Groundwater Availability Modeling (GAM) for the Dockum Aquifer

GAM Stakeholder Training

October 22, 2008

Workshop Agenda

1. **Introduction**
2. **Modeling Overview**
   - Modeling Protocol and Practice
   - MODFLOW
   - Groundwater Vistas (GV)
3. **Dockum GAM Review**
   - Technical Overview
   - Data and Model Inputs
4. **Break**
5. **Modeling Demonstration**
   - The GV Interface
   - Transient/Predictive Model Exercise(s)

Workshop Goals

- Provide an introduction to groundwater modeling, MODFLOW, and GV
- Review the development of the Dockum 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

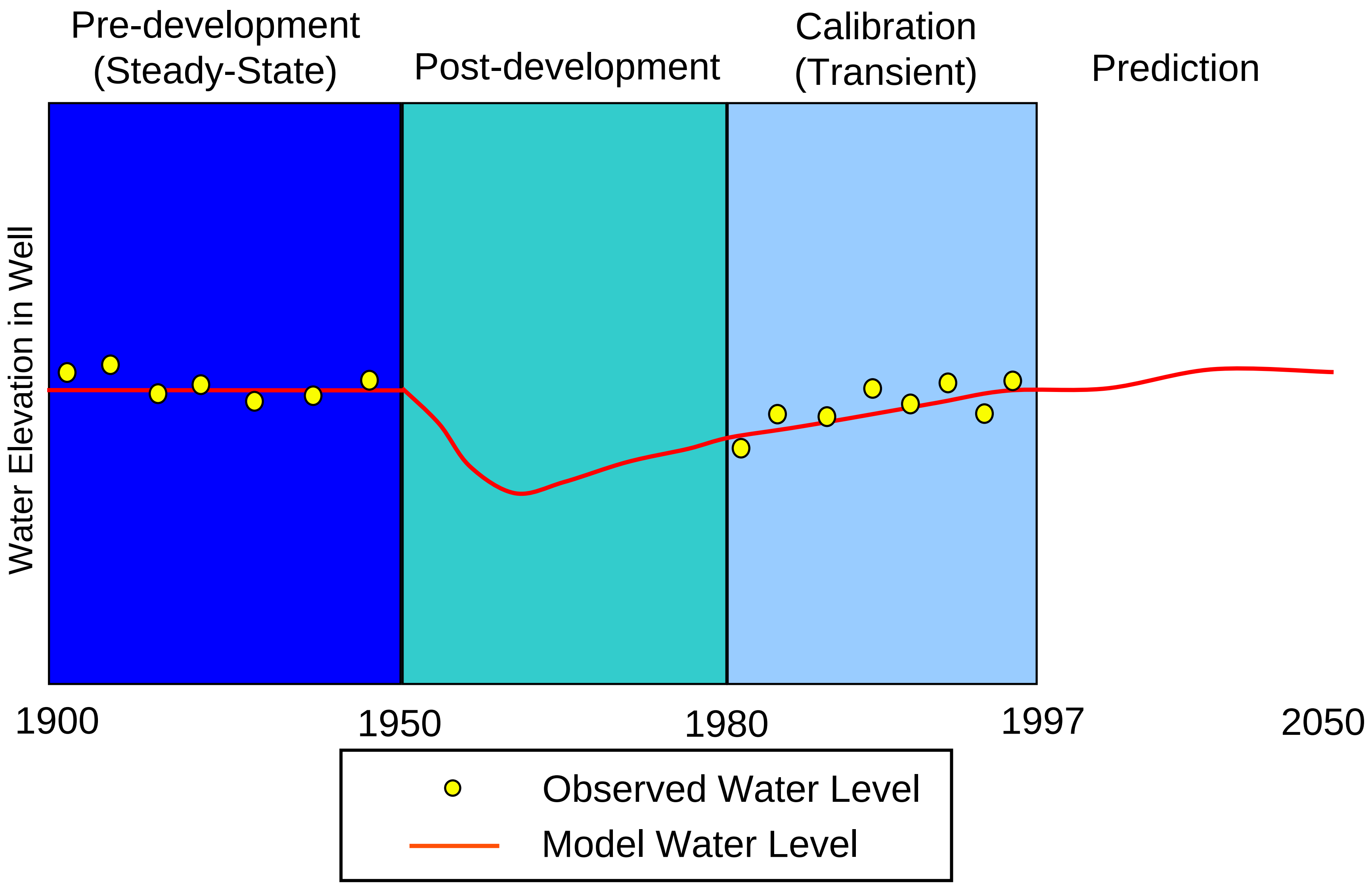
GAM Objectives

- **Develop realistic and scientifically accurate groundwater 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-2000)
- Regional scale (1000's of mi^2)
- Grid spacing of 1 square mile
- Include Groundwater/surface water interaction (Stream routing, Prudic 1988)
- Properly implement recharge
- Stress periods as small as 1 year
- Calibrate to within 10% of head drop

Schematic of Modeling Periods



Steady-state and transient calibration periods represent different hydrologic conditions

Modeling Overview

- **Modeling Protocol & Practice**
- **MODFLOW**
- **GV – Groundwater Vistas**

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

GW Models in Water Resources

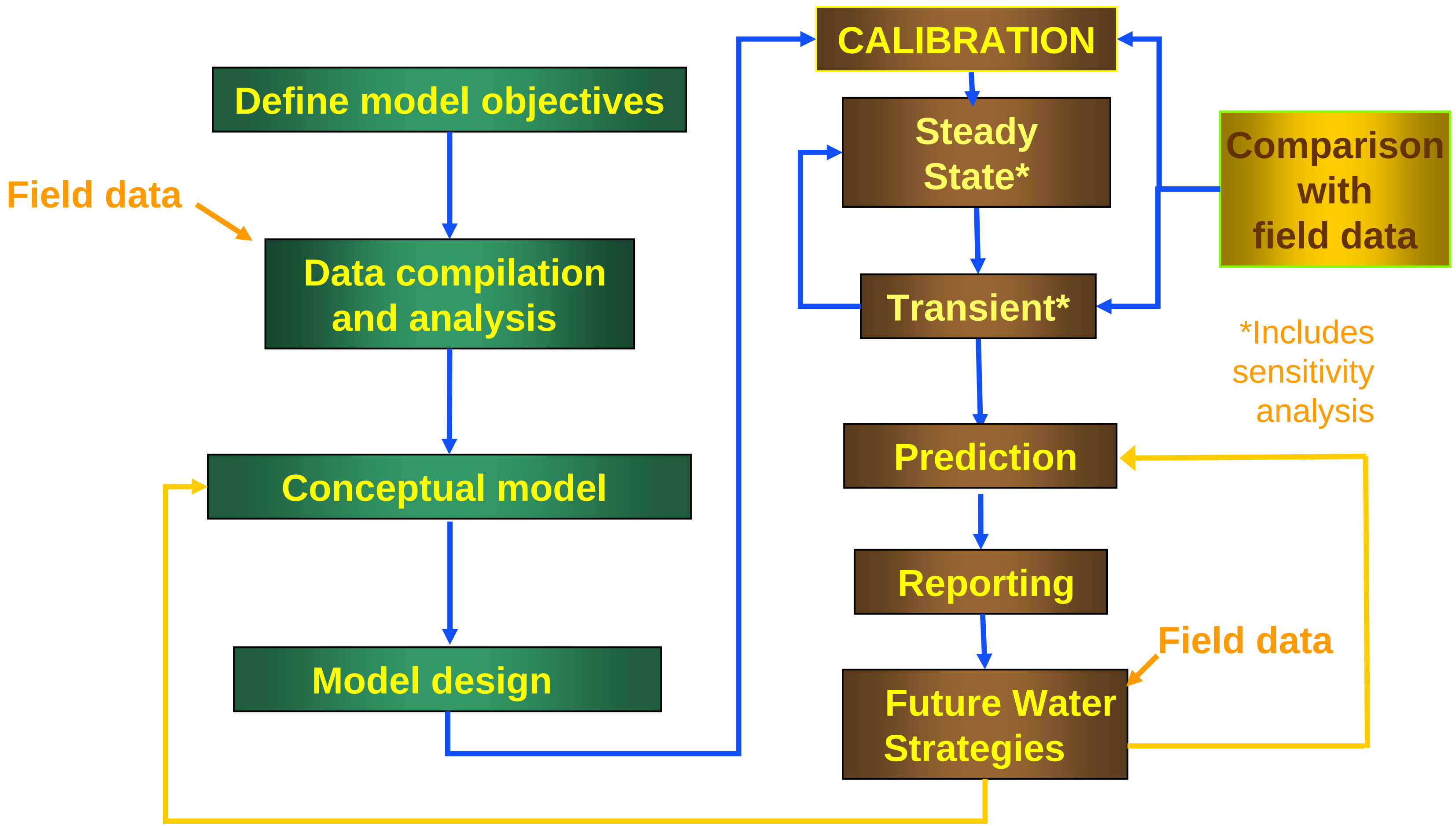
GW Models have been used in water resources in response to 4 basic issues.

- **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**

To be Considered in Code Selection

- 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

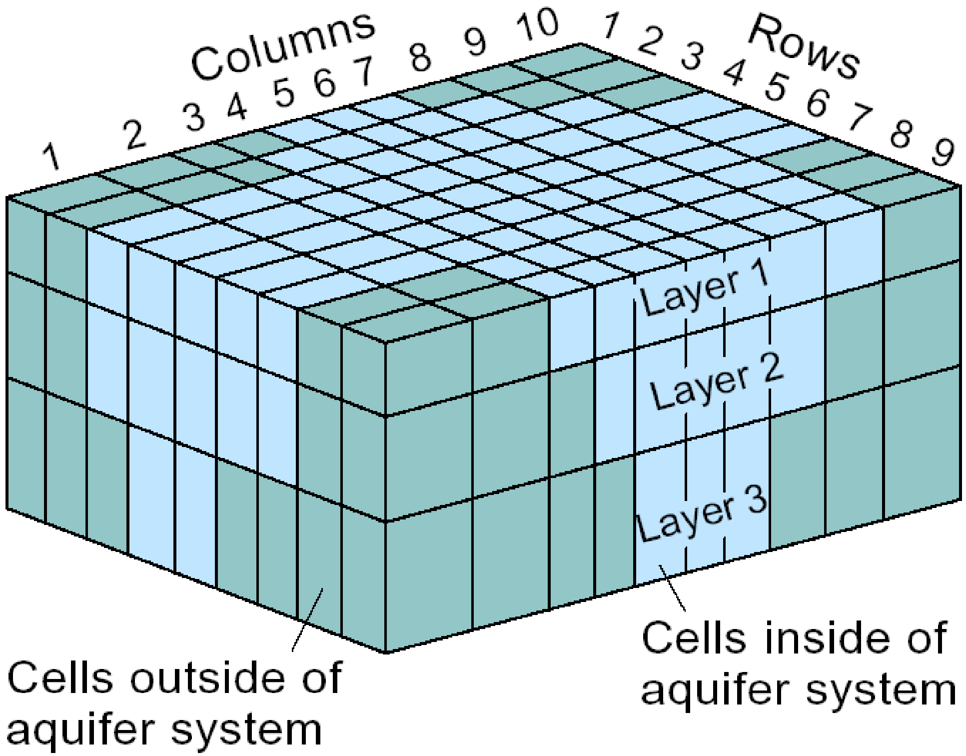
Grid Design – Typical Drivers

- **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 1 mile square

Model Grid Example



Source: USGS Fact Sheet FS-127-97

Model Inputs

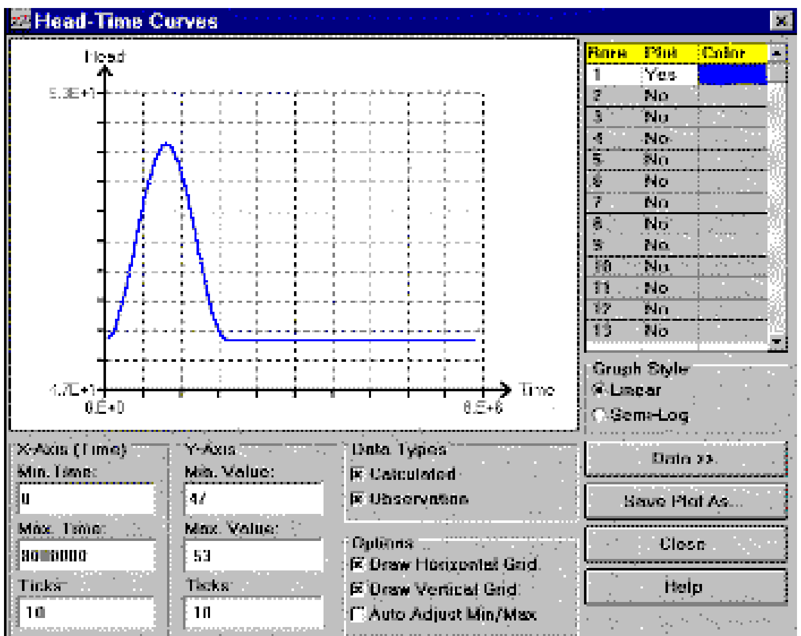
- **Hydrostratigraphic Surfaces for each Layer**
- **Hydraulic Properties:**
  - Hydraulic Conductivity
  - Storativity (transient)
- **Hydraulic heads**
- **Recharge**
- **Stream Flow (headwater flows, initial C)**
- **Pumpage**

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

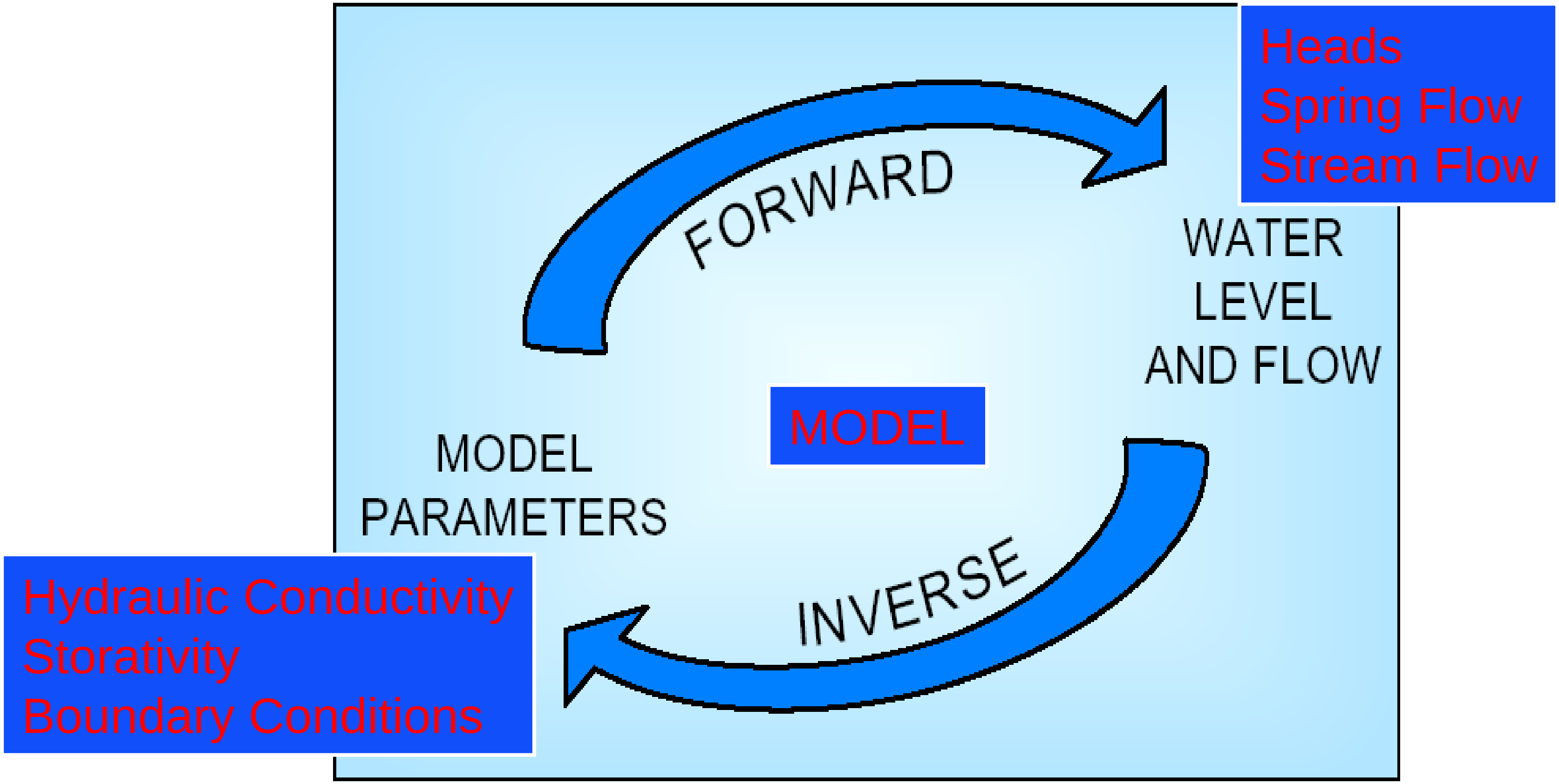
Boundary Conditions

- Boundary conditions may be static or transient



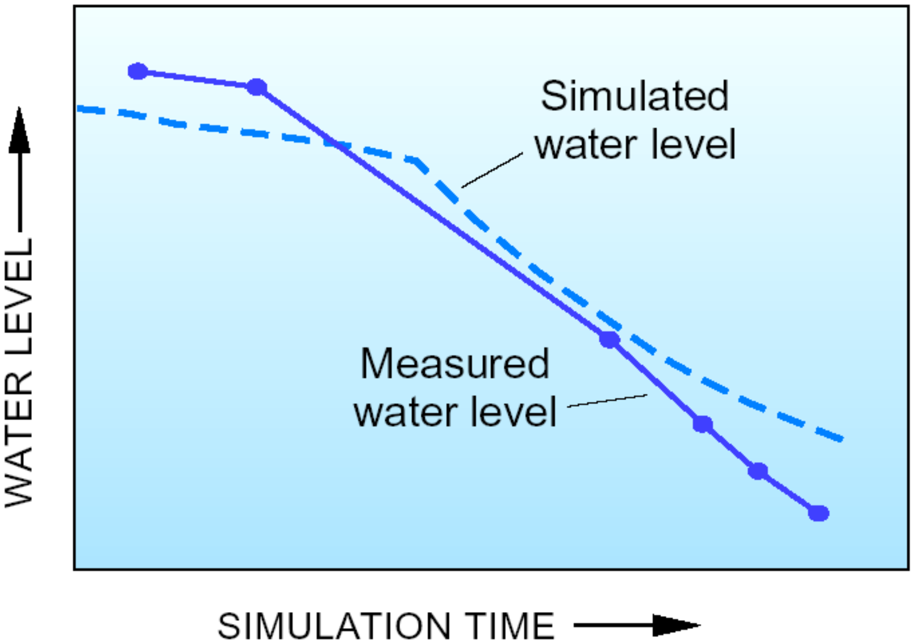
- Recharge or wells – Specified flow
- GHB, Reservoir, Stream – Head dependent flow
- Vertical or lower boundaries – specified flow @ zero = no flow

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
  - Select Calibration Metrics
  - Adjust Boundary Conditions/Properties
  - Analyze Errors

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

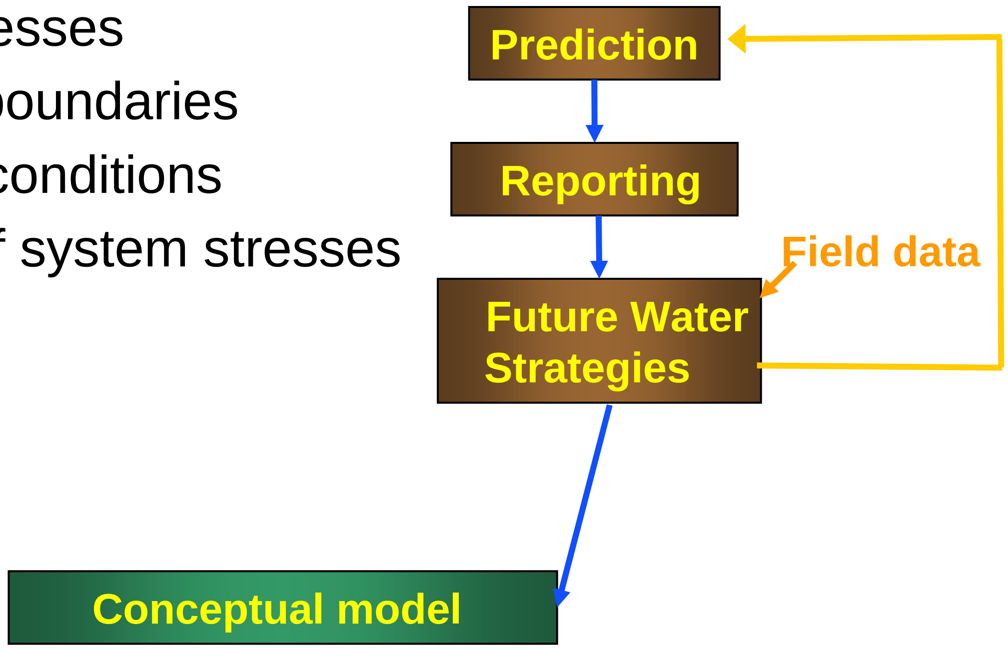
- **A sensitivity analysis is a formal means of quantifying the effect of changes in model inputs on model outputs**
- **Provides a means of identifying parameters which are:**
  - Important
  - Correlated
- **Most common method is the one-off-method**

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**

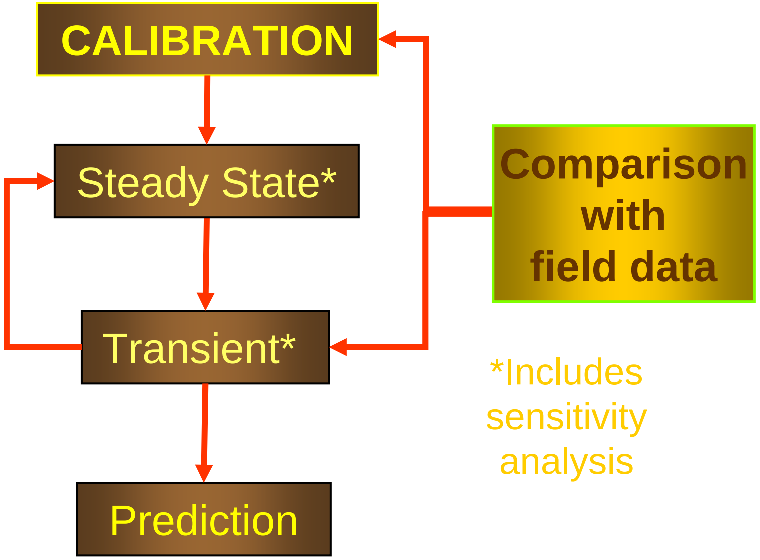
Model Uniqueness (Similarity Solutions)

- **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



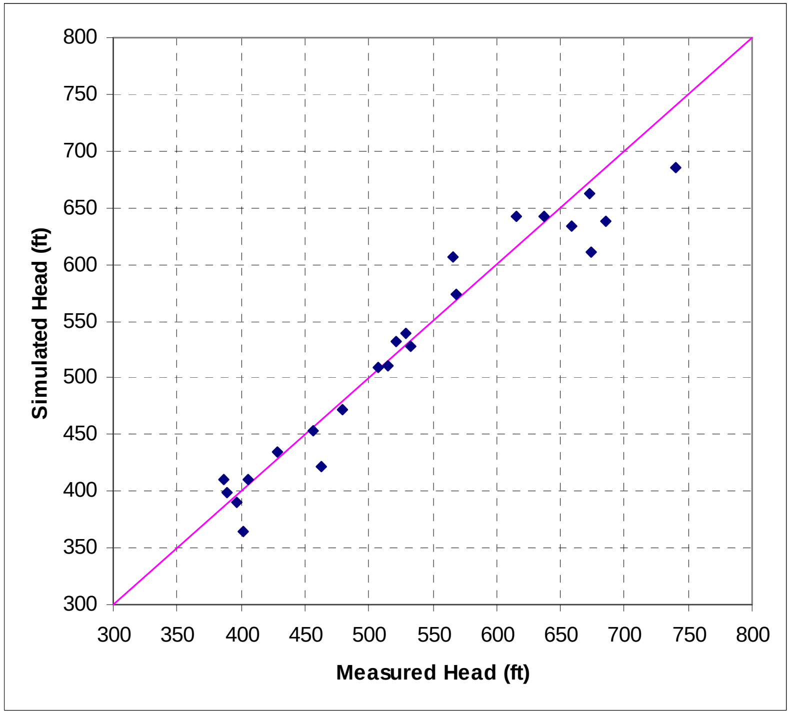
The calibration approach iterates between the steady-state and the transient calibrations to reach a consistent set of physical parameters that match both sets of observation.

