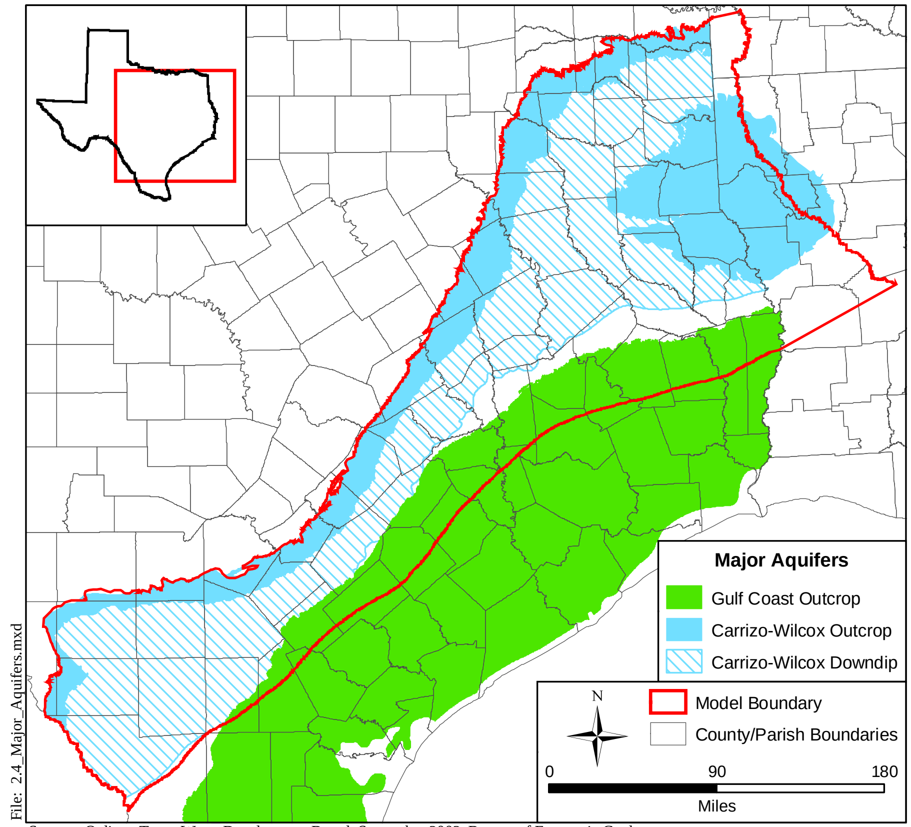


Source: N/A

Minor and Major Aquifers

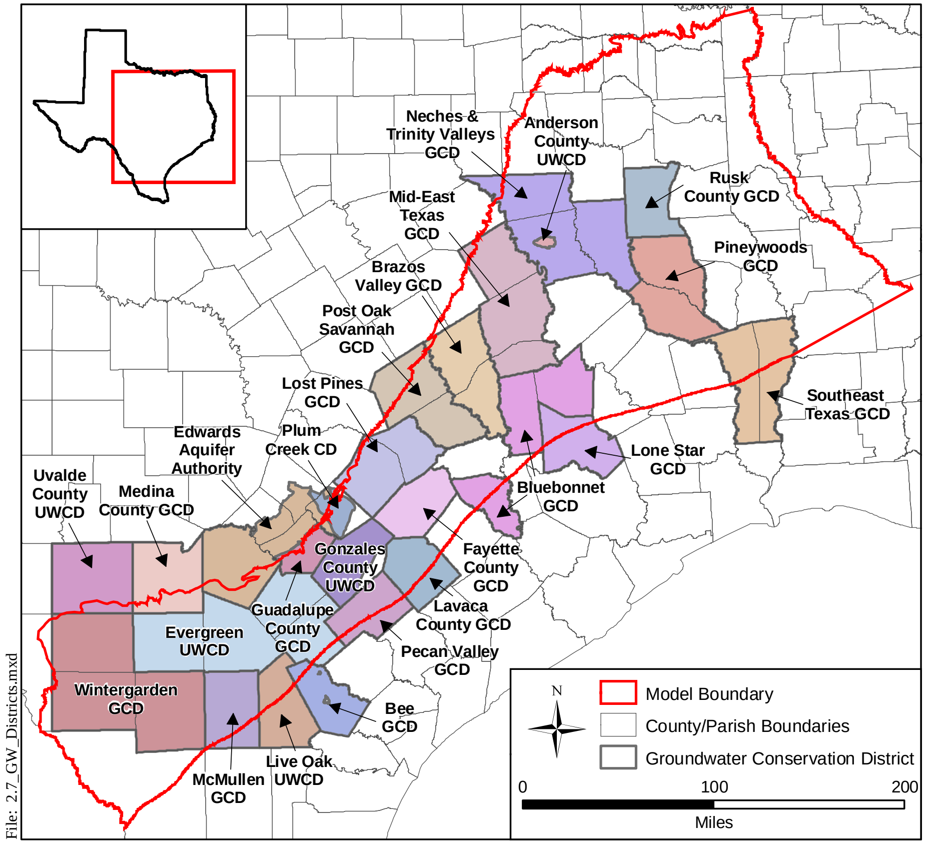


Source: Online: Texas Water Development Board, September 2002, Bureau of Economic Geology

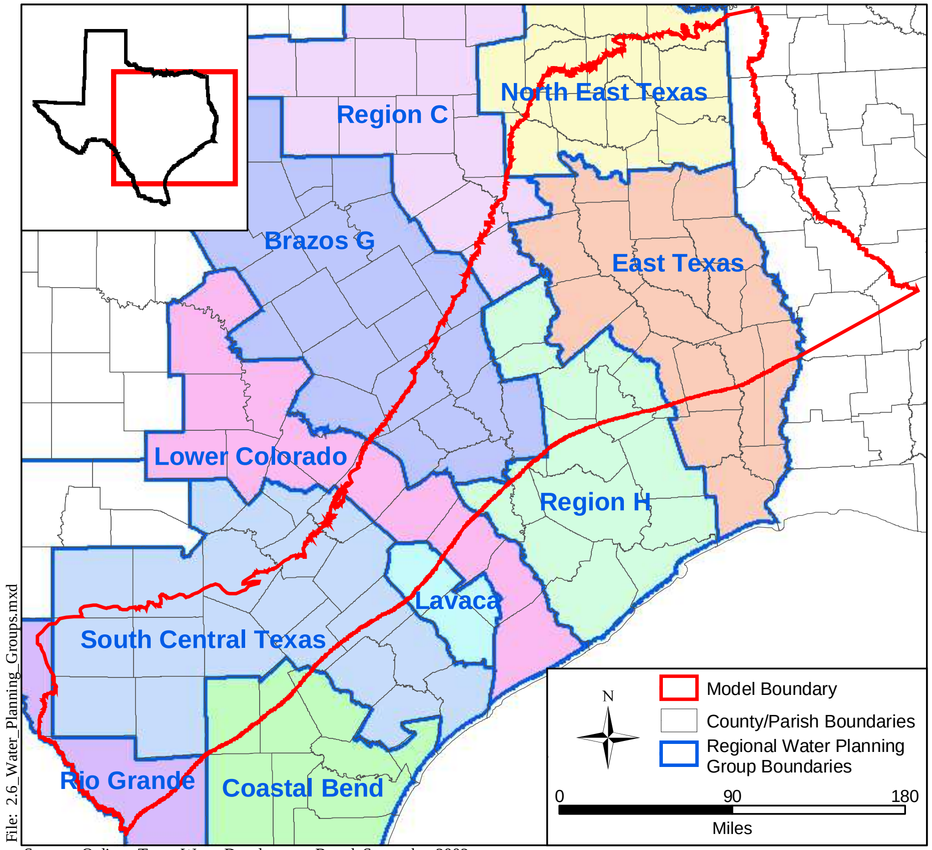


Source: Online: Texas Water Development Board, September 2002, Bureau of Economic Geology

UWCDs, GCDs, and RWPGs

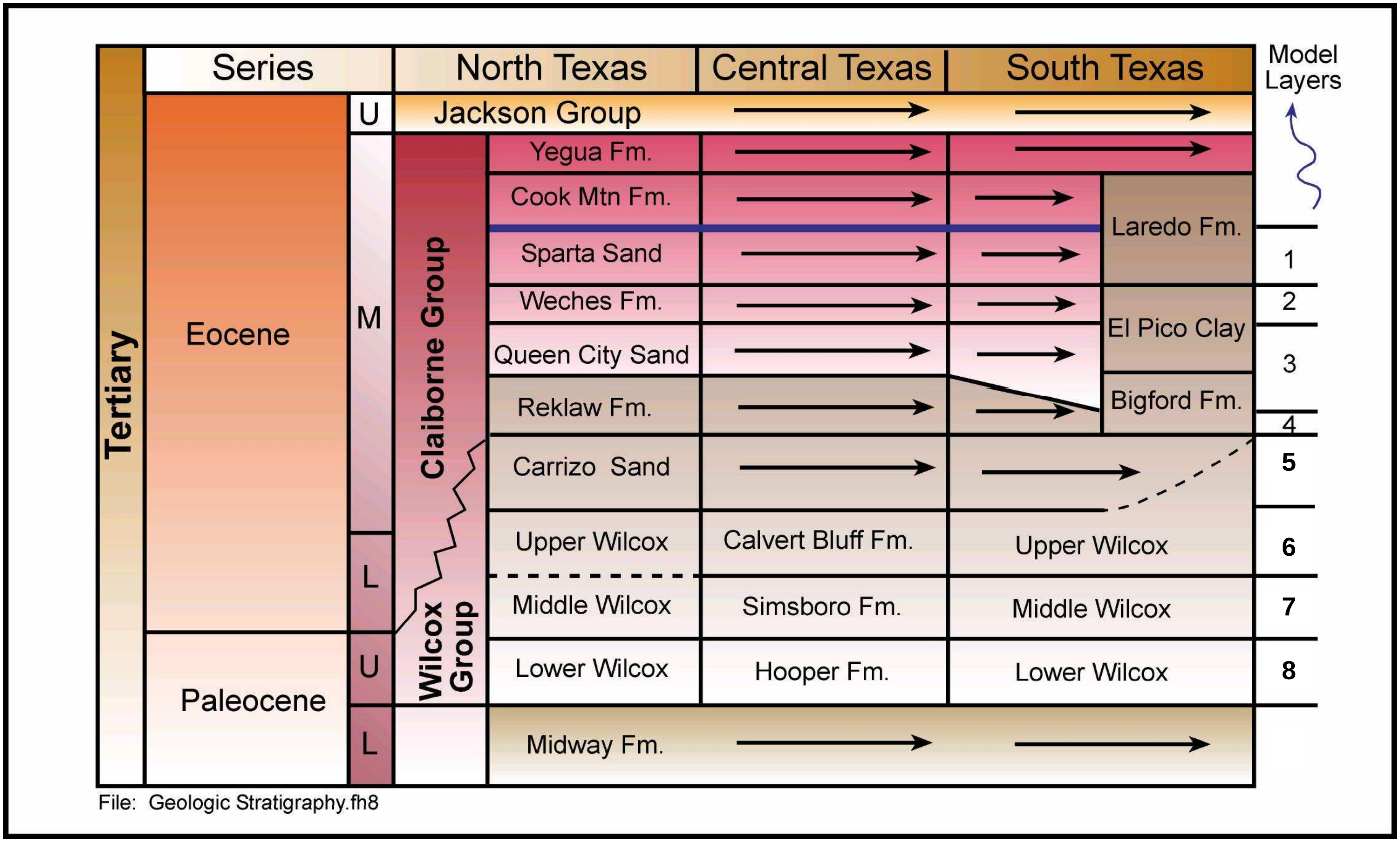


Source: Online: Texas Water Development Board, June 8, 2004



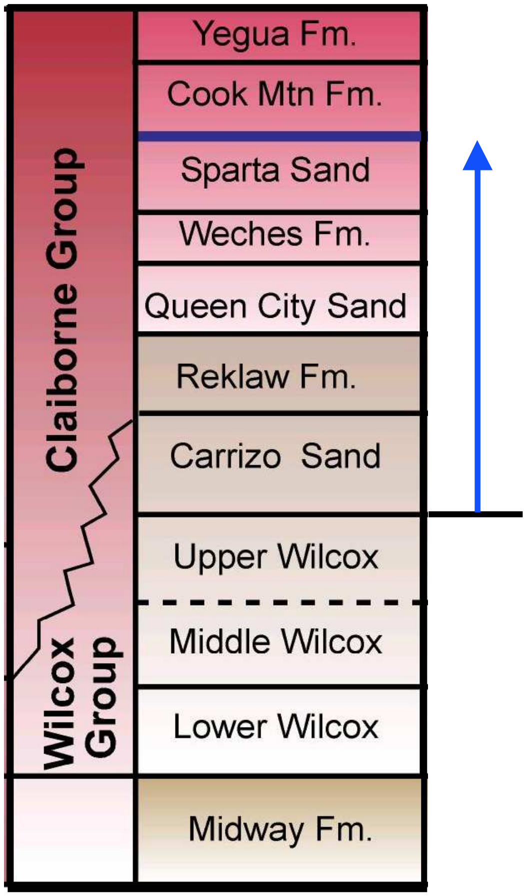
Source: Online: Texas Water Development Board, September 2002

Model Stratigraphy



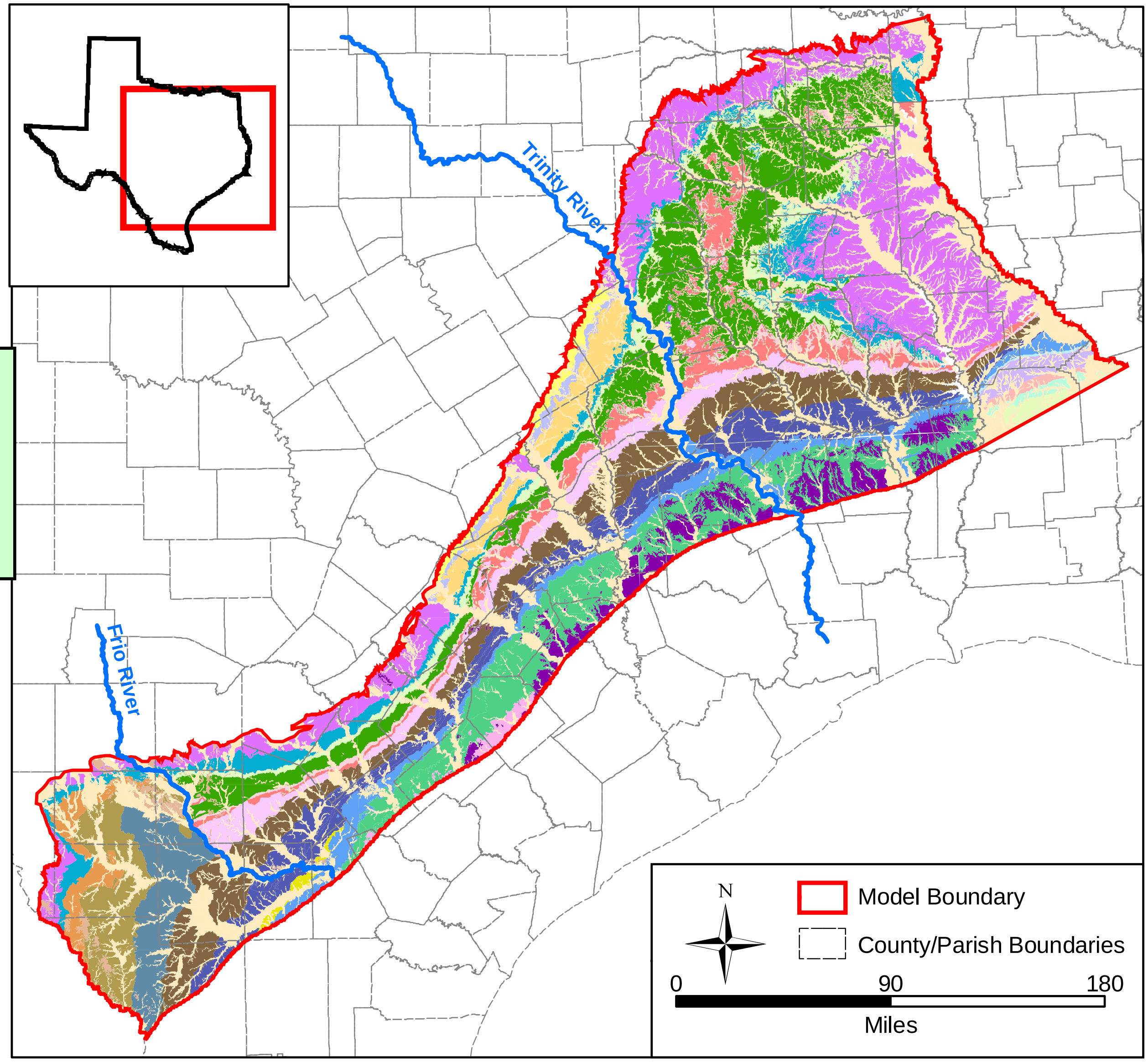
Queen City-Sparta GAM Specifications

- Original scope: Carrizo-Wilcox GAMs will be modified only as needed to properly add the Queen City and Sparta aquifers and recalibrate the entire model
- Revised scope: The Carrizo-Wilcox GAMs will be modified to be consistent in the overlap zones from the base of the Carrizo through the Sparta aquifer



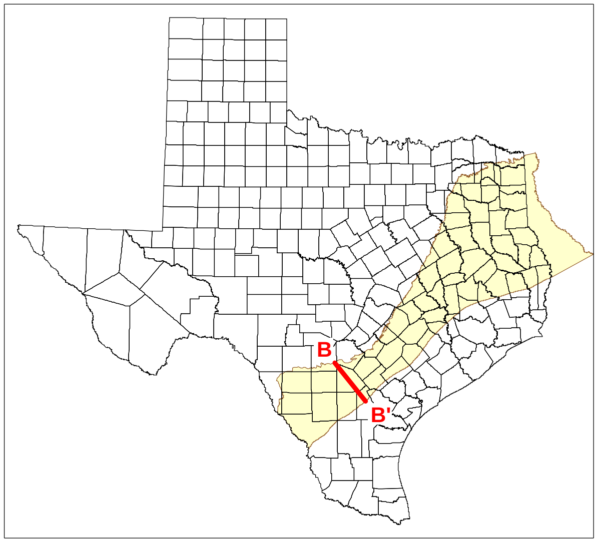
Geology

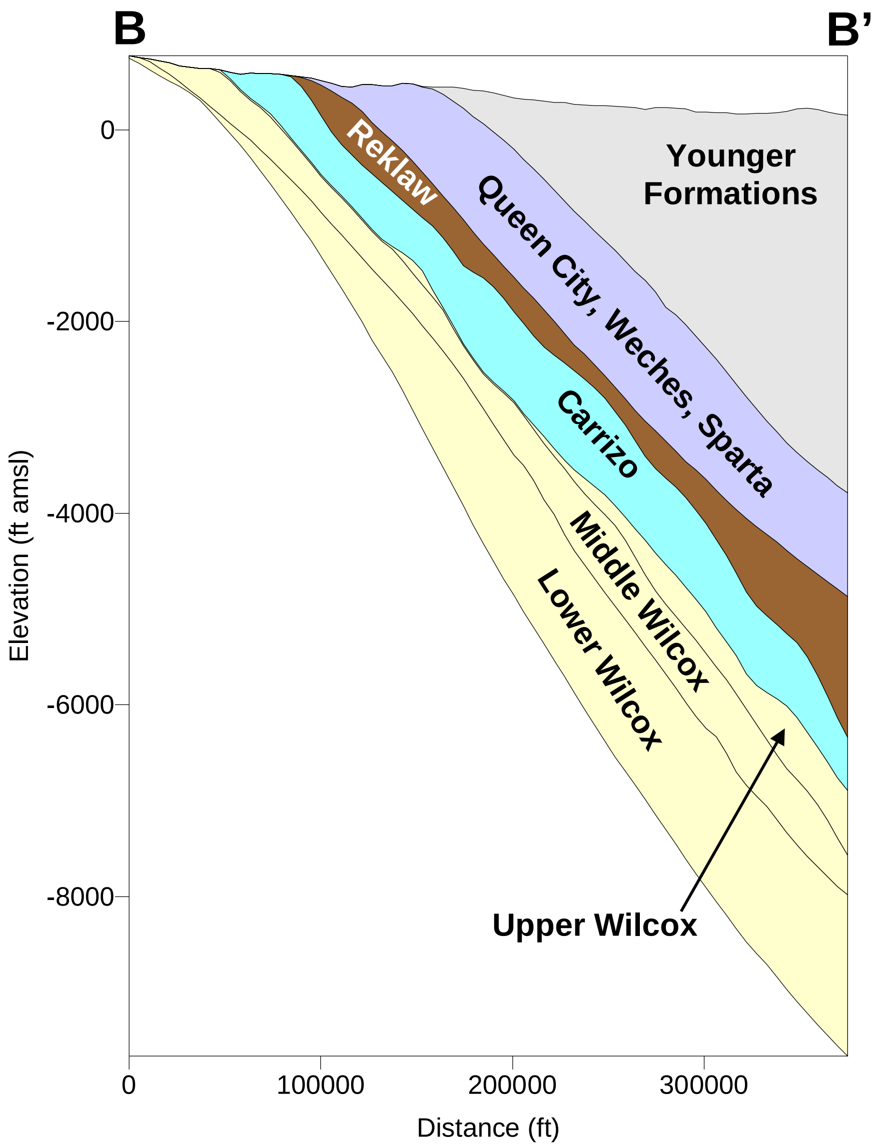
Outcrop for the active model domain



Hydrogeologic Cross section

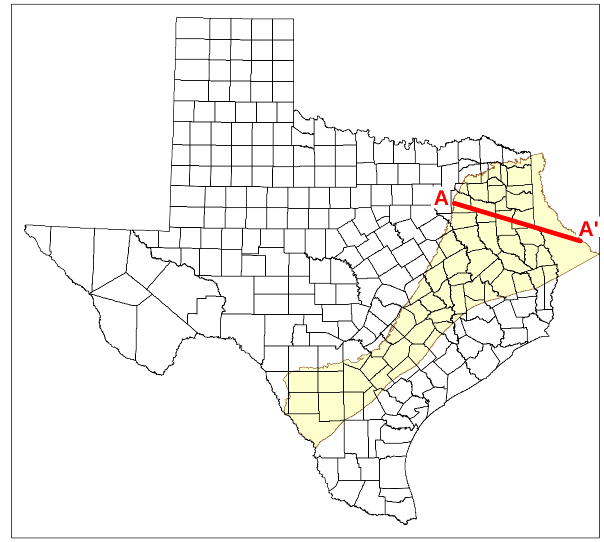
- Central and Southern Models
  - Outcrops are very narrow
  - Dips are very steep averaging 100 ft/mile or >

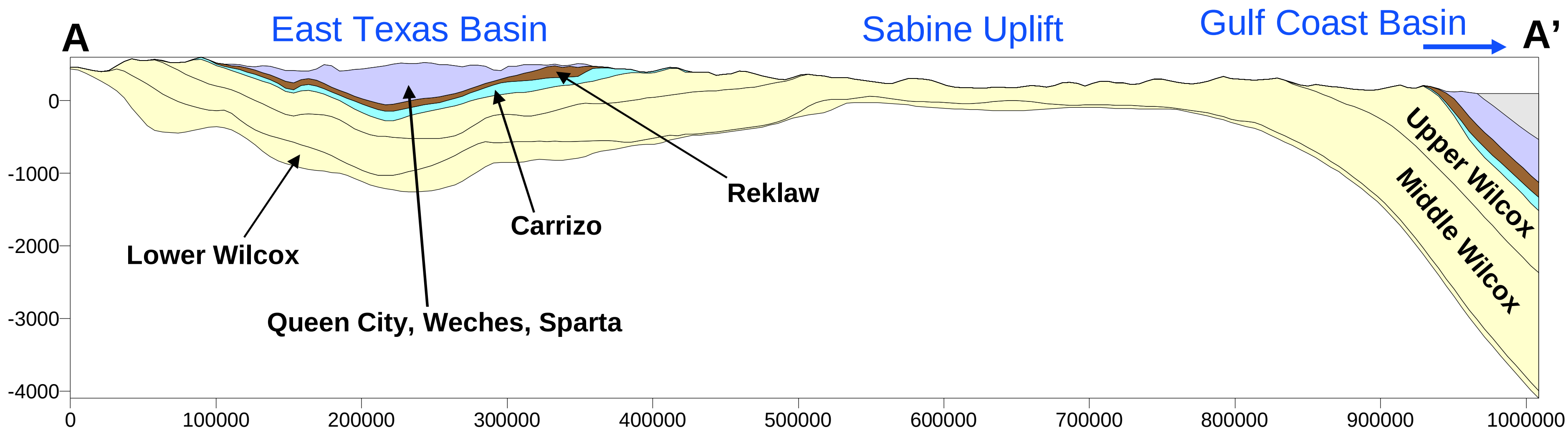




Hydrogeologic Cross Section

- Northern Model Region
  - Queen City outcrops over the majority of the East Texas Basin
  - Queen City and Sparta eroded across the Sabine Uplift
  - South of Sabine Uplift aquifers dip into the Gulf Coast Basin





Groundwater Flow Conceptual Model

North-Central

- Groundwater flows locally in the Queen City aquifer rather than regionally due to topographic controls (Fogg and Kreitler, 1982)
- Streams are gaining
- Vertical gradients can be controlled by topography (up in river basins and down on topo highs).
- Shallow water table with greater groundwater ET
- Less percentage of recharge to the confined aquifer sections

