Final Numerical Model Report for the Brazos River Alluvium Aquifer Groundwater Availability Model

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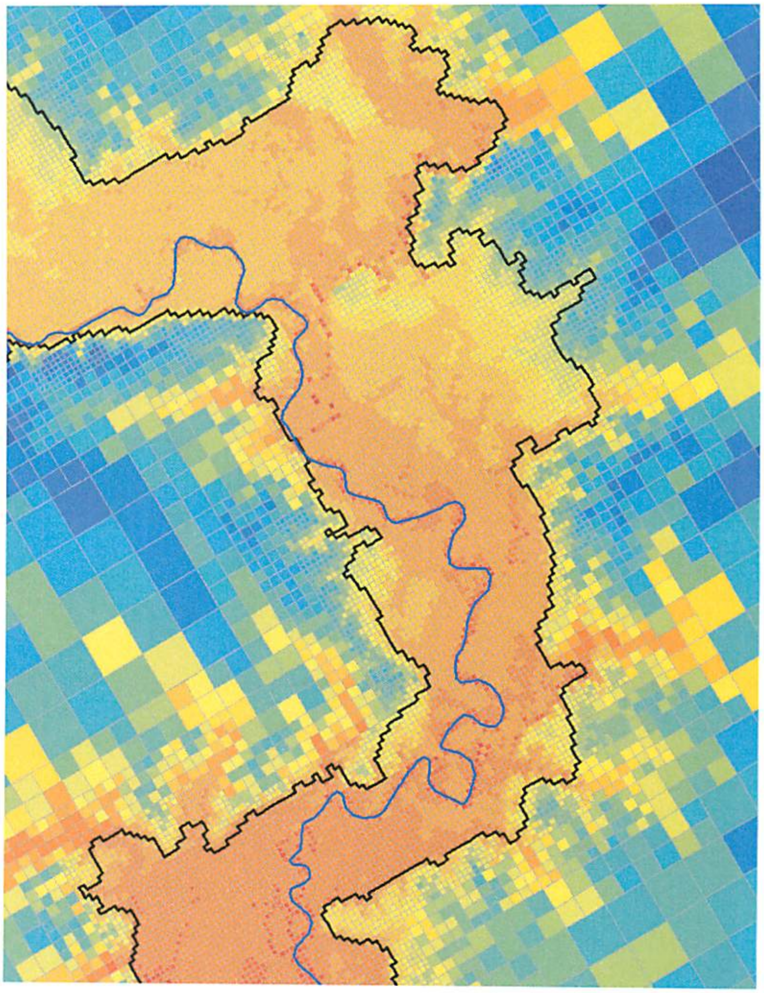

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Executive Summary

This report documents the construction and calibration of the numerical groundwater availability model for the Brazos River Alluvium Aquifer, and is targeted primarily to those with experience constructing and/or using groundwater models. The numerical model was developed as part of the Texas Water Development Board's groundwater availability model program. The purpose of the Brazos River Alluvium Aquifer model is to provide a tool for managing the groundwater resources in the study area.

The Brazos River Alluvium Aquifer consists of the floodplain deposits and hydraulically connected terrace deposits of the Brazos River in southeast Texas. Sediments comprising these deposits range from clay to large cobbles and occur in lenses that grade both laterally and vertically. The transition from one type of material to another, both laterally and vertically, can be either sharp and distinct or gradual. The Brazos River Alluvium Aquifer is unconfined with potentially locally confined conditions where clay lenses overlie lenses of sand or gravel. From northwest to southeast, the aquifer overlies the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers. The shallow portions of these aquifers are assumed to be hydraulically connected to the Brazos River Alluvium Aquifer since they are conceptualized to regionally discharge to the Brazos River.

The code used to implement the numerical model was MODFLOW-USG. The model consists of three layers, and the model grid is composed of square grid cells ranging from 1/8-mile to 1-mile in size. A quadtree mesh is used to transition from the more refined cells to the coarser cells. The model simulates the time period from 1950 to 2012, with an initial steady-state stress period that represents pre-development conditions. The model was primarily calibrated to observed heads in the Brazos River Alluvium Aquifer. It was calibrated to both steady-state and transient conditions. Both the steady-state and transient calibration statistics are well within acceptable ranges. The model was also calibrated to steady-state estimates of baseflow to the streams in the model domain and to steady-state observed heads in the formations underlying the Brazos River Alluvium Aquifer.

In the steady-state calibration, recharge is the major source of inflow to the Brazos River Alluvium Aquifer followed by cross-formational flow from the underlying units, and discharge to perennial rivers is the largest source of outflow. In the transient model, perennial rivers continue to be the largest source of outflow on average but, in individual months, pumping may eclipse outflow to perennial rivers. Recharge and cross-formational flow continue to be the major sources of inflow to the aquifer in the transient model. It should be noted that the Brazos River can, at any given day, month, or year, act as either a major source of inflow or a major source of outflow to or from the Brazos River Alluvium Aquifer based on the variations in stream stage in the river.

Cross-formational flow from the underlying formations into the Brazos River Alluvium Aquifer remains relatively constant at around 50,000 acre-feet per year throughout most of the transient record although it can fluctuate significantly on a monthly basis. The largest change in the transient water budget over the historical period is an increase in pumping in recent years.

A sensitivity analysis was performed, which indicated that heads in the Brazos River Alluvium Aquifer were most sensitive to the horizontal hydraulic conductivity of layer 1. The heads in the Brazos River Alluvium Aquifer were also sensitive, in decreasing order, to recharge to the alluvium, the horizontal hydraulic conductivity of layer 2 and to the streambed conductance of perennial streams.

All groundwater models have limitations with respect to data support, scale, and the assumptions used in their development. However, the development documented in this report resulted in a well-calibrated model of the Brazos River Alluvium Aquifer that can be used to support water availability planning at a regional scale.

1.0 Introduction and Purpose of Model

1.1 Introduction

The Texas Water Development Board (TWDB) has identified the major and minor aquifers in Texas on the basis of regional extent and amount of water produced. The major and minor aquifers are shown in Figures 1.0.1 and 1.0.2, respectively. General discussion of the major and minor aquifers is given in Ashworth and Hopkins (1995). Aquifers that supply large quantities of water over large areas of the state are defined as major aquifers and those that supply relatively small quantities of water over large areas of the state or supply large quantities of water over small areas of the state are defined as minor aquifers.

The boundary of the Brazos River Alluvium Aquifer is shown in Figure 1.0.3. The Brazos River Alluvium Aquifer consists of the floodplain and terrace deposits of the Brazos River. It extends from Bosque and Hill counties in the northwest to Fort Bend County in the southeast portion of the study area.

This report documents the construction and calibration of the numerical groundwater availability model for the Brazos River Alluvium Aquifer. A previous report (Ewing and others, 2016) documented the conceptual model development for the Brazos River Alluvium Aquifer groundwater availability model. While the conceptual model report is written in a style that should be accessible to most interested stakeholders, this numerical model report is targeted primarily to those with experience constructing and/or using groundwater models.

1.2 Purpose of the Model

The Texas Water Code codified the requirement for generation of a State Water Plan that allows for the development, management, and conservation of water resources and the preparation and response to drought, while maintaining sufficient water available for the citizens of Texas (TWDB, 2007). Senate Bill 1 (75th Texas Legislative Session, 1997) and subsequent legislation directed the TWDB to coordinate regional water planning with a process based upon public participation. Also, as a result of Senate Bill 1, the approach to water planning in the state of Texas has shifted from a water-demand based allocation approach to an availability-based approach.

Groundwater models provide a tool to estimate groundwater availability for various water use strategies and to determine the cumulative effects of increased water use and drought. A groundwater model is a numerical representation of the aquifer system capable of simulating historical conditions and predicting future aquifer conditions. Inherent to the groundwater model are a set of equations that are developed and applied to describe the primary or dominant physical processes considered to be controlling groundwater flow in the aquifer system. Groundwater models are essential for performing complex analyses and making informed predictions and related decisions (Anderson and Woessner, 1992).

Development of groundwater availability models for the major and minor Texas aquifers is integral to the state water planning process. The purpose of the groundwater availability modeling program is to provide a tool that can be used to develop reliable and timely information on groundwater availability for the citizens of Texas and to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. The groundwater availability models also serve as an integral part of the process of determining modeled available groundwater based on desired future conditions, as required by House Bill 1763 (79th Texas Legislative Session, 2005). The Brazos River Alluvium Aquifer groundwater availability model will thus serve as a critical tool for groundwater planning in the state.

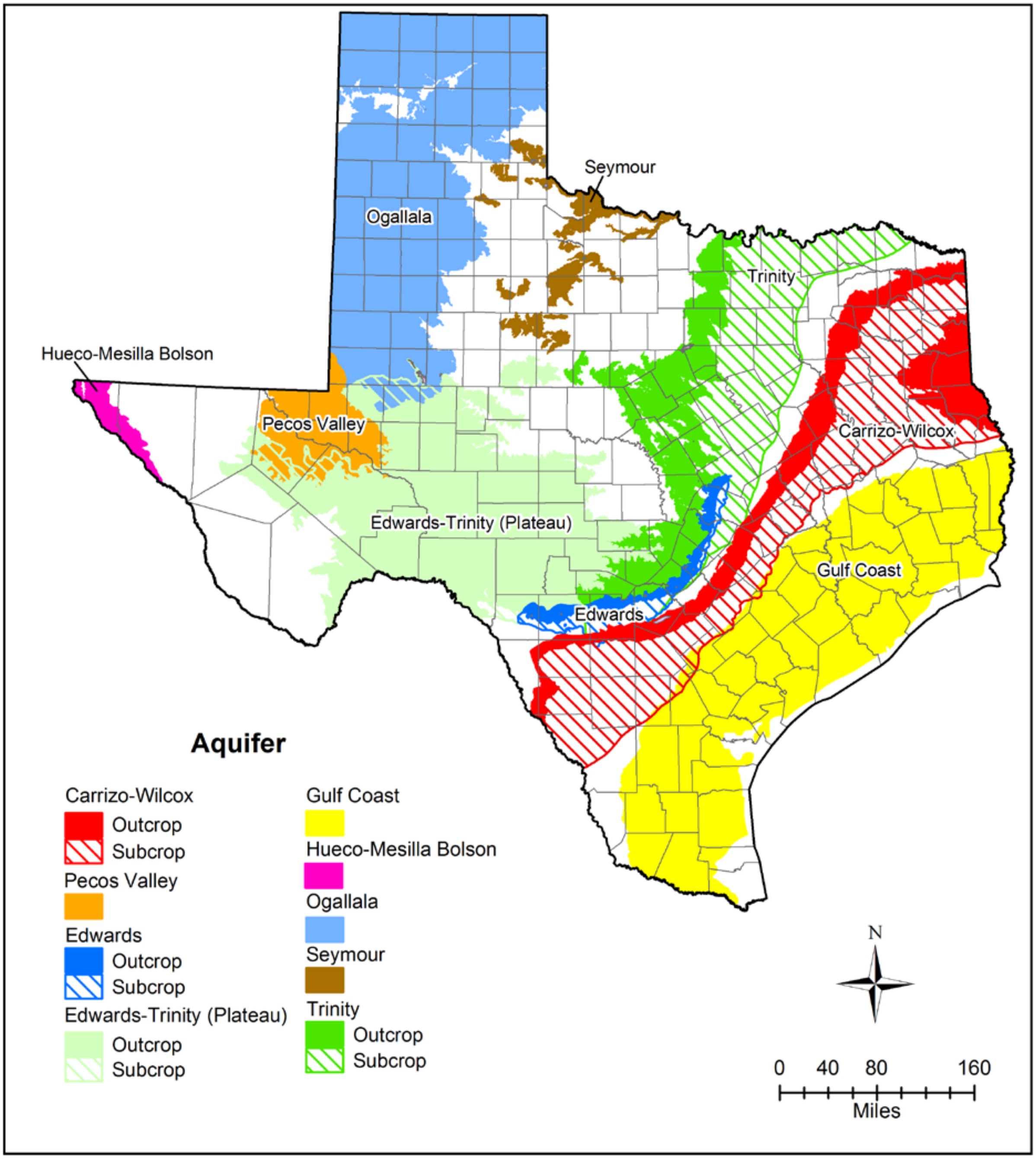

Figure 1.0.1 **Location of major aquifers in Texas (TWDB, 2006a).**

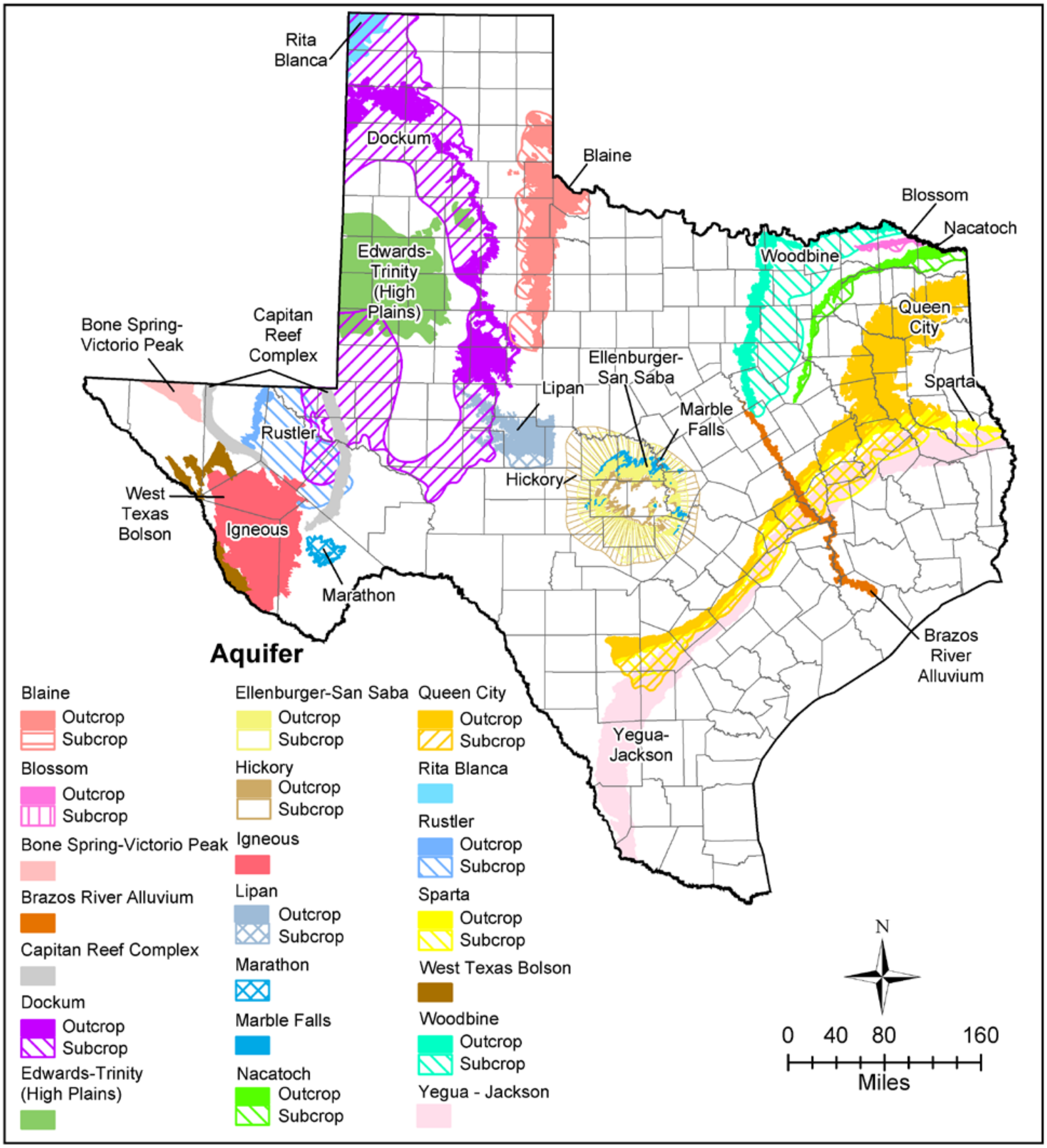

Figure 1.0.2 **Location of minor aquifers in Texas (TWDB, 2006b).**

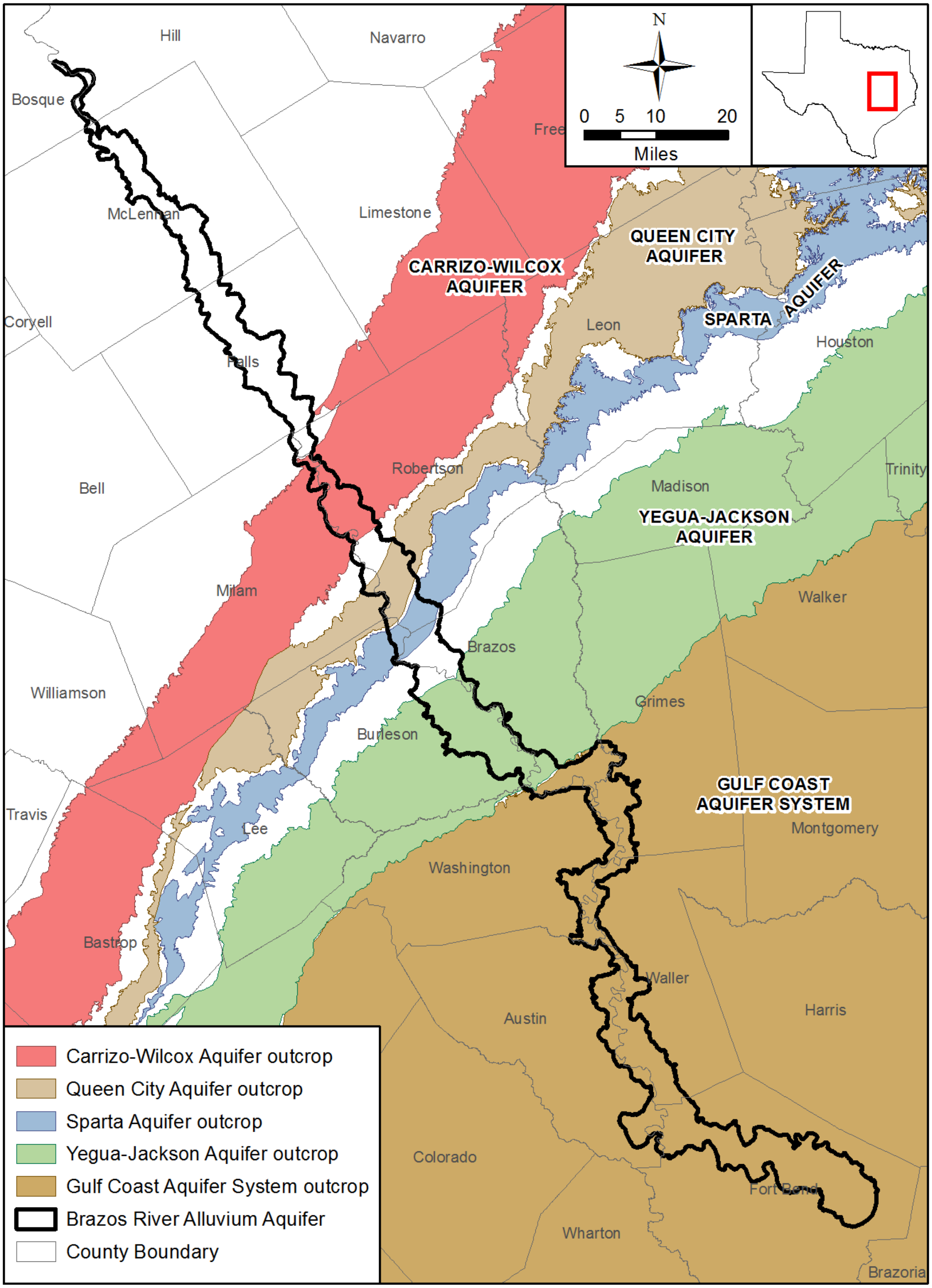

Figure 1.0.3 **Extent of Brazos River Alluvium Aquifer groundwater availability model.**

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2.0 Model Overview and Packages

The numerical model of the Brazos River Alluvium Aquifer is based on the conceptual model document by Ewing and others (2016). The schematic diagram in Figure 2.0.1 shows a west to east cross-section through the study area, along with a conceptual block diagram illustrating aquifer layering and sources and sinks for groundwater.

The code selected for the groundwater model is MODFLOW-USG (Panday and others, 2013). MODFLOW-USG is a three-dimensional control volume finite difference groundwater flow code which is supported by boundary condition packages to handle recharge, evapotranspiration, streams, springs and reservoirs. MODFLOW-USG is an enhanced version of the MODFLOW family of codes developed and supported by the United States Geological Survey. The benefits of using MODFLOW-USG for the current effort include: 1) MODFLOW incorporates the necessary physics of groundwater flow, 2) MODFLOW is the most widely accepted groundwater flow code in use today, 3) MODFLOW was written and is supported by the United States Geological Survey and is public domain, 4) MODFLOW is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000; Harbaugh, 2005; Niswonger and others, 2011; Panday and others, 2013), 5) MODFLOW has a large user group, and 6) MODFLOW-USG allows for refinement in areas of interest in a computationally efficient manner. Additionally, there are numerous graphical user interfaces that can be used to develop MODFLOW-USG models and process model results.

The graphical user interface chosen in this case is Groundwater Vistas Version 6.84. The model grid was developed using Groundwater Vistas with several packages being developed outside of the graphical user interface and then imported to Groundwater Vistas after calibration was complete, so the workflow for model creation did not necessarily follow any workflow prescribed by the use of that graphical user interface.

A MODFLOW model consists of grouping of input text files (also called “packages”) that describe various components of the groundwater flow system. The input packages and their corresponding filenames are shown in Table 2.0.1 below. The output files written by MODFLOW contain water levels (HDS), drawdown (DDN), water budget information (CBB), adjusted flow rate (AFR), streamflow-routing information (FLO), and a listing of the characteristics of the run (LST) as shown in Table 2.0.2. A description of the contents and changes to each of the input packages shown in Table 2.0.1 are included in the sections that follow.

Table 2.0.1 Summary of model input packages and filenames.

File Type Abbreviation	File Type	Input File Name
BAS6	Basic Package	braa.bas
DISU	Discretization File	braa.dis
DRN	Drain Package	braa.drn
EVT	Evapotranspiration Package	braa.evt
SMS	Sparse Matrix Solver Package	braa.sms
OC	Output Control Option	braa.oc
RCH	Recharge Package	braa.rch
SFR	Streamflow-Routing Package	braa.sfr
RIV	River Package	braa.riv
LPF	Layer Property Flow Package	braa.lpf
GNC	Ghost Node Correction Package	braa.gnc
WEL	Well Package	braa.wel

Table 2.0.2 Summary of model output packages and filenames.

File Type	Output File Name
Binary flow file	braa.cbb
Binary head file	braa.hds
Adjusted flow rate file	braa.afr
Stream flow information file	braa.flo
List file	braa.lst

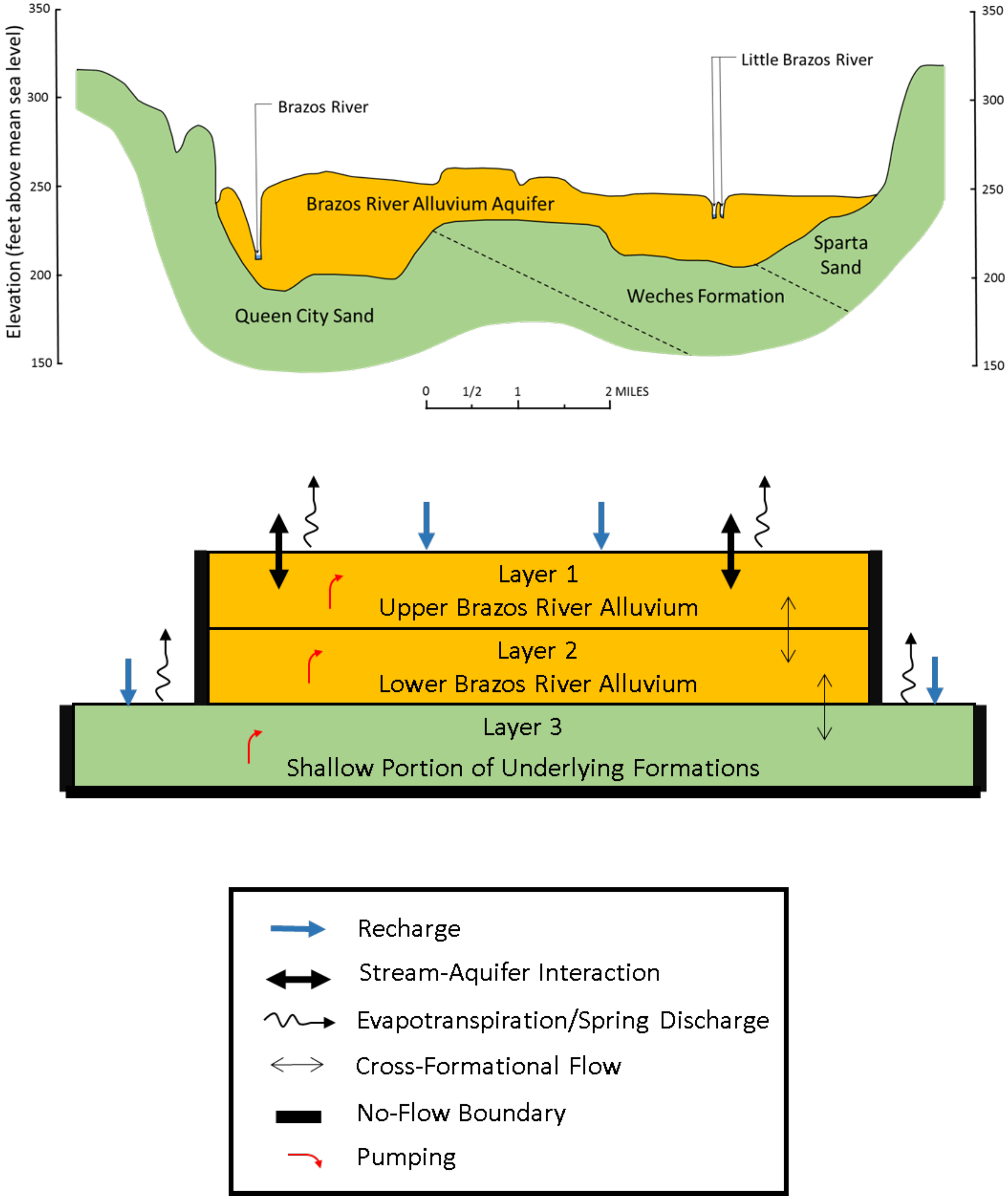

Figure 2.0.1 **Conceptual groundwater flow model (cross-sectional view) for the Brazos River Alluvium Aquifer.**

2.1 Basic Package

The MODFLOW-USG Basic (file type BAS6) package is used to 1) specify which cells in each model layer are active or inactive, and 2) specify the starting water levels in the aquifers for the simulation. The Basic package can also be used to specify constant head cells.

The groundwater model of the Brazos River Alluvium Aquifer represents the minor Brazos River Alluvium Aquifer itself as well as the surficial portions of the major Carrizo-Wilcox and Gulf Coast aquifers and the minor Queen City, Sparta, and Yegua-Jackson aquifers within the Brazos River Basin. The model has three layers: with layers 1 and 2 representing the Brazos River Alluvium Aquifer and layer 3 representing the surficial portions of the formations underlying the Brazos River Alluvium Aquifer. The model stratigraphy and layering is described in Table 2.1.1.

The active and inactive model cells for each of the three layers are shown in Figure 2.1.1 through Figure 2.1.3. Active model cells are indicated with a positive value of the variable IBOUND, an input to the Basic package.

Grid cells were associated with the Brazos River Alluvium Aquifer by selecting the grid centroids that fell within the aquifer outline. The grid cells associated with the formations underlying the Brazos River Alluvium Aquifer were selected using the grid centroids falling within the basin boundary of the Brazos River. For the aquifer, cells that were connected through corner connections and small clusters of cells along the edges of the active model boundary were removed to enhance model convergence and improve stability of the model. Also, to improve model stability, starting heads for the steady-state model were set to land surface elevation to allow all model grid cells to start wet.

The types of boundary cells are shown for the uppermost active layer in Figure 2.1.4a for the entire active model domain. Figures 2.1.4b through 2.1.4e show the same information but zoomed-in to the sub-county scale so that the finer portions of the model grid are visible. Model cell types include springs represented with the drain package, perennial streams represented with the streamflow-routing package, ephemeral streams represented with the river package, and riparian evapotranspiration represented with the evapotranspiration package. All of these model cell types are forms of head-dependent flow boundaries, and are each discussed in the sections that follow. The bottom of the model represents the vertical extent of the shallow flow system within the formations underlying the Brazos River Alluvium Aquifer, and is approximated as a no-flow boundary. While some groundwater flows into the deeper portions of these formations, this flow is conceptualized to be a very small percentage of the water balance for the shallow flow system and is ignored in this model.

Table 2.1.1 Model stratigraphy and layering.

System	Series	Geologic Unit	Aquifer	Model Layer
Quaternary	Holocene	Alluvium, higher clay content	Brazos River Alluvium	1
		Alluvium, higher sand/gravel content		2
	Pleistocene	Fluvial terrace deposits	Gulf Coast	3
		Beaumont Formation		
		Lissie Formation		
Tertiary	Pliocene	Willis Sand		
	Miocene	Goliad Sand		
		Fleming Formation		
		Oakville Sandstone		
	Oligocene	Catahoula Sandstone		
	Eocene	Jackson Group	Yegua-Jackson	
		Yegua Formation		
		Cook Mountain Formation		
		Sparta Sand	Sparta	
		Weches Formation		
		Queen City Sand	Queen City	
		Reklaw Formation		
		Carrizo Sand	Carrizo-Wilcox	
		Wilcox Group		
	Paleocene	Midway Group		
Cretaceous	Gulfian	Navarro Group		
		Taylor Marl		
		Austin Chalk		
		Eagle Ford Group		
		Grayson Marl		
	Comanchean	Washita Group		
		Fredericksburg Group		

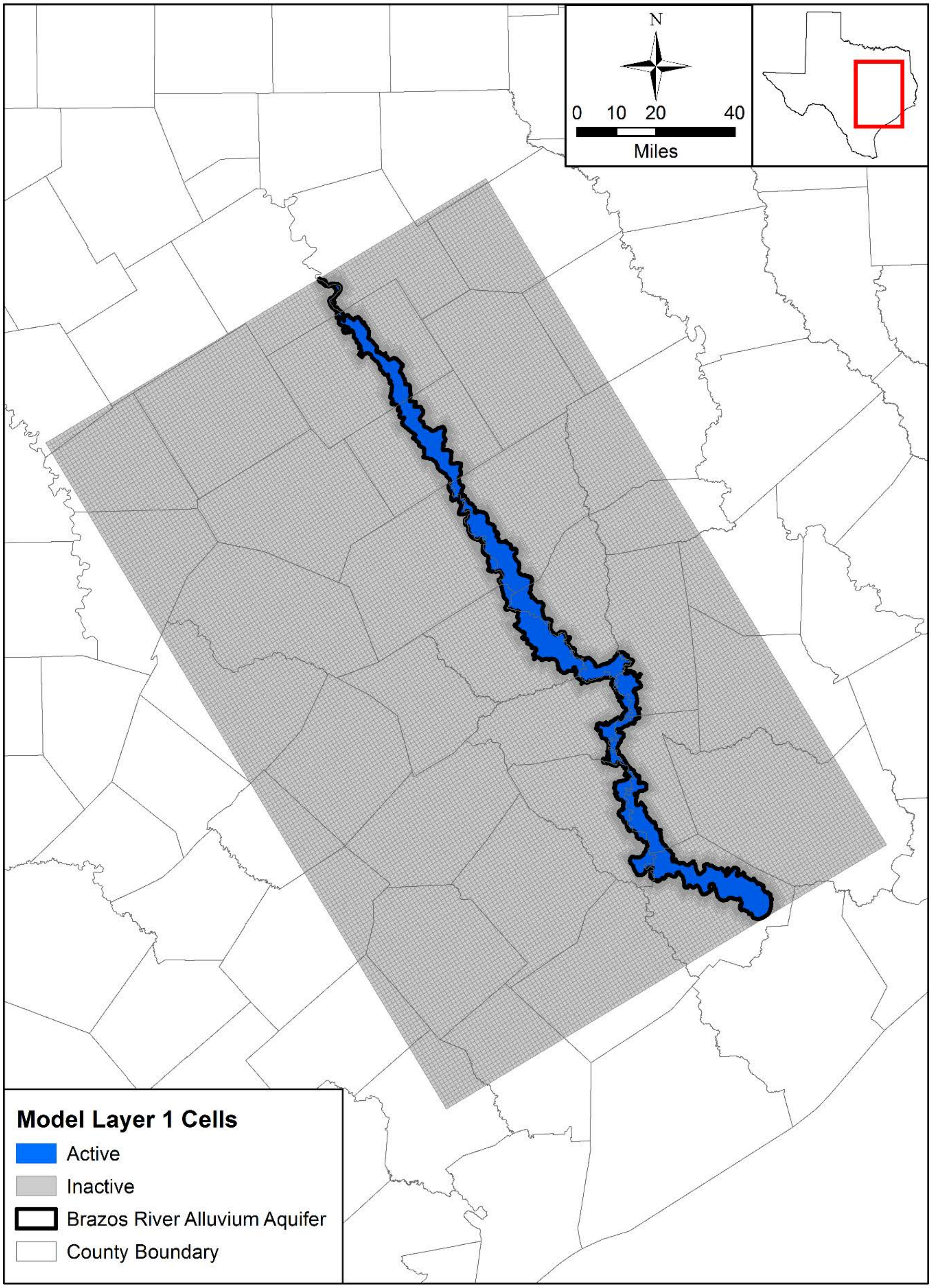

Figure 2.1.1 Layer 1 active/inactive model cells.

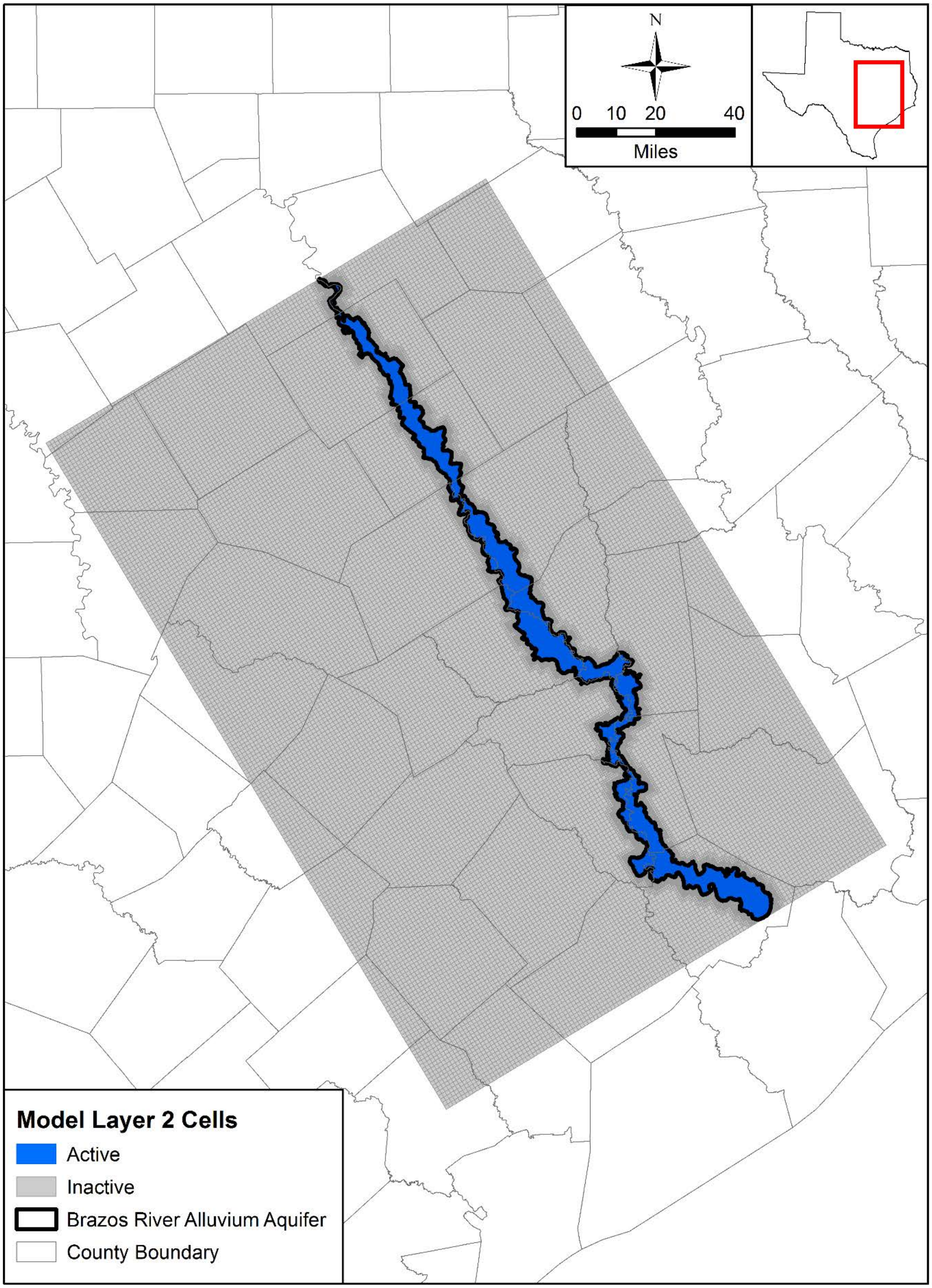

Figure 2.1.2 **Layer 2 active/inactive model cells.**

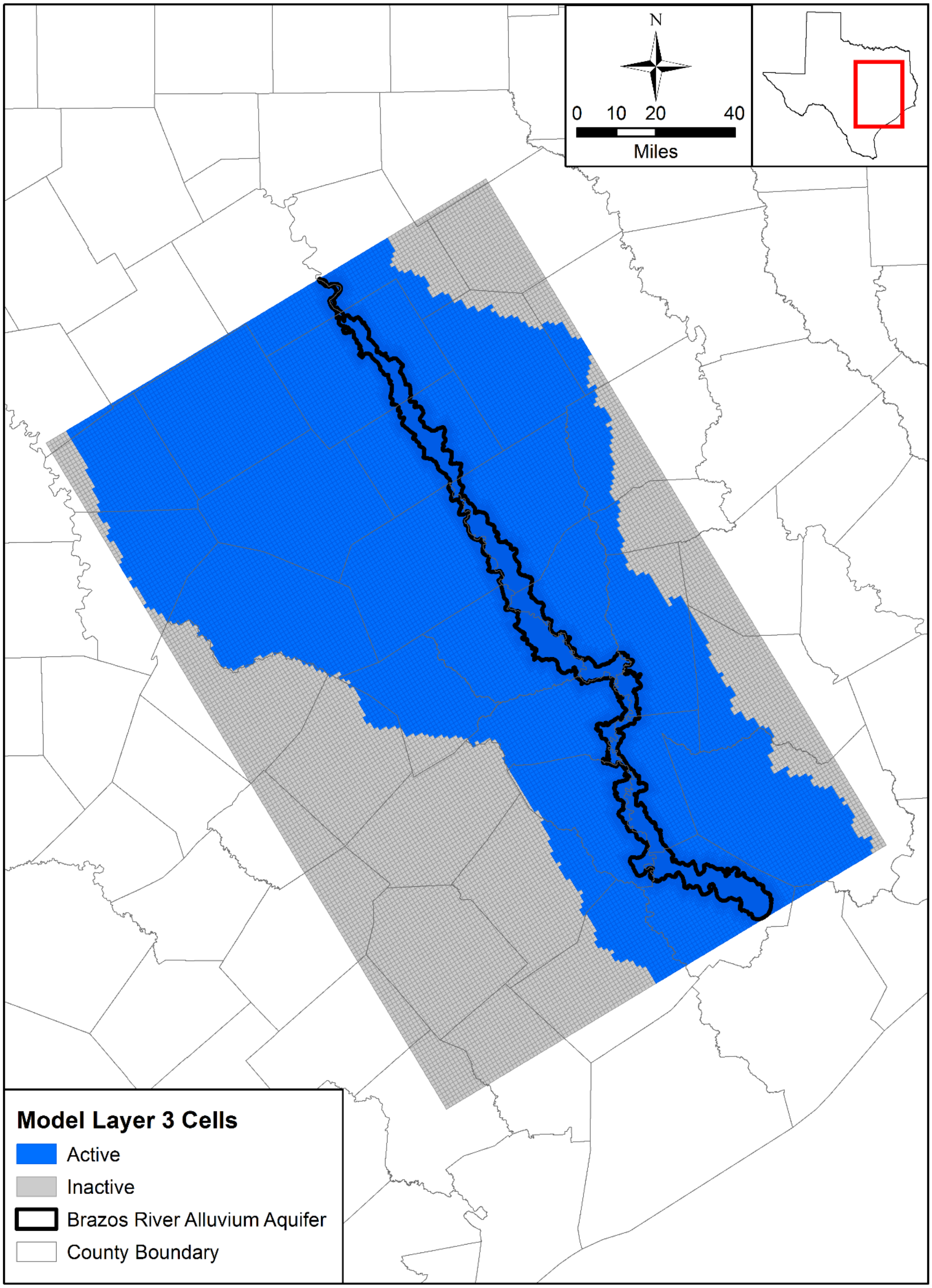

Figure 2.1.3 **Layer 3 active/inactive model cells.**

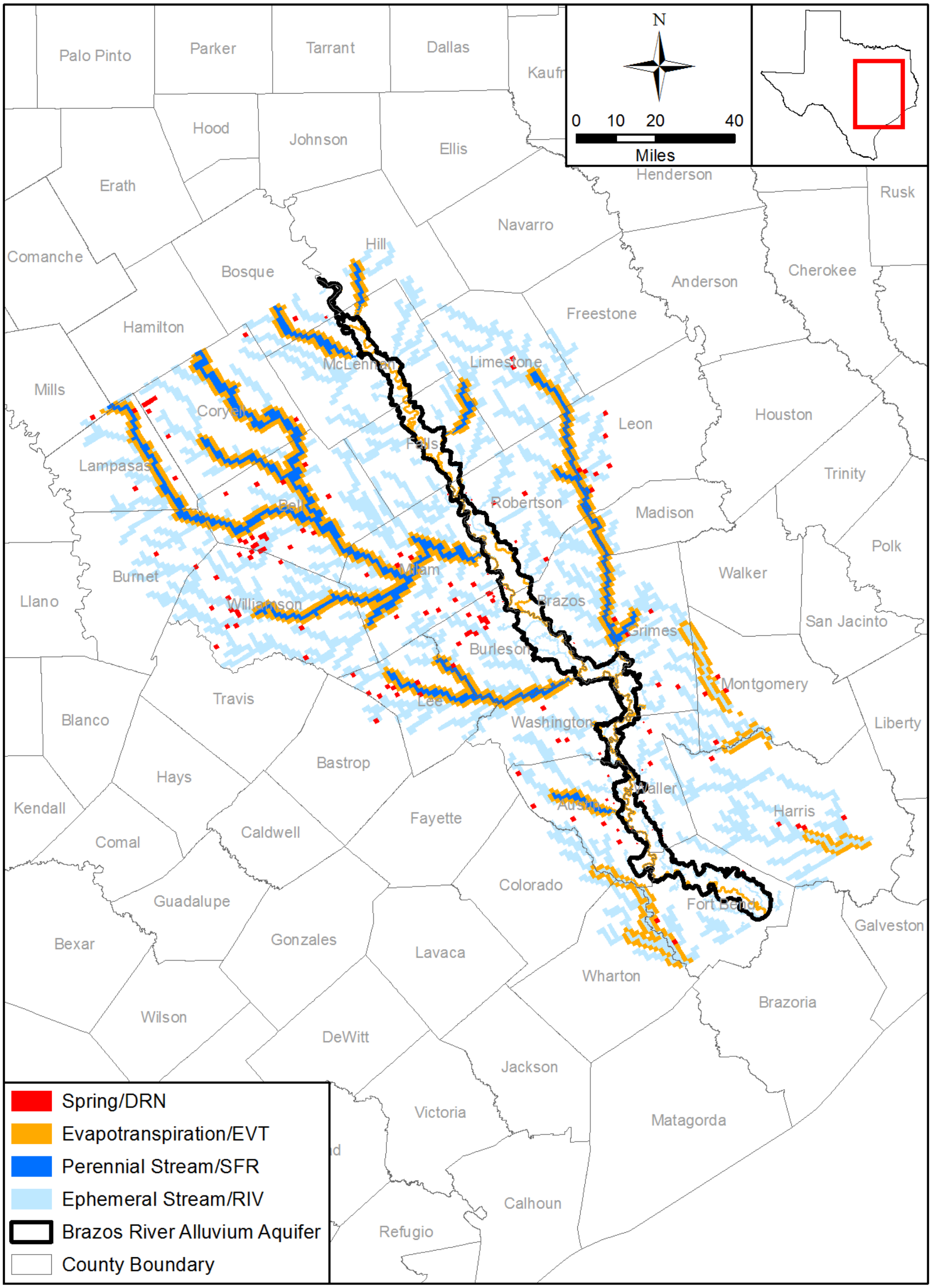

Figure 2.1.4a Uppermost active layer model cell types over the full extent of the study area.

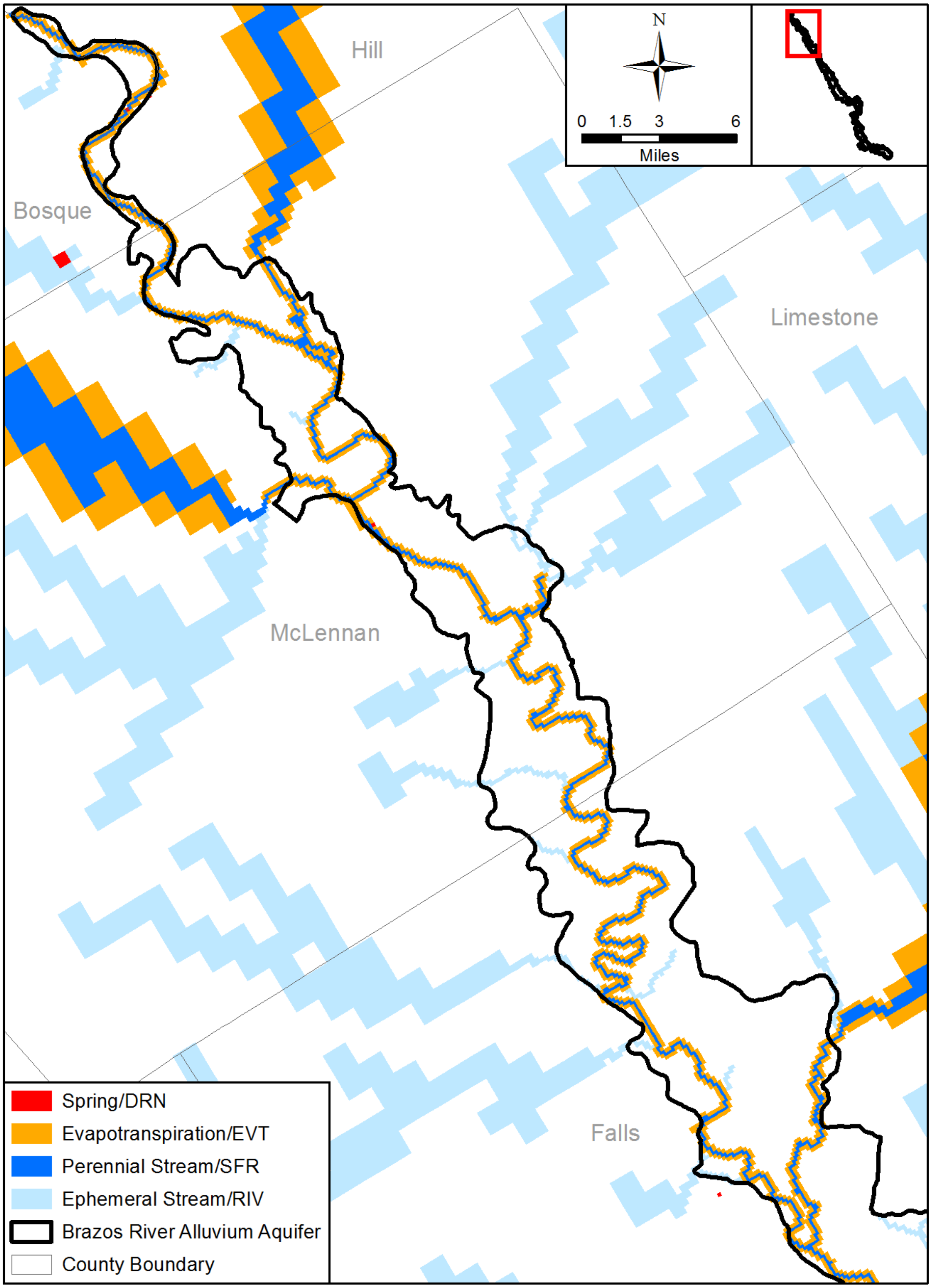

Figure 2.1.4b Uppermost active layer model cell types in the northernmost portion of the Brazos River Alluvium Aquifer.

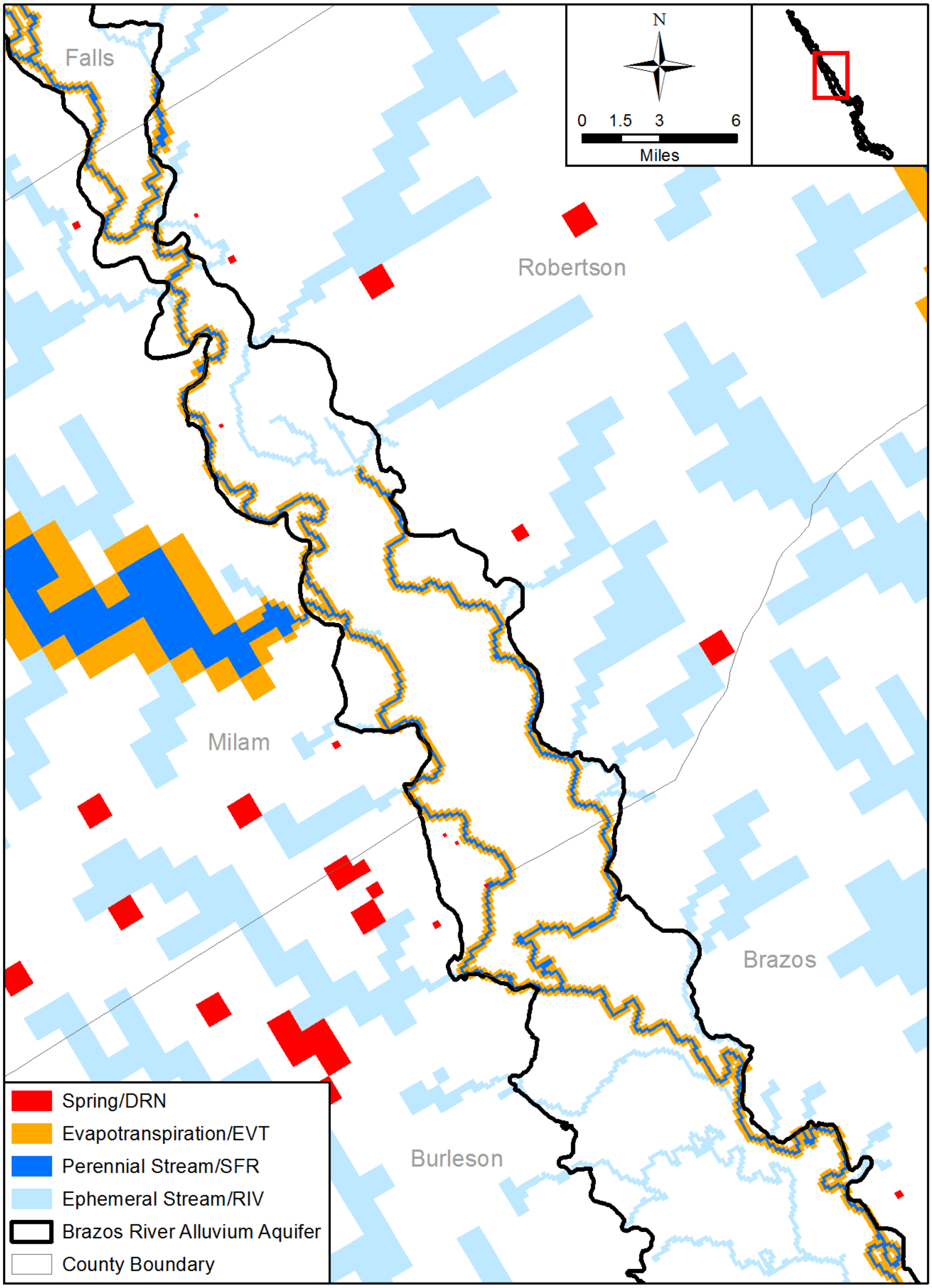

Figure 2.1.4c **Uppermost active layer model cell types in the north-central portion of the Brazos River Alluvium Aquifer.**

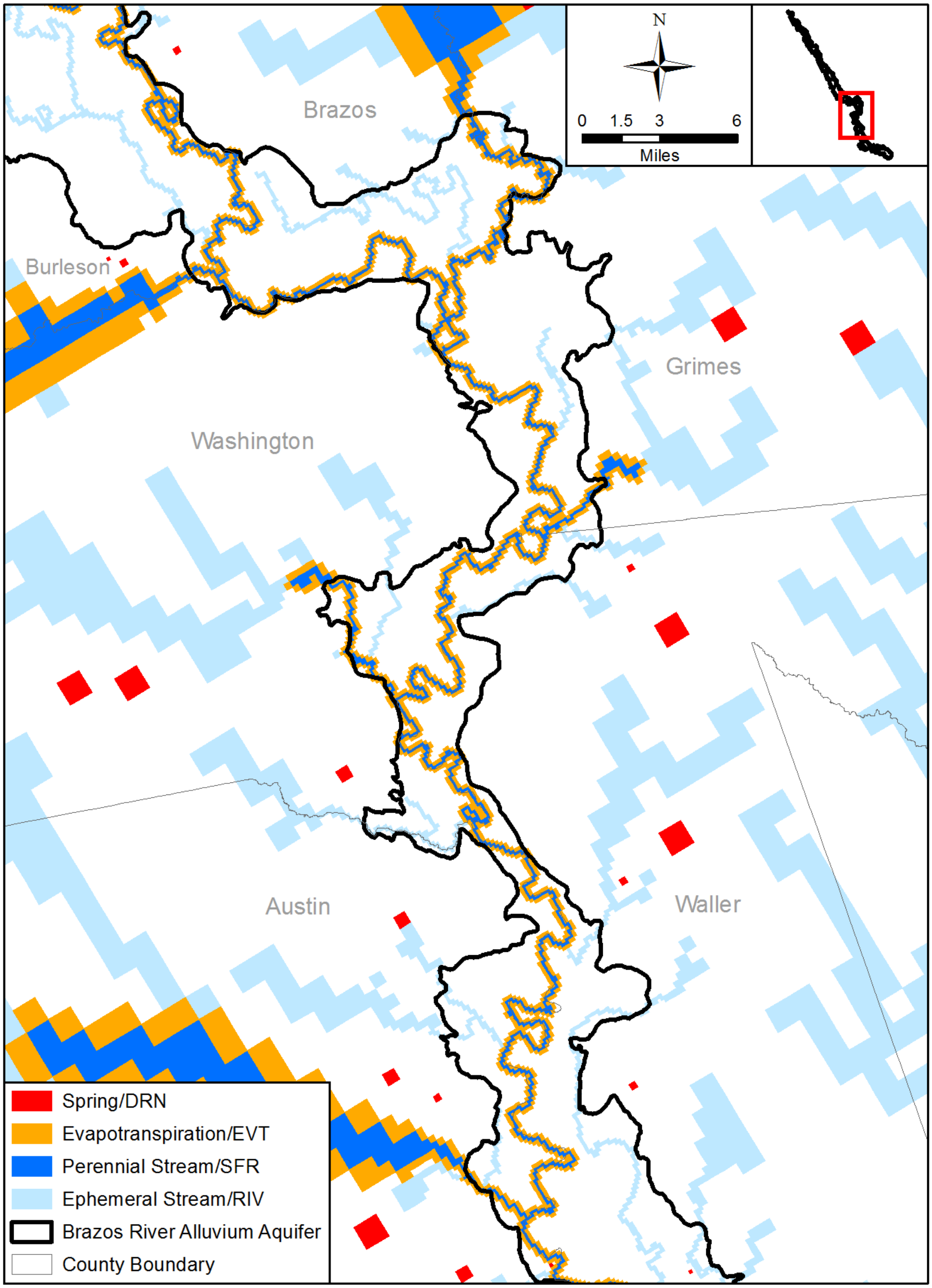

Figure 2.1.4d **Uppermost active layer model cell types in the south-central portion of the Brazos River Alluvium Aquifer.**

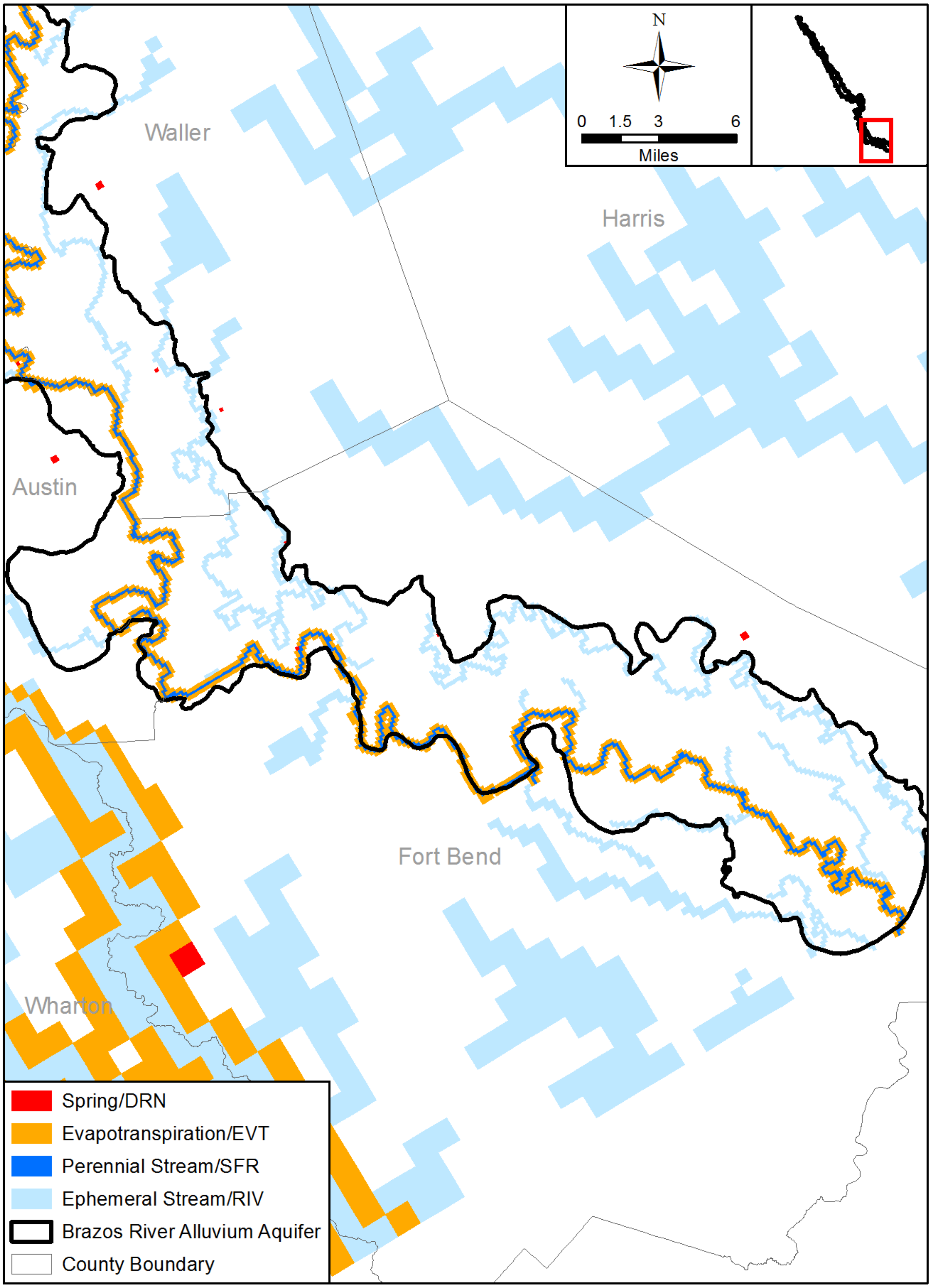

Figure 2.1.4e Uppermost active layer model cell types in the southernmost portion of the Brazos River Alluvium Aquifer.

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2.2 Discretization Package

The MODFLOW unstructured discretization (suffix DISU) package contains the model node dimensions, the nodal elevations of the model layers, the nodal connections, the connection areas and lengths between nodes, and a definition of the model stress periods.

2.2.1 Model Grid Specifications

The Brazos River Alluvium Aquifer groundwater availability model grid contains 3 layers with 124,829 nodes per layer for a total of 374,487 nodes. Layers 1 and 2 each consist of 67,676 active nodes and layer 3 consists of 116,026 active nodes for a total of 251,378 active nodes. The grid is a quadtree mesh, with cells that vary from 660 feet square throughout the footprint of the Brazos River Alluvium Aquifer to 5,280 feet square over the majority of the Brazos River Basin. Figure 2.2.1 shows an example of the model grid at a county scale for Falls County. The quadtree aspect of the grid dictates that the areas of neighboring nodes may be either identical or different, with the differences in areas between neighboring nodes never being greater than a factor of four.

The grid is oriented 31 degrees west of north in the TWDB's designated coordinate system for groundwater availability models described in Anaya (2001). The lower left corner of the grid is positioned at groundwater availability model coordinate system coordinates 5,906,497.004 easting, 18,809,374.86 northing.

The base elevation of the Brazos River Alluvium Aquifer was sampled from the surface created during the conceptual model development. Because two layers were used to differentiate between the upper and lower portions of the Brazos River Alluvium Aquifer, the base of the aquifer is defined the base of layer 2. Minimum cell thicknesses were enforced during grid creation. For layer 1 cells, representing the upper portion of the Brazos River Alluvium Aquifer, the minimum thickness was set at 10 feet. This was done to avoid convergence problems associated with dry cells. We were unable to differentiate between the upper and lower portions of the aquifer in a meaningful way. Initially, the alluvium was split equally with layers 1 and 2 each constituting half of the aquifer thickness. Because the average depth to water is approximately 20 feet, this resulted in layer 1 having significantly less saturated thickness than layer 2 which, in turn, caused many dry cells in layer 1 and convergence problems. Therefore, the cell thickness for layer 2 cells representing the lower portion of the Brazos River Alluvium

Aquifer was set equal to the minimum thickness of 10 feet. The base of layer 3, which represents the shallow portions of the formations underlying the Brazos River Alluvium Aquifer was set 200 feet below a 10-mile moving average of land surface. The top of the model represents land surface. When minimum thicknesses were enforced, elevations were pushed down from above, since land surface elevation has more certainty than the structural bottom of the aquifer. Figures 2.2.2a and 2.2.2b show representative cross sections of the model grid, for west-east sections in the northwestern and southeastern portions of the model domain, respectively.

In some areas of the model, especially along the edges of the Brazos River Alluvium Aquifer, large elevation changes in land surface occur in adjoining nodes. No smoothing of these offsets in land surface elevation was implemented, so some model cross sections may reflect these large offsets. The assignment of a minimum thickness to layers 1 and 2, representing the Brazos River Alluvium Aquifer, helped to ameliorate elevation offsets in the basal elevation between adjacent grid cells.

2.2.2 Stress Period Setup

The Brazos River Alluvium Aquifer groundwater availability model has 427 stress periods, starting with a steady-state stress period that represents predevelopment conditions. The second, and all subsequent stress periods are transient. The second stress period represents year 1950, with transient stress periods spanning one year through stress period 31, which represents year 1979. From 1980 onward, monthly stress periods are used to account for seasonality in stream stage, recharge, and pumping. Accordingly, the thirty-second stress period represents January, 1980, and the subsequent 395 stress periods represent the months until December, 2012. Table 2.2.1 shows the stress period types, times, and durations. Note that leap years were considered in the stress period setup, so transient stress periods may be either 365 or 366 days long from 1950 through 1979 and reflect the number of days in each month from January, 1980 through December, 2012.

Table 2.2.1 Table of stress period times and durations.

Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period	Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period
1	10	12/31/1949	SS	215	30	4/30/1995	TR
2	365	12/31/1950	TR	216	31	5/31/1995	TR
3	365	12/31/1951	TR	217	30	6/30/1995	TR
4	366	12/31/1952	TR	218	31	7/31/1995	TR
5	365	12/31/1953	TR	219	31	8/31/1995	TR
6	365	12/31/1954	TR	220	30	9/30/1995	TR
7	365	12/31/1955	TR	221	31	10/31/1995	TR
8	366	12/31/1956	TR	222	30	11/30/1995	TR
9	365	12/31/1957	TR	223	31	12/31/1995	TR
10	365	12/31/1958	TR	224	31	1/31/1996	TR
11	365	12/31/1959	TR	225	29	2/29/1996	TR
12	366	12/31/1960	TR	226	31	3/31/1996	TR
13	365	12/31/1961	TR	227	30	4/30/1996	TR
14	365	12/31/1962	TR	228	31	5/31/1996	TR
15	365	12/31/1963	TR	229	30	6/30/1996	TR
16	366	12/31/1964	TR	230	31	7/31/1996	TR
17	365	12/31/1965	TR	231	31	8/31/1996	TR
18	365	12/31/1966	TR	232	30	9/30/1996	TR
19	365	12/31/1967	TR	233	31	10/31/1996	TR
20	366	12/31/1968	TR	234	30	11/30/1996	TR
21	365	12/31/1969	TR	235	31	12/31/1996	TR
22	365	12/31/1970	TR	236	31	1/31/1997	TR
23	365	12/31/1971	TR	237	28	2/28/1997	TR
24	366	12/31/1972	TR	238	31	3/31/1997	TR
25	365	12/31/1973	TR	239	30	4/30/1997	TR
26	365	12/31/1974	TR	240	31	5/31/1997	TR
27	365	12/31/1975	TR	241	30	6/30/1997	TR
28	366	12/31/1976	TR	242	31	7/31/1997	TR
29	365	12/31/1977	TR	243	31	8/31/1997	TR
30	365	12/31/1978	TR	244	30	9/30/1997	TR
31	365	12/31/1979	TR	245	31	10/31/1997	TR
32	31	1/31/1980	TR	246	30	11/30/1997	TR
33	29	2/29/1980	TR	247	31	12/31/1997	TR
35	30	4/30/1980	TR	249	28	2/28/1998	TR
36	31	5/31/1980	TR	250	31	3/31/1998	TR
37	30	6/30/1980	TR	251	30	4/30/1998	TR
38	31	7/31/1980	TR	252	31	5/31/1998	TR

Table 2.2.1, continued

Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period	Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period
39	31	8/31/1980	TR	253	30	6/30/1998	TR
40	30	9/30/1980	TR	254	31	7/31/1998	TR
41	31	10/31/1980	TR	255	31	8/31/1998	TR
42	30	11/30/1980	TR	256	30	9/30/1998	TR
43	31	12/31/1980	TR	257	31	10/31/1998	TR
44	31	1/31/1981	TR	258	30	11/30/1998	TR
45	28	2/28/1981	TR	259	31	12/31/1998	TR
46	31	3/31/1981	TR	260	31	1/31/1999	TR
47	30	4/30/1981	TR	261	28	2/28/1999	TR
48	31	5/31/1981	TR	262	31	3/31/1999	TR
49	30	6/30/1981	TR	263	30	4/30/1999	TR
50	31	7/31/1981	TR	264	31	5/31/1999	TR
51	31	8/31/1981	TR	265	30	6/30/1999	TR
52	30	9/30/1981	TR	266	31	7/31/1999	TR
53	31	10/31/1981	TR	267	31	8/31/1999	TR
54	30	11/30/1981	TR	268	30	9/30/1999	TR
55	31	12/31/1981	TR	269	31	10/31/1999	TR
56	31	1/31/1982	TR	270	30	11/30/1999	TR
57	28	2/28/1982	TR	271	31	12/31/1999	TR
58	31	3/31/1982	TR	272	31	1/31/2000	TR
59	30	4/30/1982	TR	273	29	2/29/2000	TR
60	31	5/31/1982	TR	274	31	3/31/2000	TR
61	30	6/30/1982	TR	275	30	4/30/2000	TR
62	31	7/31/1982	TR	276	31	5/31/2000	TR
63	31	8/31/1982	TR	277	30	6/30/2000	TR
64	30	9/30/1982	TR	278	31	7/31/2000	TR
65	31	10/31/1982	TR	279	31	8/31/2000	TR
66	30	11/30/1982	TR	280	30	9/30/2000	TR
67	31	12/31/1982	TR	281	31	10/31/2000	TR
68	31	1/31/1983	TR	282	30	11/30/2000	TR
69	28	2/28/1983	TR	283	31	12/31/2000	TR
70	31	3/31/1983	TR	284	31	1/31/2001	TR
71	30	4/30/1983	TR	285	28	2/28/2001	TR
72	31	5/31/1983	TR	286	31	3/31/2001	TR
73	30	6/30/1983	TR	287	30	4/30/2001	TR
74	31	7/31/1983	TR	288	31	5/31/2001	TR
75	31	8/31/1983	TR	289	30	6/30/2001	TR
76	30	9/30/1983	TR	290	31	7/31/2001	TR

Table 2.2.1, continued

Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period	Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period
77	31	10/31/1983	TR	291	31	8/31/2001	TR
78	30	11/30/1983	TR	292	30	9/30/2001	TR
79	31	12/31/1983	TR	293	31	10/31/2001	TR
80	31	1/31/1984	TR	294	30	11/30/2001	TR
81	29	2/29/1984	TR	295	31	12/31/2001	TR
82	31	3/31/1984	TR	296	31	1/31/2002	TR
83	30	4/30/1984	TR	297	28	2/28/2002	TR
84	31	5/31/1984	TR	298	31	3/31/2002	TR
85	30	6/30/1984	TR	299	30	4/30/2002	TR
86	31	7/31/1984	TR	300	31	5/31/2002	TR
87	31	8/31/1984	TR	301	30	6/30/2002	TR
88	30	9/30/1984	TR	302	31	7/31/2002	TR
89	31	10/31/1984	TR	303	31	8/31/2002	TR
90	30	11/30/1984	TR	304	30	9/30/2002	TR
91	31	12/31/1984	TR	305	31	10/31/2002	TR
92	31	1/31/1985	TR	306	30	11/30/2002	TR
93	28	2/28/1985	TR	307	31	12/31/2002	TR
94	31	3/31/1985	TR	308	31	1/31/2003	TR
95	30	4/30/1985	TR	309	28	2/28/2003	TR
96	31	5/31/1985	TR	310	31	3/31/2003	TR
97	30	6/30/1985	TR	311	30	4/30/2003	TR
98	31	7/31/1985	TR	312	31	5/31/2003	TR
99	31	8/31/1985	TR	313	30	6/30/2003	TR
100	30	9/30/1985	TR	314	31	7/31/2003	TR
101	31	10/31/1985	TR	315	31	8/31/2003	TR
102	30	11/30/1985	TR	316	30	9/30/2003	TR
103	31	12/31/1985	TR	317	31	10/31/2003	TR
104	31	1/31/1986	TR	318	30	11/30/2003	TR
105	28	2/28/1986	TR	319	31	12/31/2003	TR
106	31	3/31/1986	TR	320	31	1/31/2004	TR
107	30	4/30/1986	TR	321	29	2/29/2004	TR
108	31	5/31/1986	TR	322	31	3/31/2004	TR
109	30	6/30/1986	TR	323	30	4/30/2004	TR
110	31	7/31/1986	TR	324	31	5/31/2004	TR
111	31	8/31/1986	TR	325	30	6/30/2004	TR
112	30	9/30/1986	TR	326	31	7/31/2004	TR
113	31	10/31/1986	TR	327	31	8/31/2004	TR
114	30	11/30/1986	TR	328	30	9/30/2004	TR

Table 2.2.1, continued

Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period	Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period
115	31	12/31/1986	TR	329	31	10/31/2004	TR
116	31	1/31/1987	TR	330	30	11/30/2004	TR
117	28	2/28/1987	TR	331	31	12/31/2004	TR
118	31	3/31/1987	TR	332	31	1/31/2005	TR
119	30	4/30/1987	TR	333	28	2/28/2005	TR
120	31	5/31/1987	TR	334	31	3/31/2005	TR
121	30	6/30/1987	TR	335	30	4/30/2005	TR
122	31	7/31/1987	TR	336	31	5/31/2005	TR
123	31	8/31/1987	TR	337	30	6/30/2005	TR
124	30	9/30/1987	TR	338	31	7/31/2005	TR
125	31	10/31/1987	TR	339	31	8/31/2005	TR
126	30	11/30/1987	TR	340	30	9/30/2005	TR
127	31	12/31/1987	TR	341	31	10/31/2005	TR
128	31	1/31/1988	TR	342	30	11/30/2005	TR
129	29	2/29/1988	TR	343	31	12/31/2005	TR
130	31	3/31/1988	TR	344	31	1/31/2006	TR
131	30	4/30/1988	TR	345	28	2/28/2006	TR
132	31	5/31/1988	TR	346	31	3/31/2006	TR
133	30	6/30/1988	TR	347	30	4/30/2006	TR
134	31	7/31/1988	TR	348	31	5/31/2006	TR
135	31	8/31/1988	TR	349	30	6/30/2006	TR
136	30	9/30/1988	TR	350	31	7/31/2006	TR
137	31	10/31/1988	TR	351	31	8/31/2006	TR
138	30	11/30/1988	TR	352	30	9/30/2006	TR
139	31	12/31/1988	TR	353	31	10/31/2006	TR
140	31	1/31/1989	TR	354	30	11/30/2006	TR
141	28	2/28/1989	TR	355	31	12/31/2006	TR
142	31	3/31/1989	TR	356	31	1/31/2007	TR
143	30	4/30/1989	TR	357	28	2/28/2007	TR
144	31	5/31/1989	TR	358	31	3/31/2007	TR
145	30	6/30/1989	TR	359	30	4/30/2007	TR
146	31	7/31/1989	TR	360	31	5/31/2007	TR
147	31	8/31/1989	TR	361	30	6/30/2007	TR
148	30	9/30/1989	TR	362	31	7/31/2007	TR
149	31	10/31/1989	TR	363	31	8/31/2007	TR
150	30	11/30/1989	TR	364	30	9/30/2007	TR
151	31	12/31/1989	TR	365	31	10/31/2007	TR
152	31	1/31/1990	TR	366	30	11/30/2007	TR

Table 2.2.1, continued

Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period	Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period
153	28	2/28/1990	TR	367	31	12/31/2007	TR
154	31	3/31/1990	TR	368	31	1/31/2008	TR
155	30	4/30/1990	TR	369	29	2/29/2008	TR
156	31	5/31/1990	TR	370	31	3/31/2008	TR
157	30	6/30/1990	TR	371	30	4/30/2008	TR
158	31	7/31/1990	TR	372	31	5/31/2008	TR
159	31	8/31/1990	TR	373	30	6/30/2008	TR
160	30	9/30/1990	TR	374	31	7/31/2008	TR
161	31	10/31/1990	TR	375	31	8/31/2008	TR
162	30	11/30/1990	TR	376	30	9/30/2008	TR
163	31	12/31/1990	TR	377	31	10/31/2008	TR
164	31	1/31/1991	TR	378	30	11/30/2008	TR
165	28	2/28/1991	TR	379	31	12/31/2008	TR
166	31	3/31/1991	TR	380	31	1/31/2009	TR
167	30	4/30/1991	TR	381	28	2/28/2009	TR
168	31	5/31/1991	TR	382	31	3/31/2009	TR
169	30	6/30/1991	TR	383	30	4/30/2009	TR
170	31	7/31/1991	TR	384	31	5/31/2009	TR
171	31	8/31/1991	TR	385	30	6/30/2009	TR
172	30	9/30/1991	TR	386	31	7/31/2009	TR
173	31	10/31/1991	TR	387	31	8/31/2009	TR
174	30	11/30/1991	TR	388	30	9/30/2009	TR
175	31	12/31/1991	TR	389	31	10/31/2009	TR
176	31	1/31/1992	TR	390	30	11/30/2009	TR
177	29	2/29/1992	TR	391	31	12/31/2009	TR
178	31	3/31/1992	TR	392	31	1/31/2010	TR
179	30	4/30/1992	TR	393	28	2/28/2010	TR
180	31	5/31/1992	TR	394	31	3/31/2010	TR
181	30	6/30/1992	TR	395	30	4/30/2010	TR
182	31	7/31/1992	TR	396	31	5/31/2010	TR
183	31	8/31/1992	TR	397	30	6/30/2010	TR
184	30	9/30/1992	TR	398	31	7/31/2010	TR
185	31	10/31/1992	TR	399	31	8/31/2010	TR
186	30	11/30/1992	TR	400	30	9/30/2010	TR
187	31	12/31/1992	TR	401	31	10/31/2010	TR
188	31	1/31/1993	TR	402	30	11/30/2010	TR
189	28	2/28/1993	TR	403	31	12/31/2010	TR
190	31	3/31/1993	TR	404	31	1/31/2011	TR

Table 2.2.1, continued

Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period	Stress Period	Stress Period Length (Days)	Stress Period Represents	Steady-State (SS)/Transient (TR) Stress Period
191	30	4/30/1993	TR	405	28	2/28/2011	TR
192	31	5/31/1993	TR	406	31	3/31/2011	TR
193	30	6/30/1993	TR	407	30	4/30/2011	TR
194	31	7/31/1993	TR	408	31	5/31/2011	TR
195	31	8/31/1993	TR	409	30	6/30/2011	TR
196	30	9/30/1993	TR	410	31	7/31/2011	TR
197	31	10/31/1993	TR	411	31	8/31/2011	TR
198	30	11/30/1993	TR	412	30	9/30/2011	TR
199	31	12/31/1993	TR	413	31	10/31/2011	TR
200	31	1/31/1994	TR	414	30	11/30/2011	TR
201	28	2/28/1994	TR	415	31	12/31/2011	TR
202	31	3/31/1994	TR	416	31	1/31/2012	TR
203	30	4/30/1994	TR	417	29	2/29/2012	TR
204	31	5/31/1994	TR	418	31	3/31/2012	TR
205	30	6/30/1994	TR	419	30	4/30/2012	TR
206	31	7/31/1994	TR	420	31	5/31/2012	TR
207	31	8/31/1994	TR	421	30	6/30/2012	TR
208	30	9/30/1994	TR	422	31	7/31/2012	TR
209	31	10/31/1994	TR	423	31	8/31/2012	TR
210	30	11/30/1994	TR	424	30	9/30/2012	TR
211	31	12/31/1994	TR	425	31	10/31/2012	TR
212	31	1/31/1995	TR	426	30	11/30/2012	TR
213	28	2/28/1995	TR	427	31	12/31/2012	TR
214	31	3/31/1995	TR				

SS refers to the steady-state stress period
TR refers to transient stress periods

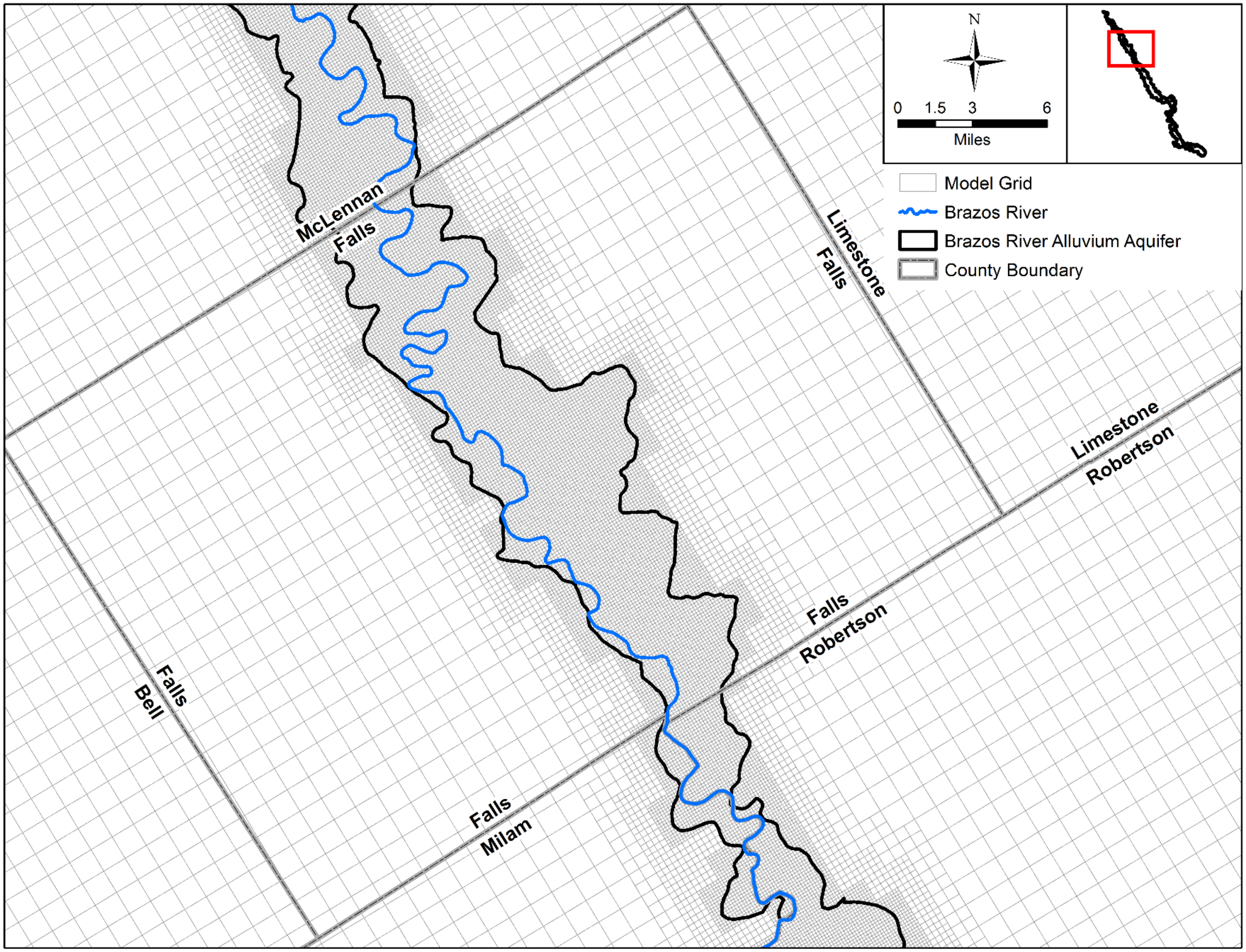

Figure 2.2.1 Example of model grid scale shown for Falls County.

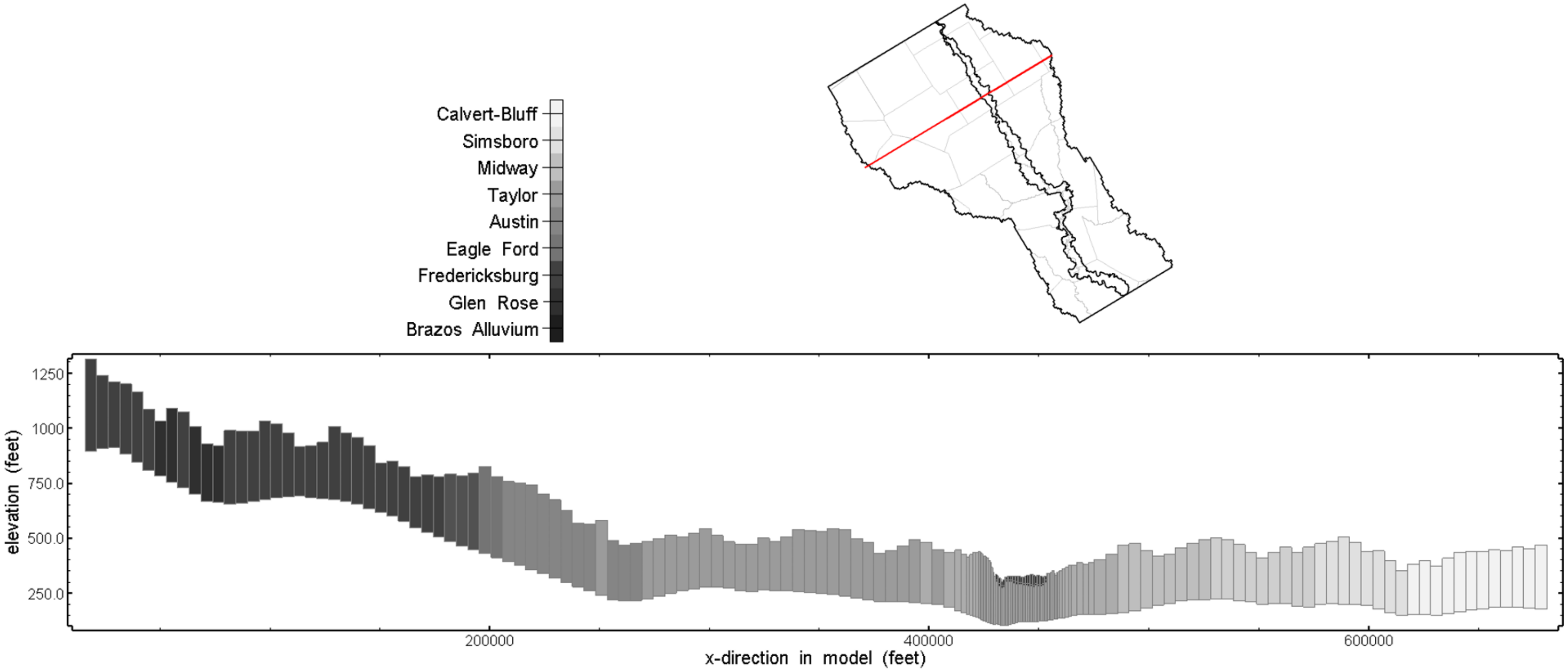

Figure 2.2.2a West-east cross section for row 140 showing model grid plotted from Discretization package (100x vertical exaggeration).

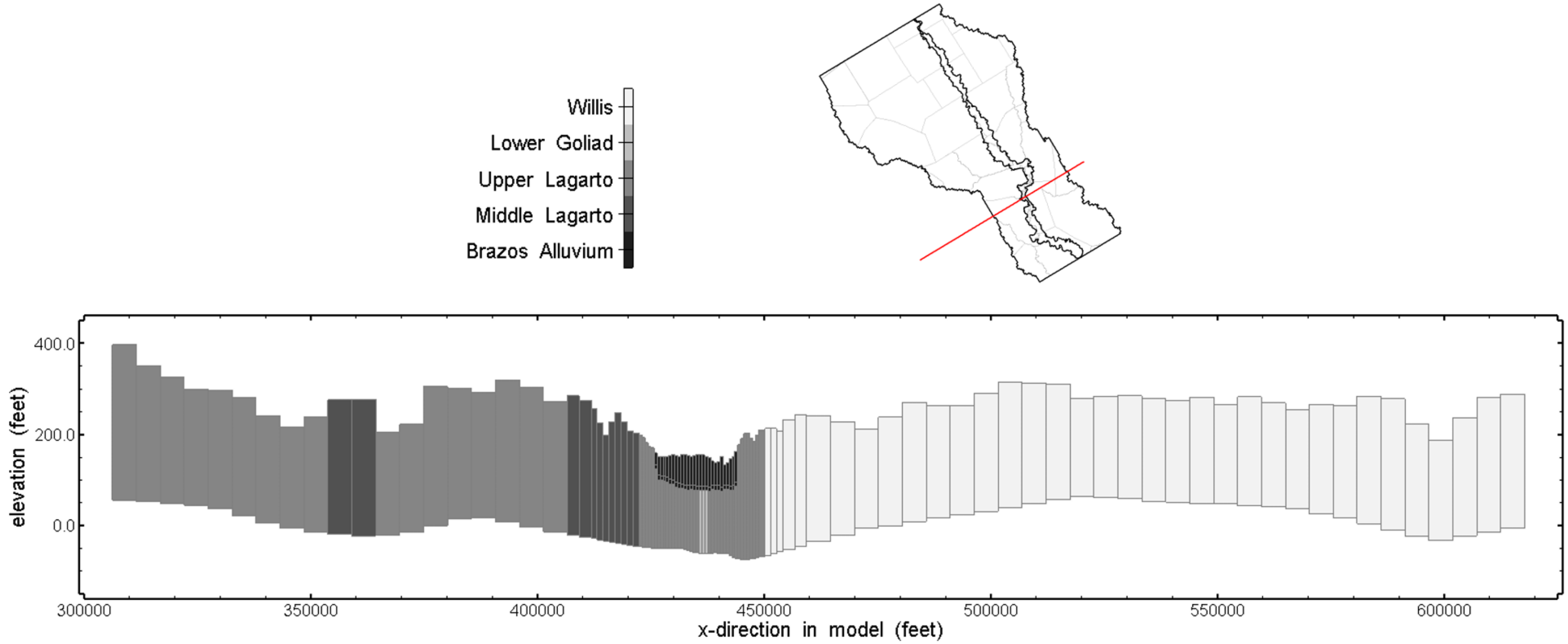

Figure 2.2.2b **West-east cross section for row 514 showing model grid structure plotted from Discretization package (100x vertical exaggeration).**

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2.3 Layer-Property Flow Package

The Layer-Property Flow (suffix LPF) package is used to specify hydraulic properties for MODFLOW-USG. These properties control how easily groundwater can flow through the aquifer and how it responds to pumping. These properties include hydraulic conductivity (both horizontal and vertical), specific yield, and storativity. Table 2.3.1 lists the hydraulic properties used in the Layer-Property Flow package with a description of each property.

2.3.1 Property Zones

During model calibration (Section 3.1), some of the hydraulic properties were adjusted. For the Brazos River Alluvium Aquifer, pilot points were used to create a multiplier matrix that was applied to the initial hydraulic conductivity field during parameter estimation. Pilot points are locations where, during parameter estimation, point values are varied from their initial estimates. The multiplier matrix is generated by kriging the values at the pilot points. This multiplier matrix is then multiplied by the initial hydraulic conductivity field on a cell-by-cell basis to result in a calibrated hydraulic conductivity field. Figure 2.3.1 shows the location of the pilot points used to generate the multiplier matrix that was applied to the Brazos River Alluvium Aquifer horizontal hydraulic conductivity. Because each pilot point represents a parameter, and each parameter requires a forward simulation during the calculation of the Jacobian matrix (an outer iteration in PEST), the modeler must try to achieve a balance between pilot point density (higher densities allow more refinement of the property field) and parameter estimation run times. We placed pilot points on approximately 8-mile centers along the main stem of the Brazos River resulting in a total of 26 pilot point calibration parameters.

For the formations underlying the Brazos River Alluvium Aquifer, property zones were primarily coincident with each formation outline. That is, the initial hydraulic property field for each formation was modified using a single multiplier for the entire formation within the Brazos River Basin. A hierarchy in values was maintained whereby confining units had significantly lower hydraulic conductivities than aquifer zones. Zones of alluvium from the Geologic Atlas of Texas (Bureau of Economic Geology, 2012) were inset into formation zones and given somewhat higher hydraulic conductivities. This was done to account for the fact that alluvial deposits are expected to exhibit higher hydraulic conductivities than the underlying formations. A composite hydraulic conductivity that accounts for both alluvium and the underlying formation was used. A uniform thickness of 50 feet of alluvium was assumed in calculating the composite hydraulic conductivity. The alluvium was assumed to have a uniform hydraulic conductivity equal to the mean value for the Brazos River Alluvium Aquifer of 160 feet per day in calculating the composite hydraulic conductivity. Figure 2.3.2 shows the 33 layer 3 property zones as they correspond to each formation outline.

2.3.2 Hydraulic Property Values

The calibration of the model is discussed in Section 3. The final, calibrated hydraulic properties used in the Layer-Property Flow package are presented here. There was not available data from water levels or well logs to quantitatively discriminate between hydraulic properties in the upper and lower portions of the Brazos River Alluvium Aquifer. Accordingly, the hydraulic properties in model layers 1 and 2 were assigned identically in the model. Table 2.3.2 lists the statistics of all the hydraulic properties used in the Layer-Property Flow package with a comparison to the values from the conceptual model. Figures 2.3.3 through 2.3.5 show the calibrated horizontal hydraulic conductivities for the three model layers. Figures 2.3.6 through 2.3.8 show the calibrated vertical hydraulic conductivities for the three model layers. A uniform specific yield value of 0.15 was used for all layers. Similarly, a uniform storativity value of 0.01 was used for all layers. All storage parameters were very insensitive and were not adjusted during calibration.

Table 2.3.1 Table of aquifer properties defined in the Layer-Property Flow package.

Property	Units	Description
Kh1	feet per day	Horizontal hydraulic conductivity for layer 1
Kv1	feet per day	Vertical hydraulic conductivity for layer 1
S1	dimensionless	Storativity for layer 1
Sy1	dimensionless	Specific yield for layer 1
Kh2	feet per day	Horizontal hydraulic conductivity for layer 2
Kv2	feet per day	Vertical hydraulic conductivity for layer 2
S2	dimensionless	Storativity for layer 2

Sy2	dimensionless	Specific yield for layer 2
Kh3	feet per day	Horizontal hydraulic conductivity for layer 3
Kv3	feet per day	Vertical hydraulic conductivity for layer 3
S3	dimensionless	Storativity for layer 3
Sy3	dimensionless	Specific yield for layer 3

Table 2.3.2 Table of initial and final statistics for hydraulic properties.

Parameter	Layer	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
		Min	Min	Max	Max	Mean	Mean	Geometric Mean	Geometric Mean	Median	Median
Kh	1	6.23E-01	1.57E+00	8.11E+02	1.00E+03	8.02E+01	2.47E+02	6.03E+01	1.61E+02	6.71E+01	1.64E+02
Kh	2	6.23E-01	1.57E+00	8.11E+02	1.00E+03	8.02E+01	2.47E+02	6.03E+01	1.61E+02	6.71E+01	1.64E+02
Kh	3	1.00E-01	2.00E-01	1.25E+02	1.61E+02	6.81E+00	1.26E+01	2.60E+00	2.30E+00	1.12E+00	3.00E+00
Kv	1	6.23E-02	1.57E-01	8.11E+01	1.00E+02	8.02E+00	2.47E+01	6.03E+00	1.61E+01	6.71E+00	1.64E+01
Kv	2	6.23E-02	1.57E-01	8.11E+01	1.00E+02	8.02E+00	2.47E+01	6.03E+00	1.61E+01	6.71E+00	1.64E+01
Kv	3	1.00E-03	2.00E-04	1.25E+00	1.61E-01	6.81E-02	1.03E-02	2.60E-02	1.88E-03	1.12E-02	1.92E-03
S	1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
S	2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
S	3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sy	1	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Sy	2	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Sy	3	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

Shading indicates that values were not changed from their initial estimates during calibration.

Kh = horizontal hydraulic conductivity in feet per day
Kv = vertical hydraulic conductivity in feet per day
S = storativity
Sy = specific yield

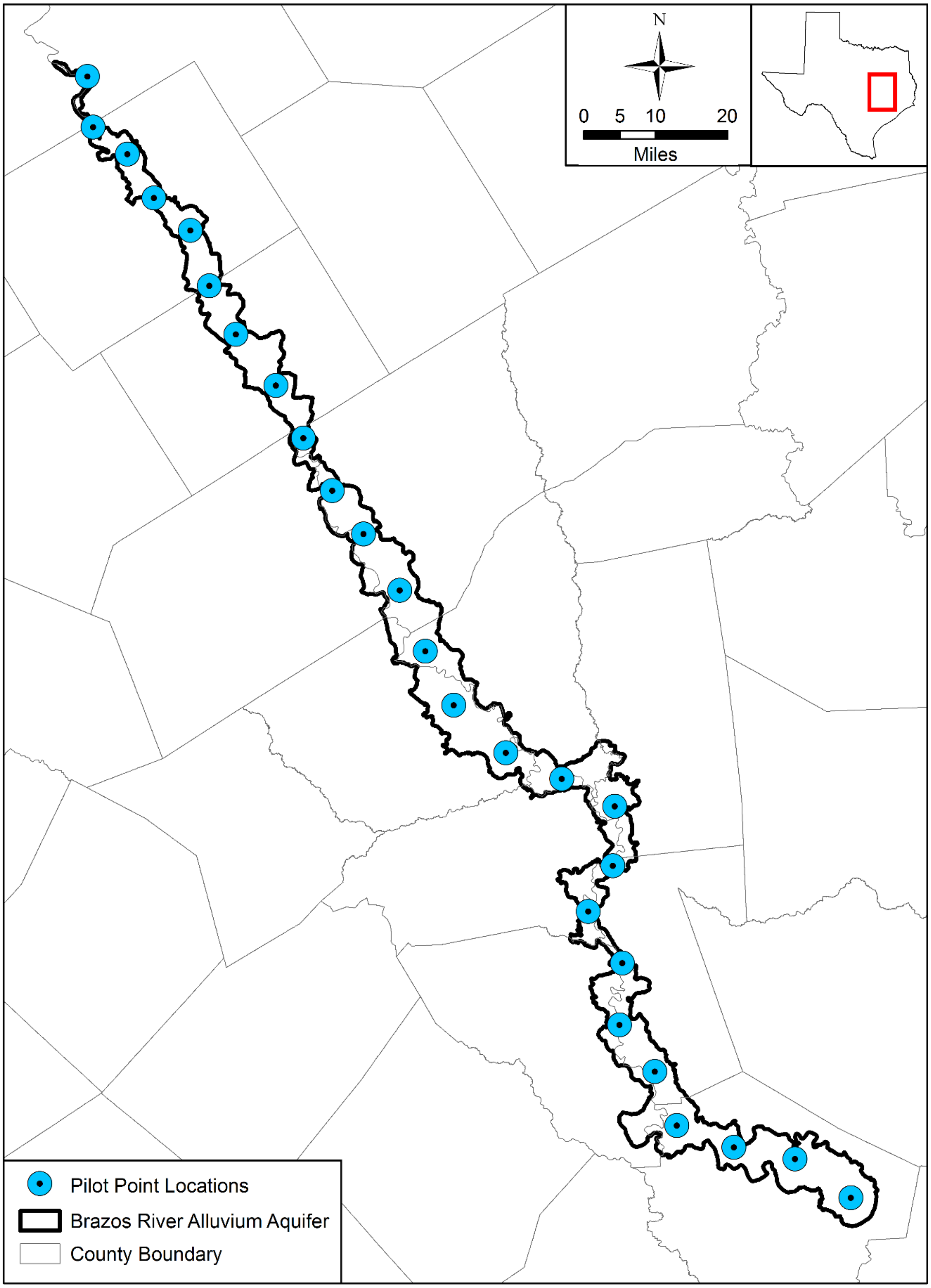

Figure 2.3.1 **Locations of pilot points for property calibration zonation in the Brazos River Alluvium Aquifer.**

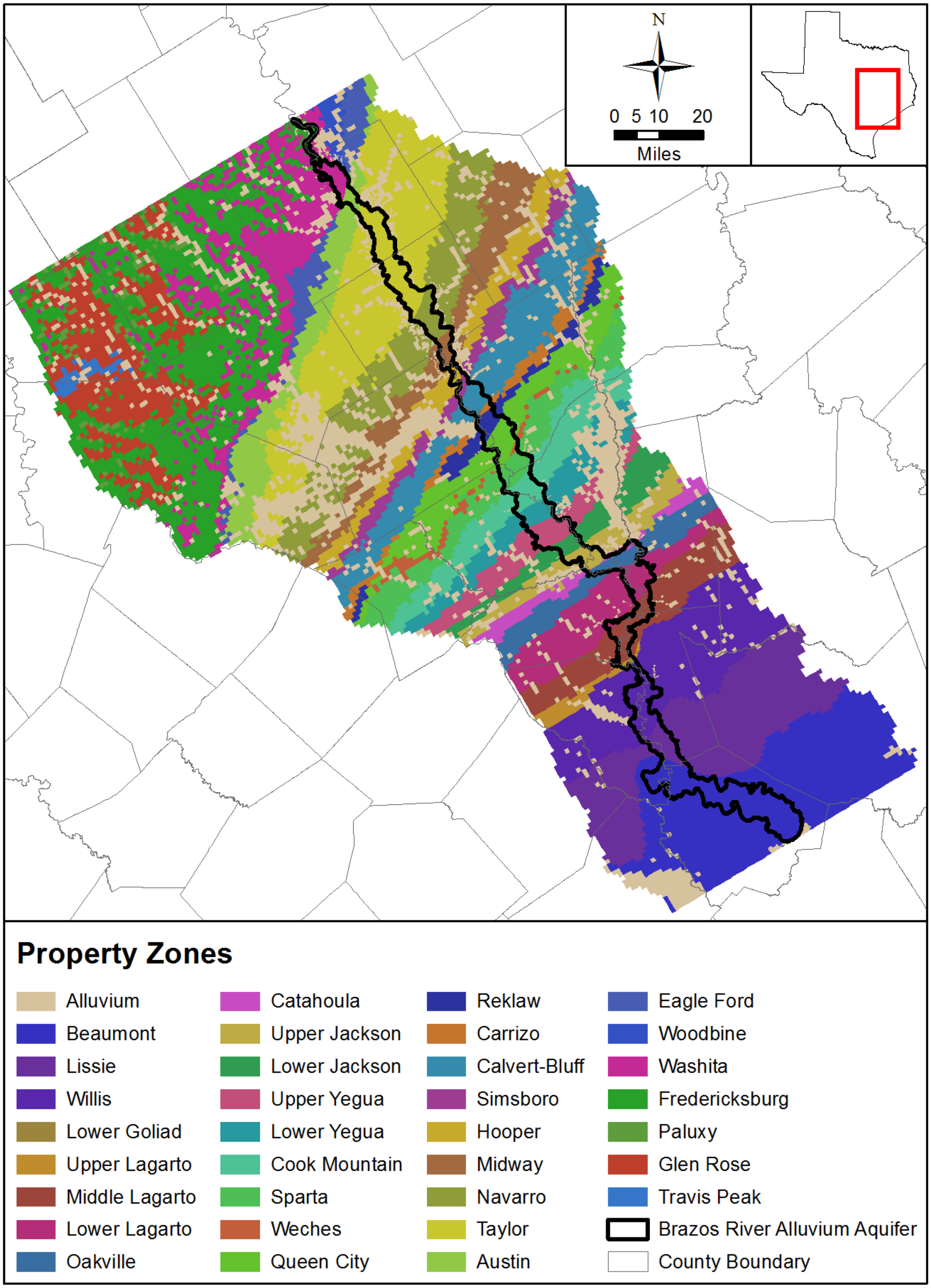

Figure 2.3.2 Property calibration zonation in the underlying formations.

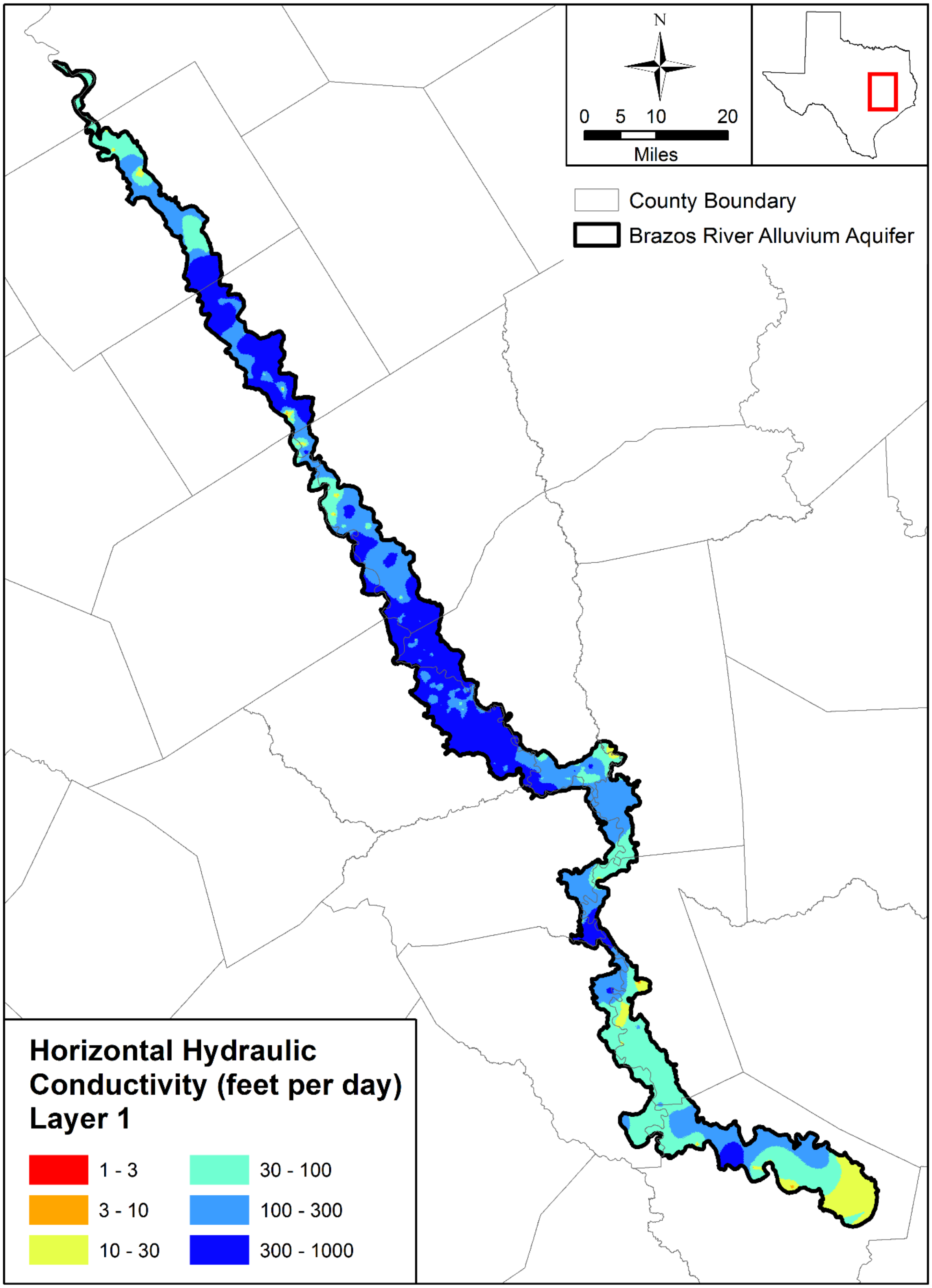

Figure 2.3.3 **Horizontal hydraulic conductivity of layer 1.**

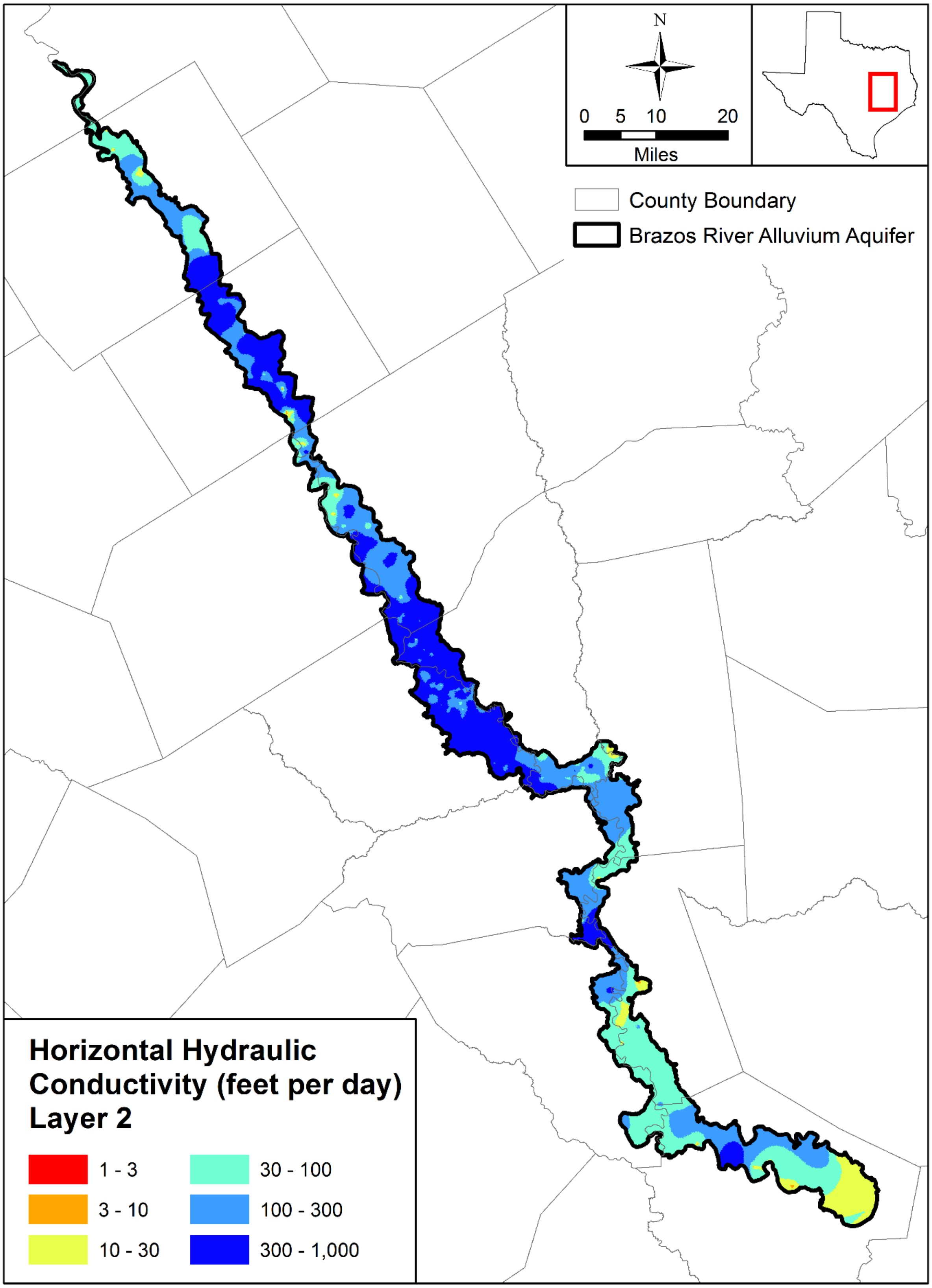

Figure 2.3.4 Horizontal hydraulic conductivity of layer 2.

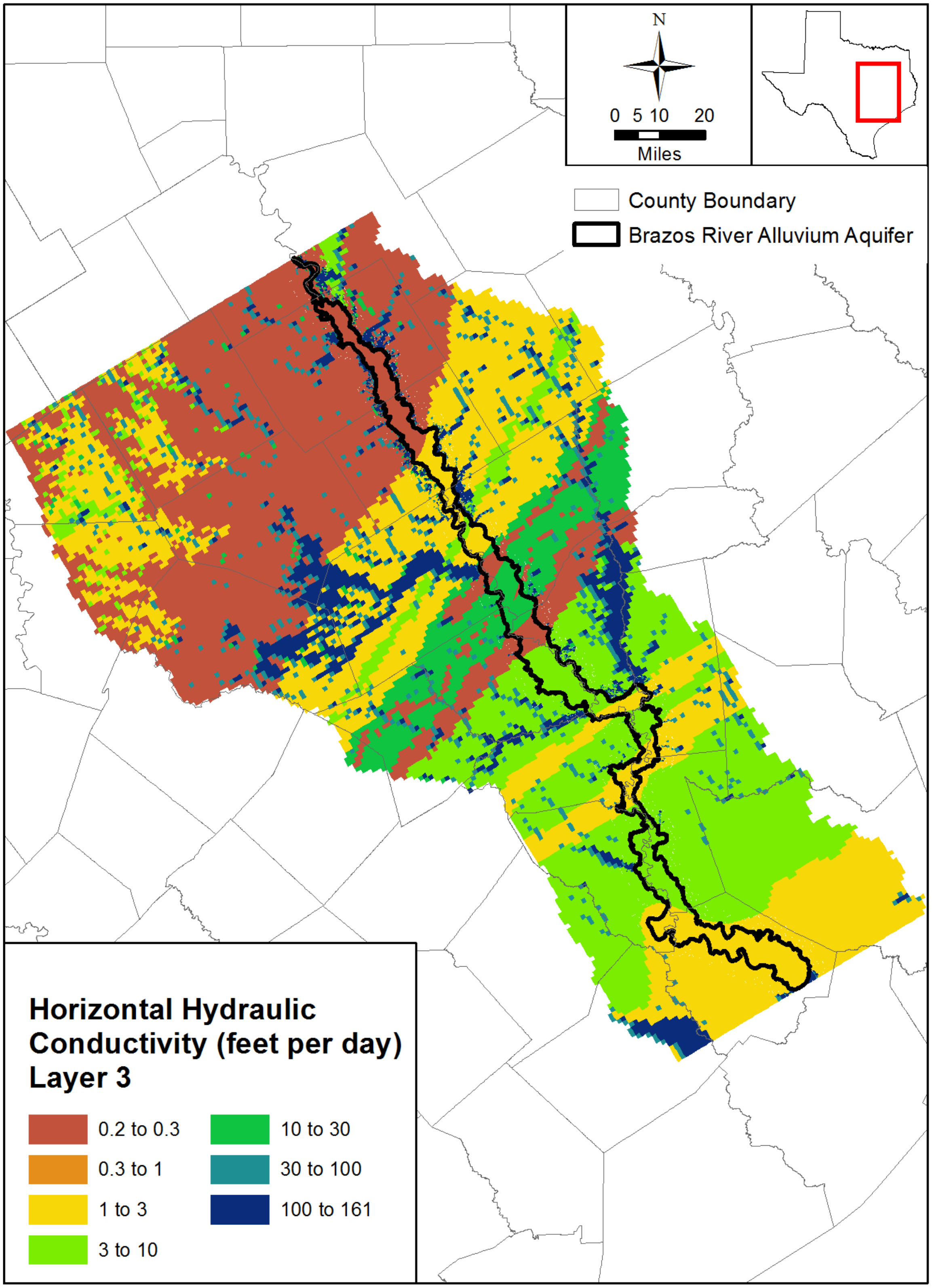

Figure 2.3.5 Horizontal hydraulic conductivity of layer 3.

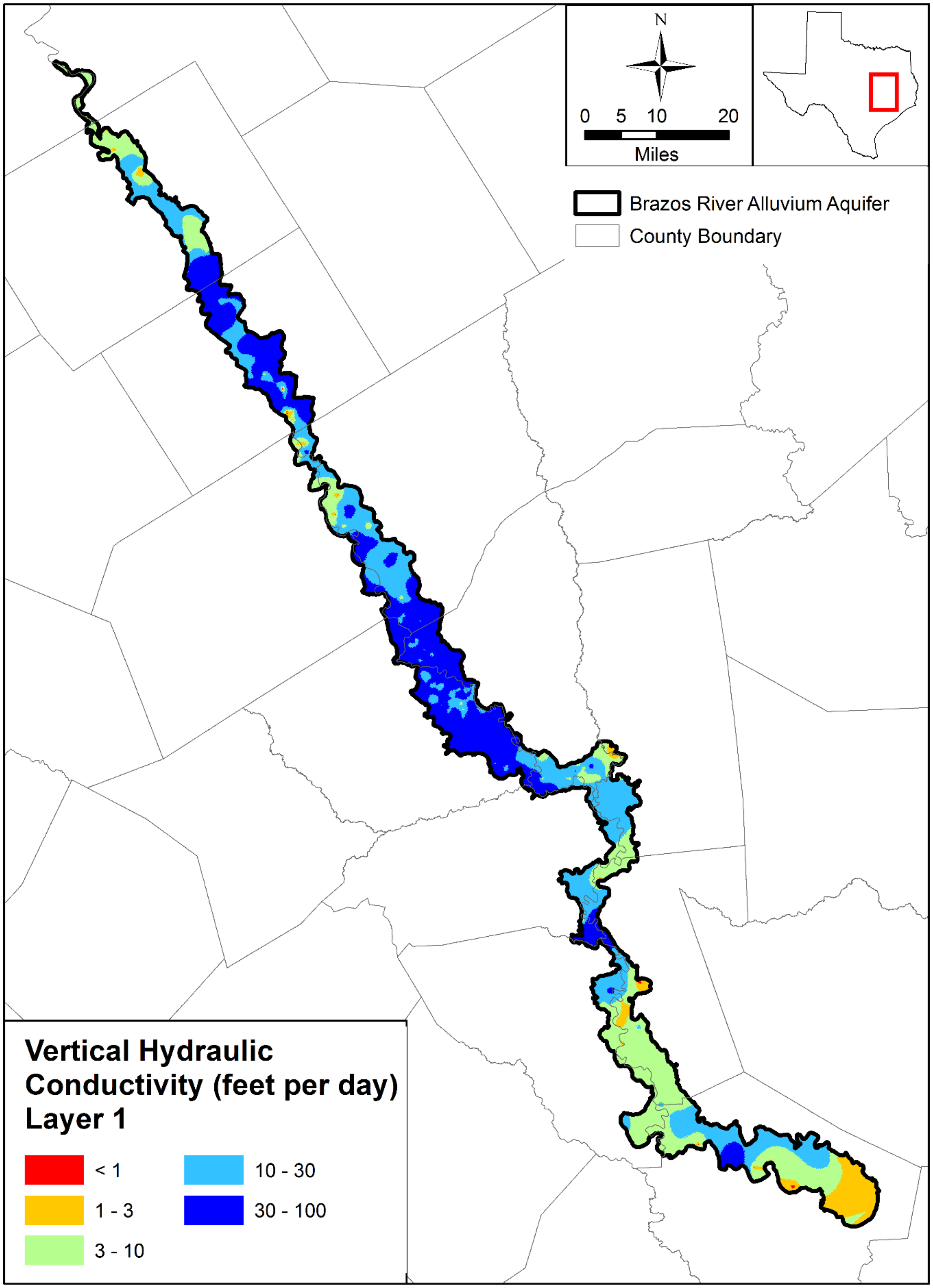

Figure 2.3.6 Vertical hydraulic conductivity of layer 1.

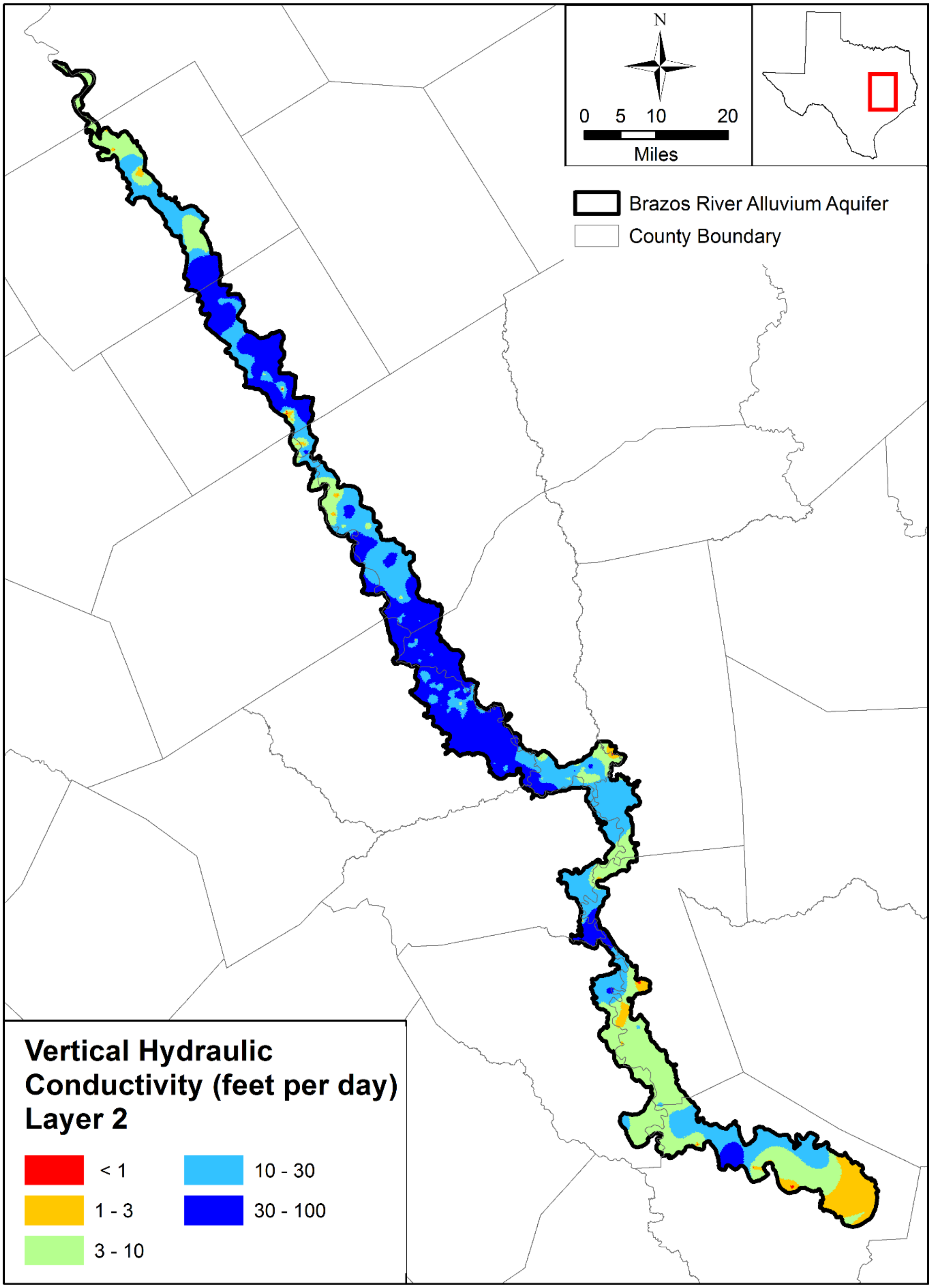

Figure 2.3.7 Vertical hydraulic conductivity of layer 2.

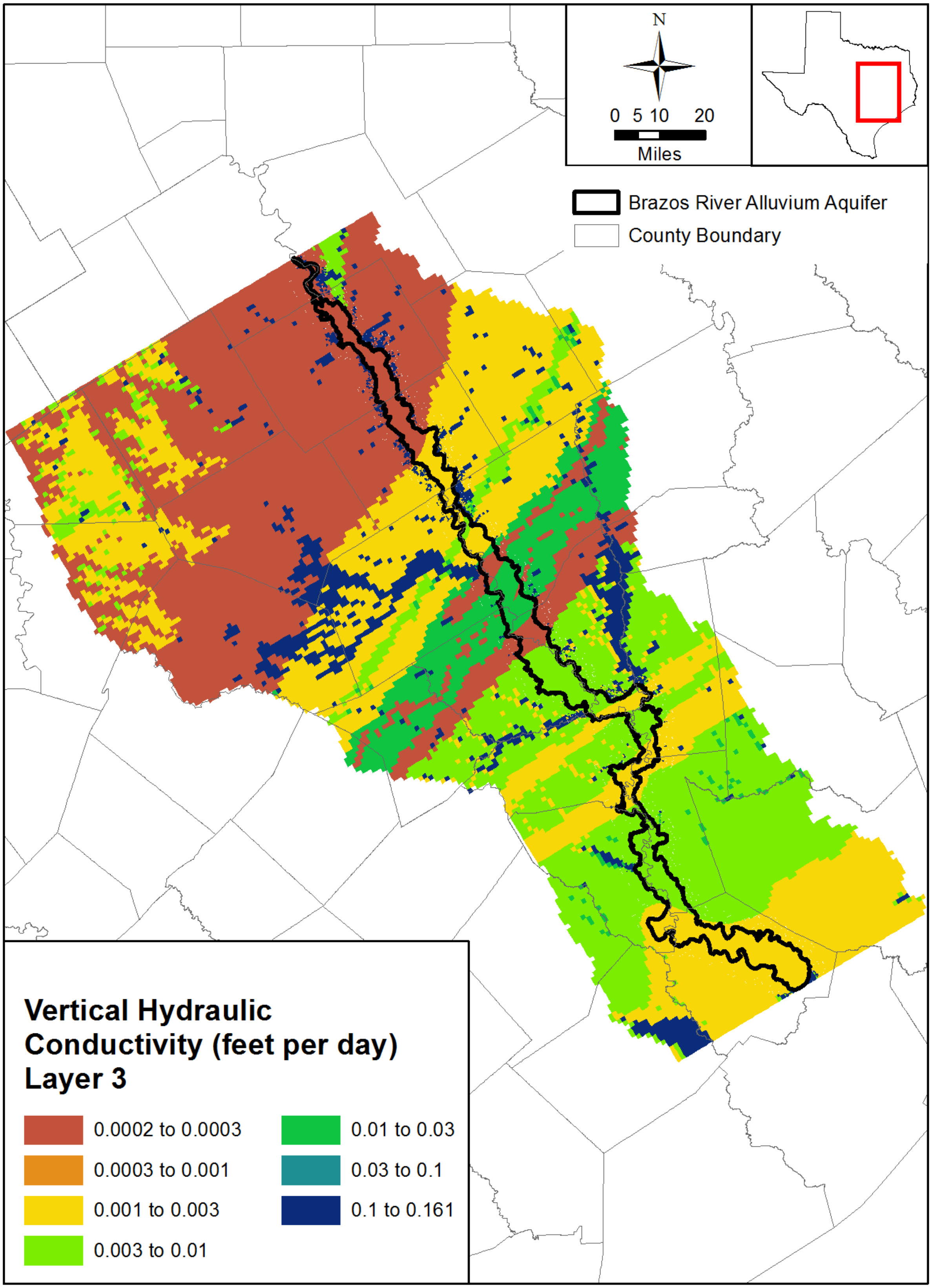

Figure 2.3.8 Vertical hydraulic conductivity of layer 3.

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2.4 Well Package

The MODFLOW Well (suffix WEL) package was used to simulate groundwater production. The Well package requires specification of a model cell location and a prescribed flow for each stress period. A table of groundwater production from the Brazos River Alluvium Aquifer by county and stress period is included in Appendix C.

2.4.1 Treatment of Minimum Saturated Thickness

One feature of MODFLOW-USG that is different from previous versions of MODFLOW other than MODFLOW-NWT is the ability for production in a cell to be automatically scaled back when the saturated thickness is one percent of the layer thickness. This simulates a decline in production that occurs in many cases when saturated thickness declines. In response to this aspect of MODFLOW-USG, we made sure that pumping within a county-aquifer was never reduced by more than ten percent of the estimated pumping within any stress-period. The maximum reduction to pumping was three percent, which is considered acceptable given the uncertainty in pumping estimates.

2.4.2 Data Sources

Two primary data sources were used in the creation of the pumping distribution. The first is a well dataset, which allows the assignment of pumping to a reported well location. The second is pumping volume estimates by water use category. These estimates were available at the county level, as determined during the development of the conceptual model (Ewing and others, 2016). In addition, the TWDB water use survey contains a further breakdown by survey name.

The master list of well locations used in the model was created by combining all available well datasets for the study area and, as much as possible, identifying and removing duplicate well records. The following datasets were analyzed and incorporated, as appropriate, into the master well list:

1. Texas Water Development Board groundwater database (TWDB, 2014a). This dataset yielded 1,486 unique wells.
2. Submitted Drillers Reports database (TWDB, 2014b). This dataset yielded 128 additional unique wells.

3. Texas Commission on Environmental Quality (2015) Public Water Supply Database. This dataset yielded 1,192 additional unique wells.
4. Data received from groundwater conservation districts for the current model
    a. Brazos Valley Groundwater Conservation District (2014): If a well had the same state well number as a well in (1), the well was removed as a duplicate. This dataset yielded 549 additional unique wells.
    b. Post Oak Savannah Groundwater Conservation District (2014): If a well had the same state well number as a well in (1), the well was removed as a duplicate. This dataset yielded 172 additional unique wells.
    c. Bluebonnet Groundwater Conservation District (2014): If a well had the same state well number as a well in (1), the well was removed as a duplicate. This dataset yielded 2 additional unique wells.
    d. Southern Trinity Groundwater Conservation District (2012): If a well had the same state well number as a well in (1), the well was removed as a duplicate. This dataset yielded 2 additional unique wells.

Wells were assigned to the Brazos River Alluvium Aquifer based on their depth and known screen information. Wells lacking depth information were not considered.

2.4.3 Initial Construction and Well Assignment

Pumping was assigned to wells based on use category, when available. For instance, irrigation pumping was assigned to wells with an irrigation use category. In general, pumping was allocated evenly to all wells within a county with a matching water use category.

Irrigation pumping constitutes the majority of the production in the Brazos River Alluvium Aquifer. However, even with the large well dataset, some pumping totals exceeded the number of wells for a county available in the well database, under the estimated maximum production rates per well. When that occurred, additional locations for pumping were identified as discussed in the following section.

For the transient period from 1980 through 2012, when monthly stress periods were used, seasonality was considered in assigning irrigation pumping. First, the United States Department of Agriculture cropland dataset (Figure 2.4.1) was used to identify irrigation wells within a

10-mile radius of cropland. These wells were then associated with the crop type for the nearest cropland and the irrigation schedule was based on the growing seasons shown in Figure 2.4.2. This is not meant to suggest that a 10-mile pipeline has been constructed to connect wells to irrigated cropland but rather that proximity to crops of a given type is a reasonable method for assigning a crop type to a given irrigation well.

2.4.4 Addition of Pumping Locations

After the initial allocation, some wells had production rates that proved to exceed the capacity of the aquifer (that is, the saturated thickness was reduced to one percent of the layer thickness prior to the end of the simulation). For these cases, no existing well locations remained at which to apply the excess production capacity, and additional locations were identified based on remaining saturated thickness. This excess production was then allocated based proportionally on saturated thickness.

In Falls, McLennan, Robertson, Waller, Grimes, Austin, Hill, and Milam counties, there was reported municipal pumping but no municipal wells existed in the database in those counties. In this case, municipal pumping was allocated to the centroids of cities overlying the Brazos River Alluvium Aquifer based proportionally on population.

All of the pumping wells considered for pumping allocation are shown in in Figure 2.4.3 along with the associated use category. This coverage includes wells from the groundwater database (TWDB, 2014a) as well as the additional wells discussed above (TWDB, 2014b; Texas Commission on Environmental Quality, 2015; Brazos Valley Groundwater Conservation District, 2014; Post Oak Savannah Groundwater Conservation District, 2014; Bluebonnet Groundwater Conservation District, 2014; and Southern Trinity Groundwater Conservation District, 2012). The pumping rates in July, 1980 and July, 2012 are shown in Figures 2.4.4 and 2.4.5, respectively.