(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, MAE, 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

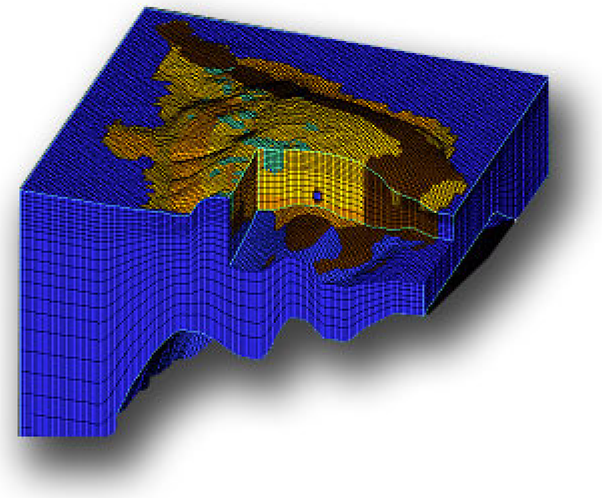
- **One must strive to not over-calibrate (tweak) a model; that is:**
  - Over parameterize lacking data support
  - Adjust parameters to bring model agreement below performance measure uncertainty
  - In the GAM model, head is the primary performance measure and we have estimated errors associated with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

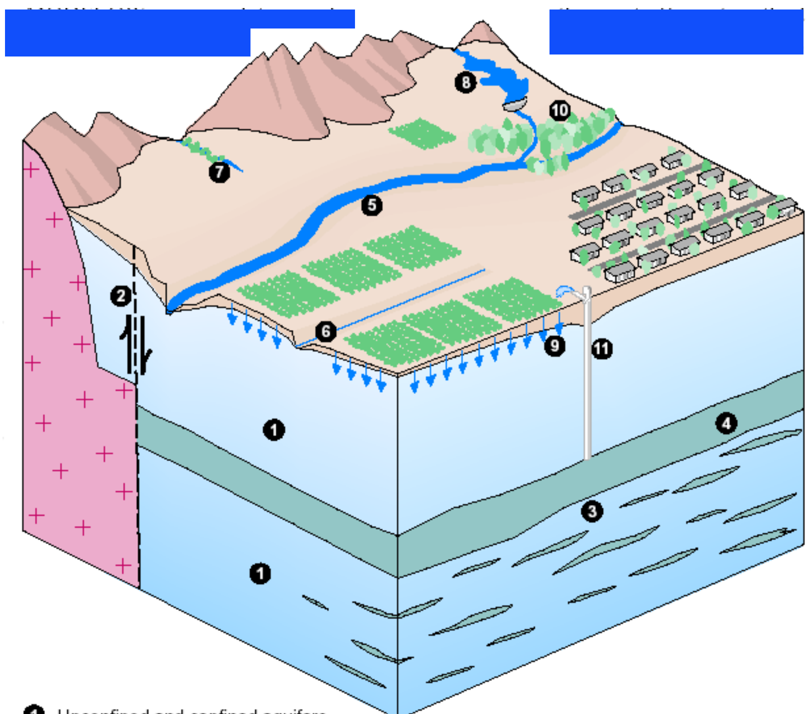
- **Original Packages (88)**
  - Basic
  - Block-Centered Flow
  - Recharge
  - Evapotranspiration
  - River
  - Well
  - Drain
  - General Head Boundary
  - Output Control
  - SIP/SOR Solvers
- **Add on Packages (2000)**
  - Block-Centered Flow 2 .. 6
  - Discretization
  - PCG/PCG2, GMG Solvers
  - 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 Advantages

- **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

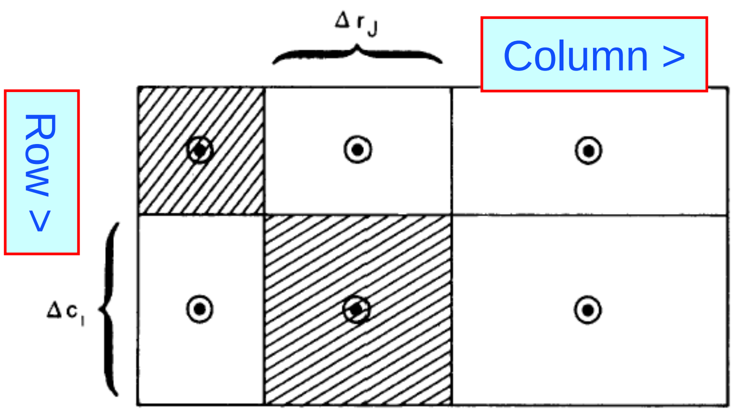


1. Unconfined and confined aquifers—Ground-water flow and storage changes
2. Faults and other barriers—Resistance to horizontal ground-water flow
3. Fine-grained confining units and interbeds
4. Confining units—Ground-water flow and storage changes
5. Rivers—Exchange of water with aquifers
6. Drains and springs—Discharge of water from aquifers
7. Ephemeral streams—Exchange of water with aquifers
8. Reservoirs—Exchange of water with aquifers
9. Recharge from precipitation and irrigation
10. Evapotranspiration
11. Wells—Withdrawal or recharge at specified rates

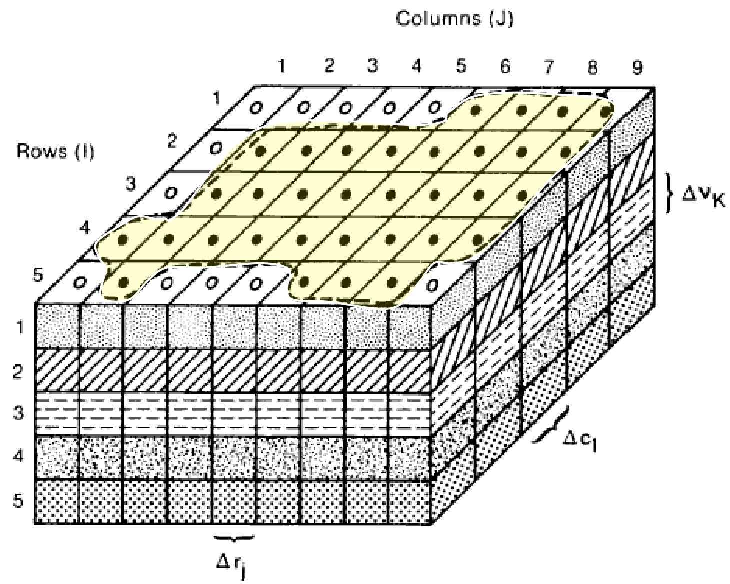
Source: USGS Fact Sheet FS-127-97

- **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

0 Inactive Cell

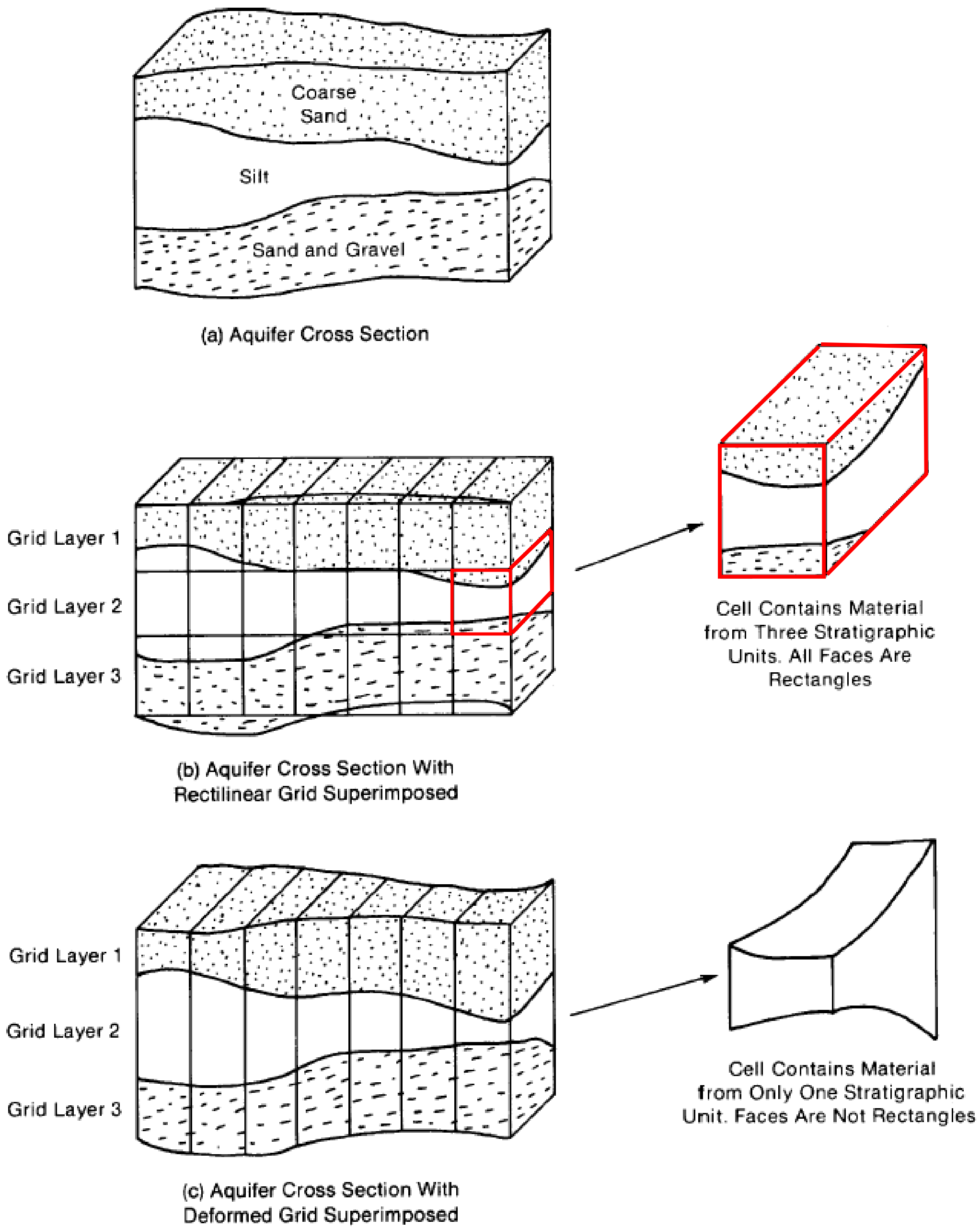
Δr_J Dimension of Cell Along the Row Direction. Subscript (J) Indicates the Number of the Column

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

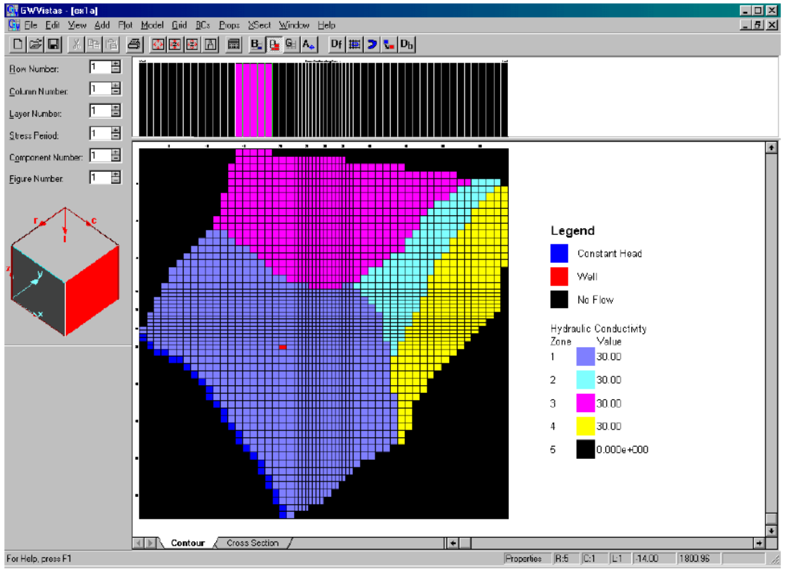
2. Modeling Overview



Vertical Discretization
Should have physical significance

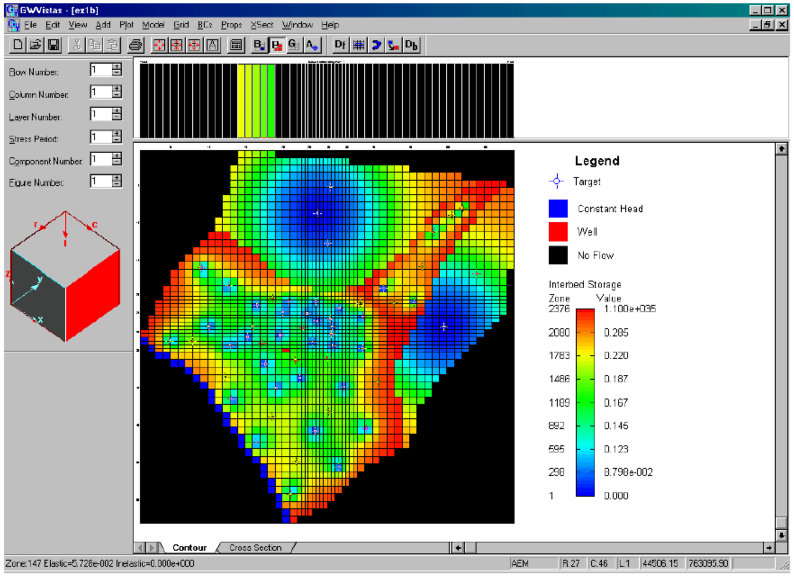
After McDonald & Harbaugh, 1988

Assignment of Properties

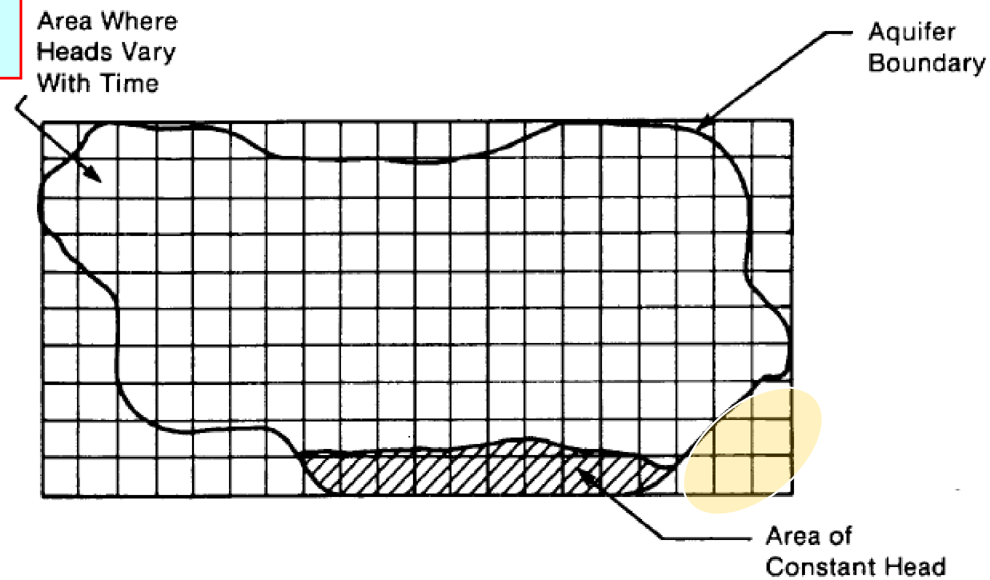


Properties can be assigned in zones as above

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

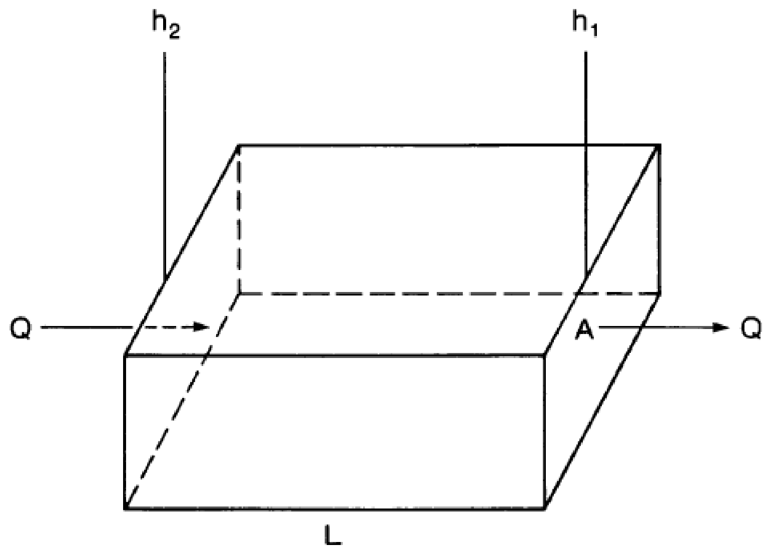
After McDonald & Harbaugh, 1988

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

$$Q = \frac{KA\,(h_2 - h_1)}{L}$$



- **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**

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

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

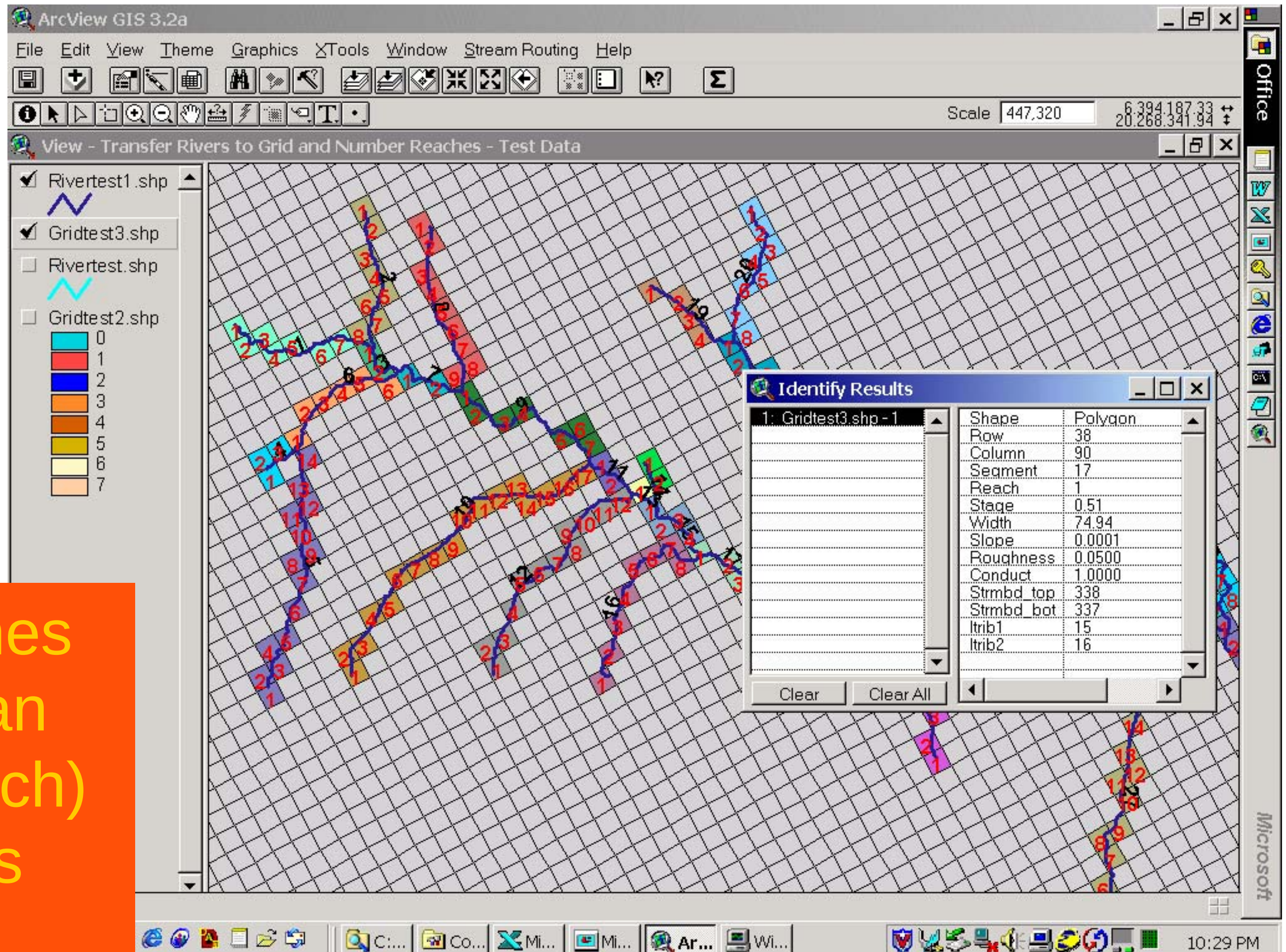
Wells in MODFLOW-2000

- **MODFLOW-2000 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

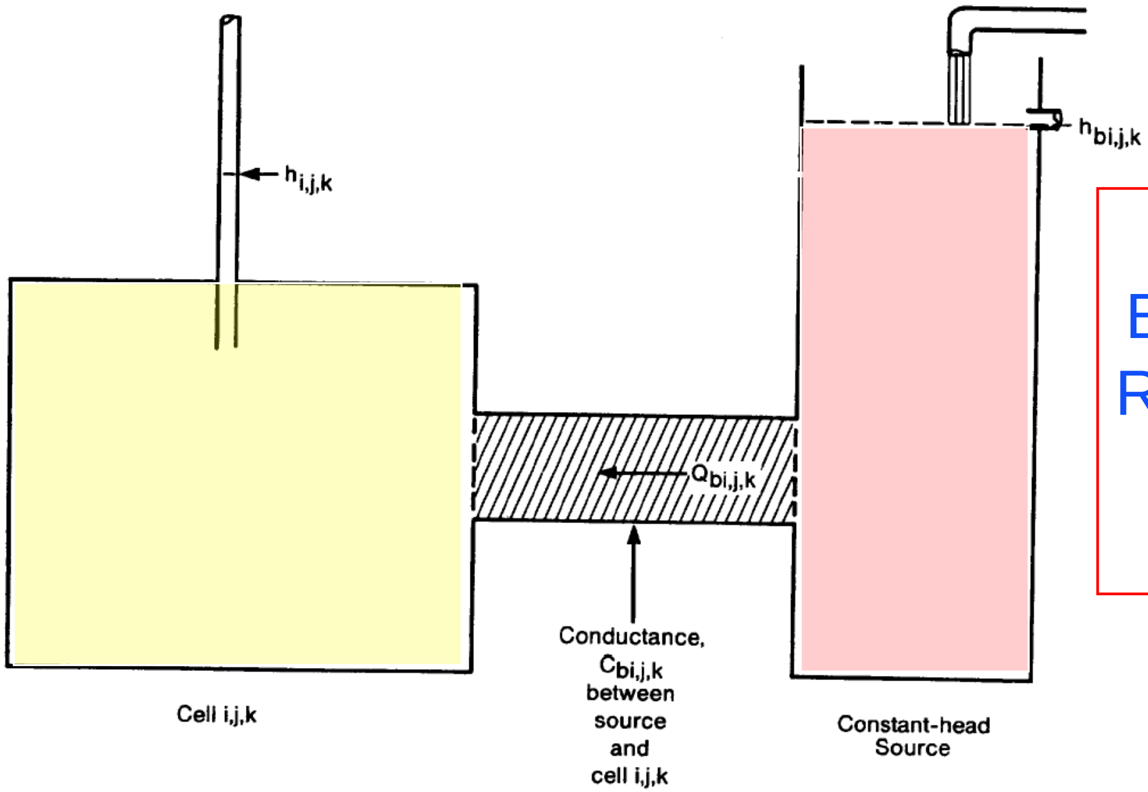


Stream reaches (each cell is an individual reach) and segments must be numbered

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)

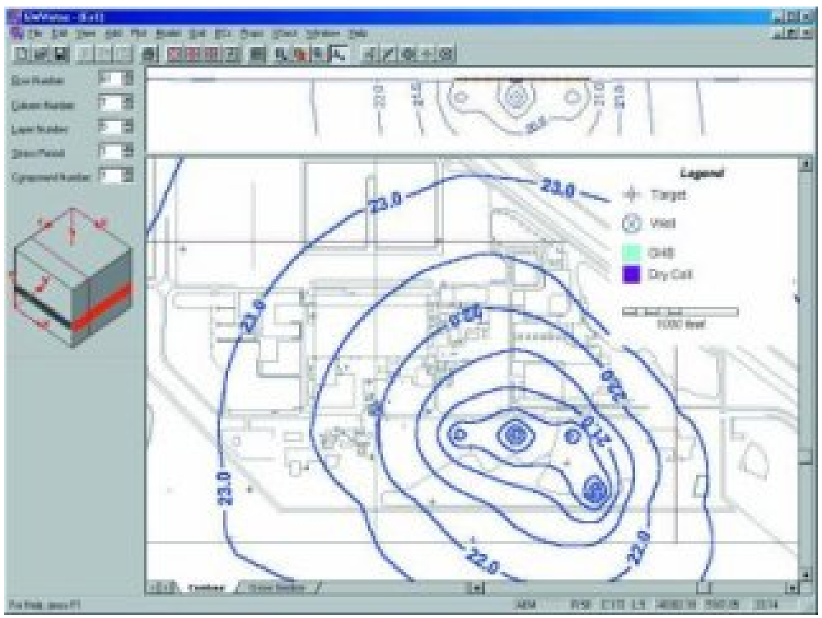
MODFLOW Interfaces

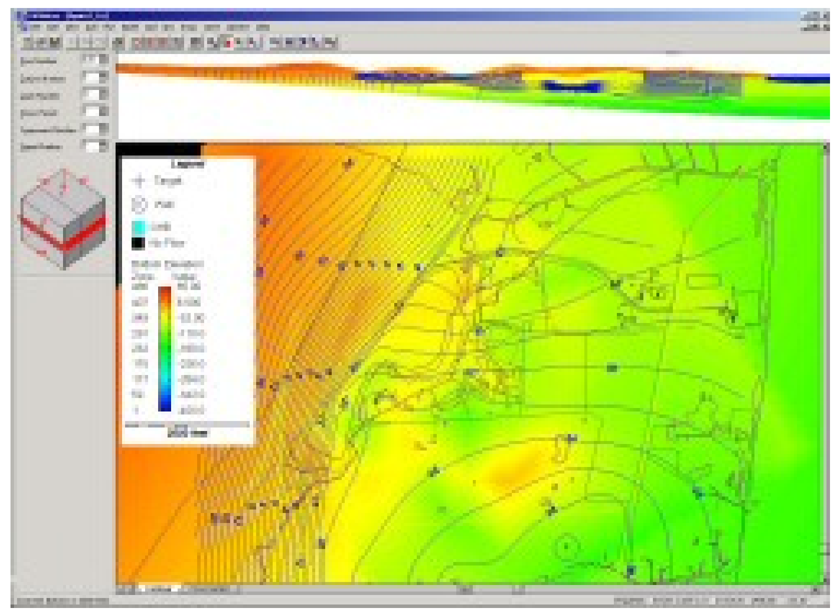
- **PMWIN**
  - Academic, commercially available
- **Groundwater Modeling System (GMS)**
  - DOD, commercially available
- **Groundwater Vistas (GV)**
  - Private, commercially available
- **Visual MODFLOW**
  - Private, commercially available

GV – Groundwater Vistas

- **Windows graphical user interface for 3-D groundwater flow and transport modeling. Developed by Environmental Simulations Incorporated.**
- **Authors:**

Jim Rumbaugh and Doug Rumbaugh





http://www.groundwatermodels.com

http://www.groundwater-vistas.com

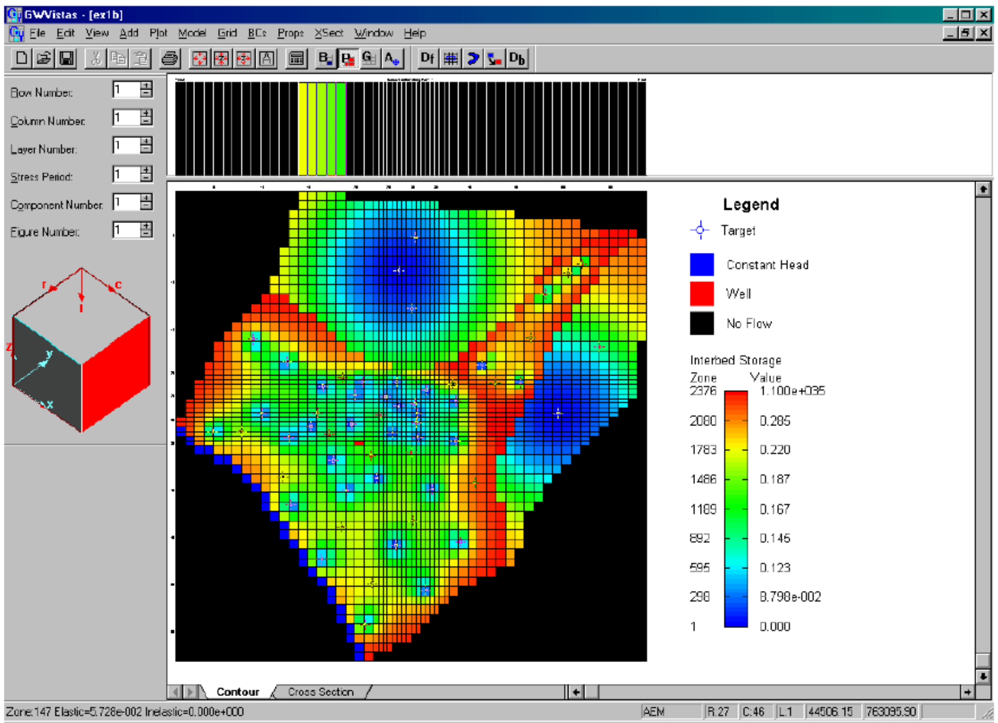
GV Capabilities

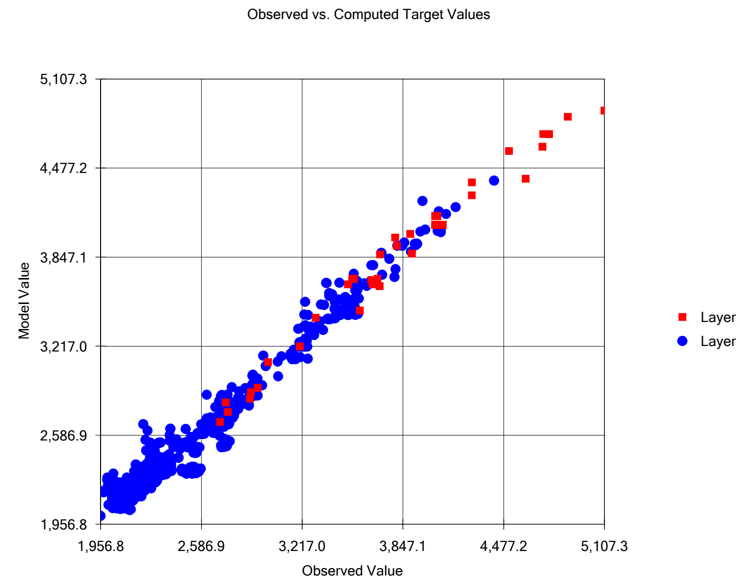
- Offers a Windows based interface for developing MODFLOW models and for using the family of MODFLOW codes
- Imports existing standard MODFLOW models
- Supports all standard packages
- Allows many options for data input: ArcView shapefiles, AutoCAD DXF files, SURFER files, and ASCII files
- Allows for telescopic grid refinement
- Some degree of checking of input prior to execution
- Offers a wide variety of analysis techniques for viewing simulation results