South-Central

- Groundwater flows regionally in the Queen City and Sparta aquifers from topographic highs in the outcrop areas to topographic lows down dip of the outcrop
- Streams are gaining to losing in west
- Vertical gradients are upward in confined section
- Groundwater ET becomes less in the south
- Greater percentage of recharge to the confined aquifer sections

Conceptual Model - Predevelopment

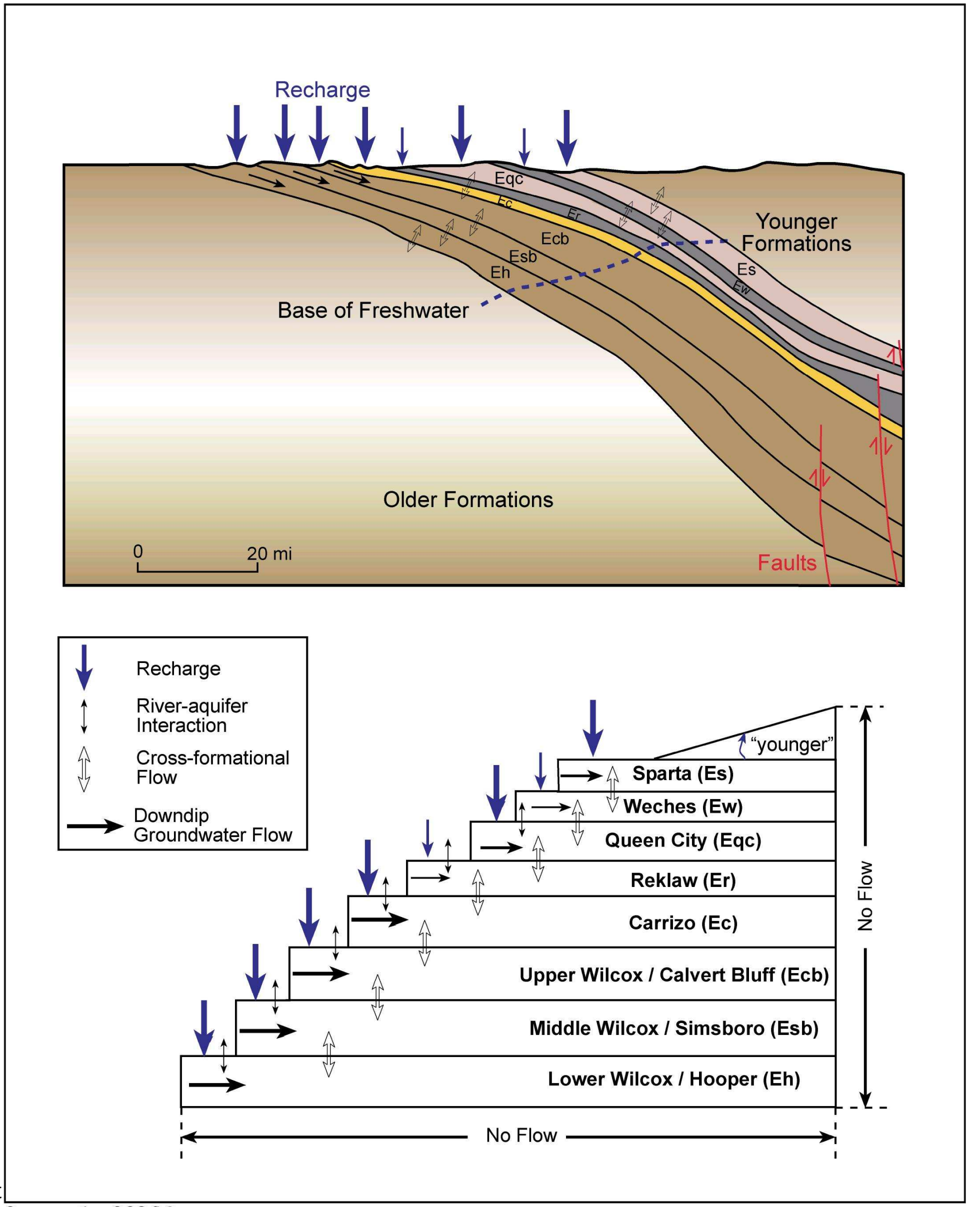
- Steady State Model
- $Q_{in}=Q_{out}$
- Recharge =

  ET groundwater

  spring flow

  stream gains

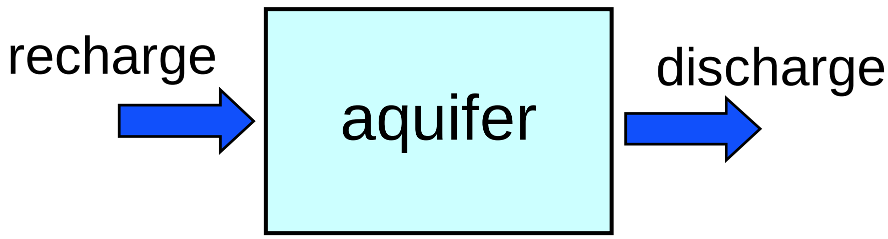
  cross formational flow



Cross-section-QCS.fh8

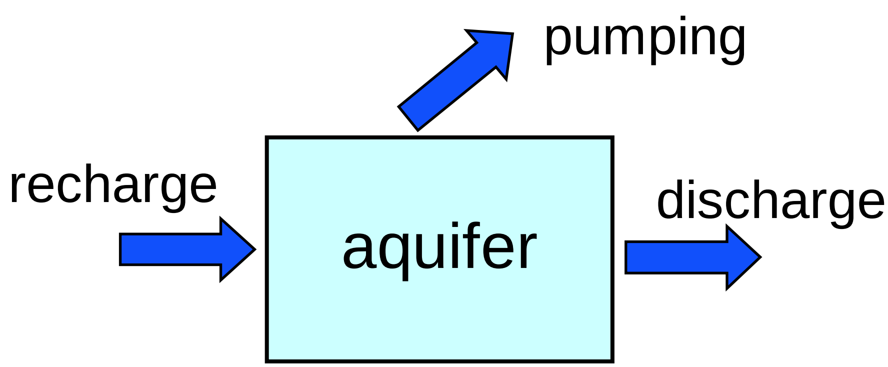
Aquifer Dynamics

Pre-development



Dynamic equilibrium:
Aquifer recharge is balanced by aquifer discharge

Post-development



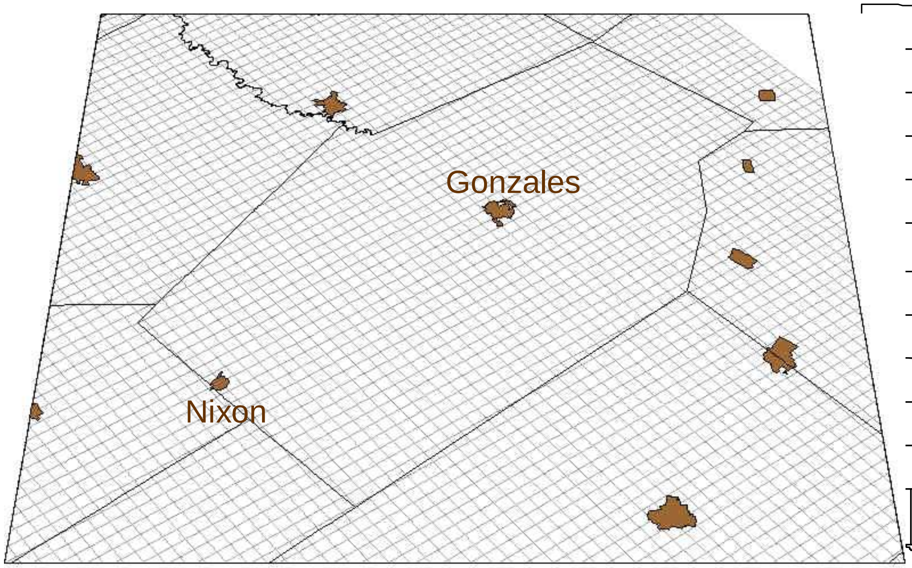
Dynamic equilibrium:
Pumping is balanced by a Reduction in discharge and in some cases an increase in recharge – sometimes termed “capture”

After Alley et al, (1999) and Bredehoeft (2002)

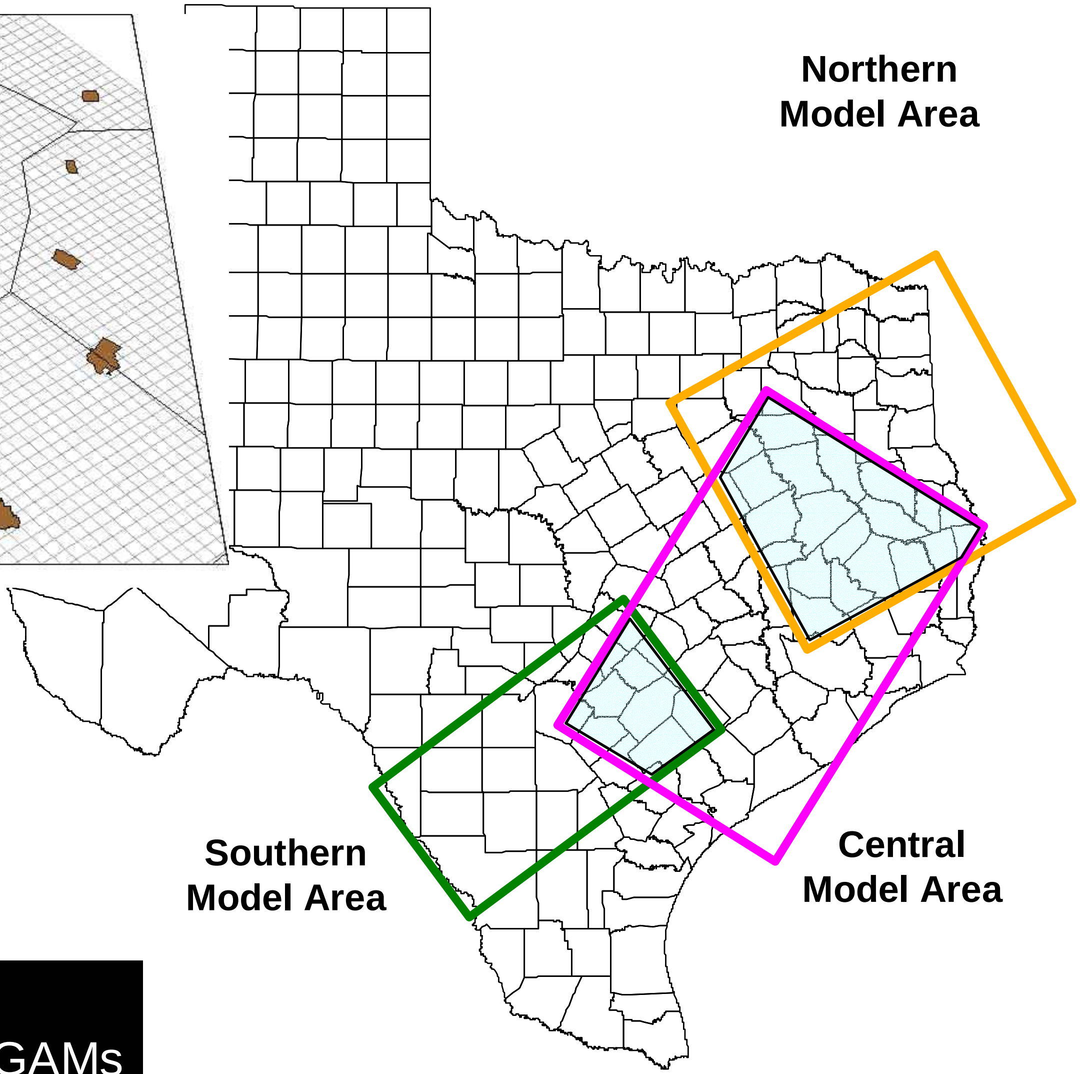
Aquifer Dynamics – Post-Development

- Development is balanced by:
  - Decrease in storage
  - Reduction in discharge (capture)
    - Stream gains
    - Spring flows
    - Groundwater ET
    - Cross-formational flow
  - Increase in recharge (generally small in comparison to discharge reduction)

Model Domains – Same as C/W GAMs



20,000 acres represents
Approximately 5 grid blocks

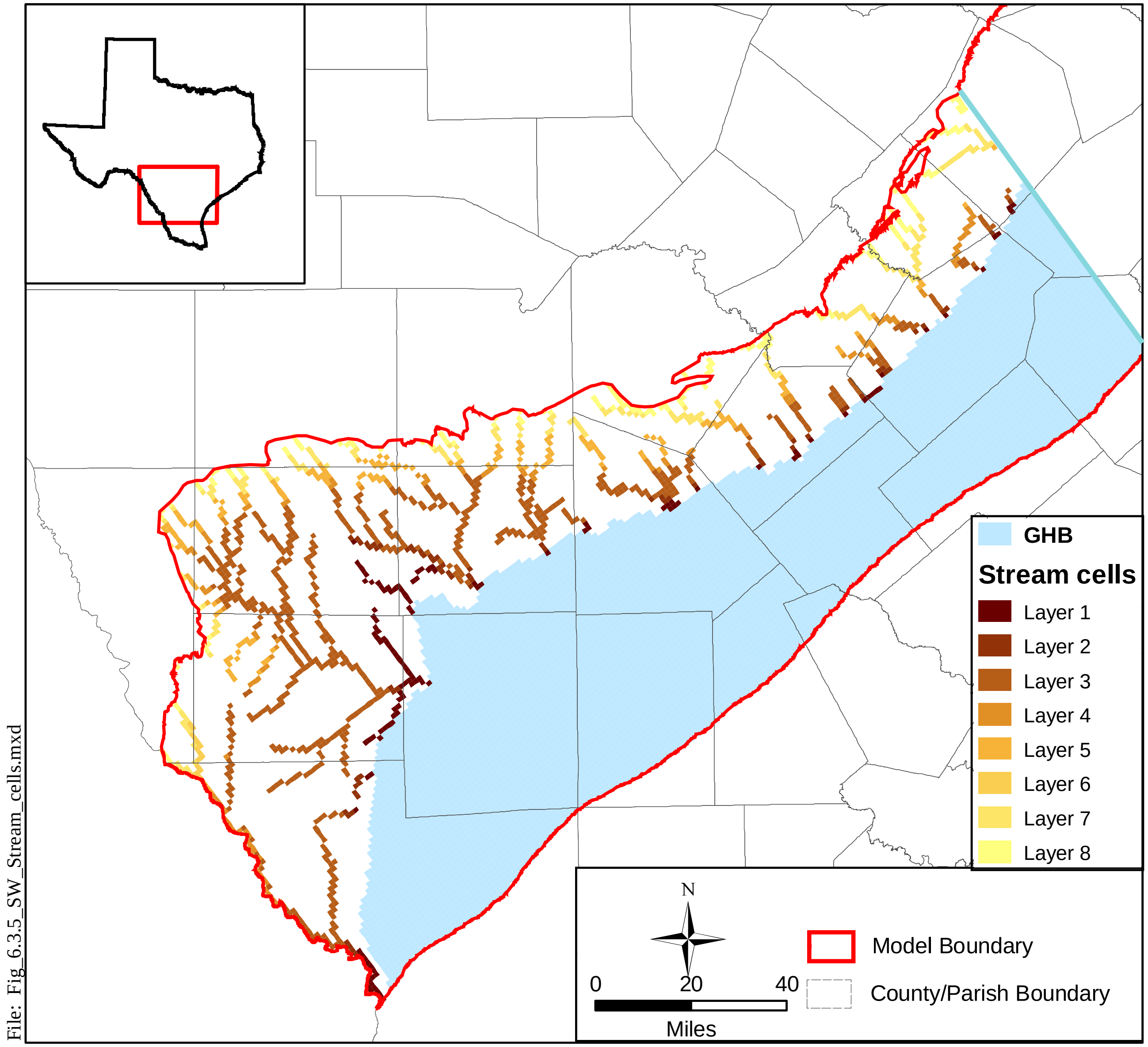


Grid - 1 square mile each
Same Grid as Carrizo-Wilcox GAMs

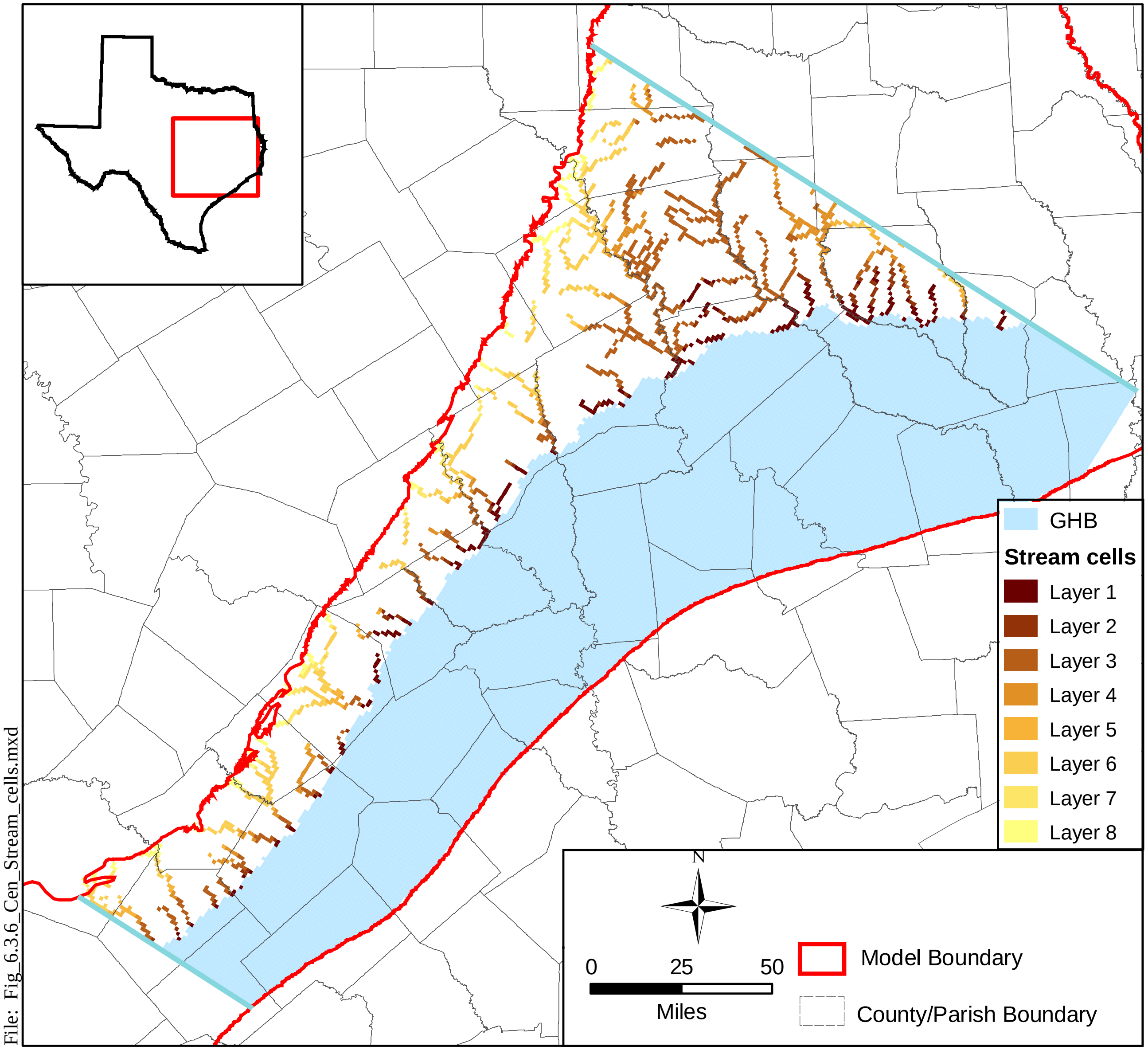
Grid Specifications

GAM Grid	Grid Origin in GAM Coordinates (ft)	X-Axis Rotation (Bearing)	Number of Grid Rows	Number of Grid Columns
Southern GAM	5,062,000 E, 18,280,000 N	E 36.727° N	112	217
Central GAM	5,382,716 E, 18,977,220 N	E 58° N	177	273
Northern GAM	6,295,000 E 19,257,000 N,	E 29.11° N	195	210

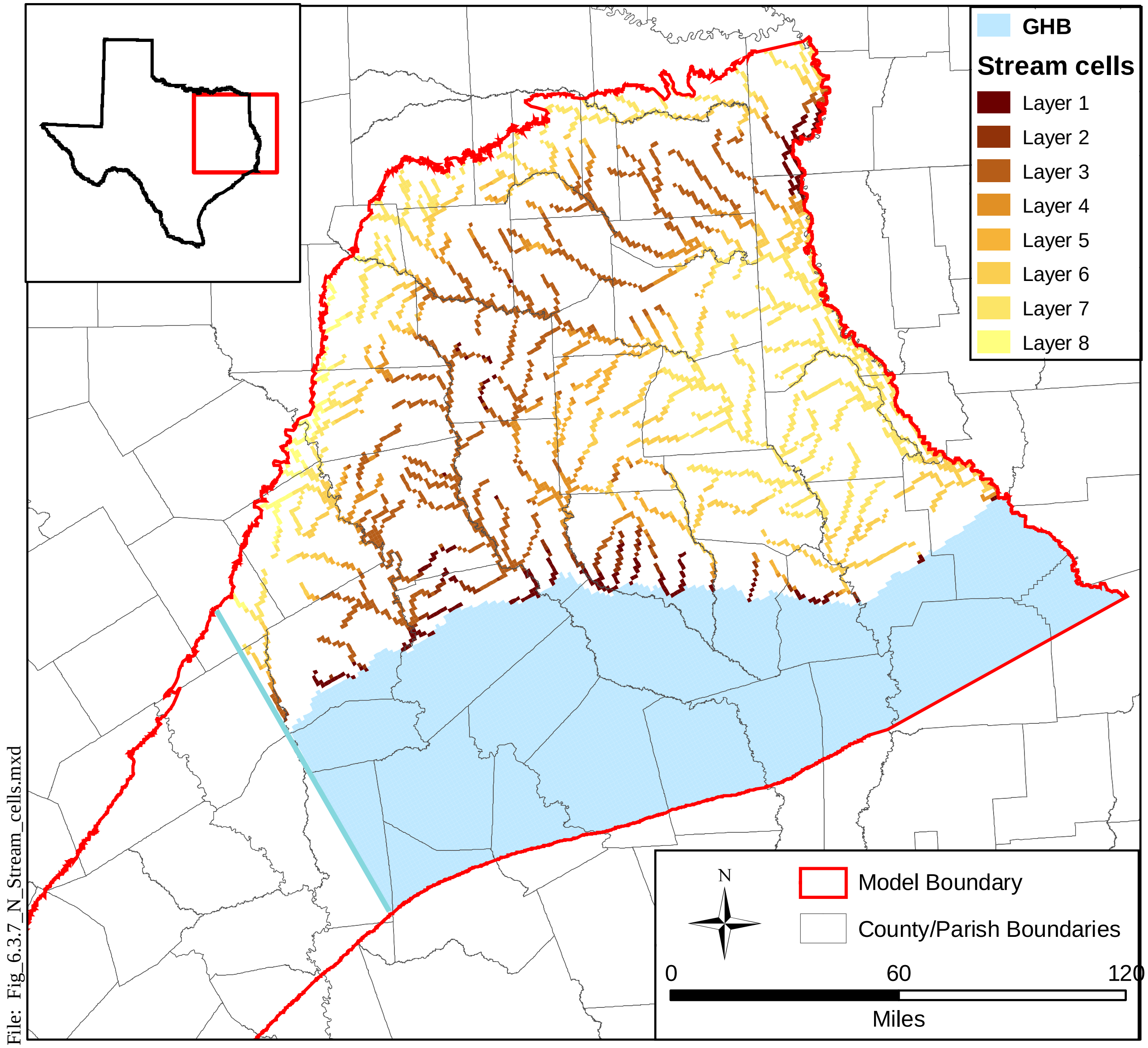
Boundaries - South



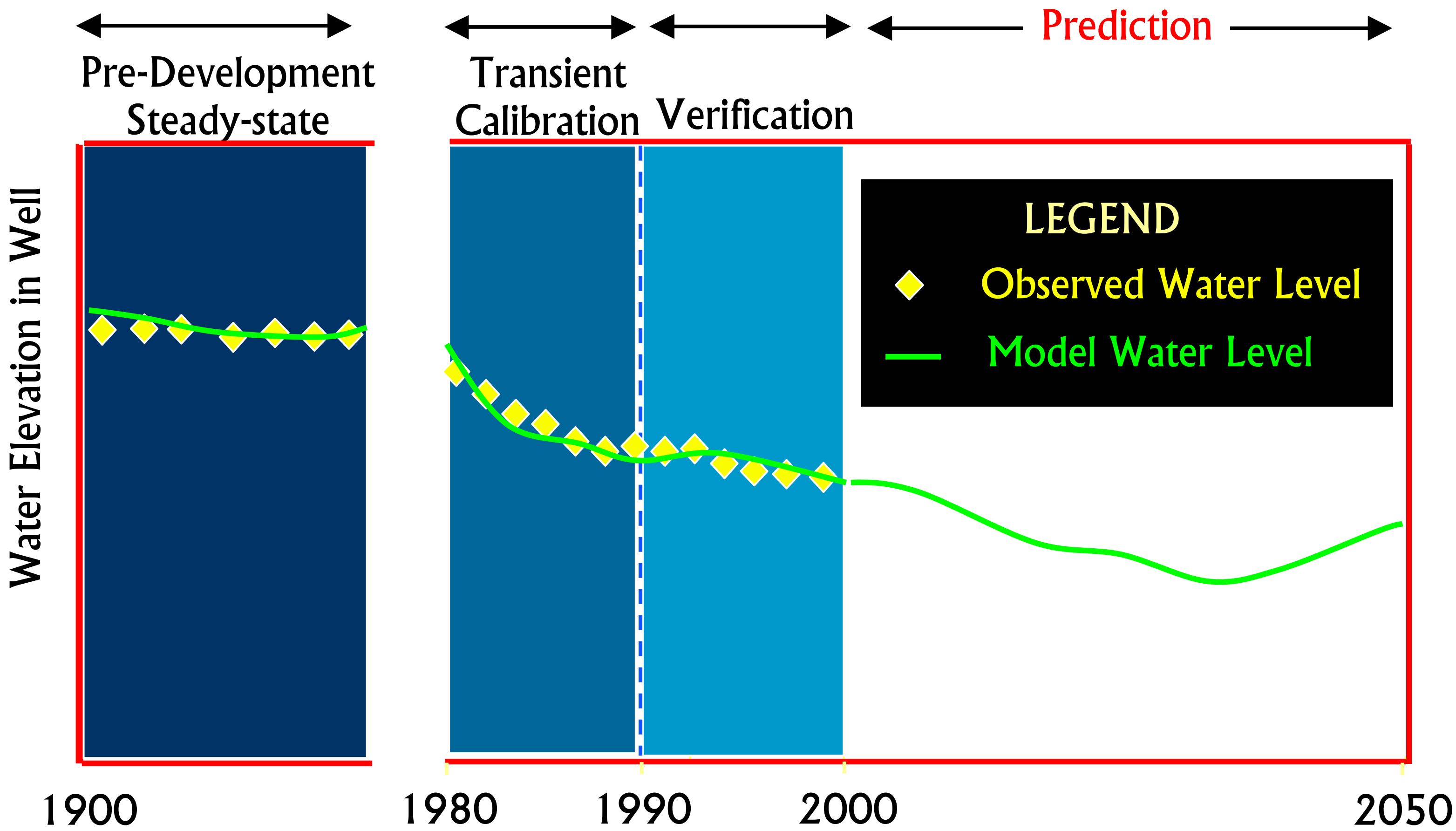
Boundaries – Central



Boundaries - North



GAM Model Periods



Pre-development and transient calibration periods represent different hydrologic conditions