2.4.5 Tool to Account for Flow Through the Base of Layer 3

The assumption of a no-flow boundary at the base of Layer 3 appears to be a reasonable approximation of the minimal groundwater flow from the shallow flow system to the deeper flow systems in the underlying formations over the historical period. However, if pumping increases significantly in the underlying formations in the future, this assumption may no longer be valid. To account for the possible pumping-induced increase in downdip flow in the underlying aquifers, a tool was developed to connect the Brazos River Alluvium Aquifer Groundwater Availabilty Model with the Groundwater Availabilty Models for the Northern Gulf Coast Aquifer System (Kasmarek, 2013), the Yegua-Jackson Aquifer (Deeds and others, 2010) and the Central Queen-City, Sparta and Carrizo-Wilcox aquifers (Kelley and others 2004). A description of the tool follows.

Three zones were created which represent the footprint of the Brazos River Alluvium Aquifer, the active model area to the southwest of the Brazos River Alluvium Aquifer and the active model area to the northeast of the Brazos River Alluvium Aquifer. These three zones were then intersected with the outcrop portions of each layer in the three underlying Groundwater Availabilty Models. This results in a total of 102 zones when the subcrop portions of each layer in the underlying models are considered as separate zones from the outcrop zones.

The outcrop zones from the underlying models were mapped to the corresponding model cells in Layer 3 of the Brazos River Alluvium Aquifer Groundwater Availabilty Model. Then the stress-periods for each of the underlying models were mapped to the stress periods in the Brazos River Alluvium Aquifer Groundwater Availabilty Model. For stress periods in the Brazos River Alluvium Aquifer Groundwater Availabilty Model that precede the first stress period in the other models, the pre-development stress period from the other models is mapped to that stress period in the current model. Similarly, for stress periods in the current model that occur after the end of the other models, the last stress period for that model is mapped to the last stress period in the current model.

The tool runs Zonebudget for each of the three underlying models and extracts the flow between the outcrop and subcrop zones for each model stress period. The tool then translates these flows to the model cells and stress periods in the Brazos River Alluvium Aquifer Groundwater Availabilty Model using the aforementioned maps. Finally, the tool adds these flows to the well package for the Brazos River Alluvium Groundwater Availabilty Model as Layer 3 well flows. Hydrographs of wells in the outcrops of the underlying aquifers (Kelley and others, 2004; Deeds and others, 2010; and Kasmarek, 2013) indicate very little drawdown over the historical period. This indicates that any shallow pumping in the outcrops will not have impacted the heads or flows in the Brazos River Alluvium Aquifer. The tool accounts for the deeper pumping in the underlying aquifers and the associated impact to flow to the Brazos River Alluvium Aquifer.

The extracted deep flow from the underlying aquifers for December, 2012 is depicted in Figure 2.4.6

To use the tool for predictive simulations that include additional pumping in the underlying Groundwater Availabilty Models, the predictive stress periods in the underlying models would need to be mapped to the predictive stress periods in the Brazos River Alluvium Aquifer Groundwater Availabilty Model in a fashion similar to what was done for the historical models. Any wells added in the outcrops of the underlying models during the predictive period would need to be added to Layer 3 of the Brazos River Alluvium Aquifer Groundwater Availabilty Model. The tool would then be run to add the effect of flow through the base of Layer 3 as additional Layer 3 wells. Then the Brazos River Alluvium Aquifer Groundwater Availabilty Model predictive model could be run with these flows included. In this way, predictive pumping scenarios will be consistent between the Brazos River Alluvium Aquifer Groundwater Availabilty Model and the underlying Groundwater Availabilty Models.

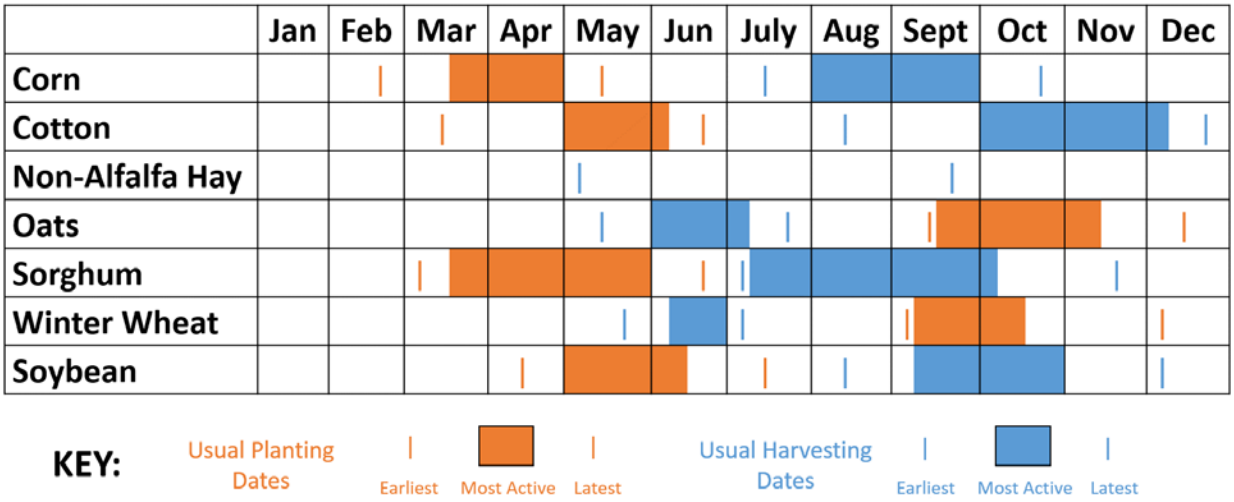

Figure 2.4.1 **Growing and cultivating schedule for various crops (United States Department of Agriculture, 1997).**

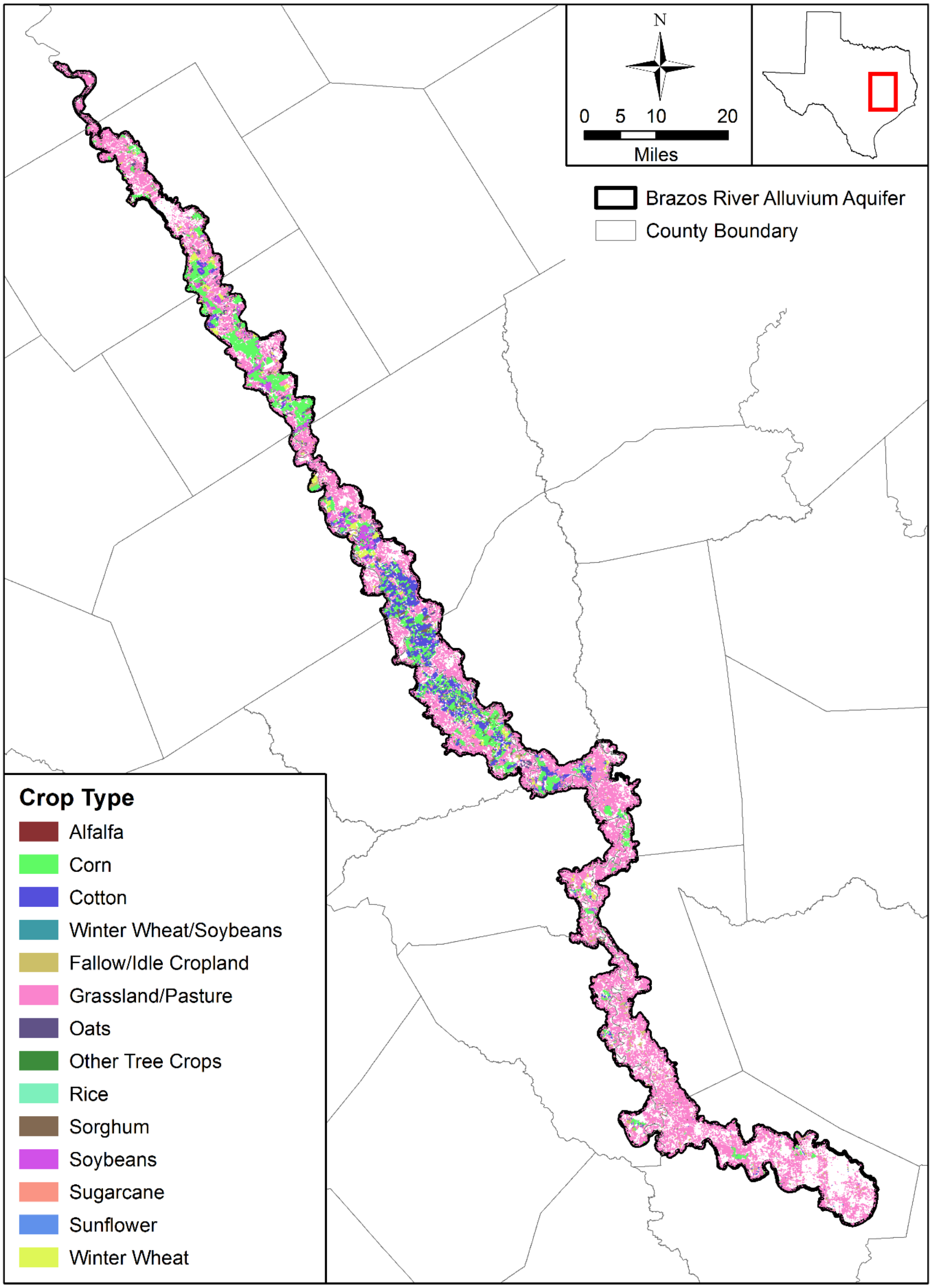

Figure 2.4.2 Location of crop types in 2008 (National Agricultural Statistics Service, 2015).

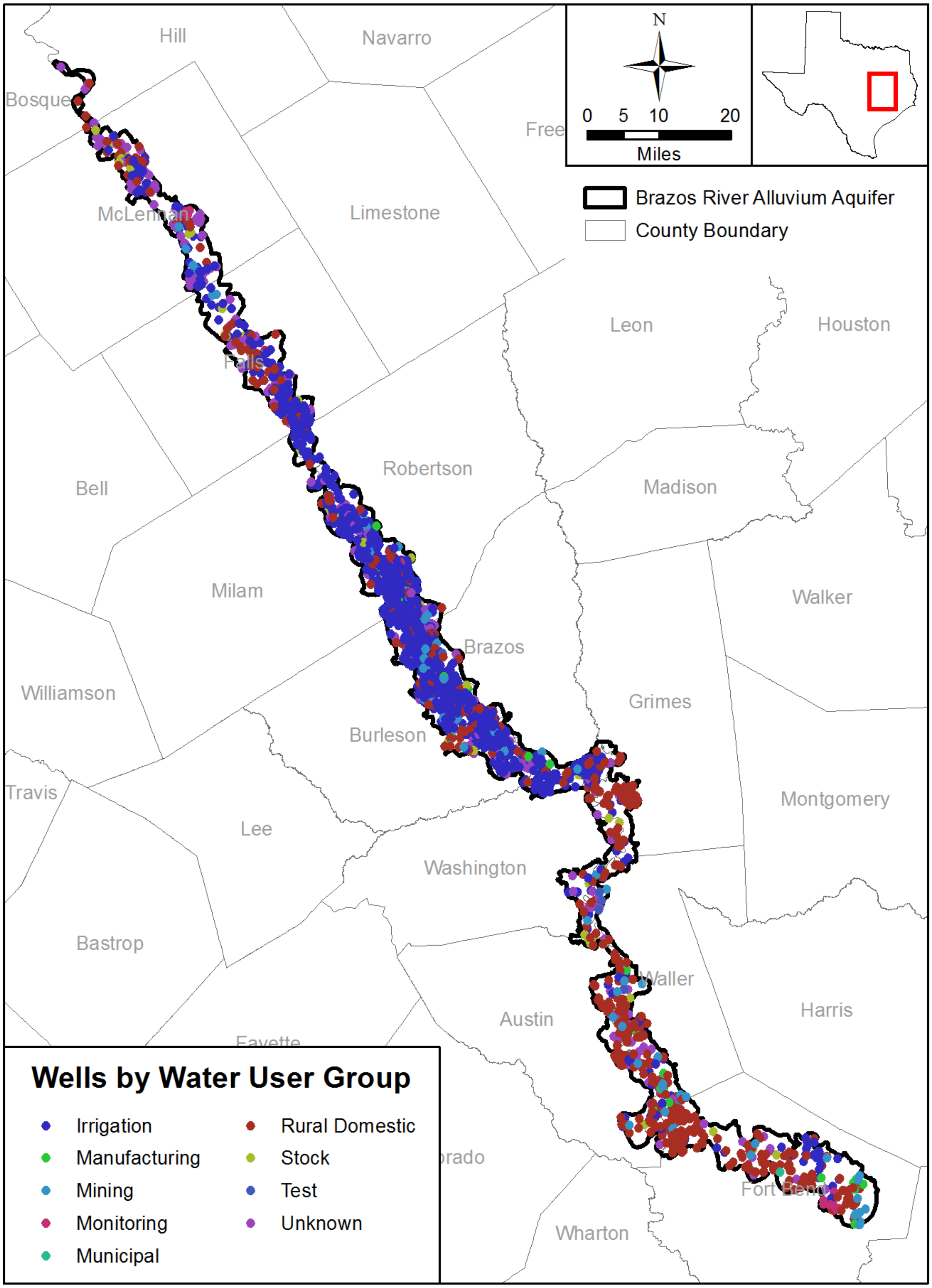

Figure 2.4.3 Well distribution and type used to allocate pumping.

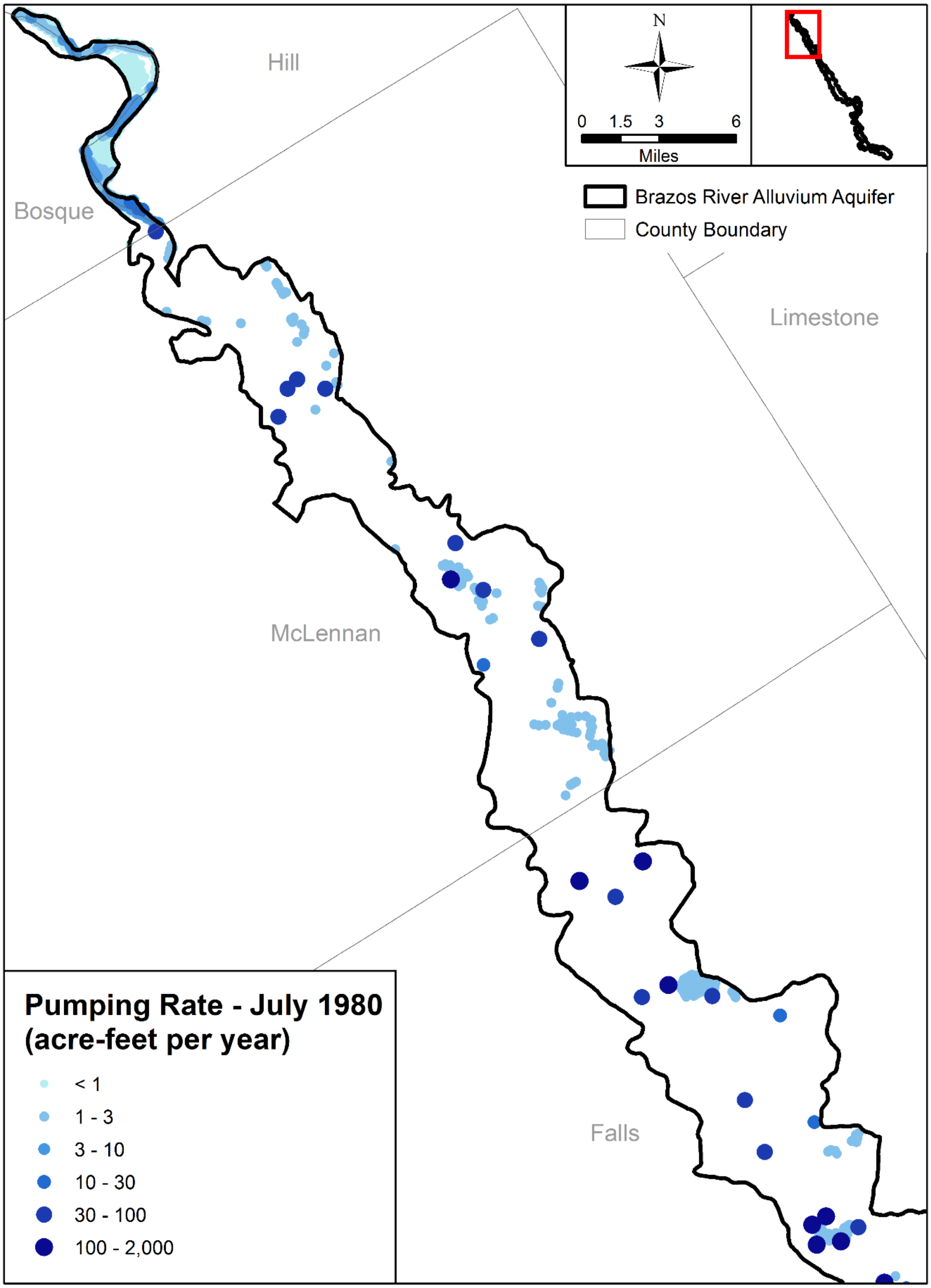

Figure 2.4.4a Pumping rates in July, 1980 in the northernmost portion of the Brazos River Alluvium Aquifer.

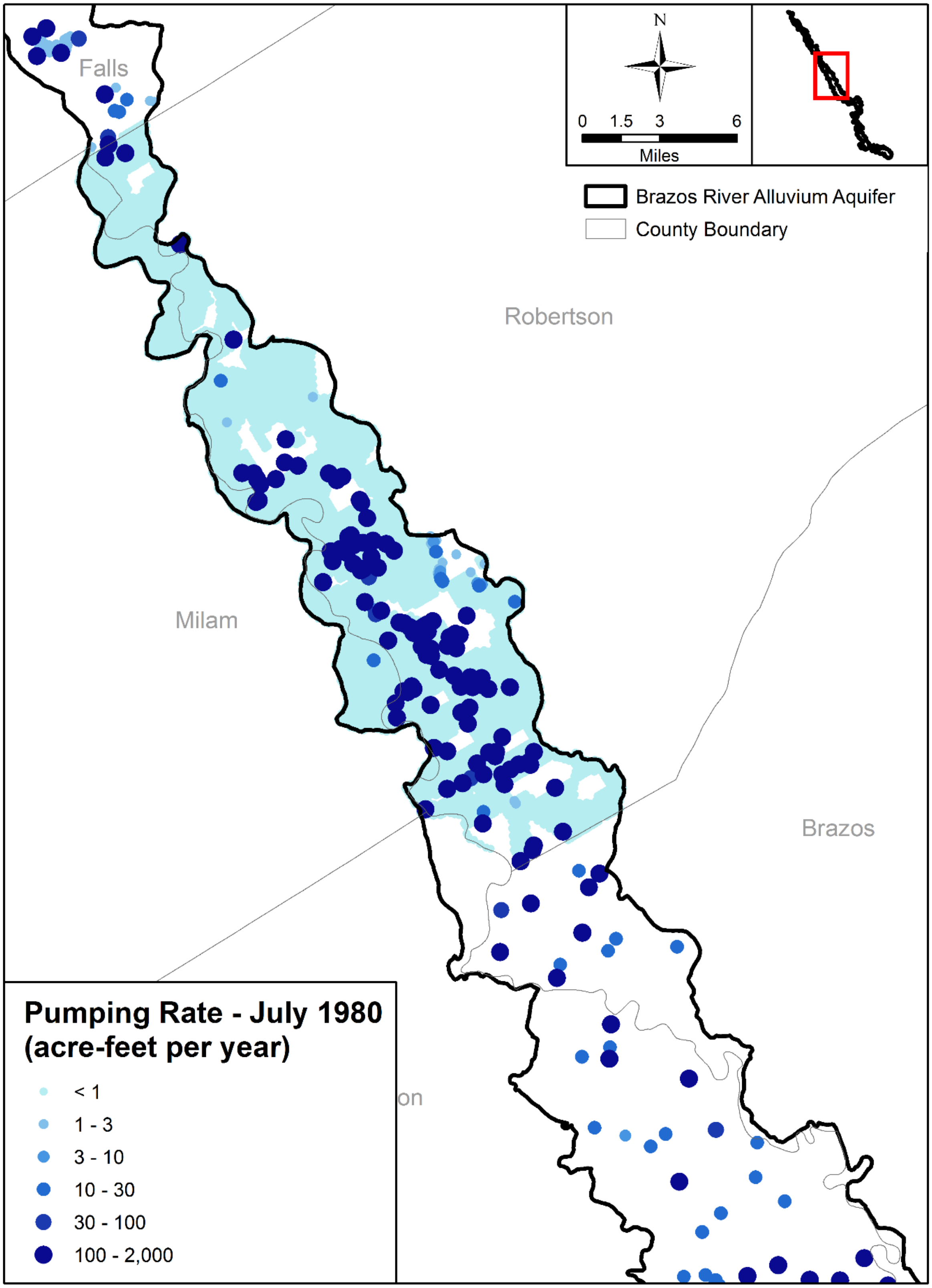

Figure 2.4.4b Pumping rates in July, 1980 in the north-central portion of the Brazos River Alluvium Aquifer.

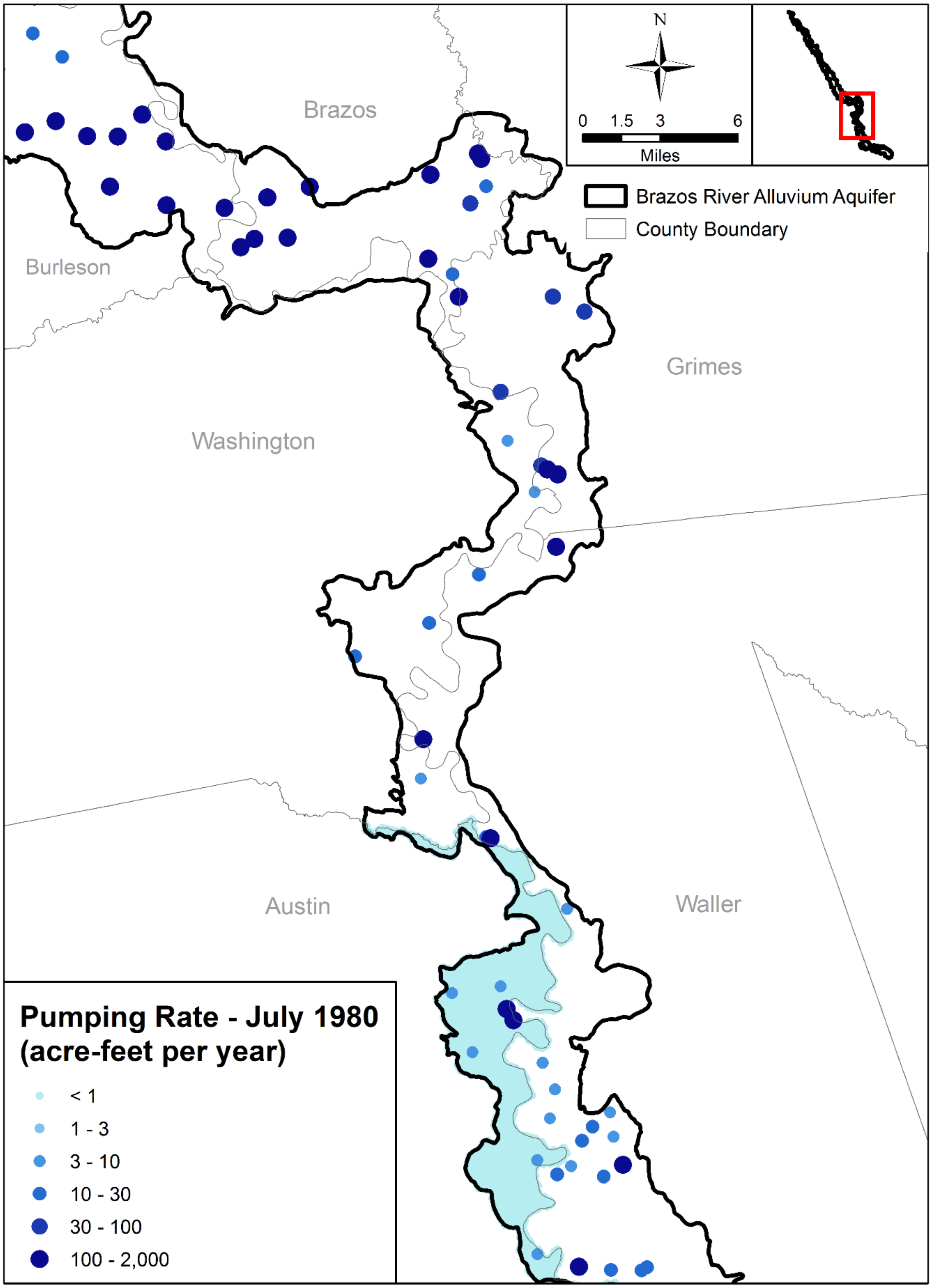

Figure 2.4.4c **Pumping rates in July, 1980 in the south-central portion of the Brazos River Alluvium Aquifer.**

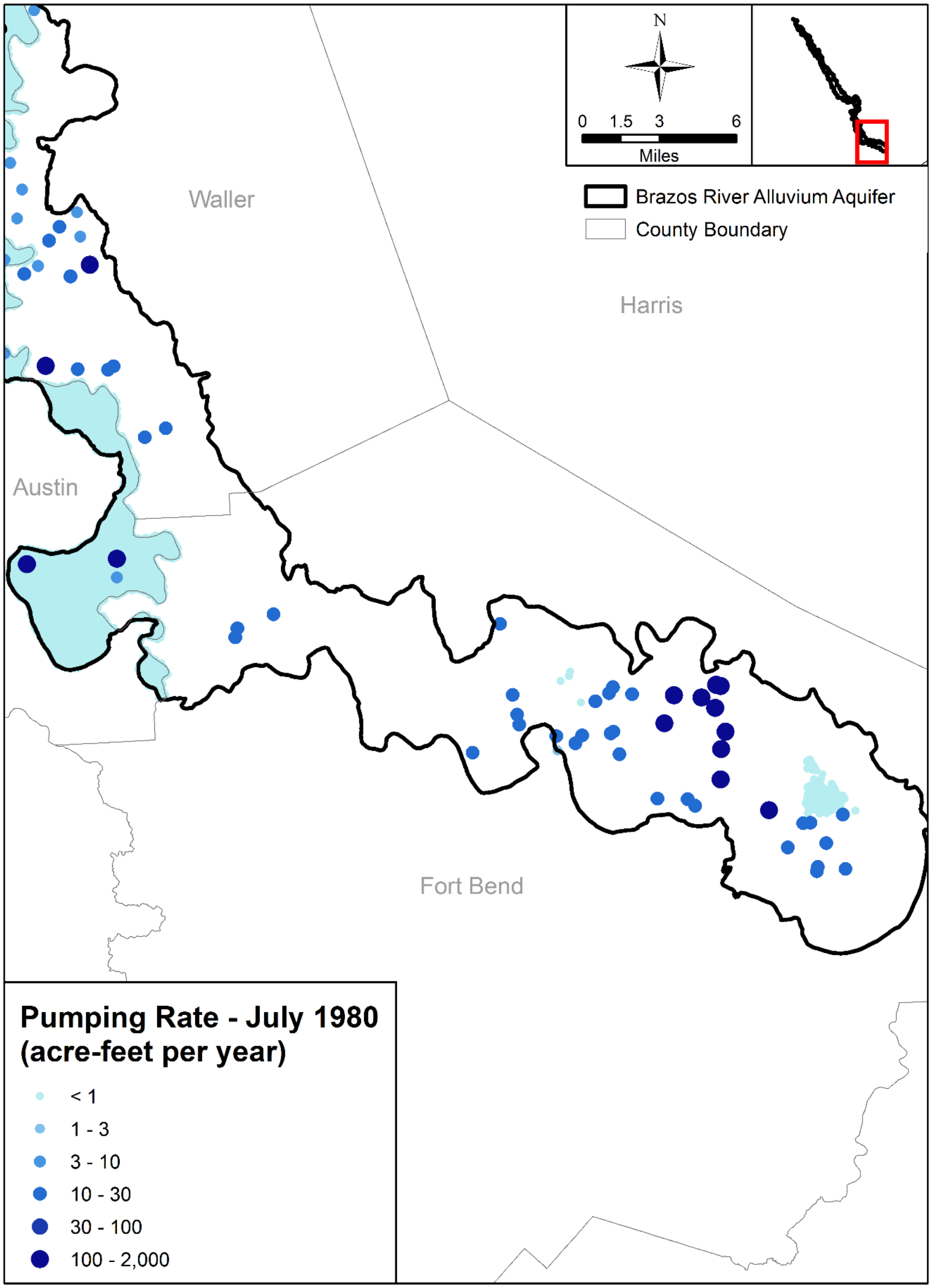

Figure 2.4.4d Pumping rates in July, 1980 in the southernmost portion of the Brazos River Alluvium Aquifer.

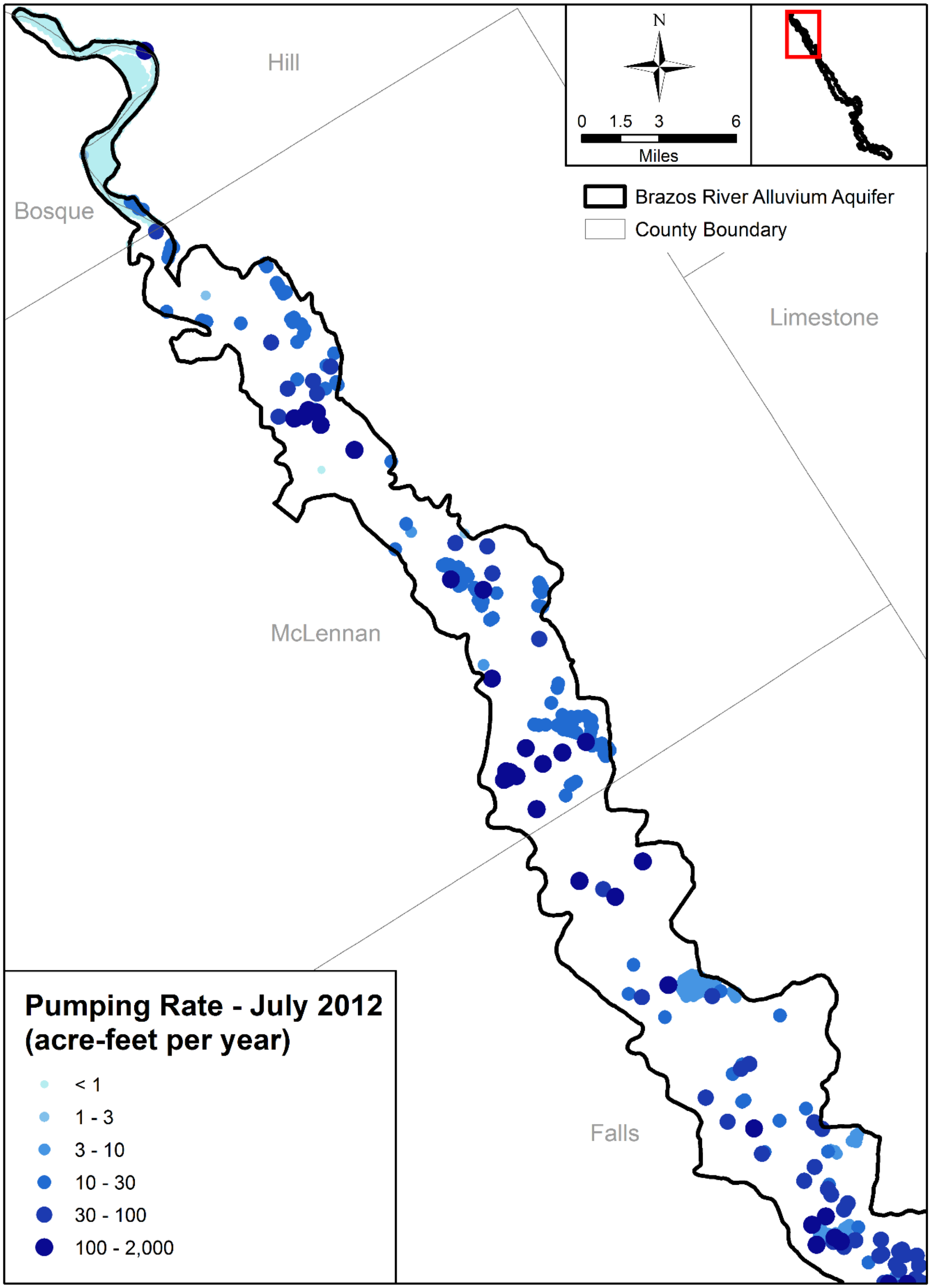

Figure 2.4.5a **Pumping rates in July, 2012 in the northernmost portion of the Brazos River Alluvium Aquifer.**

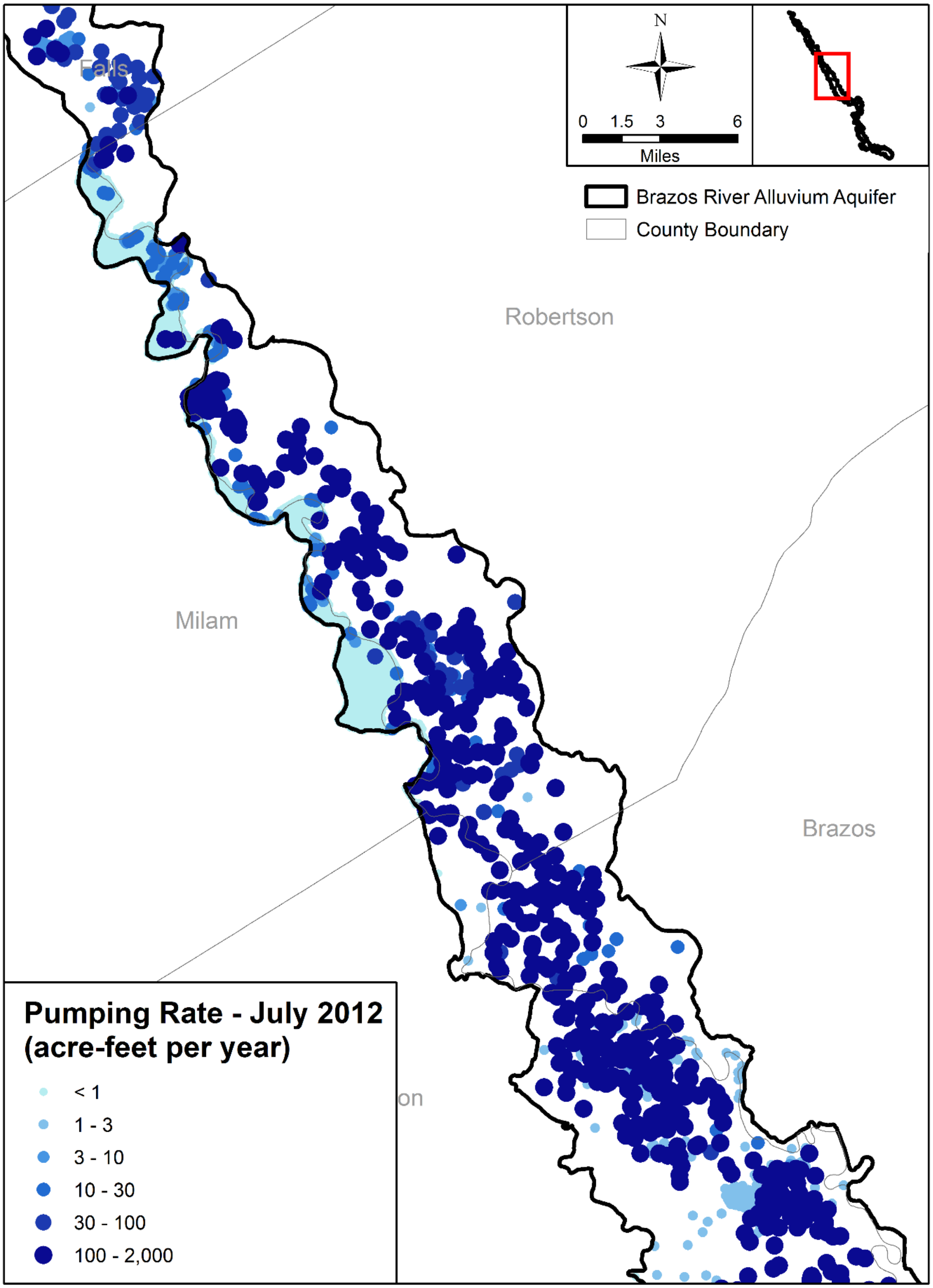

Figure 2.4.5b **Pumping rates in July, 2012 in the north-central portion of the Brazos River Alluvium Aquifer.**

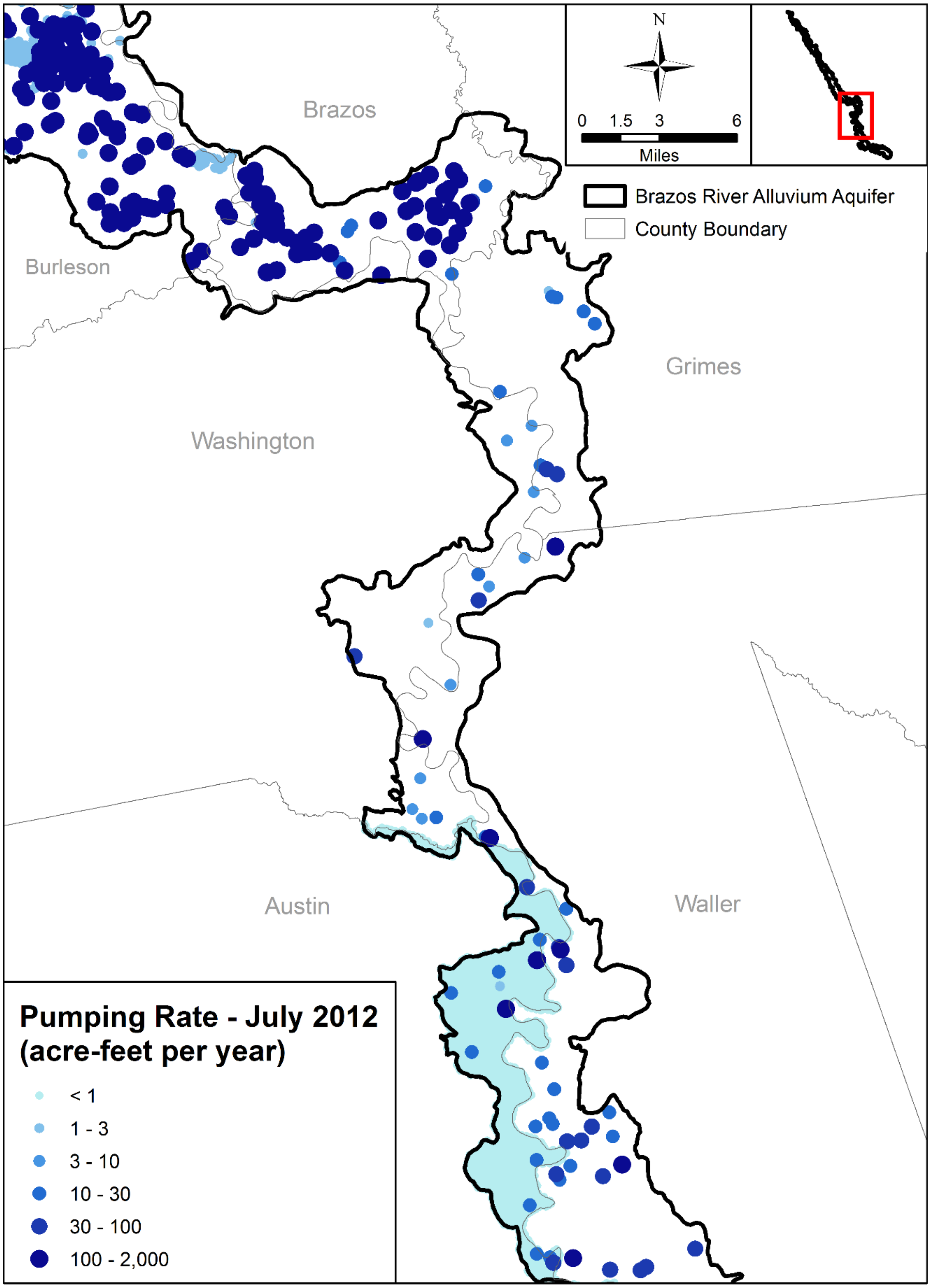

Figure 2.4.5c Pumping rates in July, 2012 in the south-central portion of the Brazos River Alluvium Aquifer.

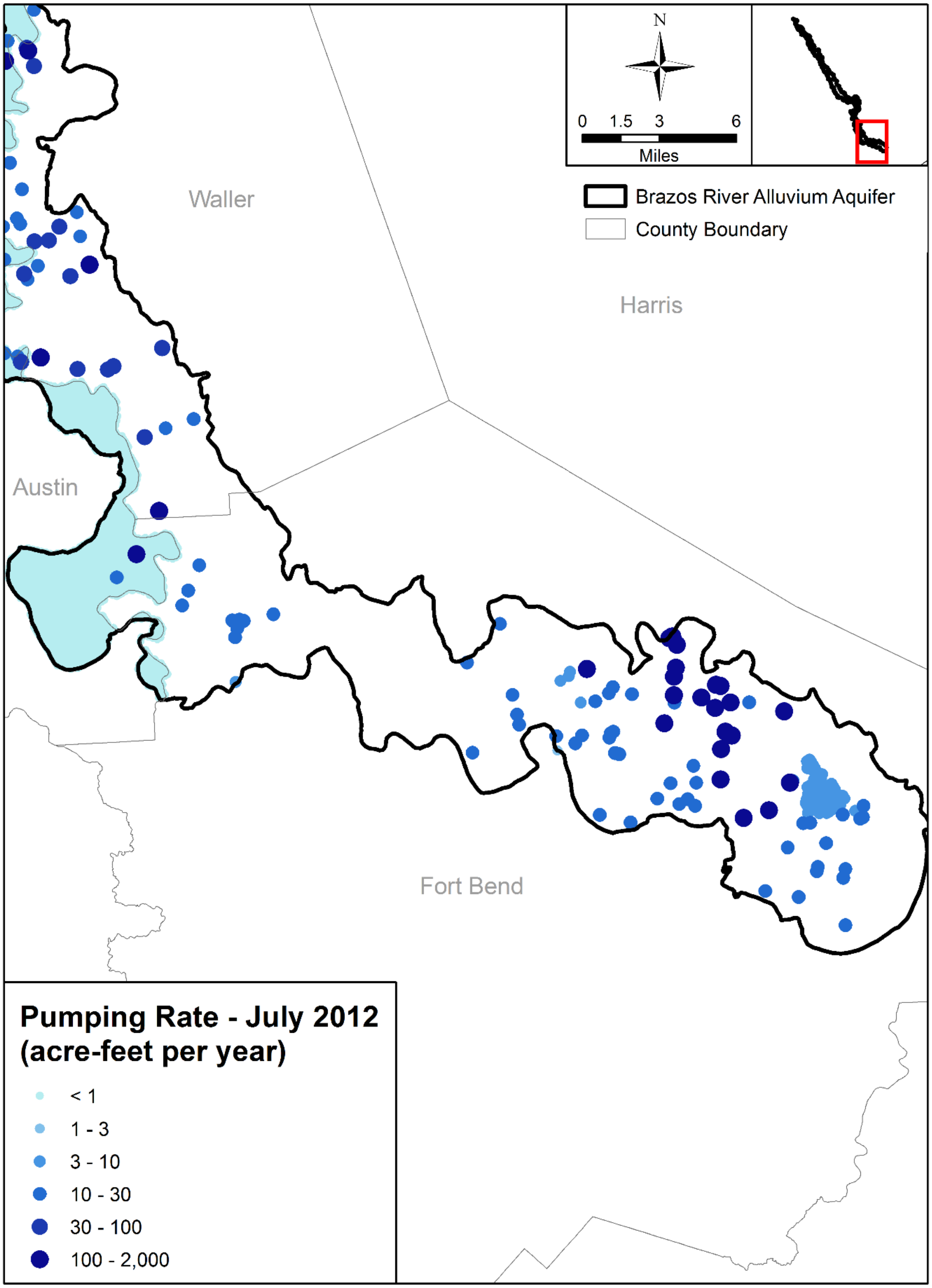

Figure 2.4.5d **Pumping rates in July, 2012 in the southernmost portion of the Brazos River Alluvium Aquifer.**

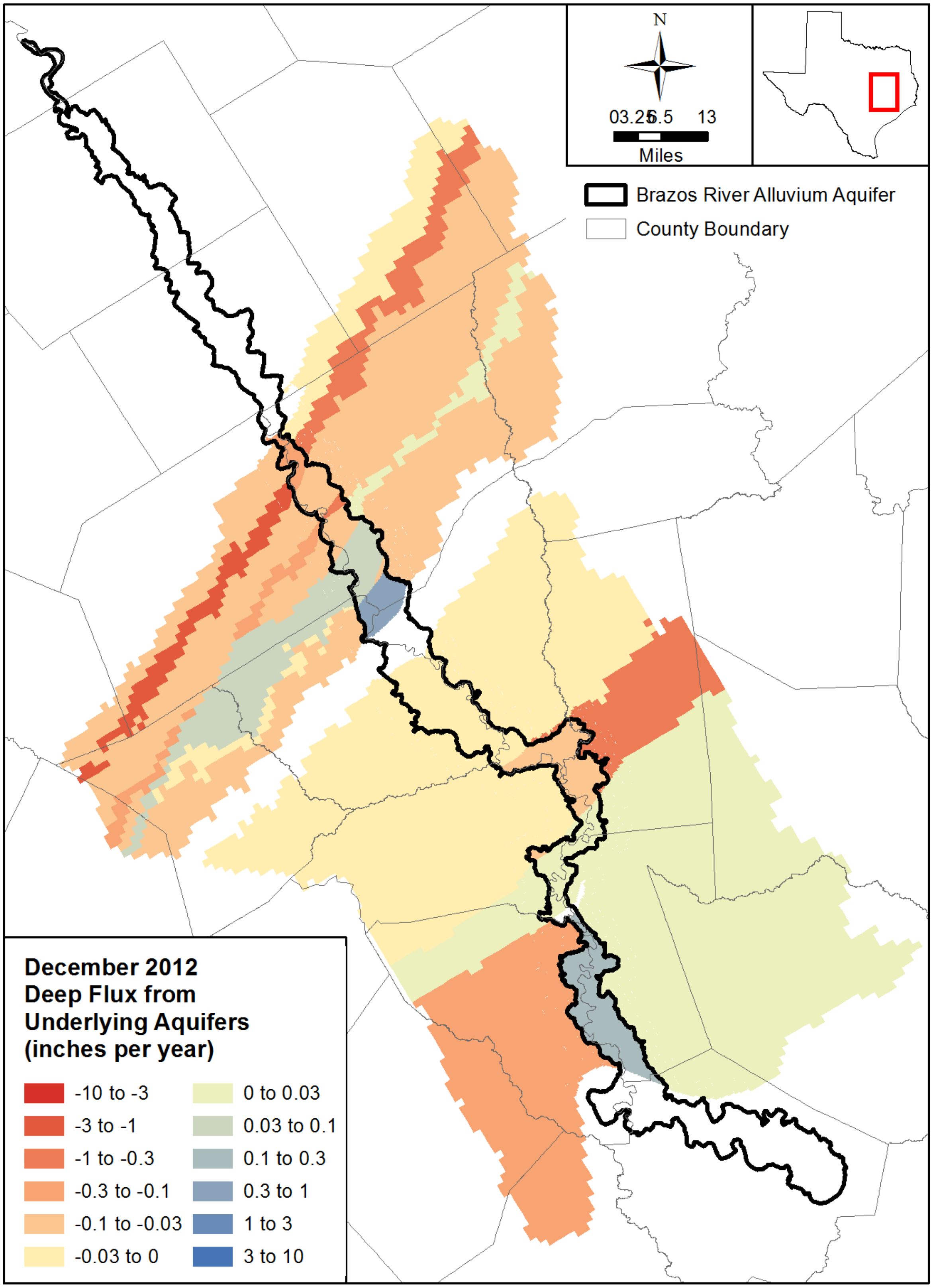

Figure 2.4.6 **Deep flux from the underlying aquifers in December, 2012 (negative fluxes are downward and positive fluxes are upward).**

2.5 Drain Package

The MODFLOW Drain (suffix DRN) package was used to simulate outflow from springs. Drain cells throughout the model are shown in Figure 2.1.4. Locations of spring cells were based on documented spring locations (Ewing and others, 2016). For these springs, a drain cell was added in the uppermost cell that contained the estimated location of the spring.

Outflow to drains occurs whenever the water level elevation in the aquifer is higher than the elevation of the drain, which represents the stage of the spring. Elevations of the drains were based on the elevation sampled from the 10-meter digital elevation model at the approximate location of the spring. In addition, the drain elevations were lowered by 10 feet to account for the fact that the springs tend to occur at a topographical minimum within the sampled 10-meter digital elevation model. The choice of 10 feet is on the same order of magnitude as the mean absolute error (6.5 feet) for the steady-state model in the Brazos River Alluvium Aquifer.

The resistance to the outflow to a drain can be controlled by the drain conductance. The drain conductances were initially set to 1,000 feet squared per day for all drains. This conductance is high enough that the underlying aquifer properties will generally provide the limiting factor for outflow. The drain conductance was increased to 1,600 feet squared per day for a single spring during calibration to better match the relatively large observed outflow at that spring. Drain location, elevation, and conductance remained constant for all stress periods.

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2.6 Recharge Package

The MODFLOW Recharge (suffix RCH) package was used to simulate recharge to groundwater in the model. Recharge was applied in the Brazos River Alluvium Aquifer as well as the outcrop portions of the underlying formations. The option was used to apply recharge in the uppermost active layer. Because MODFLOW-USG does not inactivate cells where the head falls below the layer bottom when the Newton-Raphson option is used, the layer to which recharge was applied does not vary during the course of a simulation.

2.6.1 Steady-State Recharge

Steady-state recharge in the Brazos River Alluvium Aquifer was initially based on the predevelopment distribution from Ewing and others (2016). Recharge within both the Brazos River Alluvium and the outcrops of the underlying formations was modified during calibration to better match long-term baseflow estimates. Recharge within the outcrops of the underlying formations was generally modified on a formation-by-formation basis but also reduced locally to avoid flooding in the confining units. The steady-state recharge distribution is shown in Figure 2.6.1. Recharge within the boundary of the Brazos River Alluvium Aquifer was applied to layer 1 while recharge outside the aquifer was applied to layer 3.

2.6.2 Transient Recharge

Transient recharge in the Brazos River Alluvium Aquifer was based on the post-development recharge estimate from Ewing and others (2016). In the alluvium, transient recharge increases through time due to changes in soil conditions from agricultural activities, and irrigation return flow. The average post-development recharge is shown in Figure 2.6.2. The post-development recharge associated with irrigation return flow was used for all transient stress periods following the onset of significant irrigation in agricultural activities in 1950 assumed to roughly coincide with the drought of the 1950s. The post-development recharge increase associated with mining was used for all transient stress periods following onset of mining activities assumed to begin in 1966 prior to being documented in Cronin and Wilson (1967).

Transient recharge was varied temporally based on precipitation. The relative amount of precipitation in a given year or month compared with the long-term average precipitation was used to scale annual or monthly recharge rates up and down compared with the temporally averaged recharge rate in a given grid cell. In this way, wetter than average and drier than average periods are accounted for in the transient recharge. For cells without irrigated cropland or mining, the following equation was used to distribute recharge temporally:

$$R_i = \frac{\left(P_i - P_{avg}\right)}{P_{avg}} \times damp \times R_{ss} \qquad (2.6.1)$$

where:

R_i = recharge rate for stress period i (inches per year)
P_i = precipitation rate for stress period i (inches per year)
P_{avg} = long-term average precipitation rate (inches per year)
$damp$ = damping factor equal to 0.5
R_{ss} = steady-state recharge rate (inches per year)

For cells with a gravel pit used for mining, the following adjustment was made to the transient recharge:

$$R_{i,m} = R_i \times 1.5 \qquad (2.6.2)$$

where:

$R_{i,m}$ = recharge rate in mining cell for stress period i starting in 1966 (inches per year)
R_i = recharge rate from Equation 2.6.1 (inches per year)

For cells with irrigated cropland, the following adjustment was made to the transient recharge:

$$R_{i,irr} = R_i + F_i \times 14 \qquad (2.6.3)$$

where:

$R_{i,irr}$ = recharge rate in irrigation cell for stress period i starting in 1950 (inches per year)
R_i = recharge rate from Equation 2.6.1 (inches per year)
F_i = irrigation return fraction for stress period i (dimensionless)

The rationale behind Equations 2.6.2 and 2.6.3 is discussed in the Conceptual Model Report for the Brazos River Alluvium Aquifer Groundwater Availability Model (Ewing and others, 2016). Irrigation return fractions for historical time periods and counties are given in Table 4.3.3 of Ewing and others (2016). To be consistent with the transient model, predictive models can use estimates of precipitation and irrigation return fractions for the predictive period along with

Equations 2.6.1, 2.6.2, and 2.6.3. The cells associated with irrigation and mining are listed in the "braa_grid_rch" feature class of the geodatabase.

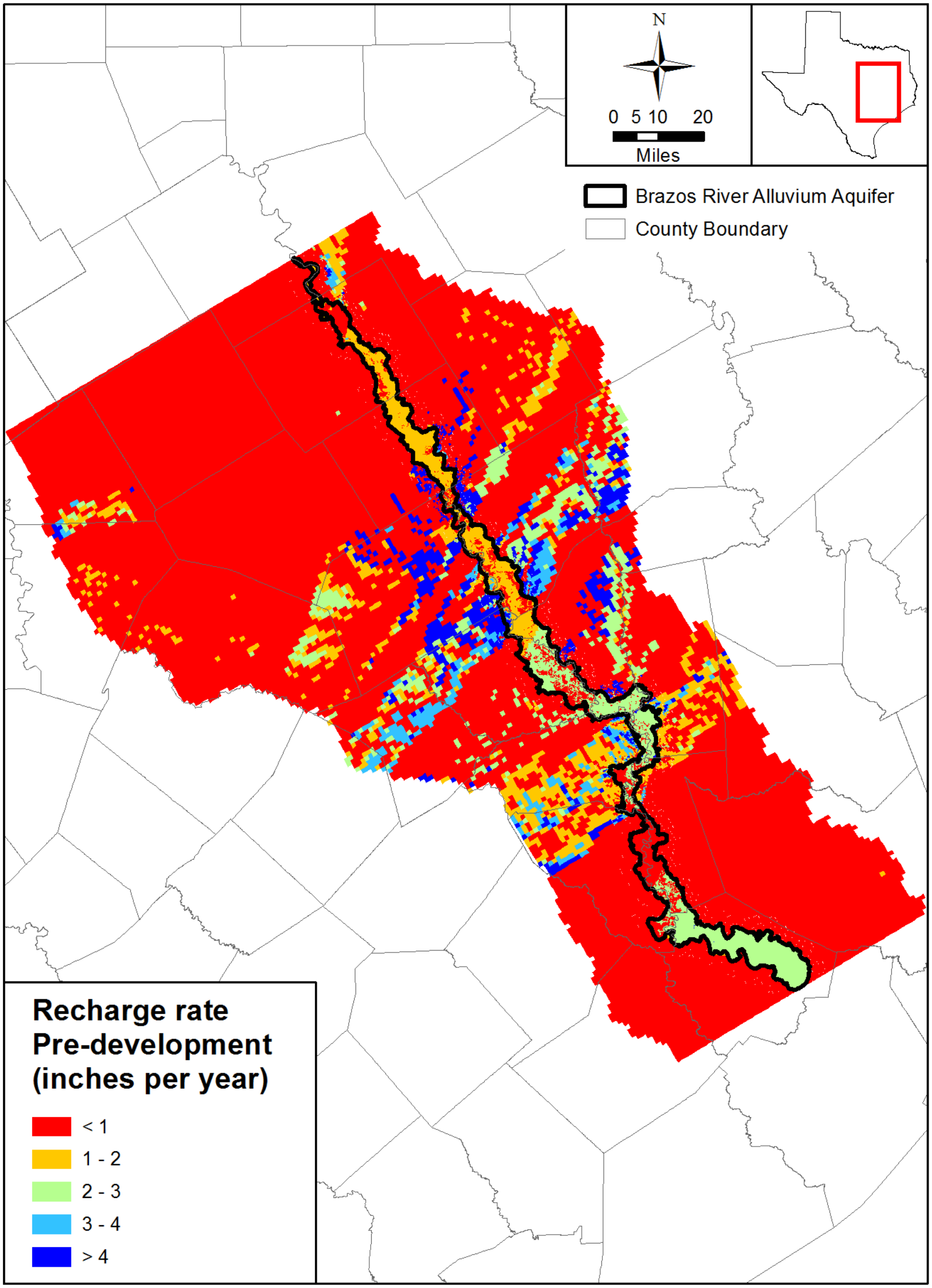

Figure 2.6.1 Steady-state recharge rate.

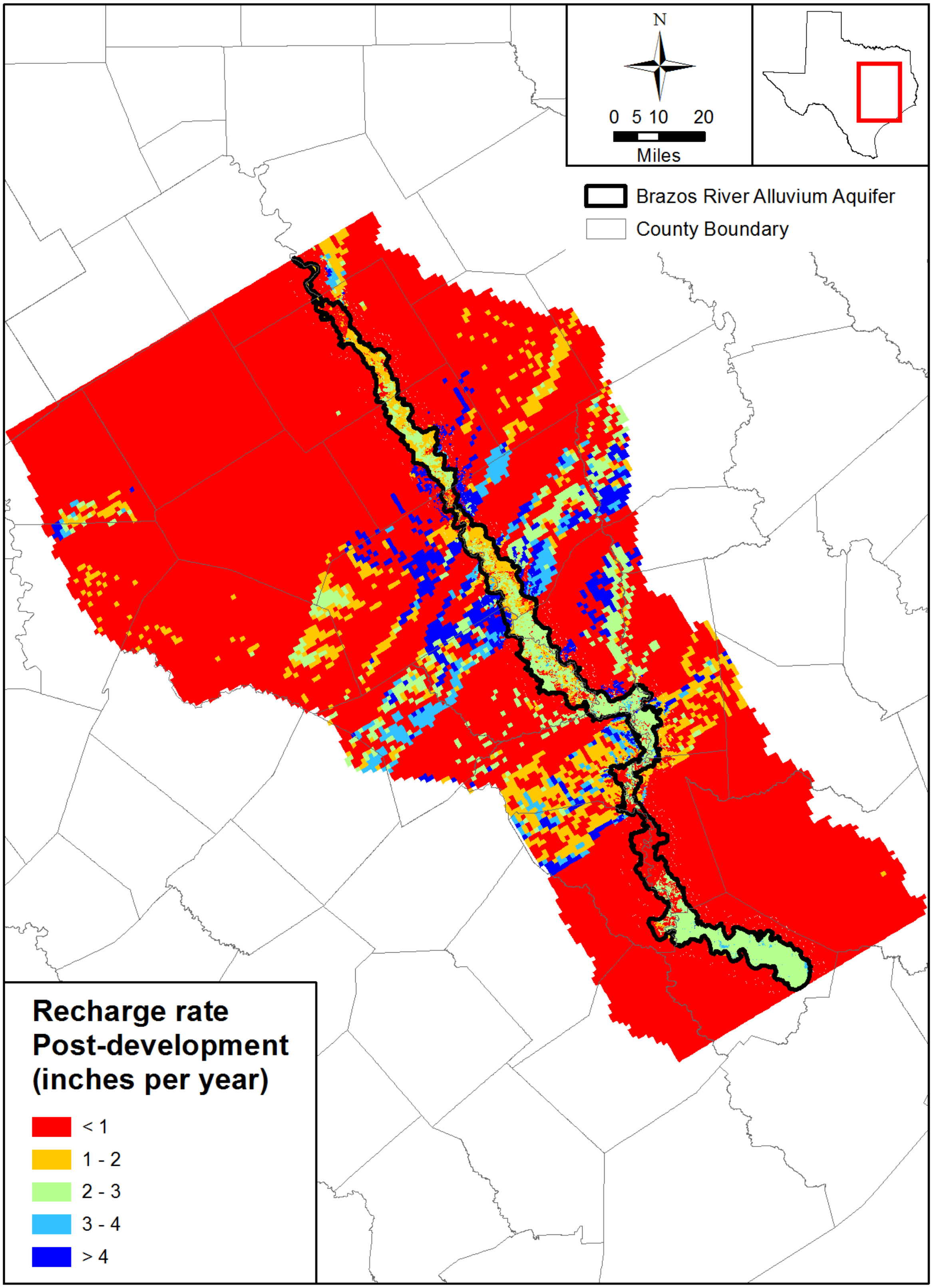

Figure 2.6.2 **Average post-development recharge rate.**

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2.7 Streamflow-Routing Package

The MODFLOW Streamflow-Routing (suffix SFR) package was used to simulate the interaction of the Brazos River Alluvium Aquifer with perennial streams. In addition, the Streamflow-Routing package was used to simulate perennial streams occurring in the outcrops of the underlying formations within the Brazos River Basin. The locations of these stream cells are shown in Figure 2.1.4. Several perennial streams in the outcrops of the underlying formations but outside of the Brazos River Basin were simulated using the River package (Section 2.8) because streamflow routing was not considered necessary in these streams.

2.7.1 Streams

Stream cells were selected based on the intersection of the model grid with the polyline feature class representing streams from Ewing and others (2016). The Streamflow-Routing package was used to represent perennial streams which were defined here as streams with a Strahler Order of four or greater, while the River package (Section 2.8) was used to represent ephemeral streams defined as those with a Strahler Order less than four. Stream cells were placed only in outcrop cells. The Streamflow-Routing package includes several options for calculating streamflow, stream stage and streambed conductance.

For this model, the streamflow was routed by the model in between stream gages. The streamflow was input based on a combination of stream gage data (United States Geologic Survey, 2015) and output from the United States Army Corps of Engineers RiverWare model of the Brazos River Basin (see Section 3.2 of Ewing and others, 2016). When stream gage data existed, it was preferentially used to specify streamflow and, in the numerous gaps in the stream gage data, the RiverWare model was used to specify streamflow. Synthetic gages from the RiverWare model were also included in locations where no gage existed to better constrain the streamflow inputs. In this way, a comprehensive and rigorous accounting of streamflow in each of the perennial streams in the Brazos River Basin was accomplished in the model.

Daily streamflow was compiled for the entire transient period from 1950 through 2012. The stress period lengths in the model were either monthly or annual, depending on the time period, and the median of the daily values within each stress period was used as streamflow input to the model.

Based on these specified and routed stream flows and the streambed elevation, the Streamflow-Routing package then calculated stream stage in every stream cell using a rating curve that was input into the package. The rating curves were taken from the WaterWatch website (United States Geologic Survey, 2016). Where no rating curve was available for a given stream gage, the nearest gage with an available rating curve was used. The streambed elevation in each stream cell was set based on the minimum land surface elevation along the polyline feature class in the grid cell, determined from the 10-meter digital elevation model. The stream bottom was further constrained such that the height between the stream bottom and the model cell bottom was a minimum of 1 foot. The 1-foot minimum was used to improve model stability with respect to cells drying out.

The streambed conductance was calculated for each stream cell during the simulation by the Streamflow-Routing package based on the streambed hydraulic conductivity, the length of the stream reach in that stream cell, and the streambed width. An initial streambed hydraulic conductivity of 0.1 feet per day was used and then adjusted during calibration. Figure 2.7.1 depicts the calibrated streambed hydraulic conductivities of the stream cells. The stream reach lengths were specified for each stream cell based on the length of the stream polyline intersecting the cell. In this way, a cell with only a small corner intersected by the polyline feature would have a lower conductance than a cell where the polyline runs diagonally from corner to corner, because the smaller intersection indicates that the cell represents less stream length and therefore should have less interaction with the aquifer. The stream widths were specified for each stream segment based on Strahler Order and were not adjusted during calibration. As shown in Figure 2.7.2, the stream widths ranged between 67 feet (Strahler Order 4) and 300 feet (Strahler Order 7).