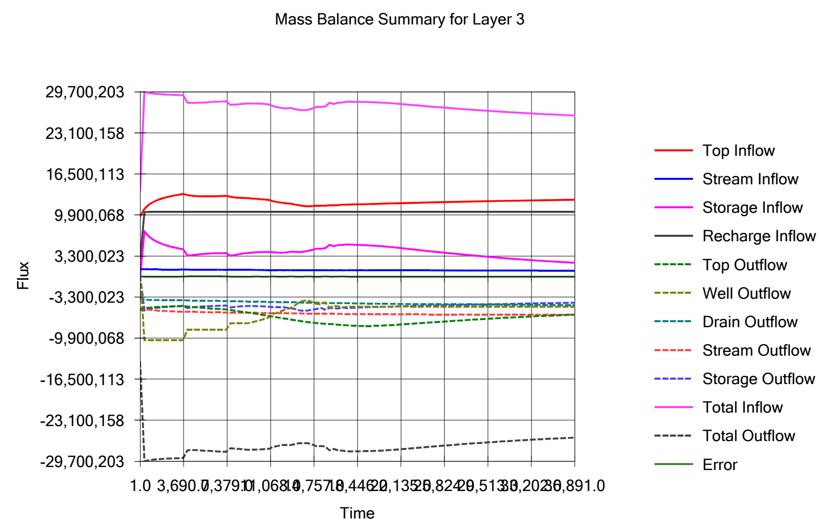
GV Requirements

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

GV Interface





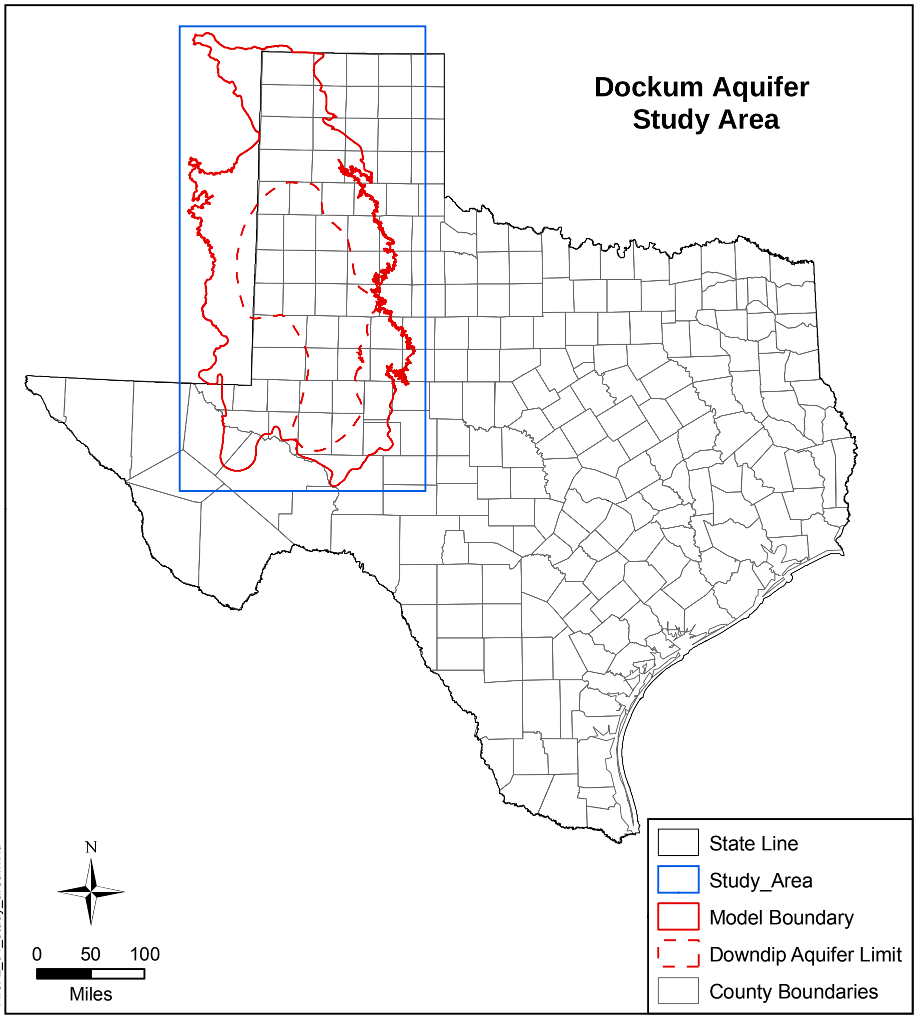


Dockum GAM Review

- **Technical Overview**
  - Emphasis on Data and Model Inputs

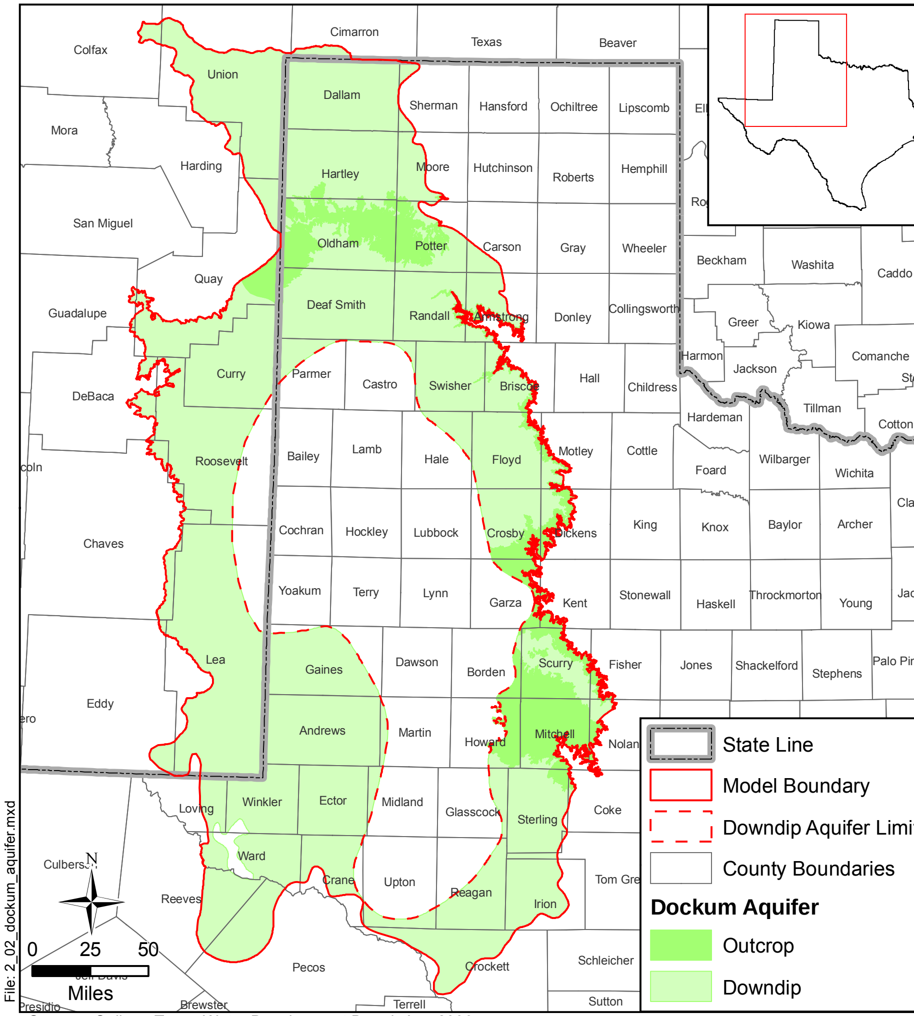
Model Area

Study Area



Source: N/A

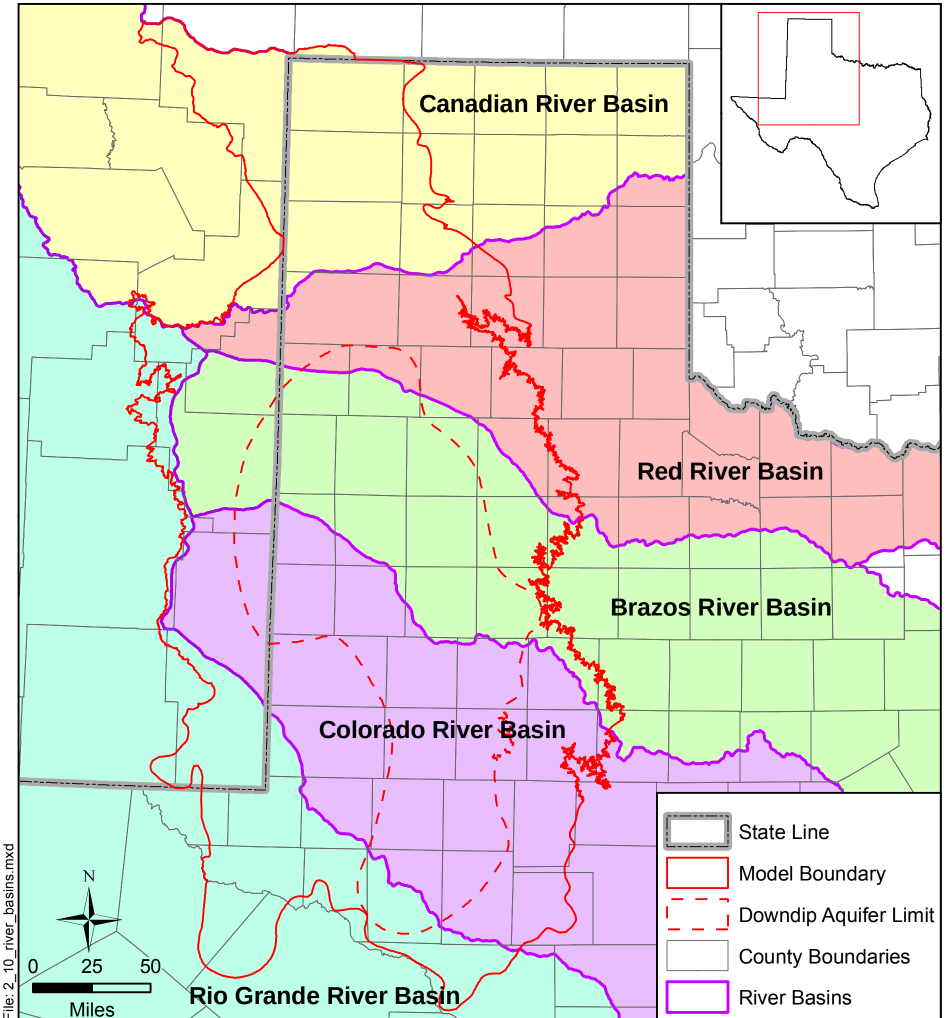
Model Domain



Source: Online: Texas Water Development Board, Aug 2006

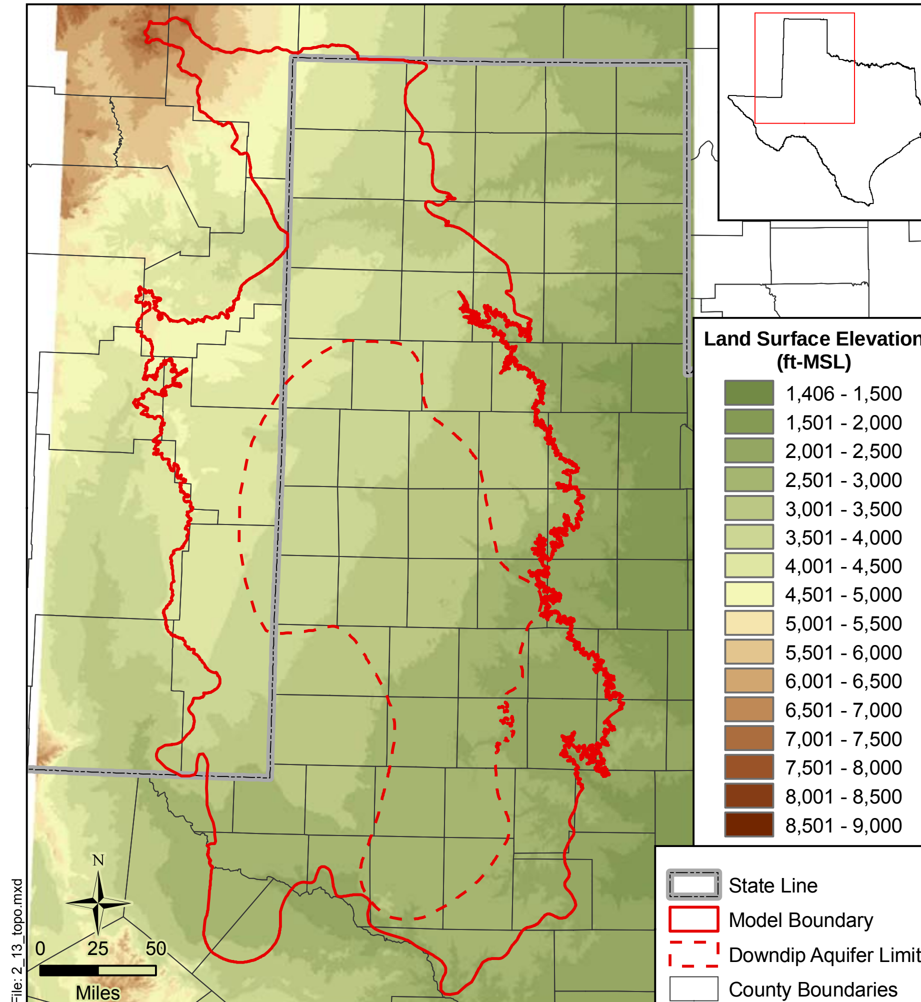
River Basins and Topography

Major River Basins



Source: Online: Texas Water Development Board, June 2006; New Mexico Resource GIS Program, June 2006

Topography



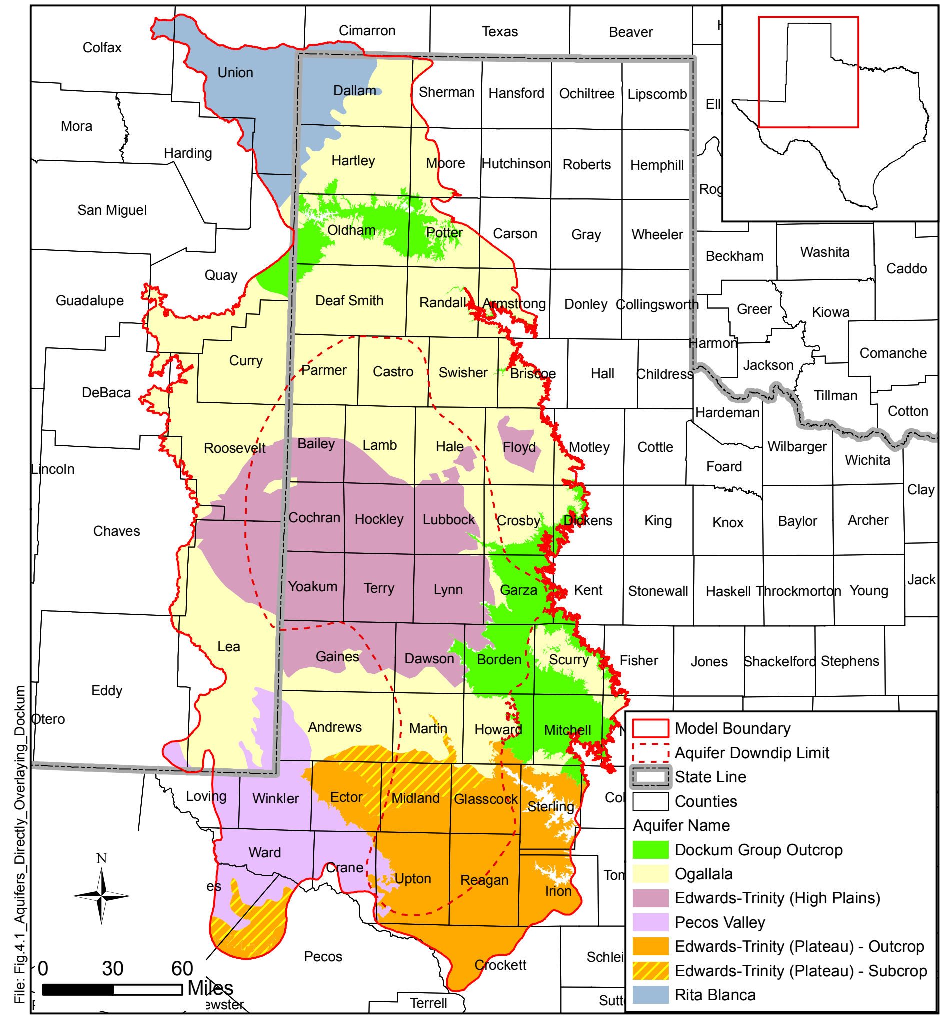
Source: Online: USGS, Aug 2006

Geology

Stratigraphic Units

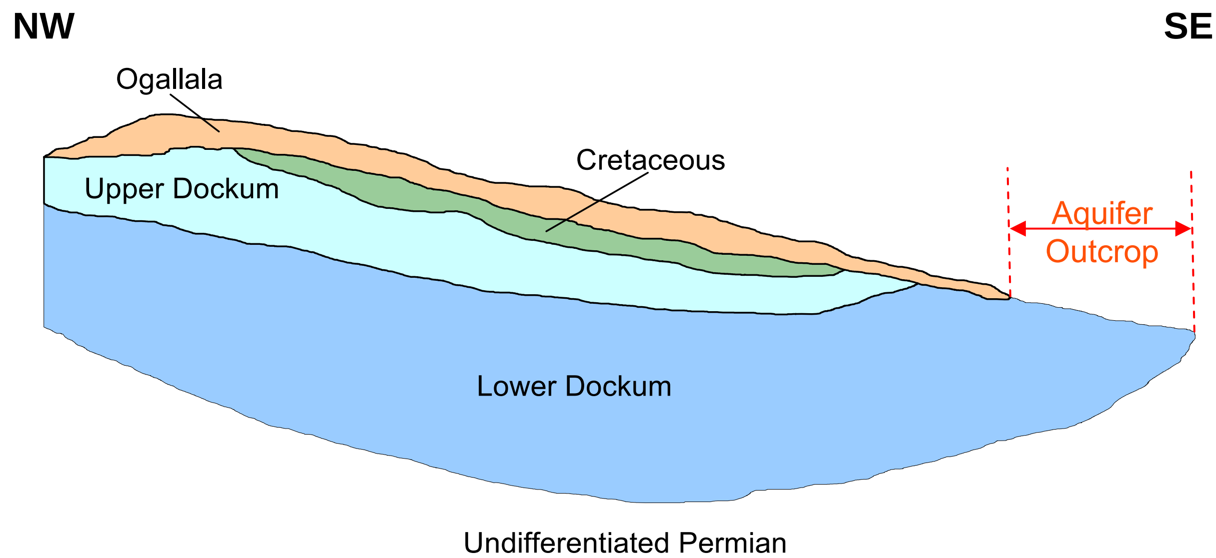
Ogallala/Alluvium	
Cretaceous-age Sediments (not continuous)	
Upper Dockum	Cooper Canyon Formation
	Trujillo Sandstone
Lower Dockum	Tecovas Formation
	Santa Rosa Sandstone
Permian-age Sediments	

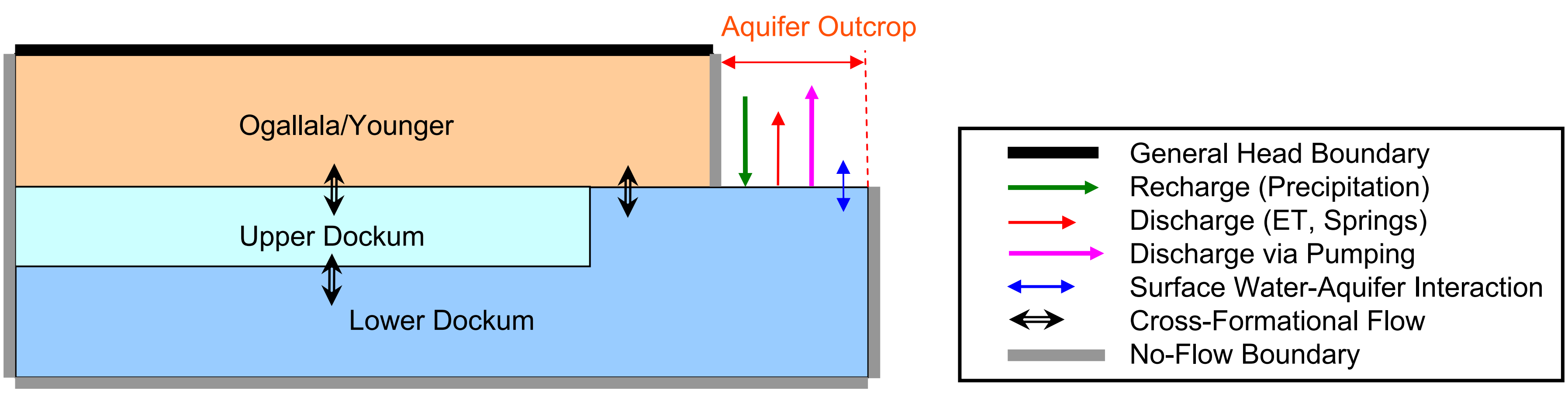
Overlying Aquifers



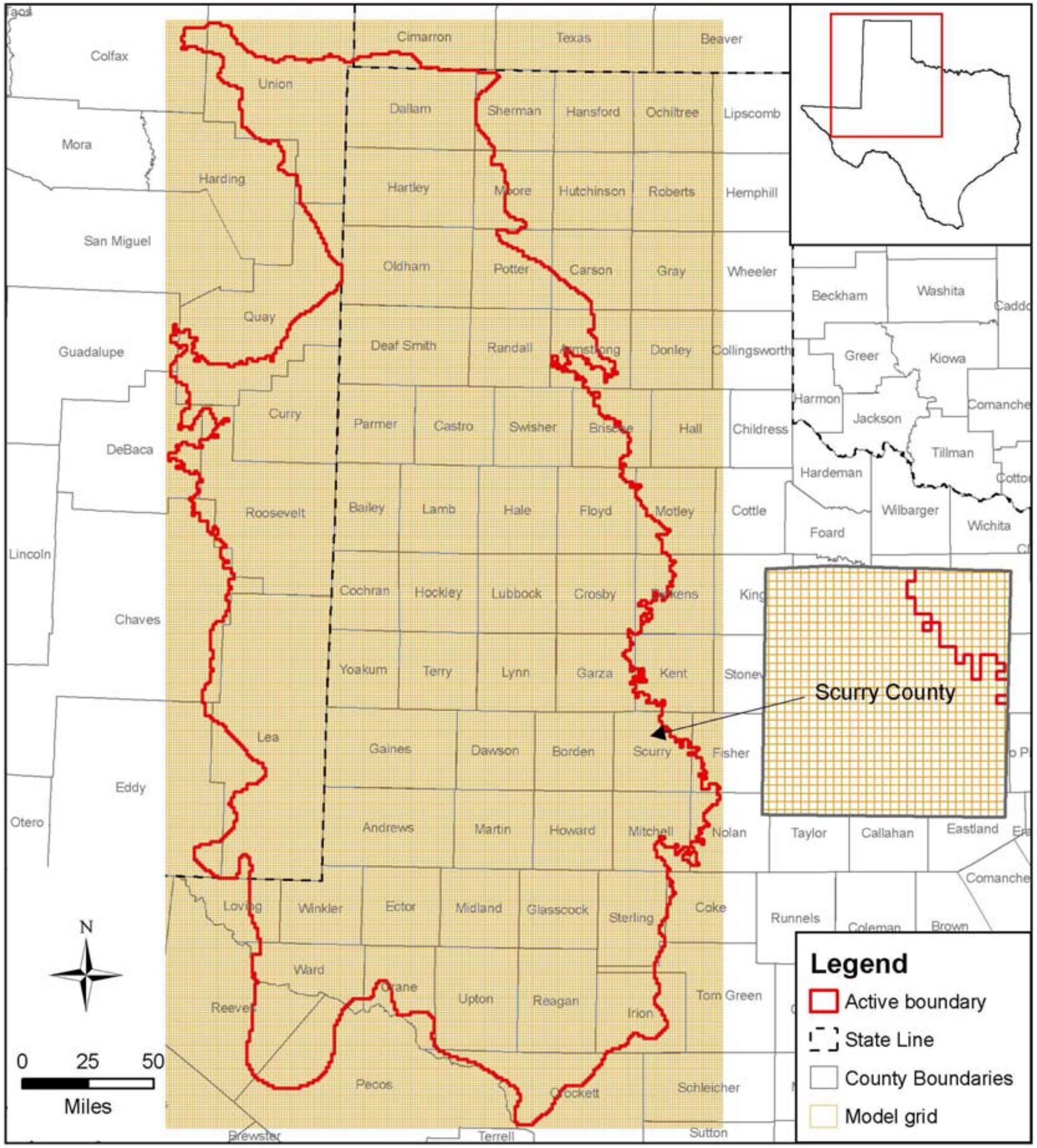
Source: Adapted from Texas Water Development Board, Dec 2006