Model Input

- Model parameters for the Carrizo through the Sparta were developed state wide to force consistency in the overlap regions
  - Structure
  - Hydraulic Conductivity
  - Hydraulic Heads
  - Recharge
  - Boundaries
  - Storage
  - Pumping

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

Geologic Structure Data Sources

- Structure – Refers to the elevation of the tops of the Queen City, the Weches, and the Sparta formations
- BEG interpreted structure from the following sources:
  - Approximately 250 logs used across the 3 model areas
  - Guevara (1972) & Garcia (1972) – Queen City
  - Ricoy (1976) - Sparta
  - Payne (1968)
  - East Texas Model
- Sand thickness maps:
  - Guevara (1972) & Garcia (1972) – Queen City
  - Ricoy (1976) and Payne (1968) – Sparta
  - GUWCD – Carrizo, Gonzales County

Hydraulic Properties

Soft Data:

- USGS
  - Payne (1968)
  - McWreath et al (1991)
  - RASA – Prudic (1991)
- BEG
  - Guevara & Garcia (1972)
  - Ricoy (1977)
- TWDB
  - Myers (1969)
  - County Reports

Hard Data:

- TCEQ file search of the drillers logs
  - Queen City - 444 estimates
  - Sparta - 33 estimates
- Mace et al. (2000) database
  - Which includes Myers (1969) data

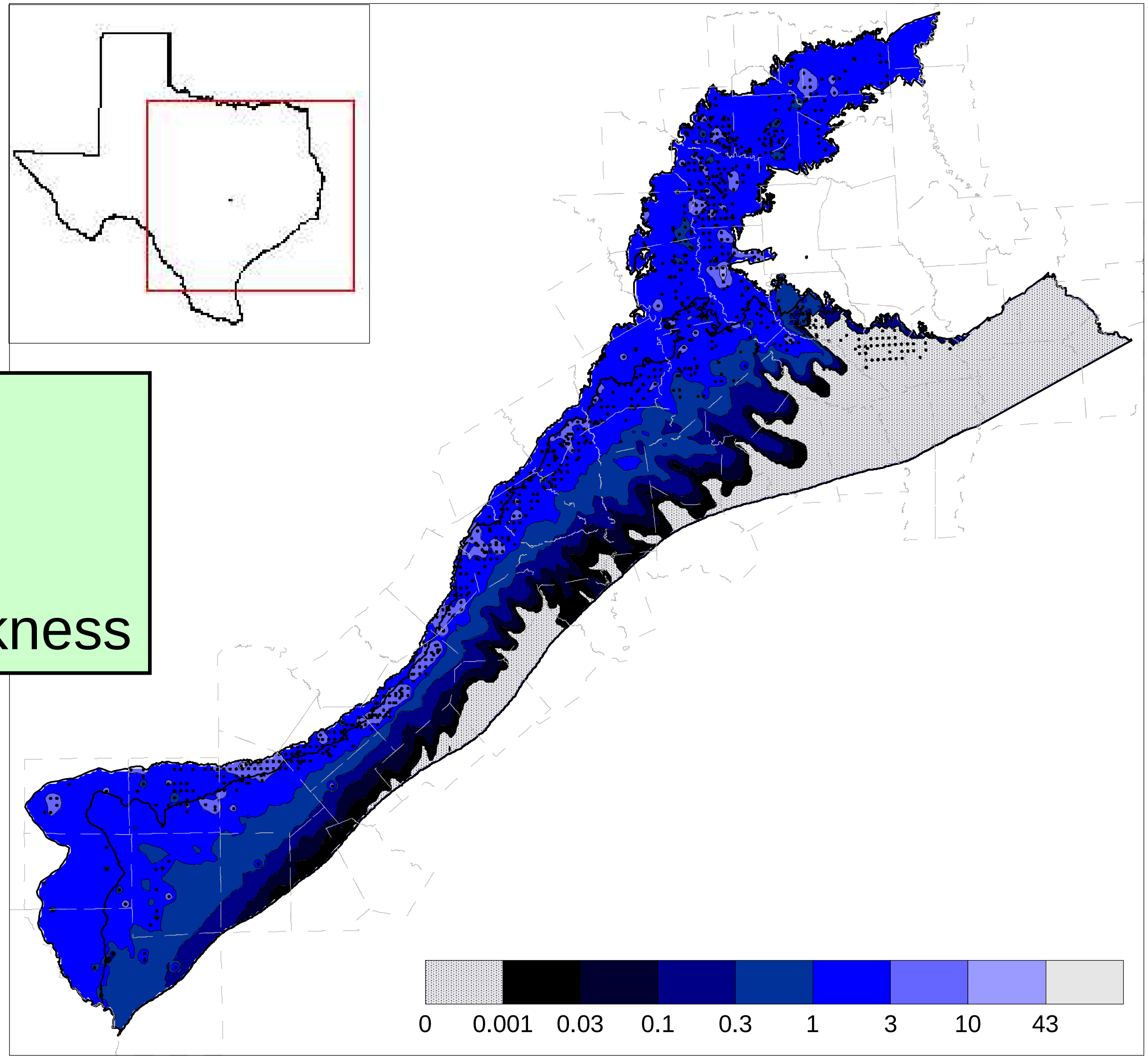
Hydraulic Conductivity Analysis Approach

- Krige available conductivity measurements
- Impose a depth trend based on Prudic (1991)
- Multiply by net sand fraction to convert to effective conductivity for import to MODFLOW

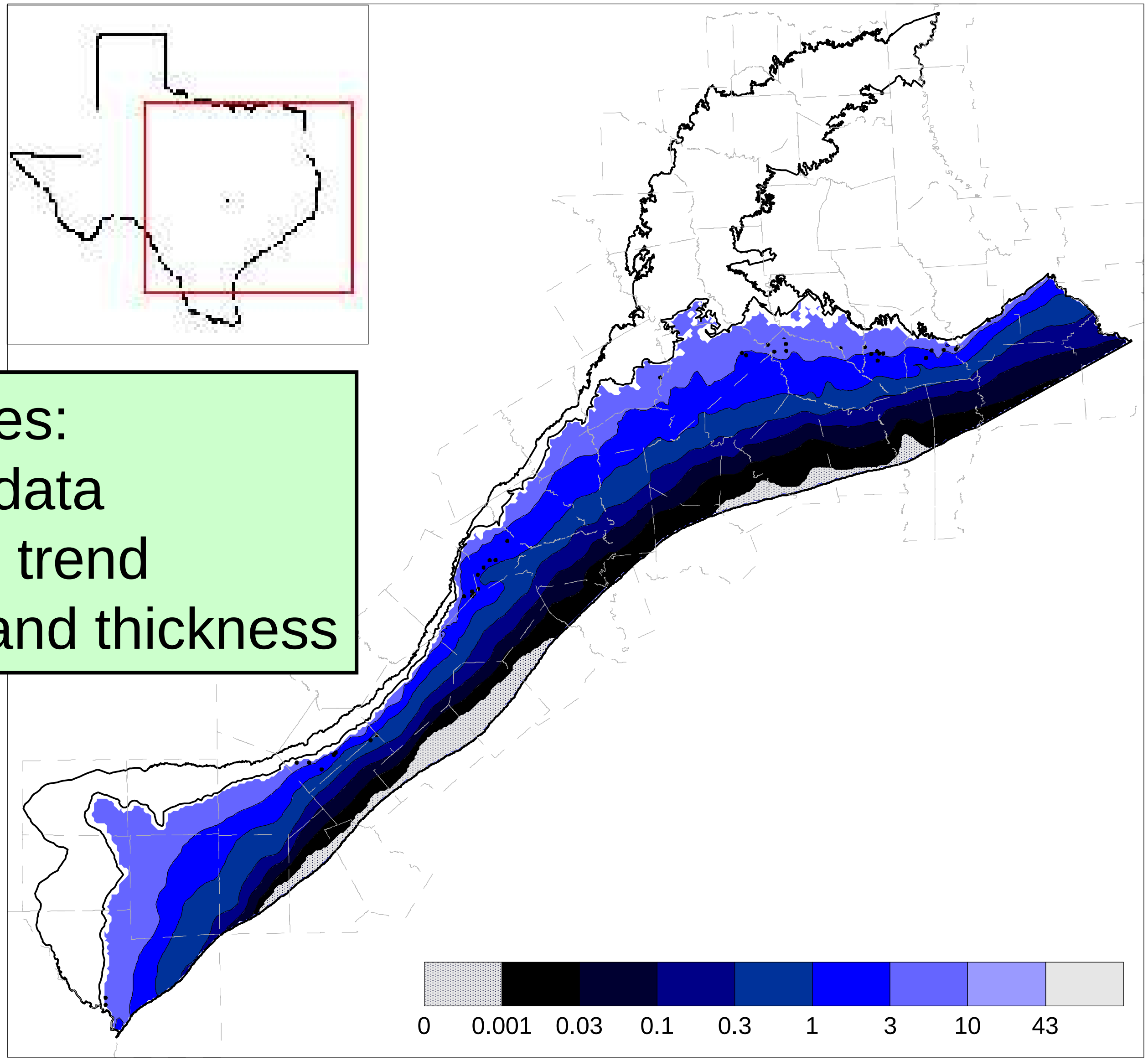
$$K_H = (SF)(K_{sand}) + (1 - SF) \times K_{clay}$$

Queen City Effective Hyd. Conductivity

Combines:
* Test data
* Depth trend
* Net sand thickness



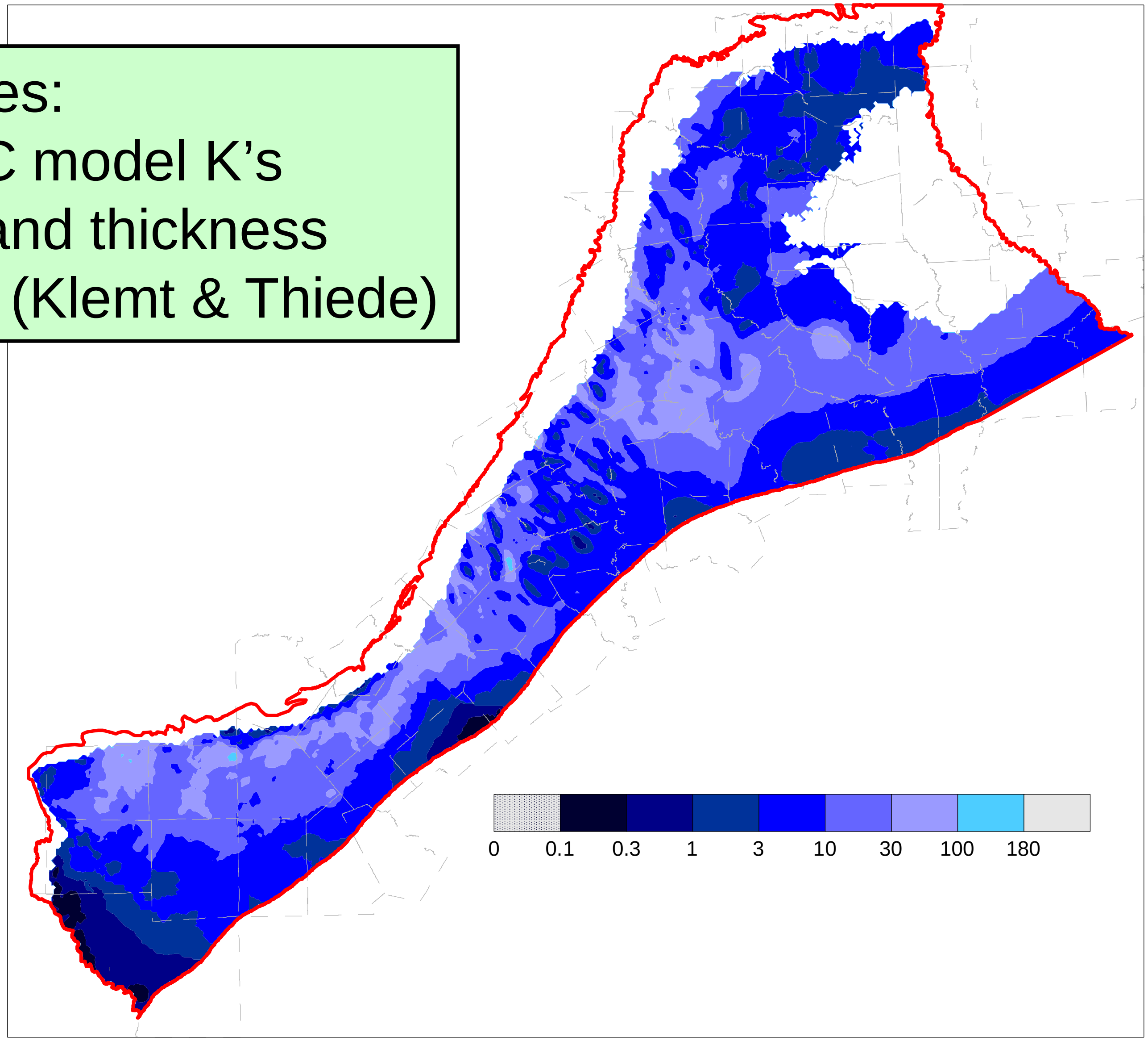
Sparta Effective Hyd. Conductivity



Combines:
* Test data
* Depth trend
* Net sand thickness

Effective K – Carrizo

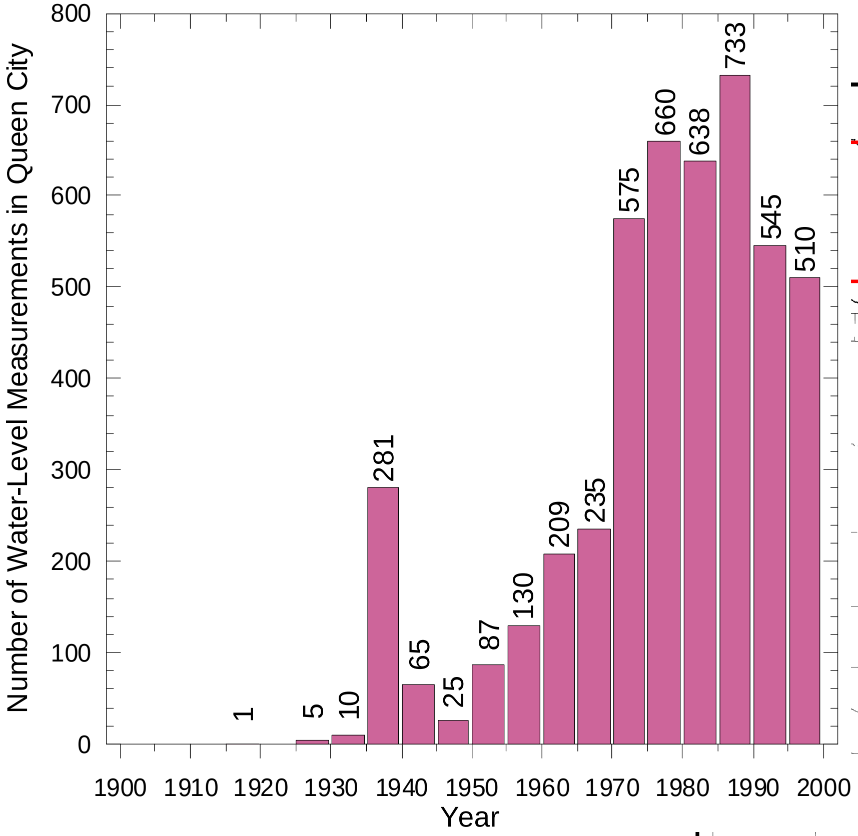
Combines:
* CZWC model K's
* Net sand thickness
* South (Klemt & Thiede)

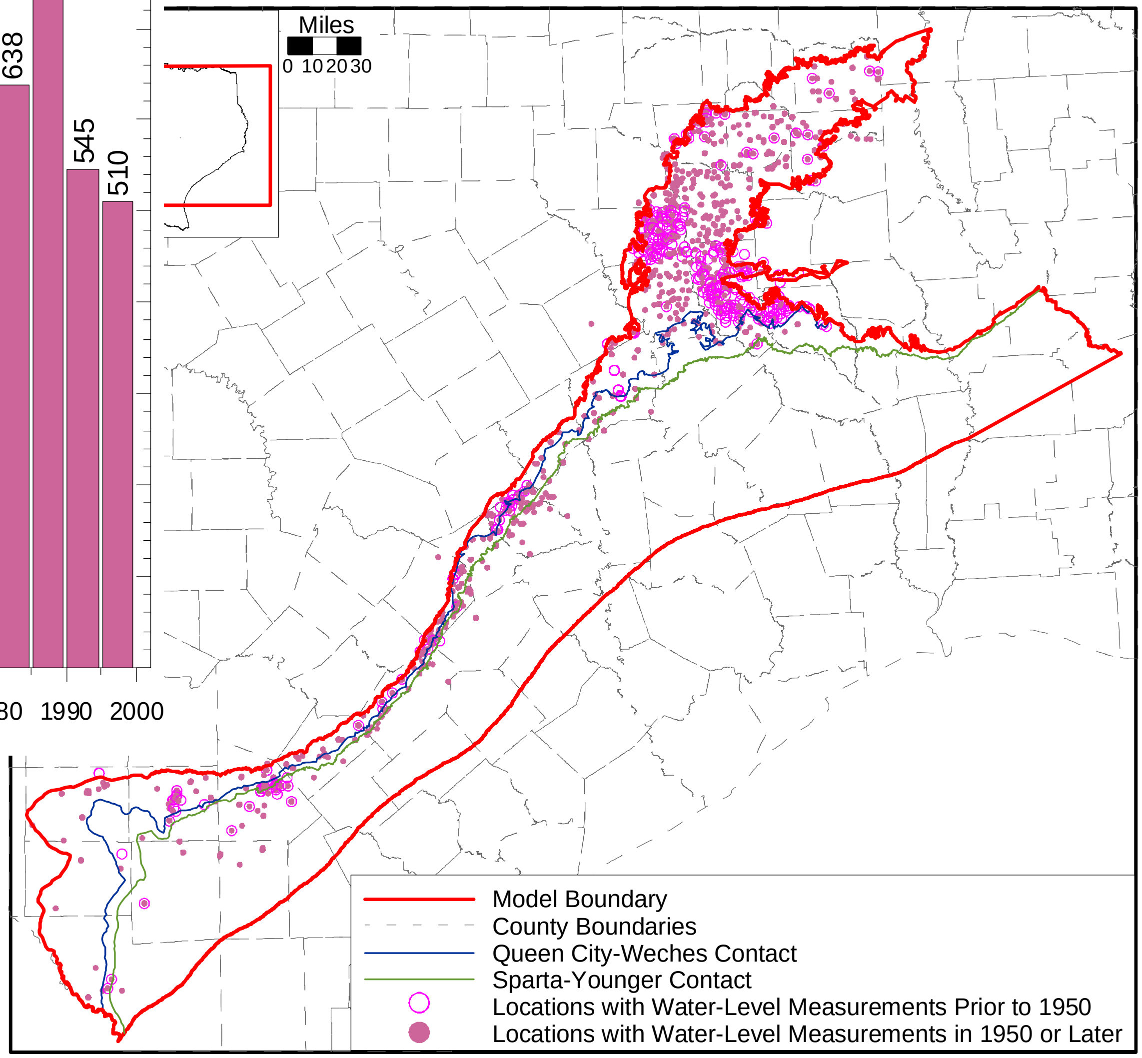


Kv – Implementation

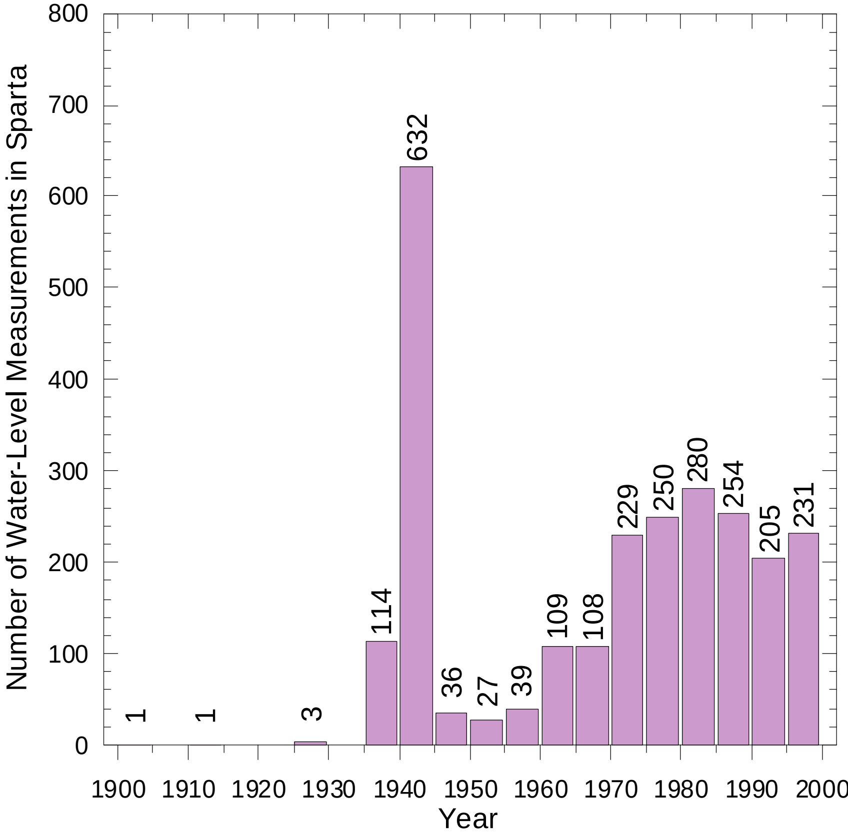
- No measurements
- Aquifers
  - Used clay fraction and an assumed clay conductivity to calculate geometric mean conductivity
- Aquitards
  - Used estimated clay fraction and an assumed clay conductivity to calculate harmonic mean conductivity
- Clay conductivity initially set:
  - 1 X 10^{-4} ft/day, (0.0001)
  - Established as a calibration parameter