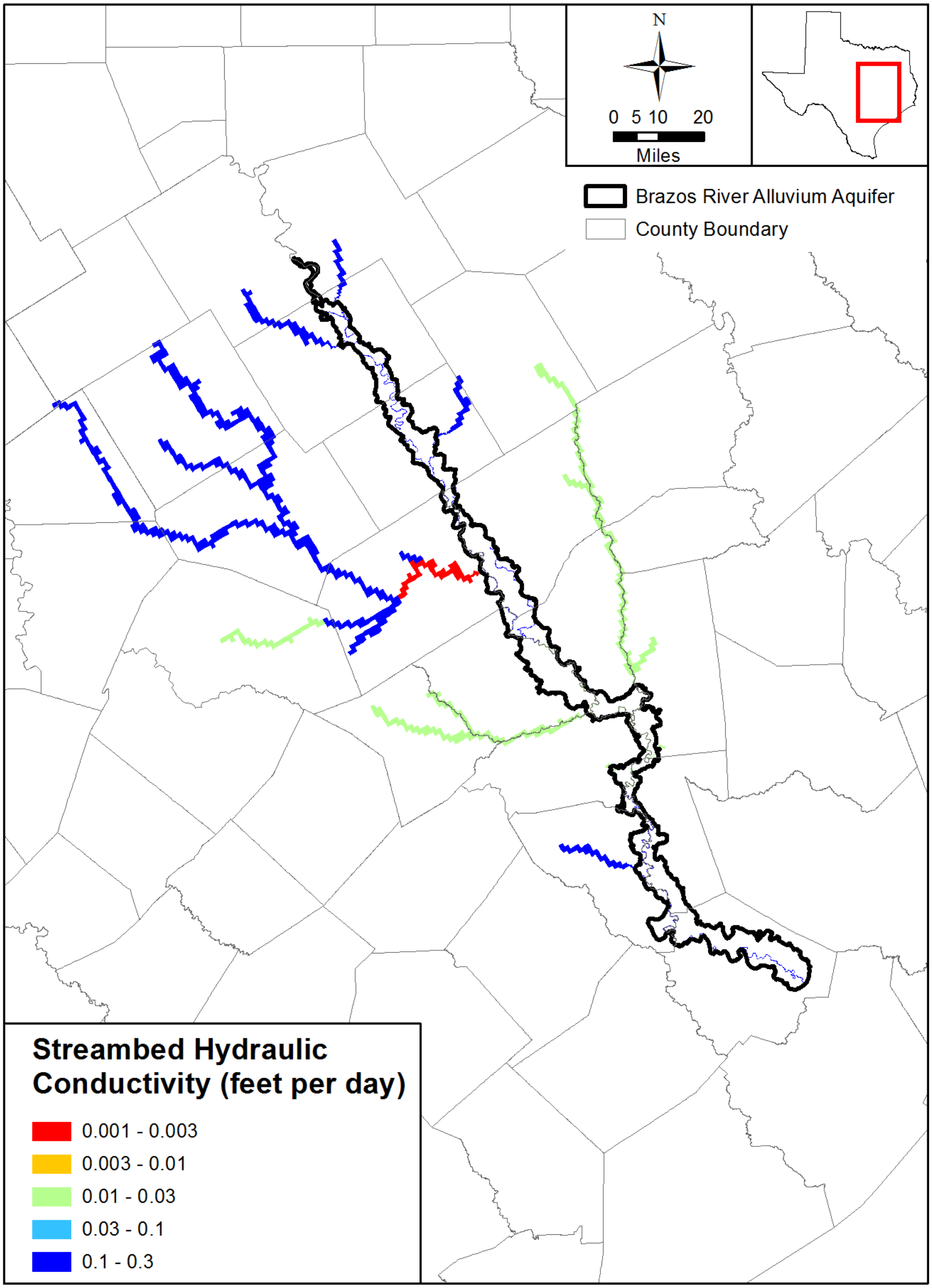

Figure 2.7.1 Perennial streambed hydraulic conductivities.

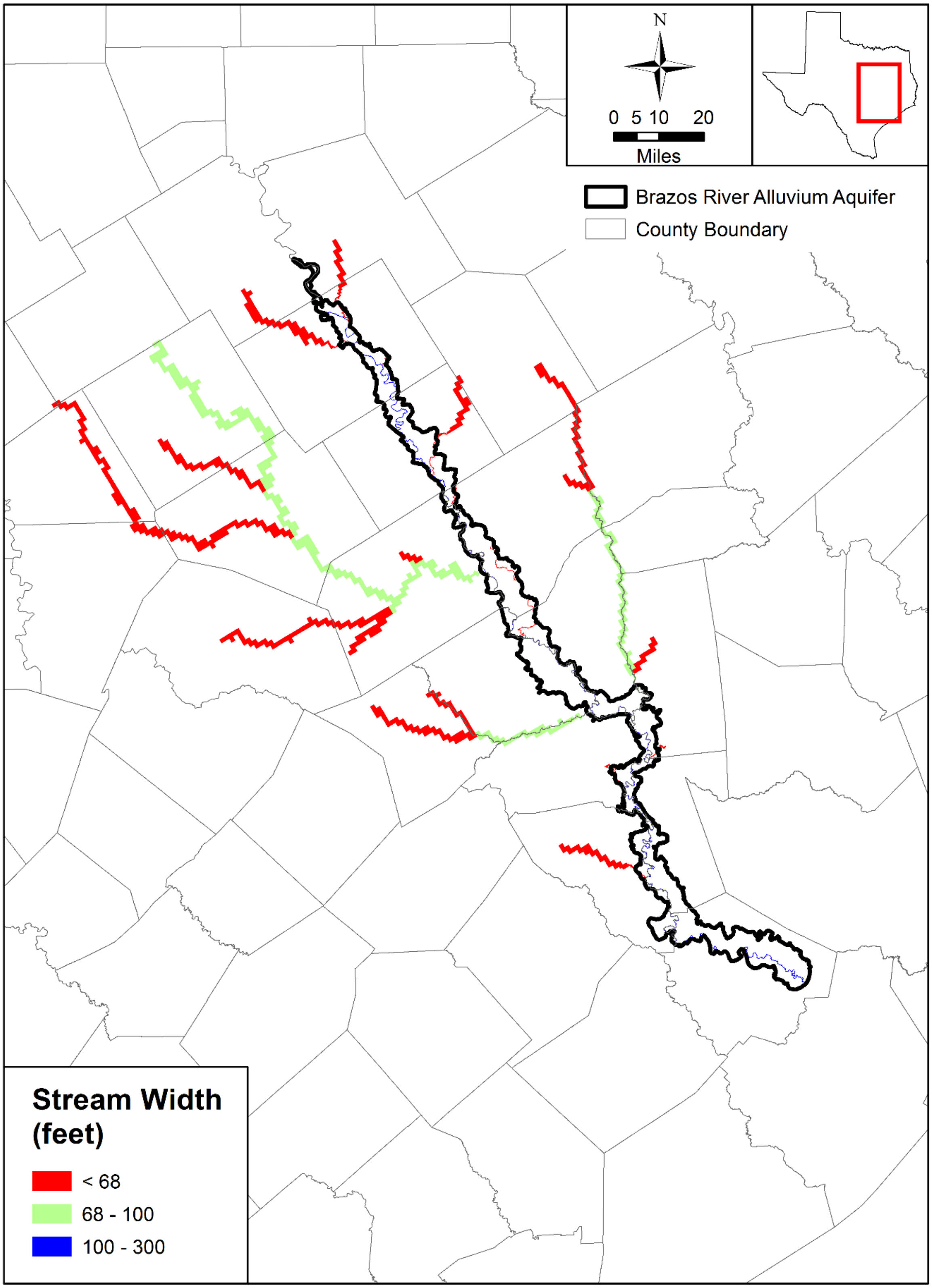

Figure 2.7.2 Perennial stream widths.

2.8 River Package

The MODFLOW River package was used to simulate ephemeral streams. The model cells described by the River package are depicted in Figure 2.1.4. The river stage was placed coincident with the river bottom so that the River package would behave identically to the MODFLOW Drain package. Specifically, when the simulated head in a river cell was greater than the river stage, the river cell would act as a head-dependent outflow boundary condition and, when the simulated head in a river cell was less than or equal to the river stage, no inflow or outflow would occur to the boundary condition. This is considered appropriate for ephemeral streams whereby recharge (as discussed in Section 2.6) would be the only source of inflow in river cells when the simulated head was less than or equal to the bottom of the river. In this way, it is easier to differentiate simulated flows between ephemeral streams (River package) and springs (Drain package) even though both types of boundary conditions behave identically as implemented in the model.

The conductance for each river cell was scaled by the length of the polyline feature that intersected the cell. For example, a cell with only a small corner intersected by the polyline feature would have a lower conductance than a cell where the polyline runs diagonally from corner to corner, because the smaller intersection indicates that the cell represents less river length and therefore should have less interaction with the aquifer. The initial riverbed conductance was set based on a hydraulic conductivity of 0.1 feet per day multiplied by the intersecting length and an assumed width of 50 feet. The overall conductance was adjusted during calibration. Figure 2.8.1 depicts the calibrated conductances of the river cells.

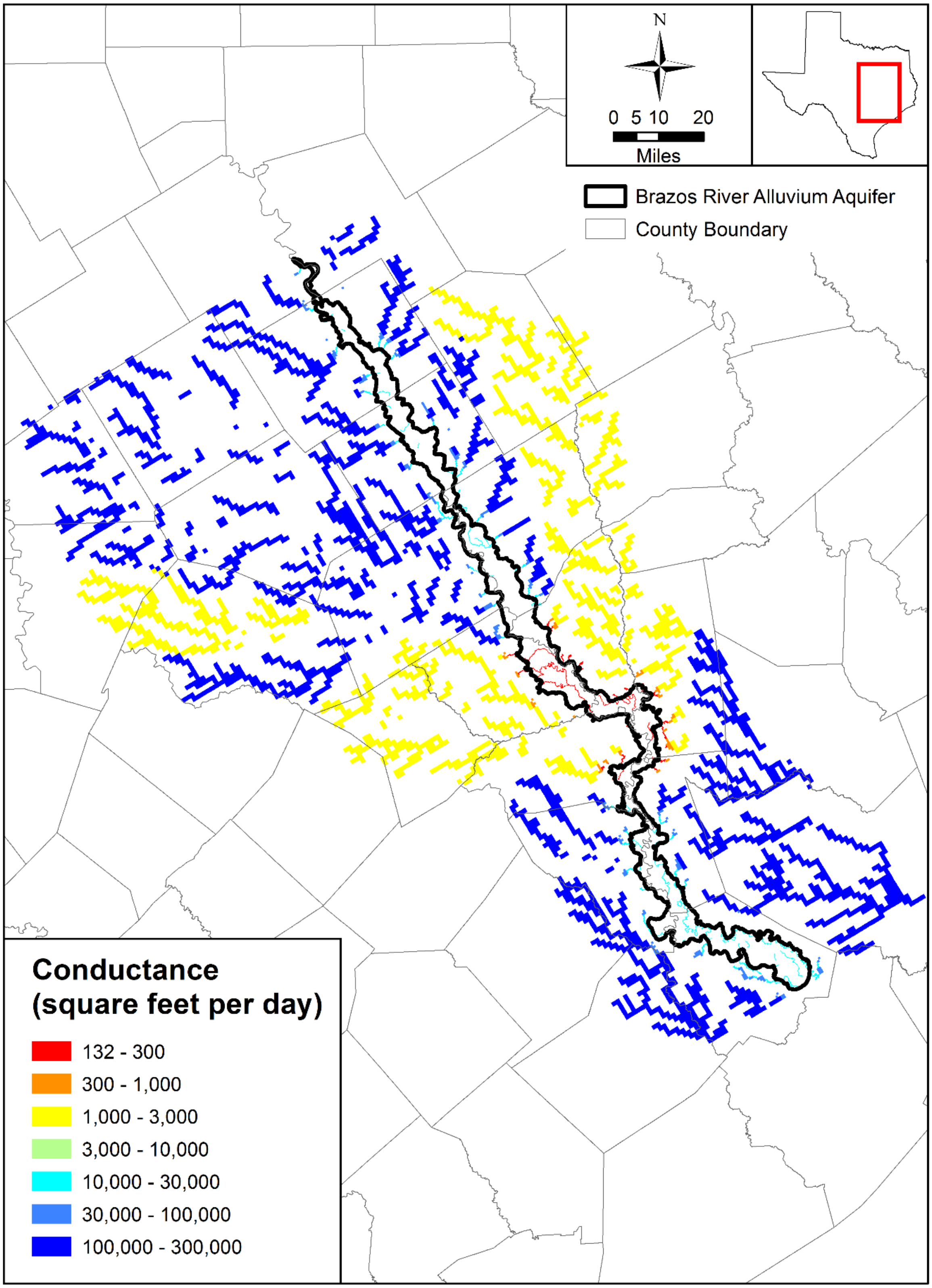

Figure 2.8.1 **River cell conductances.**

2.9 Evapotranspiration Package

The MODFLOW Evapotranspiration (suffix EVT) package was used to simulate groundwater evapotranspiration from the model. Note the distinction between overall evapotranspiration, which may occur either in the vadose or saturated zone, and groundwater evapotranspiration, the portion that occurs in the saturated zone. Groundwater evapotranspiration occurs primarily in riparian areas. To simulate evapotranspiration that may occur in riparian areas, evapotranspiration cells were added adjacent to cells representing perennial streams (Section 2.7). The locations of evapotranspiration cells are depicted in Figure 2.1.4.

The Evapotranspiration package as implemented required specification of the elevation of the evapotranspiration surface, the maximum evapotranspiration rate, and the extinction depth. If the elevation of the water table exceeds the elevation of the evapotranspiration surface, evapotranspiration occurs at the maximum rate. As the water table drops below the elevation of the evapotranspiration surface, the rate decreases linearly until the extinction depth is reached, at which point the rate is zero.

The evapotranspiration surface was set to the average ground surface elevation in a model grid cell, which is coincident with the top of the uppermost active model layer. The maximum evapotranspiration rate in the model was based on the coverage provided in the TWDB study by Scanlon and others (2005). The maximum evapotranspiration rate in a given model cell was area-weighted based on the various vegetation types in that cell as shown in Figure 2.1.14 of the Conceptual Model Report for the Brazos River Alluvium Aquifer (Ewing and others, 2016). The maximum evapotranspiration rates are depicted in Figure 2.9.1. The extinction depth varies between 0.01 feet and 10 feet, which corresponds to the area-weighted average rooting depth for the various vegetation types in a given model cell. The rooting depths are depicted in Figure 2.9.2.

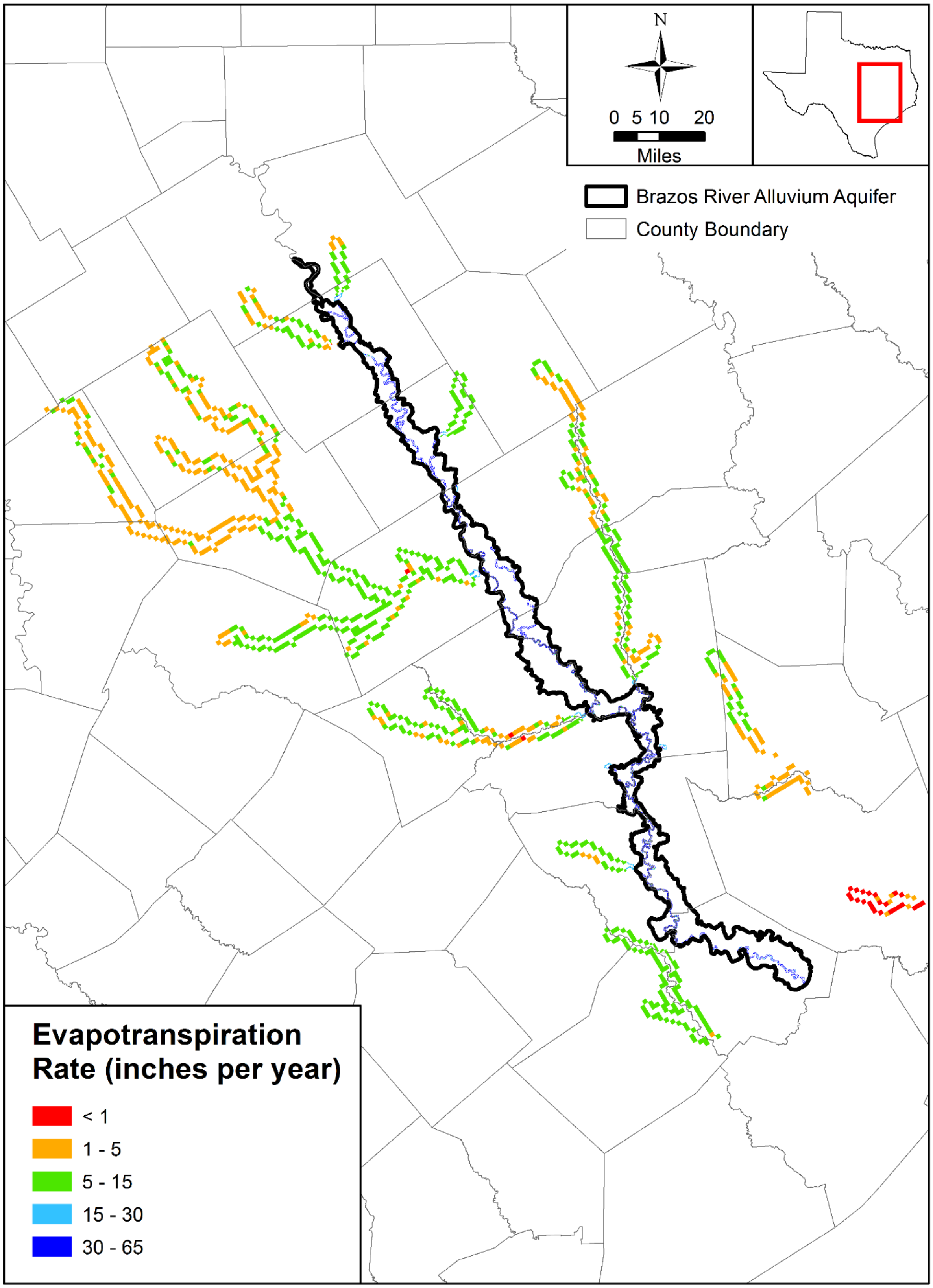

Figure 2.9.1 Maximum evapotranspiration rates.

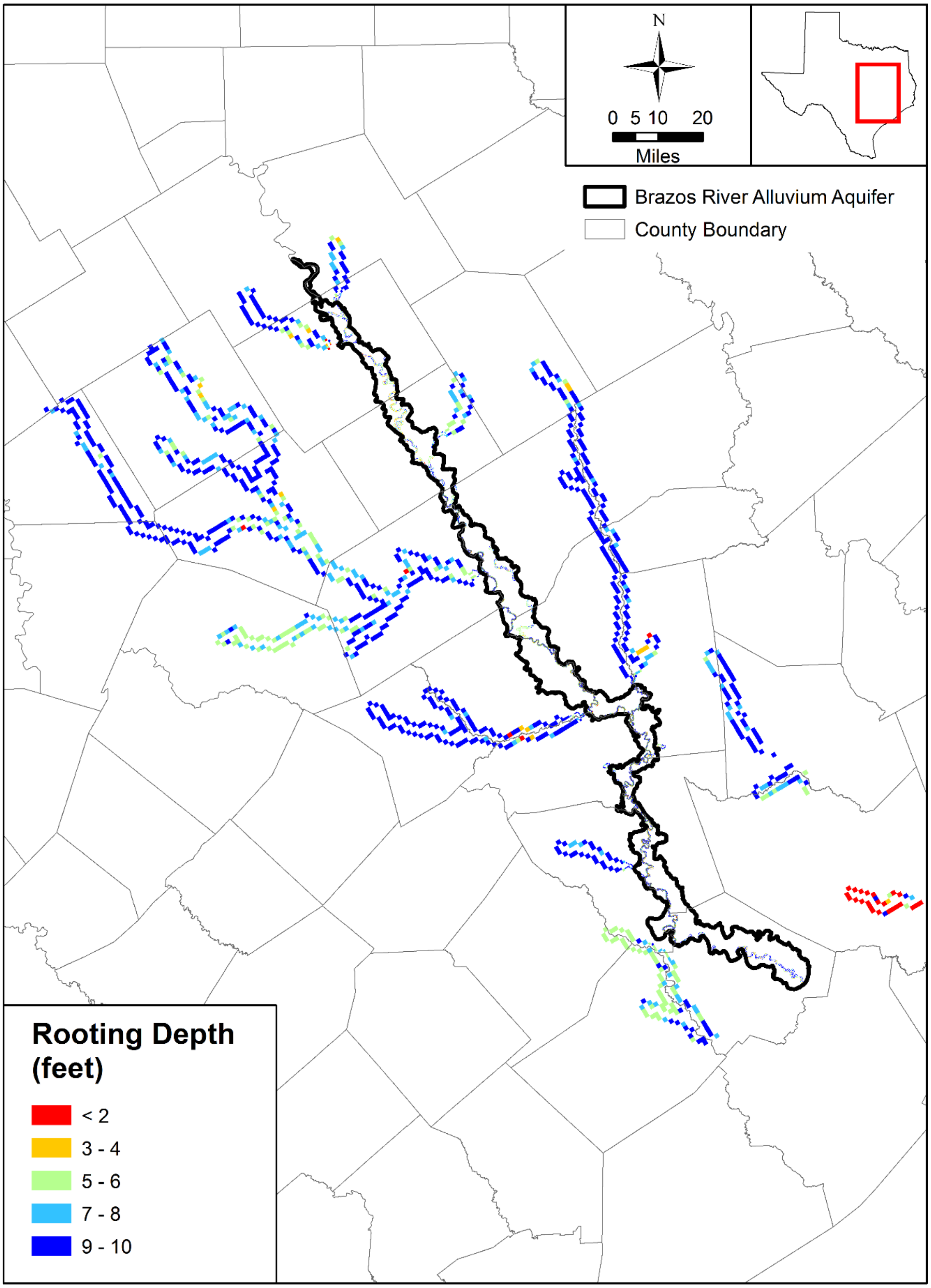

Figure 2.9.2 Evapotranspiration rooting depths.

2.10 Output Control File

The MODFLOW Output Control file specifies when, during the simulation, water level and water budget information are saved to disk. The Output Control file was set up to save these results at the end of each stress period (that is, at the end of the pre-development period, annually between 1950 and 1979, and monthly between January, 1980 and December, 2012).

2.11 Solver

The MODFLOW-USG Sparse Matrix Solver parameters are entered in the SMS file. The head closure criteria was set to 0.01 feet. The Newton-Raphson linearization method with Delta-Bar-Delta under-relaxation was used and this provided convergence stability with respect to rewetting cells. The χMD solver was used for the matrix solution. In general, the solver parameter values suggested in the MODFLOW-USG manual were used.

2.12 Ghost Node Correction

In a quadtree grid, the line connecting two nodes is not always perpendicular to, and coincident with, the midpoint of the shared face. For these cases, the control volume finite difference formulation represents a lower order approximation than that for a regular grid. This can result in errors in simulated heads and flows. However, MODFLOW-USG includes an optional Ghost Node Correction package to correct these errors. A Ghost Node Correction package was developed specifically for the quadtree grid used in this model and included in the MODFLOW name file to take advantage of this correction to the control volume finite difference formulation.

3.0 Model Calibration and Results

Once a model has been designed and constructed, it is usually calibrated to match observed characteristics of the aquifer. Typically these calibration targets consist of observed water levels in wells, but can also include discharge to surface water or other processes. The calibration process involves adjusting the hydraulic properties and flux boundaries of the model, within pre-defined constraints, in order that simulated output metrics better match observed metrics. This section describes that process of calibration, and presents the simulated results in terms of heads and fluxes. In addition, the simulated water budgets, which account for all of the water flowing in and out of an aquifer, are presented.

3.1 Calibration Procedure

3.1.1 Targets

The steady-state model represents the condition prior to significant development of the aquifer system, which was considered to be prior to 1950. Selection of water-level measurements representative of predevelopment conditions is a challenge for most groundwater modeling studies and was discussed in Section 4.2 of the conceptual model (Ewing and others, 2016). There were 30 steady-state targets for the Brazos River Alluvium Aquifer and 311 steady-state targets for the underlying formations. These totals are in contrast to the 1,178 well locations and 5,078 measurements in the transient target dataset for the Brazos River Alluvium Aquifer. However, because the steady-state simulation sets the starting heads for the transient simulation, early time transient targets have a strong influence on the steady-state calibration, which adds additional constraint to the steady-state calibration. The locations of the targets in the Brazos River Alluvium Aquifer and underlying formations are presented in Section 3.2.

Some estimates of stream gain/loss and spring flow were available from the conceptual model development. A re-analysis of the study by Turco and others (2007) of synoptic gains/losses along the main stem of the Brazos River was conducted as part of the conceptual model development (Ewing and others, 2016). In addition, long-term baseflow separation analyses of unregulated gages on streams in the Brazos River Basin were also conducted as part of the conceptual model development. Attempts to quantify shorter duration estimates of stream-aquifer interaction were also conducted during the development of the numerical model but were determined to be inconclusive either because of the relatively high magnitude of errors associated with stream flow differentials or because of high uncertainty in short-duration baseflow separation analyses. Because many of these measurements were over very short time periods (the stream gain/loss estimates were from synoptic studies of 1 or 2 days and spring flow observations consisted of a single measurement) or had considerable uncertainty associated with them, they were not considered to be quantitative targets for transient calibration, but rather qualitative indicators of the presence of recharge or discharge at surface locations. A total of twelve long-term estimates of baseflow and five observations of spring flow were used as quantitative targets during the calibration. The locations of the stream and spring targets are presented in Section 3.3.

3.1.2 Calibration Metrics

Traditional calibration measures (Anderson and Woessner, 1992), such as the mean error and the mean absolute error, quantify the average error in the calibration process. The mean error is the mean of the differences between measured hydraulic heads and simulated hydraulic heads:

$$\text{mean error} = \frac{1}{n}\sum_{i=1}^{n}\left(h_m - h_s\right)_i \tag{3.1.1}$$

where:

h_m = measured hydraulic head (feet above mean sea level)
h_s = simulated hydraulic head (feet above mean sea level)
n = number of calibration measurements

The mean absolute error is the mean of the absolute value of the differences between simulated hydraulic heads and measured hydraulic heads:

$$\text{mean absolute error} = \frac{1}{n}\sum_{i=1}^{n}\left|\left(h_m - h_s\right)_i\right| \tag{3.1.2}$$

The difference between a measured hydraulic head and a simulated hydraulic head is termed a residual.

The mean absolute error was used as the basic calibration metric for hydraulic heads. A typical calibration criterion for hydraulic heads is a mean absolute error that is less than or equal to 10 percent of the observed hydraulic head range in the aquifer being simulated.

The mean absolute error is useful for describing model error on an average basis but, as a single measure, does not provide insight into spatial trends in the distribution of residuals. Examination of the distribution of residuals is necessary to determine if they are randomly distributed over the model grid and not spatially biased. Post plots of hydraulic head residuals for both the steady-state and transient portions of the model were used to check for spatial bias. These plots indicate the magnitude and direction of the differences between observed and simulated hydraulic heads. Finally, crossplots of simulated versus observed hydraulic heads and residual versus observed hydraulic heads were used to determine if bias varies with the magnitude of the observed hydraulic heads.

3.1.3 Calibration of Hydraulic Properties

Section 2.4 includes a description of the pilot points and zones used when adjusting hydraulic properties during calibration. The parameter estimation software, PEST (Doherty, 2005), was used to assist in the calibration of hydraulic properties. A total of 105 parameters were used in the calibration of the model including 47 pilot point multipliers used in adjusting the Brazos River Alluvium Aquifer horizontal hydraulic conductivity. The initial value of every pilot point was 1.0, so if PEST did not adjust the pilot point value, then the resulting conductivity field near that pilot point would be identical to the initial conductivity field created during conceptual model development. On average the pilot point multipliers increased from 1.0 to 1.14. The maximum increase in a pilot point multiplier was 5.0 and was located in Falls County. Because the initial properties based on aquifer tests and specific capacity tests are likely biased to the more productive portions of the alluvium, the lower bound for pilot points was set to 0.001. The minimum pilot point value was 0.0075 and was located at the McLennan-Falls county line. Maps of the calibrated horizontal hydraulic conductivities of the Brazos River Alluvium Aquifer are shown in Figures 2.3.3 and 2.3.4.

The horizontal hydraulic conductivities of the underlying formations were specified and adjusted through the formation-wide values. The initial values for the underlying formations from the conceptual model were largely extracted from previous models which represent the deeper portions of these formations as well as the shallow portions pertinent to this model. The overall trend for adjustment of conductivities was one of increase from initial values, which is consistent with surficial sediments exhibiting less consolidation than the deeper portions of the same formations. Maps of the calibrated horizontal hydraulic conductivities of the underlying formations are shown in Figure 2.3.5.

The vertical hydraulic conductivities for the Brazos River Alluvium Aquifer and the underlying formations were based on vertical to horizontal anisotropy ratios, whereby the vertical hydraulic conductivity varied spatially as a function of the horizontal hydraulic conductivity. The vertical hydraulic conductivity of the Brazos River Alluvium Aquifer was not sensitive in calibration, since the vertical conductivities of the underlying units were all significantly lower. It should be noted that, within the construct of this numerical model, the vertical conductivity of the underlying formations is only a factor where those formations are directly beneath the Brazos River Alluvium Aquifer. Elsewhere, the underlying formations represent a single surficial layer without vertical numerical connection to any other hydrogeologic layer. Because the overall vertical conductance between two layers is typically calculated as a harmonic mean, the lower of the two values will tend to dominate the calculation. The initial assumption of a vertical to horizontal anisotropy ratio of 0.1 in the alluvium was not altered during calibration. For the underlying formations, a reasonable overall vertical to horizontal anisotropy ratio 0.001 was used because the vertical hydraulic conductivity of the underlying formations represents approximately 200 feet of stratified deposits and a greater resistance to flow. Maps of the calibrated vertical hydraulic conductivities are shown in Figures 2.3.6 through 2.3.8.

Changes in specific yield or storativity from initial estimates were not found to improve calibration results in any meaningful way, so the calibrated values are identical to the initial estimates. Both the specific yield and the storativity of the Brazos Valley Alluvium Aquifer and of the underlying formations remained at 0.15 and 0.01, respectively, through the calibration process. A comparison of the initial and final hydraulic conductivities and storage properties is given previously in Table 2.3.2.

3.1.4 Calibration of Recharge

Recharge to the Brazos River Alluvium Aquifer was altered by a single multiplier during calibration, however, the calibrated recharge was only three percent less than the initial rate. Recharge to the outcrops of the underlying formations was adjusted by the formation zones to account for the hydraulic conductivity of the different underlying formations. The mean steady-state recharge in the underlying formations decreased slightly from 0.85 inches per year to 0.82

inches per year during calibration. The calibrated recharge distribution generally shows decreases in recharge within the lower conductivity formations and increases in recharge to the underlying aquifers. The calibrated steady-state recharge was propagated through the transient period. In other words, the initial variation in recharge from steady-state to transient was maintained for the calibrated case. The steady-state and average transient recharge distributions were shown earlier in Figures 2.6.1 and 2.6.2, respectively. The model sensitivity to recharge was equally sensitive during the steady-state and transient stress periods.

3.1.5 Calibration of Head Boundary Conductances

The streambed hydraulic conductivity for perennial streams was adjusted by Strahler Order as part of the automated model calibration using PEST (Doherty, 2005). In other words a single streambed hydraulic conductivity value was used for all streams of a given Strahler Order. Initially, the simulated heads appeared to be biased low in the vicinity of the streams. The streambed hydraulic conductivities are directly proportional to the streambed conductances and were systematically reduced during calibration to better match observed hydraulic heads in the Brazos River Alluvium Aquifer and the underlying formations as well as the long-term stream gain/loss estimates identified as calibration targets. The calibrated streambed hydraulic conductivities were previously shown in Figure 2.7.1. The conductances of the Drain package which represents springs were adjusted manually following the automated calibration step to better match observed spring flows. Apart from the flow from individual springs, the model was largely insensitive to drain conductance. The streambed conductance of ephemeral streams was not altered during model calibration as the model and calibration targets were largely insensitive to that parameter.

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3.2 Model Simulated Versus Measured Heads

This section describes the results of the model calibration to observed heads, both spatially and temporally. The calibration will be discussed first in terms of summary statistics and crossplots, followed by a discussion of trends in head residuals, both distribution about the mean and spatial distribution. This will be followed by a presentation of simulated head surfaces, simulated drawdown, and change in saturated thickness, where appropriate.

3.2.1 Summary Statistics and Crossplots

Figures 3.2.1 and 3.2.2 show the steady-state hydraulic head target locations for the Brazos River Alluvium Aquifer and the underlying formations, respectively. The locations of the transient head targets for the Brazos River Alluvium Aquifer are shown in Figure 3.2.3. Hydrographs of wells in the outcrops of the underlying aquifers (Kelley and others, 2004; Deeds and others, 2010; and Kasmarek, 2013) indicate very little drawdown over the historical period. Accordingly, the steady-state targets are considered adequate to represent historical conditions and no transient targets were used for the calibration of the hydraulic properties in the underlying formations. Table 3.2.1 shows the head calibration statistics for the Brazos River Alluvium Aquifer and the underlying formations for the steady-state stress period (representing predevelopment), and two transient time ranges, 1950 to1979, and 1980 to 2012. The two transient periods have similar lengths (30 years versus 33 years), but have different magnitudes of samples, with the earlier period having more as the result of groundwater studies conducted in the 1960s and 1970s (Cronin and Wilson, 1967; Cronin and others, 1973). The summary statistics can be considered along with Figures 3.2.4 through 3.2.7, which show crossplots for both the Brazos Alluvium Aquifer and the underlying formations for the steady-state period (Figures 3.2.4 and 3.2.5) and for the Brazos River Alluvium Aquifer during the early transient period from 1950 through 1979 (Figure 3.2.6) and the last 33 years from 1980 to 2012 (Figure 3.2.7).

The Brazos River Alluvium Aquifer has a very small negative mean error of -0.05 feet in steady-state, indicating that the model simulates with very little bias on average compared to estimated water levels. The mean absolute error is less than 6.5 feet, which is very small given the uncertainty in the water level measurements. The relative error (mean absolute error divided by the range) is less than 3 percent, due to the large range compared to mean absolute error. This is comfortably lower than the industry standard relative error of 10 percent.

The shallow portions of the underlying formations have a relatively small mean error of 3.3 feet in steady-state, indicating that simulated heads were somewhat lower on average than measured heads. However, this mean error is within the acceptable range, especially considering the uncertainty in, and general lack of, steady-state targets for the shallow portions of these formations. The mean absolute error for the shallow portions of the underlying formations is less than 23 feet with a relative error less than 3 percent, which was considered an acceptable calibration for the underlying formations outside the Brazos River Alluvium Aquifer. The crossplot shown in Figure 3.2.5 shows very little bias in simulated heads, with an approximately equal number points falling above the line as below and good clustering around the 1:1 line.

The mean error for the Brazos River Alluvium Aquifer over the transient period from 1980 to 2012 is a very small value of 0.013 feet. The mean absolute error for this period is approximately 6.4 feet, with a relative error less than 2 percent, which is even smaller than that for the steady-state period, again indicating an acceptable calibration. The crossplots shown in Figures 3.2.6 and 3.2.7 show good clustering around the 1:1 line, with only a handful of points outside the main cluster.

3.2.2 Residual Distributions

Figures 3.2.8 through 3.2.11 show histograms of the head residuals for the steady-state period, the early transient calibration period from 1950 through 1979 and the late transient calibration period from 1980 through 2012. Perfectly normally distributed histograms will exhibit the classic symmetric bell shape centered on zero. Residual datasets with a nonzero mean error will be shifted away from zero by approximately the magnitude of the mean error. The head residual histograms behave as expected, showing good symmetry in most cases, and are shifted from zero the amount of the mean error. Figure 3.2.8, however, suffers from a small data population which does not allow good representation in a histogram.

Figures 3.2.12 and 3.2.13 show spatial plots of residuals for the steady-state calibration period for the Brazos River Alluvium Aquifer and the underlying formations, respectively. As noted previously, negative residuals indicate that the model is simulating high compared to estimated steady-state water levels, while positive residuals indicate that the model is simulating low in comparison. The figures show that residuals are distributed with very little apparent spatial bias. In other words, there is a good mix of positive and negative residuals distributed throughout the aquifer, and no obvious trends from north to south. Figures 3.2.14 and 3.2.15 show the mean residuals in the Brazos River Alluvium Aquifer for the periods from 1950 through 1979 and 1980 through 2012, respectively. Again, the figures show that residuals are distributed with very little apparent spatial bias.

3.2.3 Simulated Water Levels

In this section the model simulated water levels, hydrographs, and drawdown from steady-state are presented. Figures 3.2.16 through 3.2.20 show the simulated head contours for the steady-state stress period, 1960, July, 1980, and July, 2012. The overall trend in heads for all periods is from the northwest to the southeast following regional topographic trends. In some areas, the contours show an additional gradient toward the main stem of the Brazos River.

Select hydrographs of simulated versus observed hydraulic head, including each county intersected by the Brazos River Alluvium Aquifer and giving preference to wells with the most observed measurements of hydraulic head, are shown in Figures 3.2.21 through 3.2.23. All of the hydrographs indicate a generally good agreement between simulated and observed hydraulic head throughout the entirety of the historical record. Wells nearest to the Brazos River show the greatest degree of variability in hydraulic head. Both the simulated and observed hydraulic heads are seen to decrease in recent years in Brazos, Burleson and Robertson counties. This is likely a result of increases in production in these counties.

Maps of the simulated drawdown from steady-state conditions in the Brazos River Alluvium Aquifer in 1979 and December, 2012 are shown in Figures 3.2.24 and 3.2.25, respectively. The figures indicate that simulated drawdown has generally increased from pre-development and that even greater increases in drawdown are simulated for the most recent years. A region of high simulated drawdown at the end of the transient period in December, 2012 can be observed in Milam, Robertson, Burleson and Brazos counties along with a smaller region of high simulated drawdown in Fort Bend County.

3.2.4 Dry and Flooded Cells

MODFLOW-USG, when using the Newton option, does not allow cells to go dry, but does allow heads to drop below cell bottom (and then restricts hydraulic conductivity so the cell becomes minimally active), which will be called "dry" for the purposes of this discussion. Cells where the simulated head is above the top of the cell are typically called "flooded" cells. Dry cells were monitored closely during model construction and calibration.

Large variation in local topography increases the chances of flooded cells. A small amount of flooding, within the mean absolute error of the model, is considered normal, but a model should not have large areas with heads consistently far above land surface. For the most part, the boundary conditions representing streams and springs controlled flooding.

The calibrated model was assessed for dry cells and flooding in the model outcrops. This included the active outcrops for the formations underlying the Brazos River Alluvium Aquifer. The tolerance for flooding was set at 6.5 feet for the Brazos River Alluvium Aquifer and 23 feet for the underlying formations, the approximate mean absolute error for each formation in the steady-state period. The maximum flood value for the steady-state heads was 13.5 feet above tolerance for the Brazos River Alluvium Aquifer and 39.4 feet above tolerance for the underlying formations. Less than 1 percent of cells were flooded during steady-state or at the end of the simulation in 2012. During steady-state and at the end of the simulation in 2012, there were no dry cells in either the Brazos River Alluvium Aquifer or the underlying formations. The flooded cells and lack of dry cells are shown in Figures 3.2.26 and 3.2.27 for the steady-state period and the end of the transient period, respectively.

Table 3.2.1 Calibration statistics for steady-state, 1950 through 1979, and 1980 through 2012.

Year Range	Aquifer	Mean Error (feet)	Mean Absolute Error (feet)	Range (feet)	Mean Absolute Error/Range	Number
Predevelopment	Brazos River Alluvium	-0.05	6.5	251	0.026	30
	Underlying Formations	3.3	23.0	858	0.027	311
1950-1979	Brazos River Alluvium	-2.4	5.9	425	0.014	3,732
1980-2012	Brazos River Alluvium	0.042	6.4	371	0.017	1,346

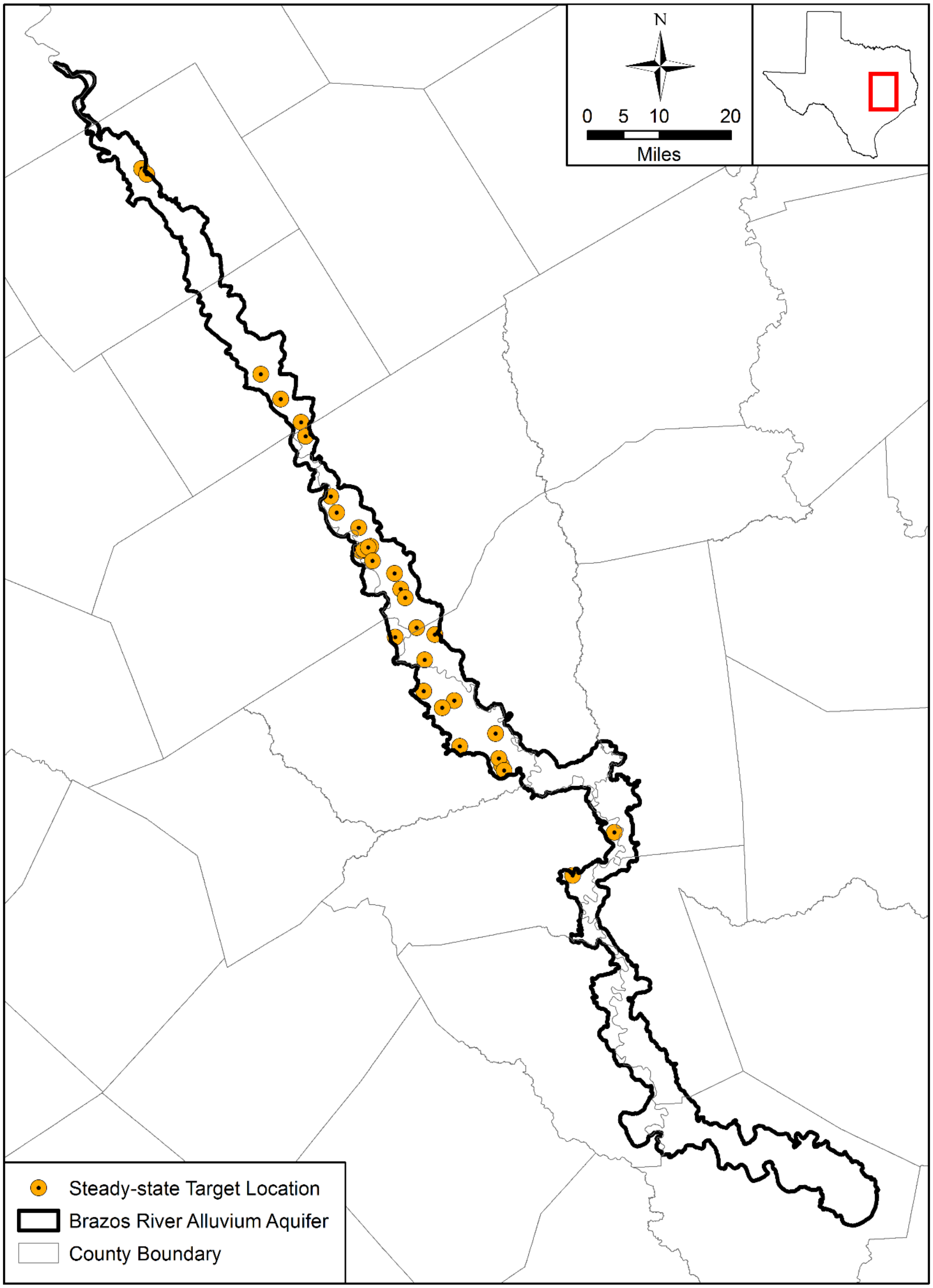

Figure 3.2.1 Locations of hydraulic head targets in the Brazos River Alluvium Aquifer for the steady-state stress period.

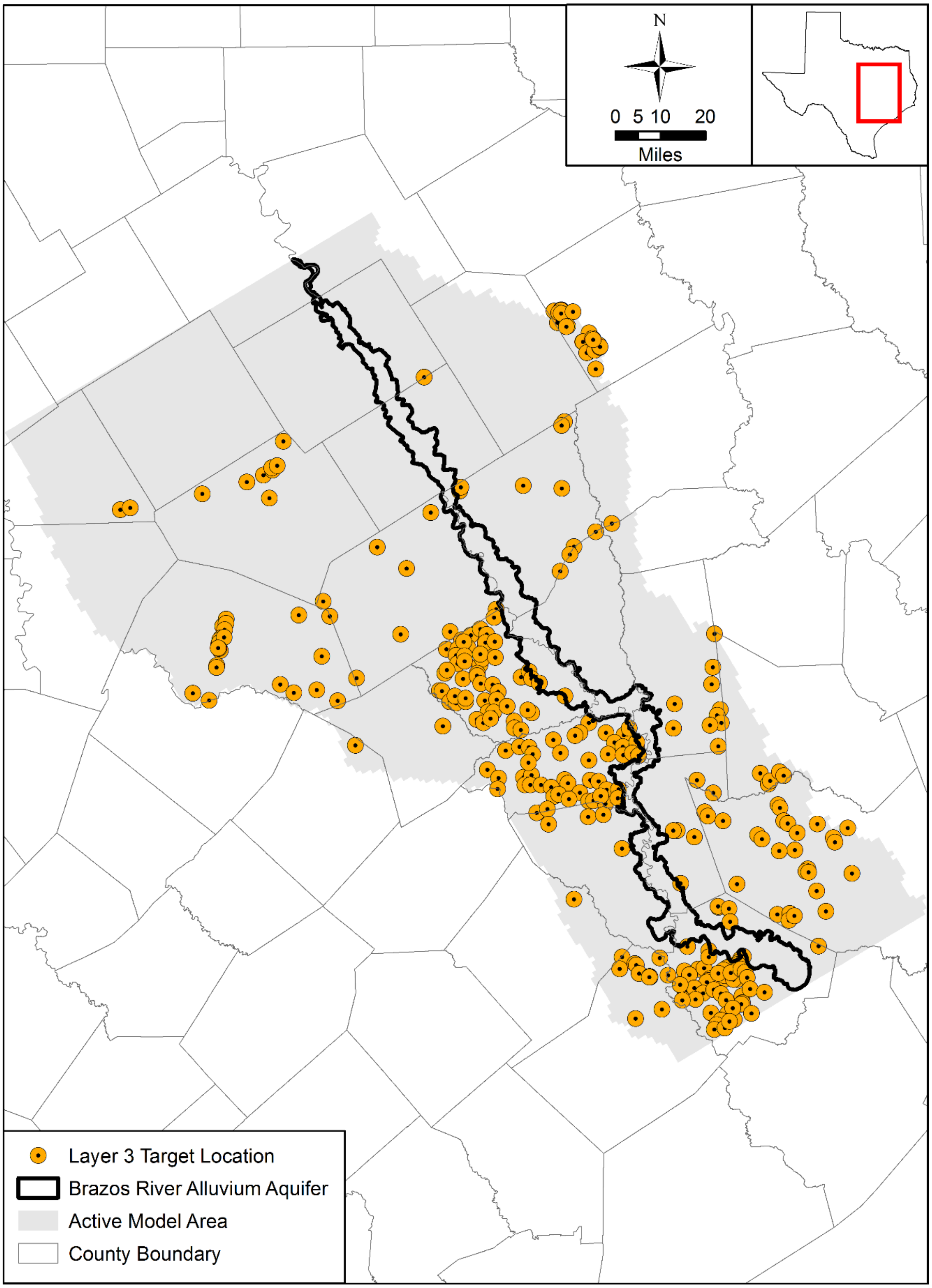

Figure 3.2.2 **Locations of hydraulic head targets in the underlying formations for the steady-state stress period.**

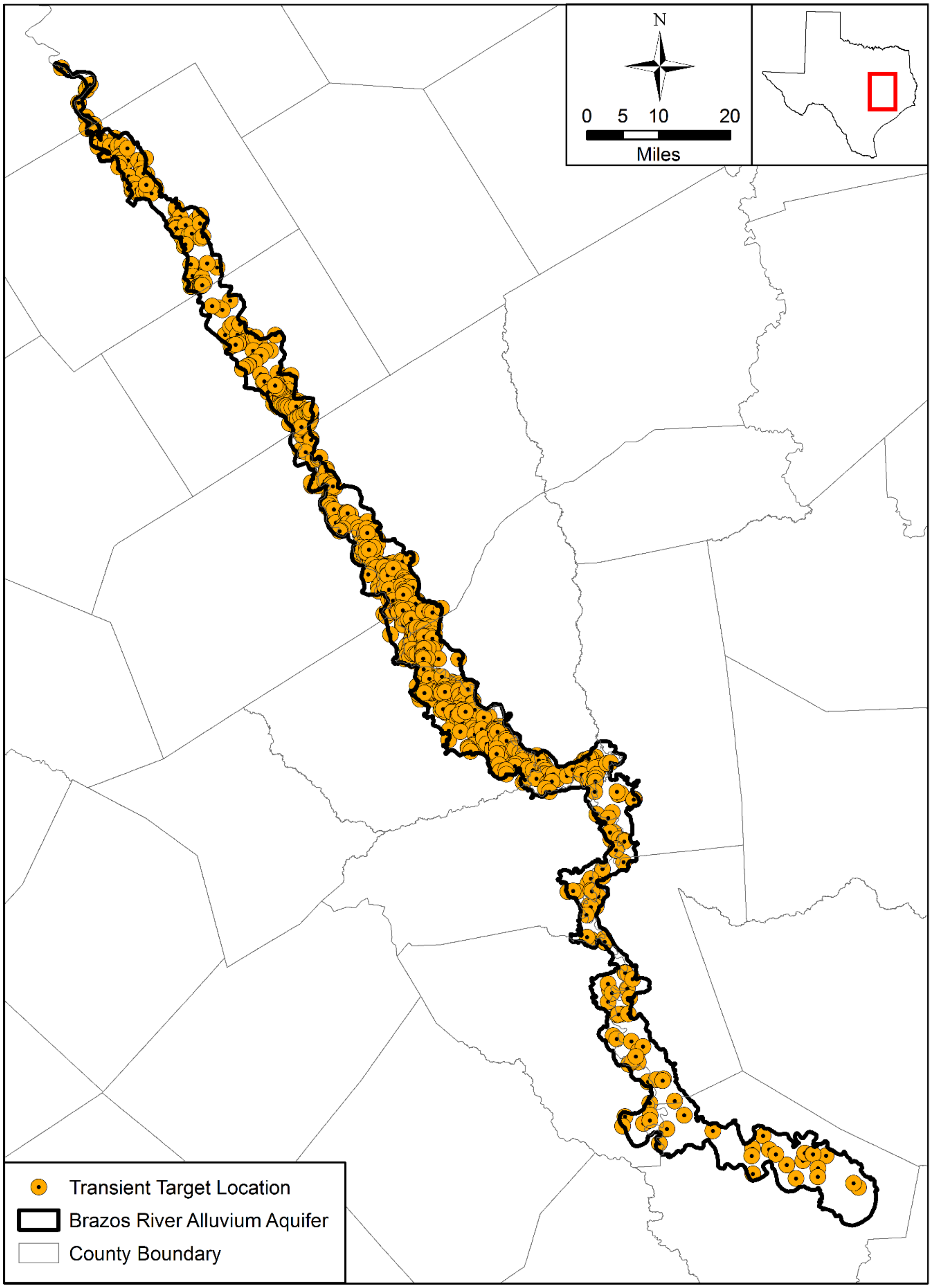

Figure 3.2.3 **Locations of hydraulic head targets in the Brazos River Alluvium Aquifer for the transient period.**

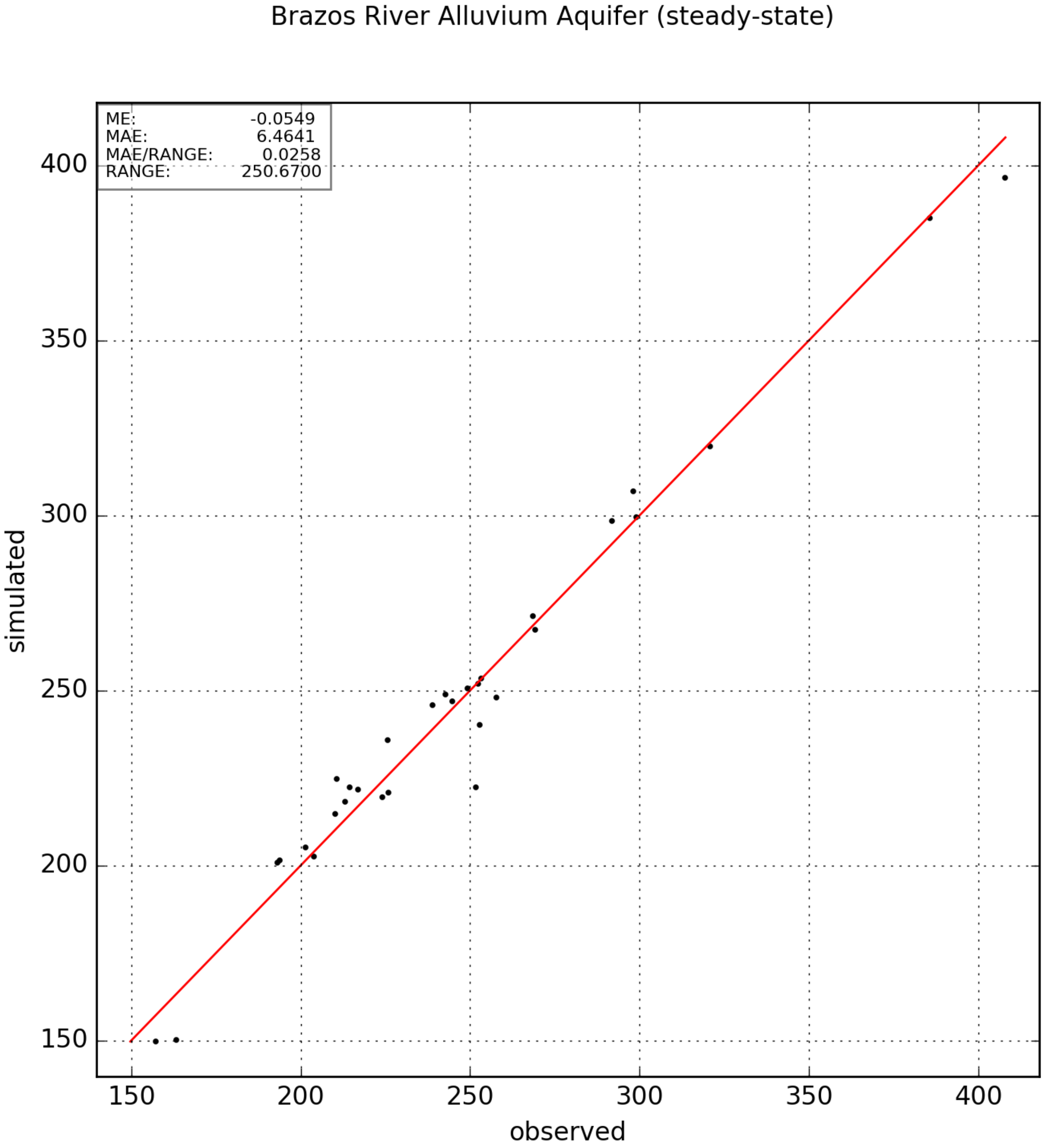

Figure 3.2.4 **Scatter plot of simulated versus observed hydraulic head in the Brazos River Alluvium Aquifer in feet above mean sea level for the steady-state stress period.**

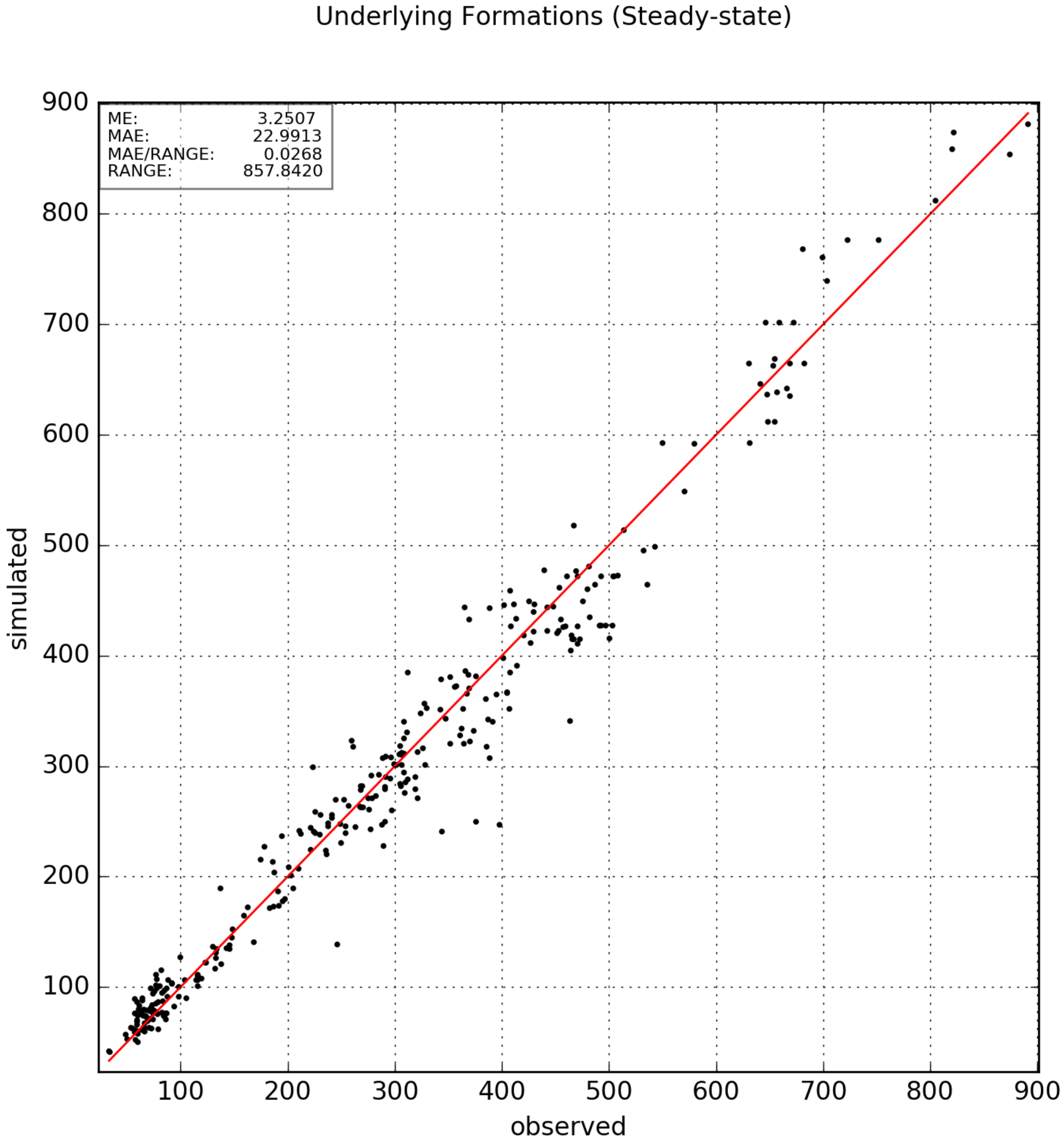

Figure 3.2.5 **Scatter plot of simulated versus observed hydraulic head in the underlying formations in feet above mean sea level for the steady-state stress period.**

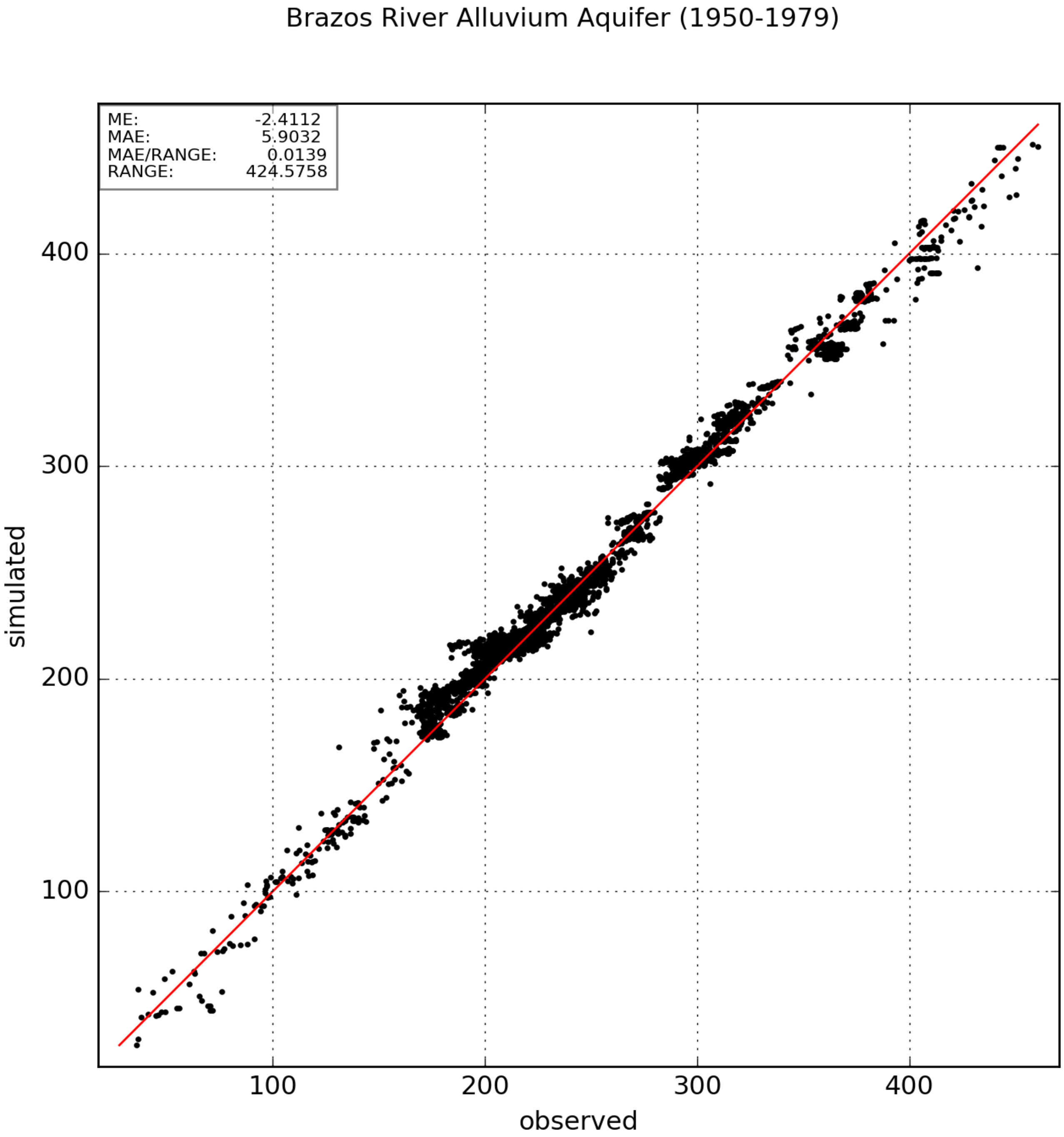

Figure 3.2.6 **Scatter plot of simulated versus observed hydraulic head in the Brazos River Alluvium Aquifer for the period from 1950 through 1979.**

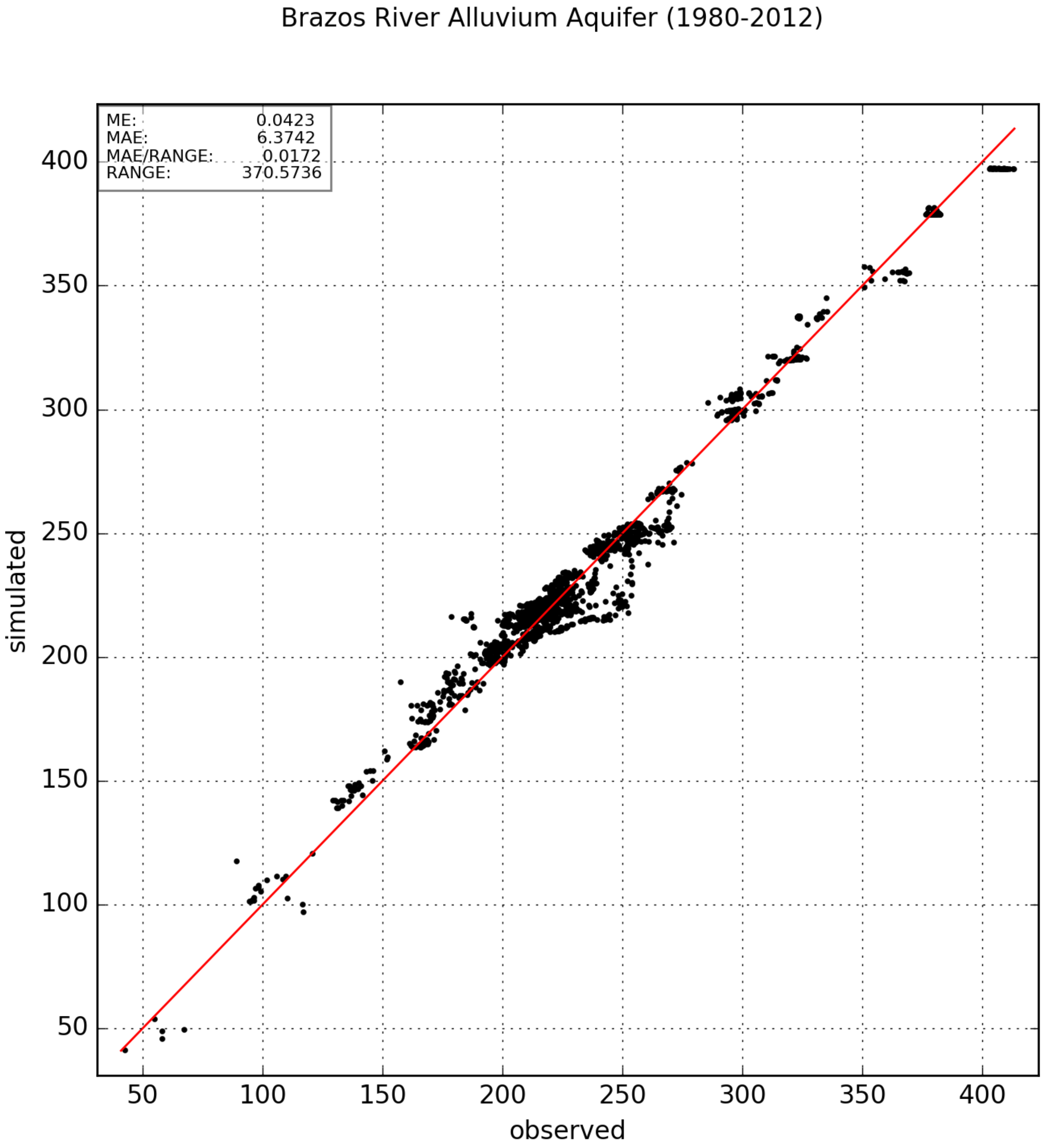

Figure 3.2.7 **Scatter plot of simulated versus observed hydraulic head in the Brazos River Alluvium Aquifer for the period from 1980 through 2012.**

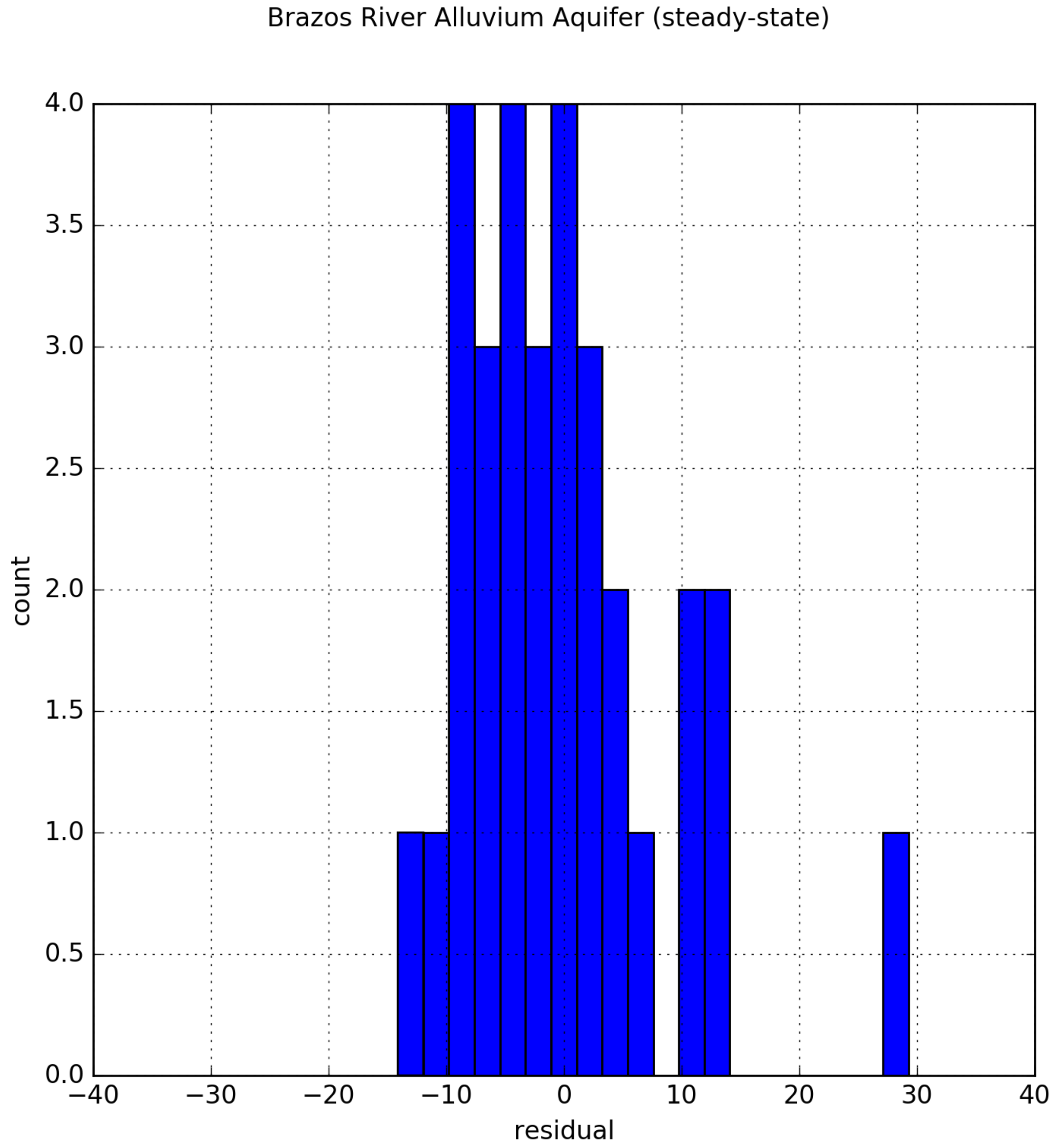

Figure 3.2.8 **Histogram of hydraulic head residuals in the Brazos River Alluvium Aquifer for the steady-state period.**

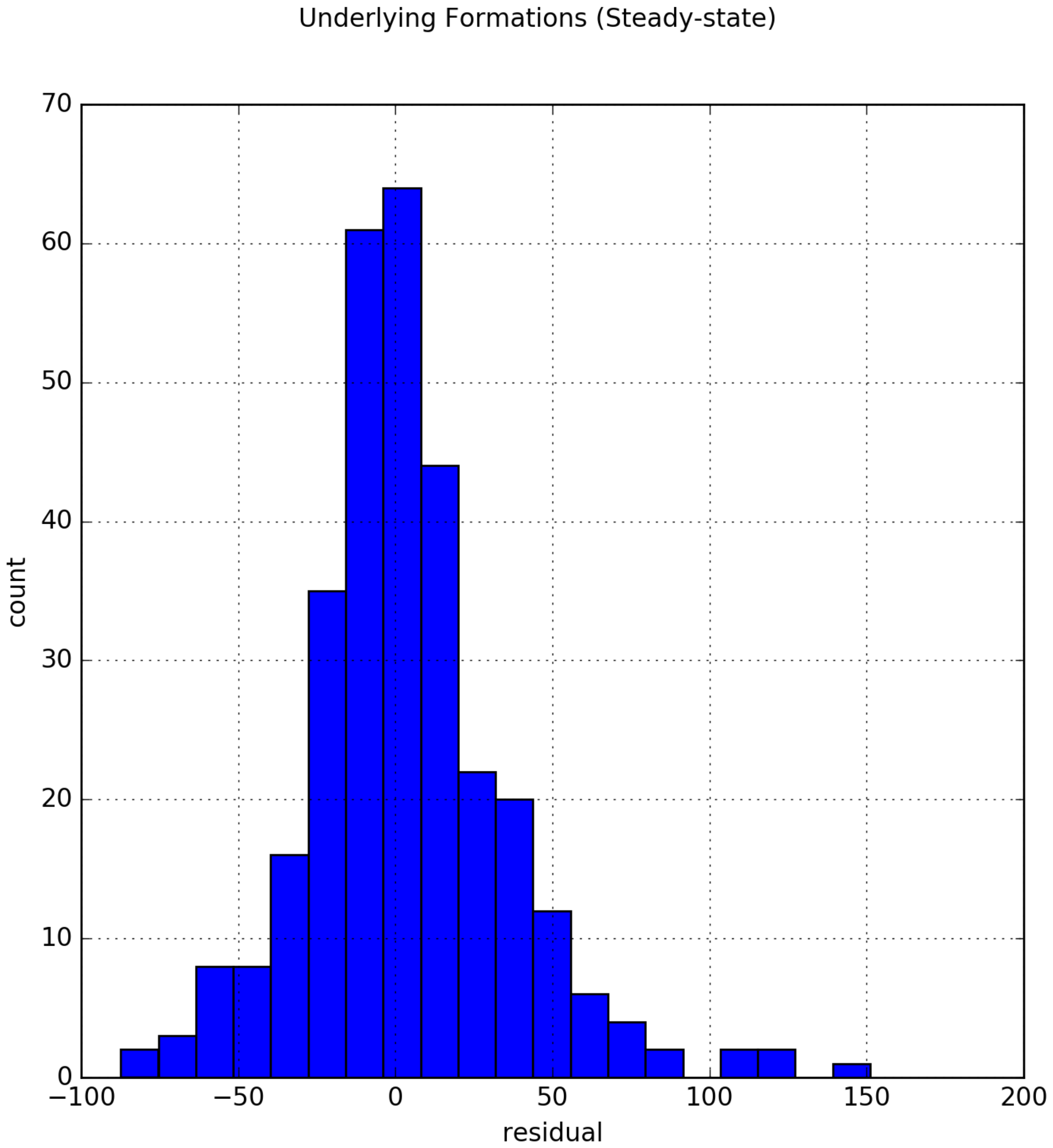

Figure 3.2.9 Histogram of hydraulic head residuals in feet in the underlying formations for the steady-state period.