Model Flow Conceptualization



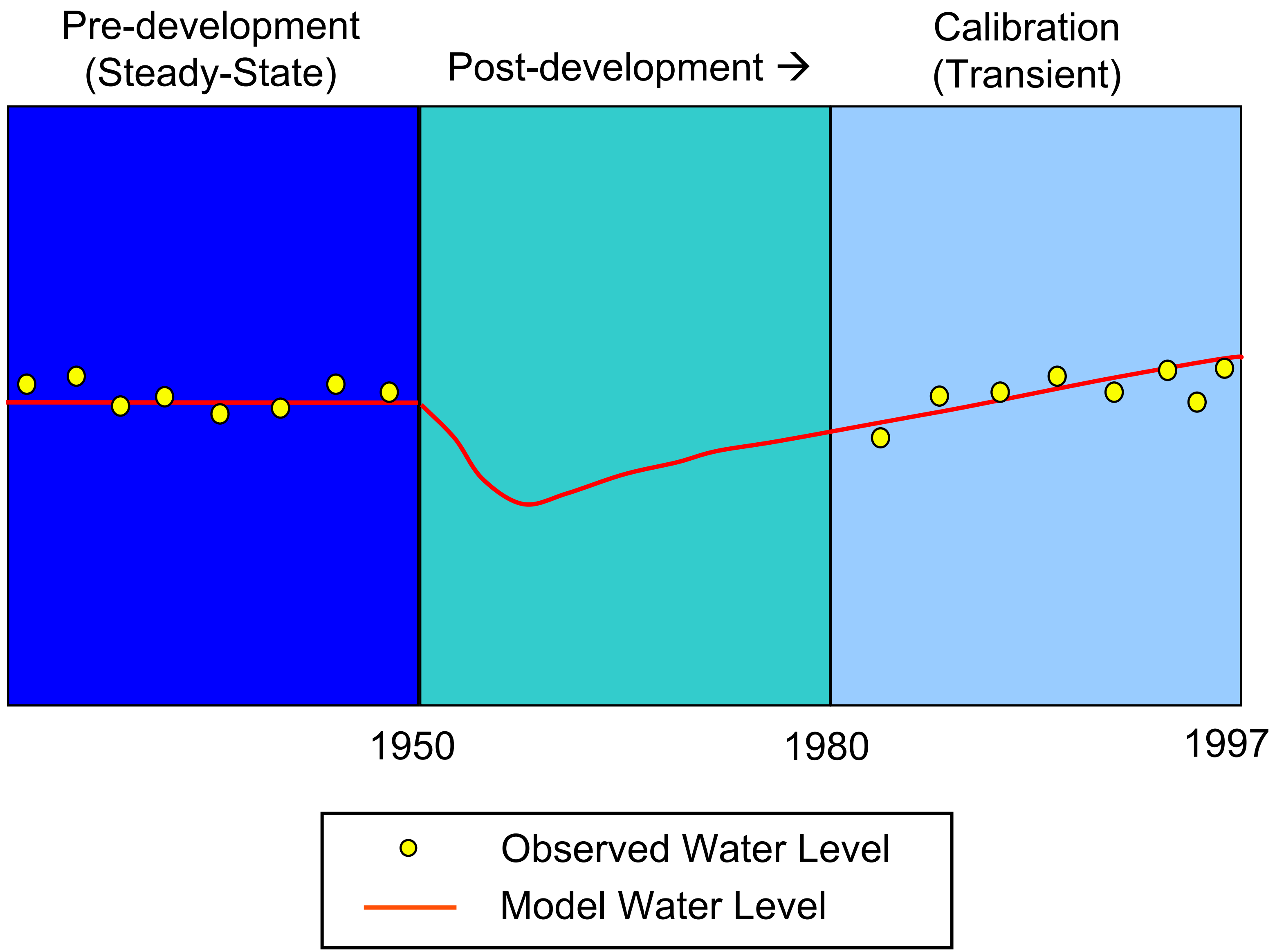


Model Grid



1 square mile grid blocks
212 columns
422 rows
3 layers
150,548 active cells

Schematic of Modeling Periods



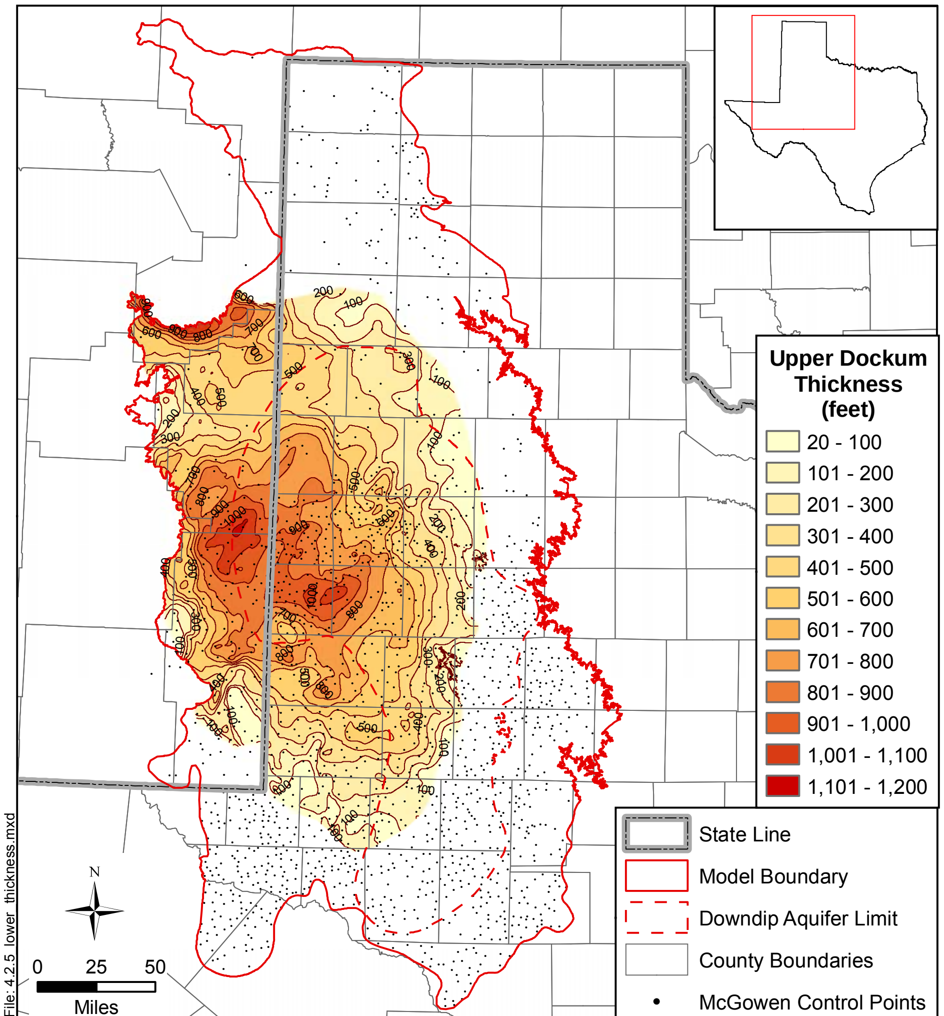
Model Input – Supporting Data

- Hydrostratigraphic surfaces for each layer
- Hydraulic properties
  - Hydraulic Conductivity
  - Storativity (transient)
- Water Levels
- Recharge
- ET
- Stream Flow
- Pumpage

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

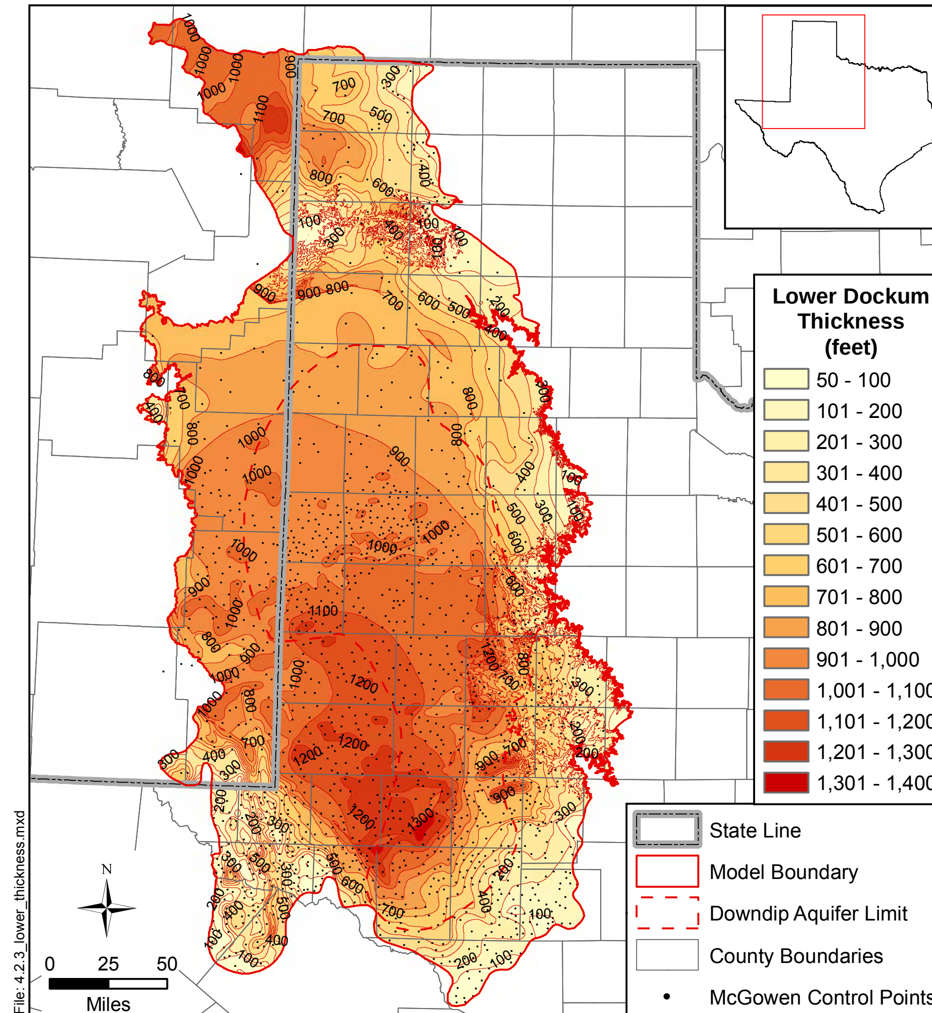
Dockum Thickness

Upper Dockum



Source: McGowen et al. (1977)

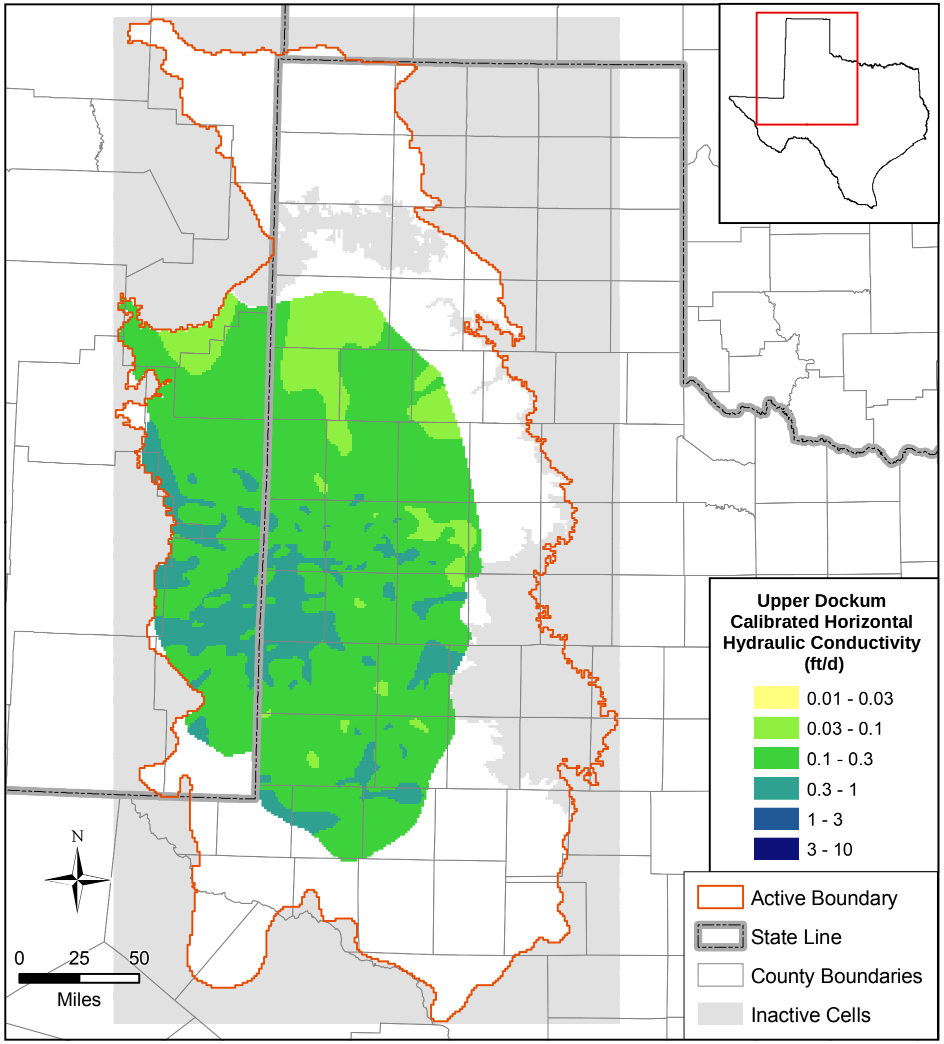
Lower Dockum



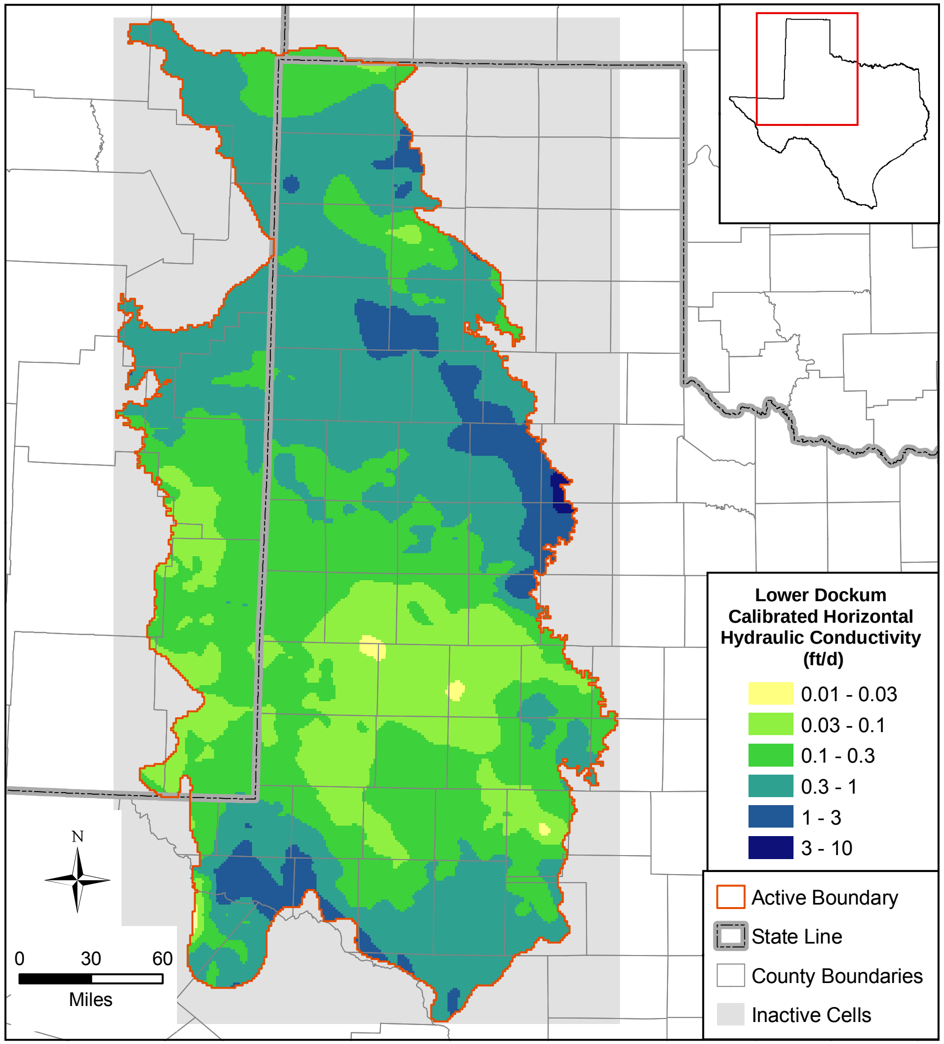
Source: McGowen et al. (1977)