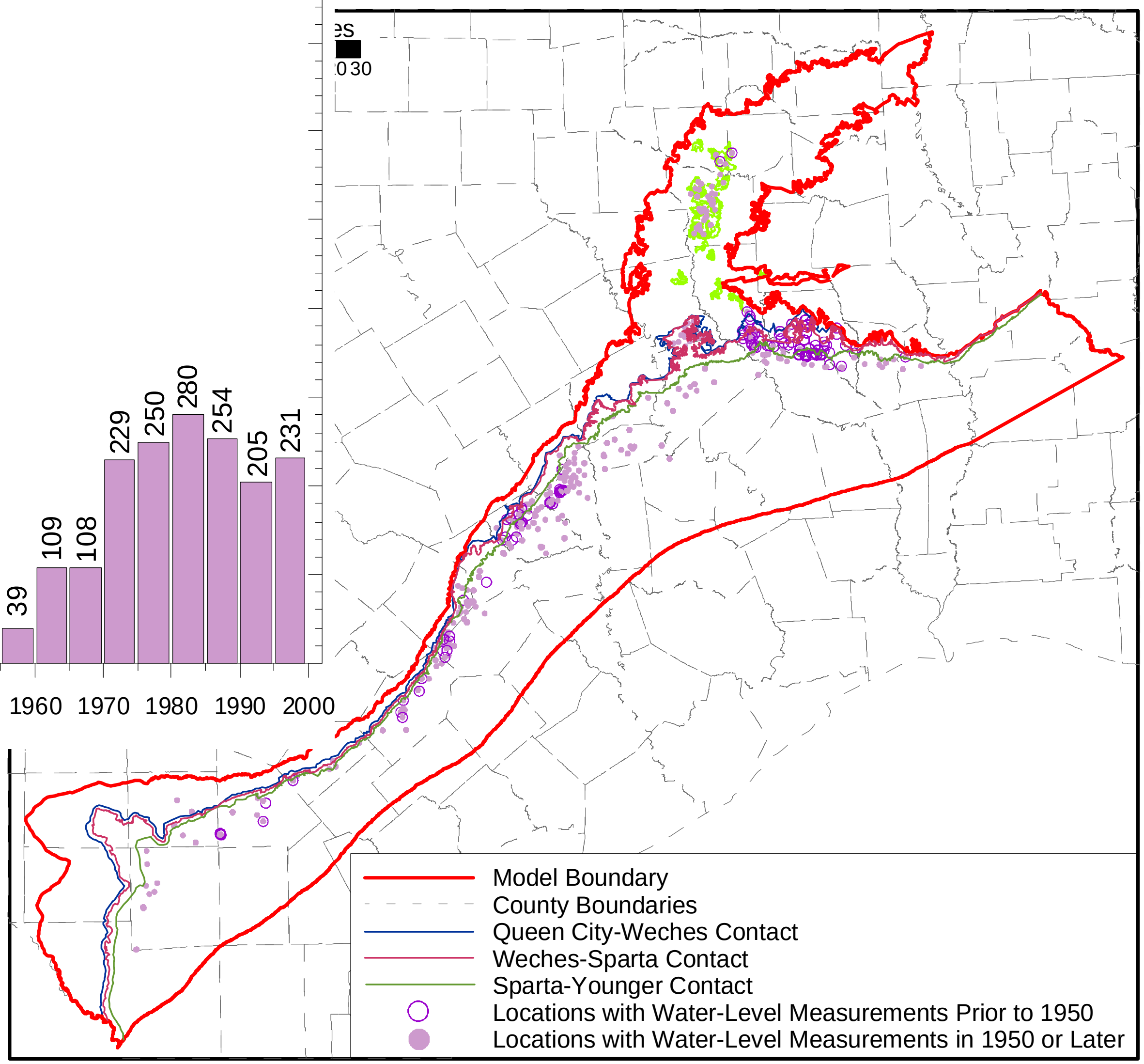
Queen City Water Level Control





Water Level Control – Sparta aquifer





Hydraulic Heads - Predevelopment

- Evaluated water-level data on a county by county basis
- Conducted a literature review on the historical development of the Carrizo and Wilcox in each county
- In many areas, artesian pressures within the aquifer were originally sufficient to drive water above ground surface
  - In select cases, heads were adjusted to account for the effects of pumping. These are documented in the report.
  - Not a significant issues in QCSP relative to Carrizo

Hydraulic Heads – 1975-2000

- Used the TWDB head database
  - QA/QC measurements for outliers, pumping or obvious measuring point busts
- Developed head surfaces for Queen City and Sparta
- 1980, 1990, 2000
- Developed hydrographs (time series) for transient calibration

Recharge Conceptual Model

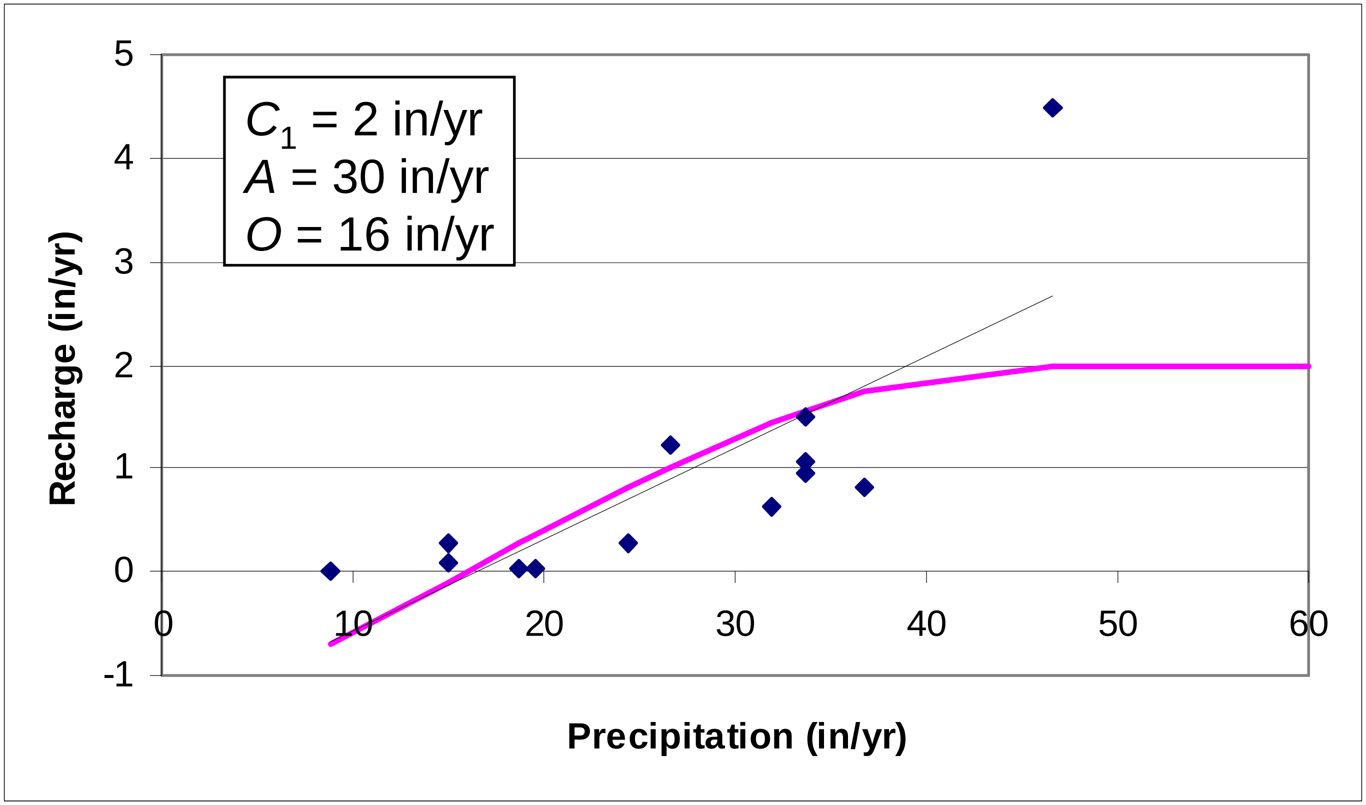
- Based upon the work of Scanlon (2003), Meyboom (1966) and Toth (1966), we expect recharge to be a function of:
  - Precipitation,
  - Topography, and
  - Underlying geology
- Topographic control:
  - North and Central - Recharge would be enhanced in the higher elevations relative to the low elevations
  - We expect that this trend would be more subdued to reversed in the arid southwest
- In steady-state, recharge is also fixed by the aquifers (also models) ability to discharge

Recharge Implementation

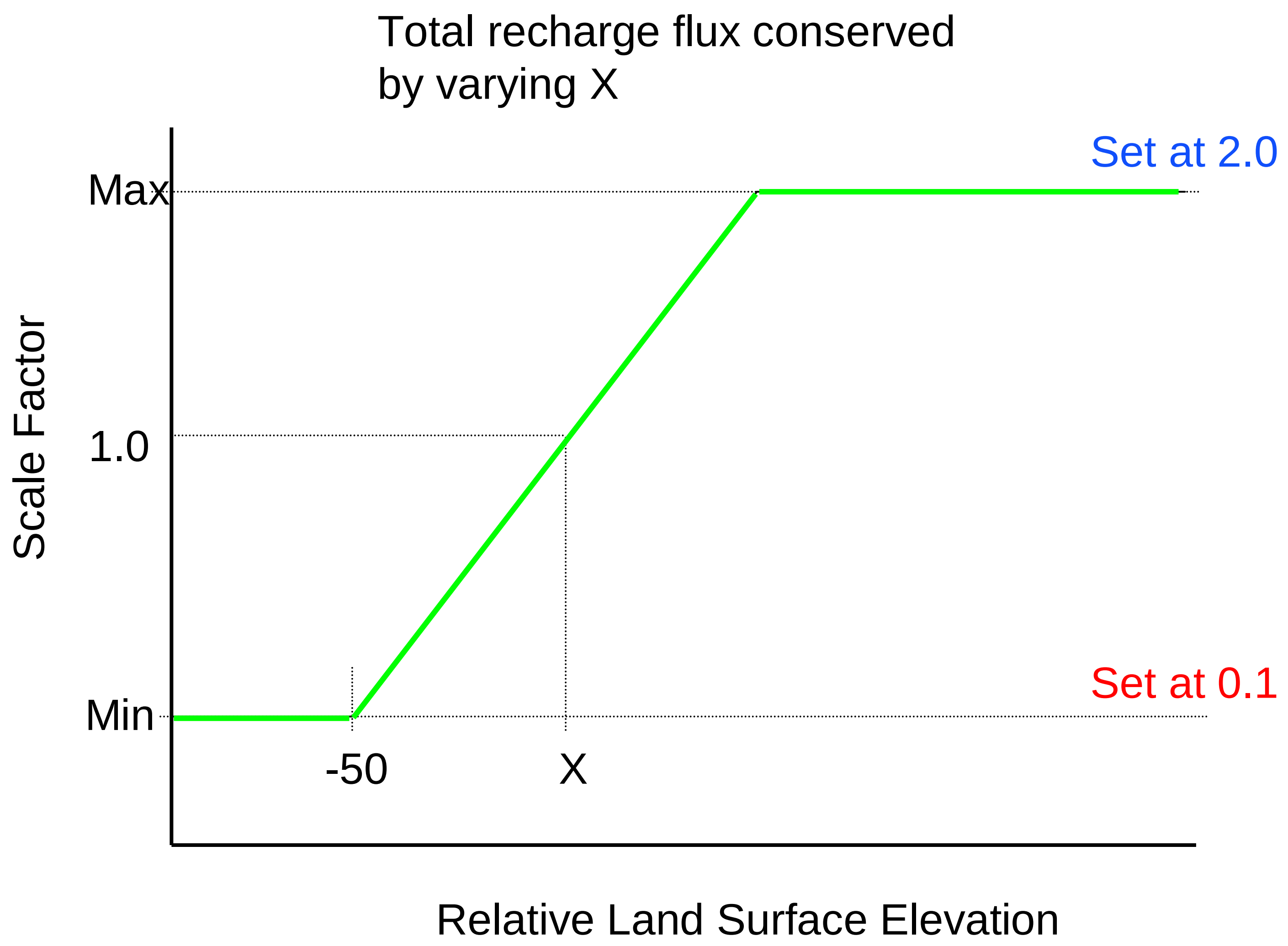
- We developed a method based upon
  - precipitation,
  - topographic relationships, and
  - underlying aquifer properties
- Method is based upon the recently published recharge report by Dr. Scanlon (BEG).
- The recharge estimates are constrained based upon previous estimates
- Consistency in recharge implies some change within the Carrizo-Wilcox models
- Recharge is calibrated in the SS models
- Transient recharge is derived from precipitation variation (SPI)

Fit to Scanlon et al. 2003 simulations

$$R(P) = \begin{cases} C_1\left(1.5\dfrac{P-O}{A} - 0.5\left(\dfrac{P-O}{A}\right)^3\right) & (P-O) < A \\ C_1 & (P-O) \geq A \end{cases}$$



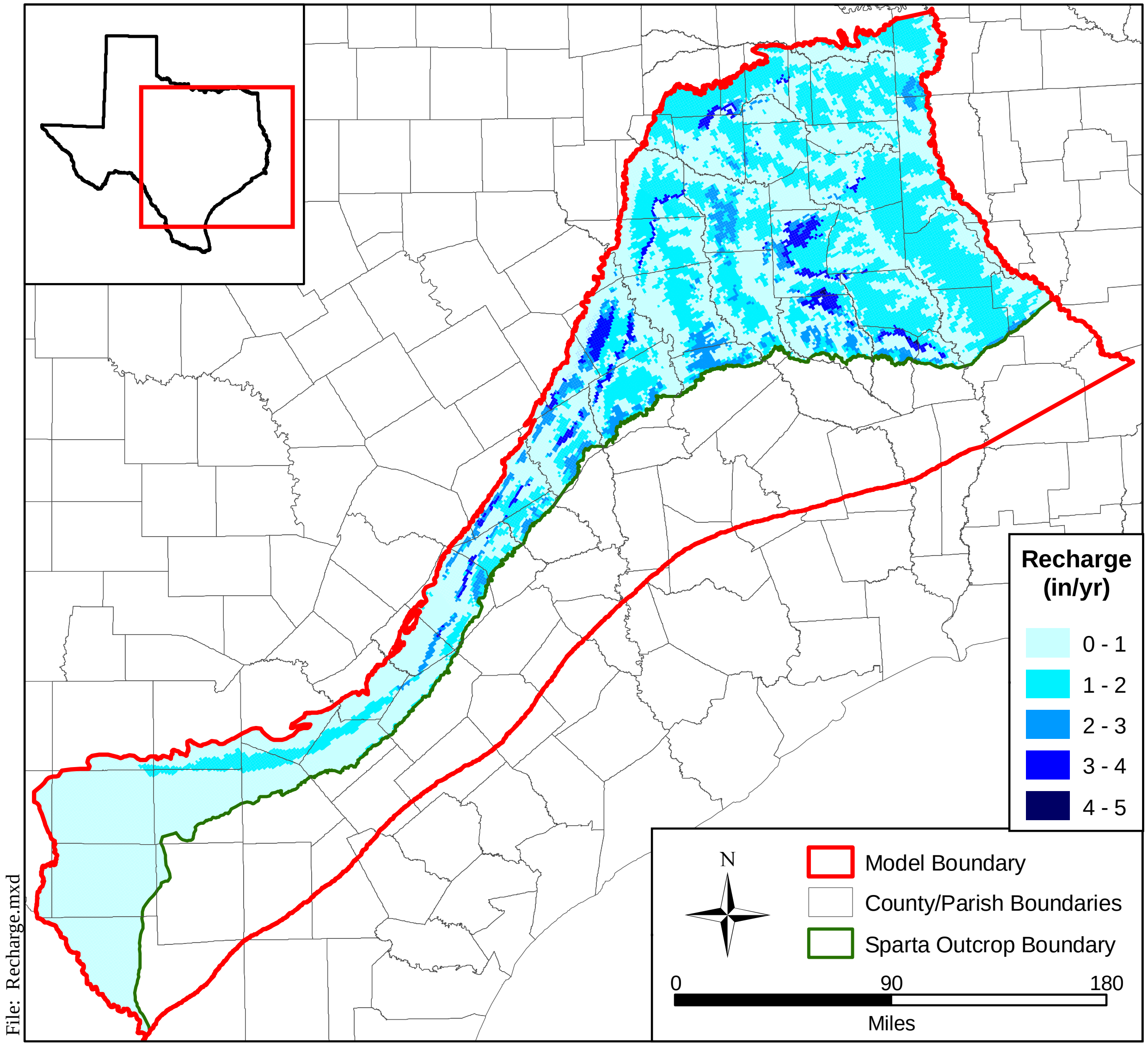
Topographic Scale Factor



Formation Scale Factor

Formation	Layer	All	S	C	N
			Model Region		
Sparta	1	0.8			
Weches	2	0.2			
Queen City	3	0.5	0.5	0.5	0.4
Reklaw	4	0.2			
Carrizo	5	1.2			
Upper Wilcox/Calvert Bluff/Upper Wilcox	6		0.4	0.4	0.5
Upper Wilcox/Simsboro/Upper Wilcox	7		0.4	1.2	0.5
Upper Wilcox/Hooper/Upper Wilcox	8		0.5	0.3	0.3

Steady-State Recharge Distribution



Calibrated SS Recharge

Recharge (AFY) (Minus the Reklaw and Weches)

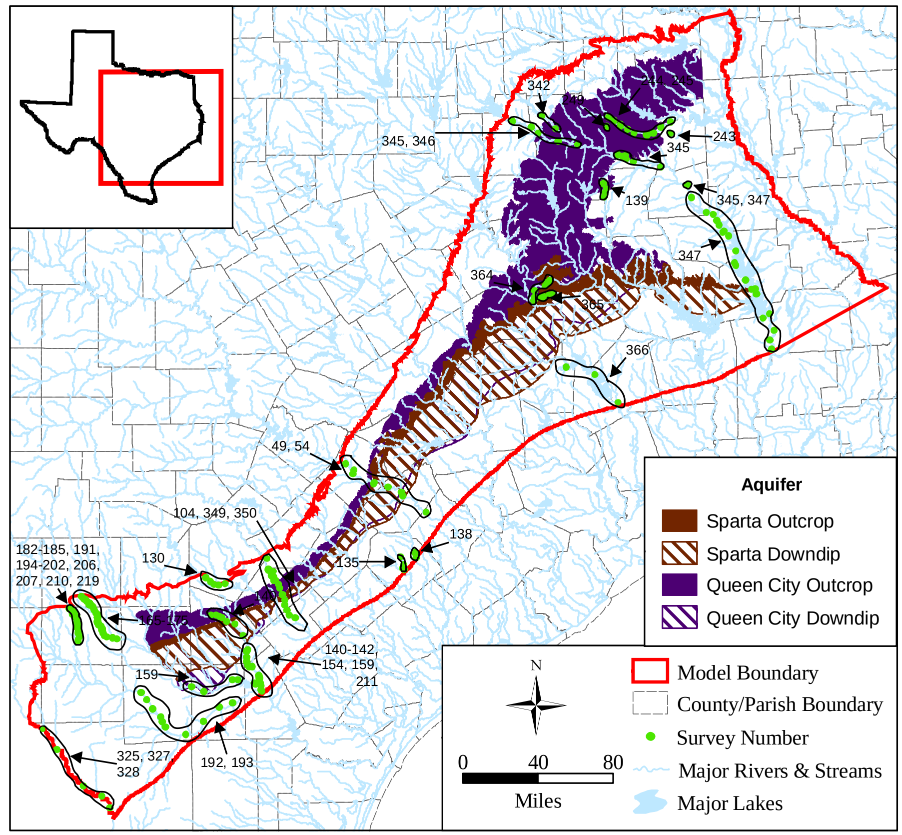
Aquifer	South GAM	M&P 1979	Central GAM	M&P 1979	North GAM	M&P 1979
Sparta	24,486	60,000	126,400	136,400	140,025	96,800
Queen City	69,019	23,800	154,300	294,300	275,580	655,600
Carrizo/W	113,602	186,340	220,300	479,700	728,106	327,460
Total	207,107	270,140	501,000	910,400	1,143,711	1,079,860

Recharge (in/year)

Formation	South GAM	Central GAM	North GAM
Sparta	0.6	1.6	1.7
Weches	0.2	0.4	0.5
Queen City	0.4	0.8	0.8
Reklaw	0.2	0.3	0.4
Carrizo	1.2	2.2	2.6
U. Wilcox	0.5	0.7	1.2
M. Wilcox	0.4	1.8	1.3
L. Wilcox	0.6	0.6	0.5

Stream Gain/Loss Calibration Targets

- LBG-HDR (1998)
- Slade et al., (2002)
- HDR Central GAM (Dutton et al., 2003)
- This Study
  - R.J. Brandes WAM Study



WAM Gain/Loss Results

River	Incremental Distance (miles)	Mainstem Incremental Drainage Area (square miles)	# of Tributary Gages	Tributary Drainage Area (square miles)	Tributary DA/ Mainstem DA (%)	Gain/Loss (ft^3/day/mile)	Gain/Loss (AF/day/mile)
ANGELINA R	43	1,278	2	534	41.80%	-32,639	-0.7
ATASCOSA R	65.8	1,171	1	783	66.90%	18,064	0.4
BIG CYPRESS CREEK	-----	-----	-----	-----	-----	-----	-----
BLACK CYPRESS BAYOU	48.5	365	1	383	104.90%	64,198	1.5
BRAZOS R	152.8	13,444	4	9,723	72.30%	159,763	3.7
CIBOLO CR	69.2	553	1	549	99.30%	4,895	0.1
COLORADO R	68.5	363	NA	NA	NA	4,846	0.1
FRIO R	79.4	2,798	4	1,341	47.90%	12,926	0.3
GUADALUPE R	180.5	2,874	3	1,435	49.90%	28,038	0.6
LEONA R	-----	-----	-----	-----	-----	-----	-----
NAVASOTA R	93	1,214	1	97	8.00%	5,223	0.1
NECHES R	249	7,342	2	268	3.70%	153,851	3.5
NUECES R	263.4	13,566	3	5,383	39.70%	-18,924	-0.4
RIO GRANDE	139.3	5,266	NA	NA	NA	-8,344	-0.2
SABINE R	134.1	2,232	4	964	43.20%	41,845	1.0
SAN ANTONIO R	57.5	370	1	827	223.50%	25,690	0.6
SAN MARCOS R	37.9	426	1	309	72.50%	-33,111	-0.8
SULPHUR R	114.7	2,916	2	770	26.40%	-557	0.0
TRINITY R	125.8	5,373	5	2,261	42.10%	202,366	4.6

Steady-State Model Review

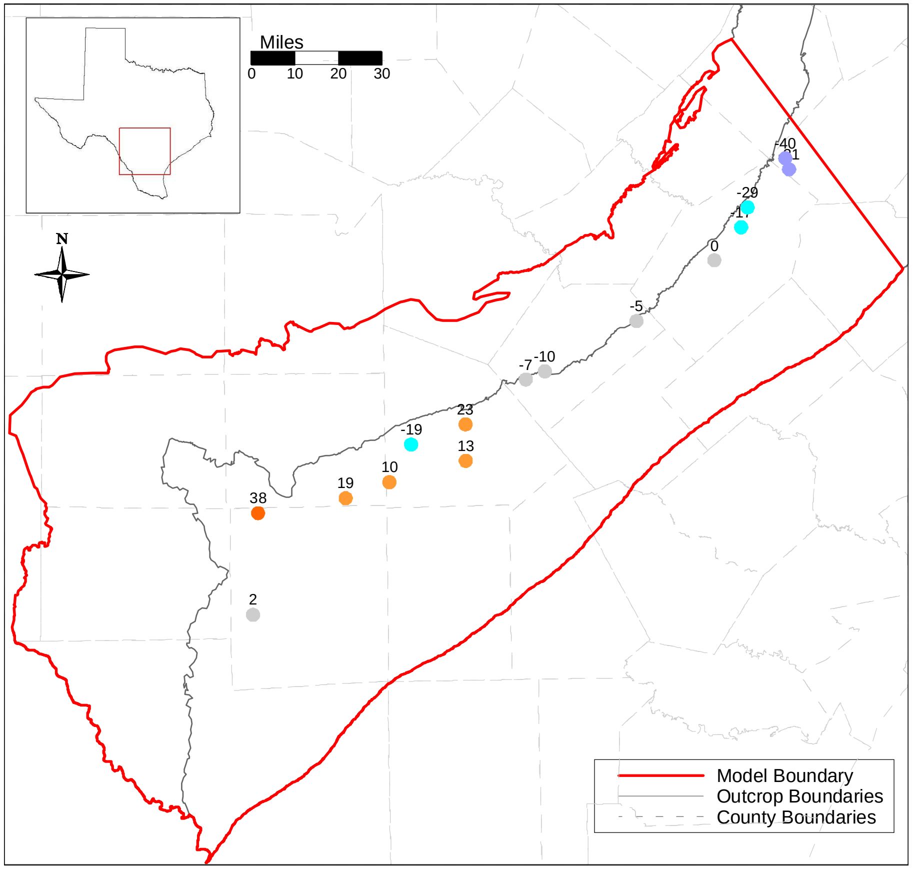
Steady-State Calibration Approach

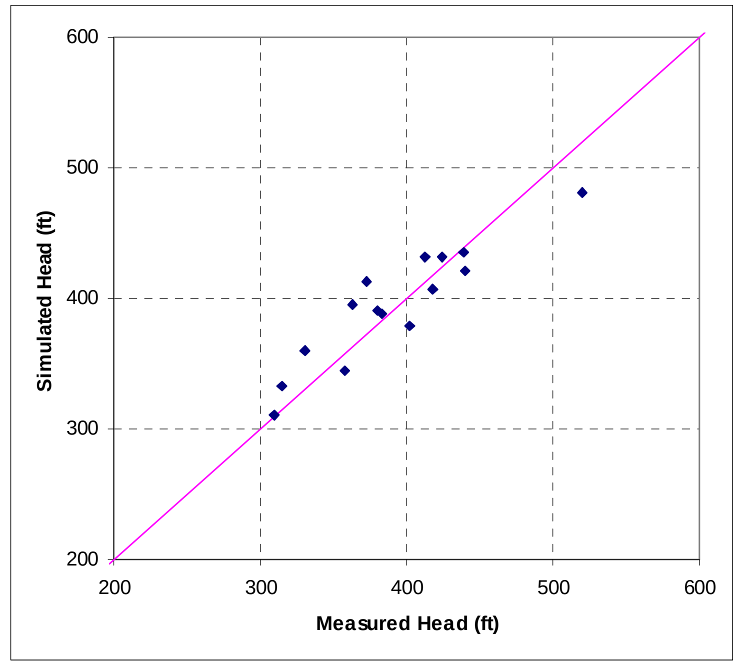
- Approach to Calibration
  - Use multiple performance measures
    - Statistics
    - Head surfaces
    - Stream Gain and Loss
  - Use regularization (interpolation functions) to estimate parameters trying to limit the degree of unknowns
    - Kh depth trend
    - Recharge factors and topographic scalar
  - Parameters poorly known were preferentially altered if they were important (the model responded to them)