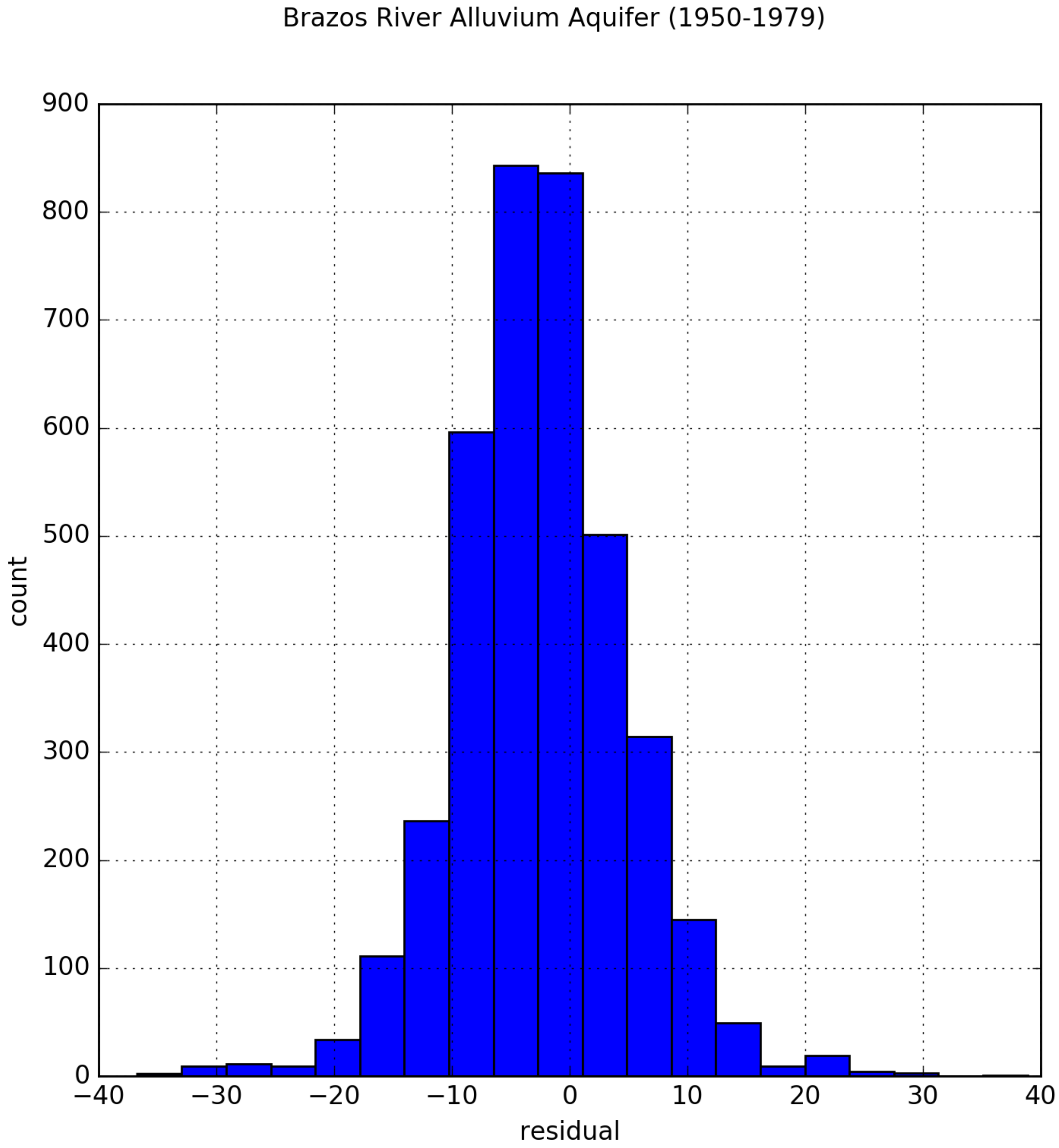

Figure 3.2.10 **Histogram of hydraulic head residuals in feet in the Brazos River Alluvium Aquifer for years 1950 through 1979.**

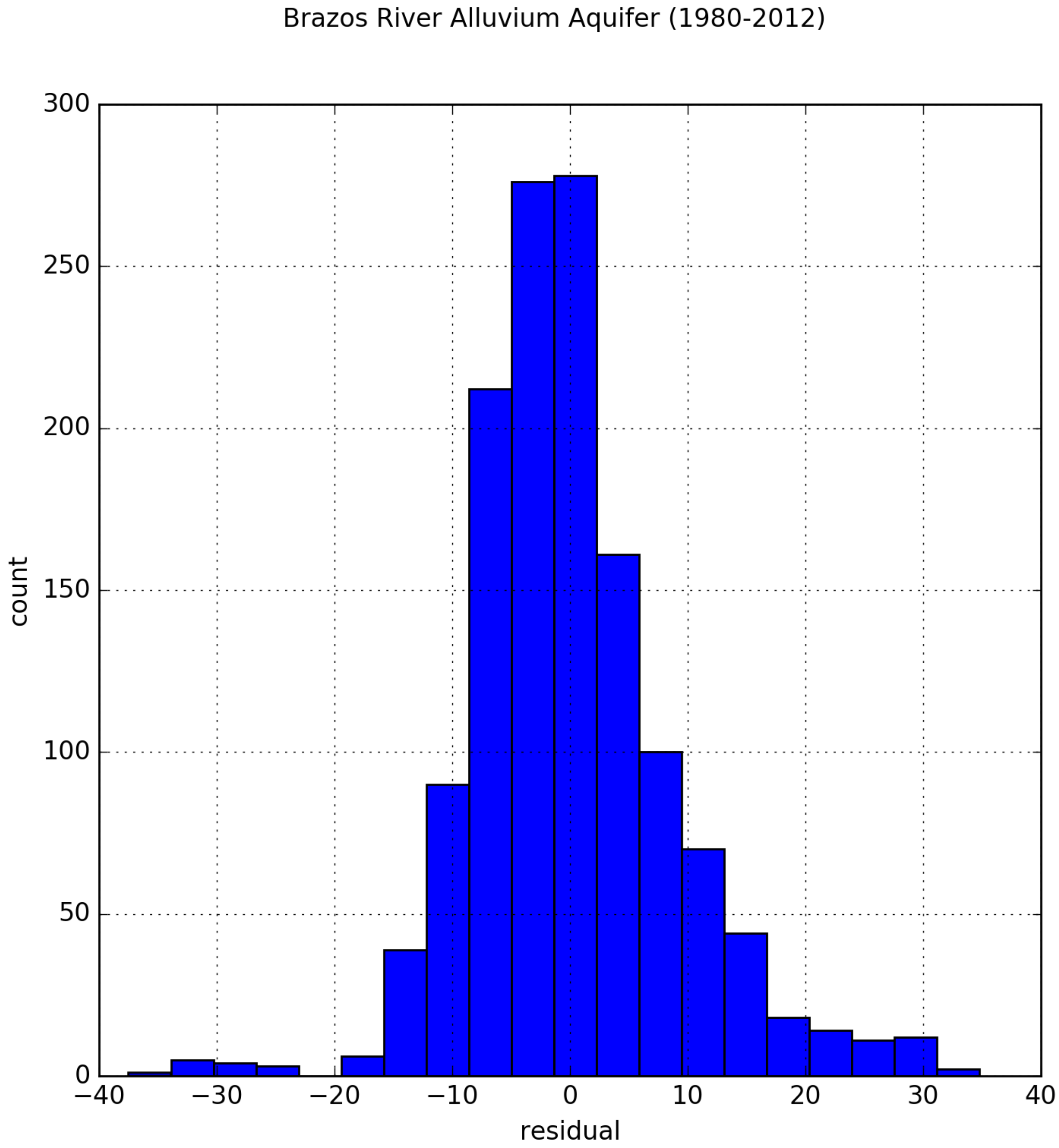

Figure 3.2.11 **Histogram of hydraulic head residuals in feet in the Brazos River Alluvium Aquifer for years 1980 through 2012.**

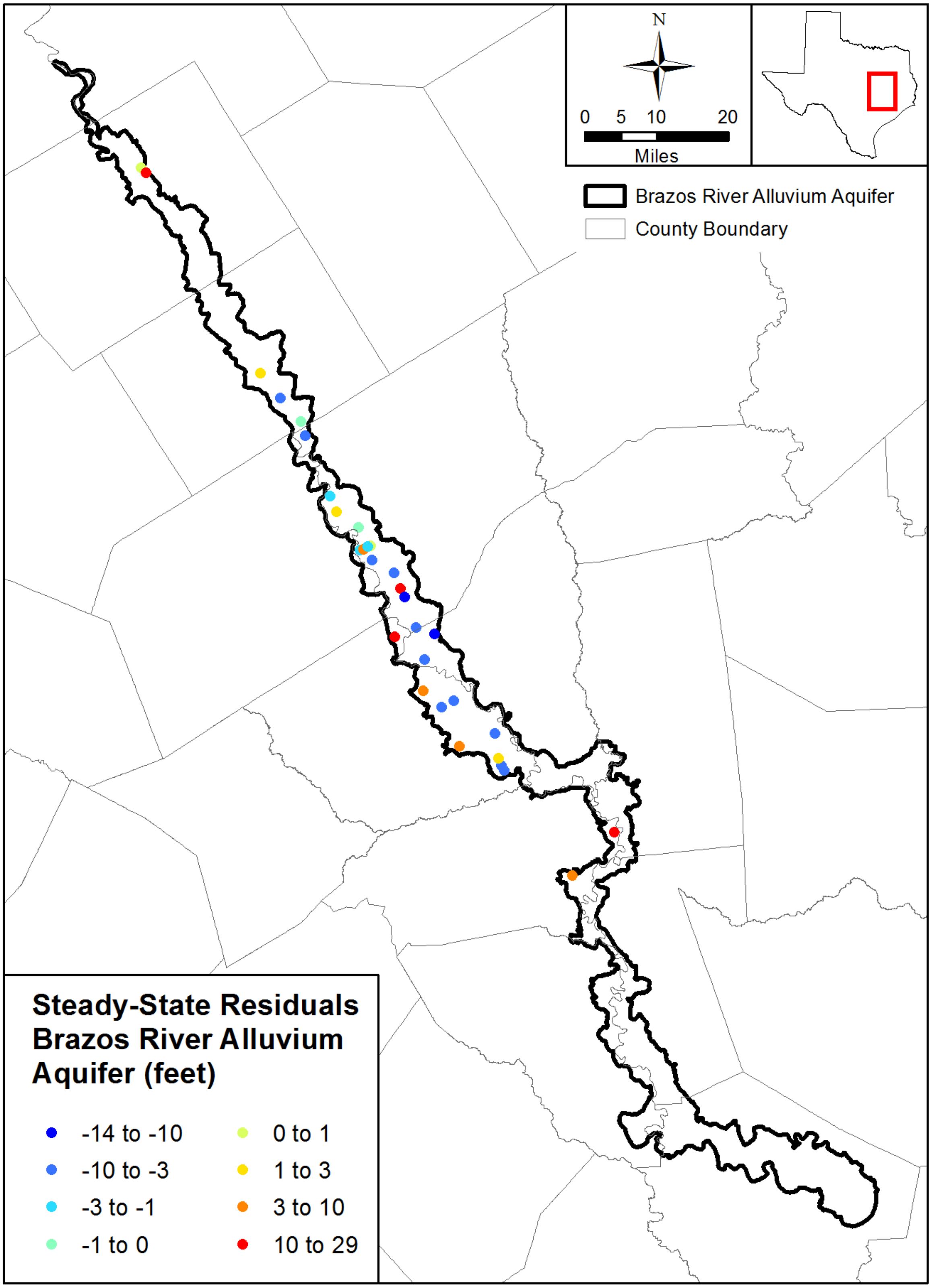

Figure 3.2.12 **Spatial distribution of head residuals in feet in the Brazos River Alluvium Aquifer for the pre-development (steady-state) stress period.**

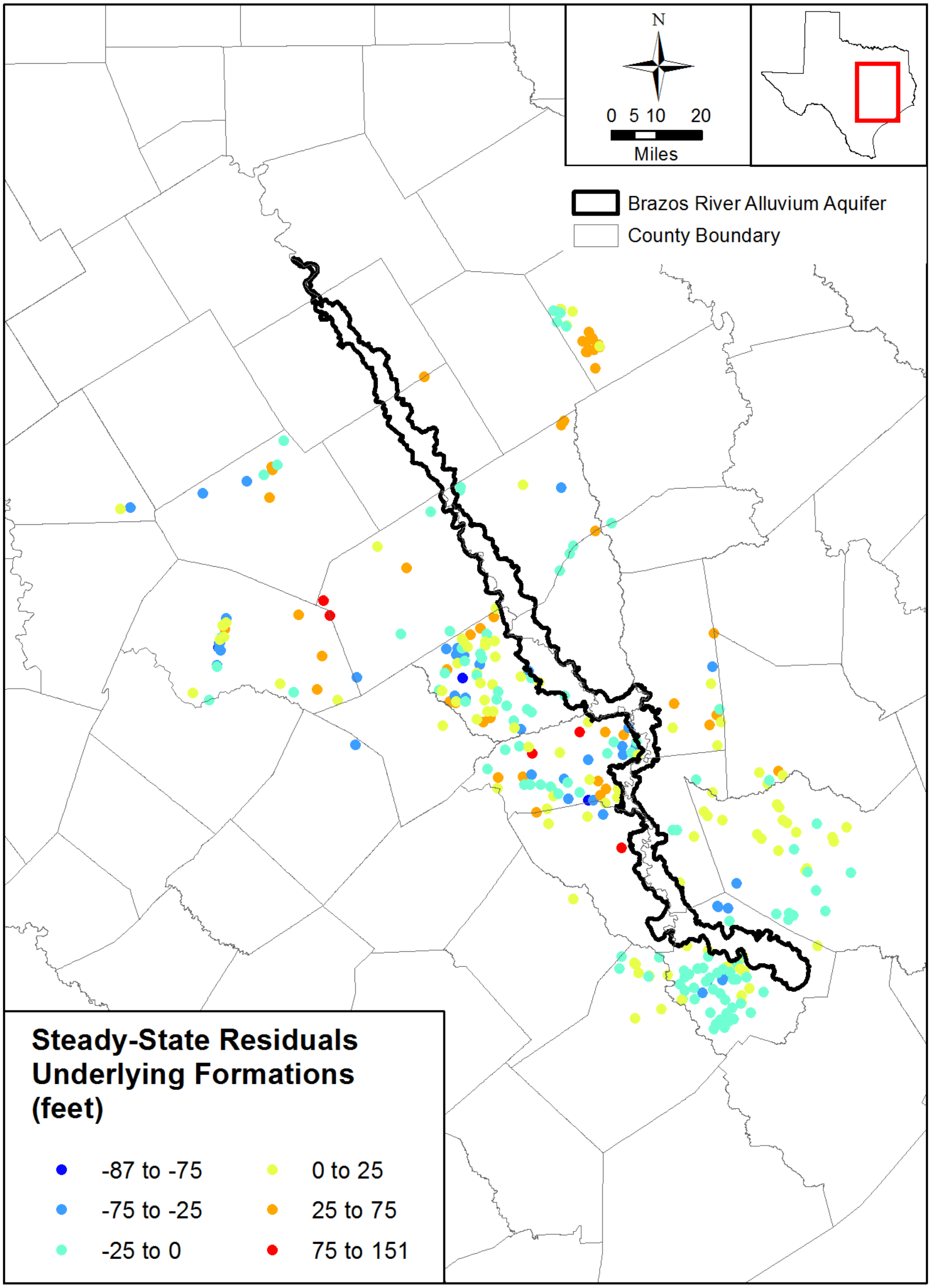

Figure 3.2.13 Spatial distribution of head residuals in feet in the underlying formations for the pre-development (steady-state) stress period.

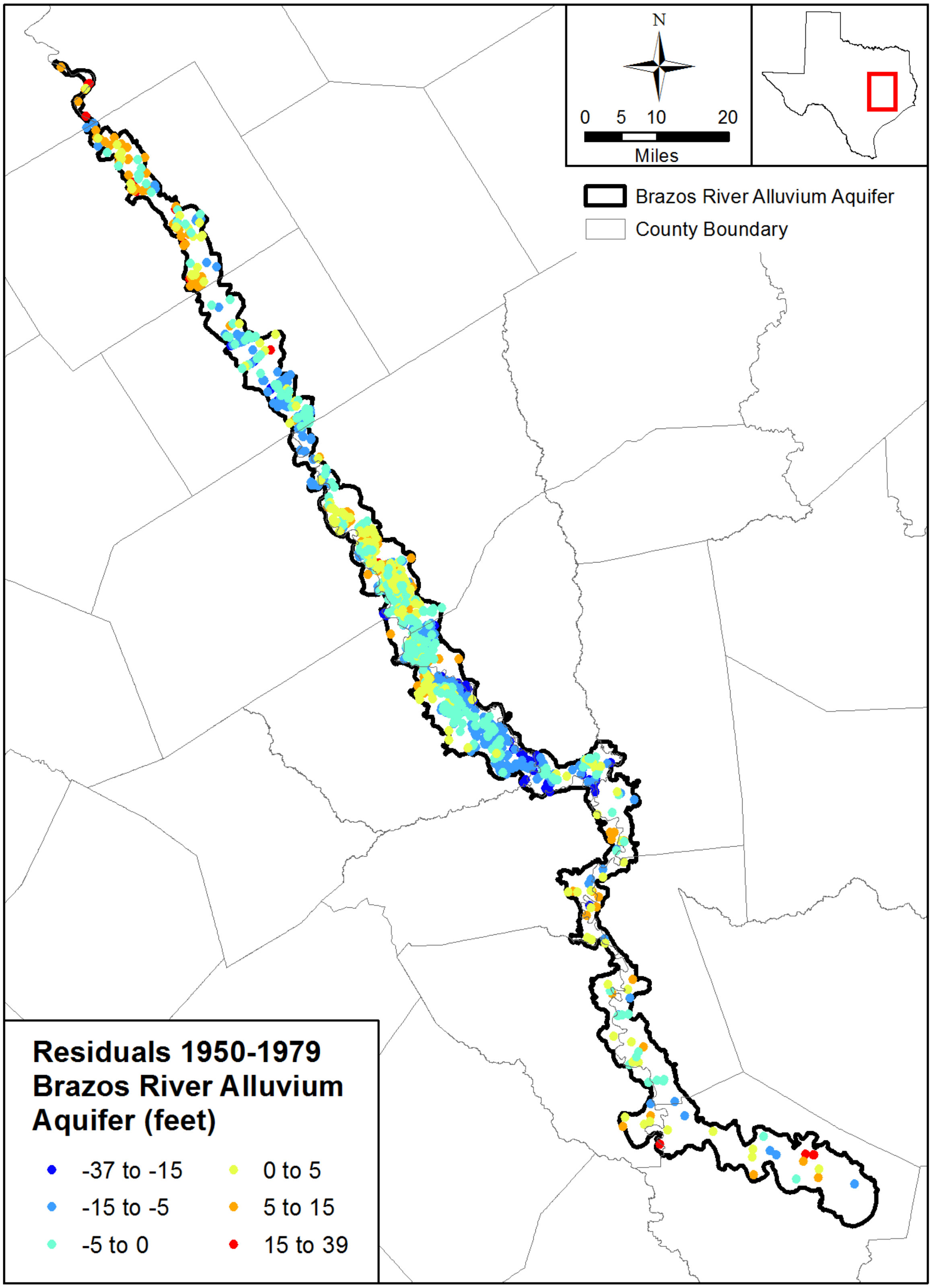

Figure 3.2.14 **Spatial distribution of head residuals in feet in the Brazos River Alluvium Aquifer for the period from 1950 through 1979.**

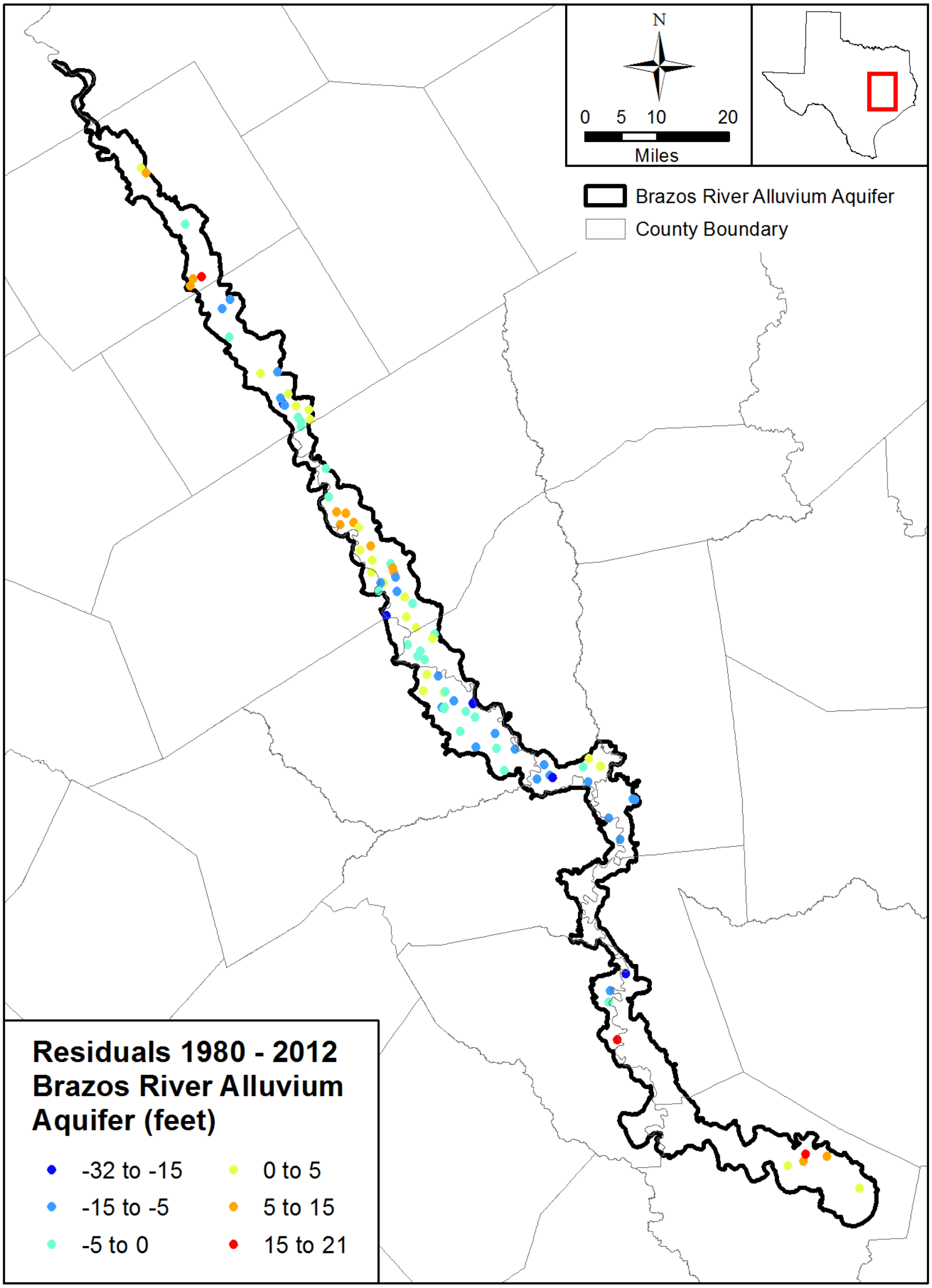

Figure 3.2.15 **Spatial distribution of head residuals in feet in the Brazos River Alluvium Aquifer for the period from 1980 through 2012.**

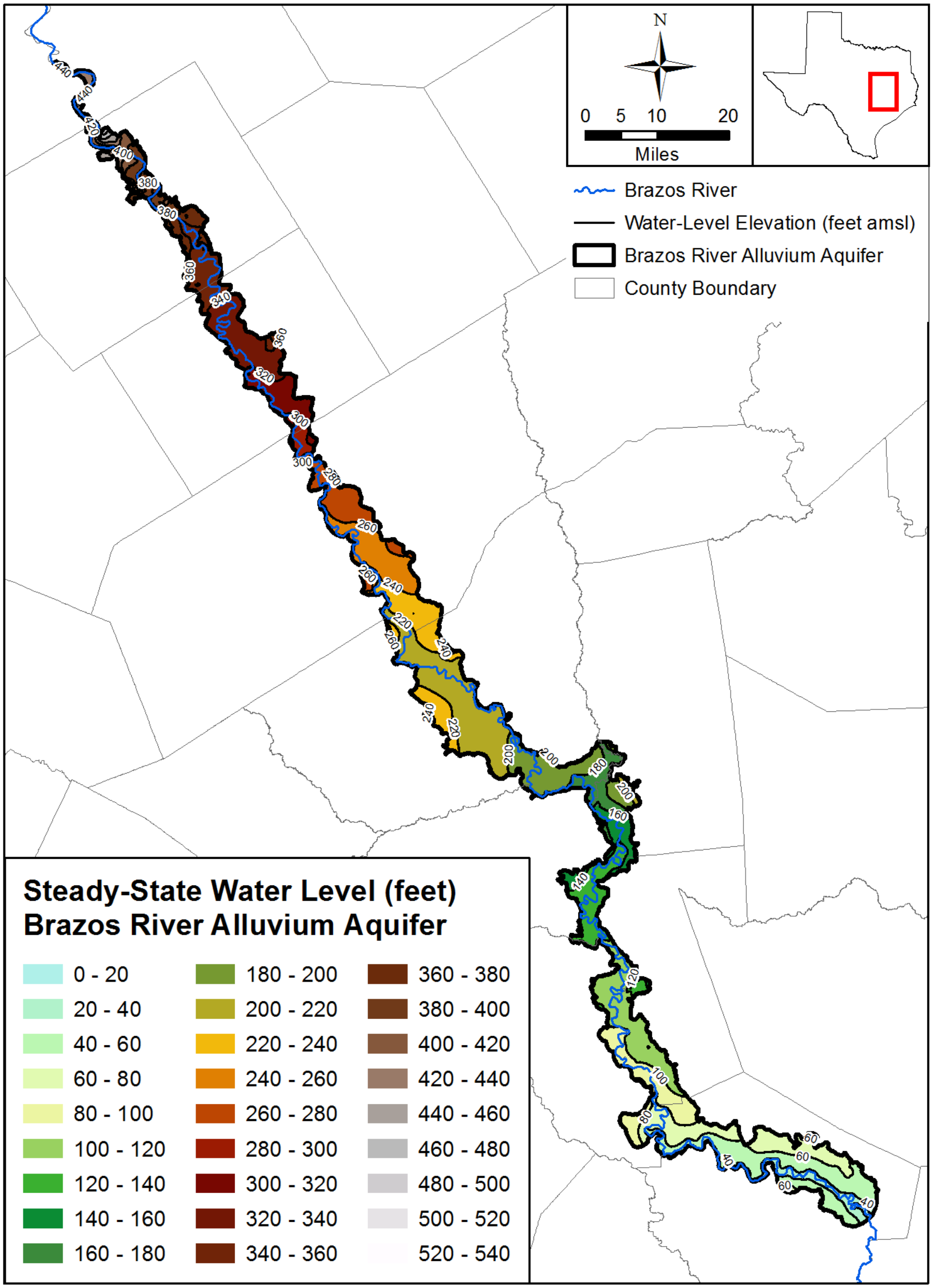

Figure 3.2.16 **Contours of hydraulic head in the Brazos River Alluvium Aquifer for the steady-state period.**

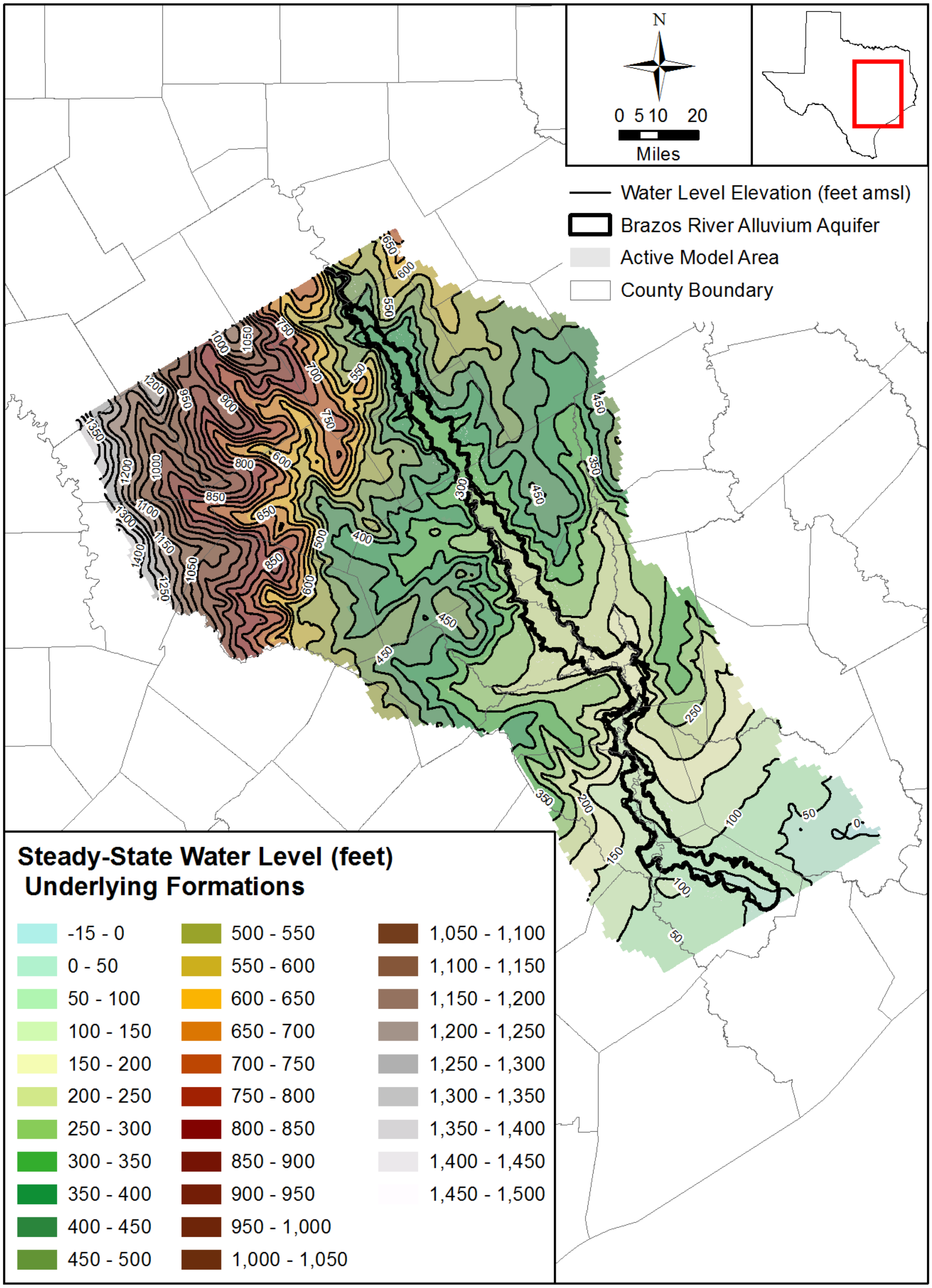

Figure 3.2.17 **Contours of hydraulic head in the underlying formations for the steady-state period.**

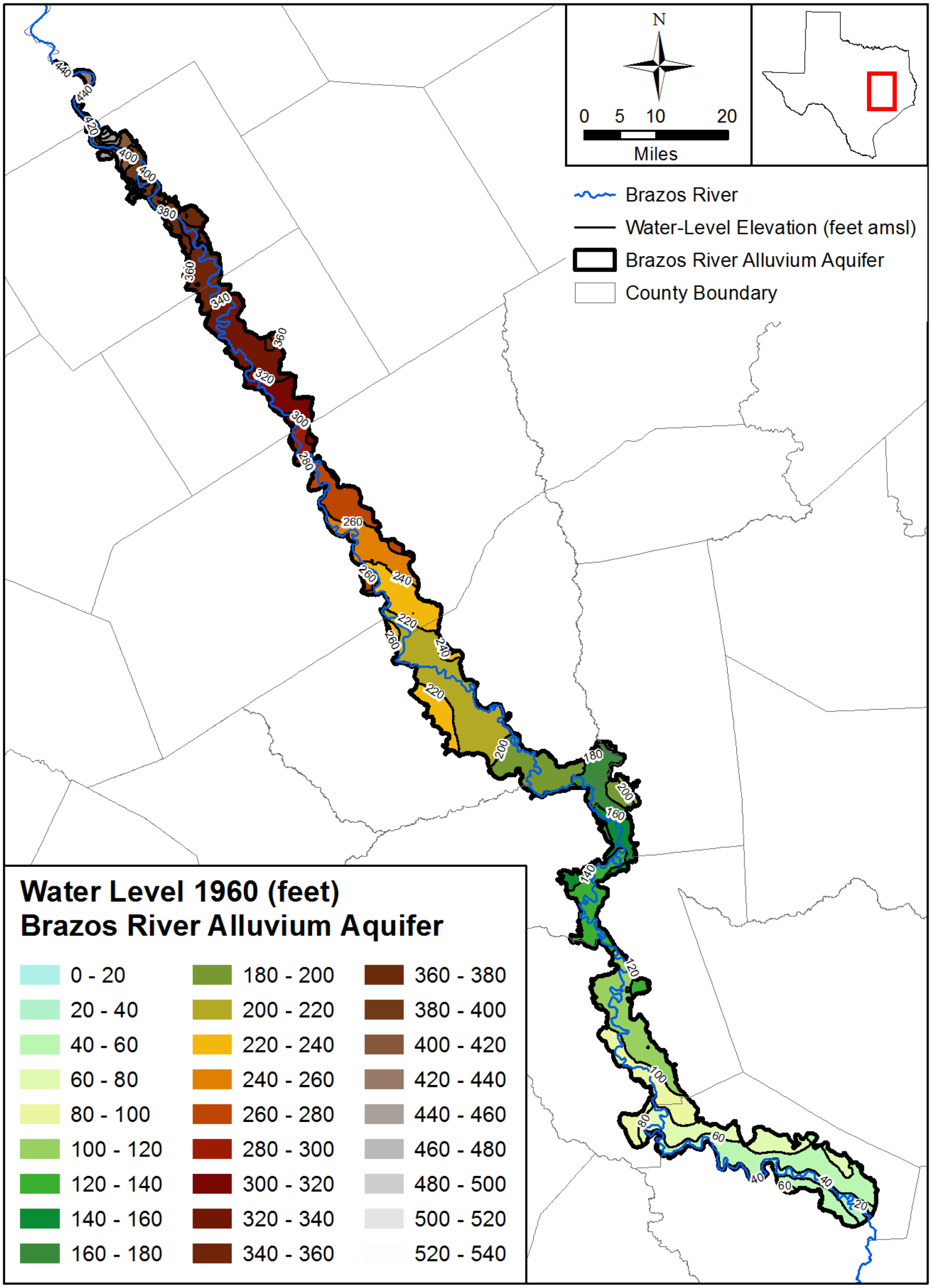

Figure 3.2.18 Contours of hydraulic head in the Brazos River Alluvium Aquifer in 1960.

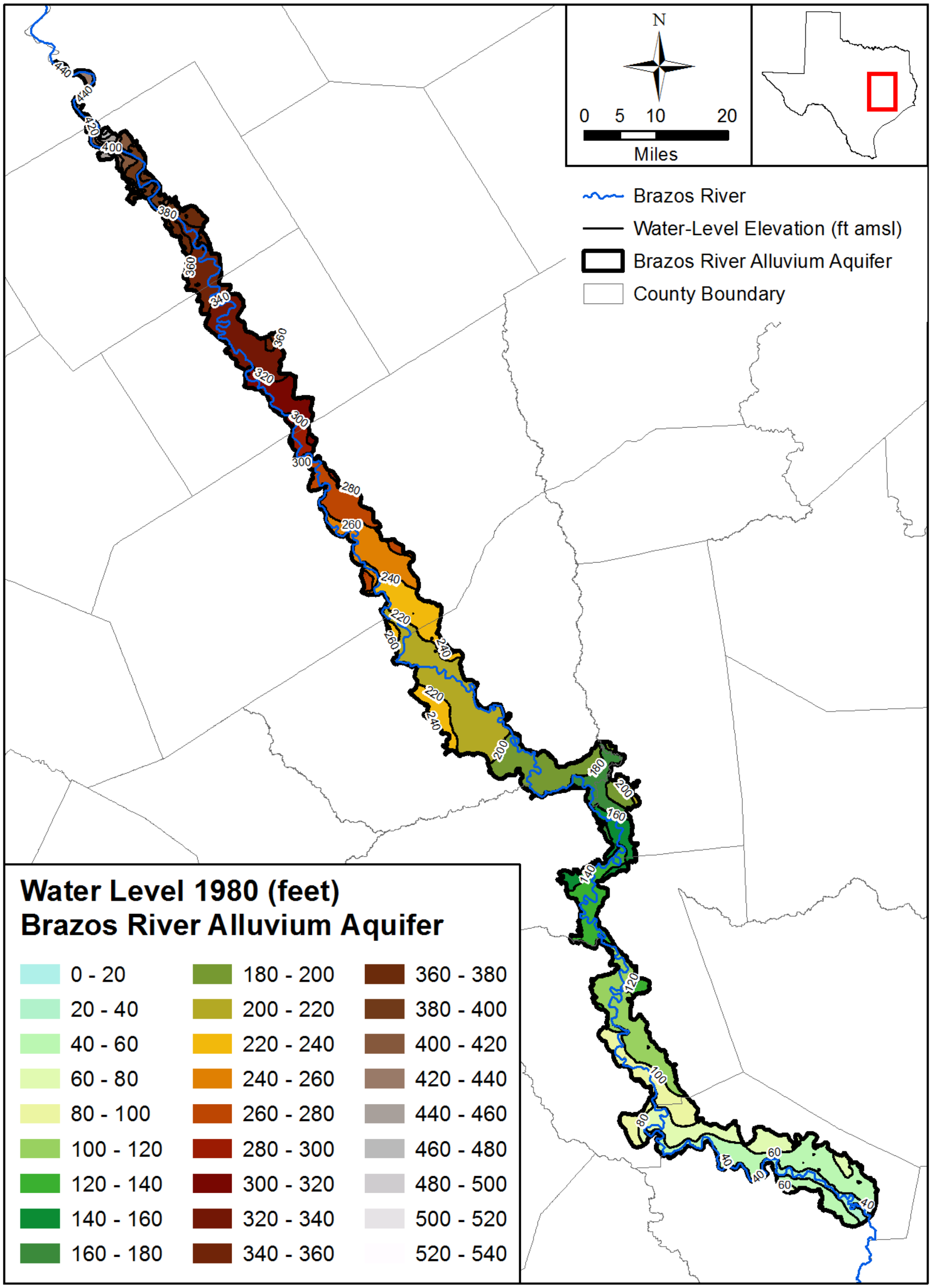

Figure 3.2.19 Contours of hydraulic head in the Brazos River Alluvium Aquifer in July, 1980.

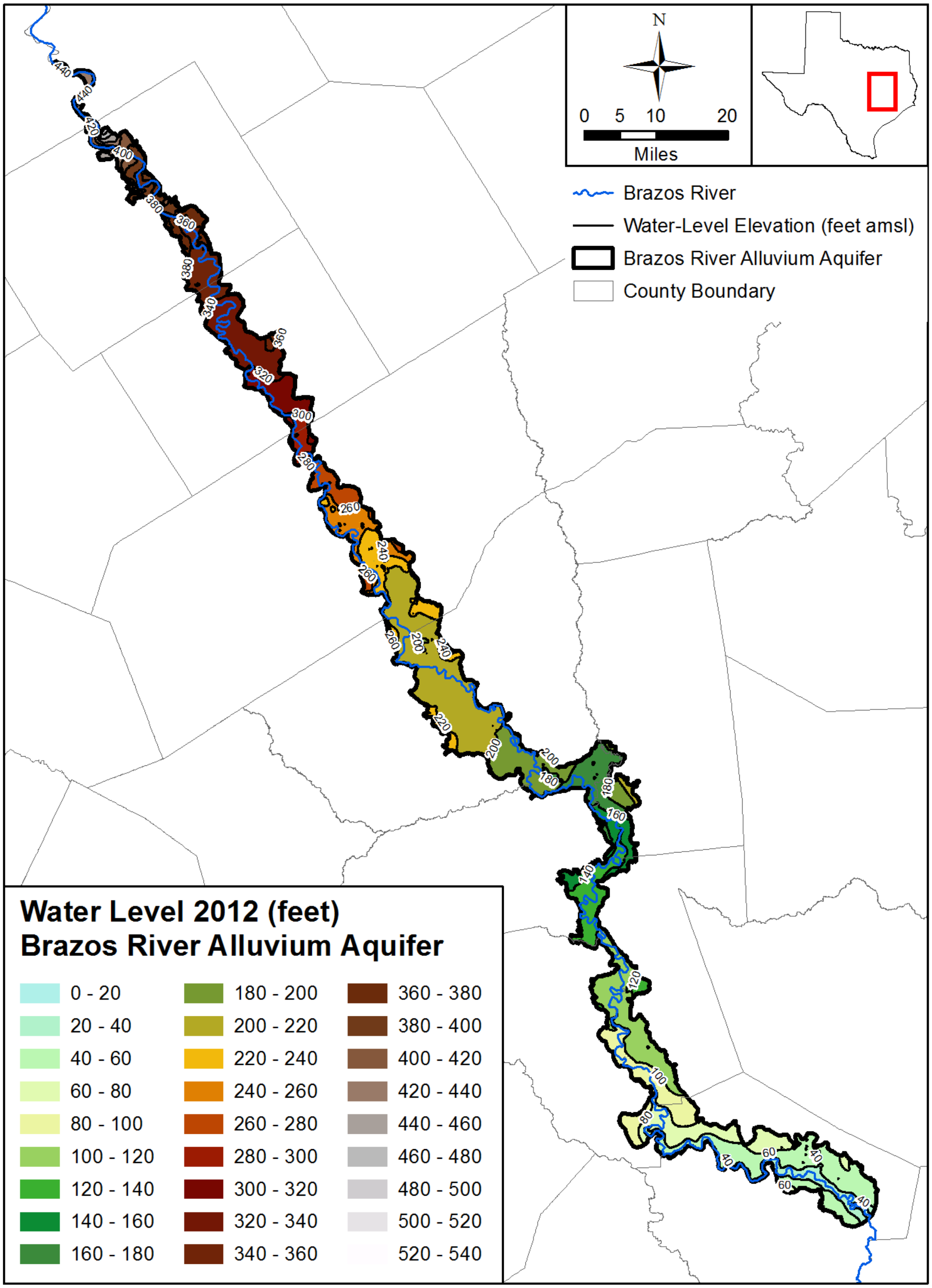

Figure 3.2.20 Contours of hydraulic head in the Brazos River Alluvium Aquifer in July, 2012.

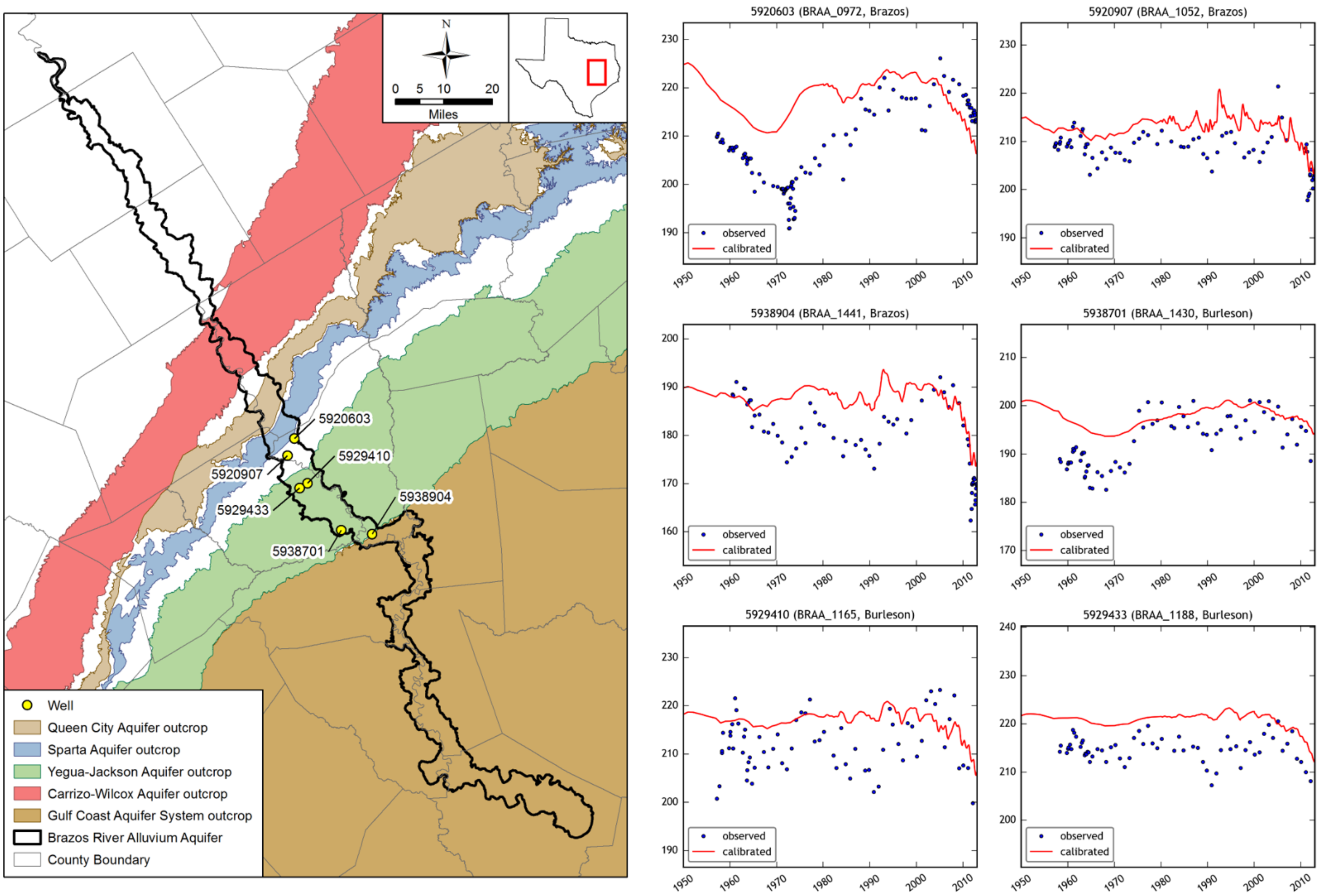

Figure 3.2.21 Select hydrographs (feet above mean sea level) for wells in Brazos and Burleson counties.

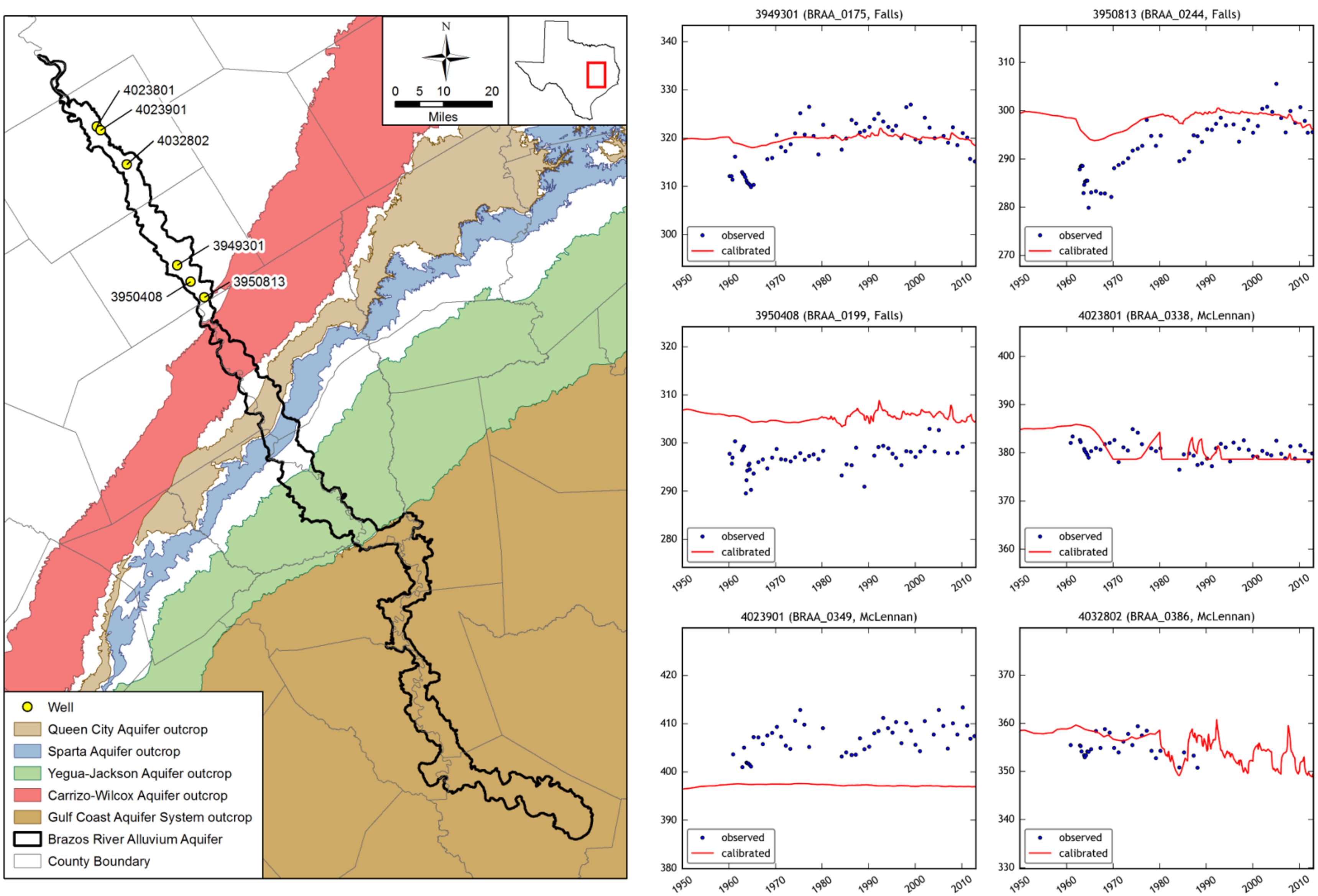

Figure 3.2.22 **Select hydrographs (feet above mean sea level) for wells in Falls and McLennan counties.**

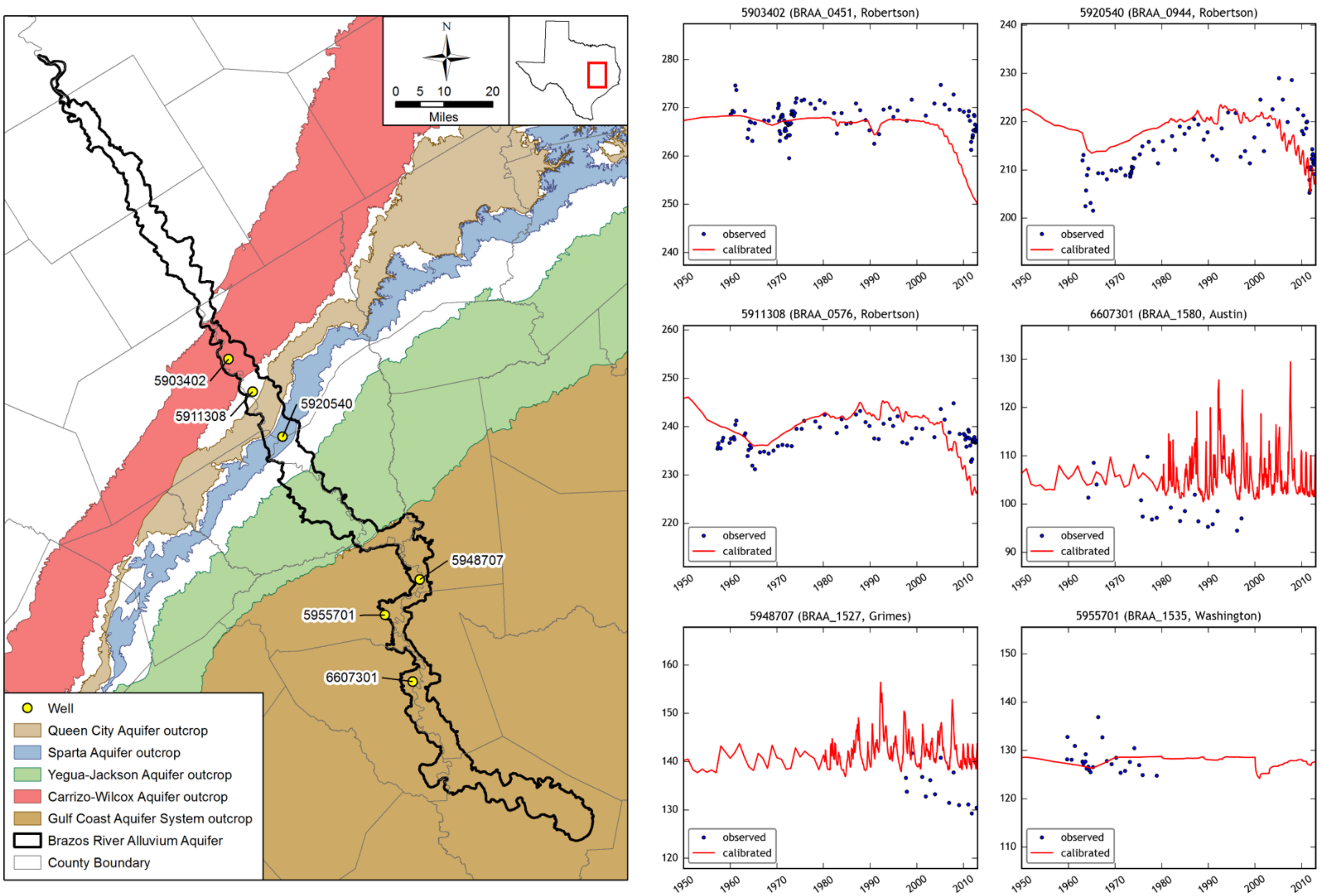

Figure 3.2.23 **Select hydrographs (feet above mean sea level) for wells in Robertson, Austin, Grimes and Washington counties.**

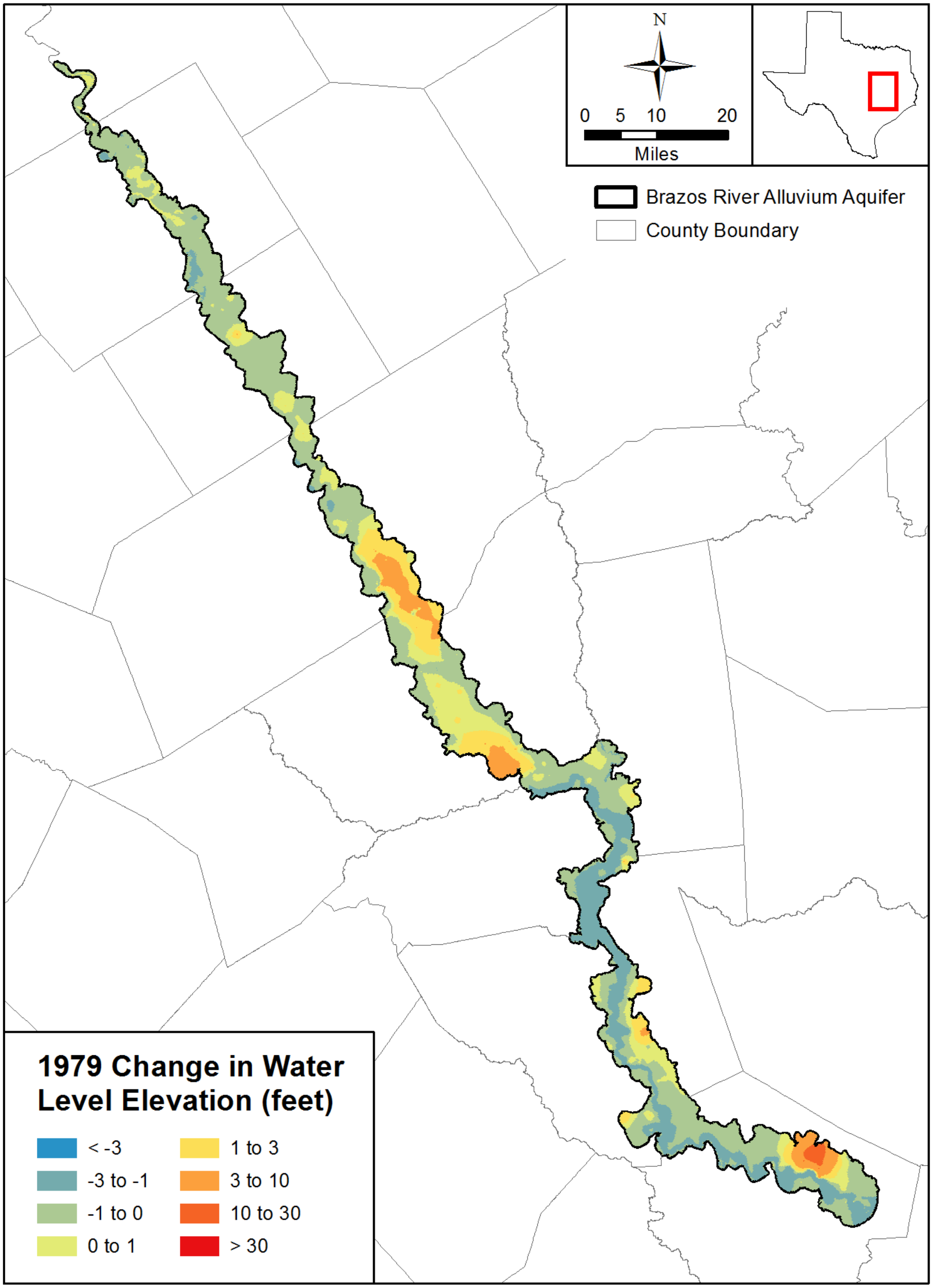

Figure 3.2.24 **Simulated drawdown in hydraulic head from pre-development in the Brazos River Alluvium Aquifer in 1979.**

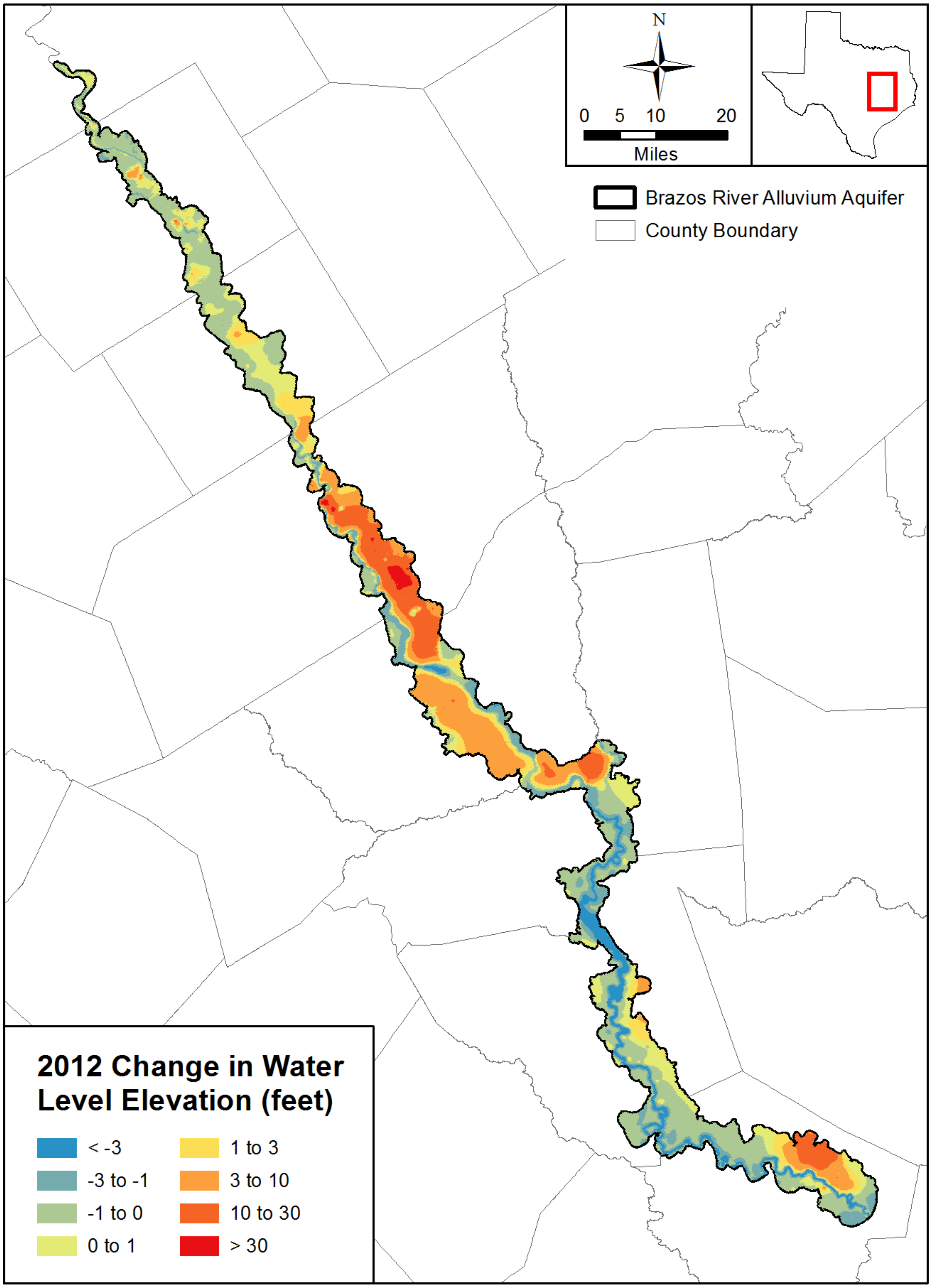

Figure 3.2.25 Simulated drawdown in hydraulic head from pre-development in the Brazos River Alluvium Aquifer in December, 2012.