Horizontal Hydraulic Conductivity – K_H

Upper Dockum

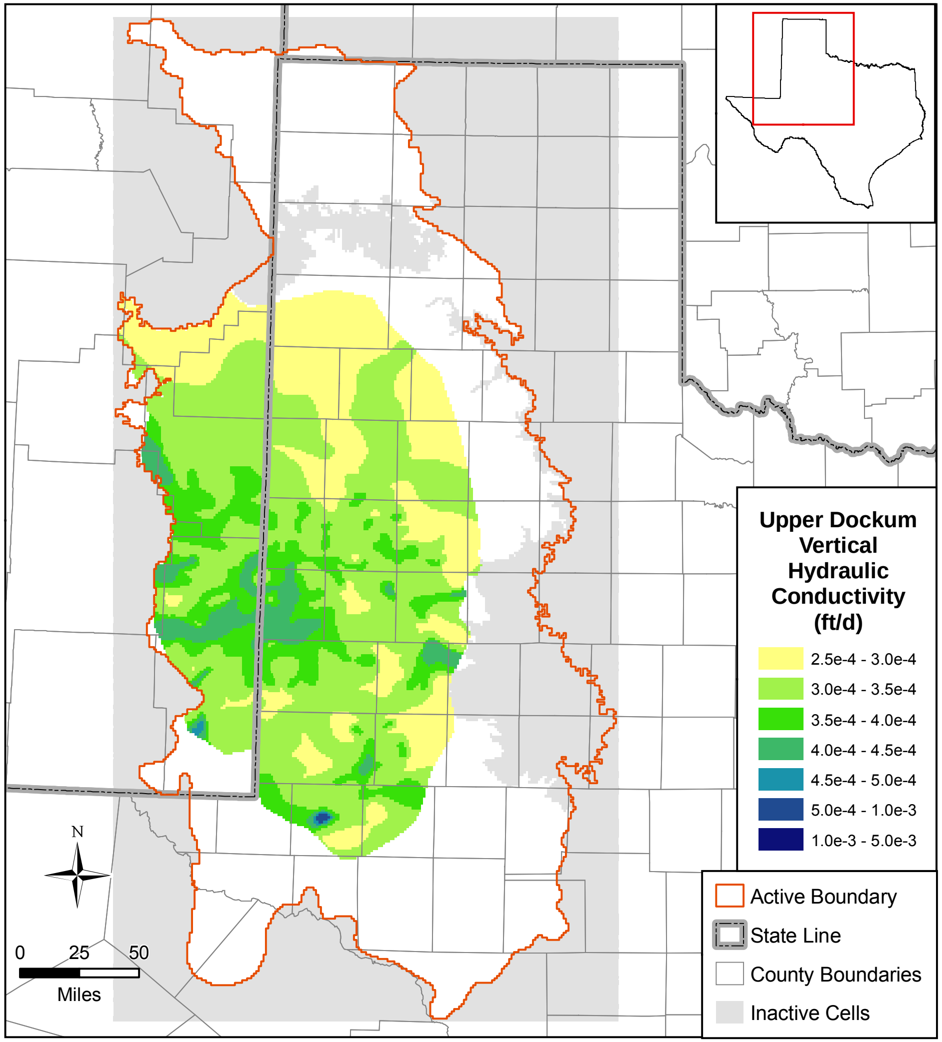


Lower Dockum

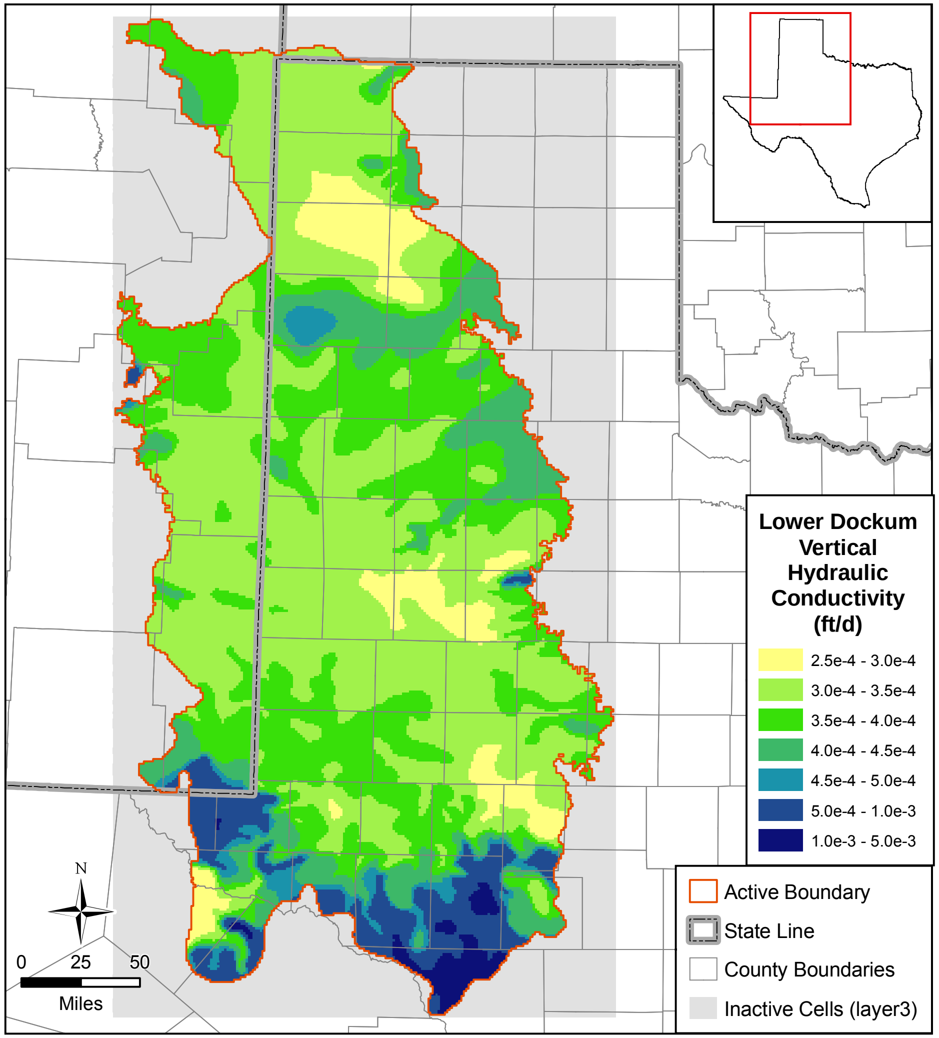


Vertical Hydraulic Conductivity – K_V

Upper Dockum

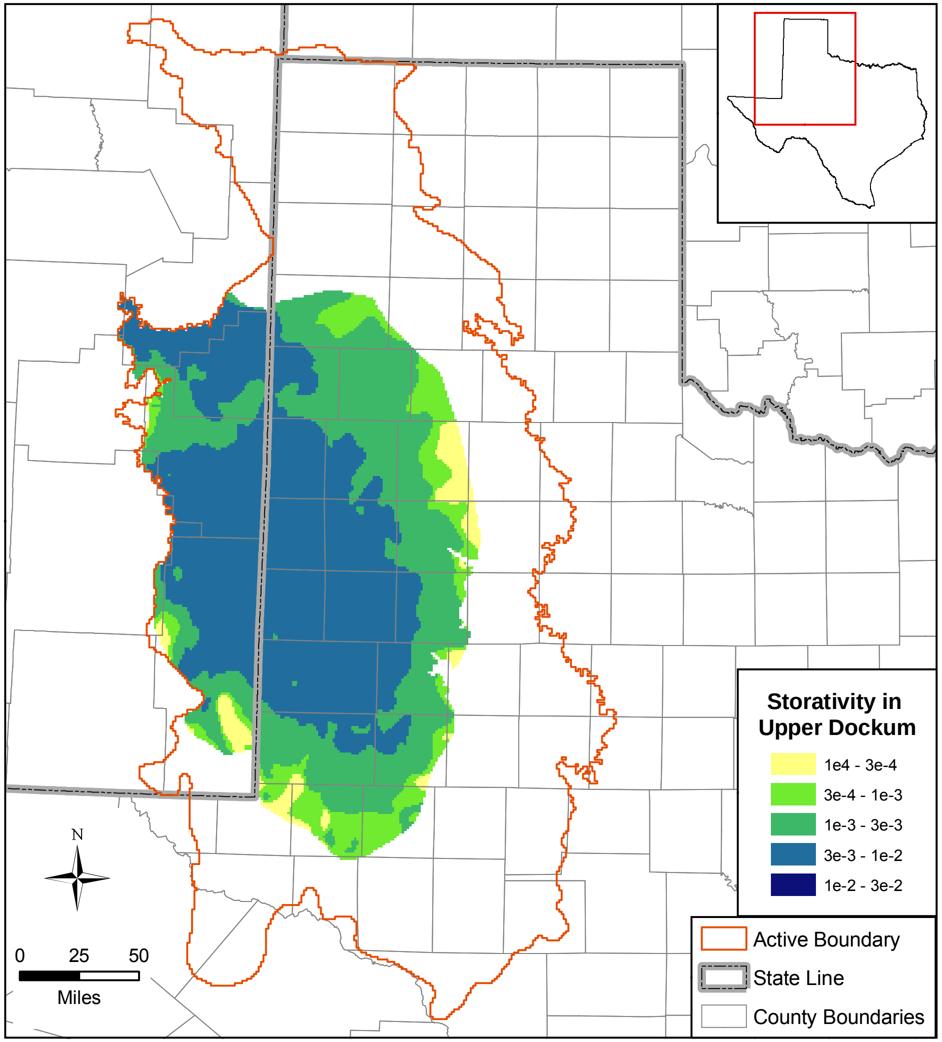


Lower Dockum

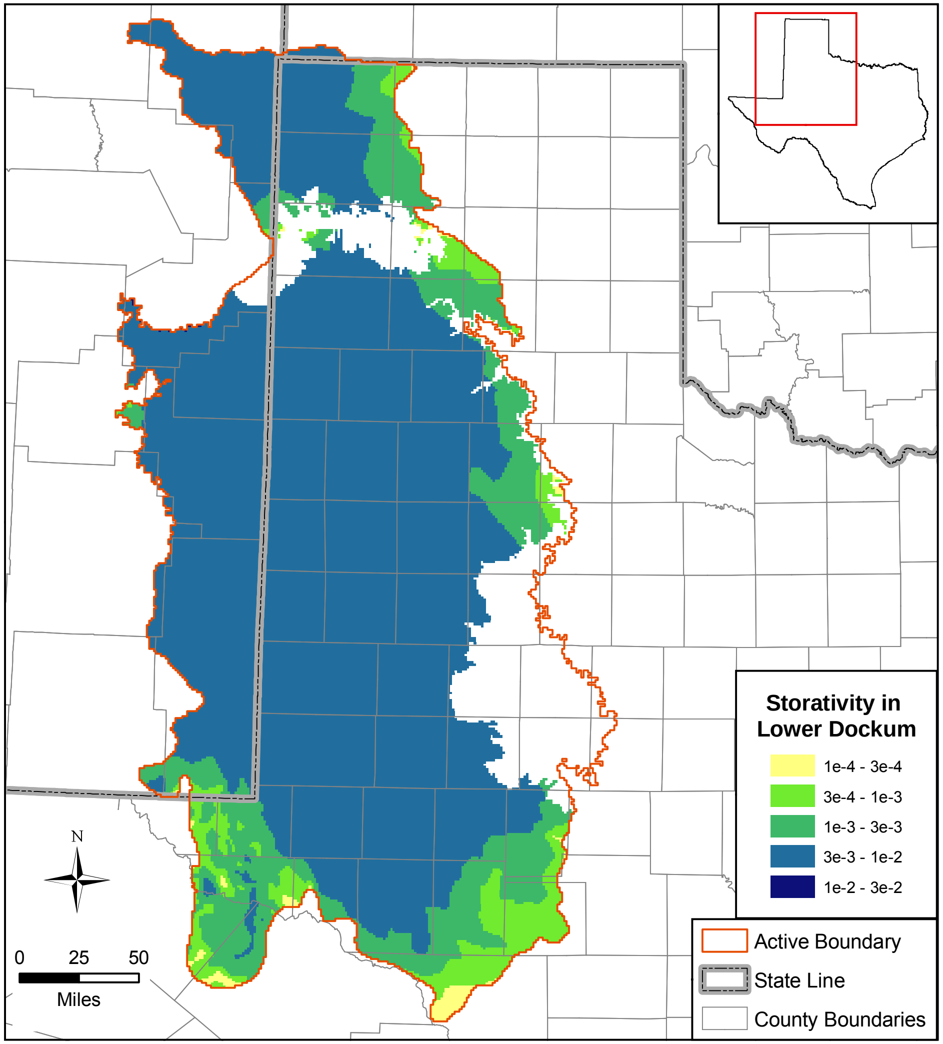


Storativity

Upper Dockum

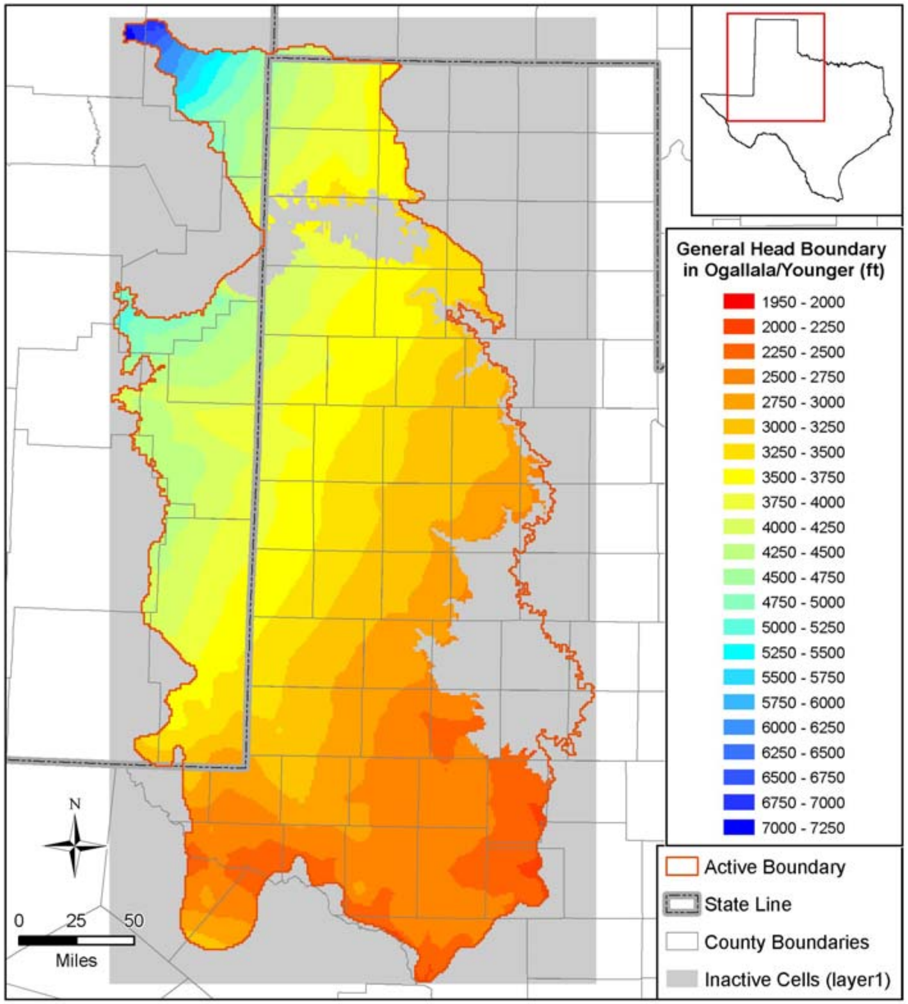


Lower Dockum

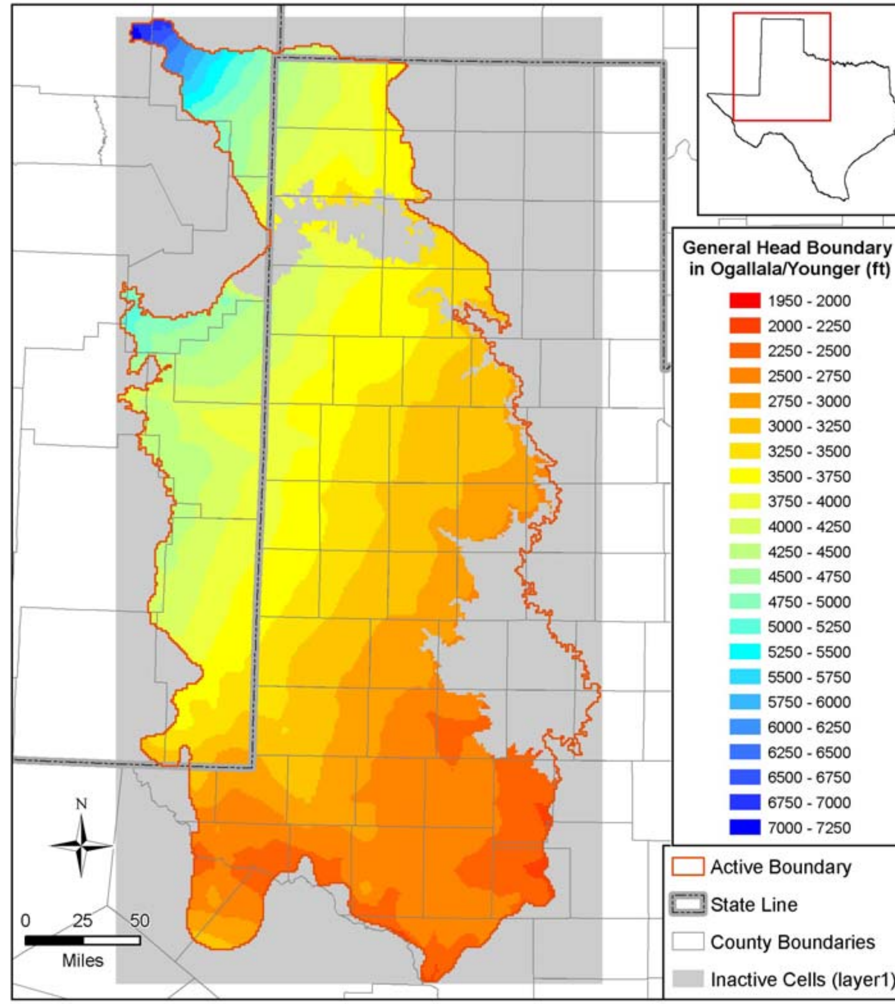


General Head Boundary

1980

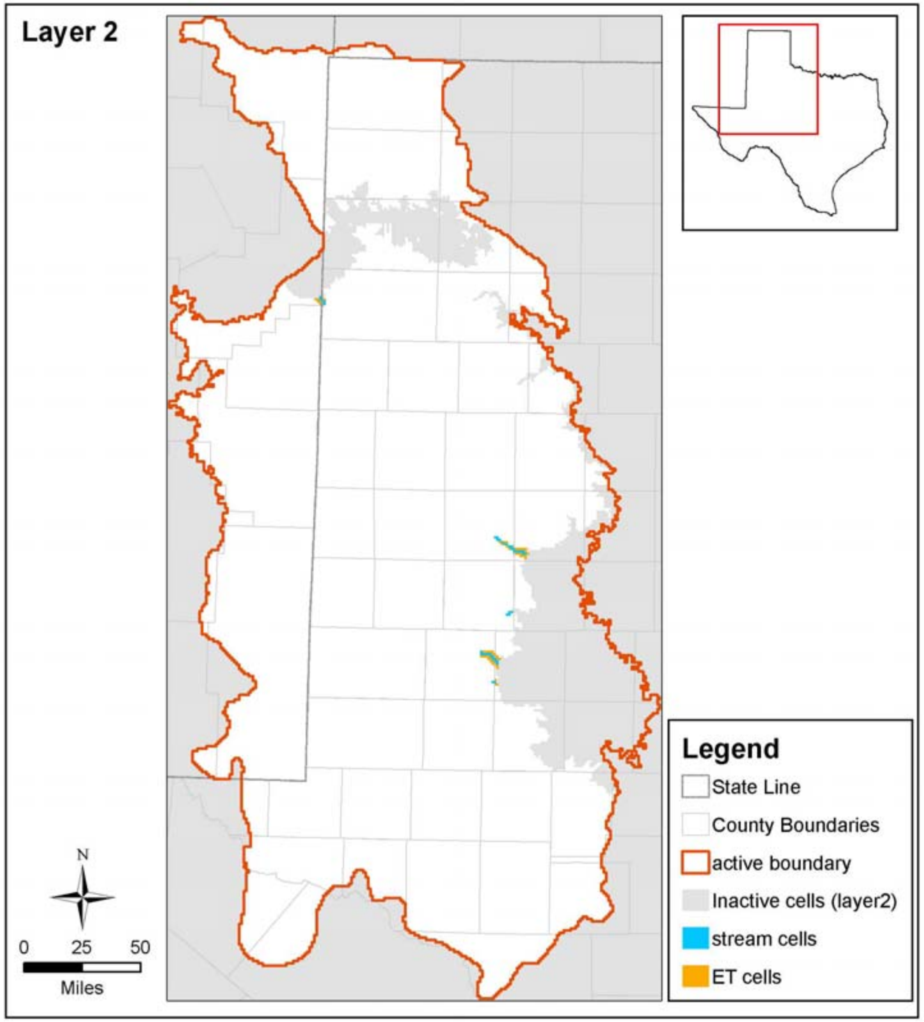


1997

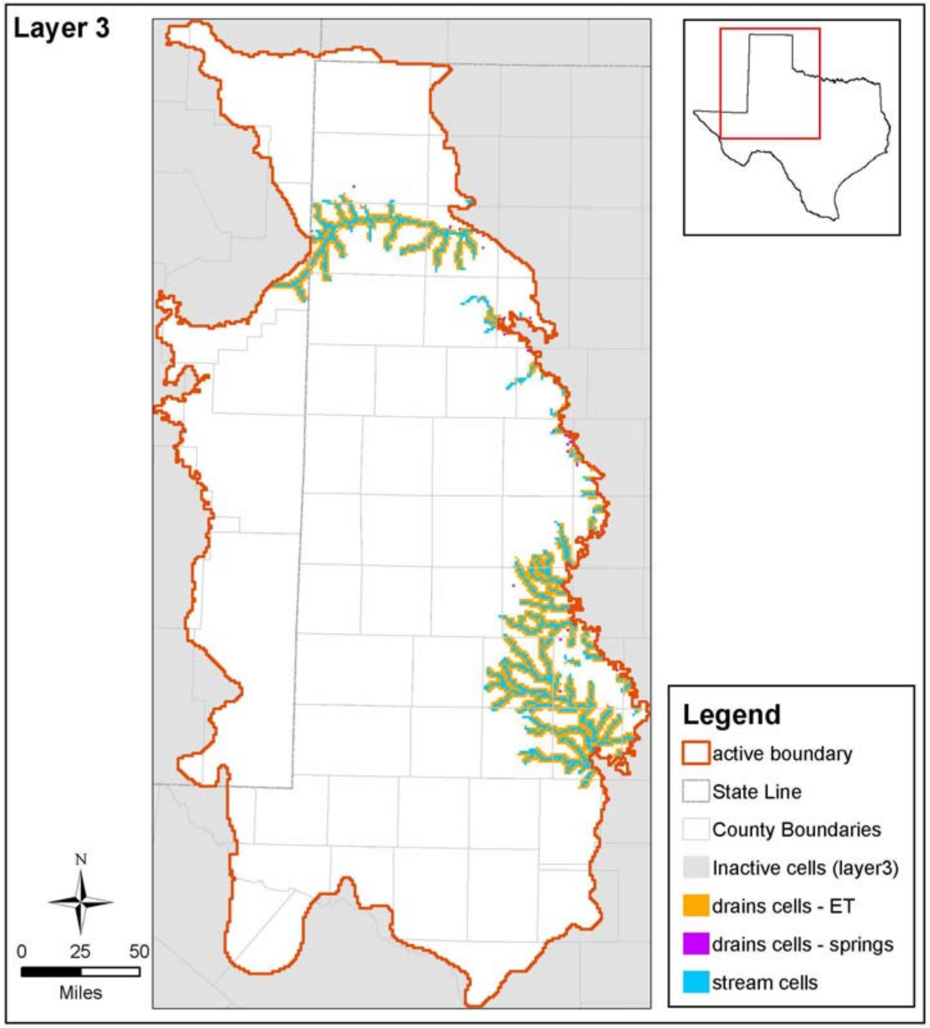


Surface Water Boundary Conditions

Upper Dockum



Lower Dockum



Recharge Rate Estimates

County/Area	Land use	Aquifer	Recharge (in/yr)	Technique	Reference
Dockum Aquifer – Colorado River outcrop area					
All of the Colorado River outcrop area - Predevelopment	Grassland and shrubland	Dockum	0.08	SZ chloride mass balance	This report
Sandy areas (Nolan and eastern Mitchell counties) - Predevelopment	Grassland and shrubland	Dockum	0.22	SZ chloride mass balance	This report
All of the Colorado River outcrop area		Dockum	0.08 to 0.2	UZ numerical modeling	Scanlon et al. (2003)
Western Scurry and Mitchell counties	Grassland and shrubland	Dockum	<0.01	SZ chloride mass balance	This report
Scurry County - Predevelopment		Dockum	0.02 to 0.04	Water budget on playas	This report
All of the Colorado River Outcrop area - Postdevelopment		Dockum	2.2	regional water level rise	This report
Sandy areas (Nolan and eastern Mitchell counties) - Postdevelopment	Cropland	Dockum	Geom. Average = 1.7 Median = 1.6 Range = 0 to 4.3	linear water level rises in individual wells	This report

County/Area	Land use	Aquifer	Recharge (inch/yr)	Technique	Reference
Dockum Aquifer – Canadian River outcrop area					
All of the Canadian River outcrop area- Predevelopment and Postdevelopment	Grassland and shrubland	Dockum	0.17	SZ chloride mass balance	This report
All of the Canadian River outcrop area		Dockum	<0.08	UZ numerical modeling	Scanlon et al. (2003)
Dockum Aquifer – high TDS outcrop area					
Howard, Borden and Garza counties - Predevelopment	Grassland and shrubland	Dockum	<0.01	SZ chloride mass balance	This report

Predevelopment Recharge

- **Recharge was estimated on limited points (80) using:**

$$R = P \frac{Cl_P}{Cl_{GW}}$$

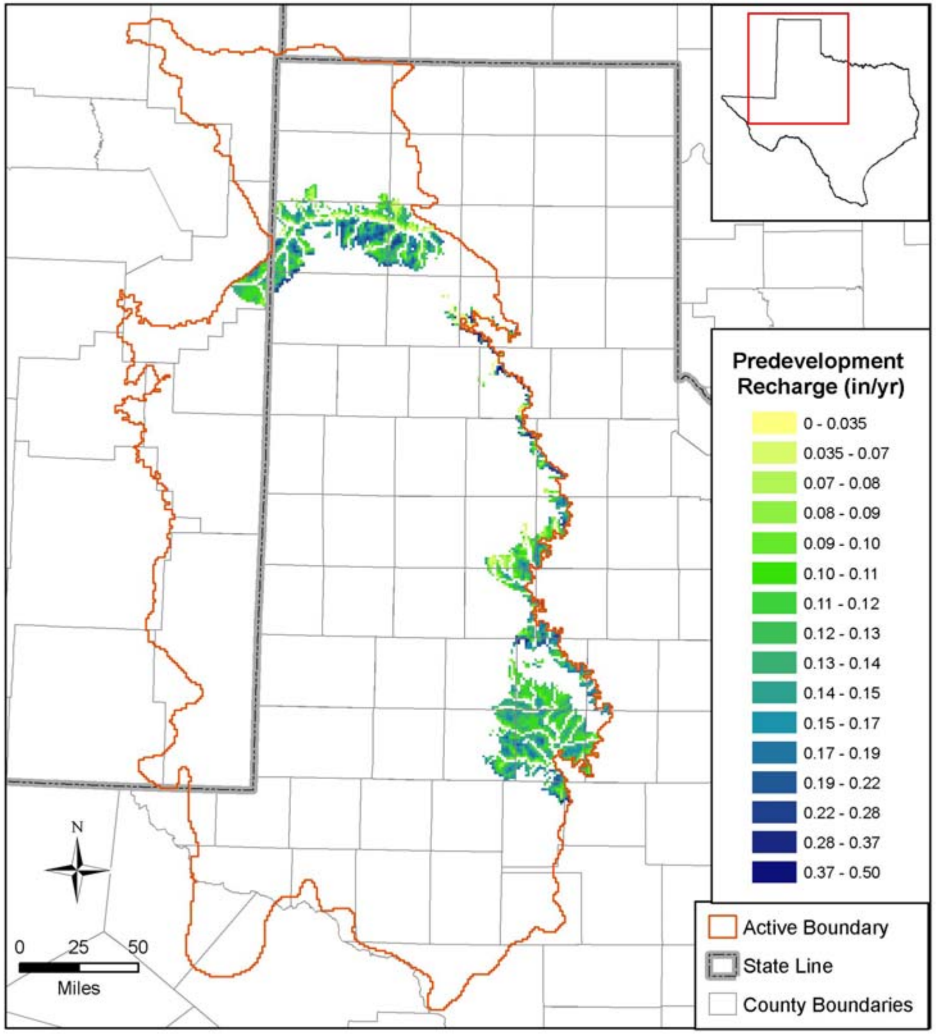
- **The correlation of estimated recharge to physical parameters was tested, however, no obvious correlation was found**
- **A significance analysis (t-test) was conducted to determine whether average recharge rates should be divided into regions; no significant difference existed**
- **Recharge rates were weighted as a power function of the local topography and normalized to conserve total recharge**
- **Power coefficient adjusted until maximum recharge rate was reasonable (~0.5 in/yr)**

Modern Recharge

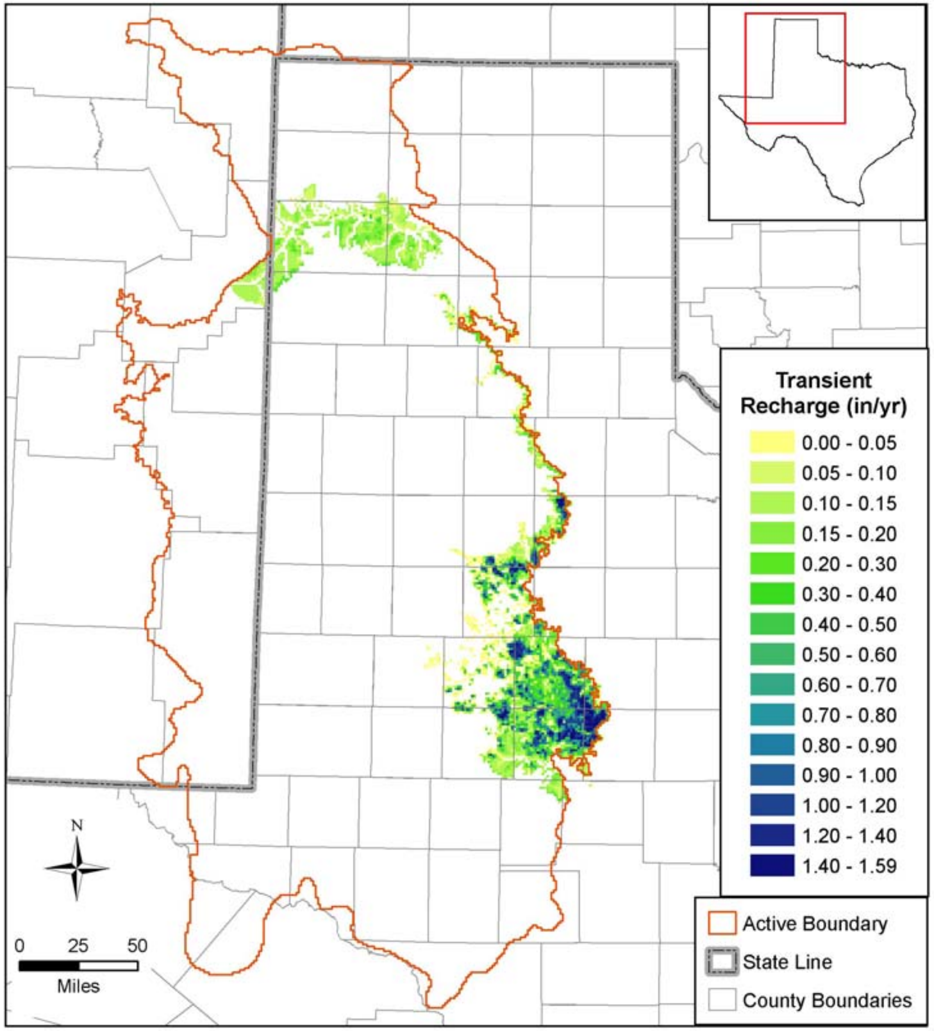
- **Analysis of regional water-level rise was conducted**
  - Colorado River outcrop rise indicates 2.2 in/yr effective recharge
  - Canadian River outcrop indicates no appreciable rise
  - includes recovery, stream loss, land-use impacts, return flow
- **For non-pumped, interstream wells with linear water table rise:**
  - Recharge = $\Delta h / S_y \Delta t$ where median = 1.6 in/yr
  - Already have 0.15 in/yr historical recharge
- **Added 1.45 in/yr to cropland areas**
  - Only added within Colorado River outcrop
  - Added to cells by percent cropland within cell

Recharge Distribution

Predevelopment



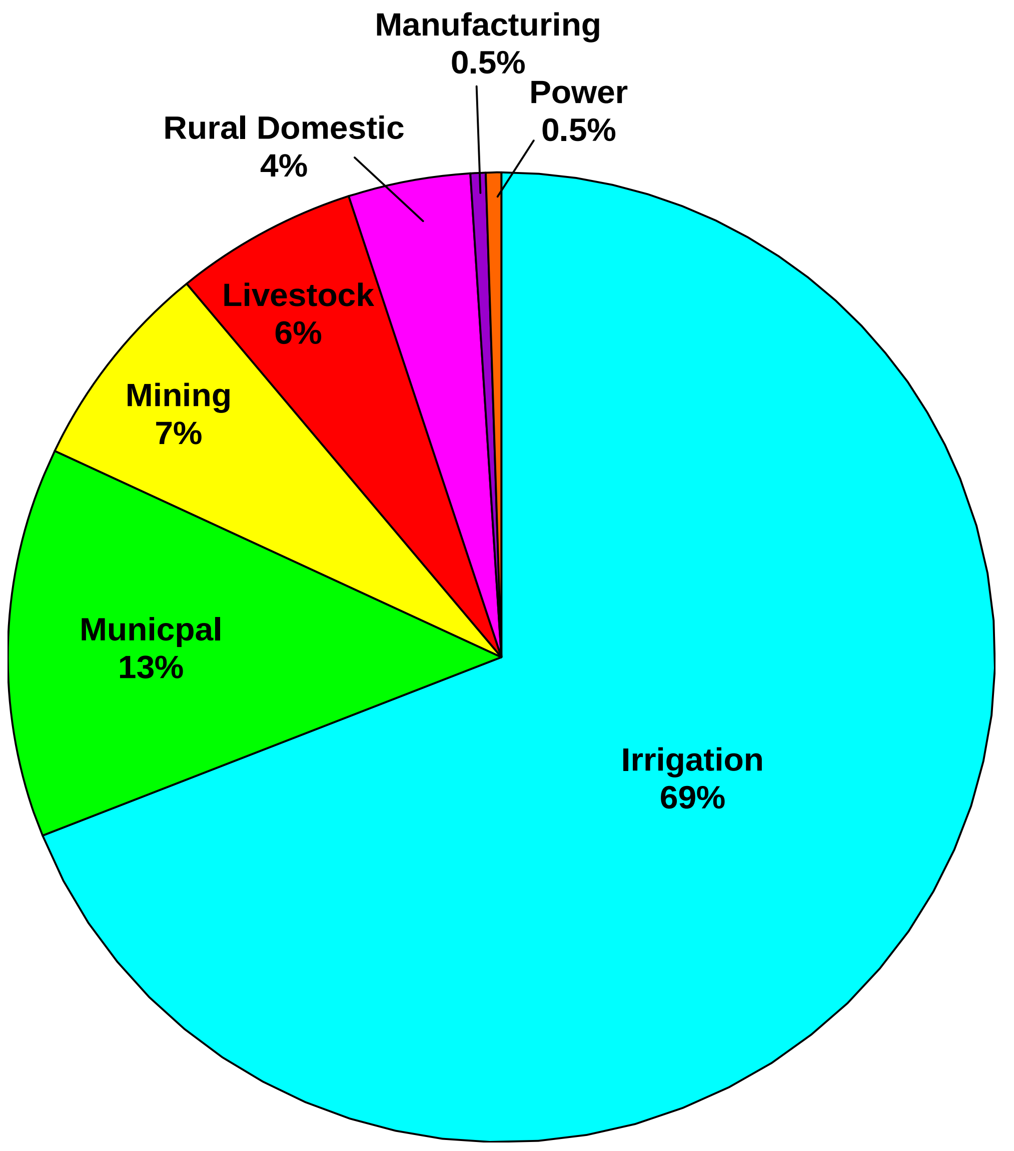
Modern



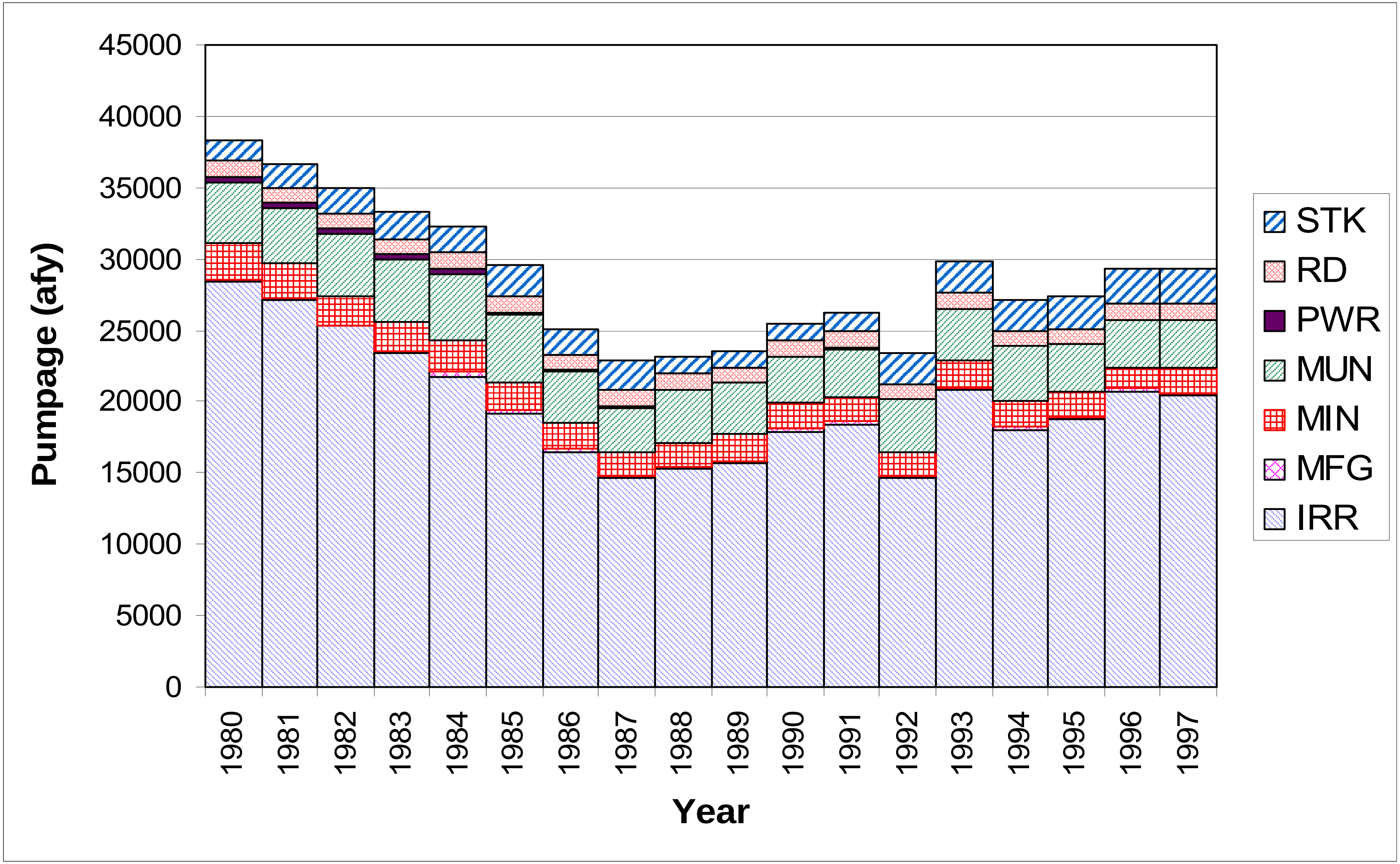
Aquifer Discharge Through Pumping

- Point Source Data
  - Municipal, power, mining, manufacturing
- Non-Point Source Data
  - Irrigation, livestock, county-other (domestic)
- Historical (1980-1997)
  - TWDB water use survey database