Significant Initial Parameter Changes

- Storativity was calculated by a consistent method in 3 GAMs from the Carrizo through Sparta (method will be described later)
- Confining unit clay conductivity was initialized at $1x10^{-4}$ ft/day
- All faults are modeled with hydraulic barrier package, but only those with evidence are activated (lower conductance)
- Carrizo horizontal conductivity fields merged
- Recharge

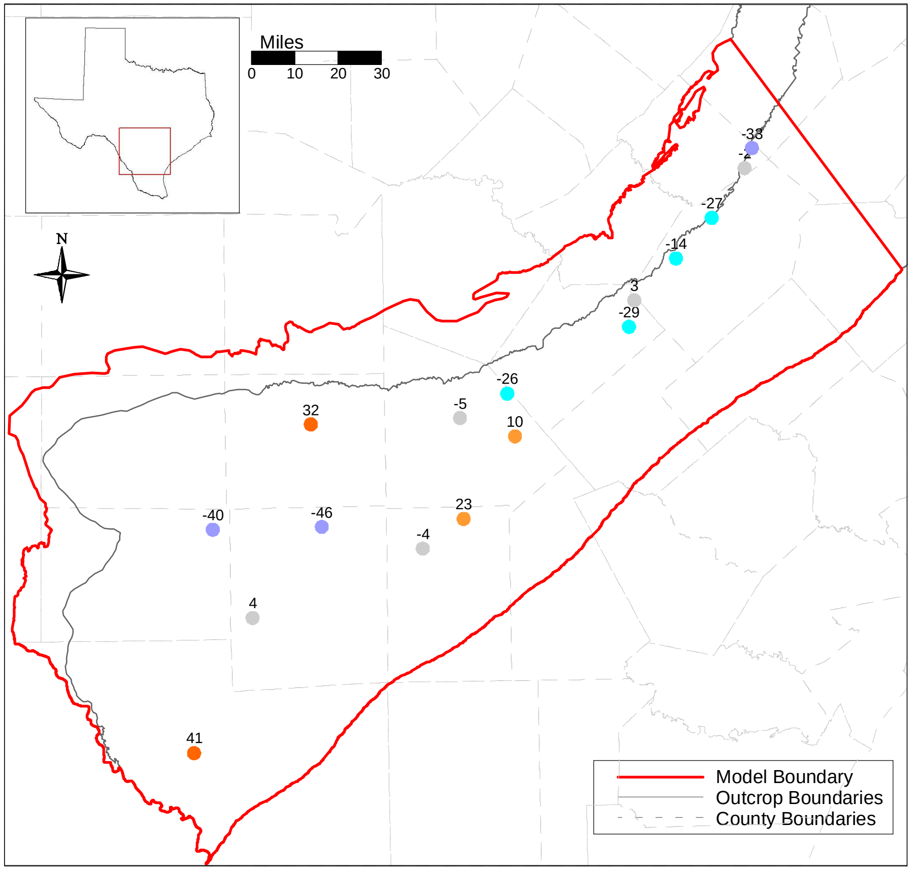
South GAM Sparta

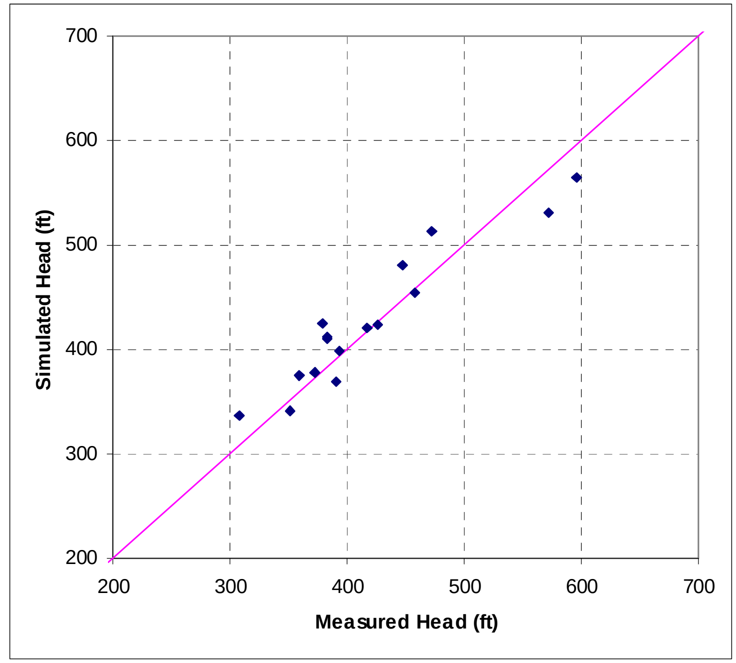




Layer	Count	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/ Range
1	15	-3.8	18	22	210	0.10
3	16	-7.4	22	26	288	0.091
5	31	-3.7	16	22	308	0.071

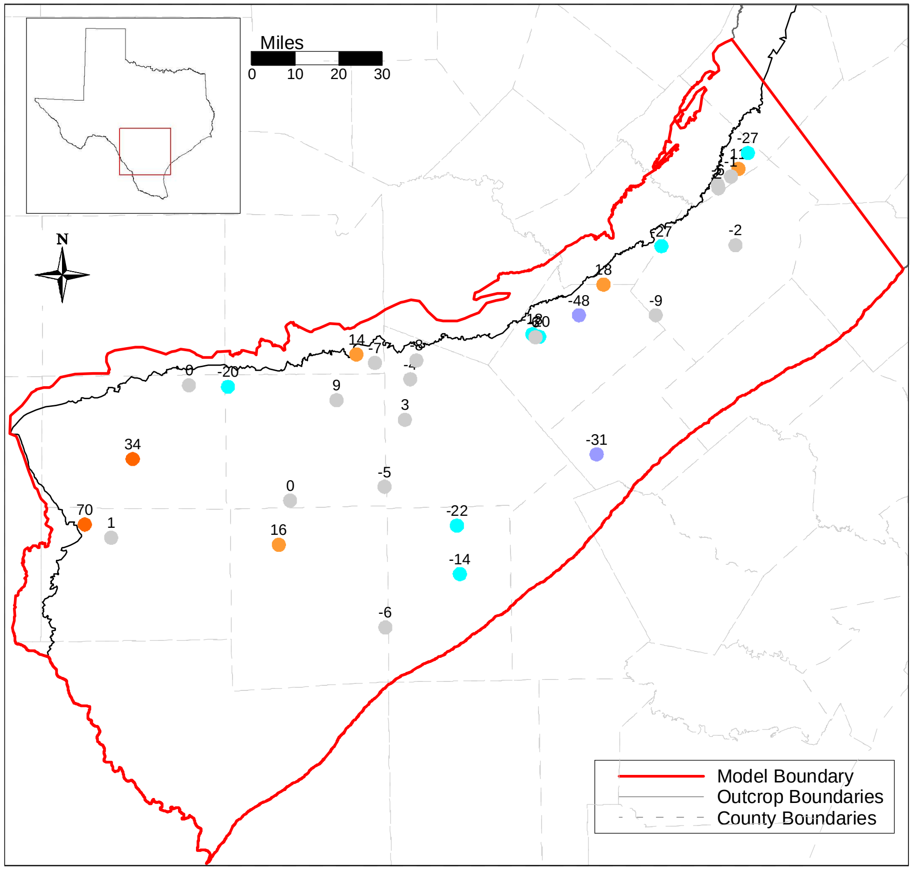
South Queen City

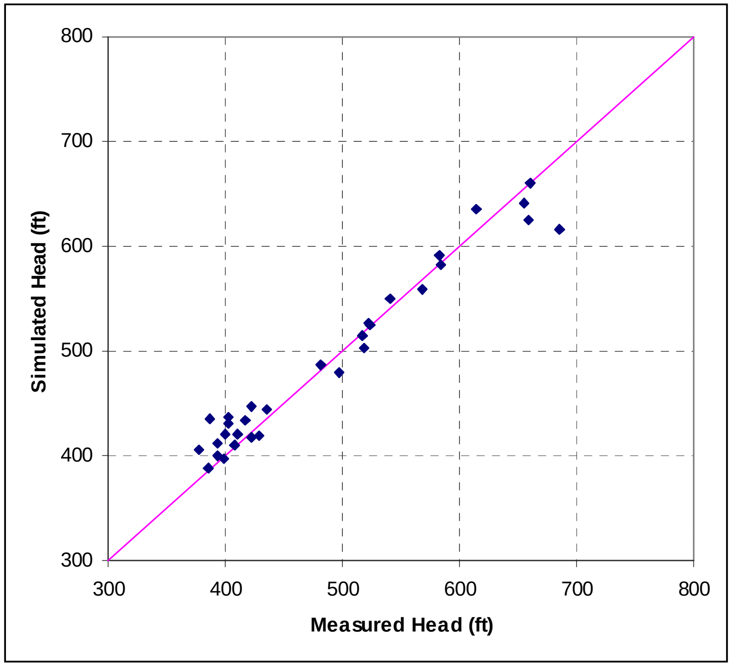




Layer	Count	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/ Range
1	15	-3.8	18	22	210	0.10
3	16	-7.4	22	26	288	0.091
5	31	-3.7	16	22	308	0.071

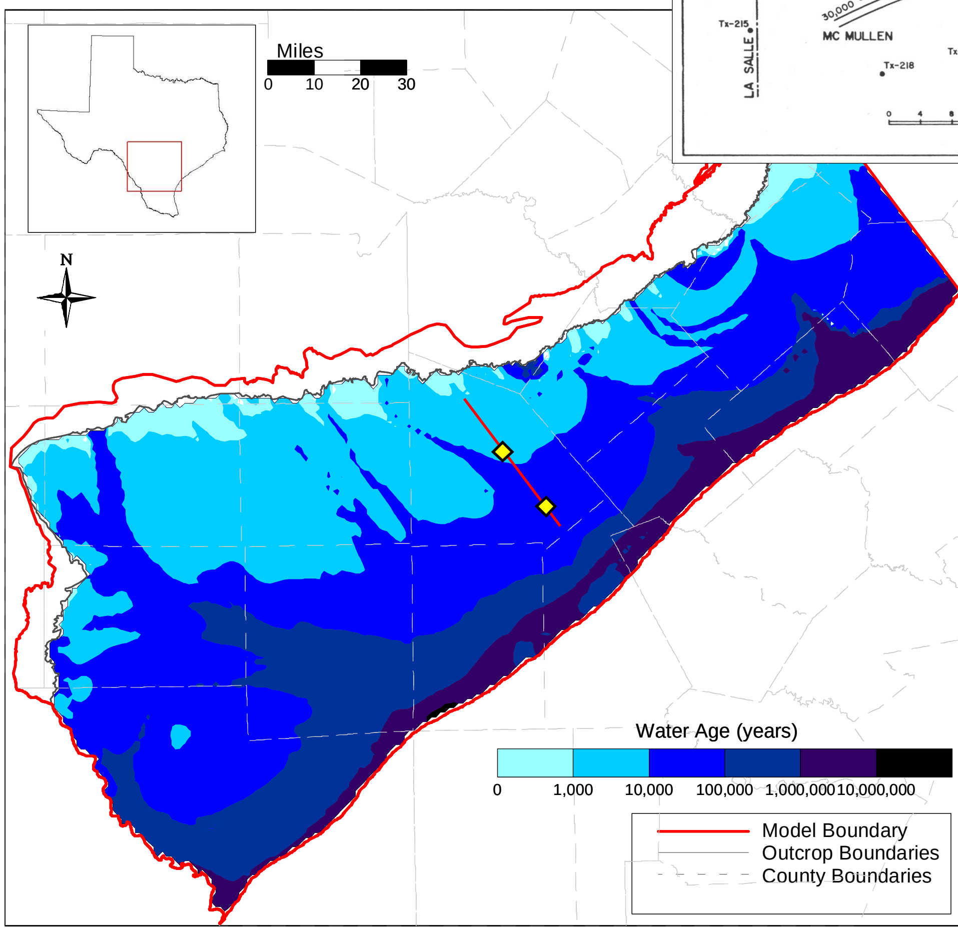
Carrizo – Southern GAM

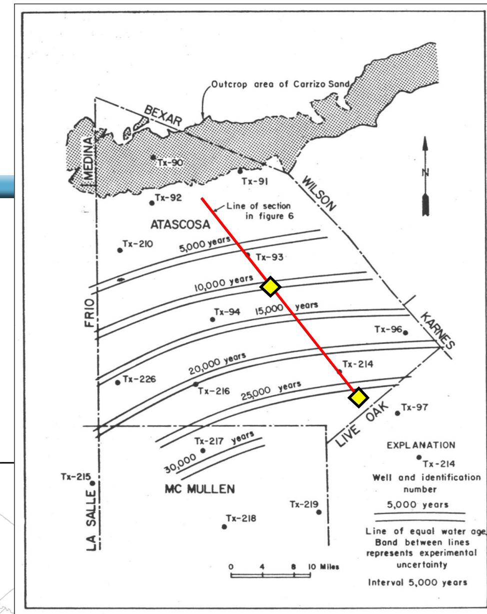




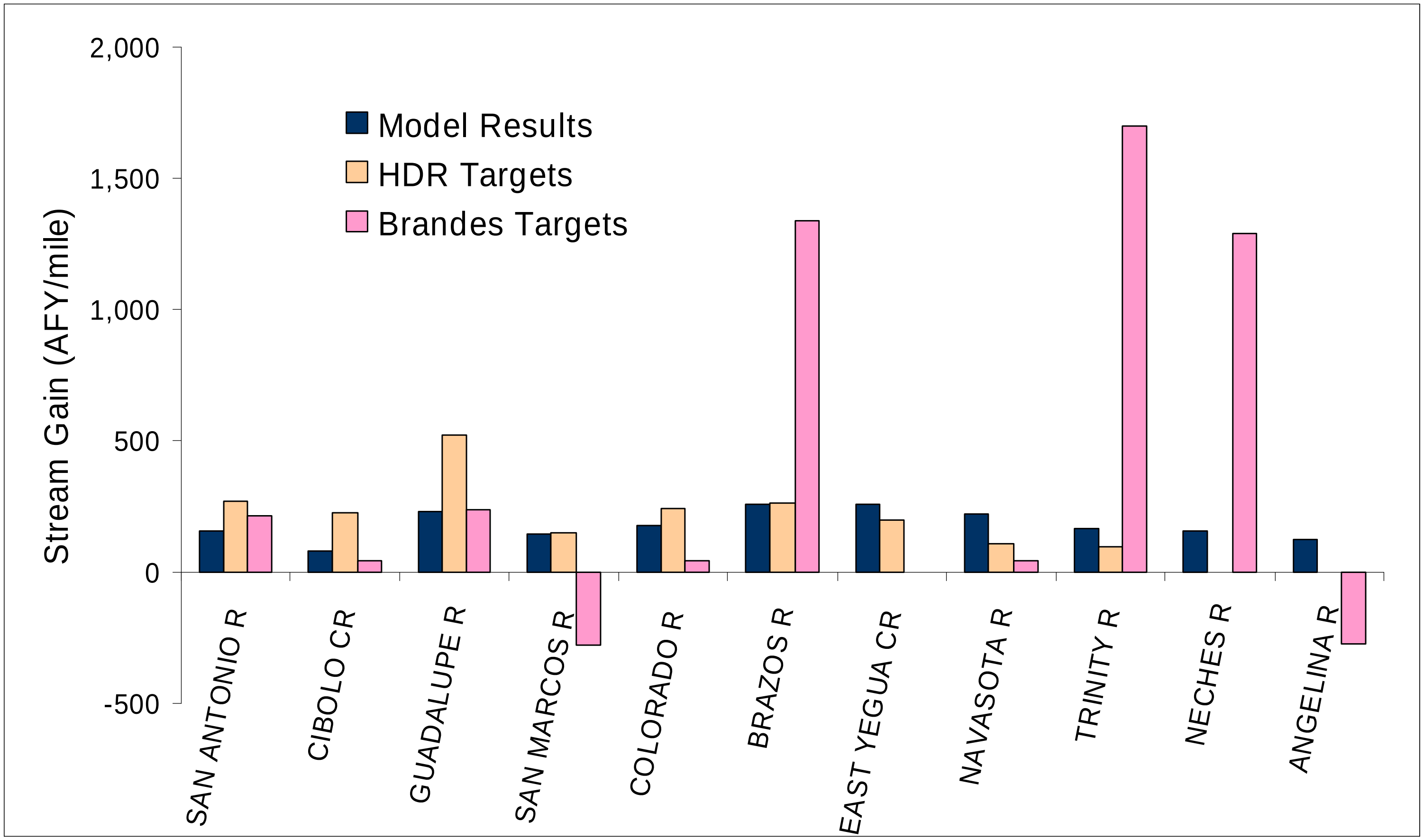
Layer	Count	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/ Range
1	15	-3.8	18	22	210	0.10
3	16	-7.4	22	26	288	0.091
5	31	-3.7	16	22	308	0.071

Travel Time (years)





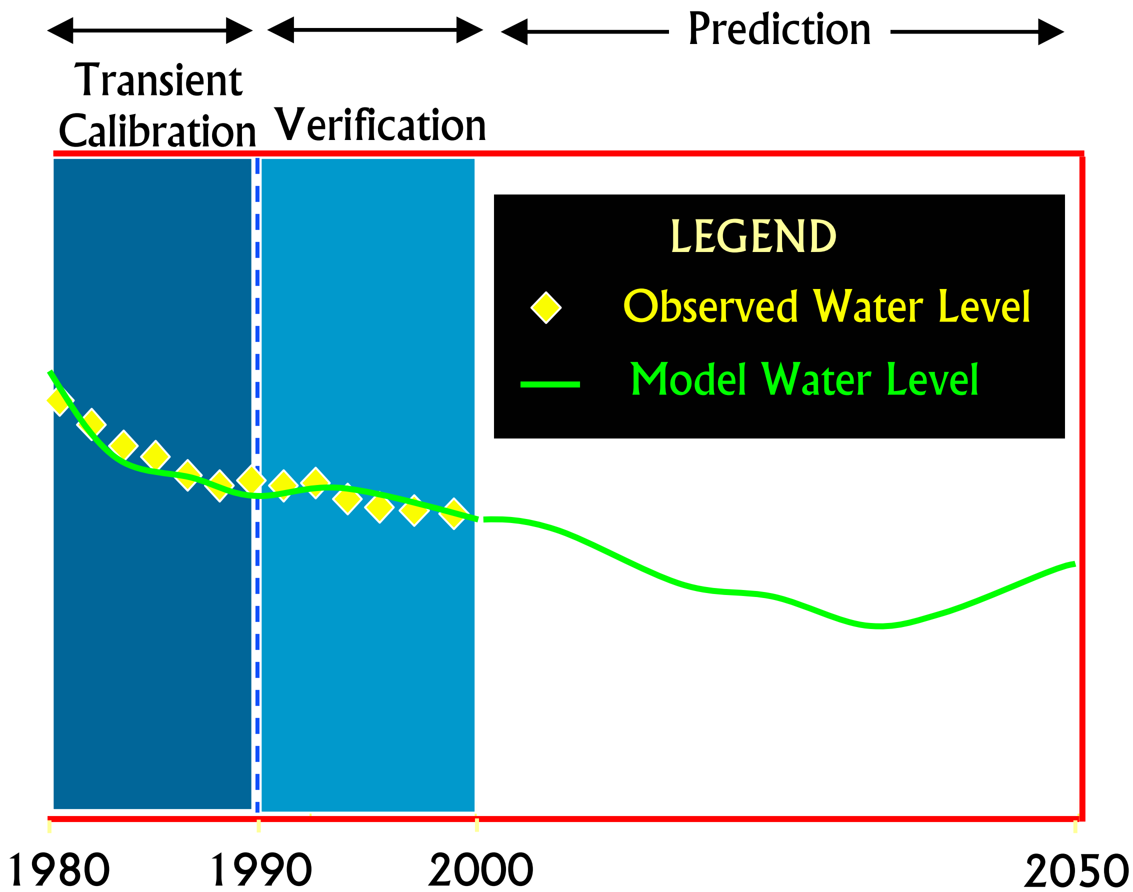
Central GAM Stream Targets



Steady-State Flow Balance Summary

GAM	Recharge (AFY)	GWET (%)	Streams/drains (%)	Confined flow (%)
South	218510	8%	69%	23%
Central	561600	34%	64%	8%
North	1187821	50%	48%	2%
	Recharge (AFY)	GWET (AFY)	Streams/drains (AFY)	Confined flow (AFY)
South	218510	16607	151209	50913
Central	561600	191400	357500	43900
North	1187821	593910	570154	23756

Transient Model



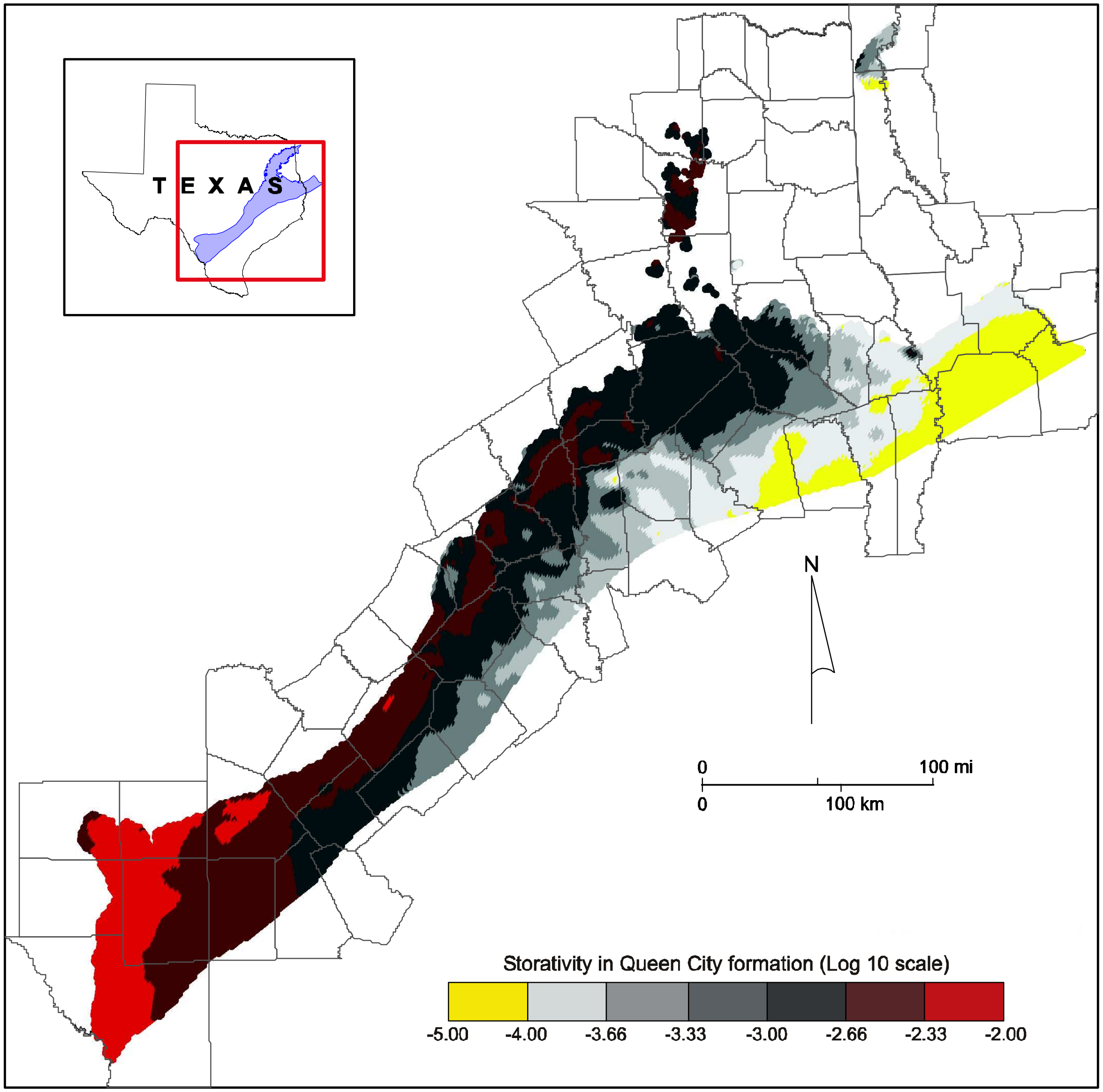
Storativity

- Storativity = Ss * b
- Specific Storage is f (depth, lithology)