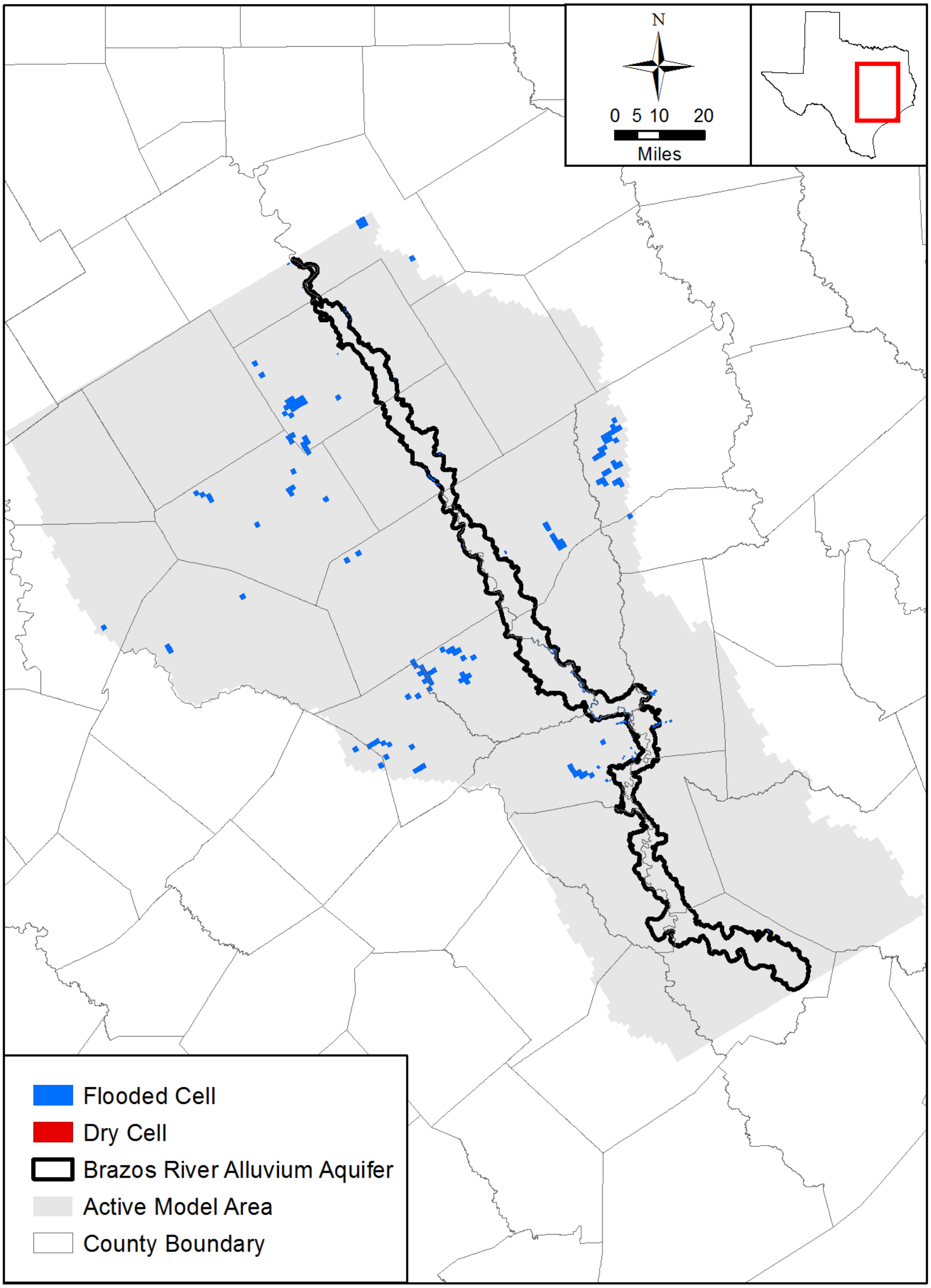

Figure 3.2.26 **Dry and flooded cells in the steady-state model.**

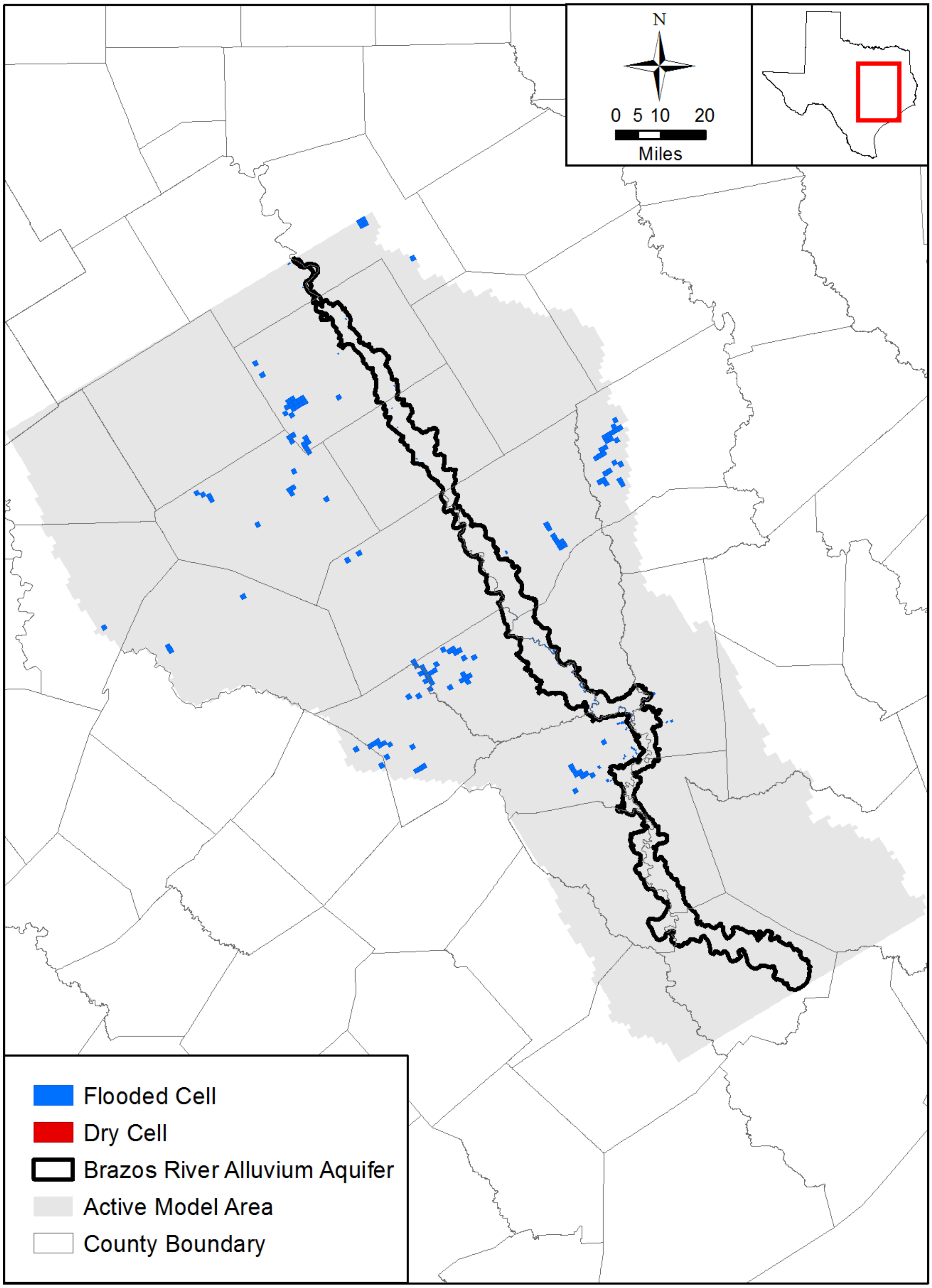

Figure 3.2.27 **Dry and flooded cells in the transient model in December, 2012.**

3.3 Model Simulated Fluxes

In this section, the model simulated fluxes are discussed, including recharge/discharge from the streams other than the Brazos River, discharge to springs, and cross-formational flows between the Brazos River Alluvium Aquifer and the underlying formations. The recharge/discharge to the Brazos River is discussed in Section 3.4. The results discussed in this section cover components of the overall water budget, which is further discussed in Section 3.5.

3.3.1 Streams and Springs

As discussed in Section 3.1, considerable effort was spent on trying to derive quantitative estimates of the interaction between the Brazos River Alluvium Aquifer and the streams in the study area to better constrain the numerical model. Only long-term estimates of the stream-aquifer interaction were deemed appropriate for quantitative comparison with the simulated model results. Figure 3.3.1 shows the locations of the stream gages used for the baseflow analyses of stream gains along with the sub-watersheds and associated streams pertinent to the analyses. The locations of the spring targets used for comparison with the simulated model results are shown in Figure 3.3.2. Of the five springs with flow measurements in the Brazos River Alluvium Aquifer, two springs in Burleson County have nearby locations and are difficult to distinguish from one another in Figure 3.3.2. Only springs within the Brazos River Alluvium Aquifer were used as targets.

Figure 3.3.3 shows the simulated ephemeral stream gains compared with long-term estimates from stream gage data. In general, the higher estimated stream gains are matched by higher simulated gains and lower estimated stream gains are matched by lower simulated gains. The calibration statistics are within the acceptable range. A comparison between simulated and observed spring flows in the Brazos River Alluvium Aquifer is shown in Figure 3.3.4. Simulated spring flows are generally in agreement with observed spring flows.

Figures 3.3.5 and 3.3.6 shows the spatial distribution of simulated flows into or out of perennial and ephemeral streams, respectively, for the predevelopment stress period. Perennial streams are predominantly gaining but have clusters of reaches that also exhibit losing conditions. The ephemeral streams can only exhibit outflow because of the way the boundary conditions were implemented. The outflow to ephemeral streams is generally an order of magnitude less than the outflow to perennial streams.

Figure 3.3.7 shows the simulated flux out of the springs in the model for the predevelopment stress period. Spring flows are only a few acre-feet per year and are inconsequential to the water balance of the Brazos River Alluvium Aquifer. The existence of springs is, however, an indication that groundwater levels are at or very near ground surface at their location. The highest simulated spring flows are seen in Bastrop, Lee, Burleson, Robertson, Leon and Washington counties.

3.3.2 Cross-Formational Flow

By including the shallow portions of the formations underlying the Brazos River Alluvium Aquifer within the Brazos River Basin, the cross-formational flow between these underlying aquifers and formations and the Brazos River Alluvium Aquifer could be analyzed under both pre-development and post-development conditions. Figure 3.3.8 shows the simulated flux into the bottom of the Brazos River Alluvium Aquifer in pre-development. The sign convention in the figure is such that upward flux into the alluvium is a positive value and downward flux out of the alluvium is negative. The positive values throughout the majority of the aquifer indicate primarily upward flow into the Brazos River Alluvium Aquifer from the underlying units. Flux rates tend to be less than 0.2 inches per year, with isolated areas that exceed that rate. The higher rates primarily occur in Fort Bend County where the Brazos River Alluvium overlies the Beaumont Clay.

Figure 3.3.9 shows the simulated flux through the bottom of the Brazos River Alluvium Aquifer for December, 2012. Again, the convention is positive downward, so flux from the Brazos River Alluvium Aquifer to an underlying unit is positive and the reverse is negative. The most visible change between steady-state and December, 2012 is a region between Milam, Robertson, Burleson and Brazos counties where a region of downward flux in steady-state is reversed to an upward flux in December, 2012. This coincides to the area with the highest pumping rates (Figure 2.4.5c) and largest drawdowns (Figure 3.2.25). Like in steady-state, flux rates tend to be less than 0.2 inches per year, with higher rates primarily occurring in Fort Bend County where the Brazos River Alluvium overlies the Beaumont Clay.

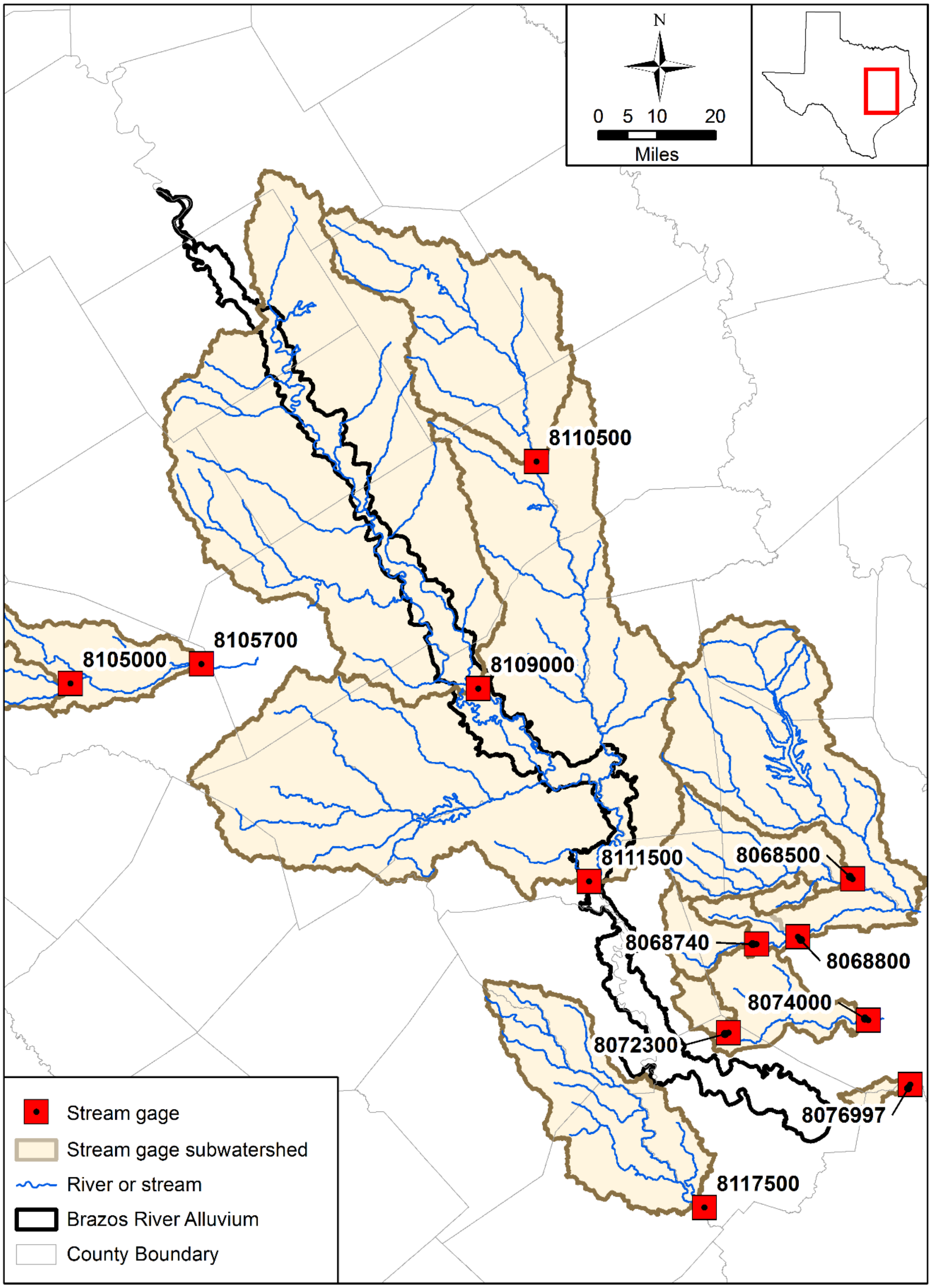

Figure 3.3.1 **Locations of stream gain/loss targets showing differential gages and associated watershed and stream cells.**

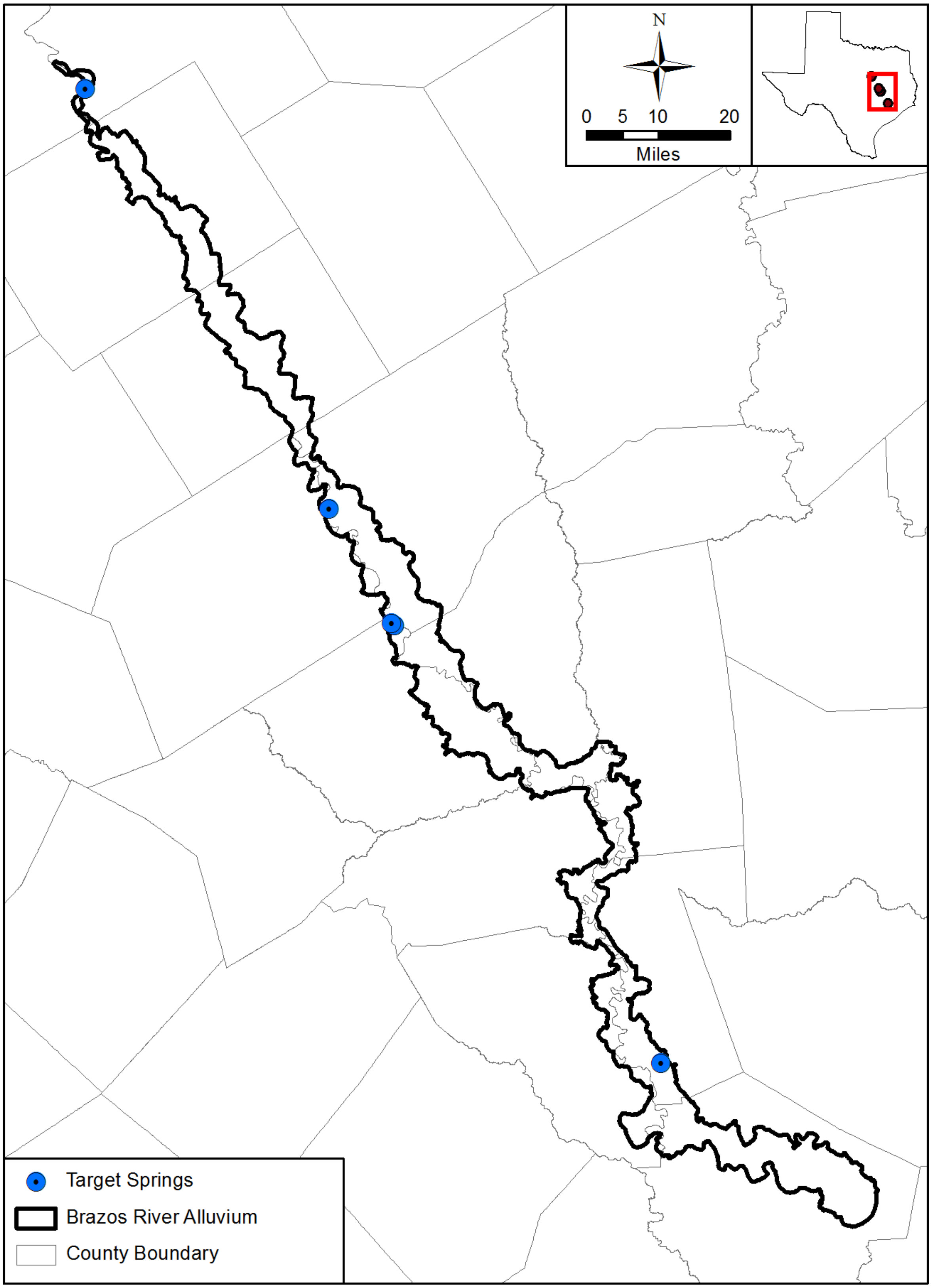

Figure 3.3.2 **Locations of spring flow targets.**

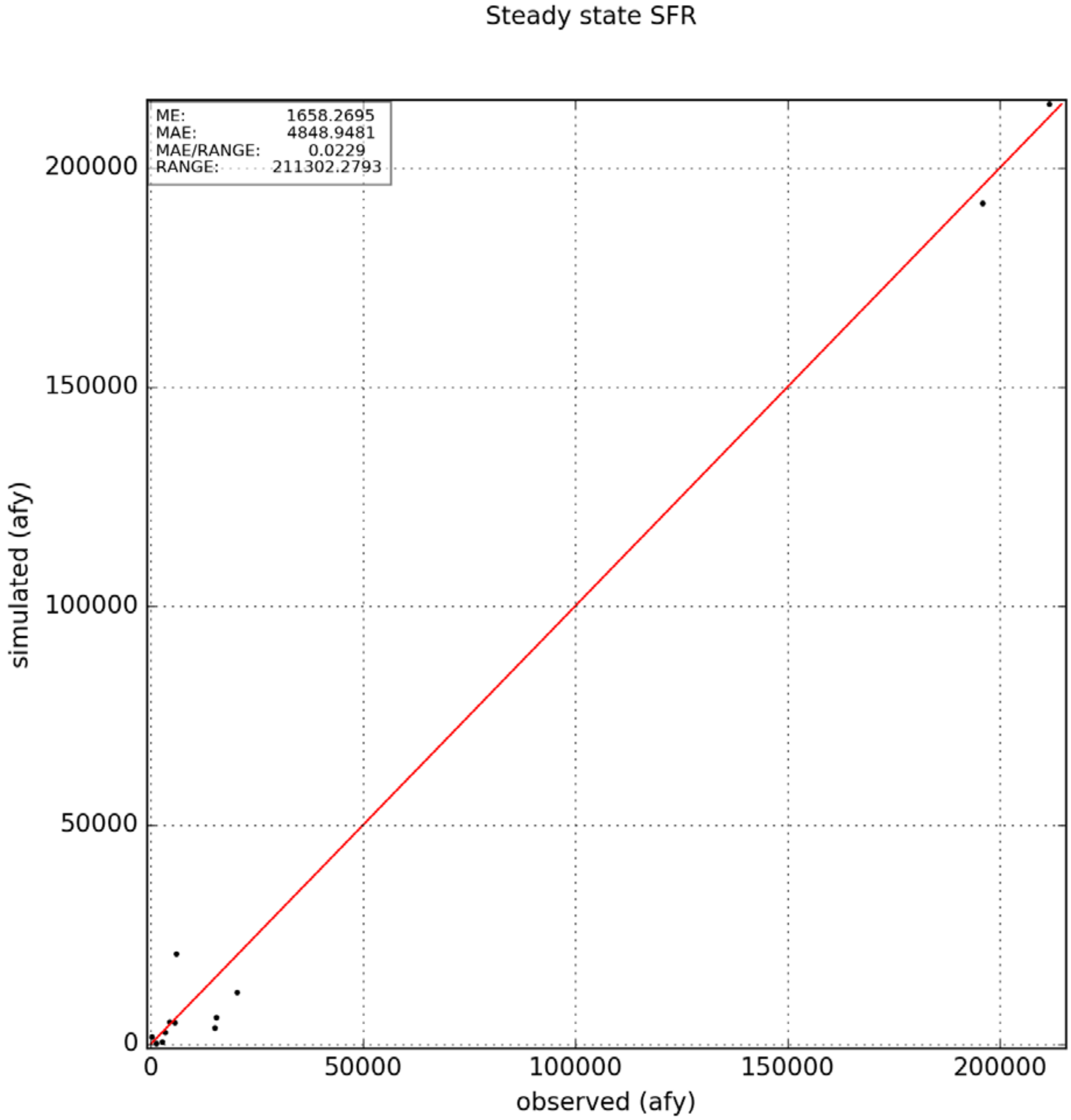

Figure 3.3.3 **Scatter plot of simulated versus estimated stream gain/loss in acre-feet per year.**

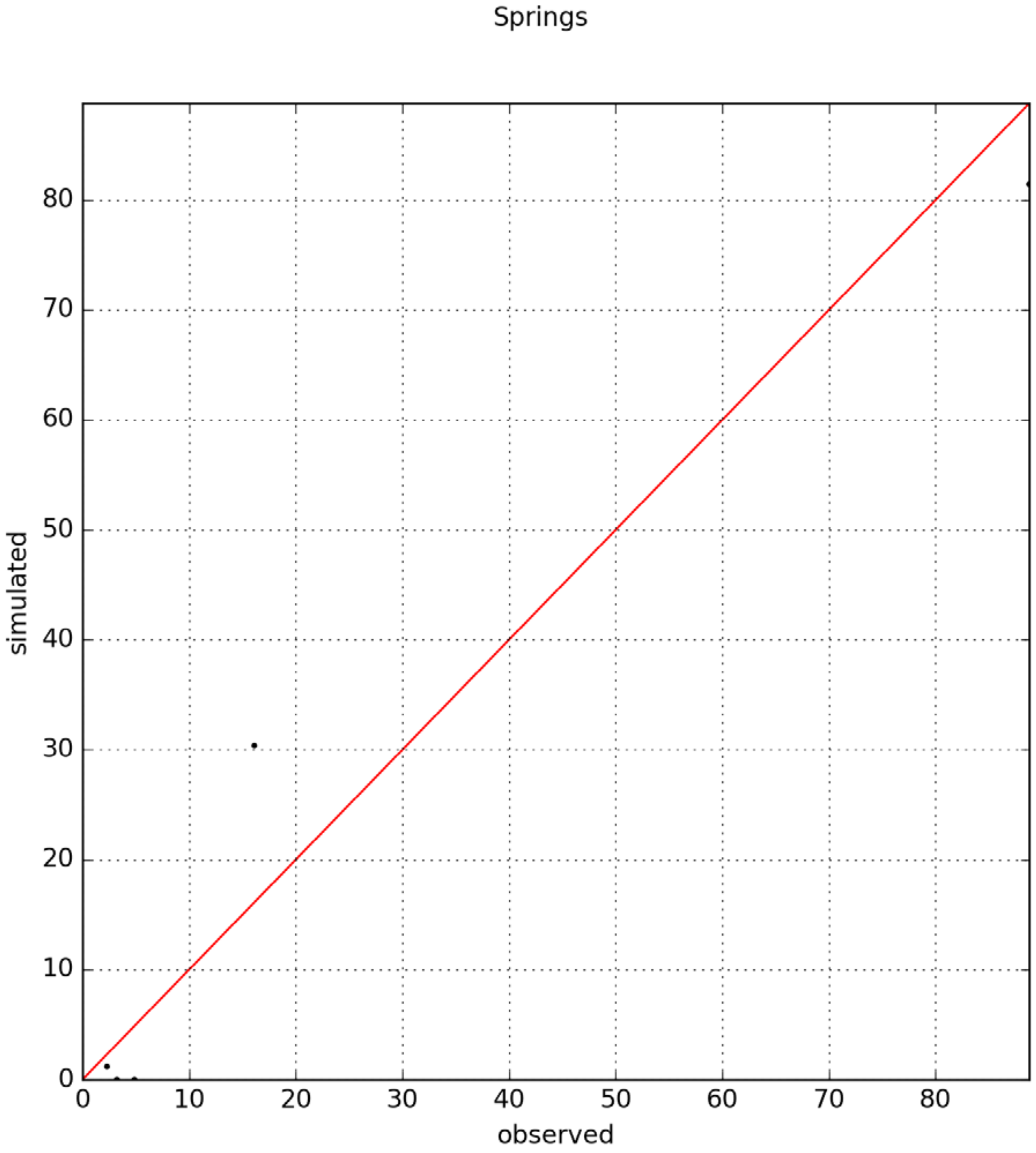

Figure 3.3.4 Scatter plot of simulated versus observed spring flows in acre-feet per year.

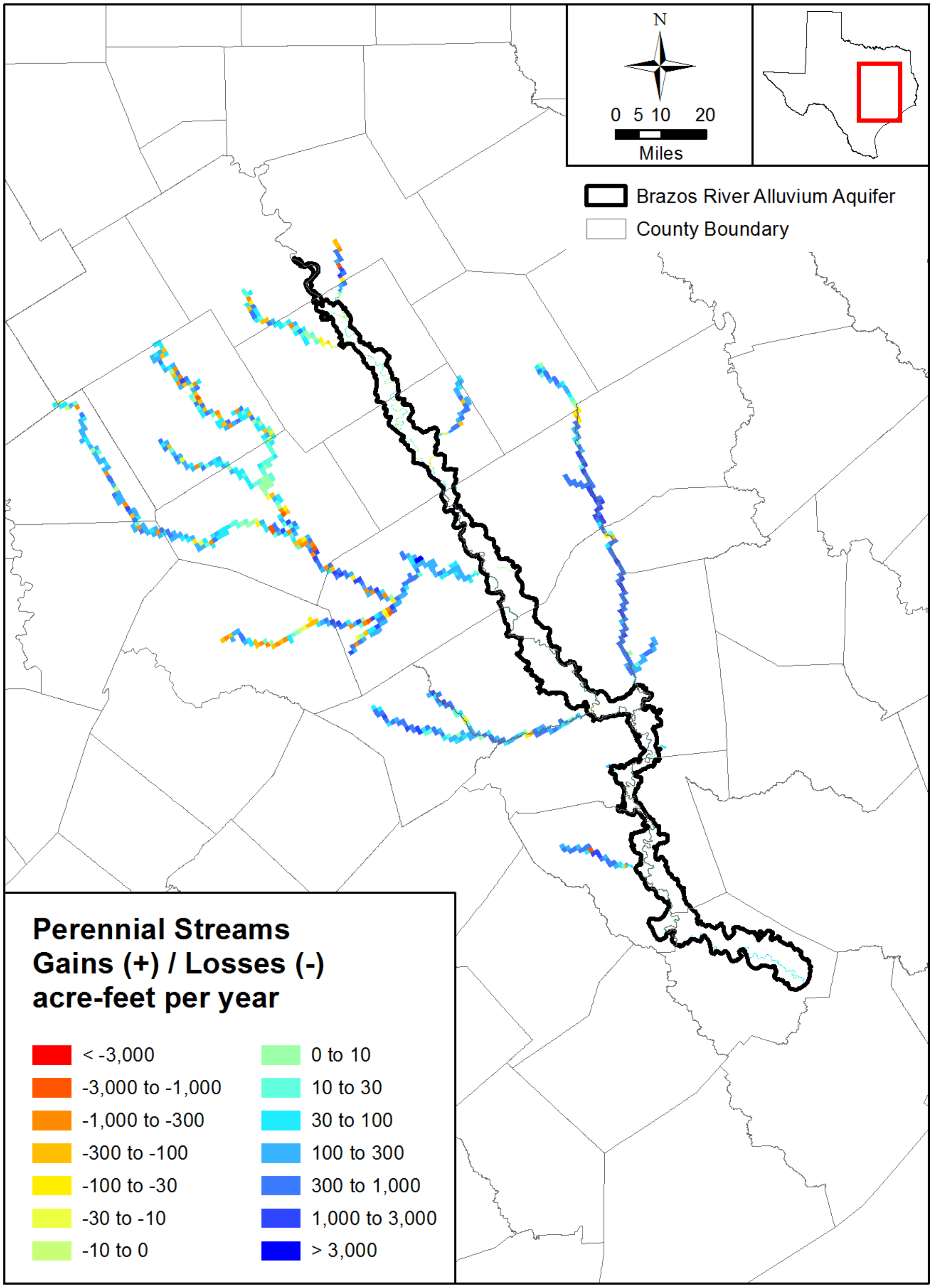

Figure 3.3.5 **Spatial distribution of flux in and out of perennial streams in acre-feet per year in the pre-development (steady-state) stress period.**

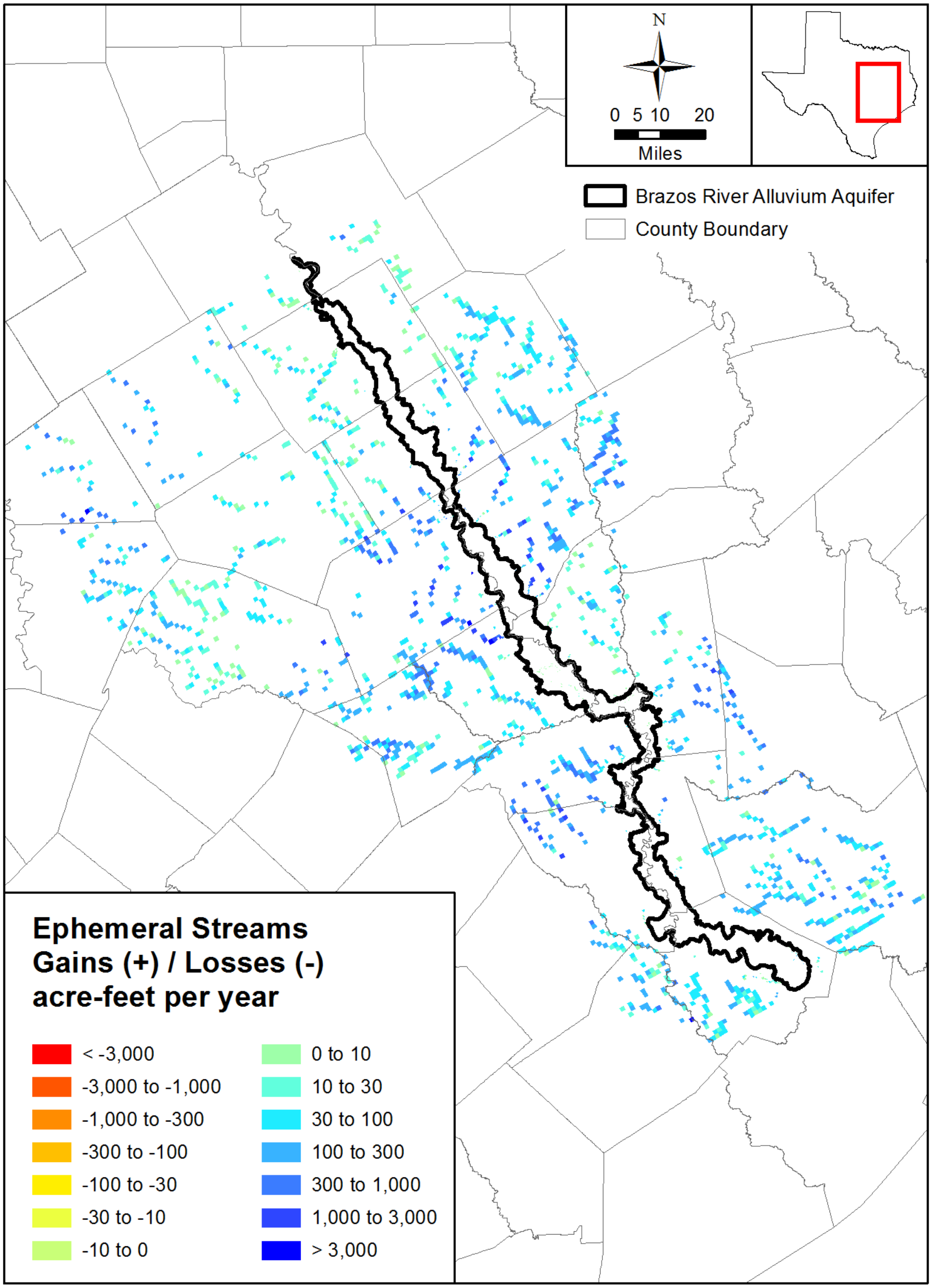

Figure 3.3.6 **Spatial distribution of flux out of ephemeral streams in acre-feet per year in the pre-development (steady-state) stress period.**

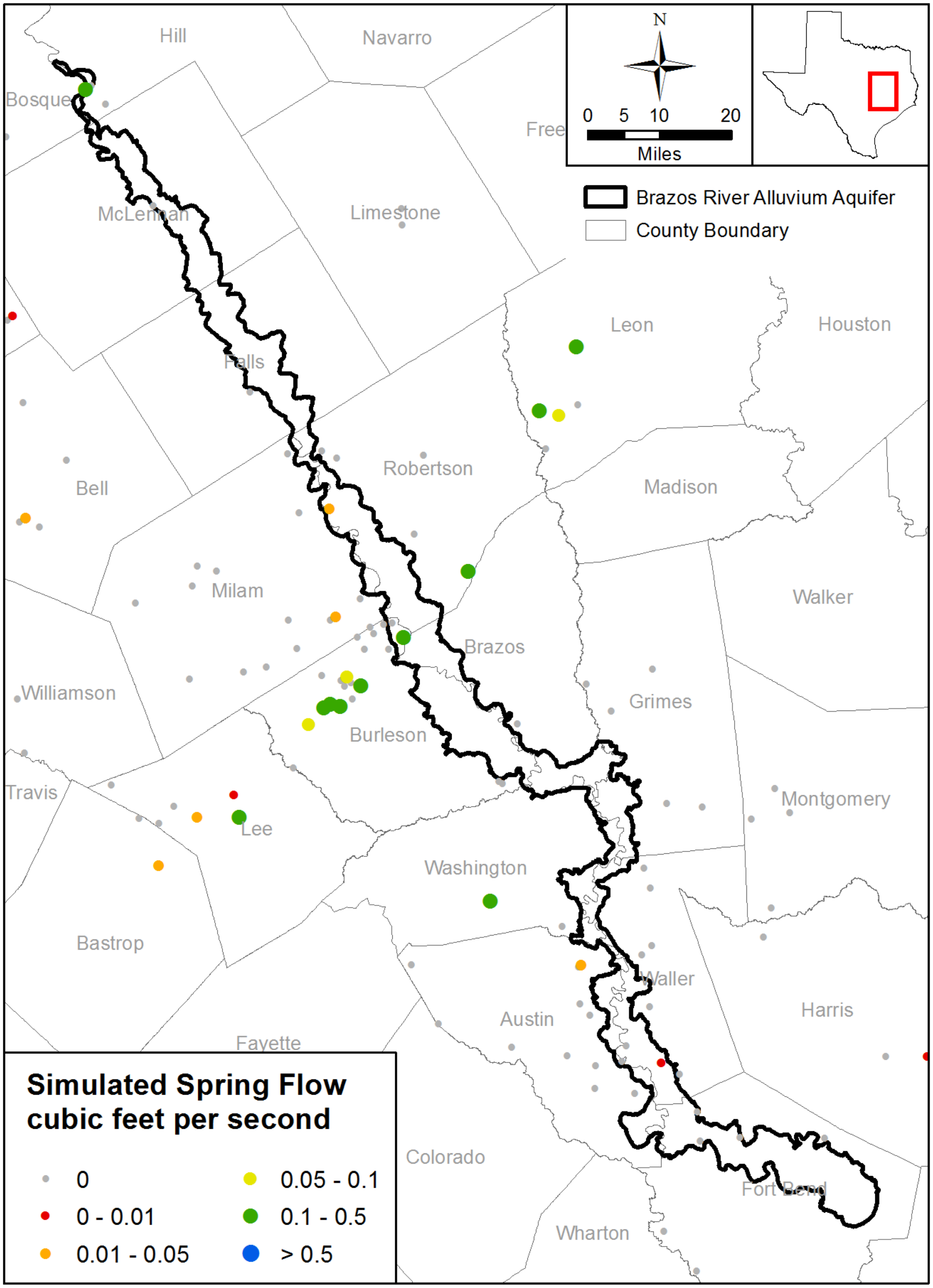

Figure 3.3.7 **Spatial distribution of flux out of springs in cubic feet per second in the pre-development (steady-state) stress period.**

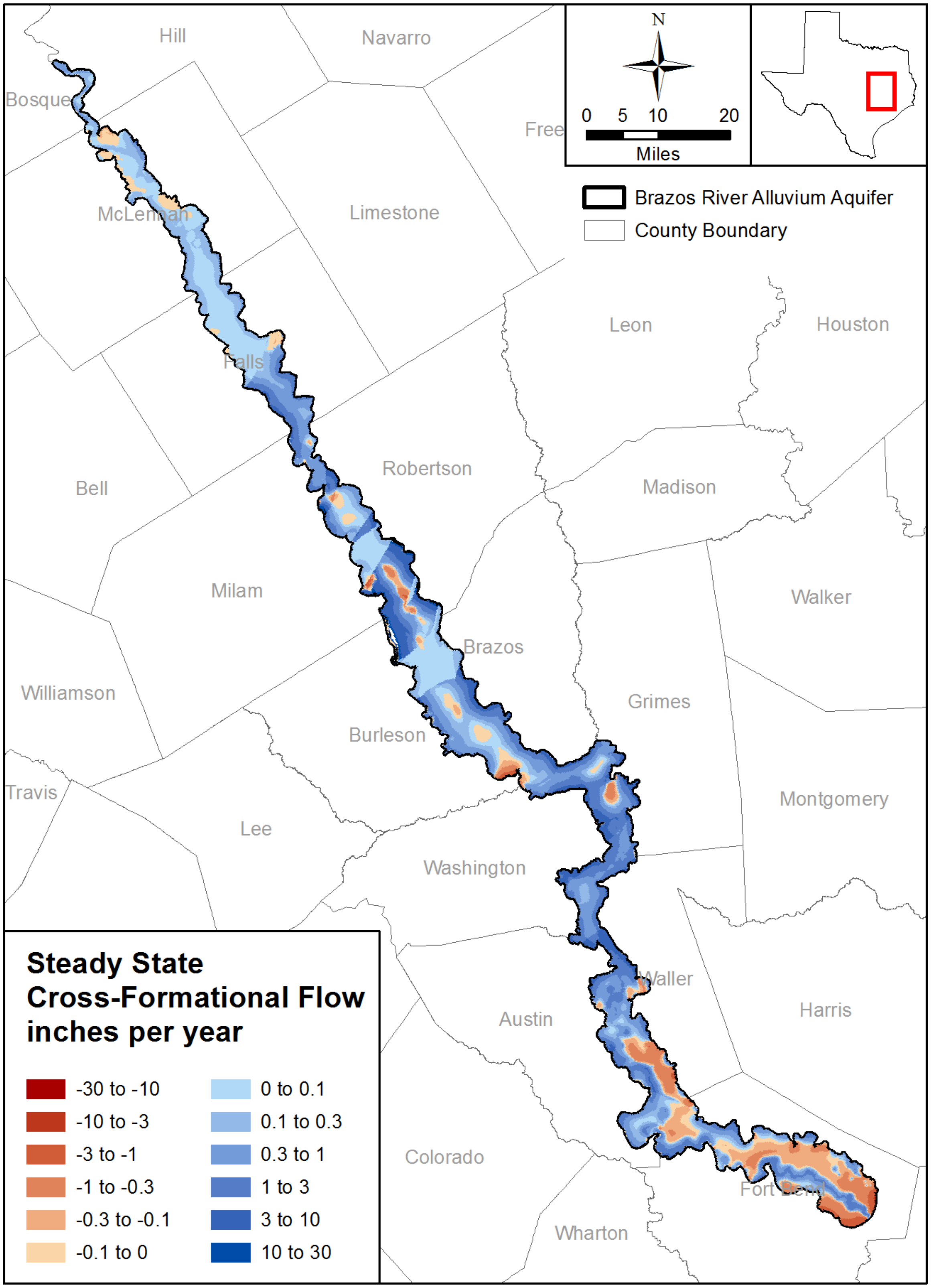

Figure 3.3.8 **Spatial distribution of cross-formational flow in inches per year in the pre-development (steady-state) stress period.**

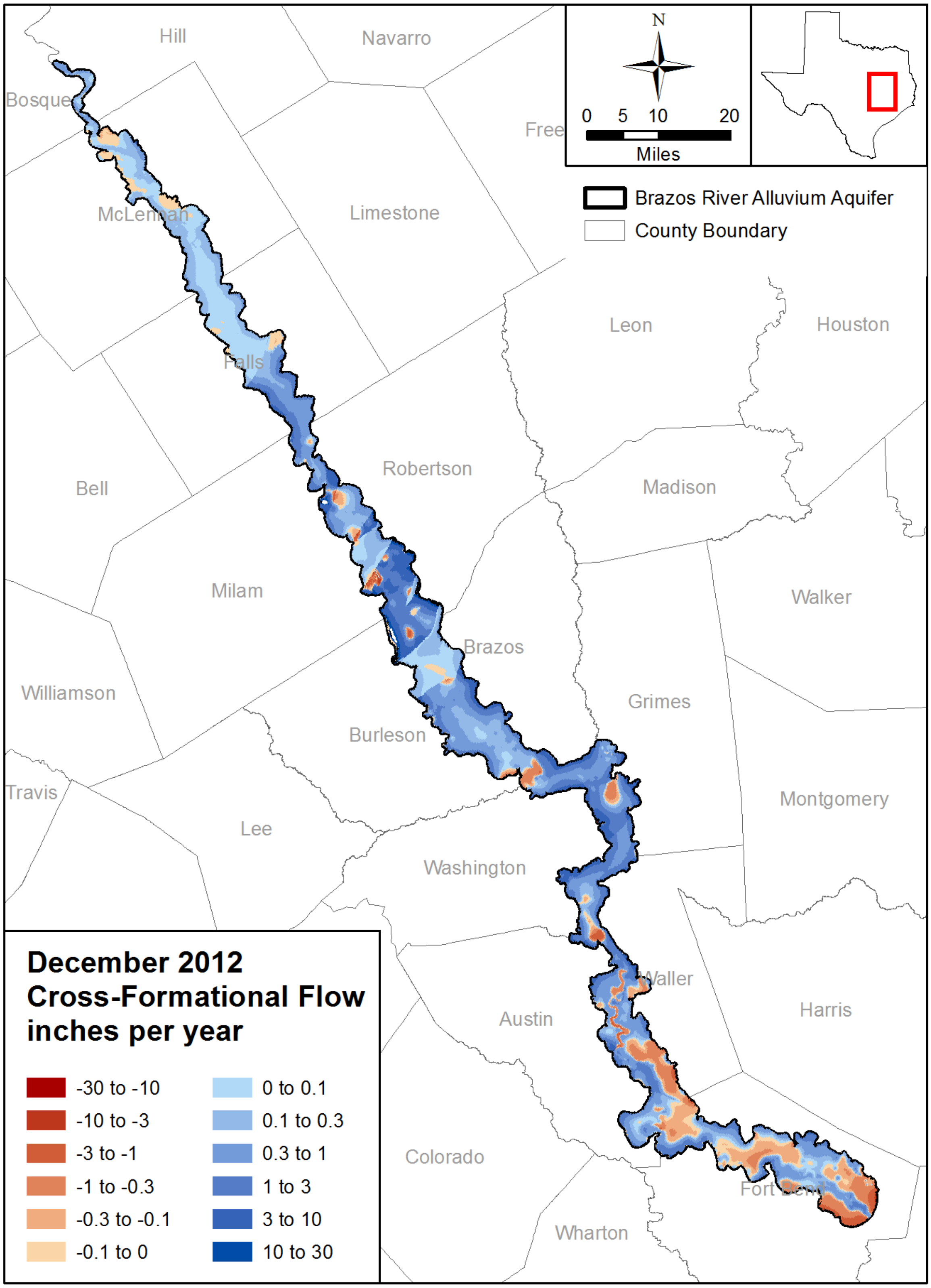

Figure 3.3.9 **Spatial distribution of cross-formational flow in inches per year in December, 2012.**

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3.4 Model Simulated Discharge to the Brazos River

In this section, the simulated recharge/discharge to the Brazos River are discussed both for the steady-state and transient stress periods. In addition, the results of a daily stress period model for 2006 are presented. The results discussed in this section cover components of the overall water budget, which is further discussed in Section 3.5.

3.4.1 Flow to and from the Brazos River

As discussed in Section 3.1, considerable effort was spent on trying to derive quantitative estimates of the interaction between Brazos River Alluvium Aquifer and the Brazos River to better constrain the numerical model. All estimates from available data were deemed too uncertain for a quantitative comparison with model results. Nevertheless, a qualitative evaluation of simulated gains and losses to the Brazos River can help to constrain the simulated flows in the model.

Figures 3.4.1a through 3.4.1d show the spatial distribution of the simulated flows between the Brazos River and the Brazos River Alluvium Aquifer for the steady-state period. The Brazos River is predominantly gaining throughout the length of the aquifer but clusters of losing reaches are also apparent in the figures. There tend to be more simulated losing reaches in the northwestern portion of the aquifer with the Brazos River generally showing more strongly gaining conditions toward the southeast.

Figure 3.4.2 depicts the simulated gains by perennial streams within the Brazos River Alluvium Aquifer over the historical record. This primarily reflects the gains to the Brazos River but also includes the flows to perennial tributaries to the Brazos River that are hydraulically connected to the Brazos River Alluvium Aquifer. The figure also shows a linear trend-line fit to the simulated gains and a five-year moving average of the simulated gains, both of which indicate an apparent systematic decline in the discharge from the Brazos River Alluvium Aquifer to the Brazos River and perennial tributaries over the historical period. The magnitude of this decrease in aquifer discharge to the Brazos River (approximately 50,000 acre-feet per year) is similar to the amount of pumping in the aquifer in December, 2012.

The streamflow in the Brazos River is highly variable and, because stream stage is calculated as a function of streamflow via the rating curves in the Streamflow-Routing package, stream stage in the Brazos River is also highly variable. To illustrate the effect of this variability on simulated gains and losses for the Brazos River, two months, January, 1992 and November, 2007 with high and low Brazos River streamflow, respectively, were chosen. Figure 3.4.3 shows the flow to and from the Brazos River in the low streamflow month of January, 1992 for the south-central region of the model that is depicted in Figure 3.4.1c for the steady-state period. Figure 3.4.4 shows flow to and the Brazos River in the high streamflow month of November, 2007 for the same area. Losses from the Brazos River are noticeably higher in the high streamflow month of January, 1992 than they are for the steady-state period. Conversely, gains to the Brazos River are noticeably higher in the low streamflow month of November 2007 than they are for the steady-state period.

3.4.2 Daily model for 2006

Surface water flow in streams is typically evaluated at a much shorter time increment (hours or days) than that typically used to evaluate groundwater flow in aquifers (months or years). To evaluate the differences in stream-aquifer interaction for different temporal discretization levels, a daily stress period version of the Brazos River Alluvium Aquifer model was constructed for 2006. This includes both time periods (March and August of 2006) reported in the synoptic gain/loss study conducted by Turco and others (2007).

To illustrate the differences in variability in simulated stream-aquifer gain/loss, three model runs were conducted for 2006: 1) an annual run with a single yearly stress period; 2) a monthly run with 12 monthly stress periods; and 3) a daily run with 365 daily stress periods. Each model run used identical initial conditions based on December, 2005 and identical hydraulic parameters and boundary condition conductances. The only differences between the model runs were the variability in streamflow and the variability in recharge. Recharge was varied at no finer temporal discretization than monthly so it was identical for the monthly and daily runs. Figure 3.4.5 depicts the gains and losses to the Brazos River for these three model runs. The figure very clearly illustrates the differing magnitudes in stream gains and losses for the three levels of temporal discretization. This is a direct result of the higher variability in the streamflow and the associated stream stage for the shorter stress period lengths. For instance, a storm may produce high streamflow for a period of hours to days. This peak flow would be better represented in the daily stress period model than in the monthly stress period model which uses the median value of high and low streamflows.

Figure 3.4.6 shows a comparison of the stream gains and losses for the three model runs when they are averaged over a year for several stream segments (between gages on the Brazos River) denoted by the downstream gage corresponding to each segment. Interestingly, the figure demonstrates that, despite the very dissimilar magnitudes in maximum stream gains and losses for each temporal discretization case, the annually-averaged effect of each model run is very similar. This indicates that, in the context of simulating the long-term effects of stream-aquifer interaction in this groundwater availability model, temporal averaging up to annual stress periods does not have any significant disadvantages compared to simulating shorter stress periods.

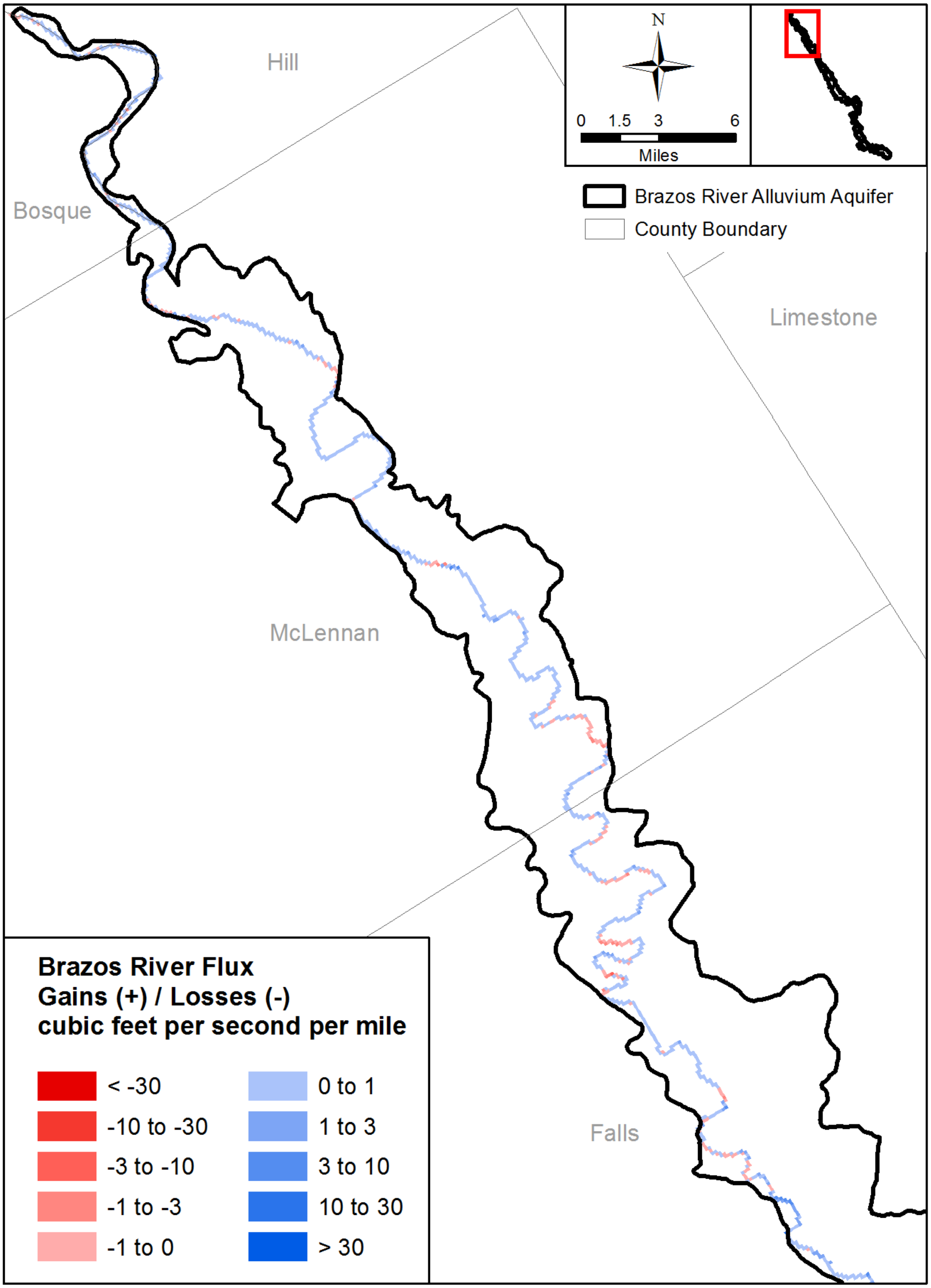

Figure 3.4.1a Spatial distribution of flux in and out of the Brazos River in cubic-feet per second per mile of stream in northernmost region for the steady-state stress period.

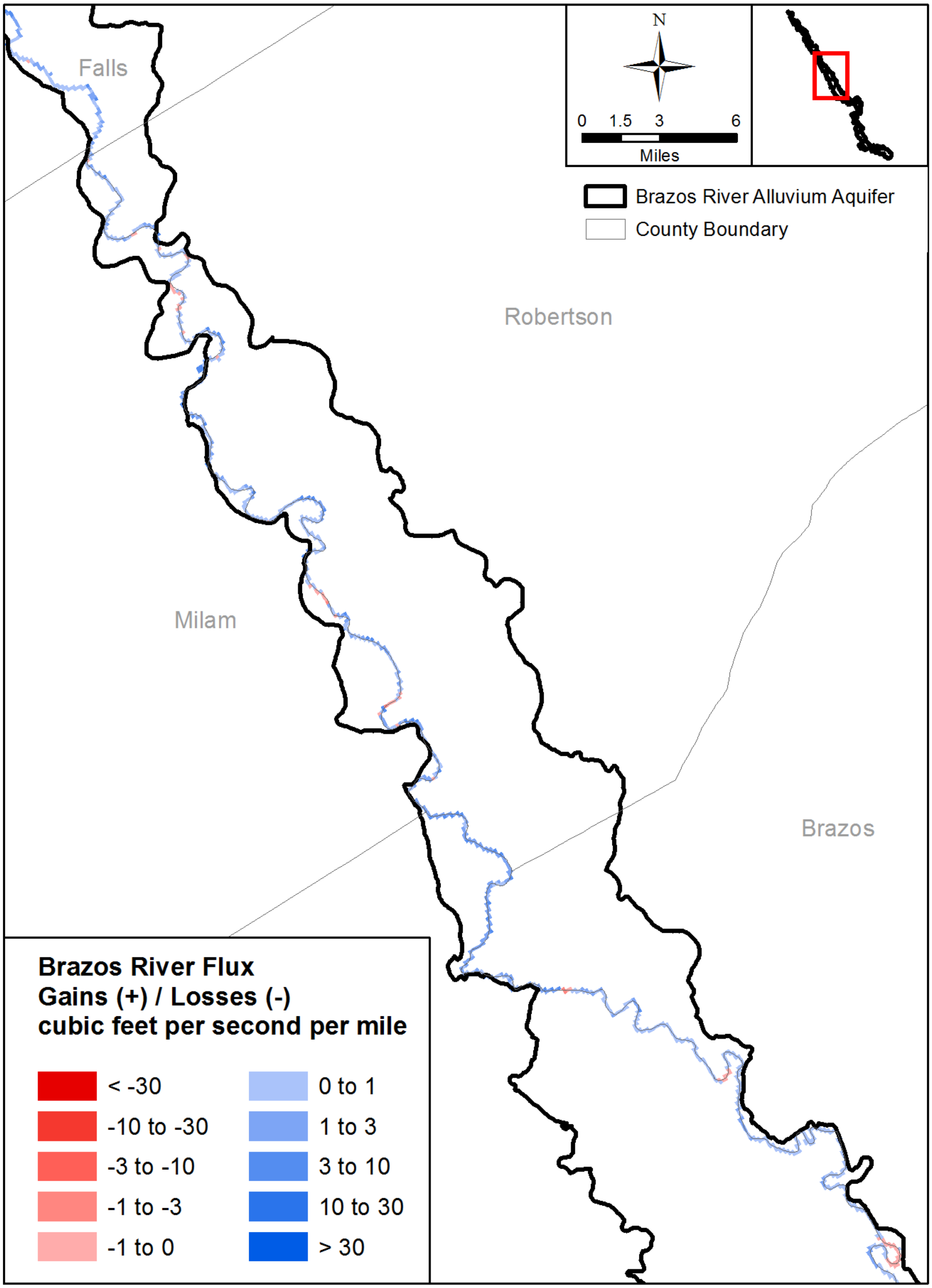

Figure 3.4.1b Spatial distribution of flux in and out of the Brazos River in cubic-feet per second per mile of stream in north-central region for the steady-state stress period.