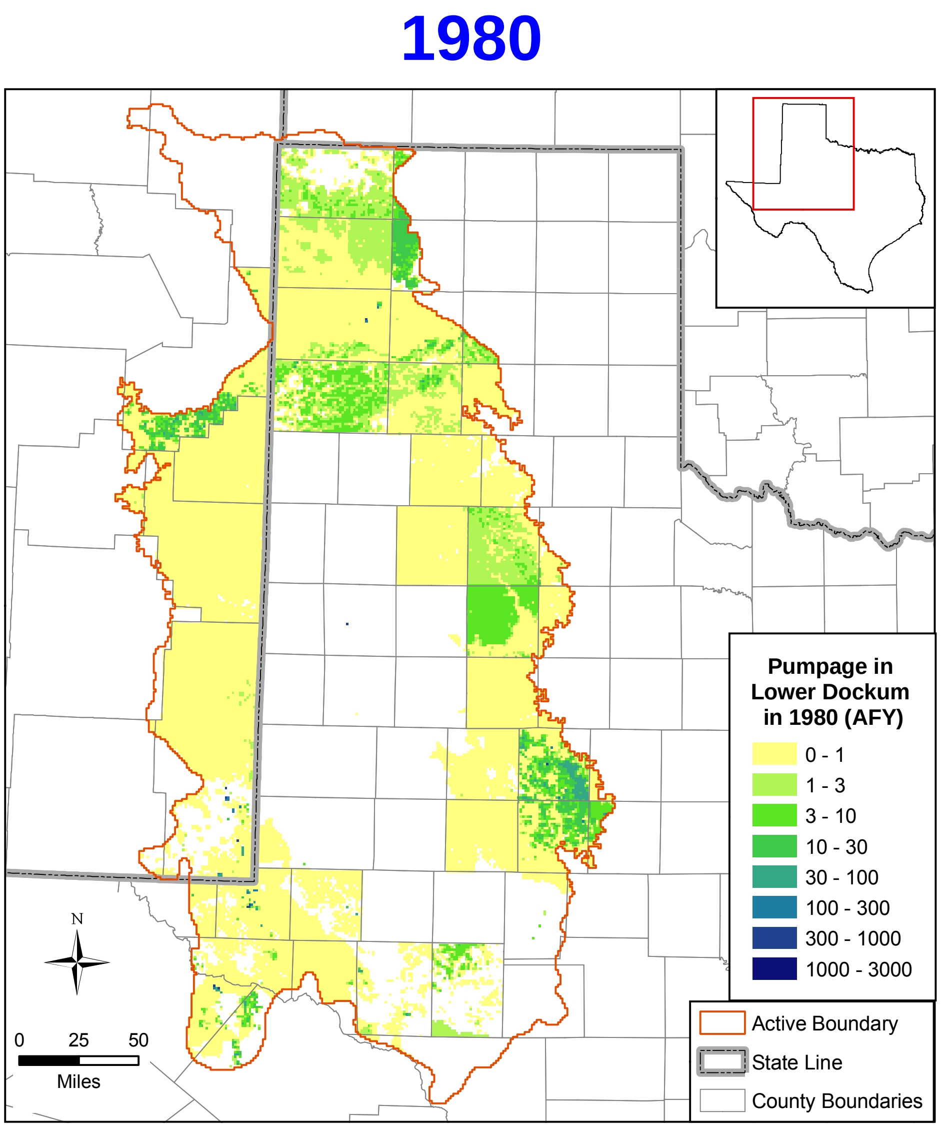
Uses of Water (1980 – 1997 Average)

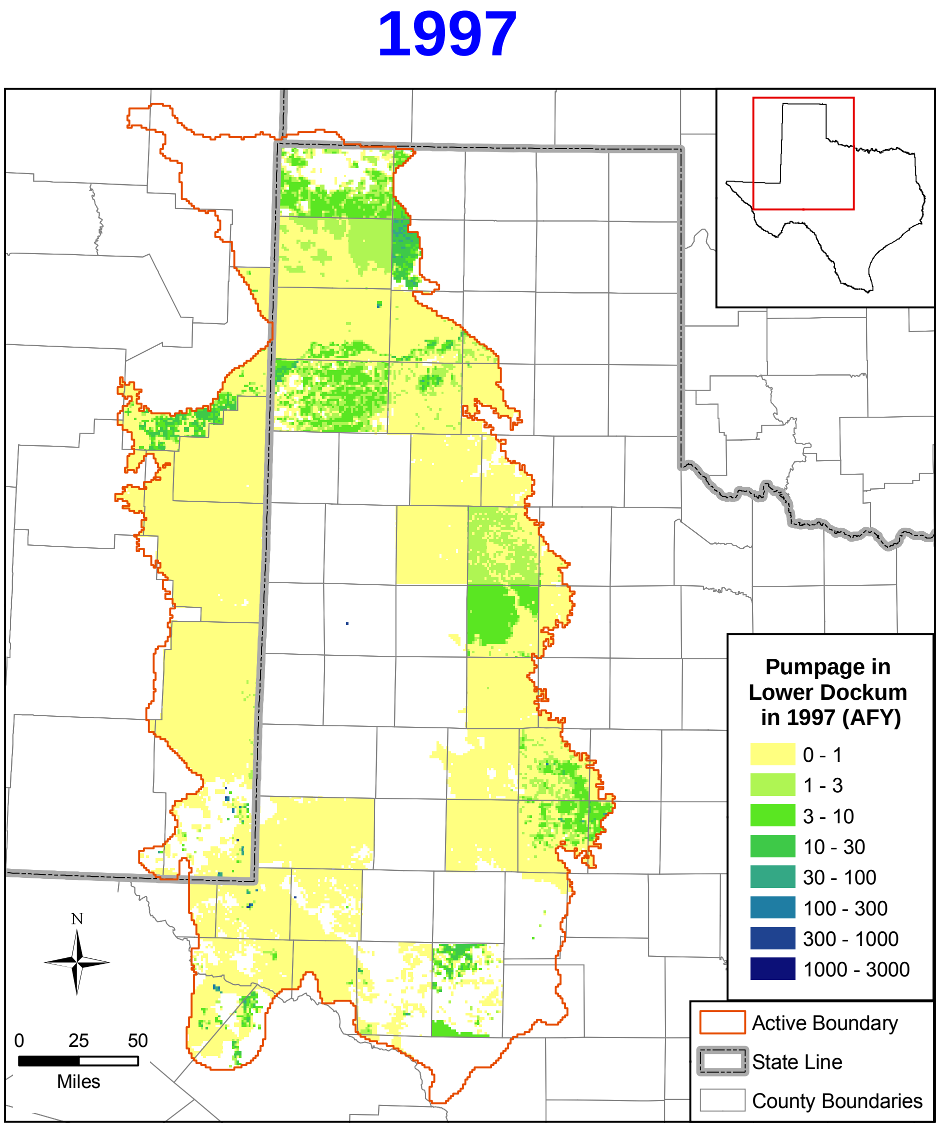


1980 – 1997 Pumpage

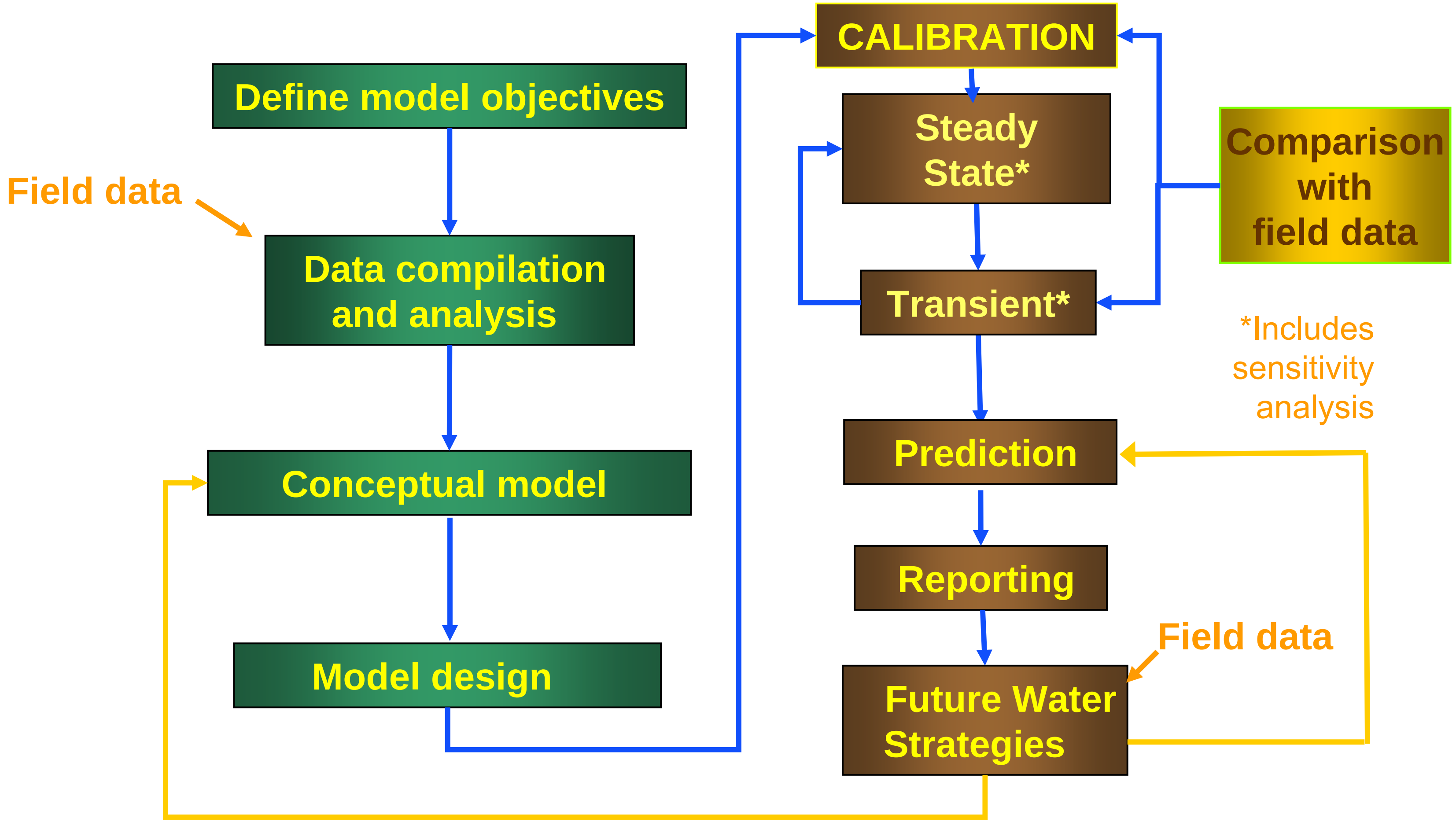


Pumpage (AFY)


1980
Pumpage in Lower Dockum in 1980 (AFY)
0 - 1
1 - 3
3 - 10
10 - 30
30 - 100
100 - 300
300 - 1000
1000 - 3000
Active Boundary
State Line
County Boundaries
N
0 25 50
Miles


1997
Pumpage in Lower Dockum in 1997 (AFY)
0 - 1
1 - 3
3 - 10
10 - 30
30 - 100
100 - 300
300 - 1000
1000 - 3000
Active Boundary
State Line
County Boundaries
N
0 25 50
Miles

Calibration Approach



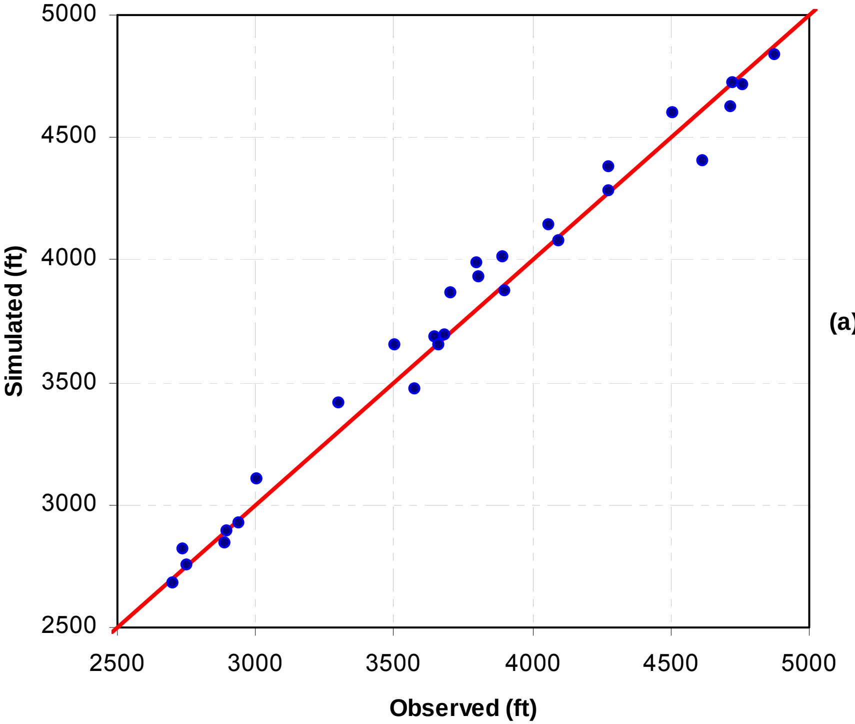
Model Evaluation

- Model results compared to observed data
  - Observed water levels
  - Stream flow
- Model results evaluated against literature data
  - Recharge
  - Hydraulic conductivities
- Model results evaluated against conceptual model
  - Flow from overlying aquifer

Model Calibration

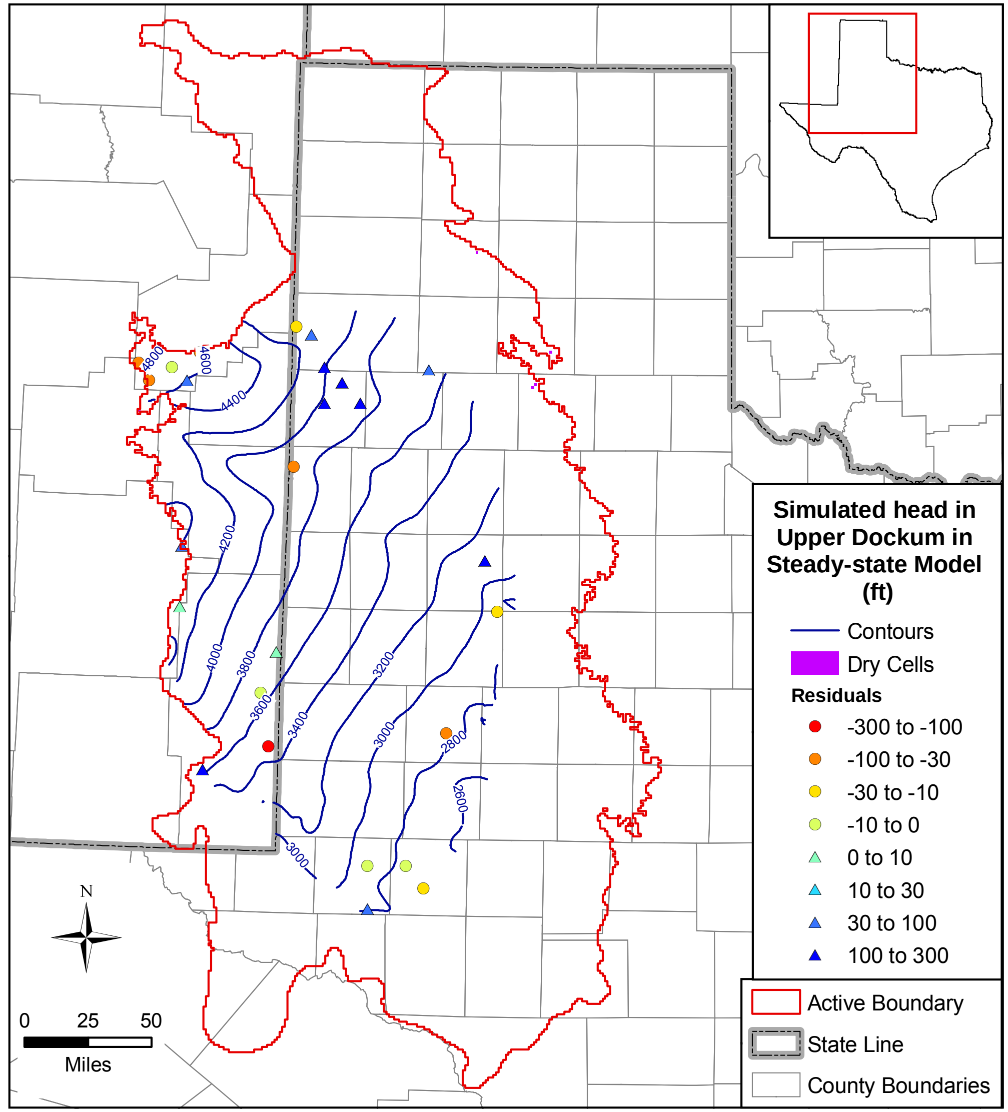
- **Calibration required:**
  - Reducing K_h of the upper and lower Dockum by factor of 0.2
  - Reducing K_v of the upper and lower Dockum by factor of 0.5
  - Reducing streambed conductances by a factor of 0.1

Upper Dockum Calibration – Predevelopment

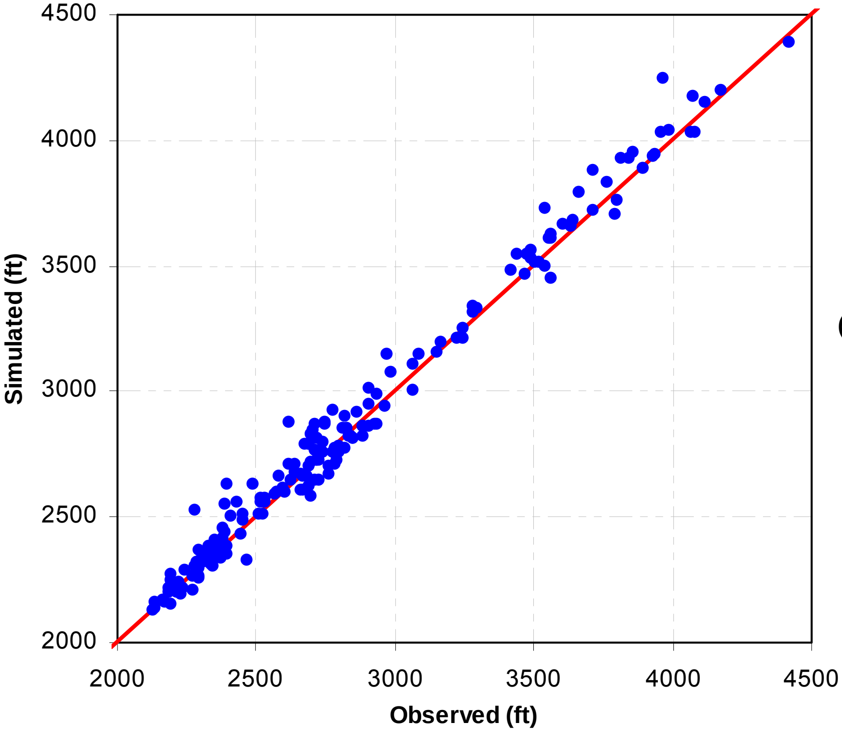


count	29
RMSE	99.8 ft
MAE	76.3 ft
ME	16.1 ft
Min E	-223.0 ft
Max E	185.6 ft
Range	2403.6 ft
RMSE/Range	4.15%
MAE/Range	3.17%
ME/Range	0.67%

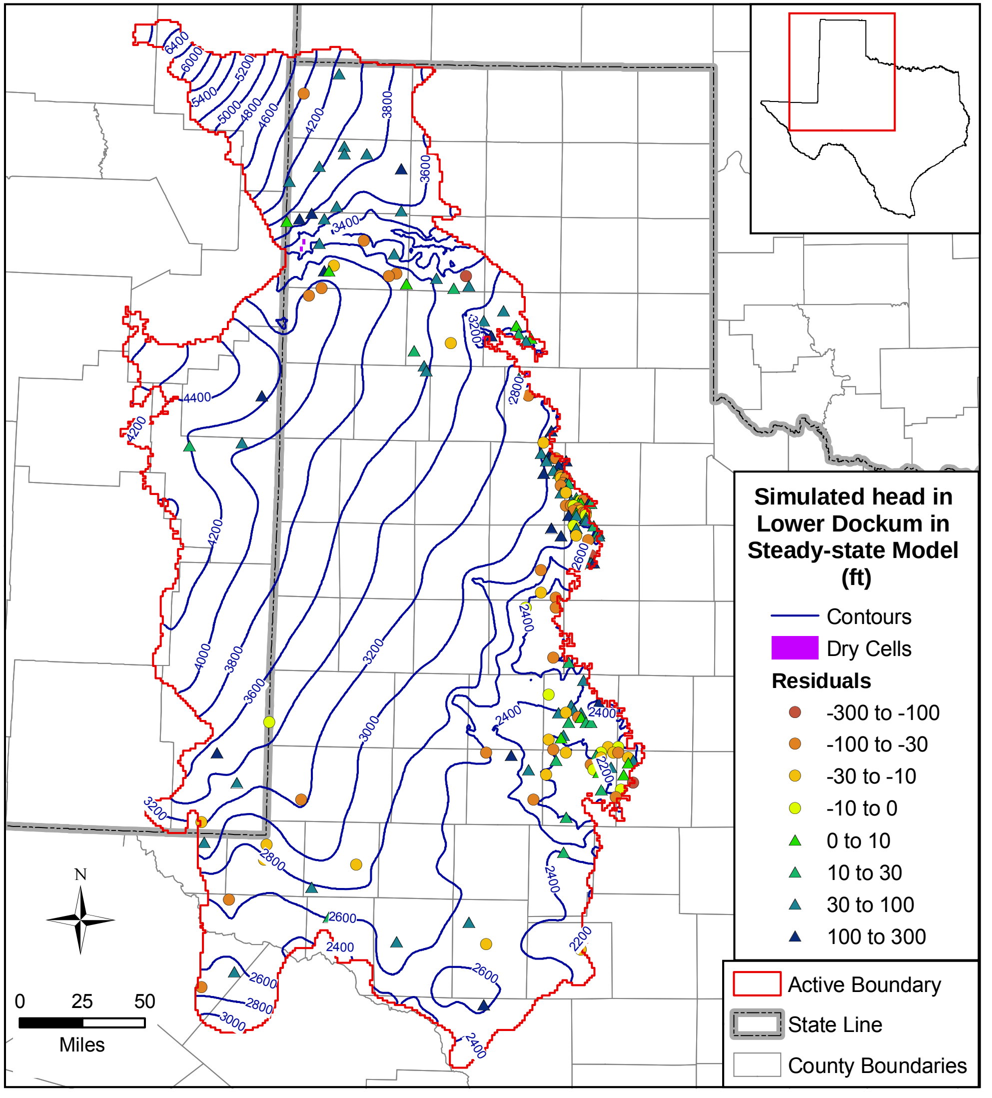
(a)



Lower Dockum Calibration – Predevelopment

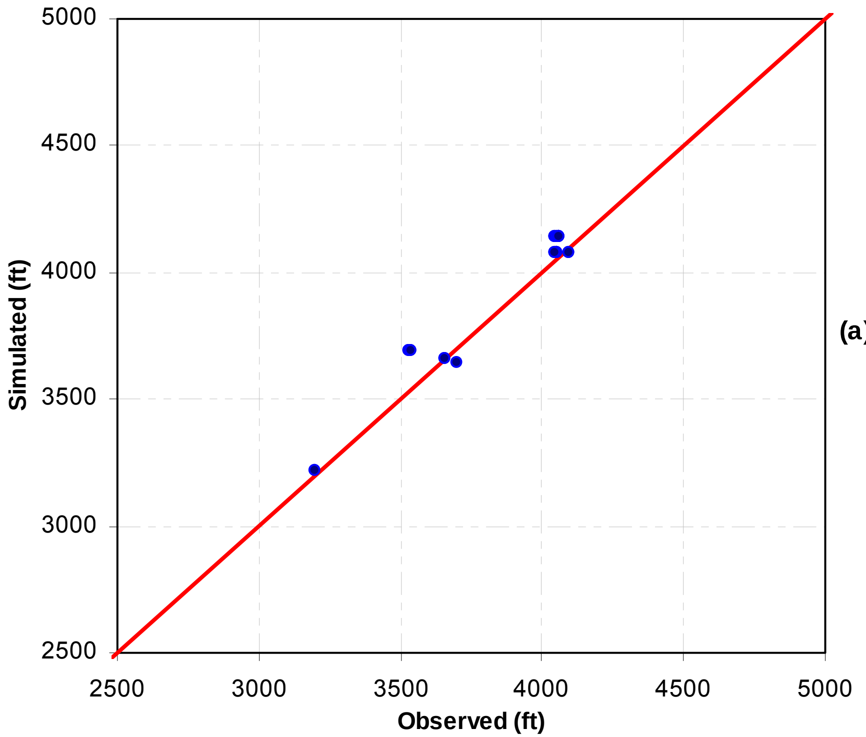


(a)