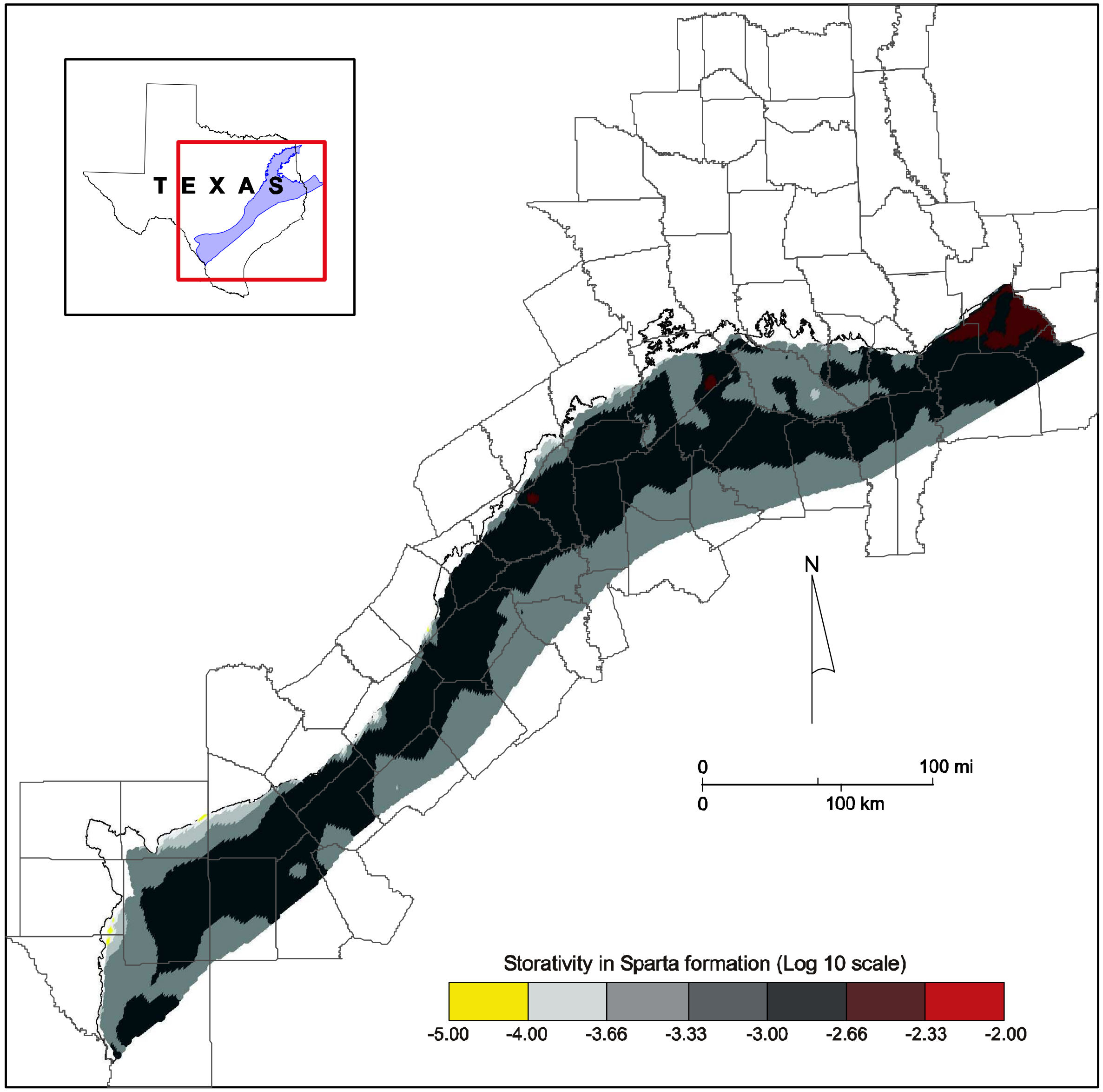
$$Ss = max\left[10^{-\frac{D_{up}-D}{D_{down}}}\left(SF \times Ss_{sand} + (1-SF)Ss_{clay}\right), Ss_{min}\right]$$

Queen City Storativity

- Method accounts for lithology and depth
- Prevents non-physical matrix compressibility



Sparta Storativity



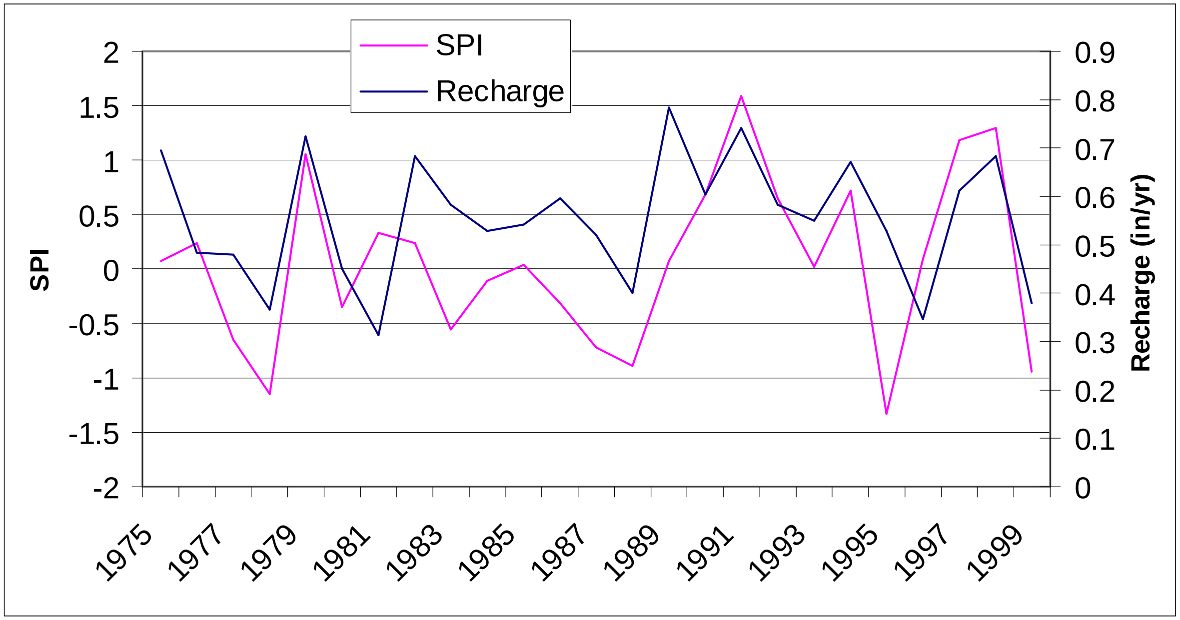
Transient Recharge Implementation

- Based upon an annual SPI
- R(t) = ((SPI(t) * 1/3) + 1) * Rss
- The limits are constrained by Scanlon (2003)
- The method reverts to the mean

Validation in Gonzales Co.

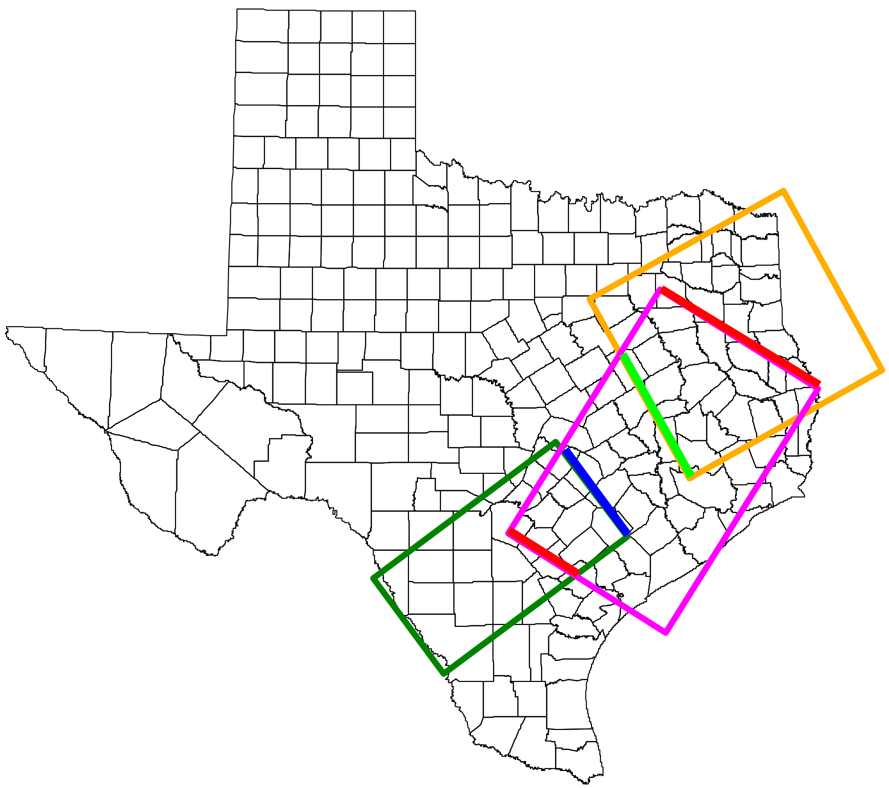
SPI from nearby gage, not used
To generate transient recharge.

Method shows good regional trends
and reverts to the SS recharge at
SPI = 0.



Lateral Boundaries

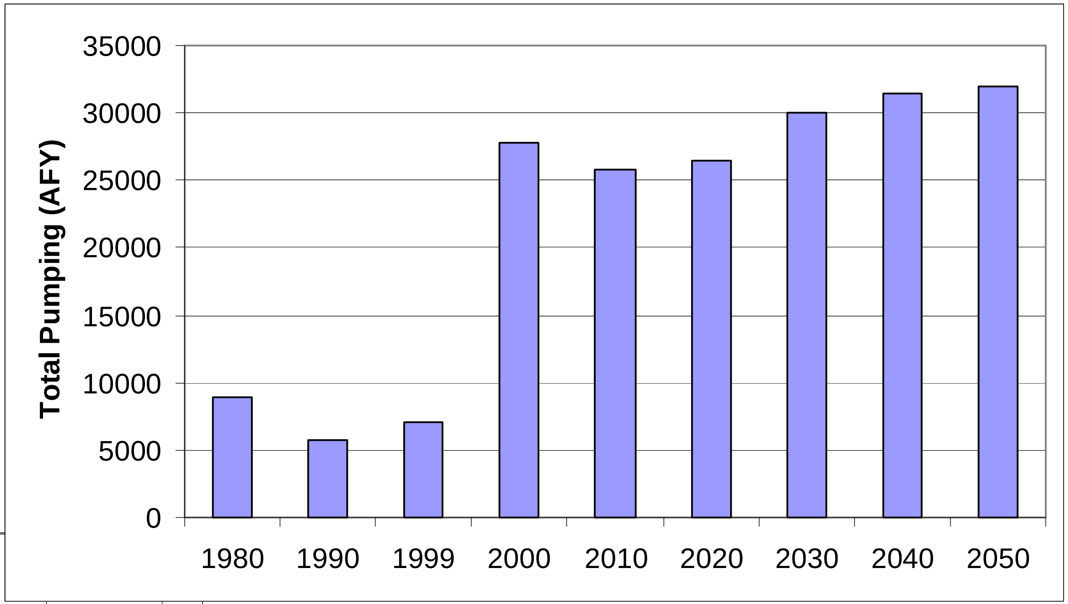
- Lateral Boundaries are treated as General Head Boundaries
- We exchanged lateral heads between models

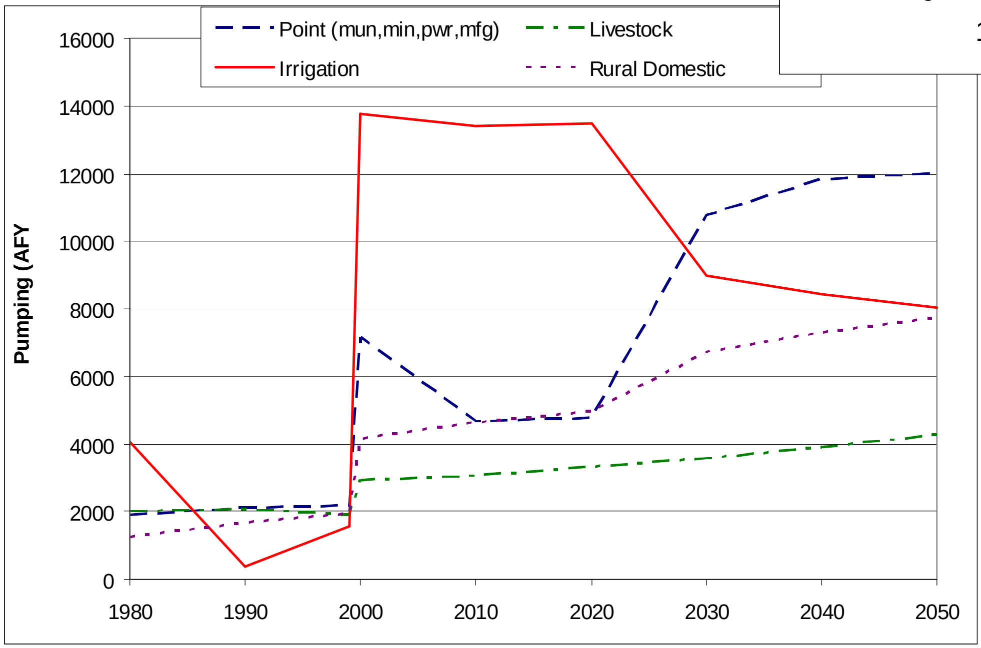


Pumping

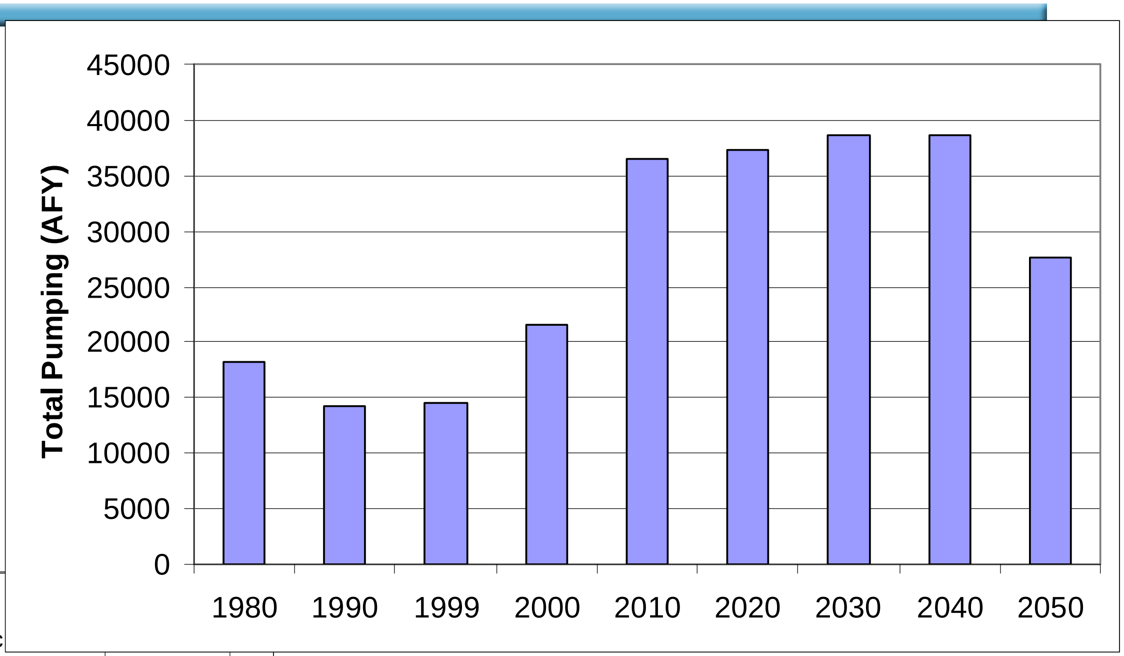
- Used SOP originally developed by Parsons based upon TWDB guidance
- Pumping in the non-overlap regions in the Carrizo-Wilcox was largely unaffected with the exception of County-Other
- With the addition of Queen City and Sparta aquifers, County-Other was re-allocated to account for modeling of additional aquifers
- Pumping distributions in overlap zones were made consistent based upon closeness to TWDB database
  - However, old CZWX distributions are largely intact from old models with the exception of C/O pumping re-allocation

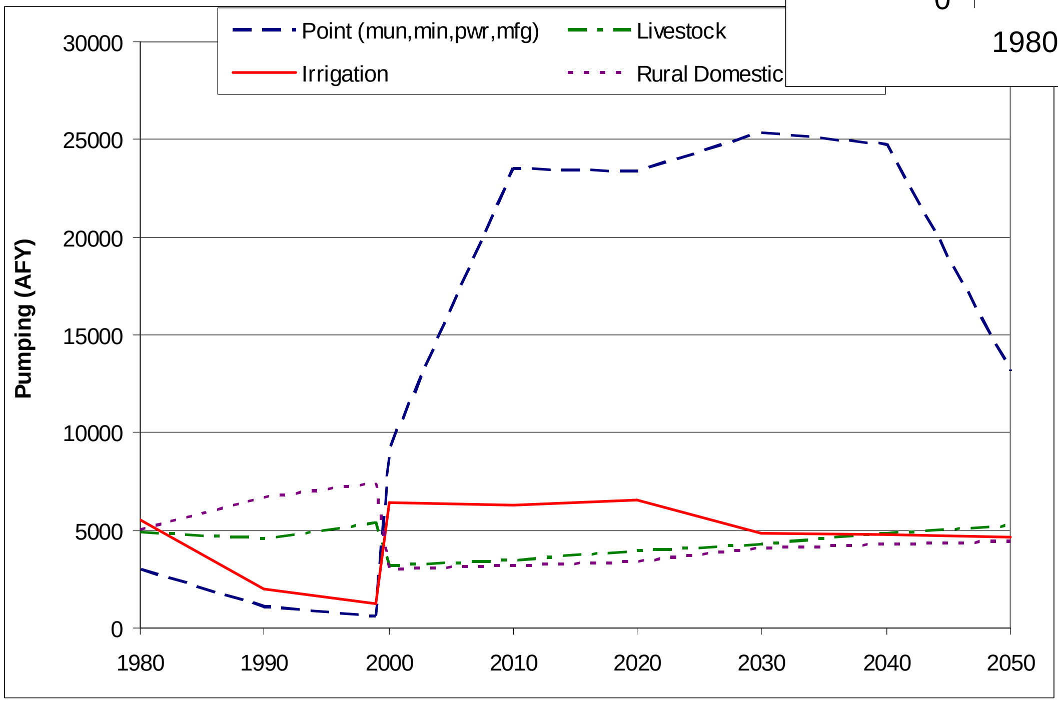
Sparta Pumping





Queen City Pumping



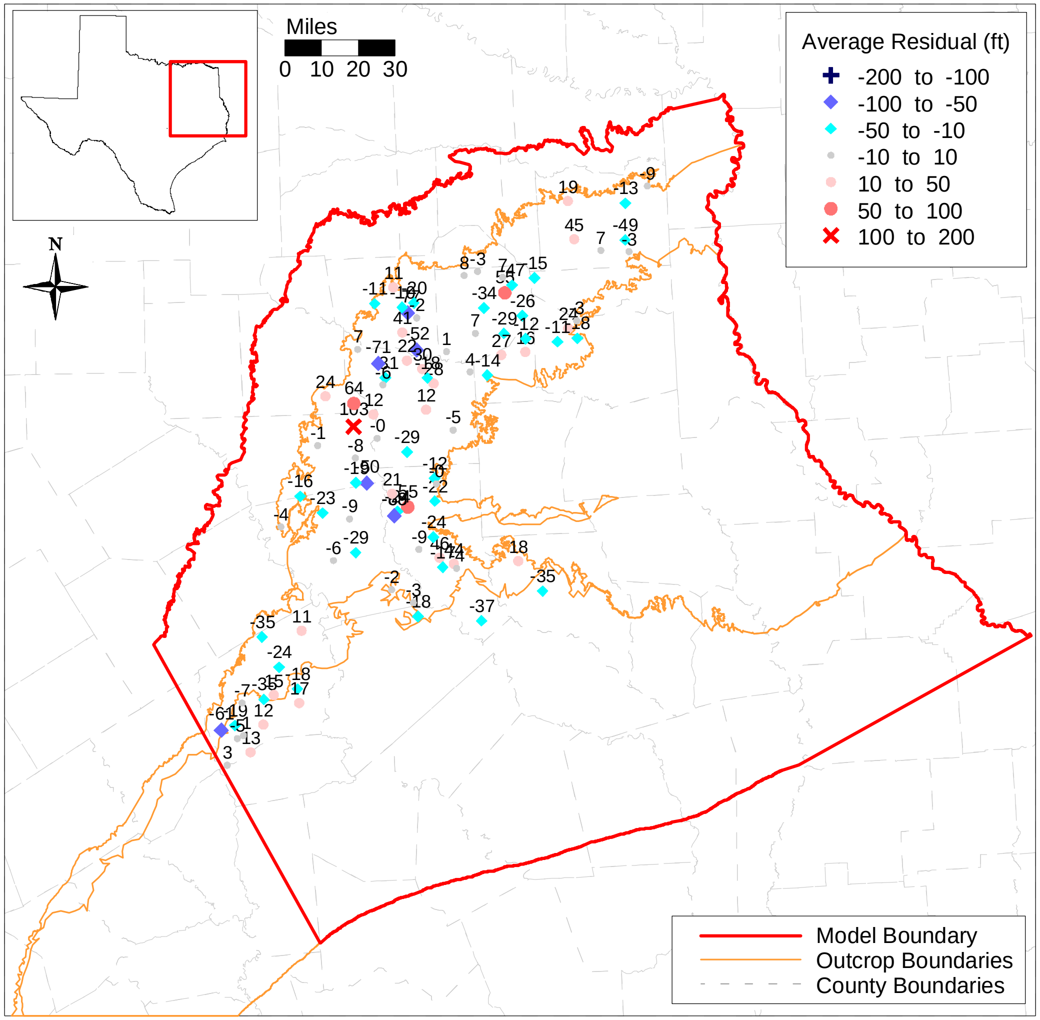


Transient Model

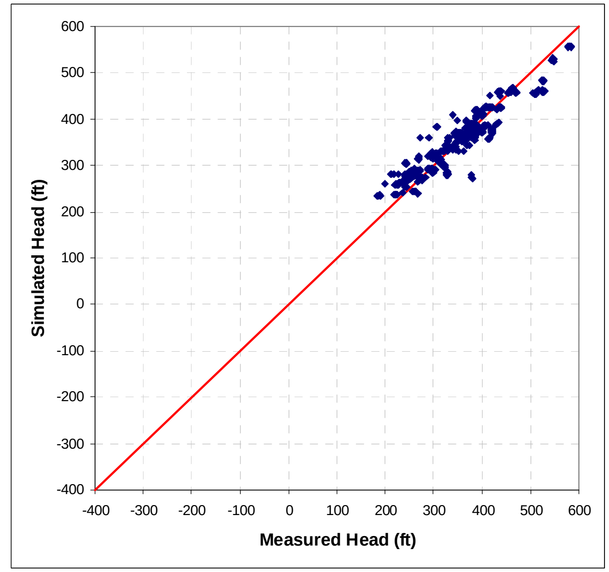
- Calibration Period – 1980 through 1989
- Verification Period - 1990 through 1999
- Approach to Calibration
  - Use multiple performance measures
    - Statistics
    - Head surfaces
    - Stream Gain and Loss
  - We use regularization (interpolation functions) to estimate parameters trying to limit the degree of unknowns
    - Kh depth trend
    - Storage depth trend and endpoints
    - Recharge factors and topographic scalar
  - Parameters poorly known were preferentially altered if they were important (the model responded to them)