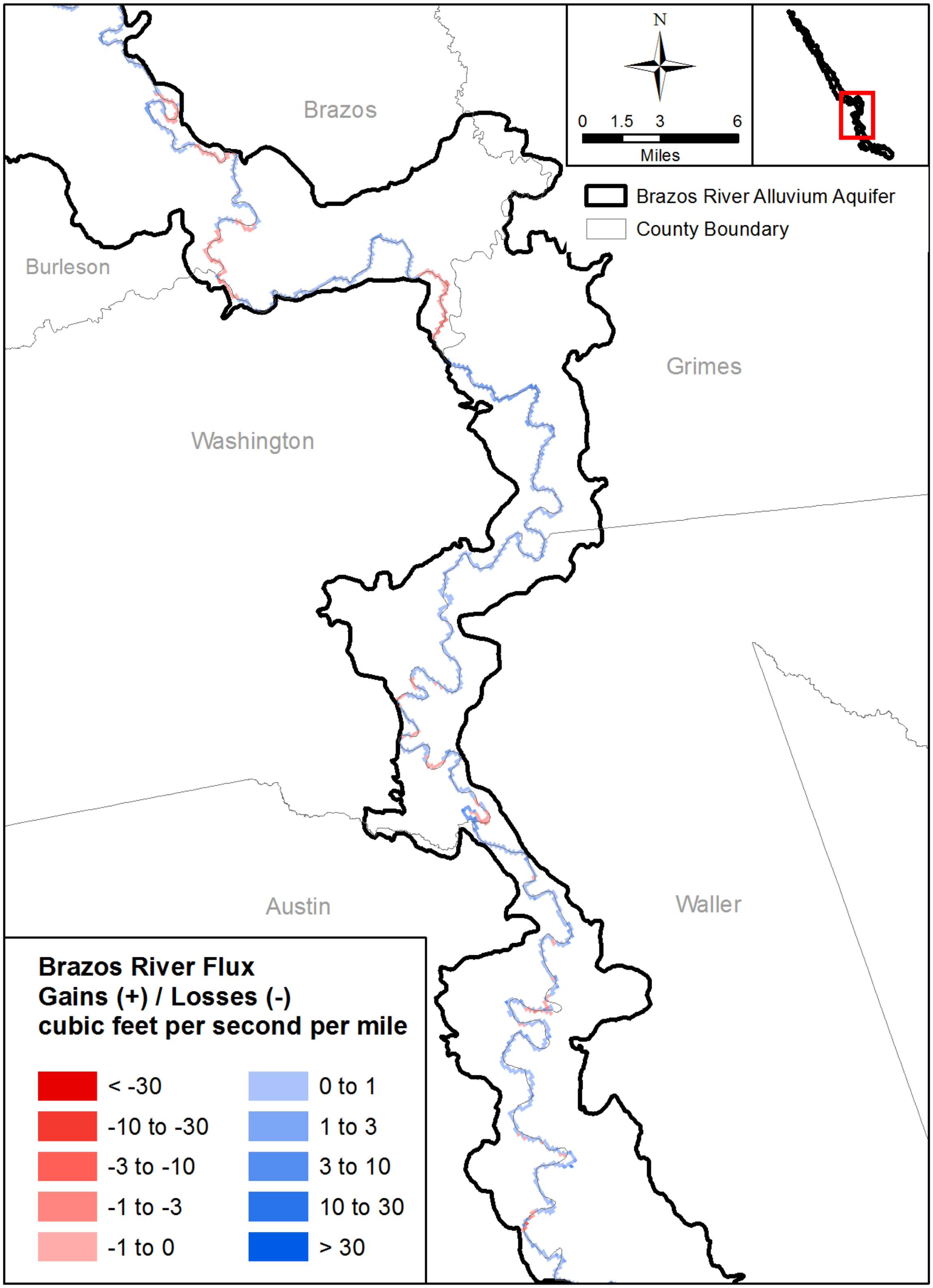

Figure 3.4.1c Spatial distribution of flux in and out of the Brazos River in cubic-feet per second per mile of stream in south-central region for the steady-state stress period.

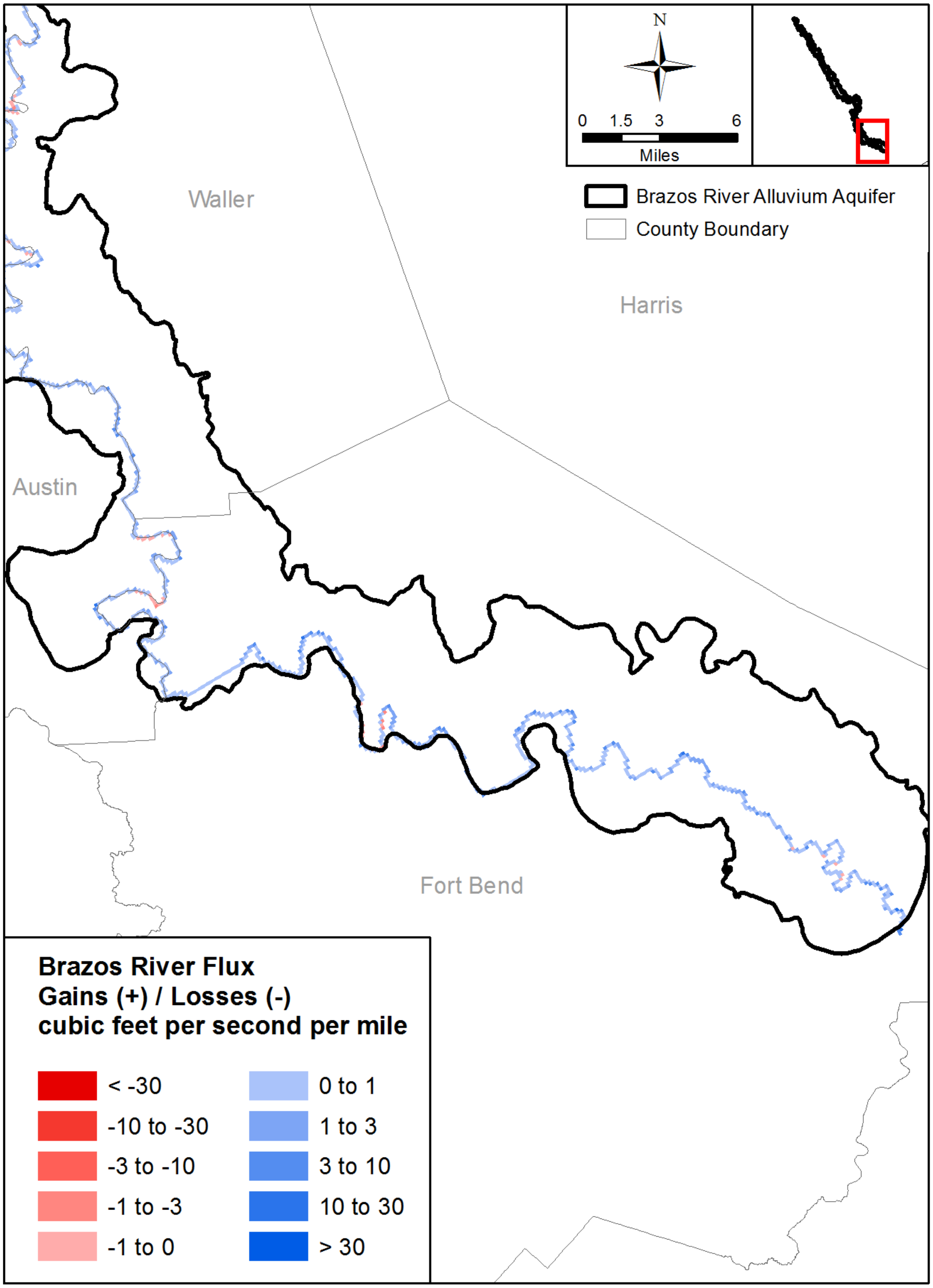

Figure 3.4.1d **Spatial distribution of flux in and out of the Brazos River in cubic-feet per second per mile of stream in southernmost region for the steady-state stress period.**

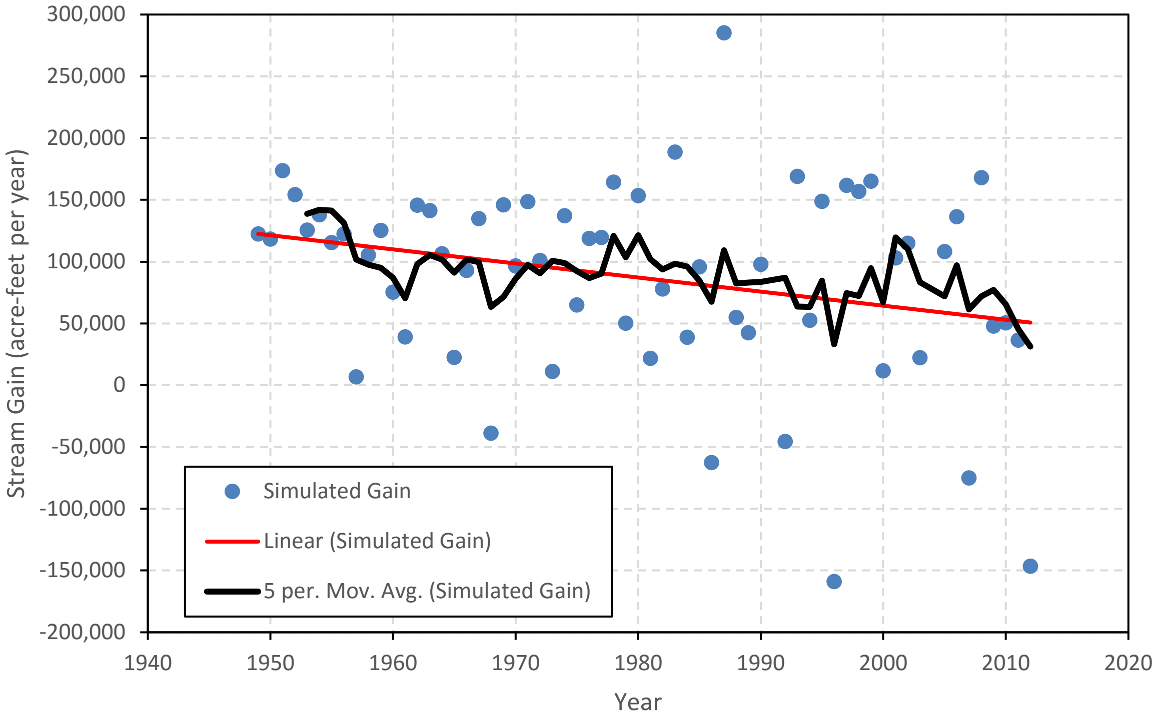

Figure 3.4.2 **Simulated stream gain in the Brazos River and tributaries over time in acre-feet per year (negative values indicate stream loss).**

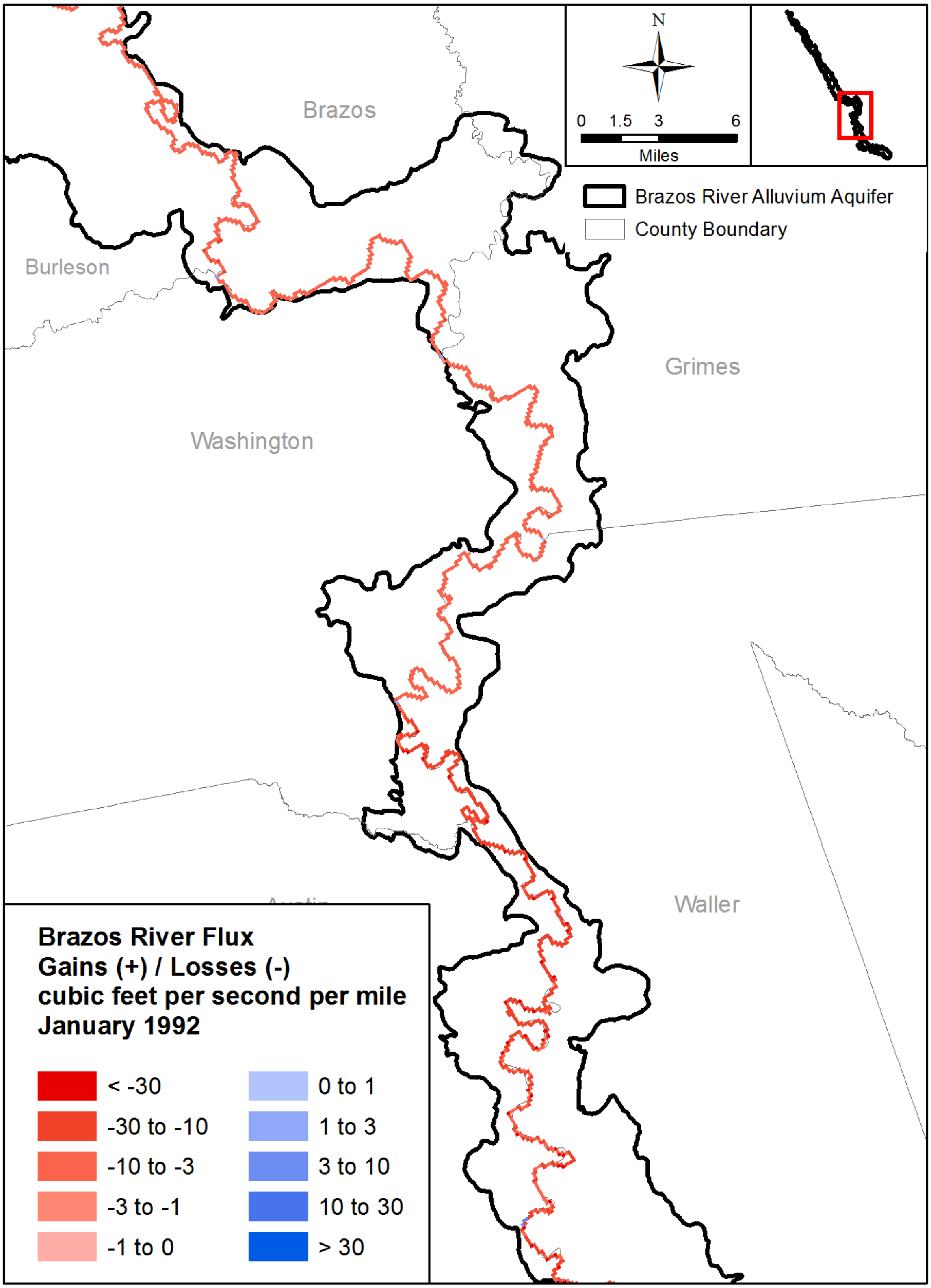

Figure 3.4.3 **Spatial distribution of flux in and out of the Brazos River in cubic-feet per second per mile of stream in south-central region for January, 1992.**

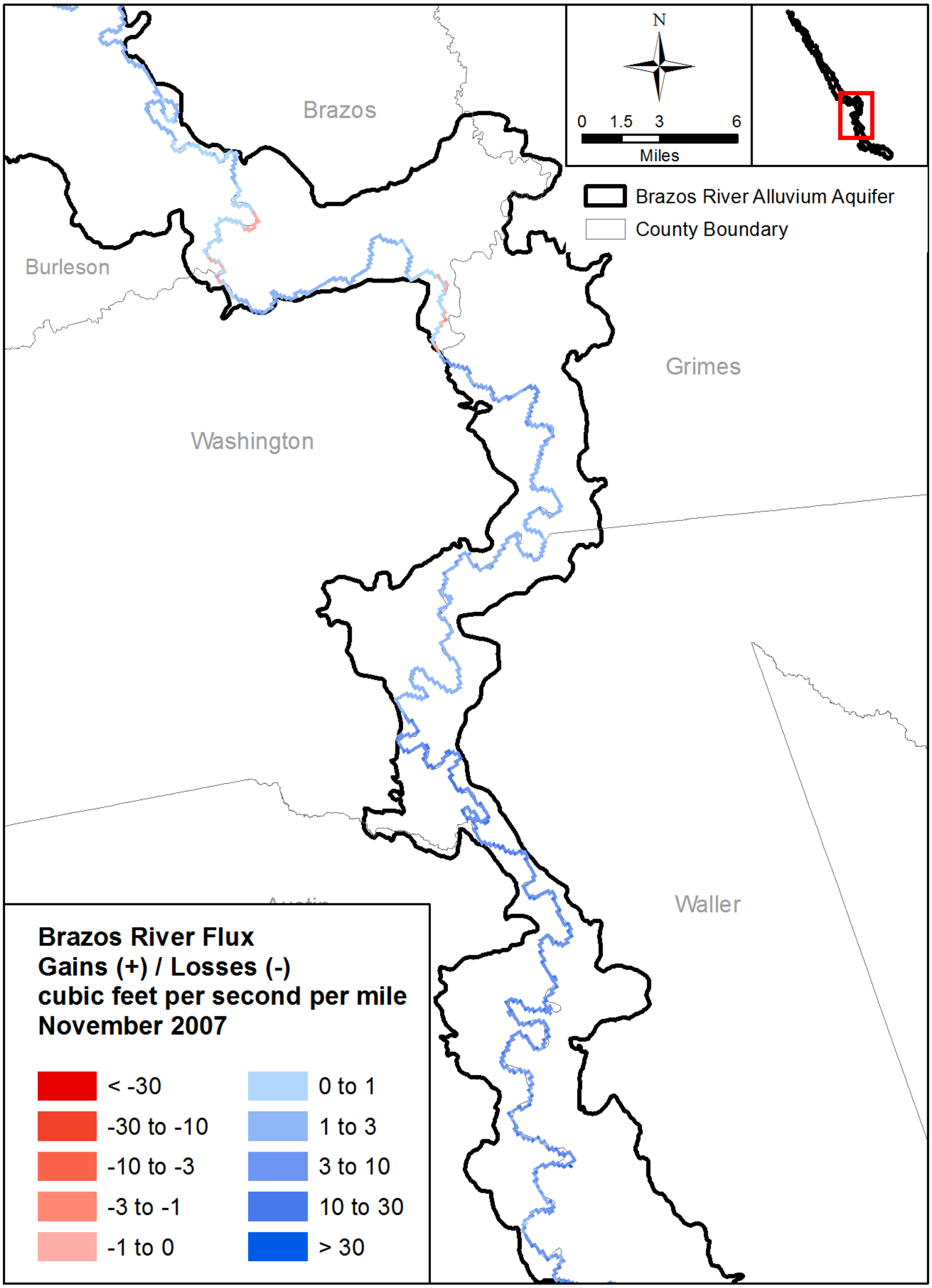

Figure 3.4.4 **Spatial distribution of flux in and out of the Brazos River in cubic-feet per second per mile of stream in south-central region for November, 2007.**

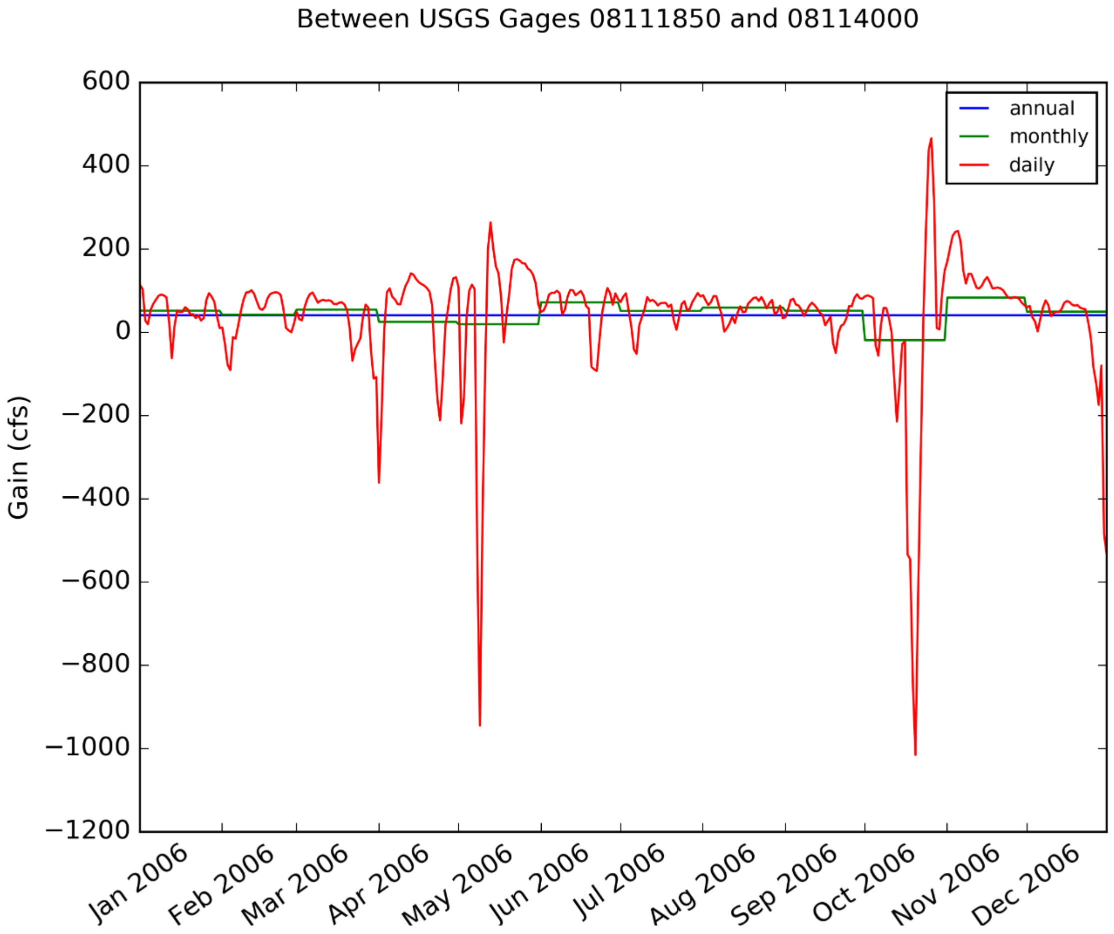

Figure 3.4.5 **Simulated gain and loss to the Brazos River in 2006 for annual, monthly and daily stress periods.**

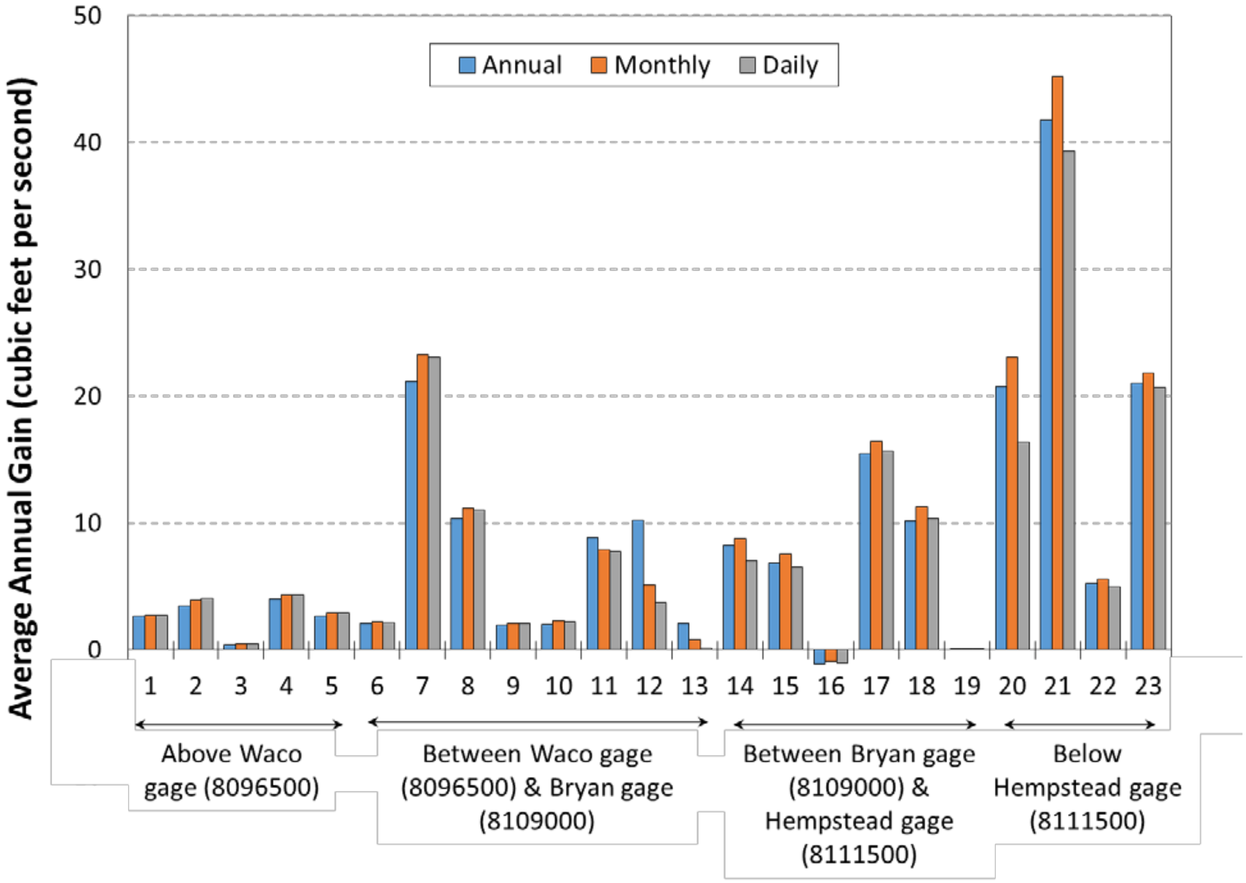

Figure 3.4.6 **Simulated annually-averaged net gain to the Brazos River in 2006 between stream gages for annual, monthly and daily stress periods.**

3.5 Model Simulated Water Budgets

In this section, the simulated water budgets are discussed both for the steady-state and transient stress periods. The water budgets are one of the more important aspects of the Brazos River Alluvium Aquifer groundwater availability model, since the model provides an opportunity to analyze flow between the alluvium and the underlying aquifers and formations that discharge regionally to the Brazos River. In this section the water budget is discussed with respect to both the model layers and the overall Brazos River Alluvium Aquifer. Appendix A contains the water budgets summarized by county and groundwater conservation district, for all counties and groundwater conservation districts in the study area.

3.5.1 Steady-State Water Budget

Table 3.5.1 summarizes the water budget for the steady-state model in acre-feet per year for Brazos River Alluvium Aquifer and the underlying formations. While the focus of this model is the Brazos River Alluvium Aquifer, the shallow portions of the underlying formations were included within the lateral extent of the Brazos River Basin to minimize uncertainty in applying boundary conditions to the model. Because the areal extent of the Brazos River Basin is much greater than the areal extent of the Brazos River Alluvium Aquifer in the study area, areal recharge and recharge/discharge to streams in layer 3, which represents the underlying formations, is much greater than in the Brazos River Alluvium Aquifer (layers 1 and 2). From the perspective of the Brazos River Alluvium Aquifer, the only flow term of interest in the underlying formations is the cross-formational flow to and from those formations. Table 3.5.2 contains the model-wide water budget components for each aquifer as a percentage of total inflow and outflow. Figure 3.5.1 shows a bar chart of the steady-state water budget for the Brazos River Alluvium Aquifer.

3.5.2 Transient Water Budget

Tables 3.5.3 and 3.5.4 show a summary of the transient water budget for December, 1980 and December, 2012, respectively. The pumping in the underlying formations represents the fluxes extracted from the three models of the underlying aquifers using the tool described in Section 2.4.5. Table 3.5.5 shows net water budgets in the Brazos River Alluvium Aquifer for several time periods. As noted at the beginning of the section, Appendix A contains the water budget summarized by county and groundwater conservation district, for all counties and groundwater conservation districts in the study area for several years of the historical period. In this subsection, time series plots will be used as the basis for the discussion of the transient water balance for each of the aquifers in the system.

Figures 3.5.2 and 3.5.3 show bar charts of the water budgets for the Brazos River Alluvium Aquifer in December, 1980 and December, 2012, respectively. These figures illustrate the variability in the relative magnitudes of gain or loss to perennial streams in the alluvium and the corresponding variability in flow to or from storage in the alluvium. This variability in stream-aquifer interaction and aquifer storage is indicative of "bank storage" where water flows to and from the perennial streams into and out of the portions of the Brazos River Alluvium Aquifer adjacent to the Brazos River at relatively small time scales (i.e., less than a month).

Figure 3.5.4 shows the water budget for the Brazos River Alluvium Aquifer in the transient model. The upper plot depicts the period from 1950 through 1979 and the lower plot shows the period from January, 1980 through December, 2012. Figure 3.5.5 depicts the same period from January, 1980 through December, 2012 as the lower plot in Figure 3.5.4 but with the y-axis zoomed to show the less variable flow components. On average recharge and cross-formational flow from the underlying formations are the dominant inflows to the model and discharge to perennial streams is the dominant outflow mechanism. Given the variability in stage in the perennial streams and the Brazos River in particular, the flow to and from perennial streams is highly variable for monthly stress periods. A correspondingly high (but opposite) variability in aquifer storage is also apparent for the monthly stress periods. This reflects what is termed "bank storage" which describes water flowing from the stream into the portion of the alluvium adjacent to the stream (the riverbank) during the brief periods of very high stream stage and then flowing rapidly back to the stream as the stream stage returns to relatively normal levels.

Table 3.5.1 Steady-state water budget in acre-feet per year.

IN								
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Cross-formational**	**Internal Layer Total**	**Layer[2] Total**
Brazos River Alluvium	96,343	17,349				48,835	162,527	113,692
Underlying Formations	583,687	45,105				3,265	632,057	628,793
Sum	680,031	62,454						742,485
OUT								
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Cross-formational**	**Internal Layer Total**	**Layer[2] Total**
Brazos River Alluvium		-139,769	-4,848	-14,405	-237	-3,265	-162,525	-159,260
Underlying Formations		-253,193	-307,293	-20,215	-2,524	-48,835	-632,061	-583,226
Sum		-392,962	-312,141	-34,621	-2,762			-742,486

[1] ET denotes evapotranspiration.

[2] Layer total does not include cross-formational flow, since cross-formational flow is internal to the overall model.

Table 3.5.2 Steady-state water budget components expressed as a percentage of total inflow and outflow.

IN						
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Layer Total**
Brazos River Alluvium	13.0%	2.3%				15.3%
Underlying Formations	78.6%	6.1%				84.7%
Sum	91.6%	8.4%				100.0%
OUT						
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET1**	**Springs**	**Layer Total**
Brazos River Alluvium		-18.8%	-0.7%	-1.9%	-0.03%	-21.4%
Underlying Formations		-34.1%	-41.4%	-2.7%	-0.3%	-78.6%
Sum		-52.9%	-42.0%	-4.7%	-0.4%	-100.0%

[1] ET denotes evapotranspiration.

Table 3.5.3 Transient Water Budget in acre-feet per year for December, 1980.

IN										
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Cross-formational**	**Storage**	**Pumping**	**Internal Layer Total**	**Layer[2] Total**
Brazos River Alluvium	88,839	24,430				52,132	61,153		226,554	174,422
Underlying Formations	529,923	41,126				2,987	119,193	1,219	694,448	691,460
Sum	618,762	65,556					180,345	1,219		865,882
OUT										
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Cross-formational**	**Storage**	**Pumping**	**Internal Layer Total**	**Layer[2] Total**
Brazos River Alluvium		-137,765	-4,386	-12,499	-250	-2,987	-43,284	-25,380	-226,551	-223,564
Underlying Formations		-275,497	-305,968	-20,651	-2,667	-52,132	-4,476	-33,052	-694,442	-642,310
Sum		-413,262	-310,354	-33,150	-2,916		-47,760	-58,432		-865,874

[1] ET denotes evapotranspiration.

[3] Layer total does not include cross-formational flow, since cross-formational flow is internal to the overall model.

Table 3.5.4 Transient Water Budget in acre-feet per year for December, 2012.

IN										
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Cross-formational**	**Storage**	**Pumping**	**Internal Layer Total**	**Layer[2] Total**
Brazos River Alluvium	104,494	67,869				50,203	109,768		332,334	282,130
Underlying Formations	616,045	78,415				3,794	33,587	2,332	734,172	730,379
Sum	720,539	146,284					143,355	2,332		1,012,509
OUT										
Aquifer	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Springs**	**Cross-formational**	**Storage**	**Pumping**	**Internal Layer Total**	**Layer[2] Total**
Brazos River Alluvium		-91,799	-3,485	-15,543	-257	-3,794	-166,149	-51,314	-332,340	-328,547
Underlying Formations		-218,865	-294,305	-20,703	-2,578	-50,203	-107,261	-40,264	-734,178	-683,975
Sum		-310,664	-297,790	-36,246	-2,835		-273,409	-91,577		-1,012,521

[1] ET denotes evapotranspiration.

[2] Layer total does not include cross-formational flow, since cross-formational flow is internal to the overall model.

Table 3.5.5 Net Water Budgets in acre-feet per year for the Brazos River Alluvium Aquifer.

Period	**Recharge**	**Perennial Streams**	**Ephemeral Streams**	**ET[1]**	**Spring**	**Cross-formational**	**Storage**	**Pumping**
Steady-State	96,343	-122,421	-4,848	-14,405	-237	45,570	0	0
Dec-1980	88,839	-113,335	-4,386	-12,499	-250	49,144	17,868	-25,380
Dec-2012	104,494	-23,930	-3,485	-15,543	-257	46,410	-56,381	-51,314

[1] ET denotes evapotranspiration.

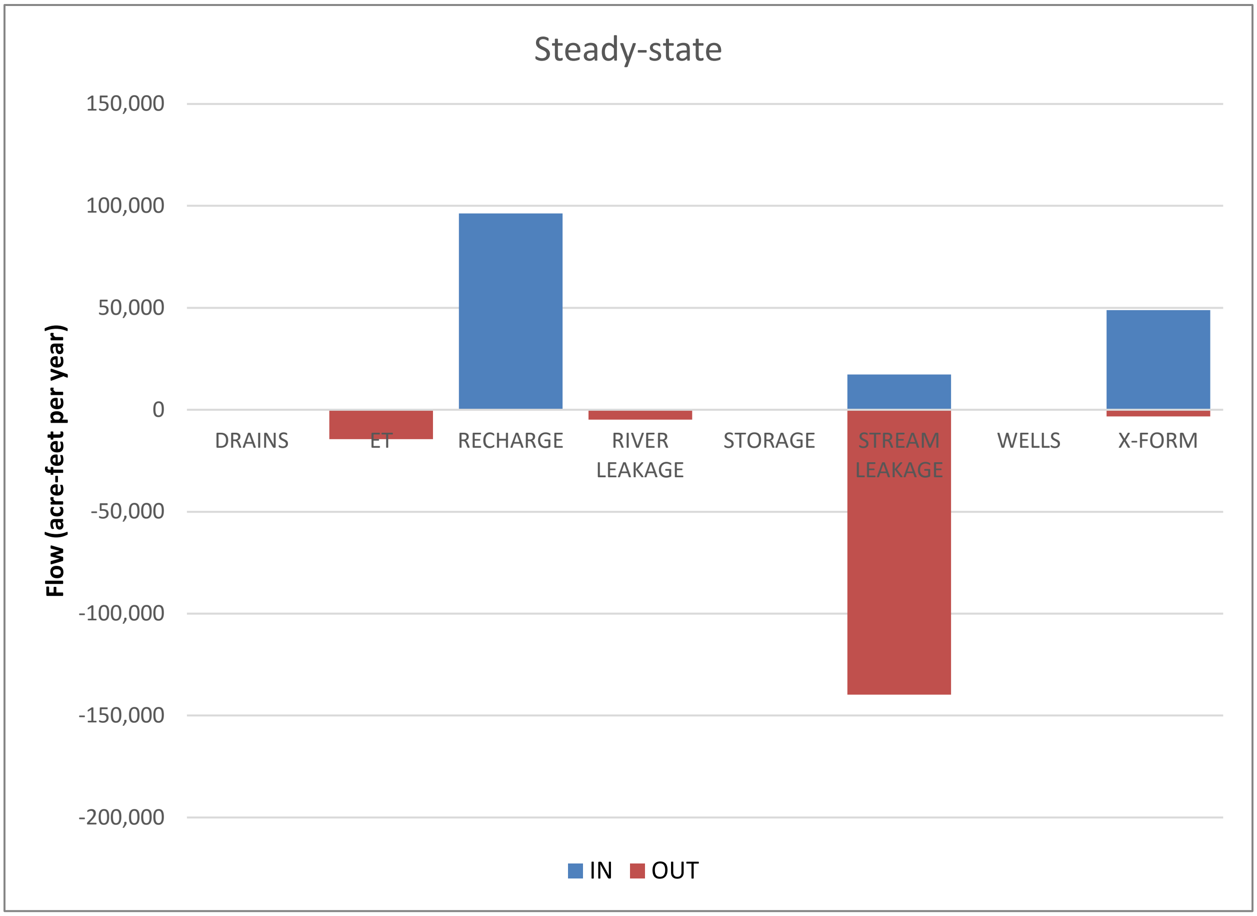

Figure 3.5.1 **Water budget in acre-feet per year in Brazos River Alluvium Aquifer for the steady-state model. (Abbreviation key: ET = evapotranspiration)**

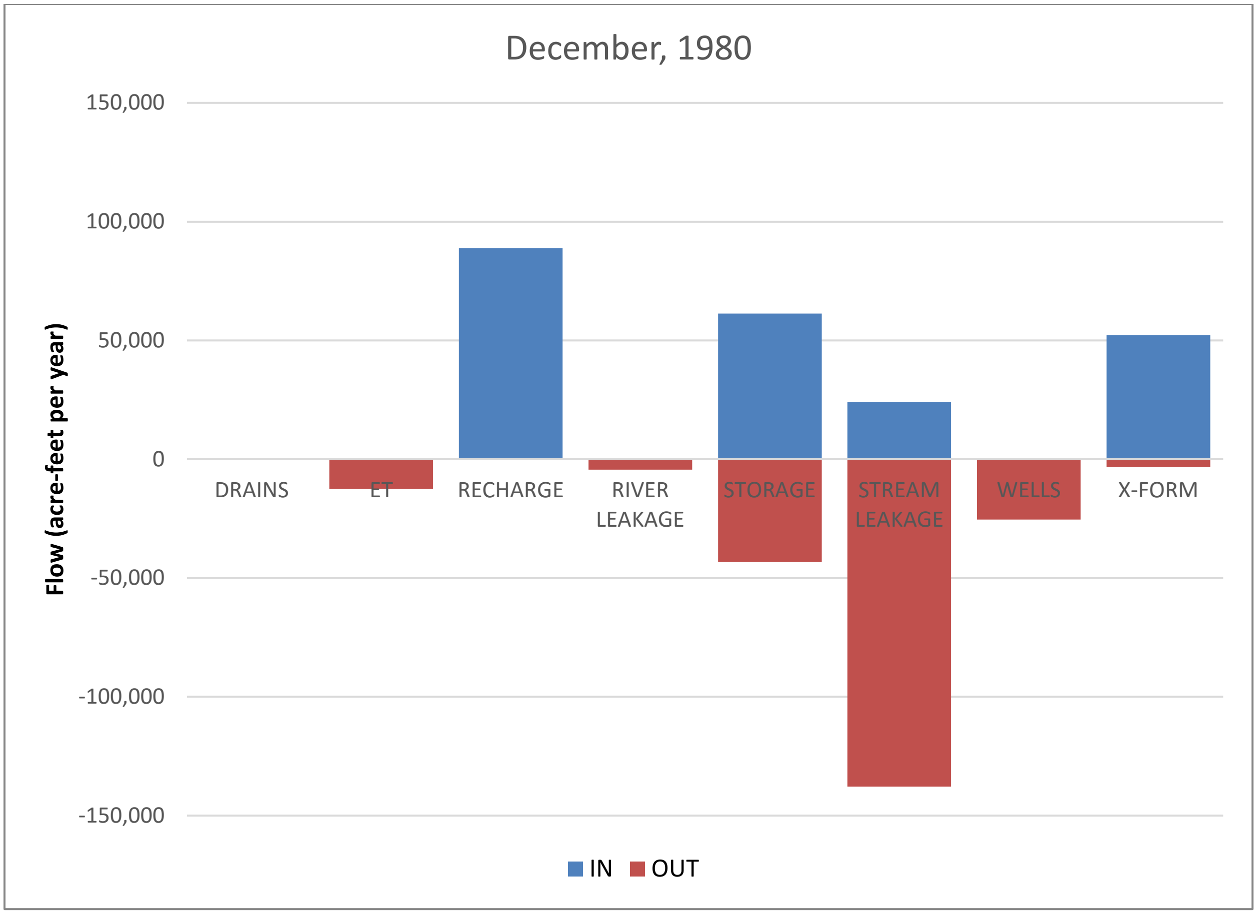

Figure 3.5.2 **Water budget in acre-feet per year in Brazos River Alluvium Aquifer in December, 1980. (Abbreviation key: ET = evapotranspiration)**

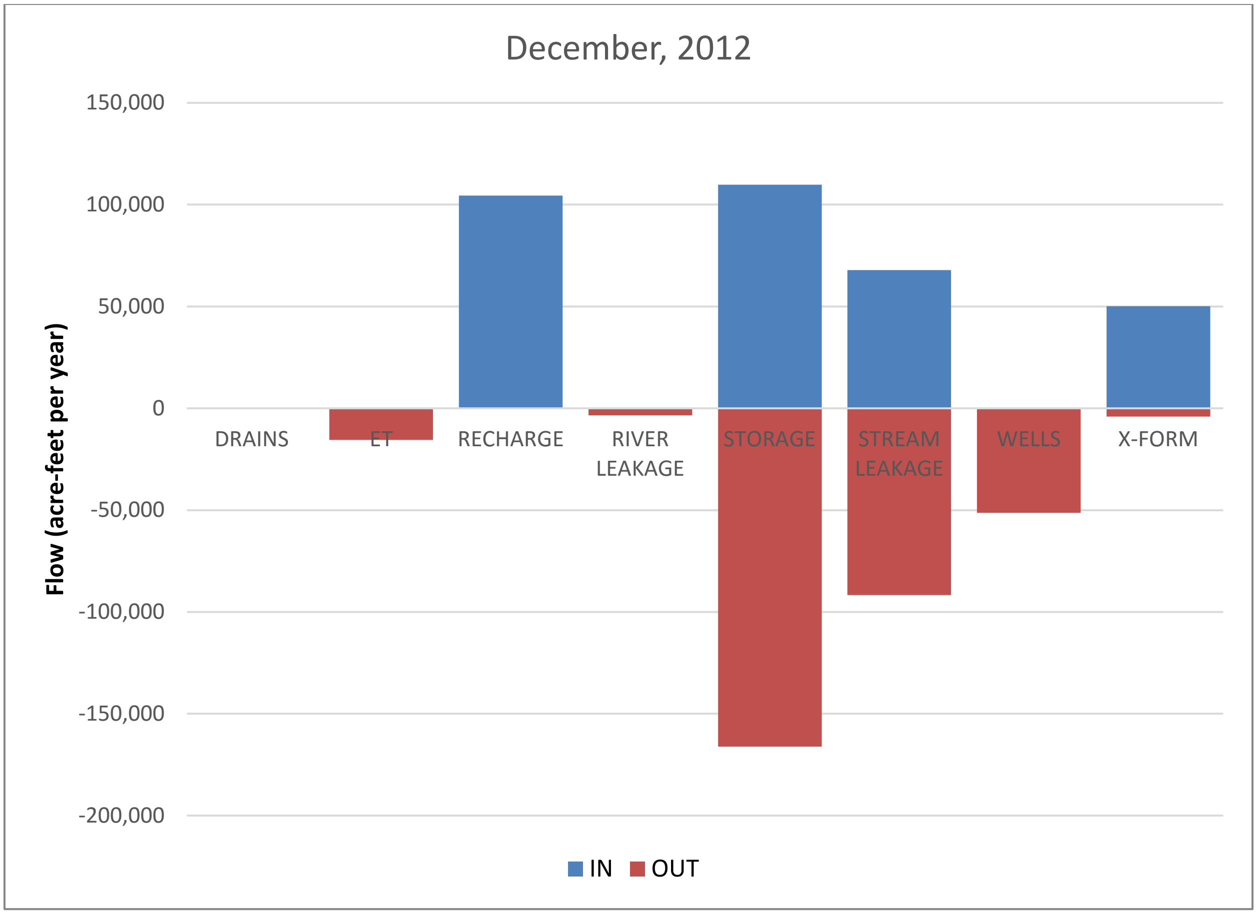

Figure 3.5.3 **Water budget in acre-feet per year in Brazos River Alluvium Aquifer in December, 2012. (Abbreviation key: ET = evapotranspiration)**

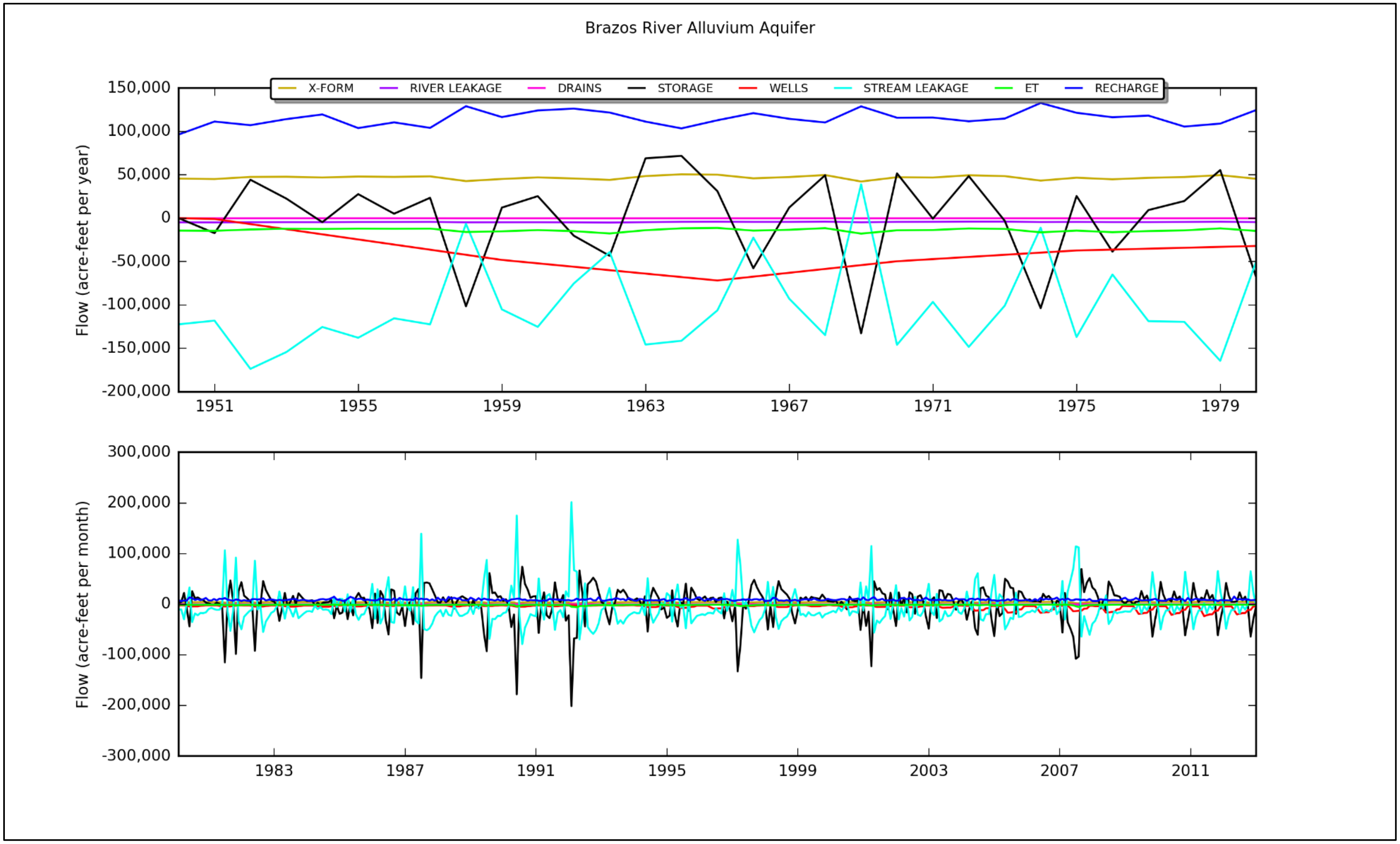

Figure 3.5.4 Water budget in the Brazos River Alluvium Aquifer for the transient model with the annual stress periods from 1950 through 1979 in acre-feet per year (upper figure) and the monthly stress periods from January, 1980 through December, 2012 in acre-feet per month (lower figure). (Abbreviation key: ET = evapotranspiration)

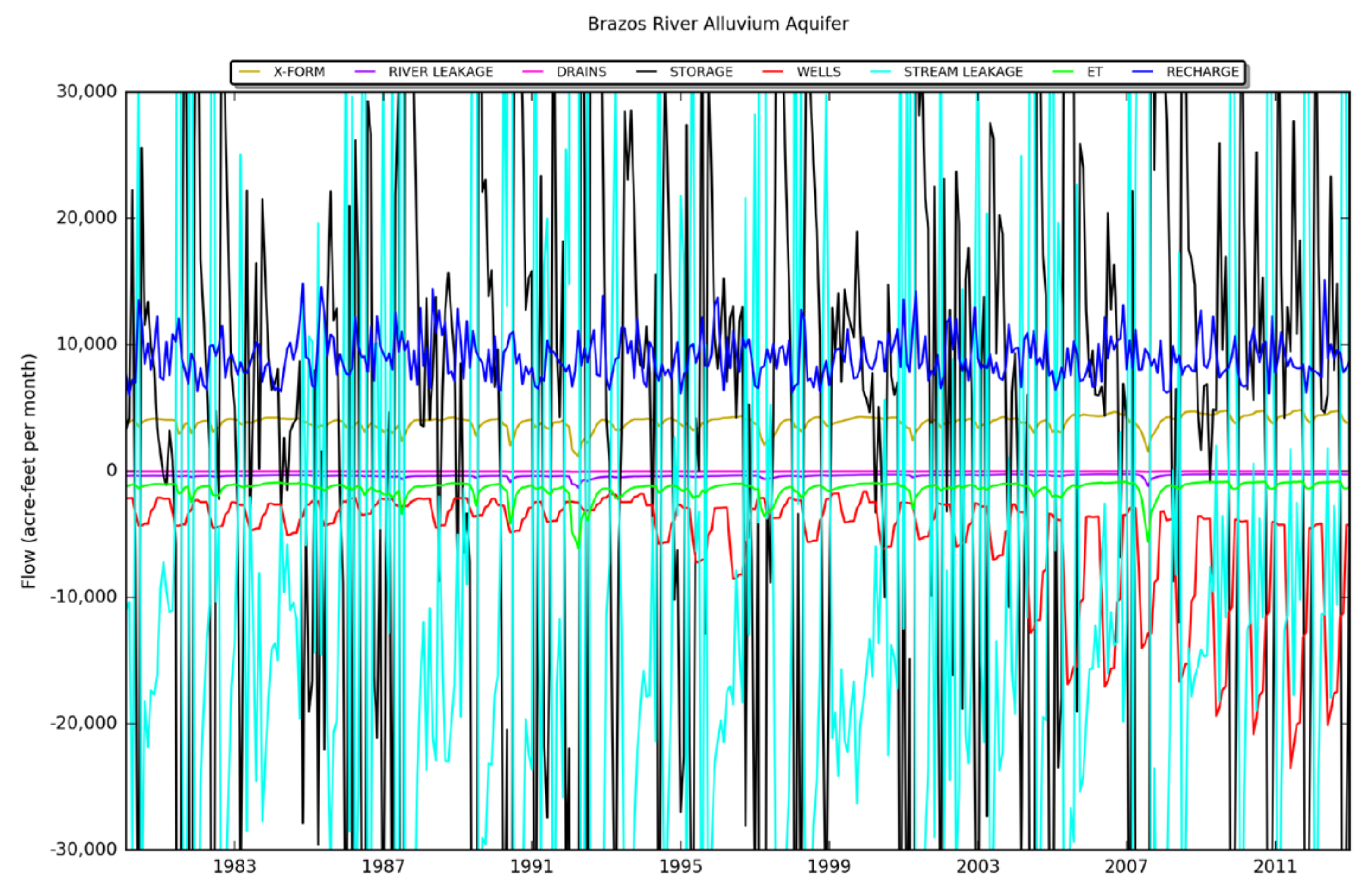

Figure 3.5.5 **Water budget in the Brazos River Alluvium Aquifer for the transient model for the monthly stress periods from January, 1980 through December, 2012 in acre-feet per month with the y-axis zoomed to show the less variable flow components. (Abbreviation key: ET = evapotranspiration)**

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3.6 Correlation Between Pumping and Recharge

In this section, the pumping and recharge applied to the Brazos River Alluvium aquifer during the transient stress periods is evaluated to test for any correlation between the two input parameters. Recharge the largest source of inflow to the Brazos River Alluvium Aquifer and pumping is a major avenue of outflow, particularly in recent years.

3.6.1 Total Pumping versus Recharge from Precipitation

To evaluate possible temporal correlation, the total pumping rate in the Brazos River Alluvium Aquifer is plotted against the total recharge rate to the aquifer in Figure 3.6.1 for each transient stress period. The 426 points on the figure represent each of the 426 transient stress periods. There is no apparent relationship between the two parameters and, indeed, a linear fit to the data results in a very low coefficient of determination (R^2) of 0.0002. This indicates that there is virtually no correlation between the two input parameters in the model. As discussed in Section 2.6, the temporal variation in recharge to the transient model is a function only of temporal variations in precipitation. While historical pumping may be affected by longer periods of lower-than-average precipitation, a larger temporal trend of increased pumping over time, particularly in recent years, is evident in the historical pumping estimates as discussed in Section 4.6.2 of Ewing and others (2016). Some of the largest and smallest rates of both recharge and pumping seen in Figure 3.6.1 occur during the monthly stress periods from 1980 through 2012 when precipitation is more variable and irrigation pumping is based on crop growing seasons.

3.6.2 Average Pumping versus Average Recharge by County

To evaluate possible spatial correlation, the temporally averaged pumping rate in the Brazos River Alluvium is plotted against the temporally averaged recharge rate to the aquifer in Figure 3.6.2 for each county that intersects the aquifer. The 13 points on the figure represent each of the 13 counties that intersect the Brazos River Alluvium Aquifer. Again, there is no clear relationship between the two parameters and a linear fit to the data results in a low coefficient of determination of 0.22. To evaluate whether this small degree of apparent correlation is partly a function of the area of the alluvium in each county, Figure 3.6.3 shows the same data normalized to the area of the alluvium in each county. Indeed there is less apparent correlation and the coefficient of determination reduces to 0.07. As discussed in Section 2.4, the spatial distribution of pumping is based largely on the location of cropland irrigated by groundwater. The spatial distribution of recharge is influenced by irrigation return flow but, as discussed in Section 4.3.2 of Ewing and others (2016), this includes croplands irrigated by surface water as well as groundwater and has a relatively small impact on recharge compared to precipitation and surficial soil type.

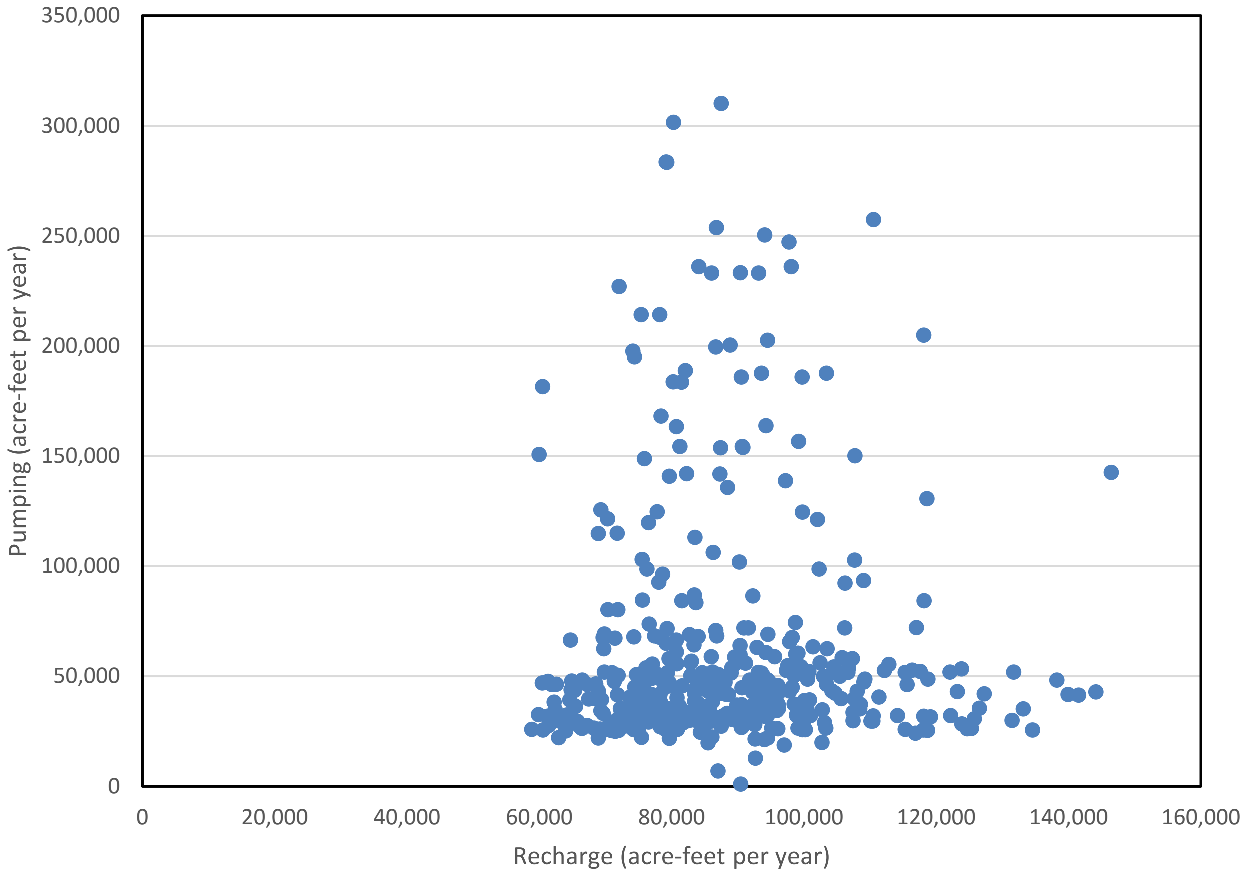

Figure 3.6.1 **Total Pumping versus Total Recharge in the Brazos River Alluvium Aquifer for each Transient Stress Period in acre-feet per year.**

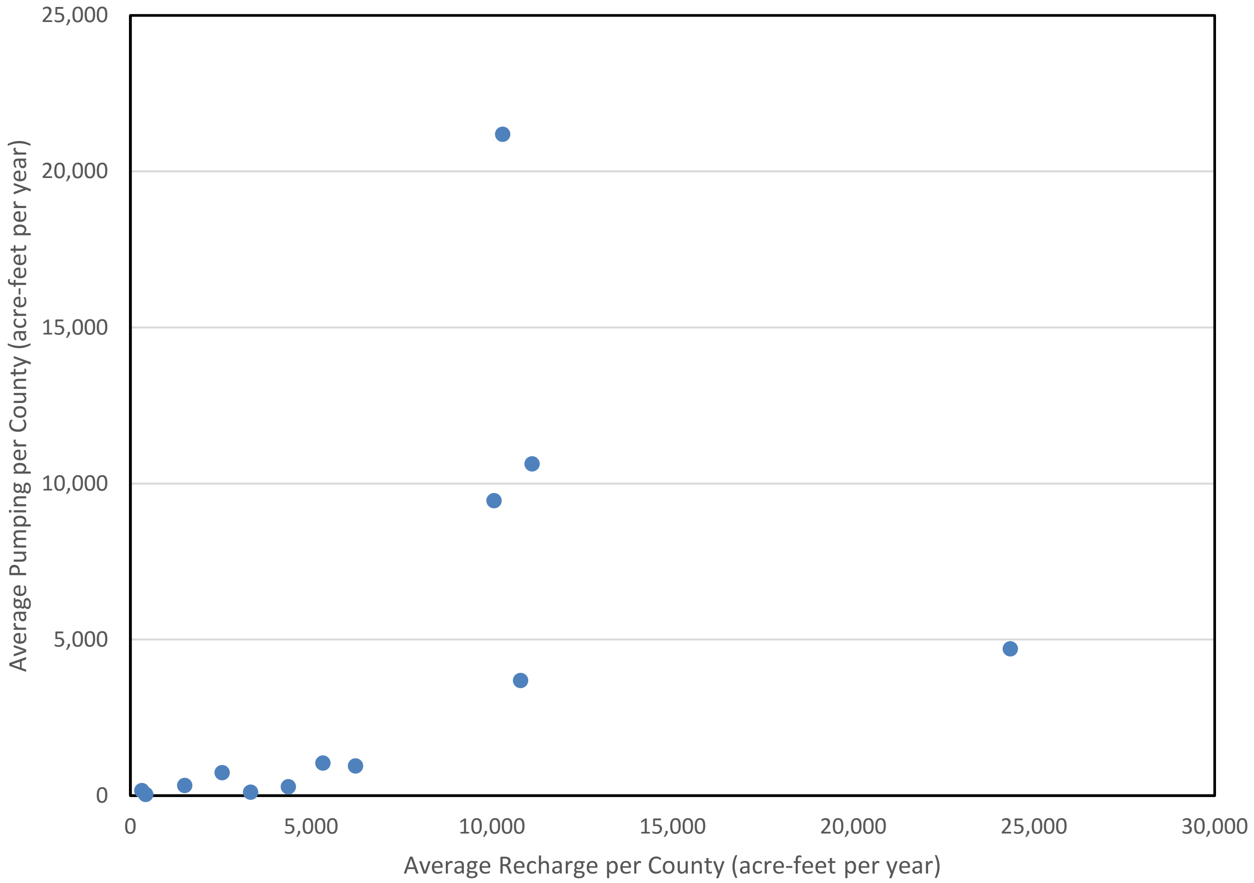

Figure 3.6.2 **Average Pumping versus Average Recharge in the Brazos River Alluvium Aquifer for each County in acre-feet per year.**

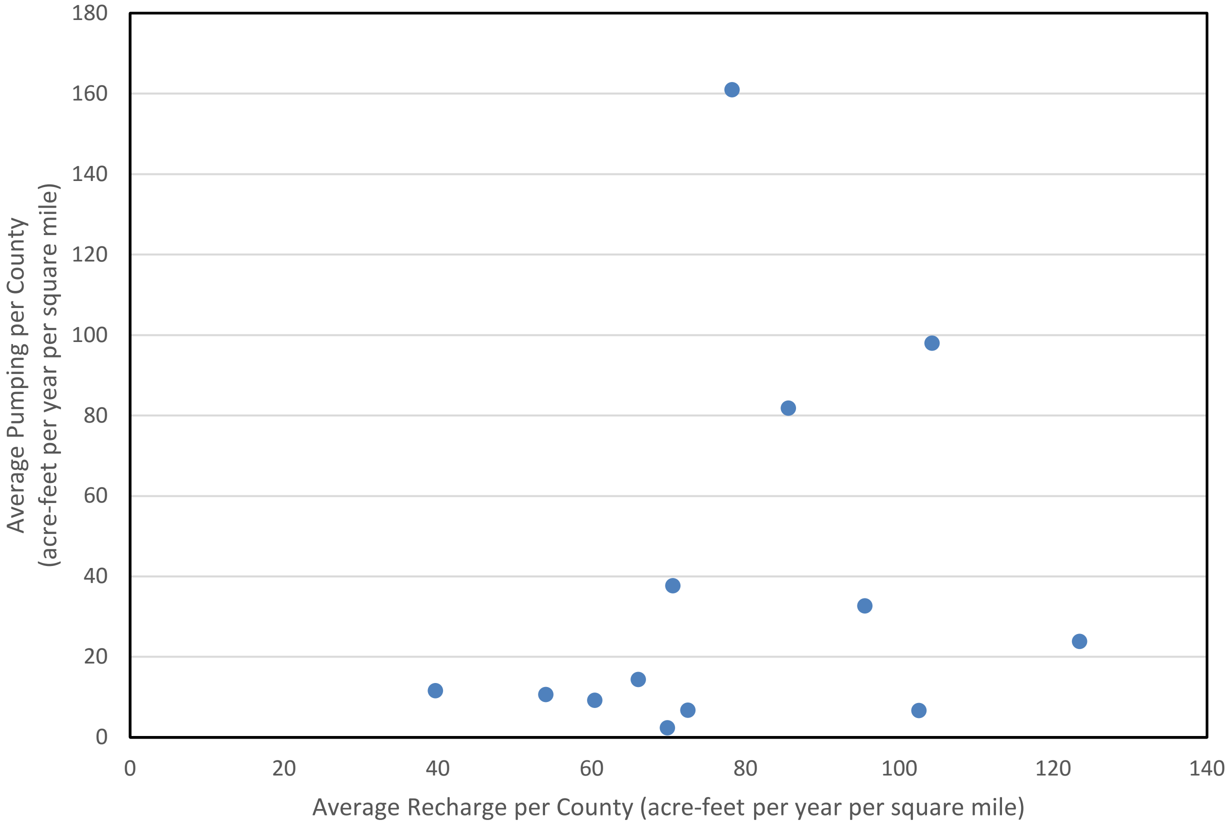

Figure 3.6.3 Normalized Average Pumping versus Normalized Average Recharge in the Brazos River Alluvium Aquifer for each County in acre-feet per year per square mile.

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4.0 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated model to determine the impact of changes in calibrated parameters on the predictions of the calibrated model. A sensitivity analysis provides a means of formally describing the impact of varying specific parameters or groups of parameters on model outputs. In this sensitivity analysis, input parameters were systematically increased and decreased from their calibrated values while the change in hydraulic heads and flows was recorded. Informally, this is referred to as a standard "one-off" sensitivity analysis. This means that hydraulic parameters or stresses were adjusted from their calibrated "base case" values one at a time while all other hydraulic parameters remained unperturbed.

Section 4.1 describes the sensitivity analysis procedure. Section 4.2 contains a discussion of the results of the steady-state and transient sensitivity analyses, primarily presented using spider plots. In addition, the sensitivity of transient simulated hydrograph responses to several parameters is shown at the end of the section.