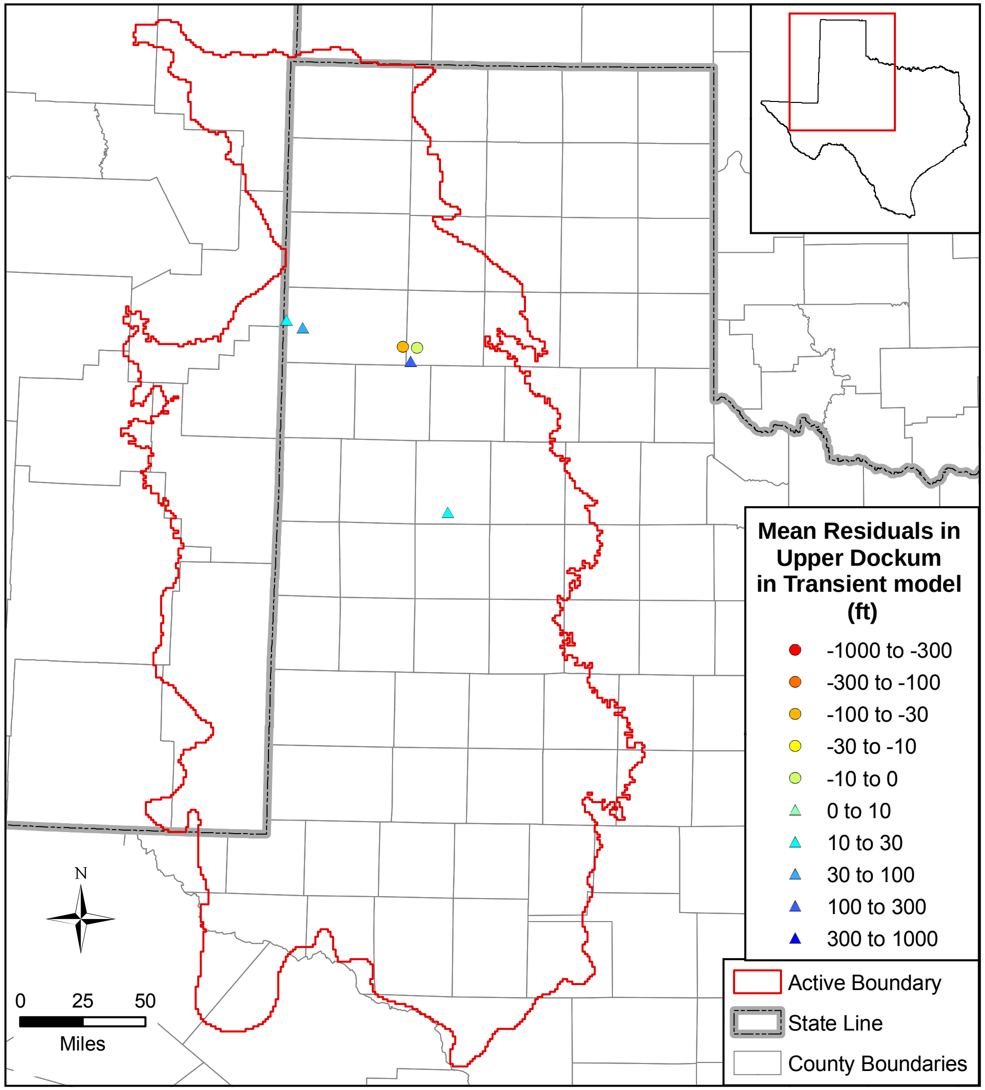


count	180
RMSE	73.0 ft
MAE	53.3 ft
ME	23.6 ft
Min E	-135.5 ft
Max E	274.4 ft
Range	2288.5 ft
RMSE/Range	3.19%
MAE/Range	2.33%
ME/Range	1.03%

Upper Dockum Calibration – Transient

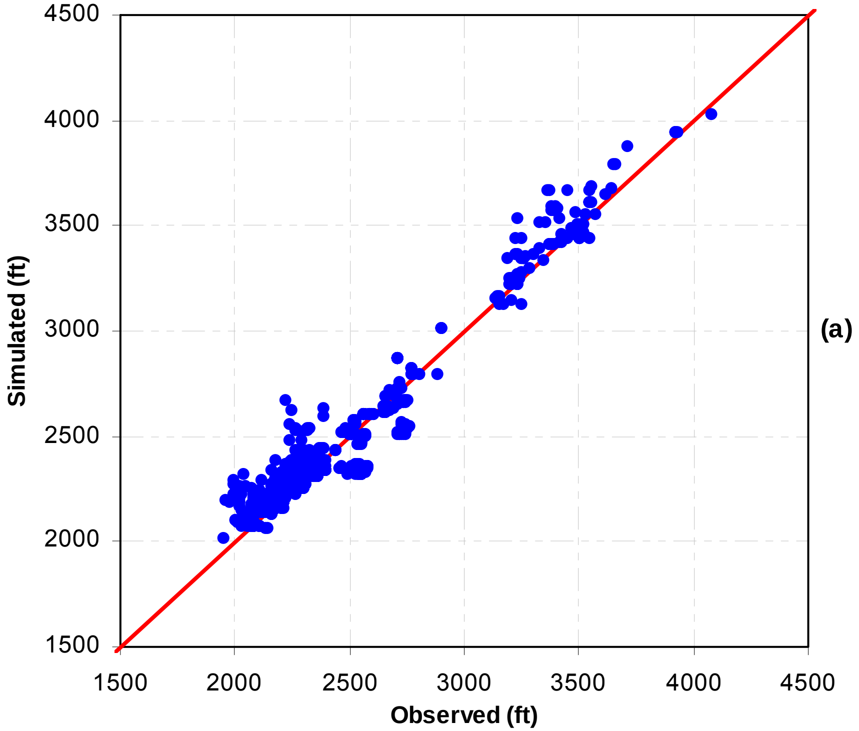


(a)

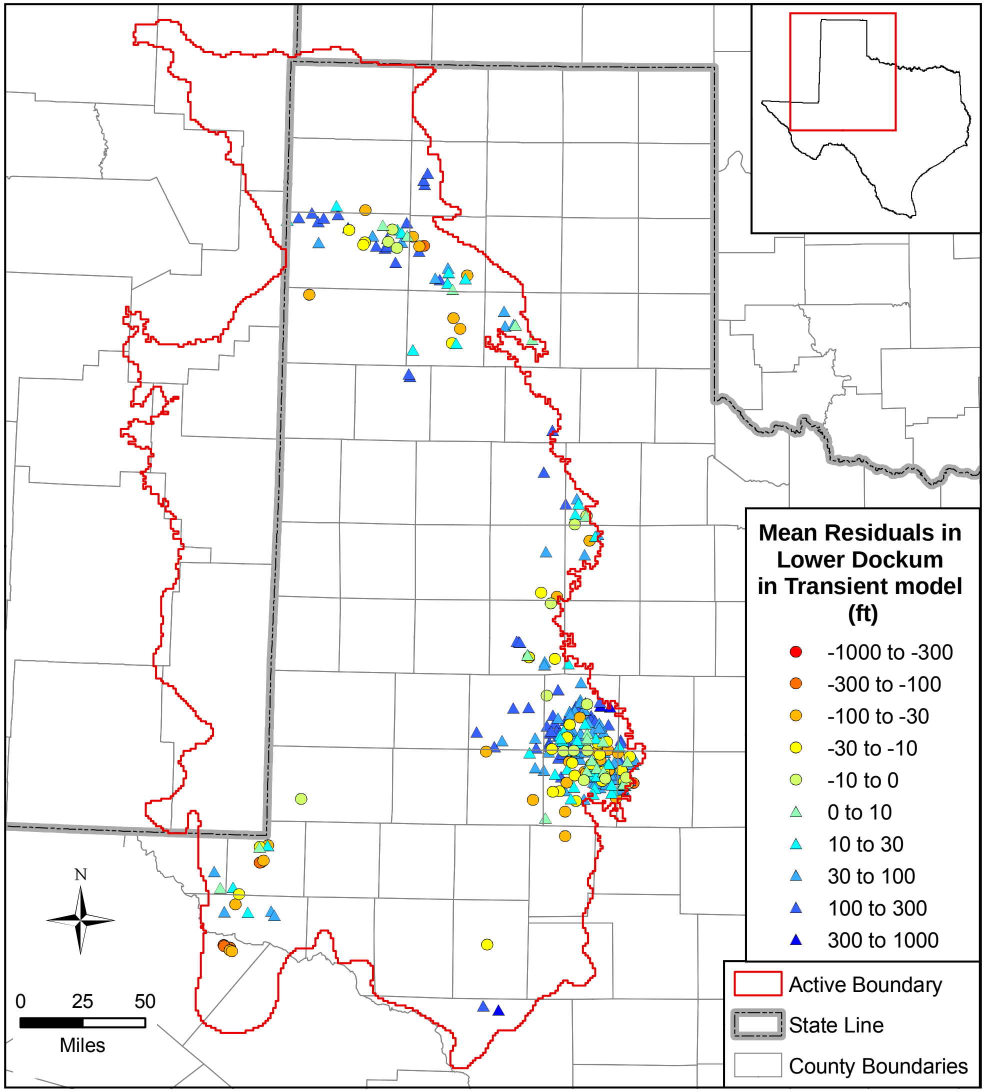


count	25
RMSE	82.2 ft
MAE	65.0 ft
ME	56.6 ft
Min E	-60.7 ft
Max E	163.7 ft
Range	2403.6 ft
RMSE/Range	3.42%
MAE/Range	2.70%
ME/Range	2.35%

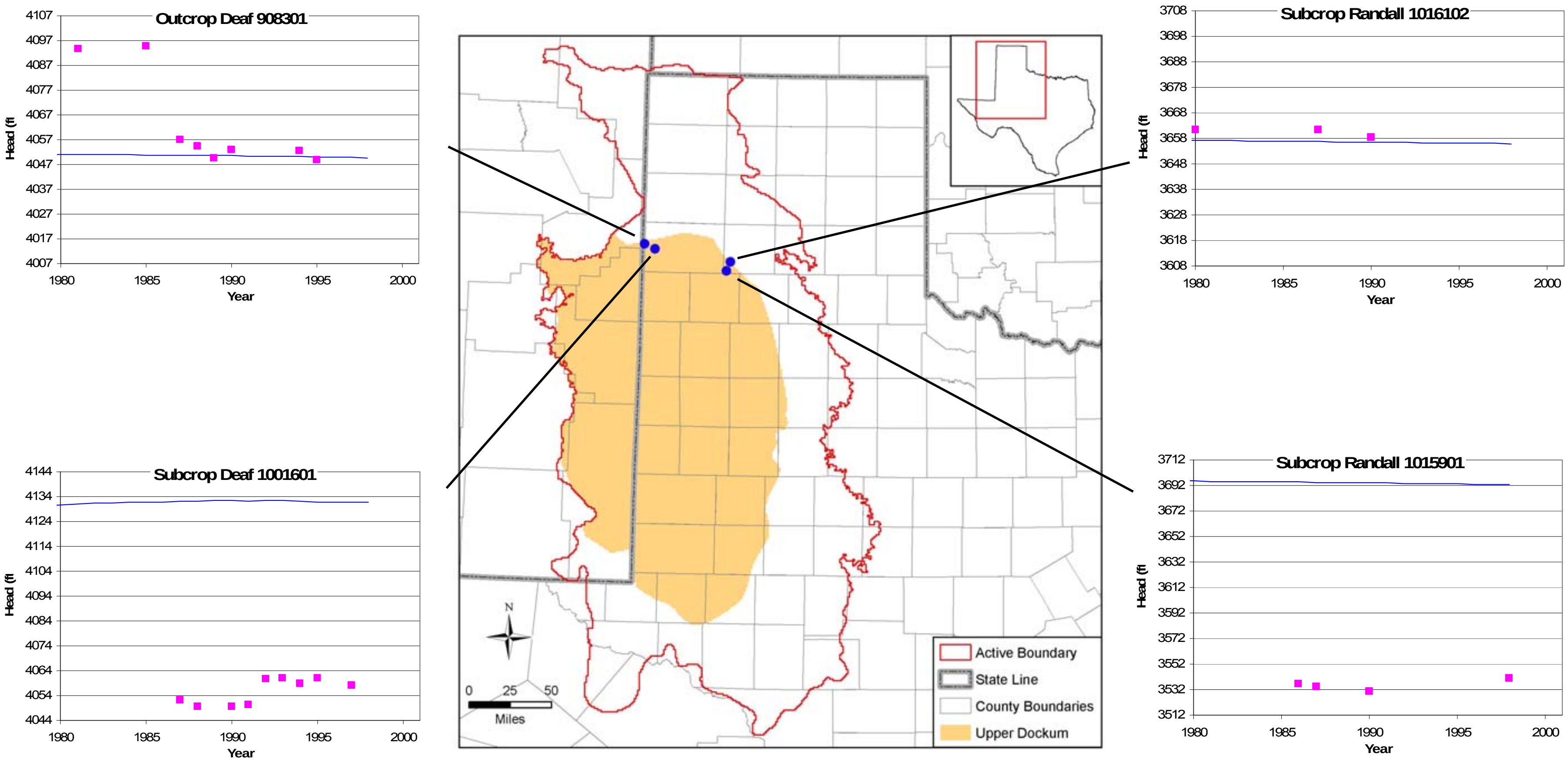
Lower Dockum Calibration – Transient



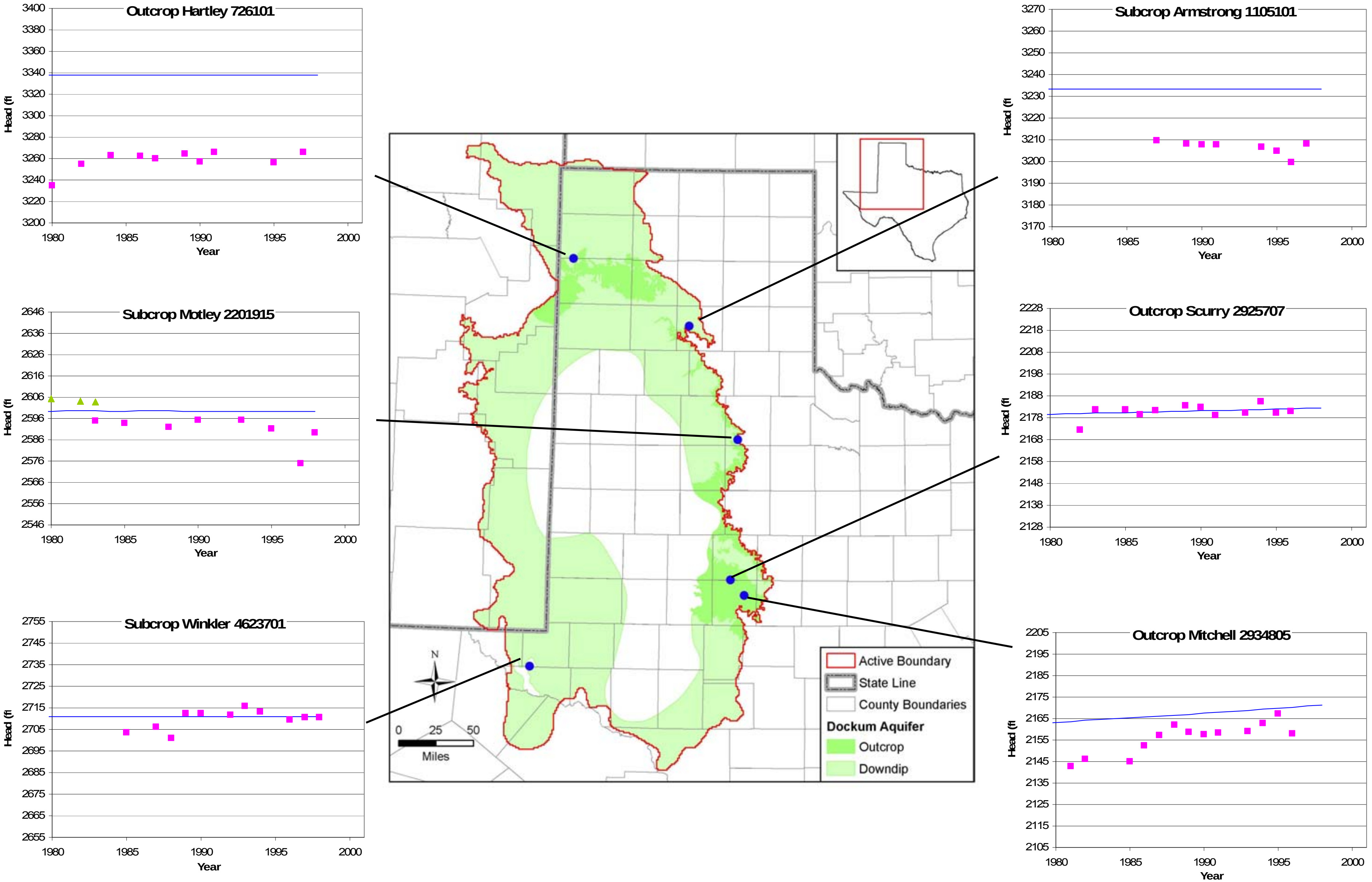
count	1293
RMSE	98.2 ft
MAE	69.6 ft
ME	6.2 ft
Min E	-243.6 ft
Max E	441.4 ft
Range	2288.5 ft
RMSE/Range	4.29%
MAE/Range	3.04%
ME/Range	0.27%