Queen City End of Calibration 1989- North

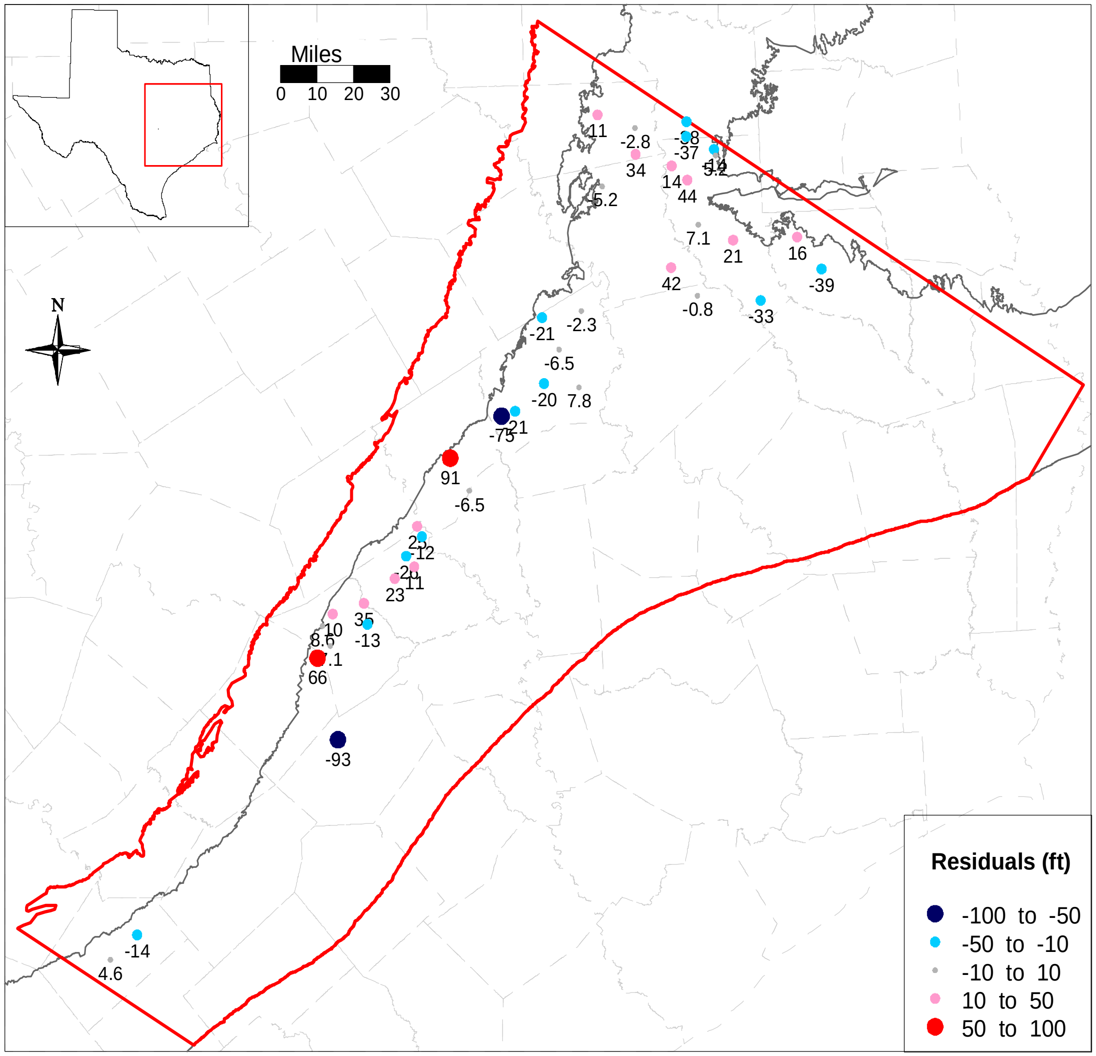
Residuals

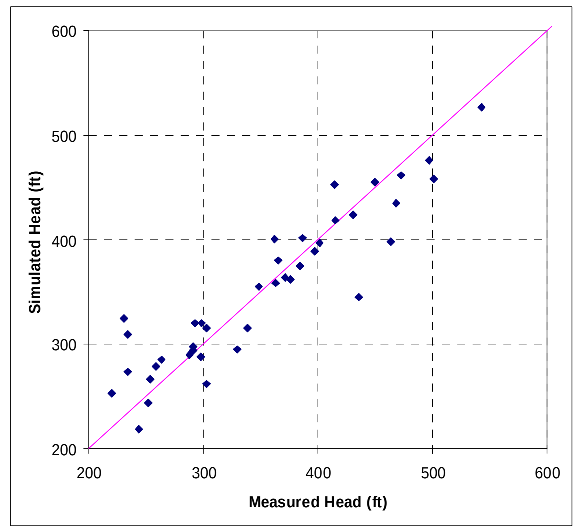


Crossplot



Queen City End of Verification 1999-Central

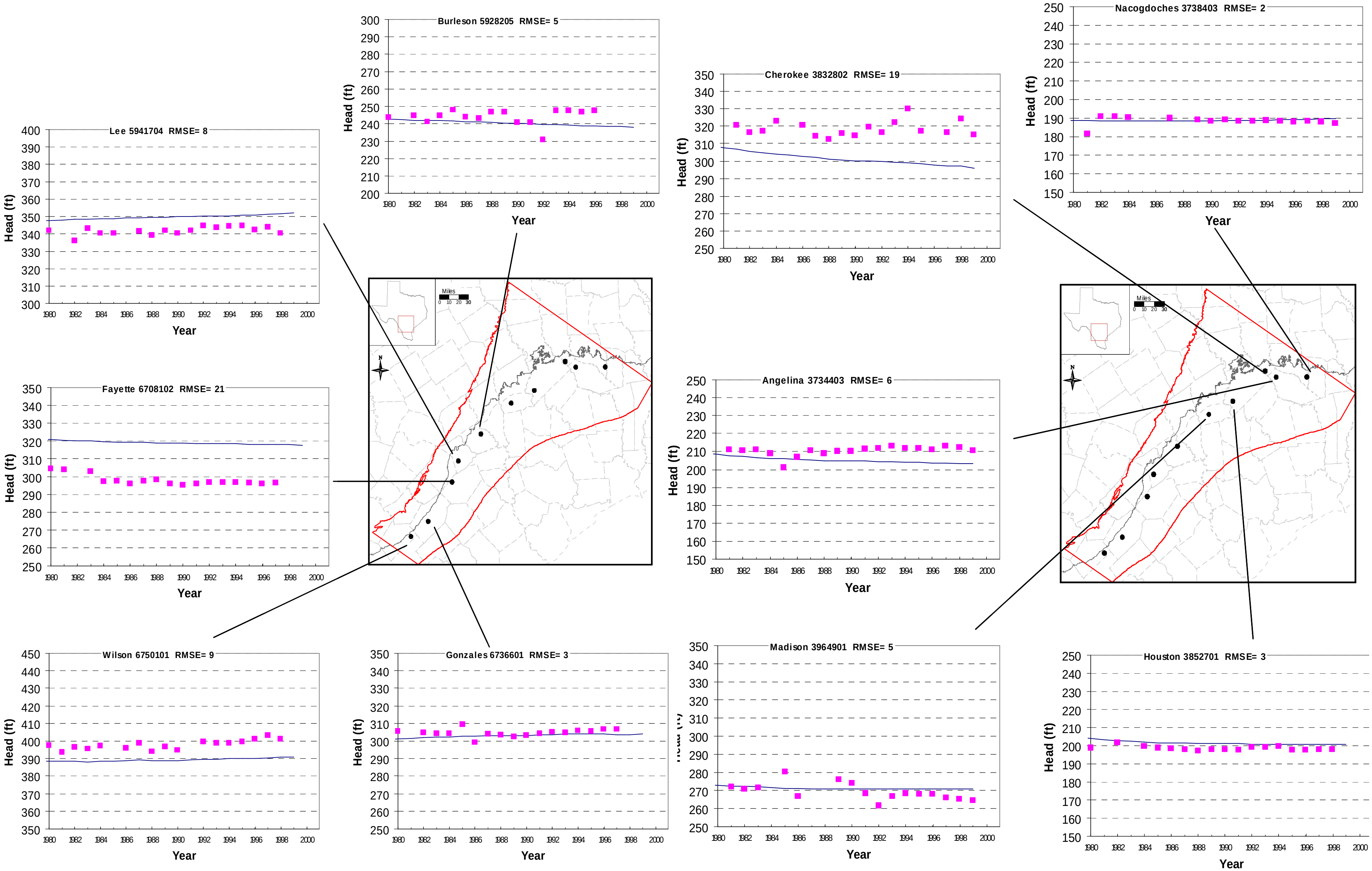




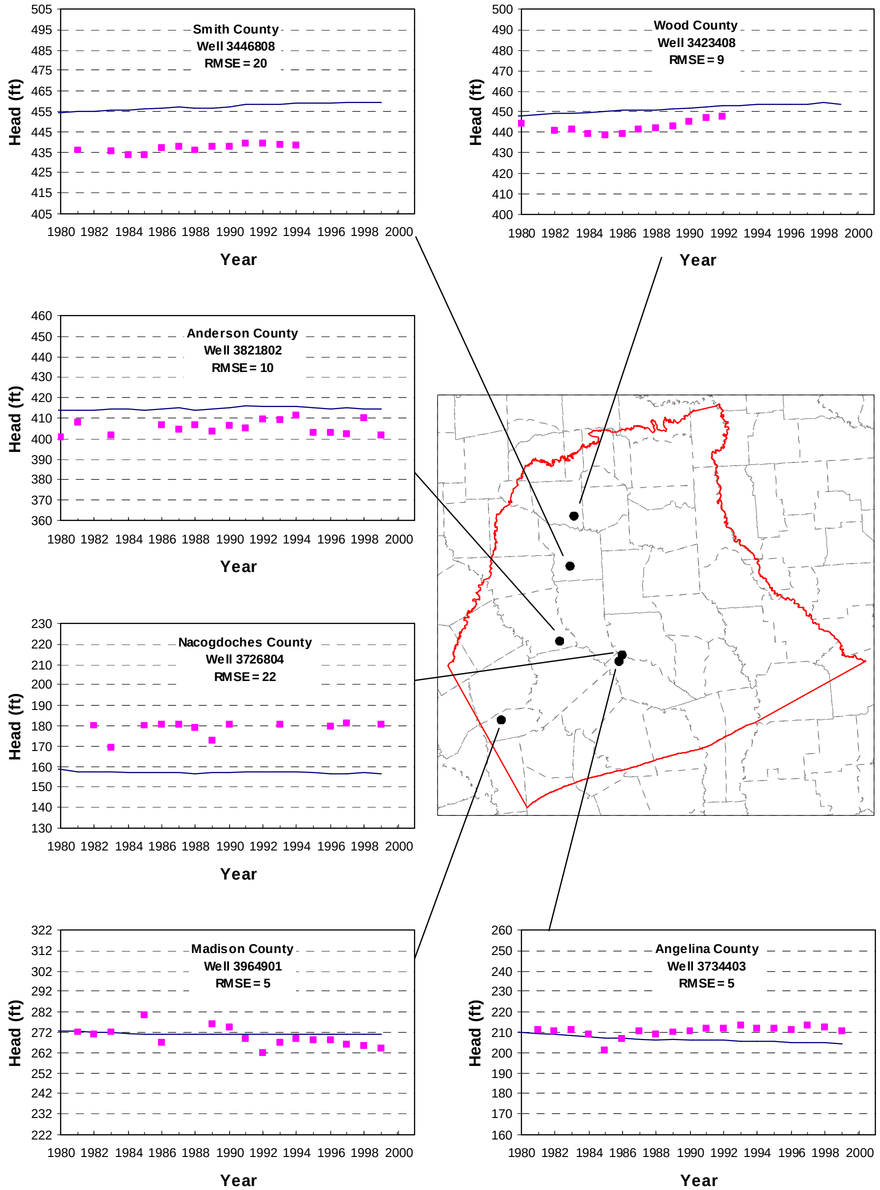
Hydrographs

- Combined error in absolute head values is on the order of 30 to 50 feet:
  - Grid elevation errors
  - LSD errors
  - Scale errors
    - effective wellbore radius,
    - vertical gradients
- Both trend and magnitude should be considered
- Offsets in magnitude of 30 feet are within the error defined above

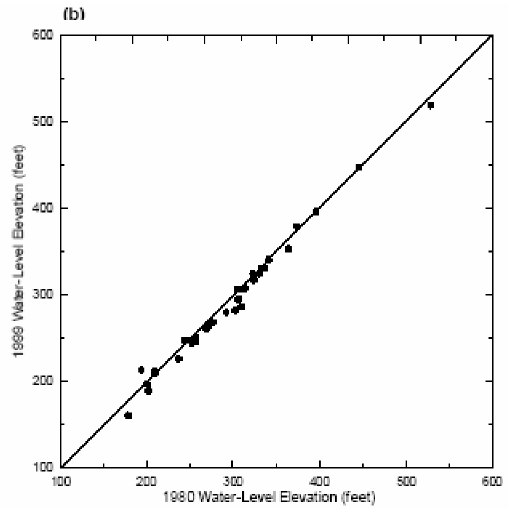
Sparta Aquifer – Central Region



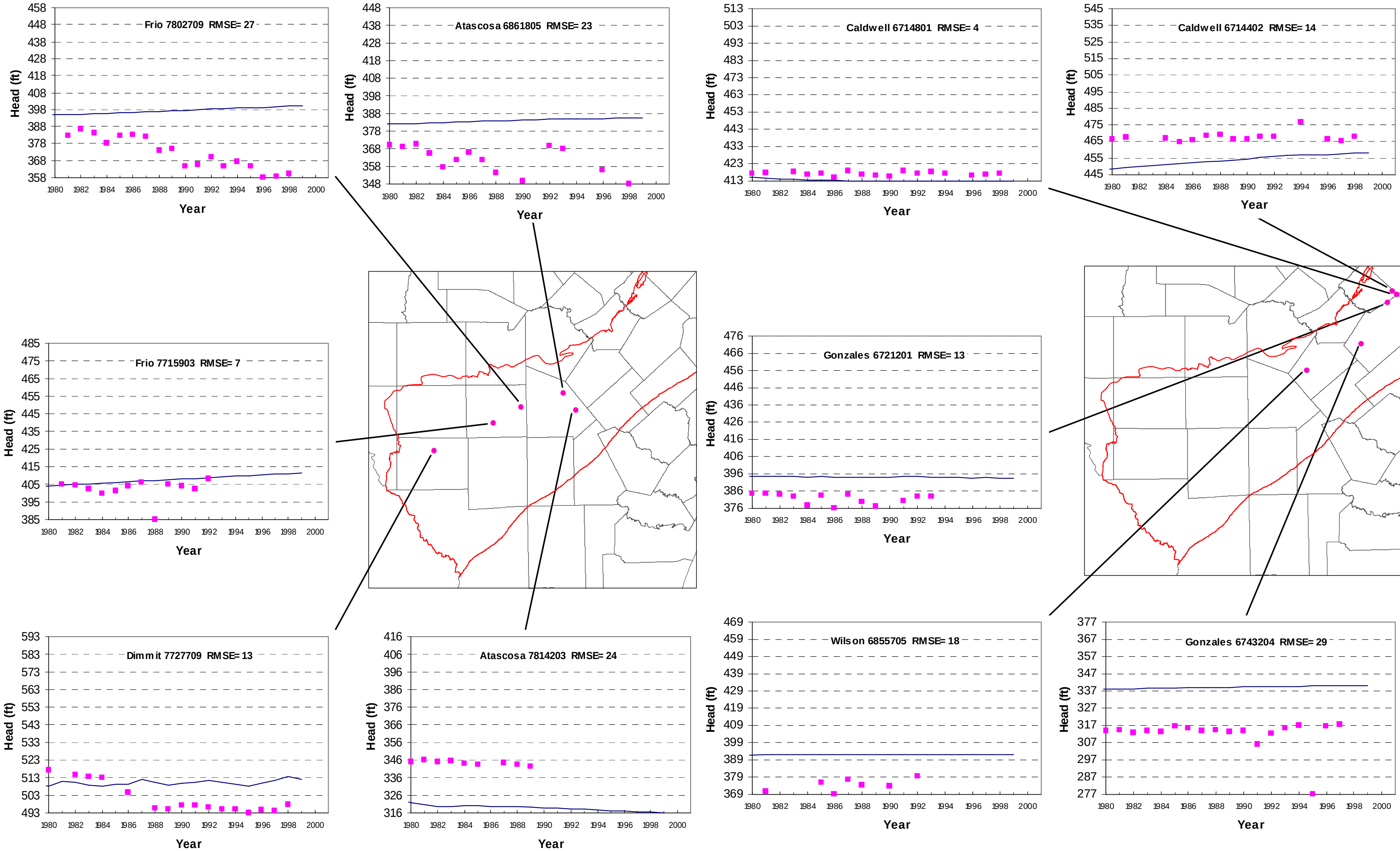
Sparta Aquifer – Northern Region



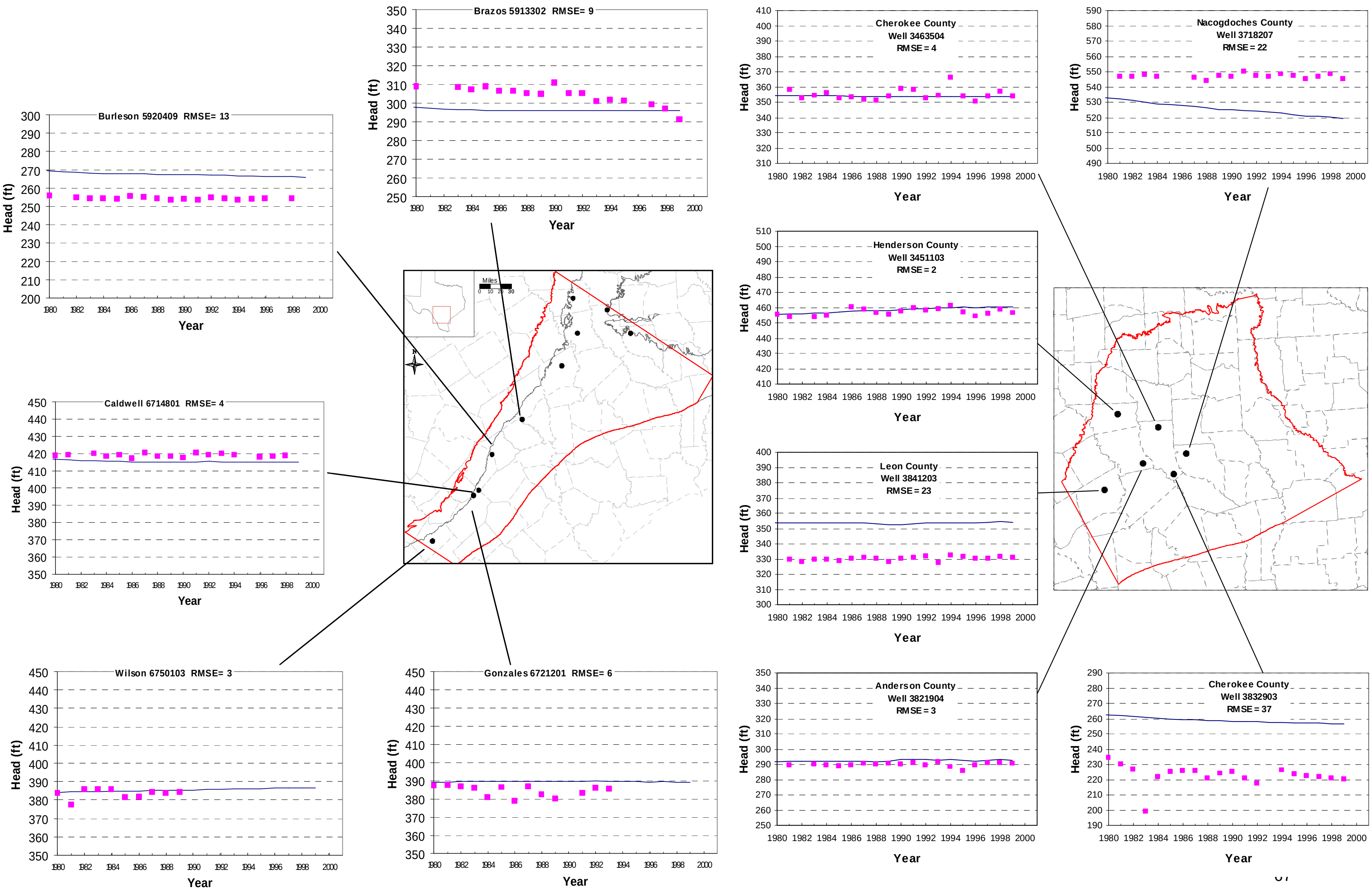
- Sparta Summary
  - Not a significant amount of regional scale drawdown in calibration period.
  - Drawdown tends to be local when they occur.



Queen City Aquifer - South



Queen City Aquifer – Central to North



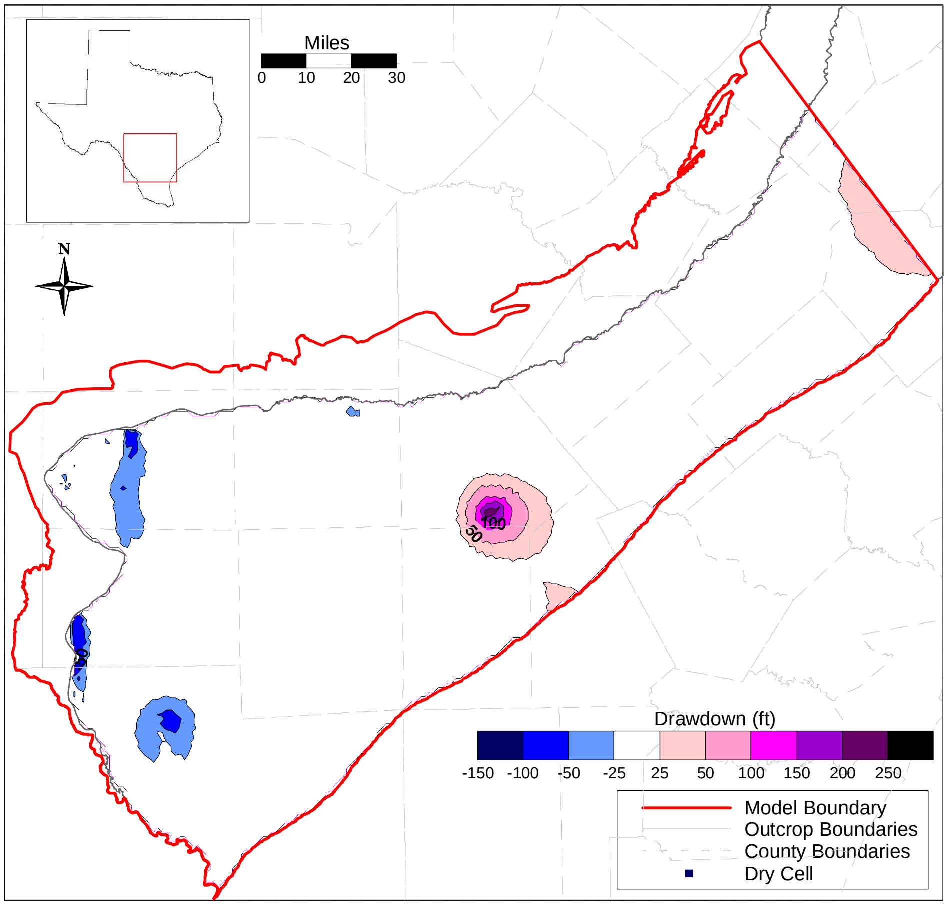
Significant calibration parameter changes

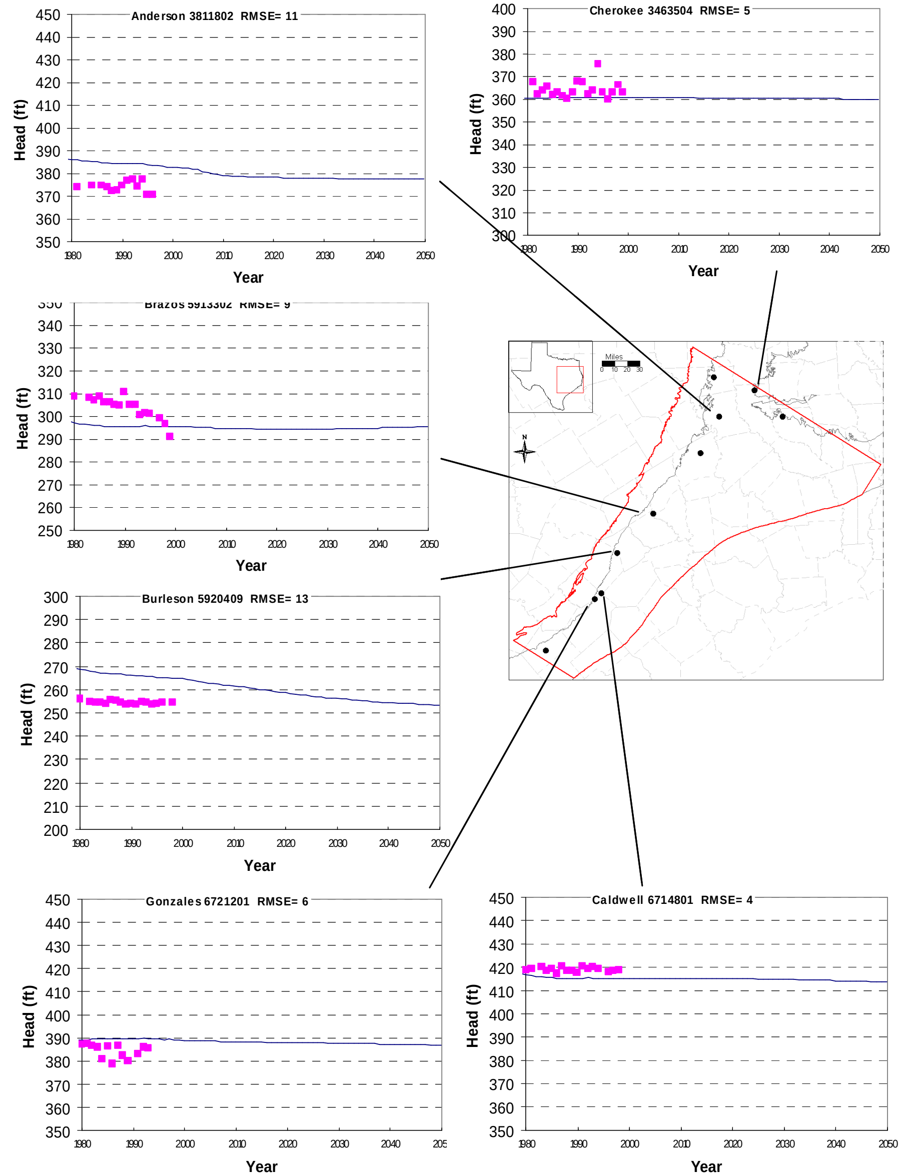
- Recharge varied significantly but our initial estimates were found to be best for the three models (compromise in overlap zones)
- Recharge in Sabine Uplift for U. and M. Wilcox slightly increased
- Reklaw Kv lowered in North GAM to $1x10^{-5}$ ft/day
- Reklaw Kv held at $1x10^{-4}$ ft/day in Nacagdoches, S. Rusk and E. Cherokee counties
- Kh lowered in Carrizo in Upshur and Smith counties and in Angelina county (Lufkin)
- Streams conductances were locally adjusted when gain/loss estimates were grossly in error