Upper Dockum Hydrographs

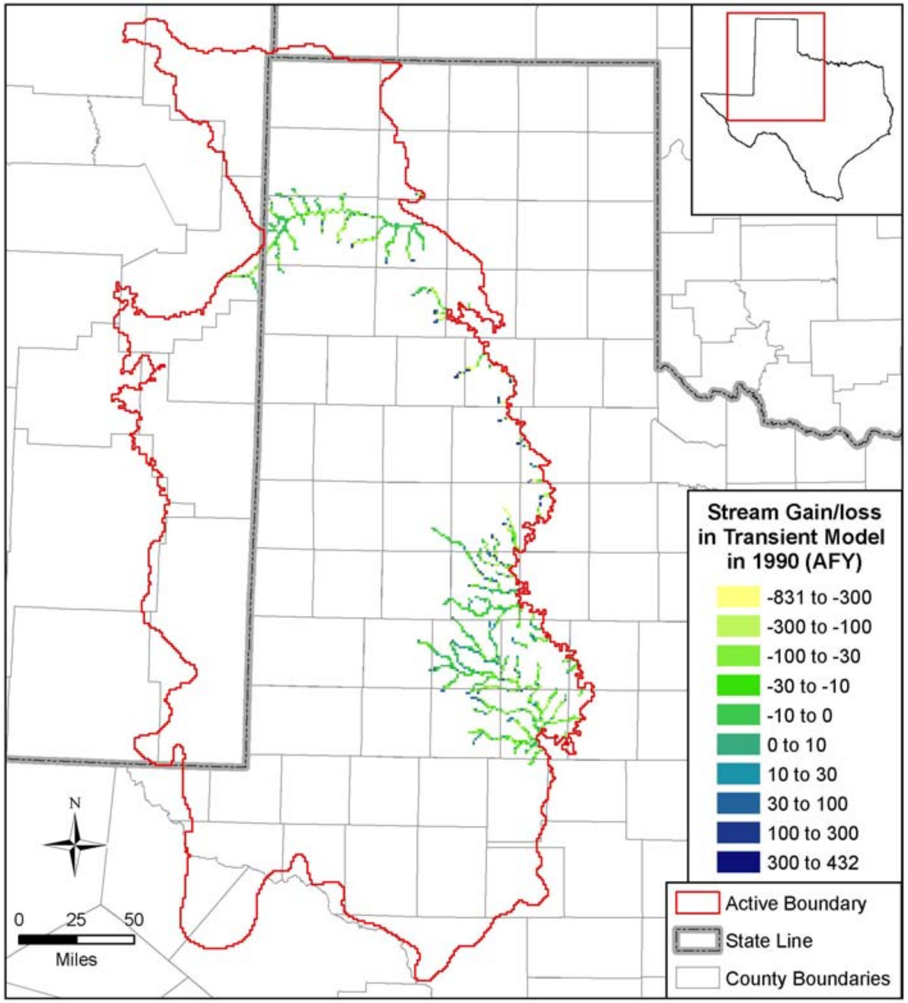


Lower Dockum Hydrographs

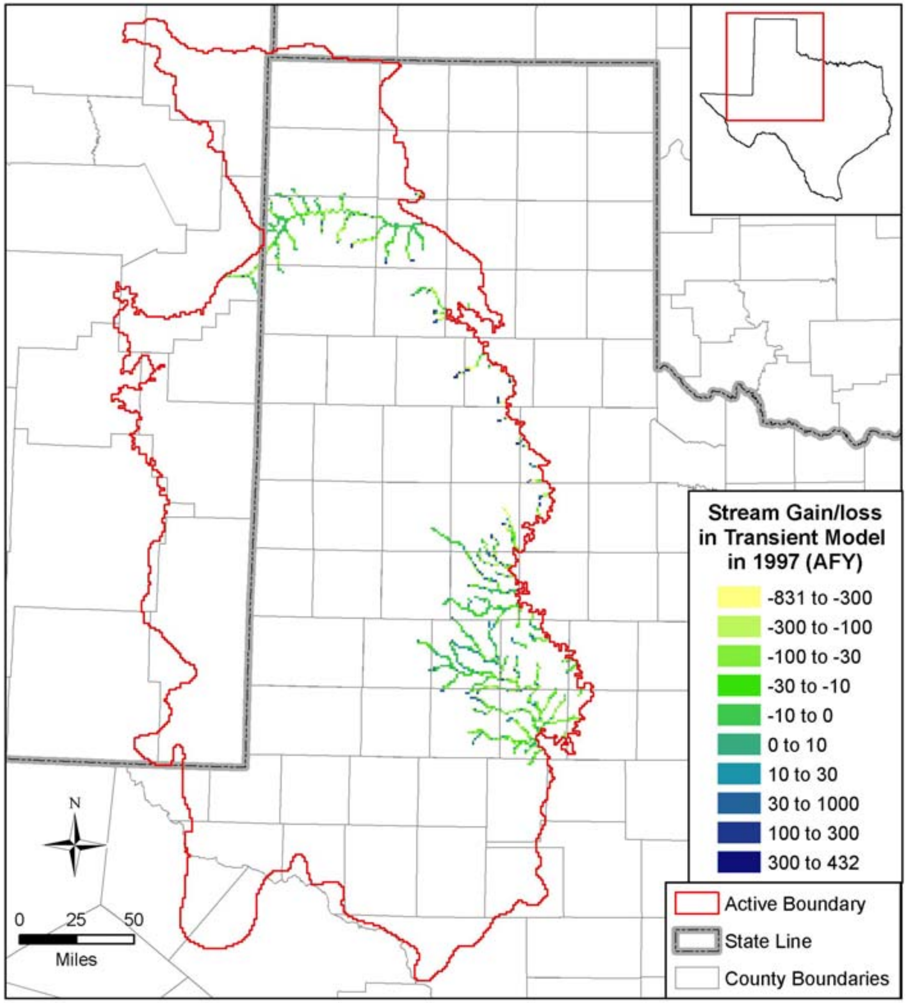


Stream Gain/loss

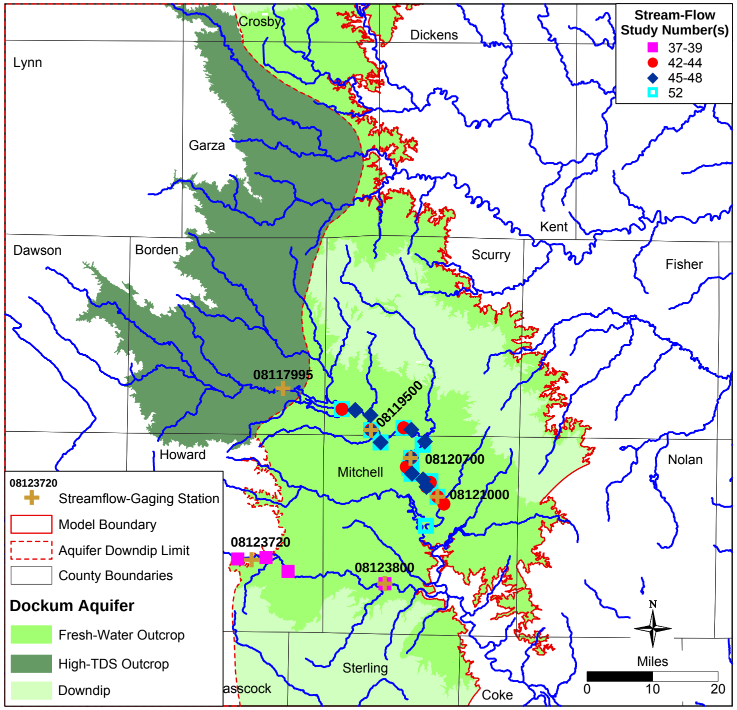
1990



1997

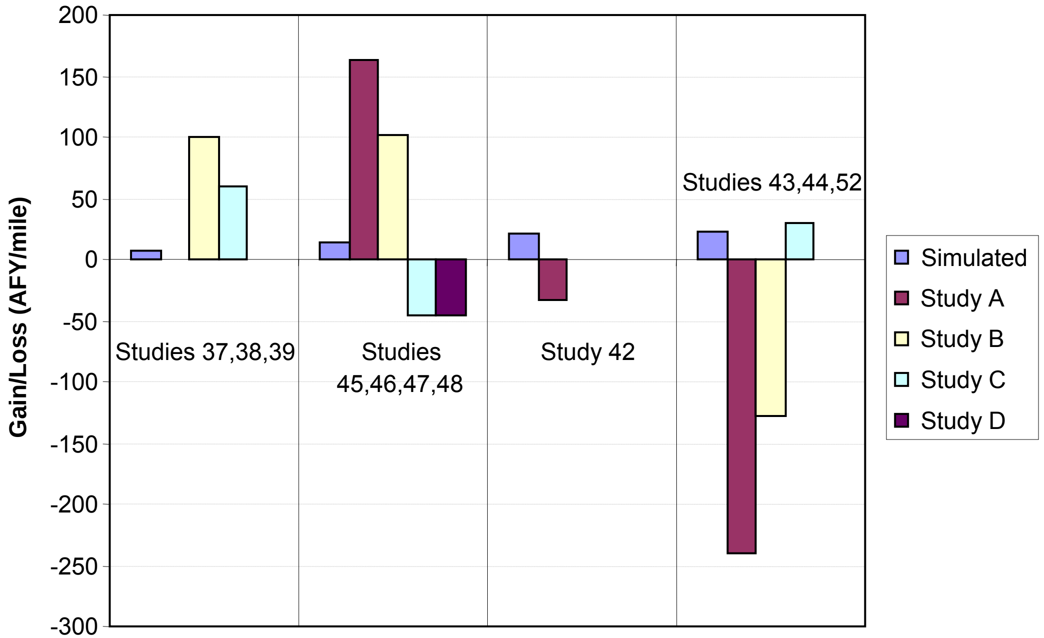


Stream Results



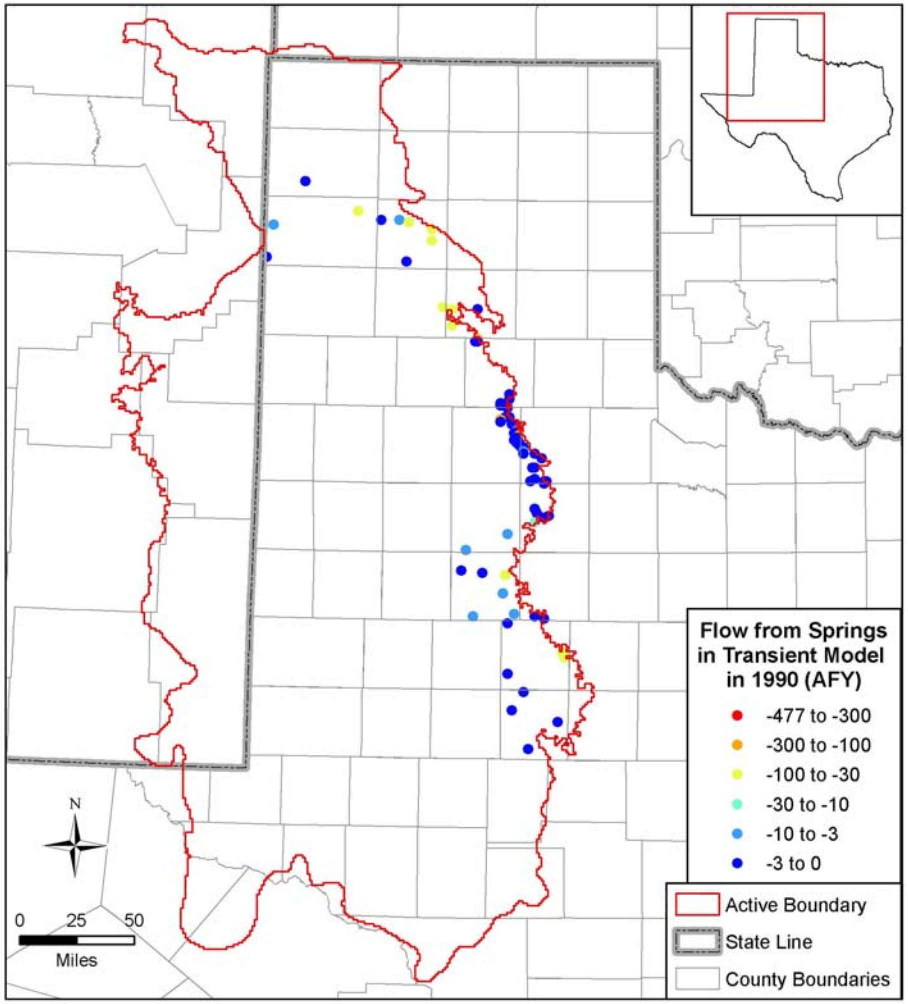
Slade et al., 2002

Comparison with Steady-State Model

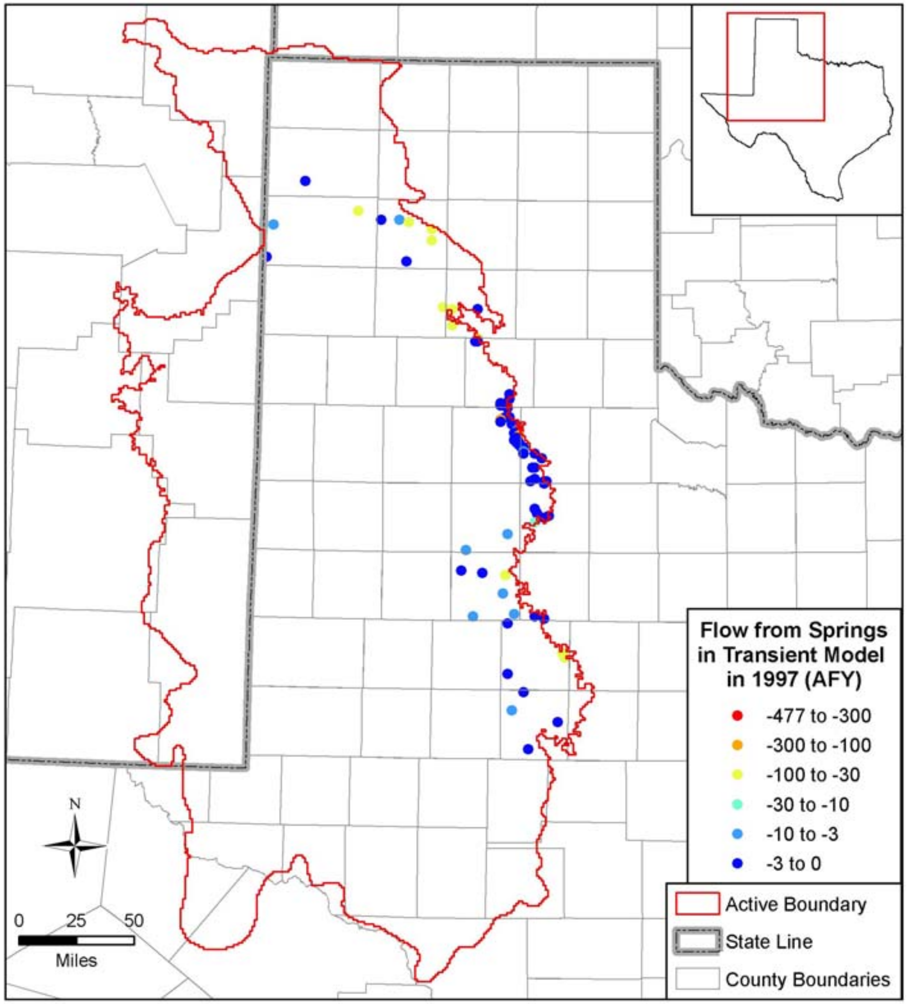


Spring Flow

1990

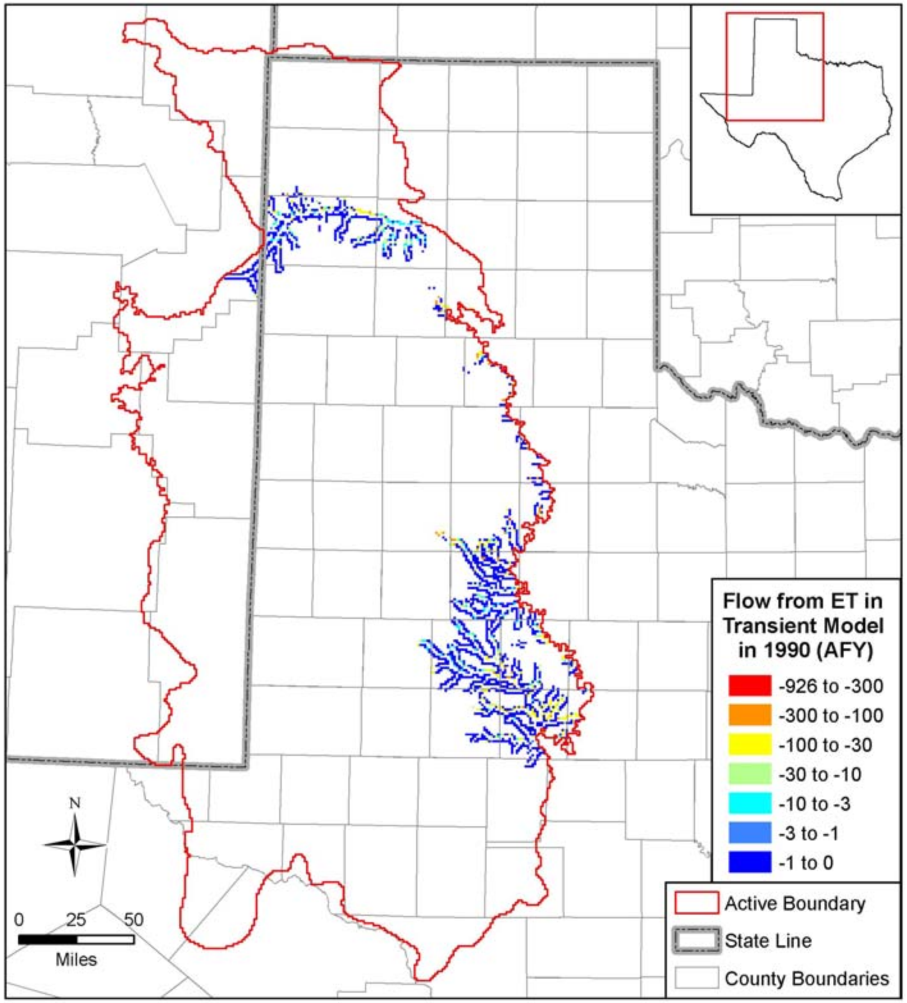


1997

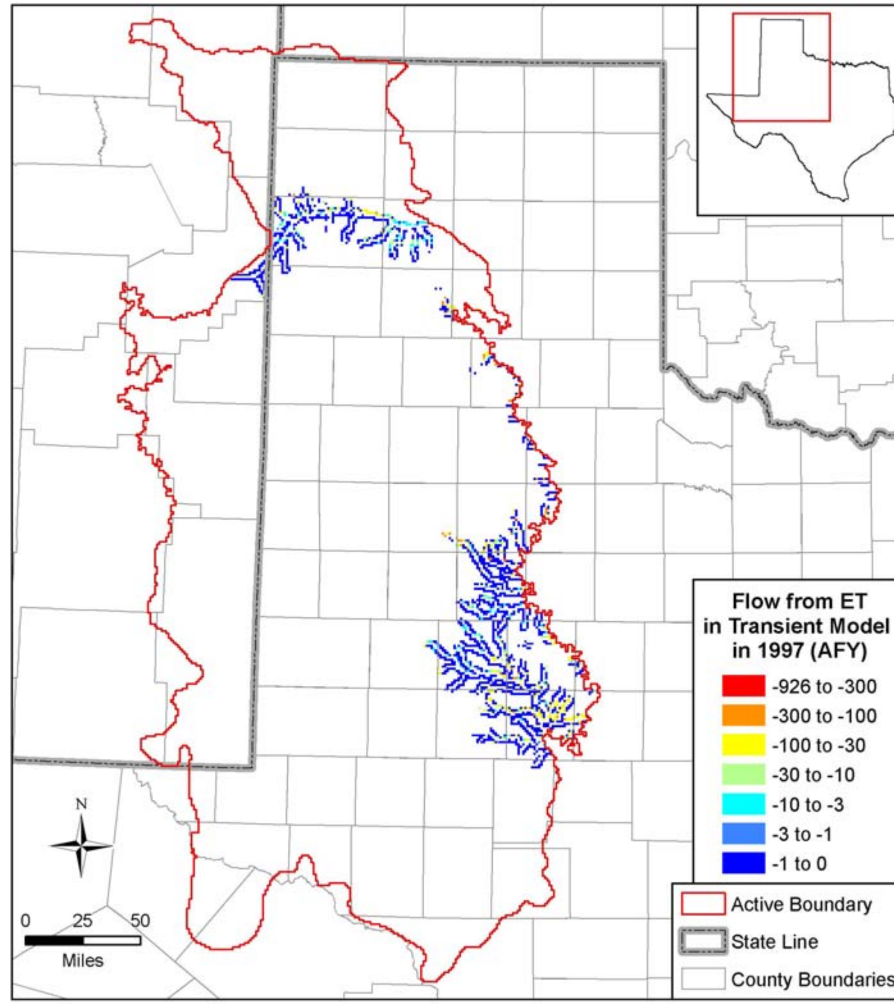


ET Flow

1990



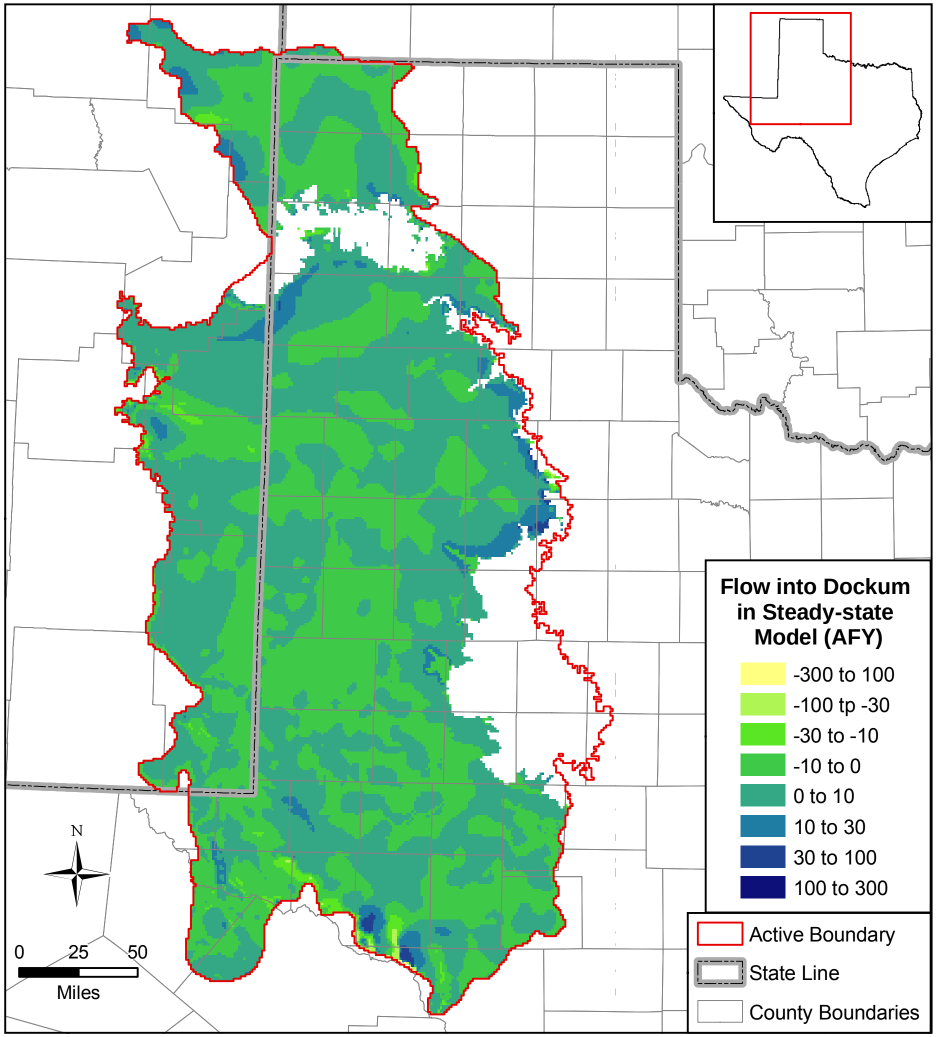
1997

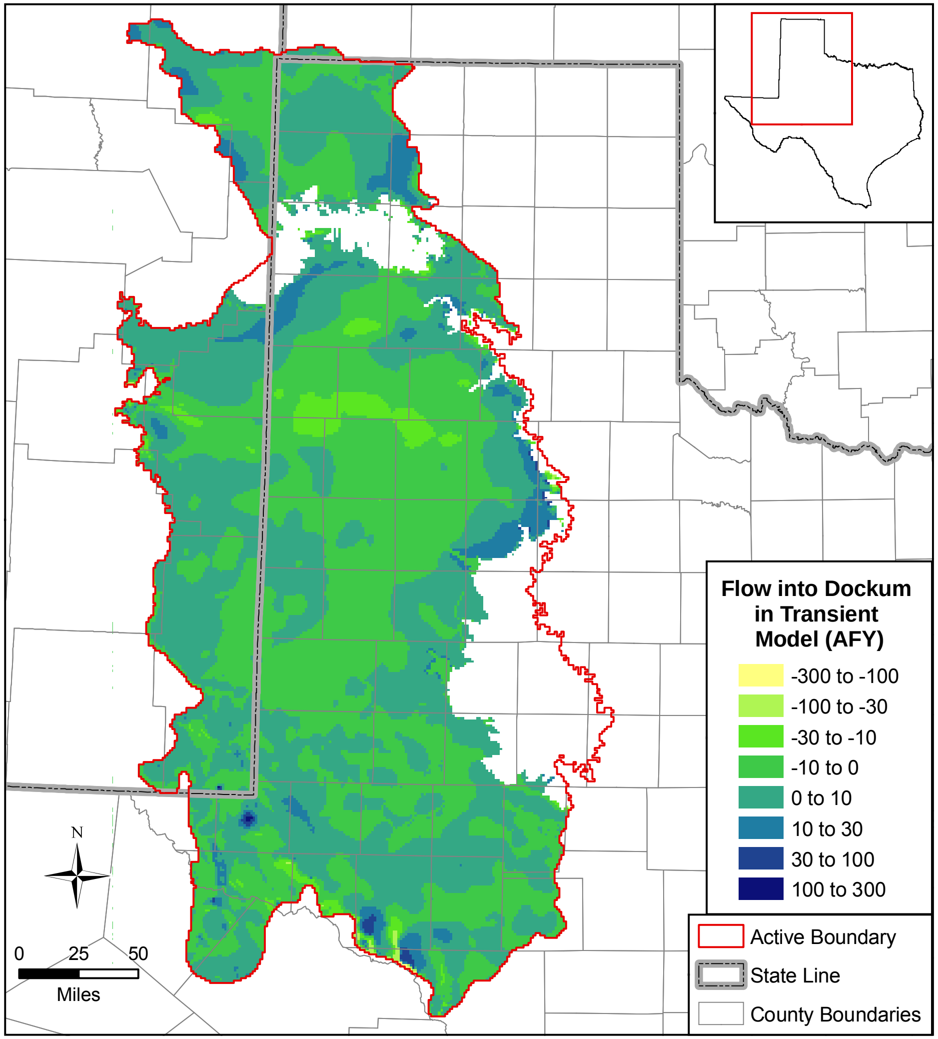


Flow into Top of Dockum

Predevelopment

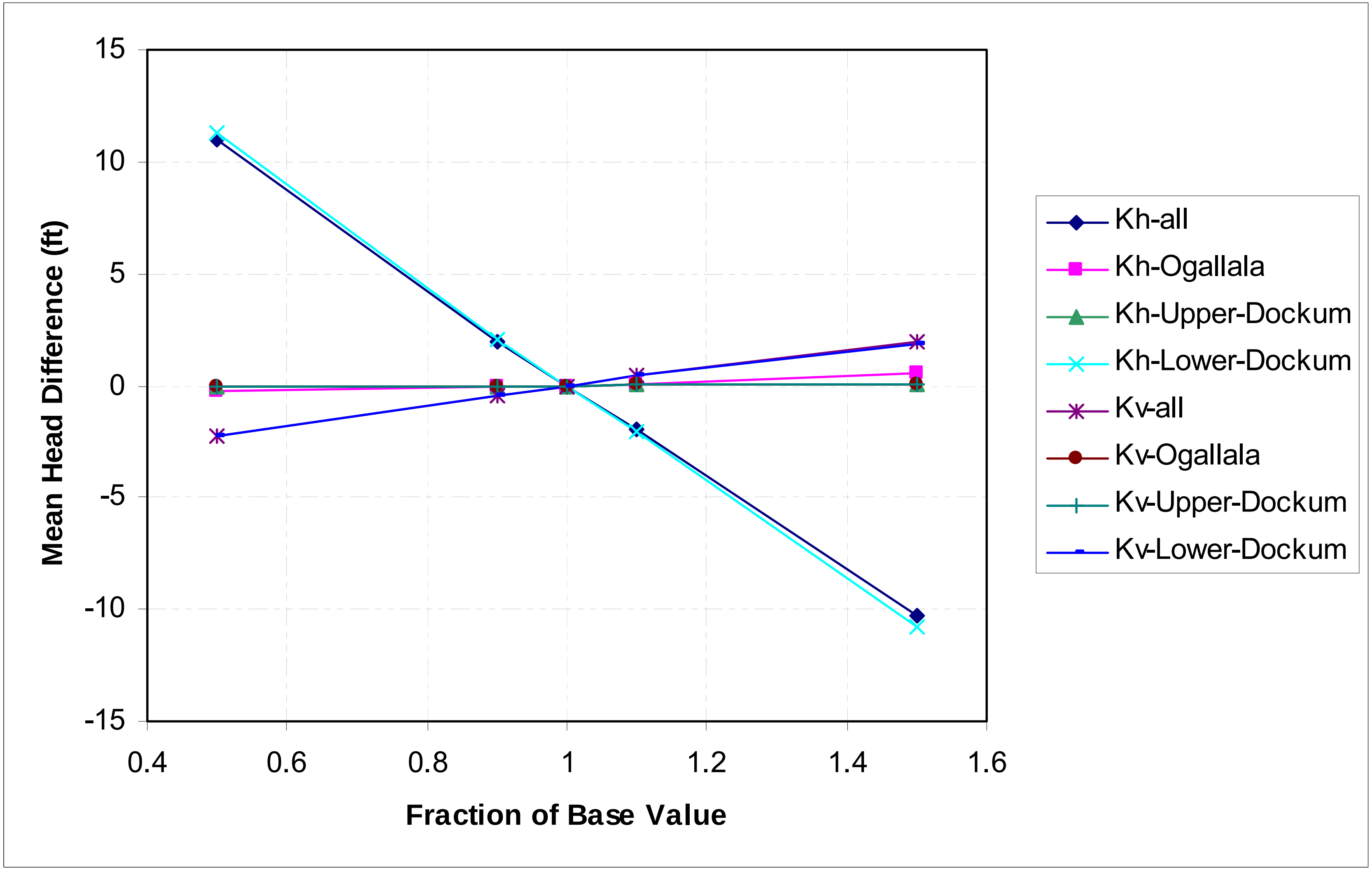
1997





Sensitivity Analysis

Example: Effect of Hydraulic Parameters on Lower Dockum Heads



Conclusions

- **GAM for Dockum Aquifer:**
  - Incorporated all relevant features, data on aquifer properties, recharge estimates, and pumpage
  - Calibrated to specifications:
    - steady-state (prior to 1950)
    - transient conditions (1980-1997)
  - Required some adjustment of properties during transient calibration (not beyond measured data)

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**
- pumpage – **contains tools for generating pumpage inputs along with output tables**
- Modflow – **contains all of the actual model input and output data files**

Data Models srcdata - examples

- Boundary – **geopolitical boundaries**
- Climate – **climatic data**
- Conservation – **natural and ecological boundaries**
- Geology – **subsurface geology, outcrop delineation**
- Geomorphology – **physiography and elevation**
- Geophysics – **well logs**
- Model* – **model inputs and results on the model grid**
- Recharge – **direct and irrigation recharge**
- Soil – **STATSGO data, runoff numbers**
- SubsurfaceHydro – **pumping rates, hydraulic conductivities, water levels, hydrographs**
- SurfaceHydro – **streamflows, stream/aquifer interaction, springflows**
- Transportation – **roads**

Data Models modflow

- mf2k
  - Input – ASCII input data sets for running modflow from the command line
  - Output – All output data sets
- vistas
  - Data sets for running the models from groundwater vistas interface along with output
- postprocessors
  - layerMB.pl – calculates layer water budgets
  - countyMB.pl – calculates budgets by county or GCD

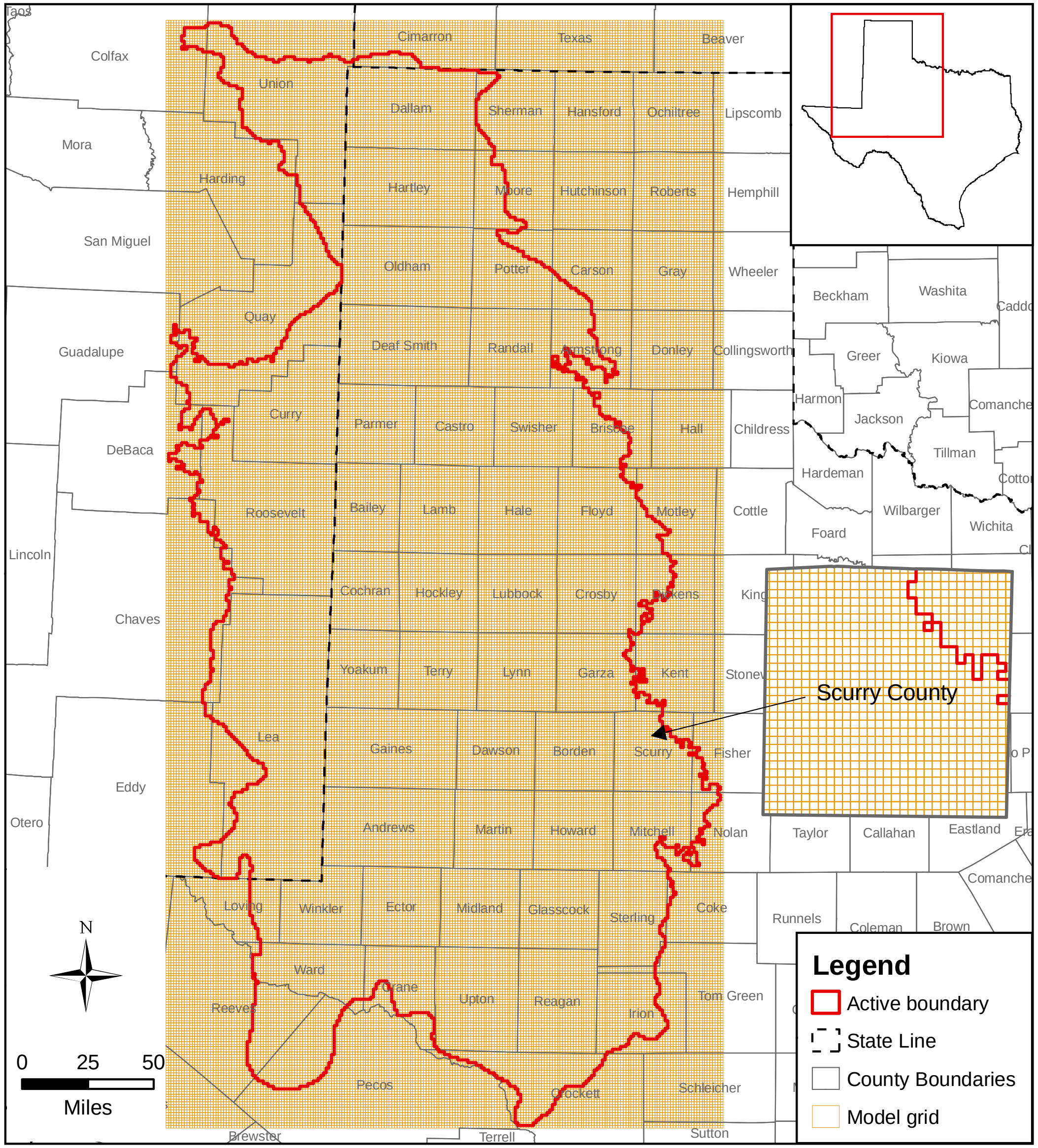
Limitations & Applicability of the GAM

- 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 of the GAM

- **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.

Model Grid Scale



Dockum Model Limitations

- Limitations of supporting data
  - Limited head targets spatially and temporally
  - Limited Stream/aquifer gain loss estimates
  - Limited data quantifying x-formational flow
  - Limited hydraulic property data in areas
- Assumptions
  - GHB used to describe overlying aquifers
  - Spatial variation in recharge
  - Lack of temporal variation in recharge
  - No flow to underlying formations

Dockum Model Limitations (continued)

- Model applicability
  - Regional scale
    - Applicable at scale of tens of miles
  - Annual stress period
    - Not applicable to seasonal trends
  - Low TDS regions
    - MODFLOW does not account for density-dependant flow in high TDS regions

Dockum Model Limitations (continued)

- Model applicability
  - Surface water/groundwater coupling
    - The model does not provide a rigorous solution to surface water modeling for GAMs
  - Water-quality issues
    - Only a preliminary assessment of water quality is conducted for the GAMs

Future Improvements

- Additional supporting data
  - Water-level monitoring in areas with sparse measurements
  - Recharge studies
  - Long-term surface water/groundwater studies
  - Additional study of structure
  - Additional estimates of flow from overlying aquifers
  - Additional data describing seasonal trends

Future Implementation Improvements

- Account for density-dependant flow
  - If simulations are to include development of high TDS portion aquifer, a different simulator (e.g., SEAWAT) may be warranted
- Account for flow to underlying units
  - If water-level data become available to describe conditions in underlying Permian formation, could add a fourth model layer
- Grid Refinement
  - If local effects of a small portion of the aquifer are to be modeled, a local-scale model with a refined grid should be considered

Dockum GAM
4th Stakeholder Training Seminar
October 22, 2008

Sign-in Sheet

Name	Affiliation
Melanie Barnes	LWV
Jim Conkwright	HPWD
Harvey Everheart	Mesa UWCD
John Ewing	INTERA
Michelle Guelker	Lone Wolf GCD
Ian Jones	TWDB
Steve Walthour	North Plains GCD
Bruce Blalack	City of Lubbock
Emmett Autrey	City of Amarillo
Ferrel Wheeler	Garza Co. U&FWCD
Aubrey Spear	City of Lubbock