Predictive Simulations

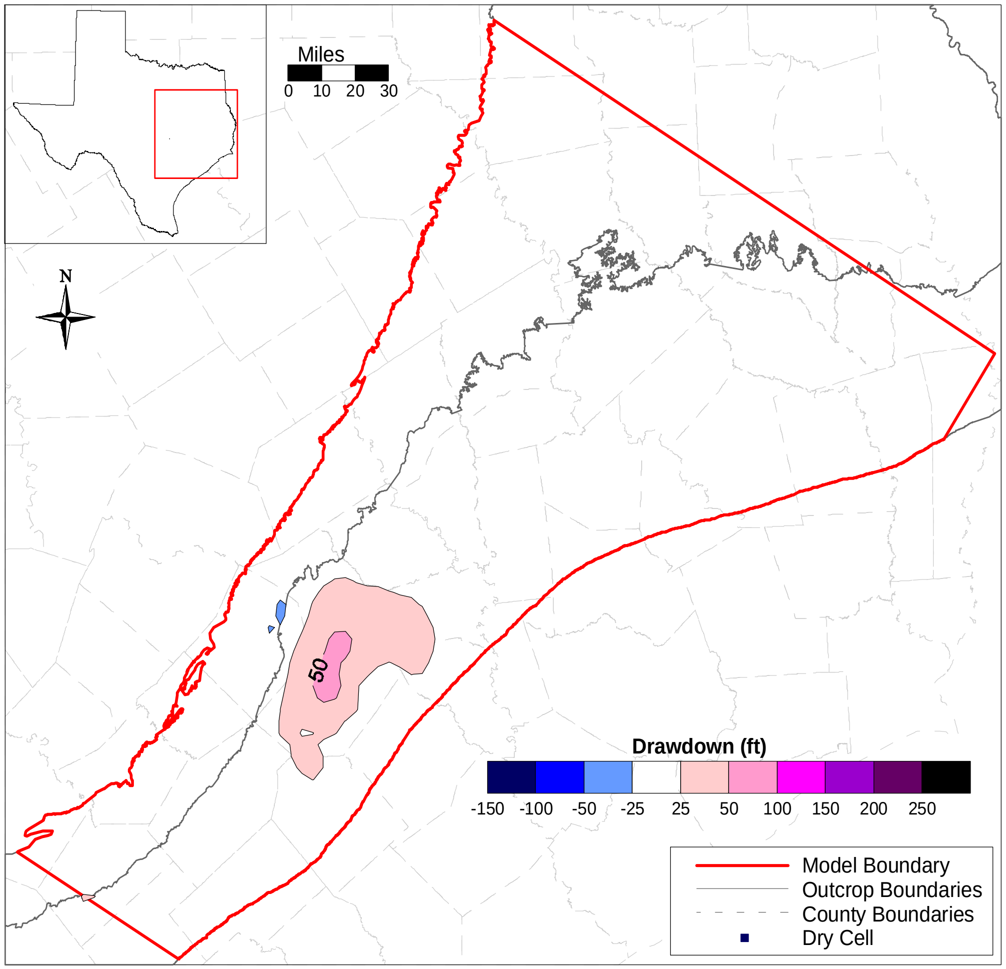
- Six Model Scenarios:
  - Average Recharge Conditions through 2050
  - Average Recharge Conditions ending with the drought of record (DOR) in 2010
  - Average Recharge Conditions ending with the drought of record (DOR) in 2020.
  - Average Recharge Conditions ending with the drought of record (DOR) in 2030.
  - Average Recharge Conditions ending with the drought of record (DOR) in 2040.
  - Average Recharge Conditions ending with the drought of record (DOR) in 2050.
- DOR is 1954 through 1956

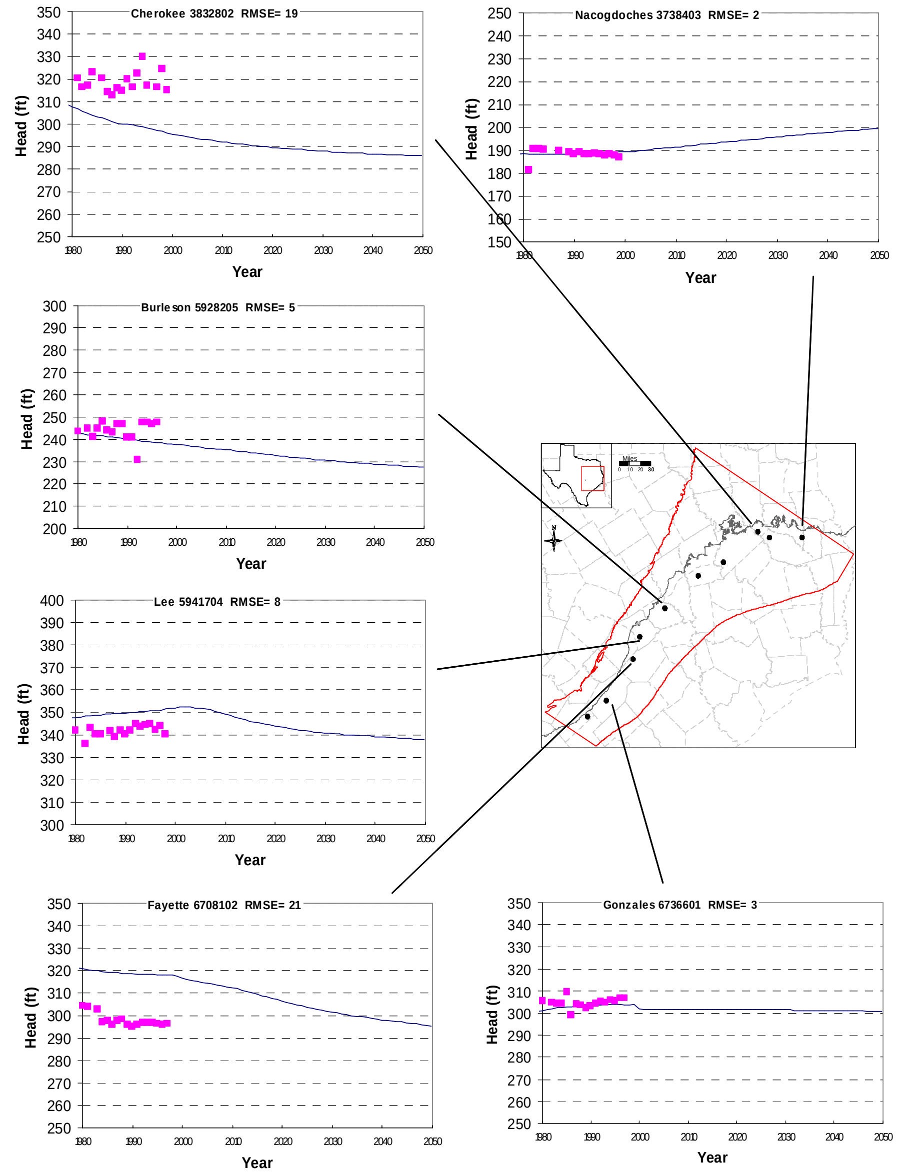
Queen City Drawdown 2050 - South



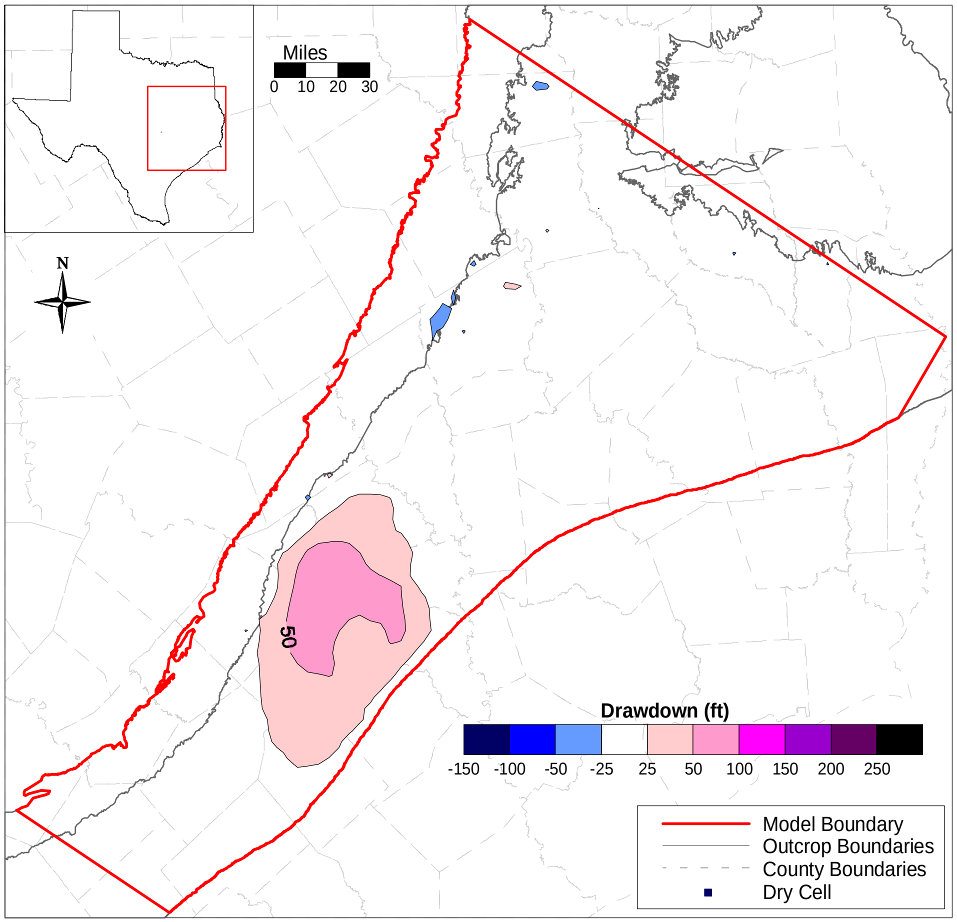


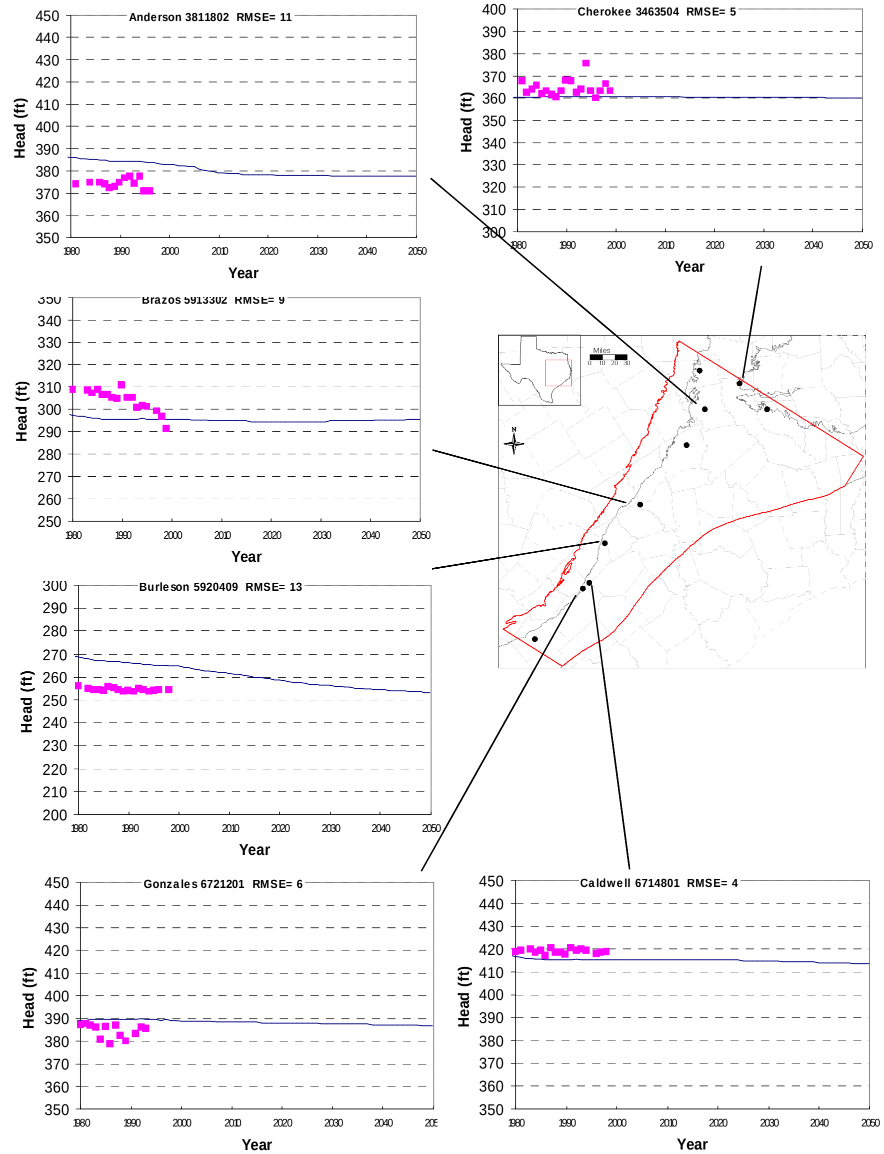
Sparta Drawdown 2050 - Central





Queen City Drawdown 2050 - Central





Conclusions from Predictive Simulations

- Significant drawdown is limited:
  - Southern Atascosa County in the Southern GAM
  - Fayette and surrounding counties in the Central GAM

- No significant effect of DOR
  - Pumping estimates do not increase in DOR

Conclusions

- GAMs for the Queen City and Sparta aquifers:
  - 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)
- Developed a consistent (though uncertain) recharge distribution across CZWX and QCSP in Texas
- Developed consistent parameterization between GAMs in the overlap

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

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**

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**

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

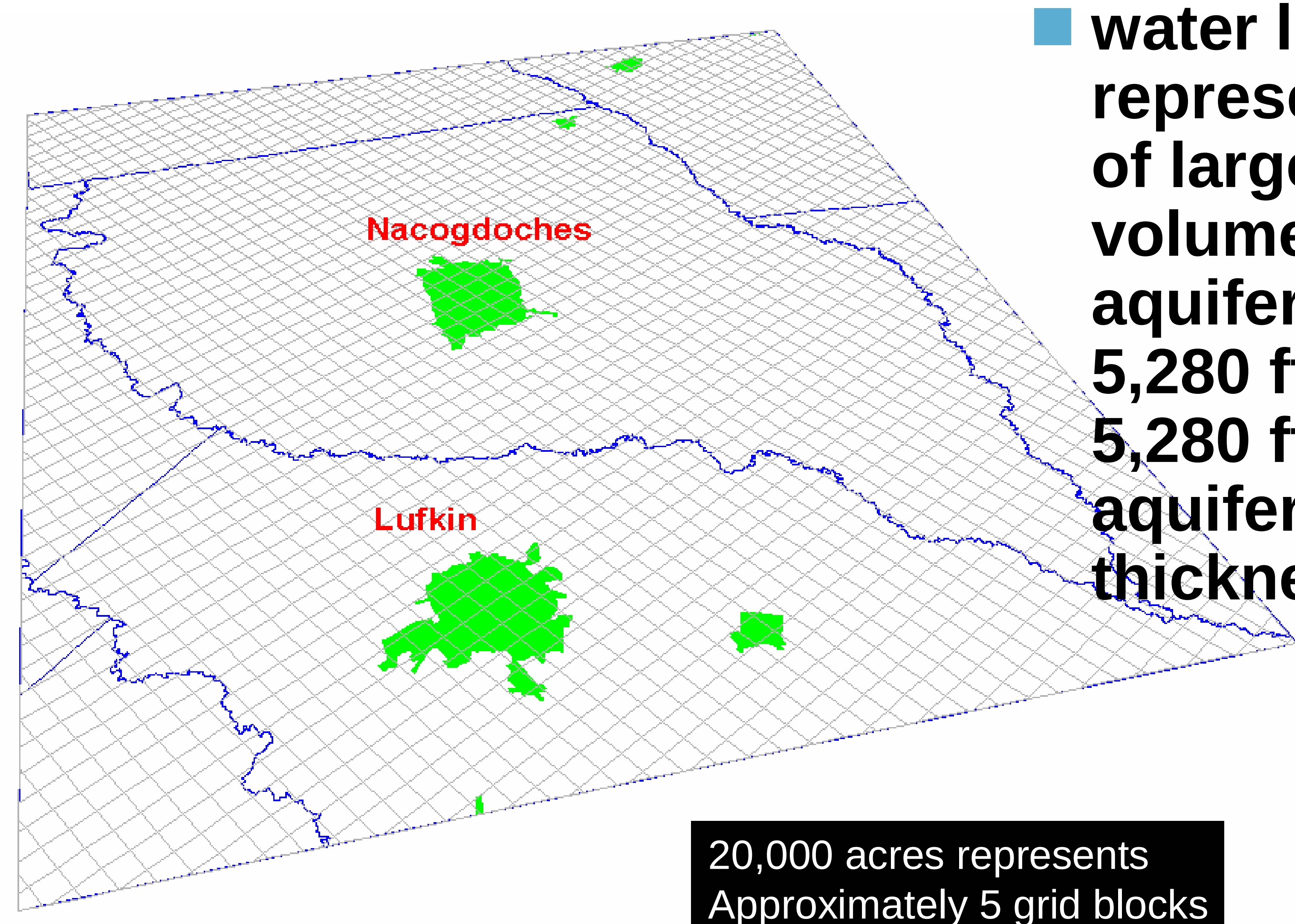
Limitations & Applicability of the GAM

- 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

Parameter Limitations

- **Structure**
  - Regionally estimated over hundreds of miles
  - Can be improved for sub-regional assessments
- **Horizontal hydraulic conductivity**
  - Limited for the Sparta (38 point values)
- **Vertical hydraulic conductivity (leakance)**
  - Not measurable, poorly constrained to <= 1E-4 ft/day
  - Very poorly defined in areas of little drawdown
- **Storativity**
  - General lack of measurements, important for sustainability assessments
- **Recharge**
  - Poorly defined by the model plus suffers from being a function of model scale
- **Pumping – Where?**

Model Grid Scale



- water levels representative of large volumes of aquifer (e.g., 5,280 ft X 5,280 ft X100 ft aquifer thickness)

20,000 acres represents
Approximately 5 grid blocks

Limited to regional scale assessments

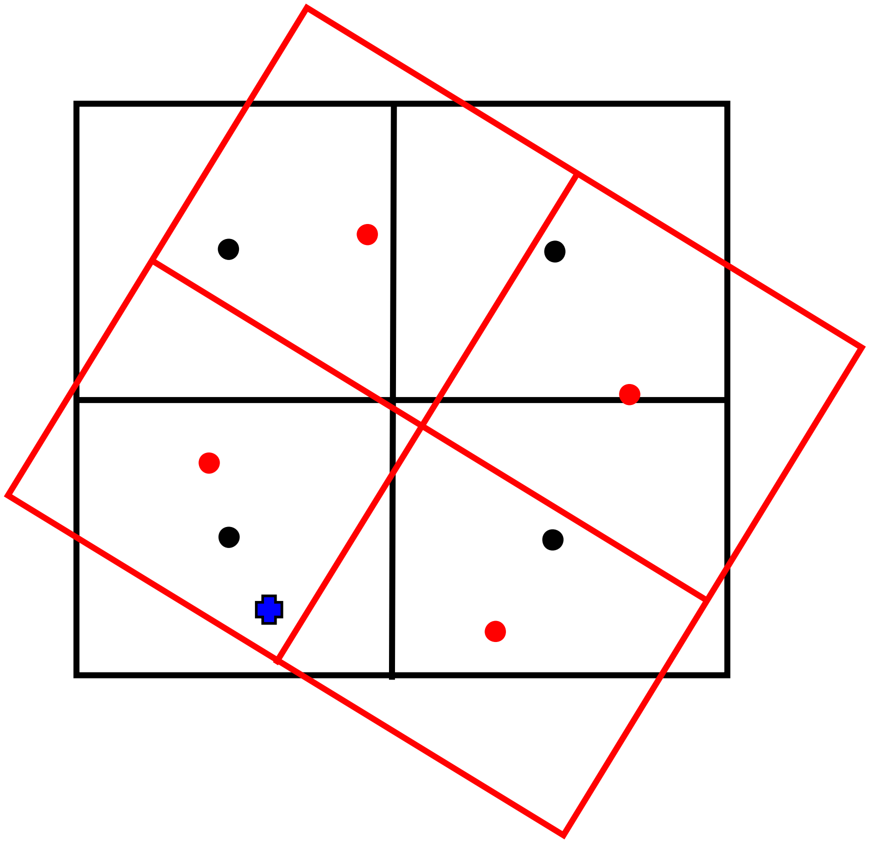
- **The GAM is a tool capable of being used to predict aquifer responses to pumping scenarios on a regional scale**
  - The model is not capable of being used in it's current state to predict aquifer responses at particular points such as a particular well
- **The model is well suited for refinement to address local-scale water resource questions.**

$$Re = \frac{0.198 \ \triangle x}{}$$

K = 15 ft/day
b = 600 ft
S = 0.0018

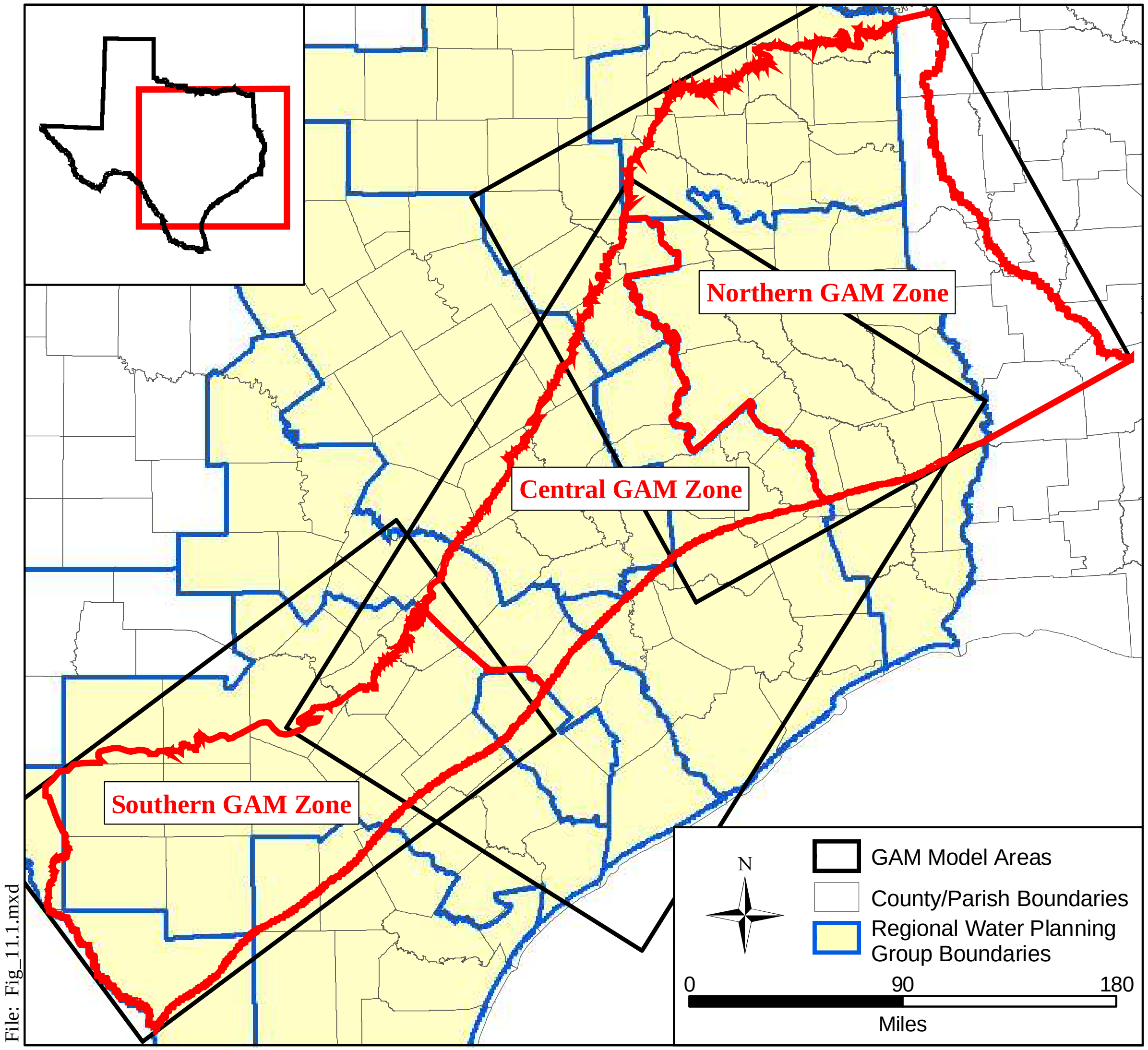
Steady-State Drawdown High-Production Well - 12 inch well		
Effective Radius of Observation	1000 gpm 1.4 MGD	500 gpm 0.7 MGD
well (0.5 ft)	43.9	22.0
gridblock (1,045 ft)	17.9	9.0

Grid Limitations in overlap



- **Models will have slightly different parameters and predicted heads as a result of the grids not being oriented**

Regions of Applicability



- **Caveats**
  - This is a recommendation by the model developers and is subject to revision by TWDB
  - If modeling the Simsboro, always use the Central GAM

Meeting Minutes for the

Sixth Queen City and Sparta Groundwater Availability Models (GAMs) Stakeholder Advisory Forum (SAF) Meeting

Model Training

October 19, 2004

Intera, Inc.

Austin, Texas

The sixth Stakeholder Advisory Forum (SAF) Meeting for the Queen City and Sparta Groundwater Availability Models (GAMs) was held on Tuesday, October 19th, 2004 at from 1:00 – 5:00 PM in the offices of Intera, Inc. located at 9111A Research Blvd in Austin. A list of meeting participants is shown at the end of these meeting notes.

The purpose of the sixth SAF meeting was to provide a "hands on" training opportunity for stakeholders interested in using the Queen City and Sparta GAMs.

Neil Deeds (INTERA) and Jean-Philippe Nicot (BEG) presented a series of prepared presentations regarding the Queen City/Sparta Groundwater Availability Models (GAMs) and also demonstrated the use of the GAMs within the PMWIN graphical user interface. The training session was structured according to the following outline:

1. Model Introduction
2. Queen City and Sparta Data Review
3. Example Model Application
4. Data Model Organization
5. Model Limitations and Applicability

The material presented at this seminar is available on the GAM website:

(http://www.twdb.state.tx.us/gam/qc_sp/qc_sp.htm)

Queen City Sparta Stakeholder Advisory Forum 6
October 19, 2004

Attendance

Name	Affiliation
Bob Kier	Robert S. Kier Consulting
Matt Uliana	Texas State University
Shirley Wade	TWDB
Neil Deeds	INTERA Inc.
Jean-Philippe Nicot	BEG