4.1 Sensitivity Analysis Procedure

Four simulations were completed for each parameter sensitivity, where the input parameters were varied either according to:

$$\text{(new parameter)} = \text{(old parameter)} * \text{factor} \tag{4.1.1}$$

or

$$\text{(new parameter)} = \text{(old parameter)} * 10^{\text{(factor - 1)}} \tag{4.1.2}$$

and the factors were 0.5, 0.9, 1.1, and 1.5. Parameters such as recharge were varied linearly using Equation 4.1.1. For parameters such as hydraulic conductivity, which are typically thought of as log-varying, Equation 4.1.2 was used. For the output variable, the mean difference between the calibrated simulated hydraulic head and the sensitivity simulated hydraulic head was calculated as:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sens,i} - h_{cal,i}\right) \tag{4.1.3}$$

where:

MD = mean difference

$h_{sens,i}$ = sensitivity simulation hydraulic head at active grid cell i

$h_{cal,i}$ = calibrated simulation hydraulic head at active grid cell i

n = number of active grid cells, or the number of target locations

Equation 4.1.3 was applied separately both model-wide (that is, in all active grid cells) and at target locations only. If the results are different between these two applications, it can be an indication that the targets are poorly distributed. However, if the results did not differ substantially, the second case will not be specifically discussed in this section.

Similarly, the mean difference in flows was calculated for flow boundaries as:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(q_{sens,i} - q_{cal,i}\right) \qquad (4.1.4)$$

where:

MD = mean difference

$q_{sens,i}$ = sensitivity simulation flow at active grid cell i

$q_{cal,i}$ = calibrated simulation flow at active grid cell i

n = number of cells for flow boundary

For the steady-state sensitivity analysis, 28 combinations of input parameters and output metrics were investigated. For each input parameter listed below, the sensitivities of hydraulic head in each model layer and the flows to boundary conditions and cross-formational flow are assessed.

1. Horizontal hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 1.
2. Horizontal hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 2.
3. Horizontal hydraulic conductivity of the underlying formations in layer 3.
4. Vertical hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 1.
5. Vertical hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 2.
6. Vertical hydraulic conductivity of the underlying formations in layer 3.
7. Recharge in the Brazos River Alluvium Aquifer.
8. Recharge in the underlying formations.
9. Conductance of the stream-flow routing boundaries representing perennial streams.
10. Width of the stream-flow routing boundaries representing perennial streams.
11. Conductance of the river boundaries representing ephemeral streams.
12. Conductance of the drain boundaries representing springs.

13. Evapotranspiration rate of the evapotranspiration boundaries representing groundwater evapotranspiration.
14. Extinction depth of the evapotranspiration boundaries representing groundwater evapotranspiration.

Equation 4.1.1 was used for sensitivities 7, 8, 10, 13 and 14, while Equation 4.1.2 was used for the remaining sensitivities.

In addition to the sensitivities computed for the steady-state model, the transient model adds storage properties and pumping sensitivities as input parameters, for a total of 42 combinations of input parameters and output metrics:

1. Horizontal hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 1.
2. Horizontal hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 2.
3. Horizontal hydraulic conductivity of the underlying formations in layer 3.
4. Vertical hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 1.
5. Vertical hydraulic conductivity of the Brazos River Alluvium Aquifer in layer 2.
6. Vertical hydraulic conductivity of the underlying formations in layer 3.
7. Recharge in the Brazos River Alluvium Aquifer.
8. Recharge in the underlying formations.
9. Conductance of the stream-flow routing boundaries representing perennial streams.
10. Width of the stream-flow routing boundaries representing perennial streams.
11. Conductance of the river boundaries representing ephemeral streams.
12. Conductance of the drain boundaries representing springs.
13. Evapotranspiration rate of the evapotranspiration boundaries representing groundwater evapotranspiration.
14. Extinction depth of the evapotranspiration boundaries representing groundwater evapotranspiration.
15. Specific yield of the Brazos River Alluvium Aquifer in layer 1.
16. Specific yield of the Brazos River Alluvium Aquifer in layer 2.
17. Specific yield of the underlying formations in layer 3.
18. Storativity of the Brazos River Alluvium Aquifer in layer 1.
19. Storativity of the Brazos River Alluvium Aquifer in layer 2.

20. Storativity of the underlying formations in layer 3.
21. Pumping.

Equation 4.1.1 was used for sensitivities 7, 8, 10, and 13 through 21, while equation 4.1.2 was used for the remaining sensitivities.

4.2 Sensitivity Analysis Results

In the discussion of sensitivity analysis results, we consider head or flow as potential output metrics. In some cases, changing a particular parameter does not result in any significant change to heads or flows. We can judge the lower bound of significant change based on the head convergence criteria used in the Sparse Matrix Solver package. The head convergence criteria was 0.01 foot, so any average changes in head that are approximately 0.01 foot or less are considered to be insignificant. As we discuss the sensitivity analysis results, we will keep these limits in mind, where this level of variation in head change is considered to be within the range of the "noise" of the model.

For some cases, parameters were varied outside the range where the model was stable, so the model did not converge within the given convergence criteria. For these cases, we allowed the model to continue to run and then evaluated the results for any inconsistencies in the model behavior. For this model, the few sensitivity cases where the model was allowed to run despite not achieving convergence were found, upon subsequent inspection, to be only slightly outside the bounds set by the convergence criteria and the results appear to be valid from the perspective of a sensitivity analysis. Specifically, the sensitivity responses were monotonic and can be used to inform model sensitivity, to the degree that it is discussed here, in all cases.

4.2.1 Steady-State Sensitivities

Figure 4.2.1 shows the sensitivity in hydraulic heads to changes in the horizontal hydraulic conductivity of layer 1 for the steady-state model. Decreasing horizontal hydraulic conductivity increases hydraulic heads in the Brazos River Alluvium Aquifer (layers 1 and 2) and, to a lesser degree, in the underlying formations. Increasing the horizontal hydraulic conductivity of layer 1 has the reverse effect. Figure 4.2.2 shows the sensitivity to changes in the horizontal hydraulic conductivity of layer 2 with decreasing horizontal hydraulic conductivity increasing hydraulic heads in all three model layers. Figure 4.2.3 shows the sensitivity to changes in the horizontal hydraulic conductivity of the underlying formations with decreasing horizontal hydraulic conductivity increasing hydraulic heads in the underlying formations. The heads in the Brazos River Alluvium Aquifer are insensitive to changes in the horizontal hydraulic conductivity of the underlying formations.

As shown in Figure 4.2.4, there is little sensitivity to changes in the vertical hydraulic conductivity in layer 1 to hydraulic heads as the absolute mean head difference is within the noise of the head convergence. Figure 4.2.5 shows that there is even less sensitivity to variation in the vertical hydraulic conductivity in layer 2. Figure 4.2.6 shows the hydraulic head sensitivity to changes in vertical hydraulic conductivity in layer 3 with decreasing vertical hydraulic conductivity increasing hydraulic heads in the underlying formations. The heads in the Brazos River Alluvium Aquifer are insensitive to changes in the vertical hydraulic conductivity of the underlying formations.

Figure 4.2.7 depicts the hydraulic head sensitivity in response to changes in recharge to the Brazos River Alluvium Aquifer, with increasing recharge increasing hydraulic heads in all three layers. Figure 4.2.8 shows the hydraulic head sensitivity to changes in recharge to the outcrops of the underlying formations with increasing recharge increasing heads in all three layers but particularly in layer 3.

Figure 4.2.9 shows the hydraulic head response to changes in the streambed conductance of perennial streams, with decreasing streambed conductance increasing heads in all three layers. Figure 4.2.10 shows the hydraulic head sensitivity to changes in the width of perennial streams, with decreasing width increasing heads in all three layers. Figure 4.2.11 depicts the response of hydraulic heads to changes in streambed conductance in ephemeral streams with decreasing streambed conductance increasing hydraulic heads in all three layers but particularly in layer 3.

Figure 4.2.12 shows the hydraulic head sensitivity in response to changes in spring conductance with decreasing spring conductance increasing heads with the overall response being relatively insensitive. Figure 4.2.13 depicts the hydraulic head response to changes in the maximum evapotranspiration rate with decreasing maximum evapotranspiration rate increasing hydraulic heads in all three layers. Figure 4.2.14 shows the hydraulic head sensitivity to changes in extinction depth for evapotranspiration with decreasing extinction depth increasing hydraulic heads in all three layers.

Figure 4.2.15 shows the sensitivity in boundary fluxes to the horizontal hydraulic conductivity of layer 1. The sensitivities in boundary fluxes are grouped into fluxes for perennial streams, fluxes for ephemeral streams, evapotranspiration fluxes, spring fluxes, and the cross-formational flow from the underlying formations to the Brazos River Alluvium Aquifer and the underlying formations. The sign convention is such that flow or net flow to a boundary or from underlying formations is always positive. Increasing the horizontal hydraulic conductivity increases both flow to perennial streams and flow from the underlying formations. In contrast, increases in the horizontal hydraulic conductivity of layer 1 decrease flow to ephemeral streams and, to a lesser degree, evapotranspiration and have very little effect on spring flow. Figure 4.2.16 shows similar boundary flux sensitivities to changes in the horizontal hydraulic conductivity of layer 2 with increasing horizontal hydraulic conductivity of layer two increasing flow to perennial streams and from the underlying formations and decreasing flow to ephemeral streams and evapotranspiration. Figure 4.2.17 shows the sensitivities of boundary flows is much larger for the horizontal hydraulic conductivity of layer 3 than for layers 1 and 2. Increasing the horizontal hydraulic conductivity of layer 3 increases flow to perennial streams and, to a far lesser degree, flow from the underlying formations and decreases flow to ephemeral streams.

Figures 4.2.18 and 4.2.19 show the comparatively small (less than 100 acre-feet per year) sensitivity in flows to the vertical hydraulic conductivity in layers 1 and 2, respectively. Increasing the vertical hydraulic conductivity of layer 1 increases flow from the underlying formations and flow to perennial streams and decreases flow to ephemeral streams. Increasing the vertical hydraulic conductivity of layer 2 increases flow from the underlying formations and flow to ephemeral streams and decreases flow to perennial streams. Figure 4.2.20 shows much higher sensitivity in flows to the vertical hydraulic conductivity in layer 3. Increasing the vertical hydraulic conductivity of layer 3 increases flow from the underlying formations and perennial stream and decreases flow to ephemeral streams while having minimal impact on evapotranspiration or spring flow.

Figure 4.2.21 depicts the sensitivity of boundary fluxes to changes in recharge to the Brazos River Alluvium Aquifer where increases in recharge result in increases in flow to perennial streams and, to a lesser degree, ephemeral streams and evapotranspiration but decreases slightly the flow from the underlying formations. Figure 4.2.22 shows that increases in recharge to the underlying formations increases flow to ephemeral streams and, to a lesser degree, flow to perennial streams.

Figure 4.2.23 illustrates the sensitivity of boundary fluxes to changes in the streambed conductance of the perennial streams. Increasing the perennial streambed conductance increases flow to the perennial streams while decreasing flow to the ephemeral streams and evapotranspiration. Figure 4.2.24 shows the sensitivity of boundary fluxes to changes in the streambed width of the perennial streams. Similar to the streambed conductance, increasing the perennial streambed width increases flow to the perennial streams while decreasing flow to the ephemeral streams and evapotranspiration. Figure 4.2.25 depicts the sensitivity of boundary fluxes to changes in the streambed conductance of the ephemeral streams. Increasing the ephemeral streambed conductance increases flow to the ephemeral streams while decreasing flow to the other boundaries and from the underlying formations. Figure 4.2.26 depicts the sensitivity of boundary fluxes to changes in the spring conductance. Increasing the spring conductance increases flow to the springs while decreasing flow to the other boundaries.

Figures 4.2.27 and 4.2.28 illustrate the sensitivity of boundary fluxes to changes in maximum evapotranspiration rate and extinction depth. In both cases, increasing the parameter increases flow to evapotranspiration and decreases flow to the other boundaries.

To summarize the relative sensitivity of boundary flows to changes in the parameters, recharge to the underlying formations and horizontal hydraulic conductivity in the underlying formations have the largest overall effect (approximately 230,000 and 100,000 acre-feet per year change, respectively), while the conductance of perennial and ephemeral streams and recharge to the Brazos River Alluvium Aquifer have a smaller but comparable effect (40,000 to 45,000 acre-feet per year change). The maximum evapotranspiration rate and the width of perennial streams both have a significant effect (20,000 to 25,000 acre-feet per year change). The remaining parameters have less than 20,000 acre-feet per year effect on boundary flow.

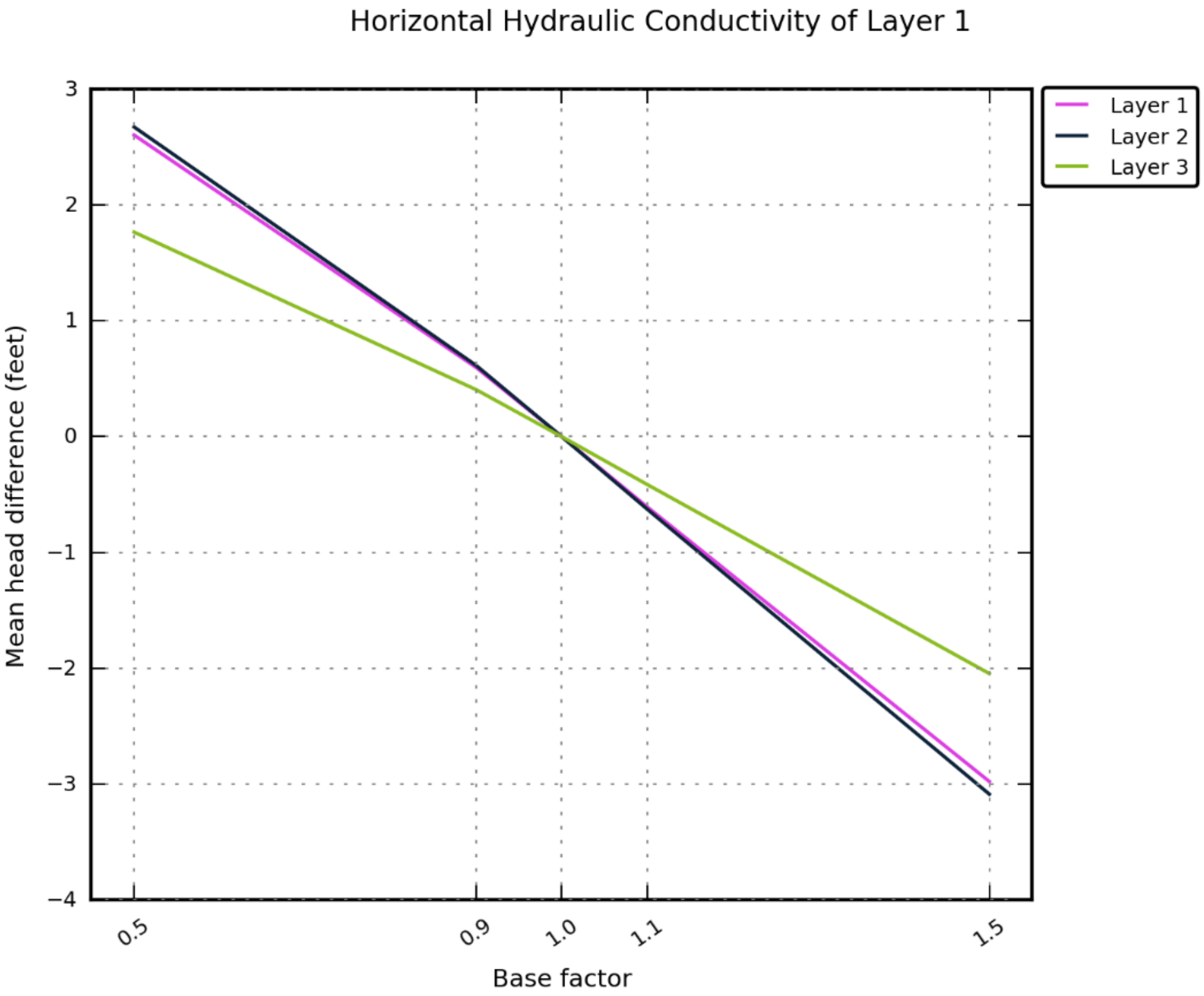

Figure 4.2.1 Hydraulic head sensitivity in feet for the steady-state model to changes in horizontal hydraulic conductivity (Kh) of layer 1.

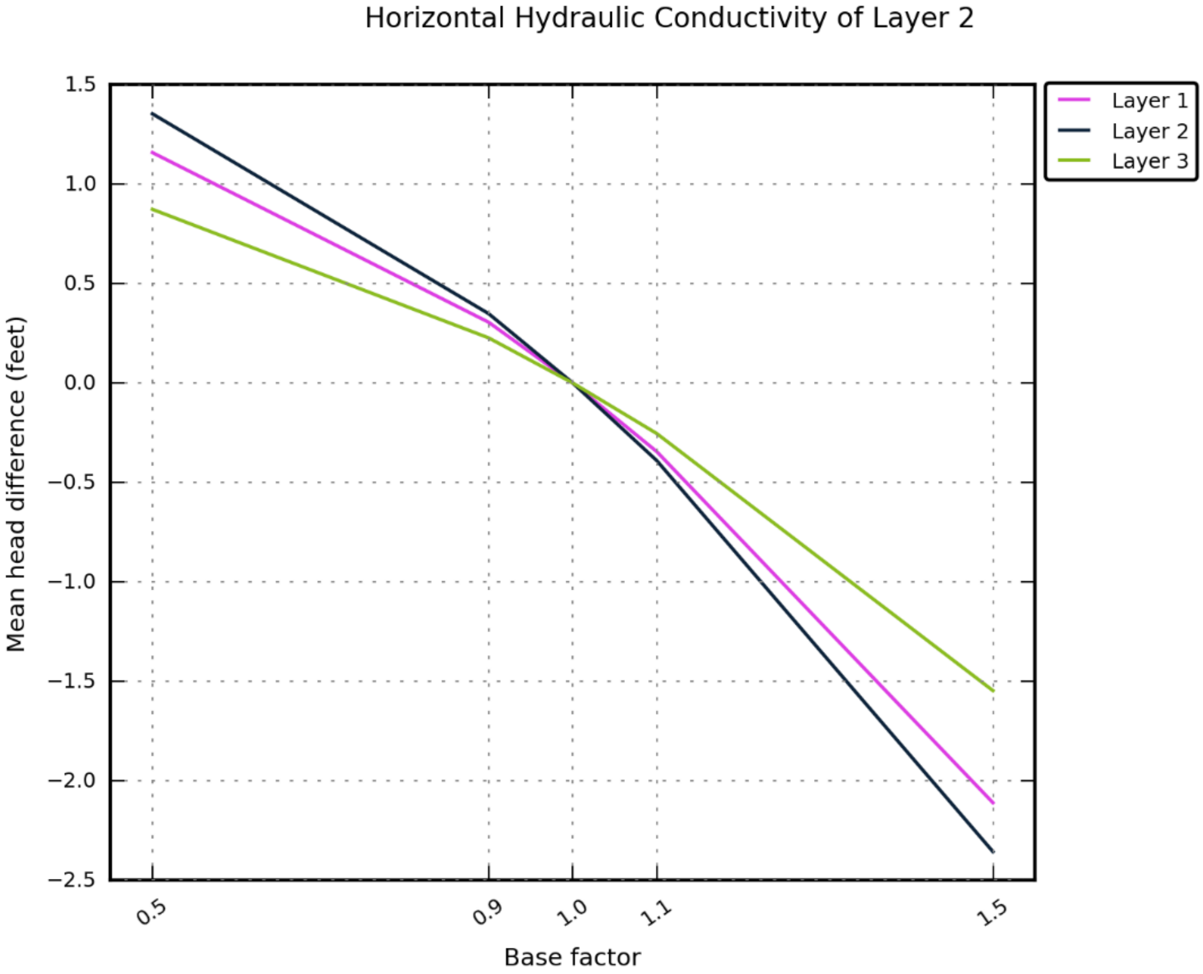

Figure 4.2.2 **Hydraulic head sensitivity in feet for the steady-state model to changes in horizontal hydraulic conductivity (Kh) of layer 2.**

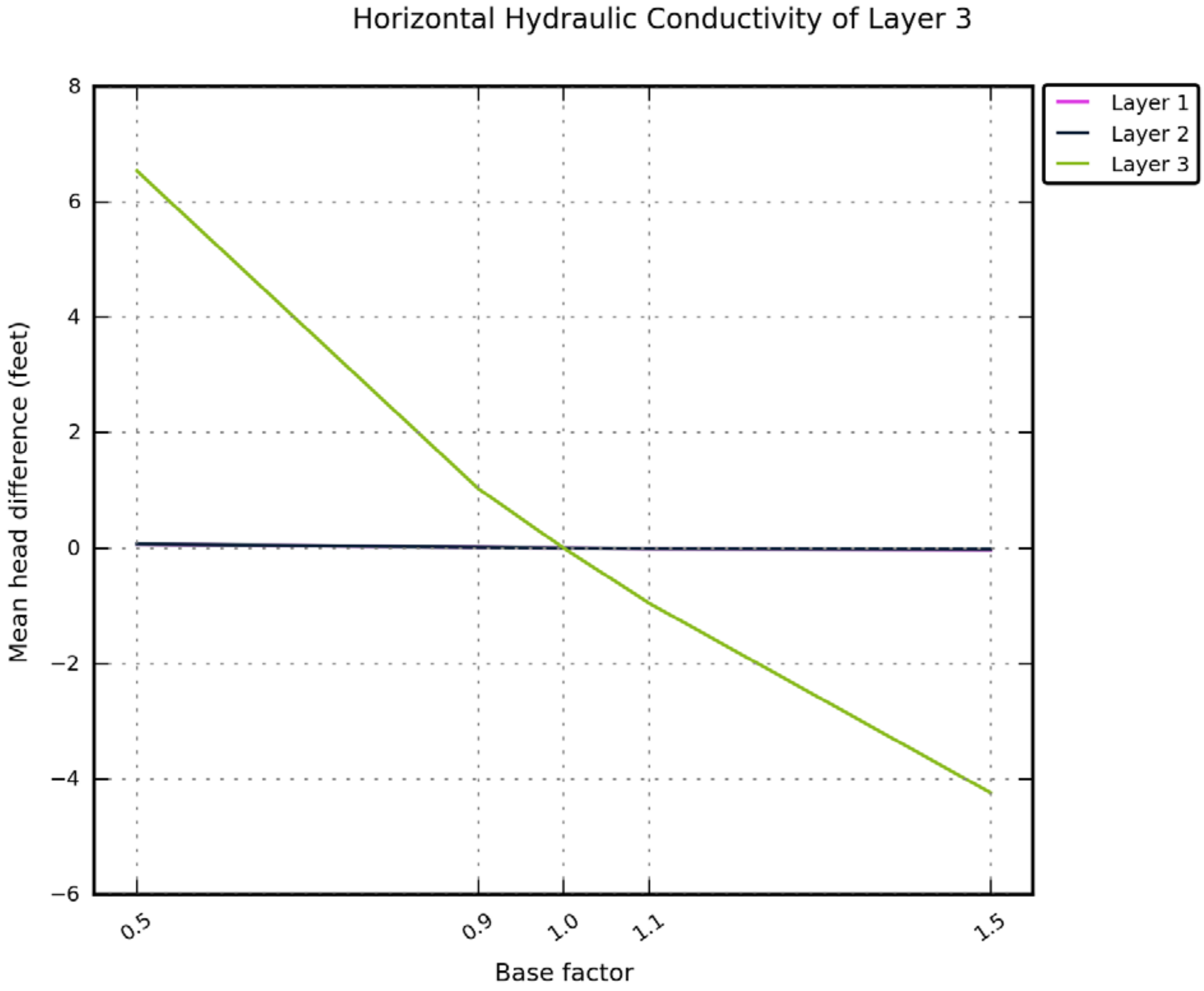

Figure 4.2.3 **Hydraulic head sensitivity in feet for the steady-state model to changes in horizontal hydraulic conductivity (Kh) of layer 3.**

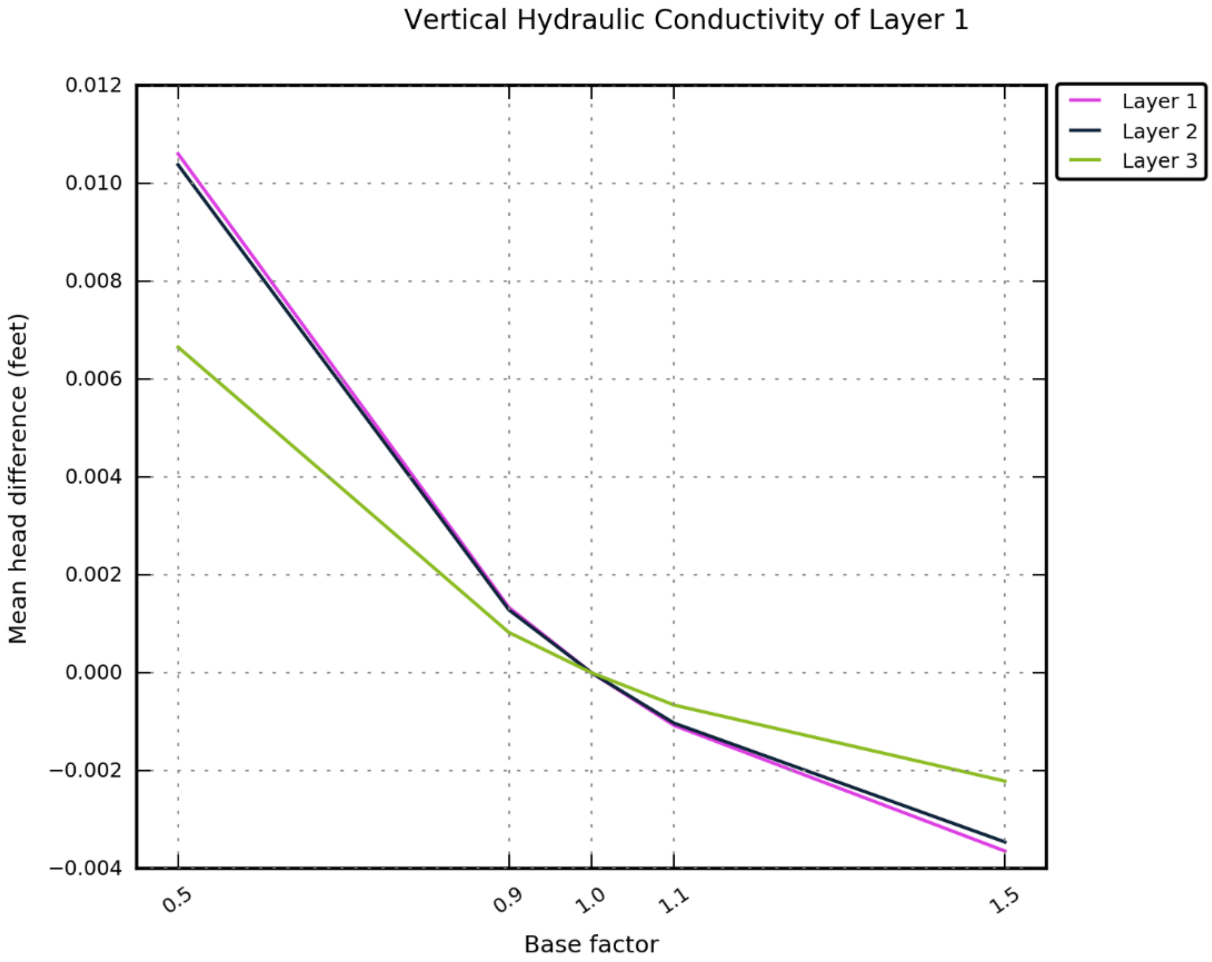

Figure 4.2.4 **Hydraulic head sensitivity in feet for the steady-state model to changes in vertical hydraulic conductivity (Kv) of layer 1.**

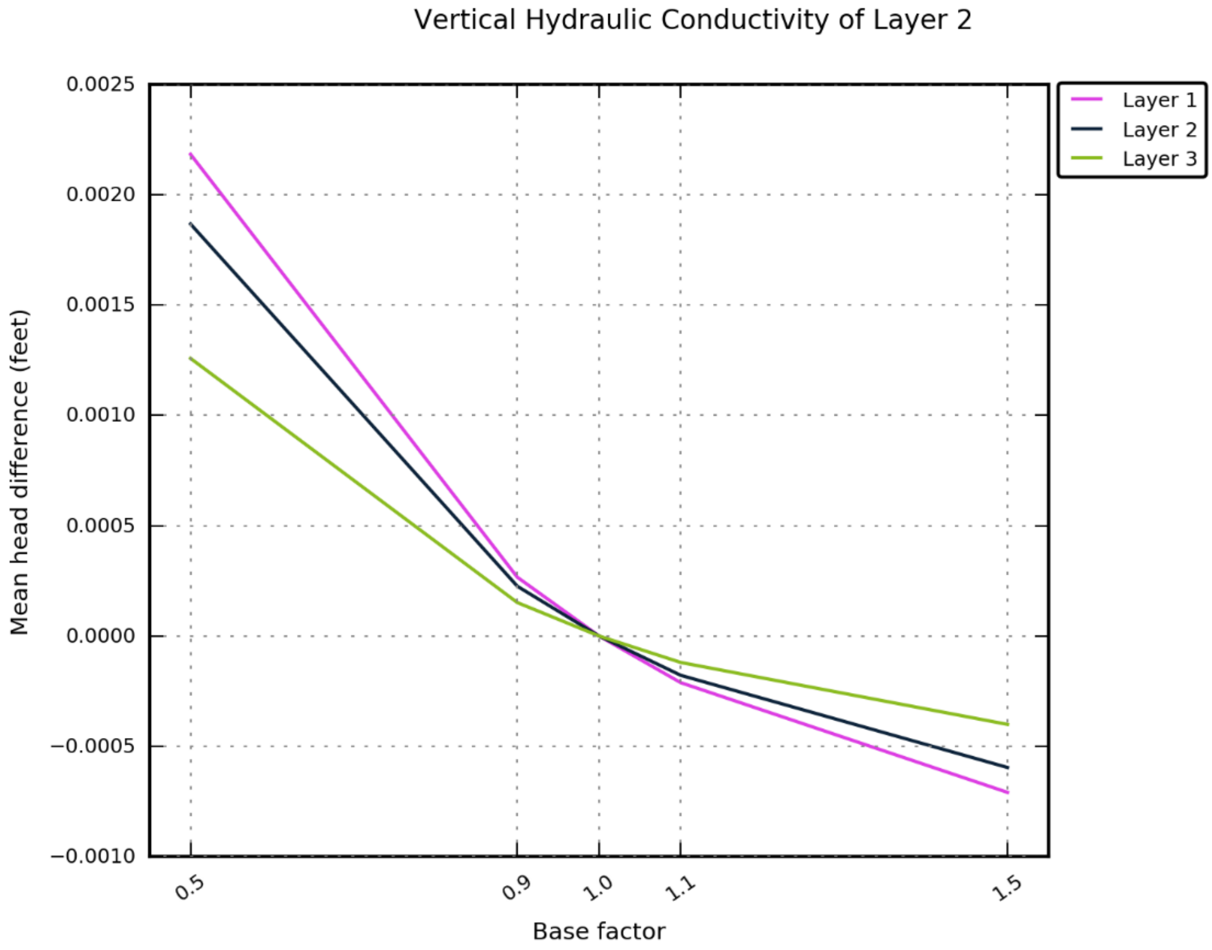

Figure 4.2.5 **Hydraulic head sensitivity in feet for the steady-state model to changes in vertical hydraulic conductivity (Kv) of layer 2.**

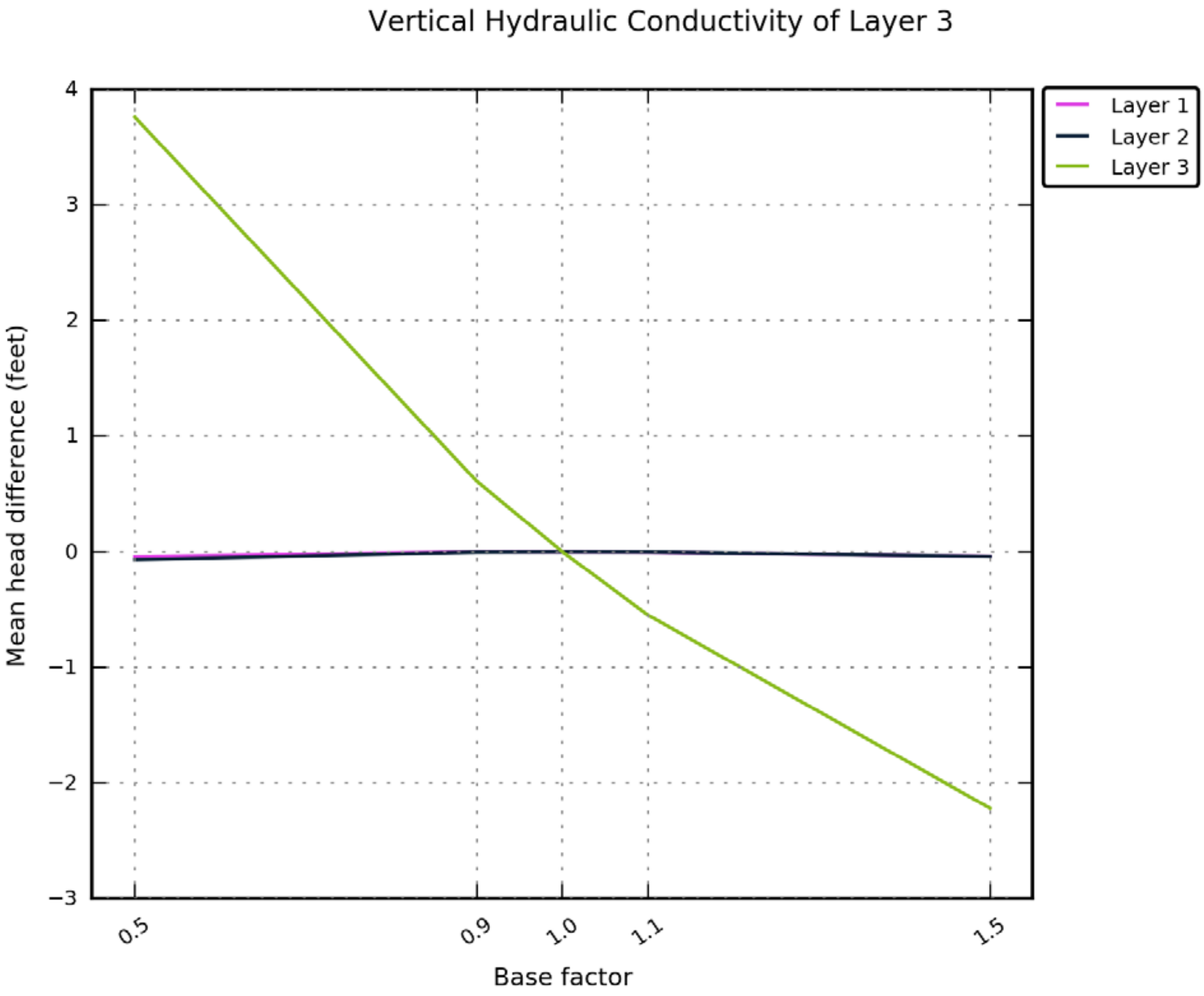

Figure 4.2.6 **Hydraulic head sensitivity in feet for the steady-state model to changes in vertical hydraulic conductivity (Kv) of layer 3.**

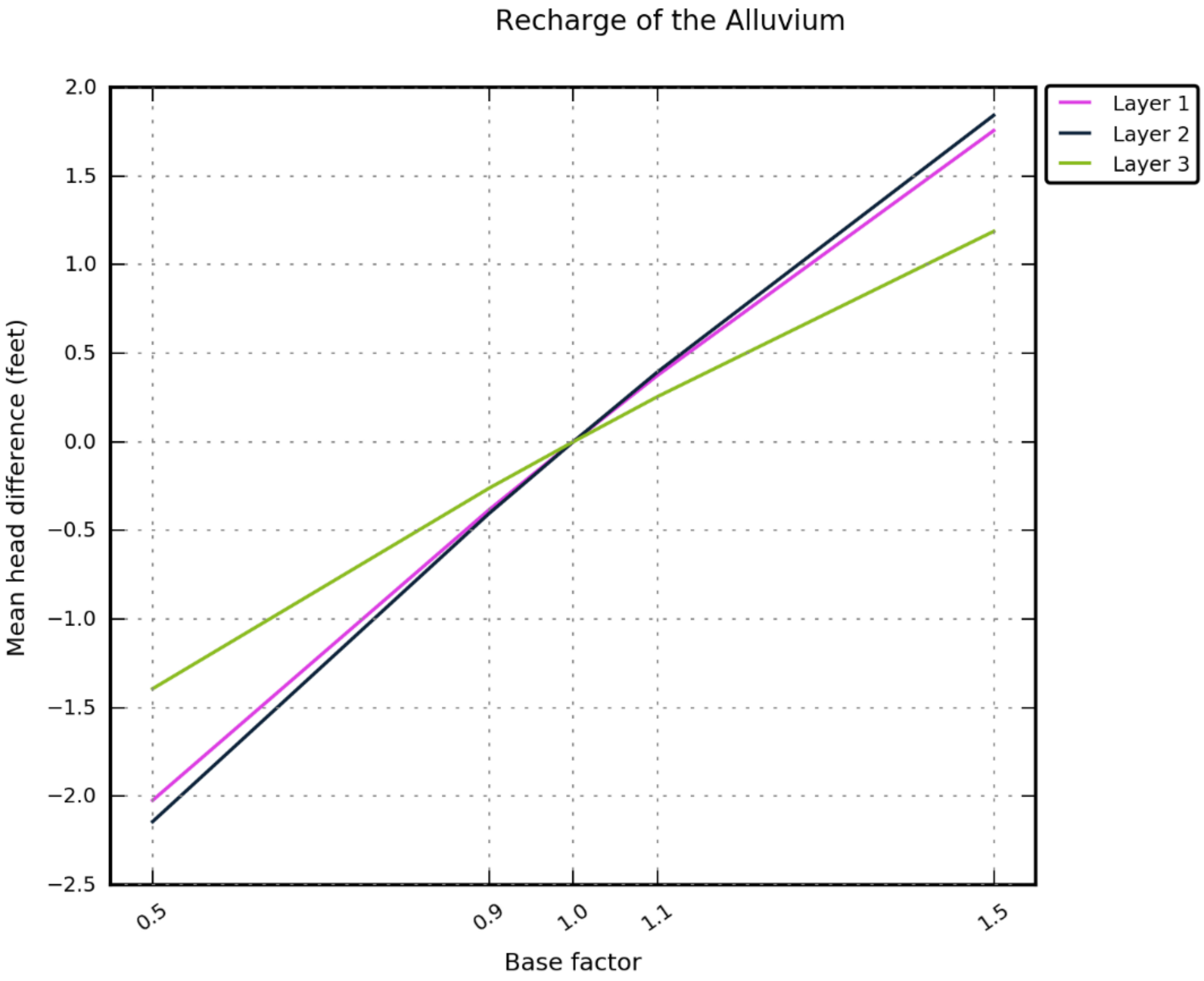

Figure 4.2.7 Hydraulic head sensitivity in feet for the steady-state model to changes in recharge to the Brazos River Alluvium Aquifer.

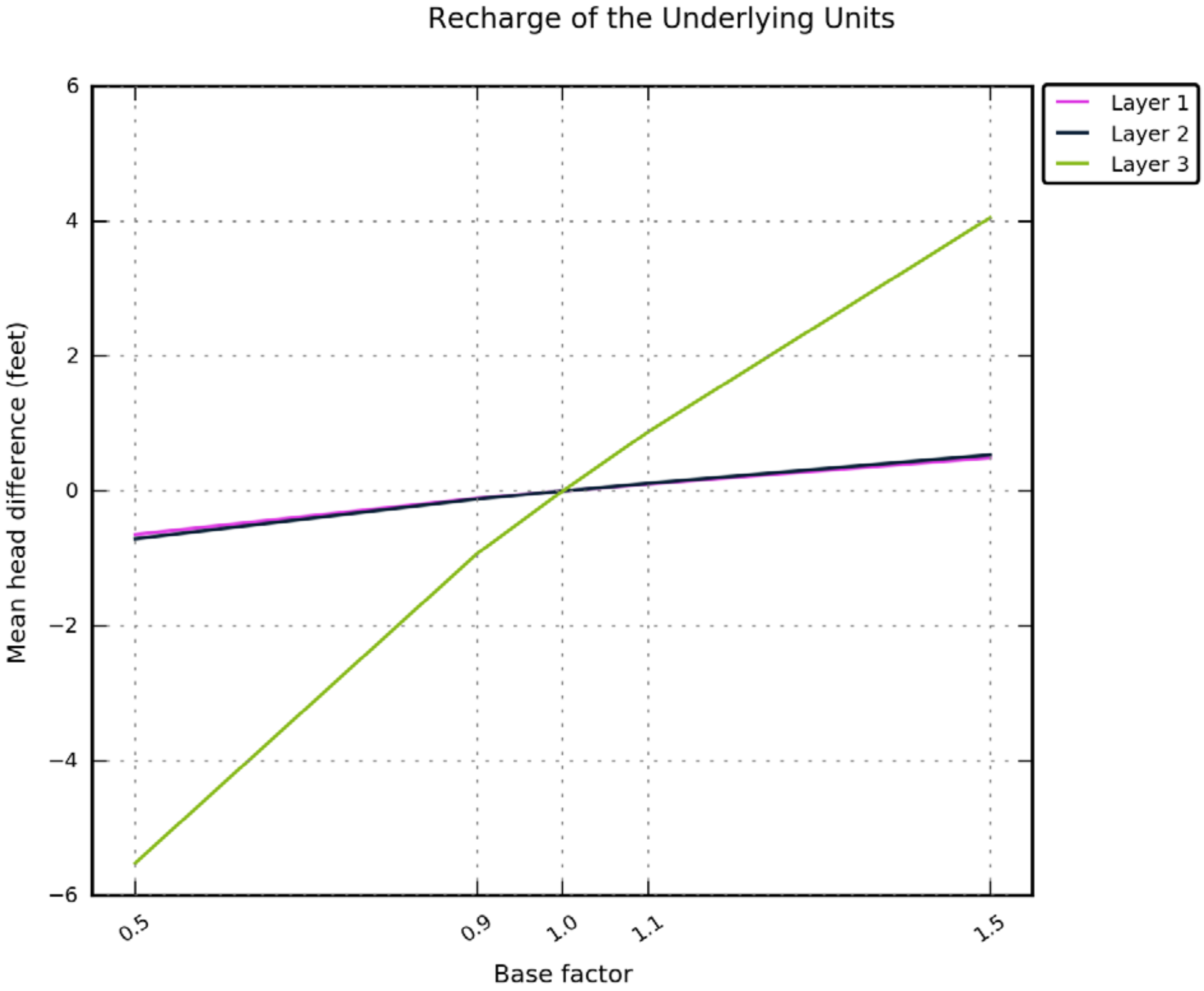

Figure 4.2.8 **Hydraulic head sensitivity in feet for the steady-state model to changes in recharge to the outcrops of the underlying formations.**

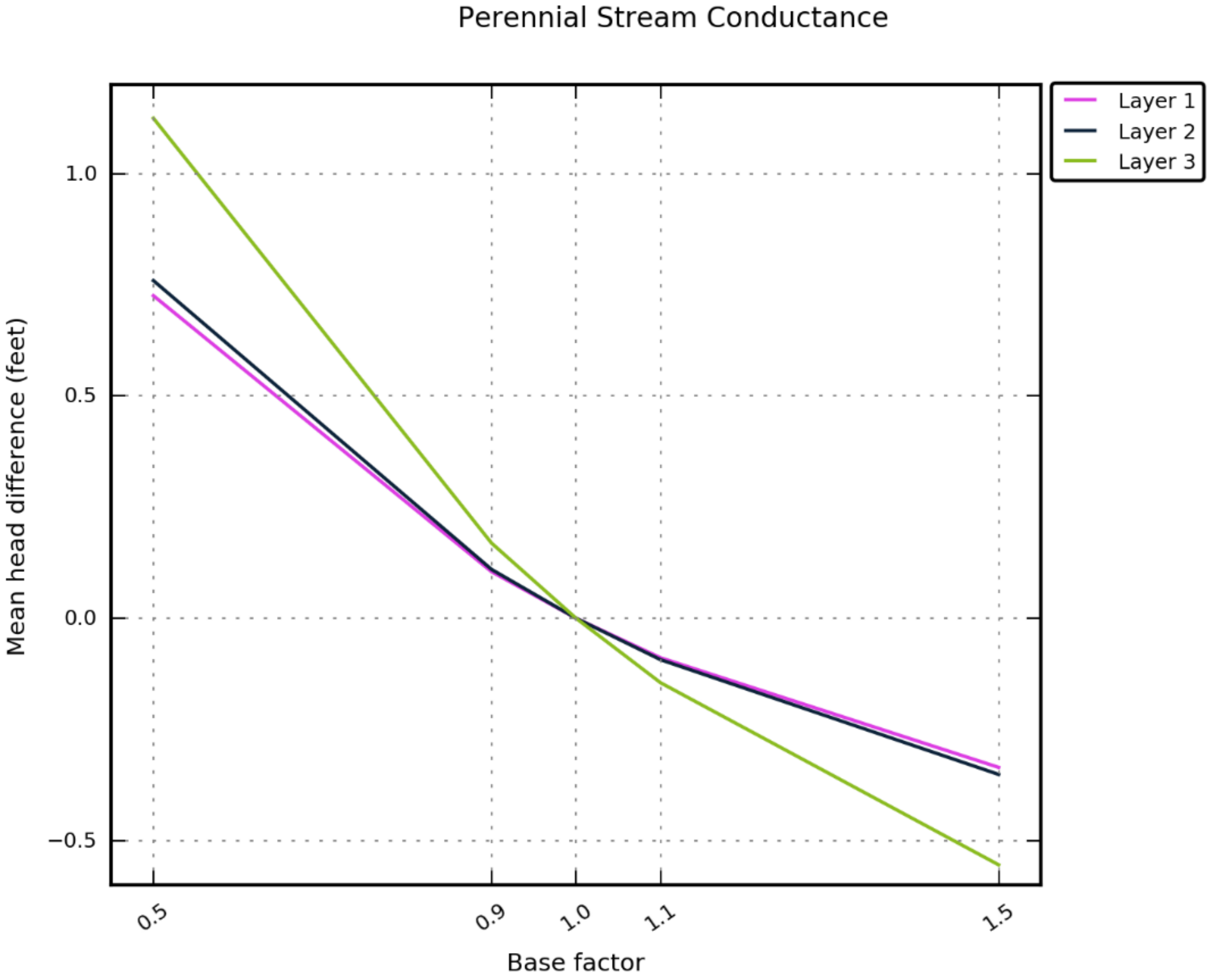

Figure 4.2.9 **Hydraulic head sensitivity in feet for the steady-state model to changes in the streambed conductance of perennial streams.**

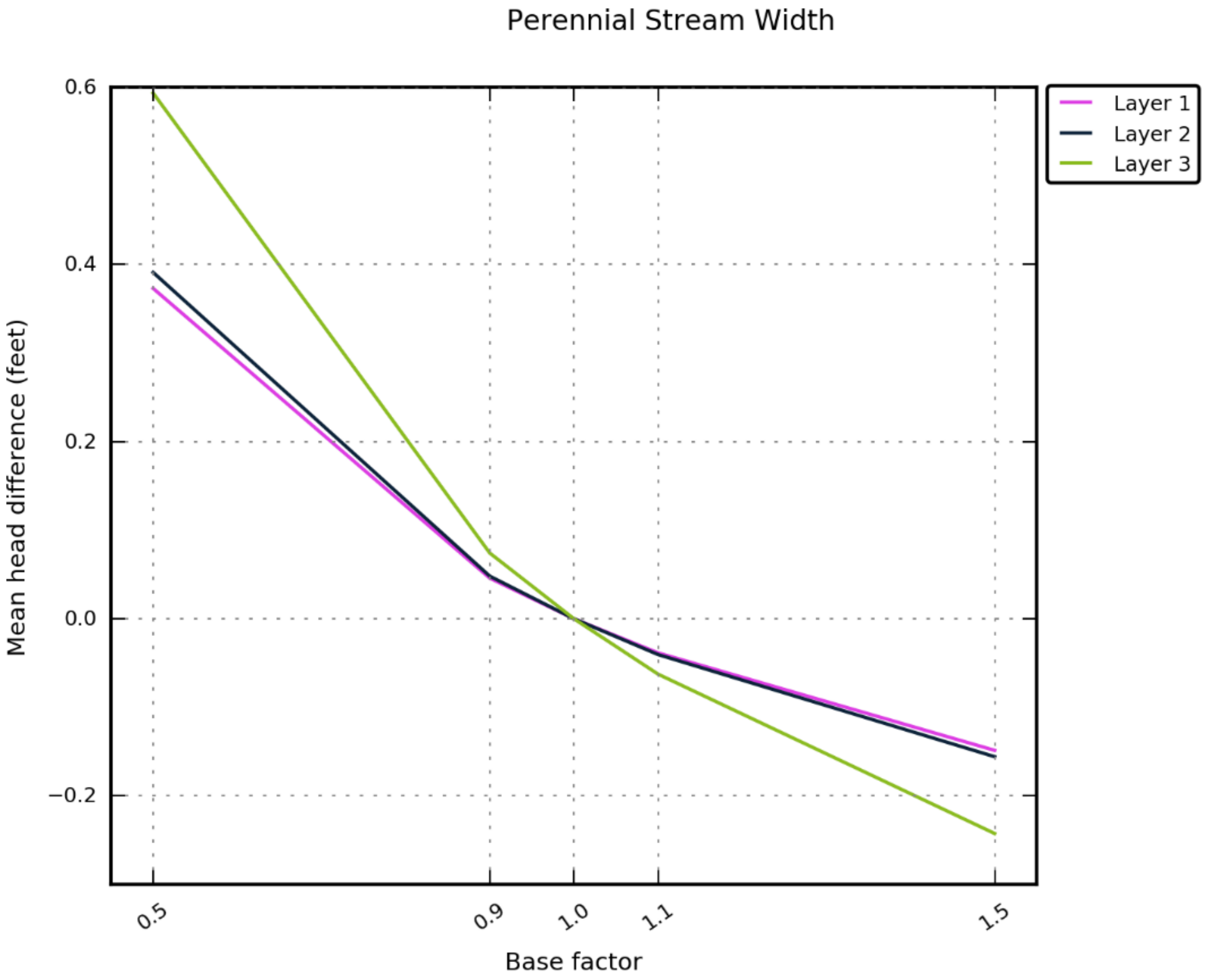

Figure 4.2.10 Hydraulic head sensitivity in feet for the steady-state model to changes in the stream width of perennial streams.

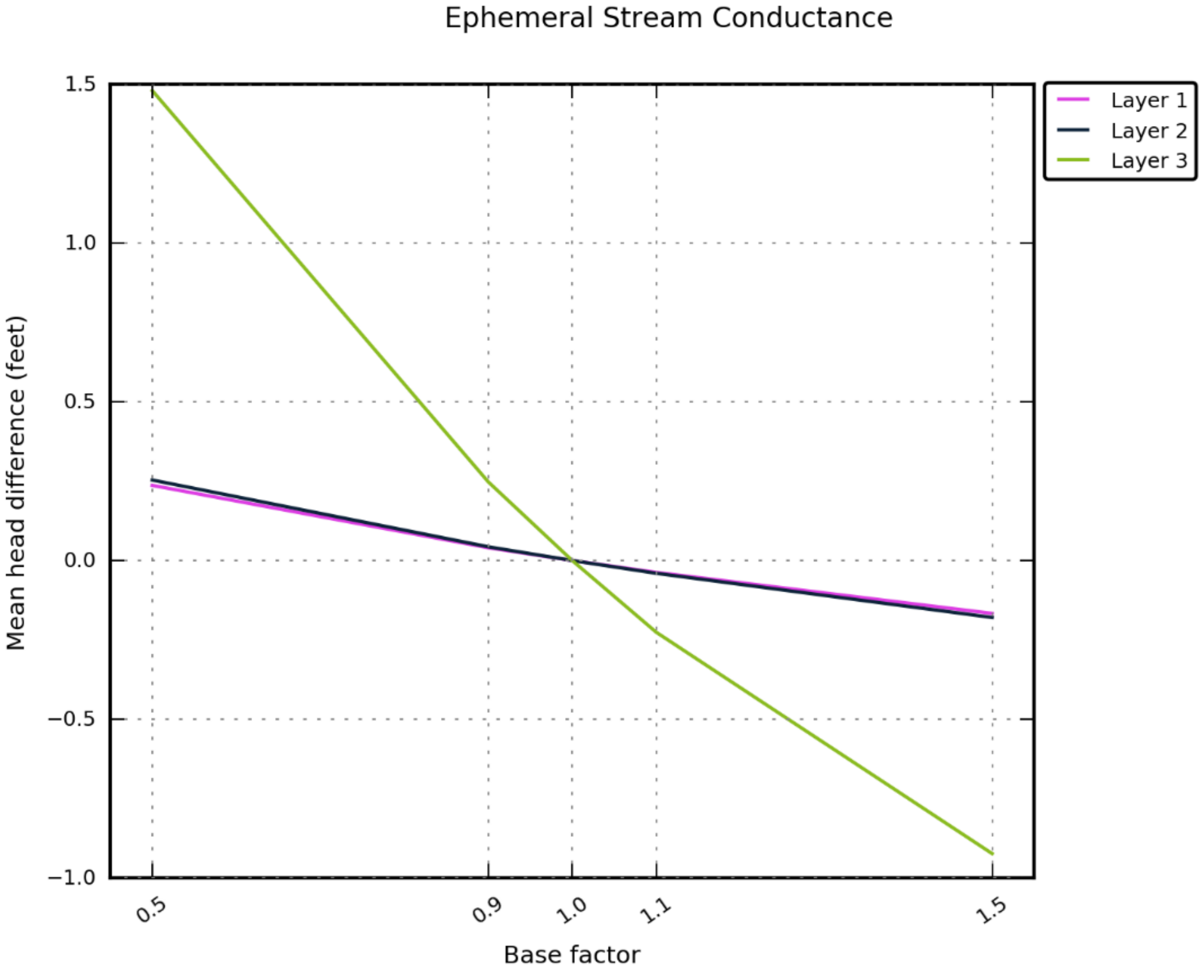

Figure 4.2.11 **Hydraulic head sensitivity in feet for the steady-state model to changes in the streambed conductance of ephemeral streams.**

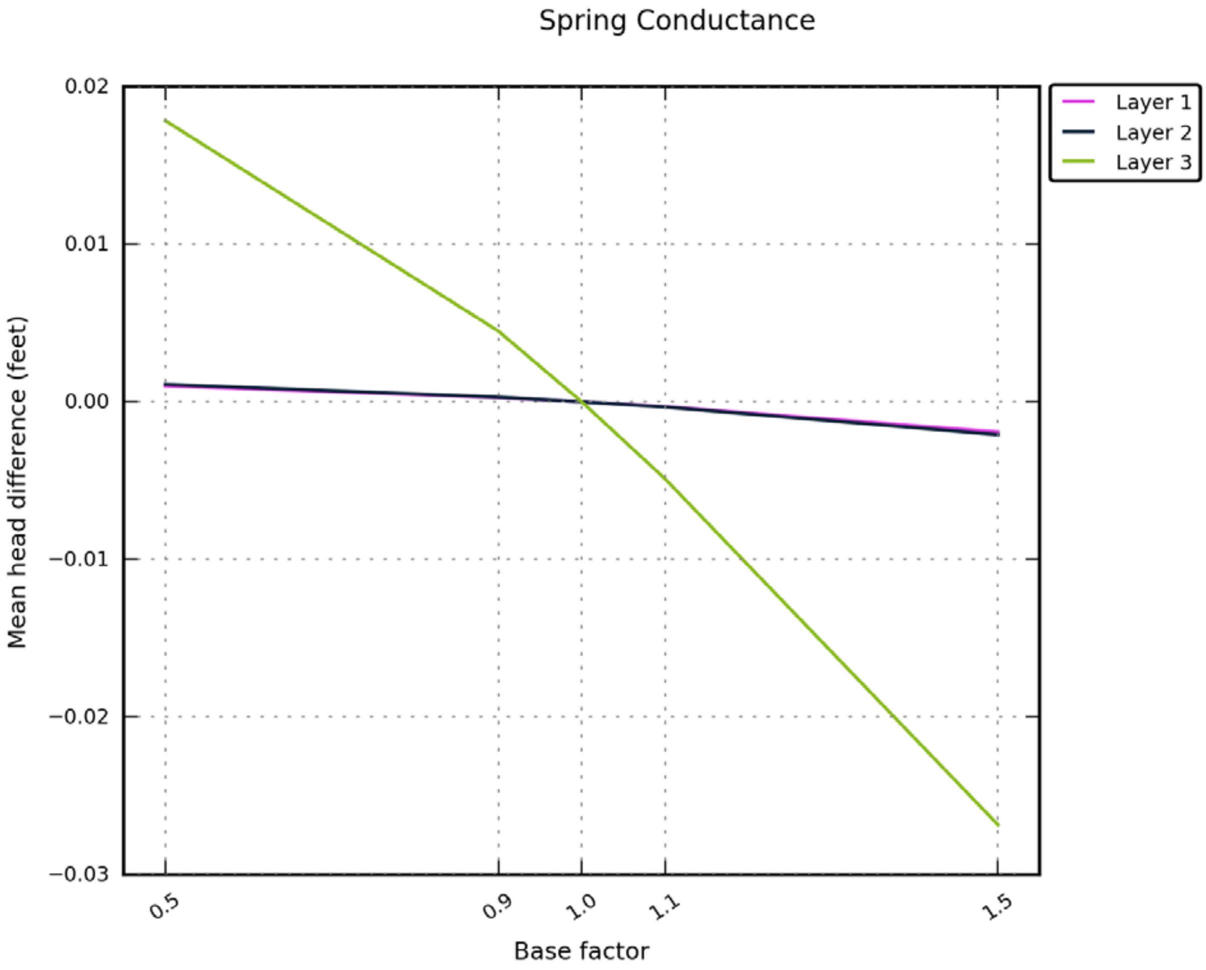

Figure 4.2.12 **Hydraulic head sensitivity in feet for the steady-state model to changes in spring conductance.**

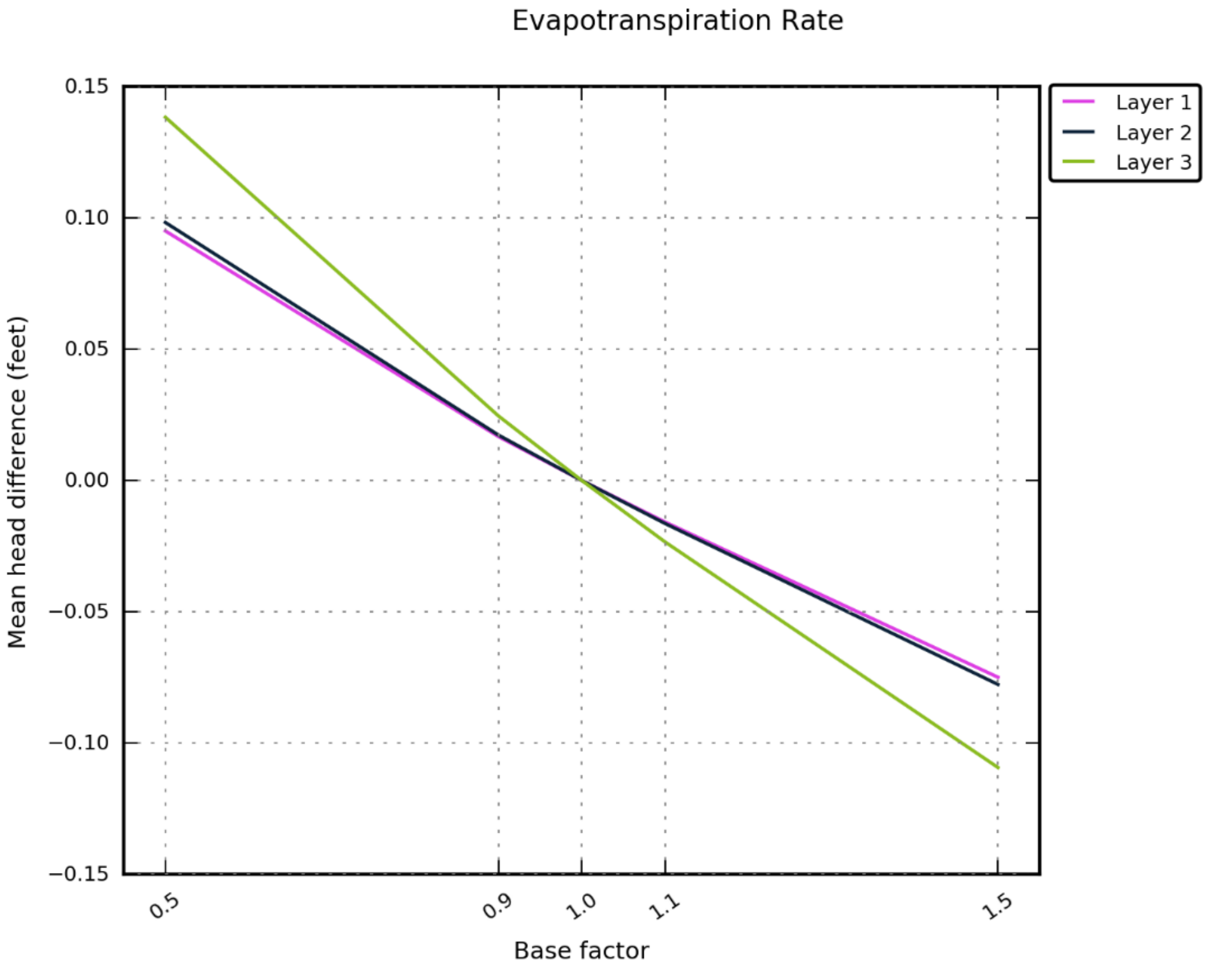

Figure 4.2.13 Hydraulic head sensitivity in feet for the steady-state model to changes in the maximum evapotranspiration rate.

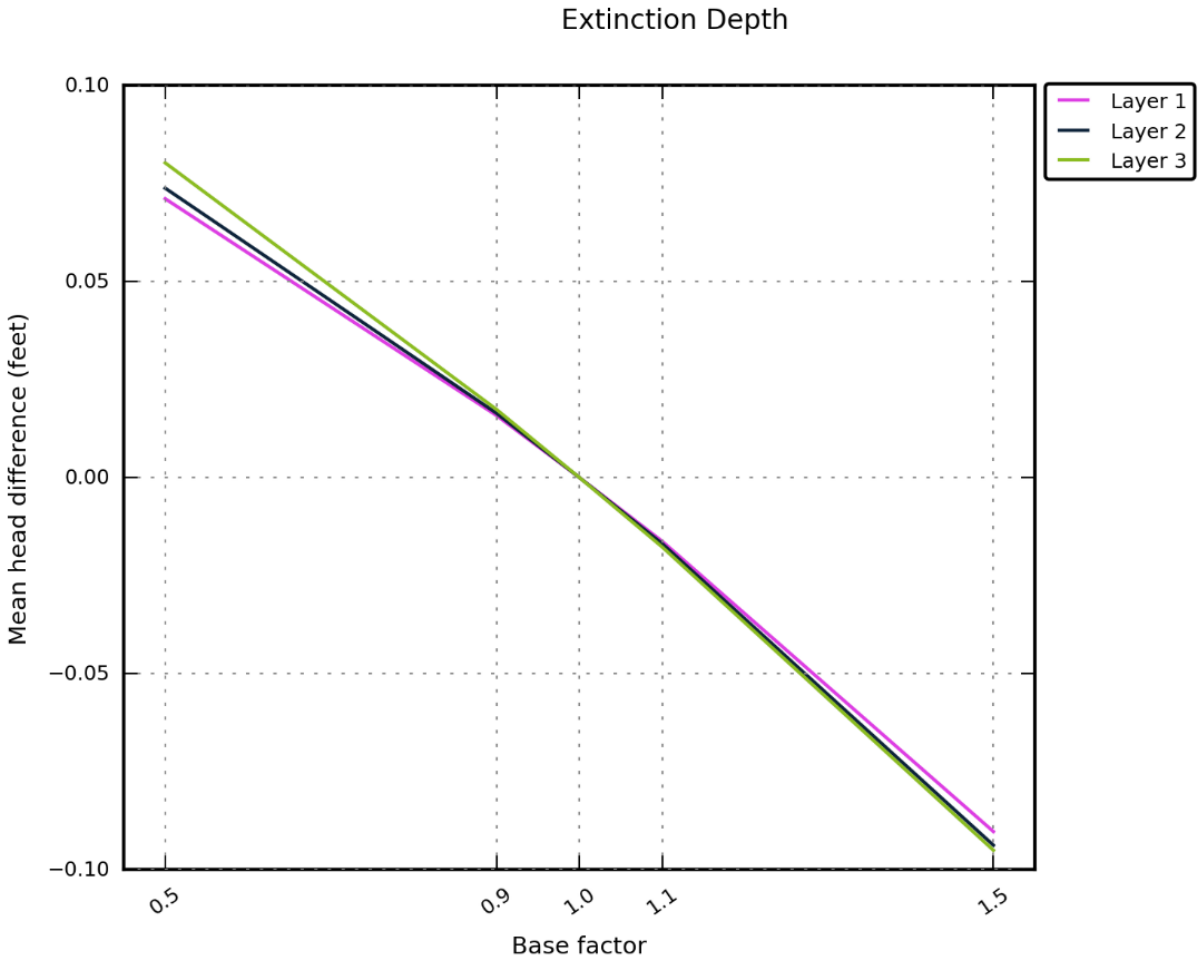

Figure 4.2.14 **Hydraulic head sensitivity in feet for the steady-state model to changes in the extinction depth for evapotranspiration.**

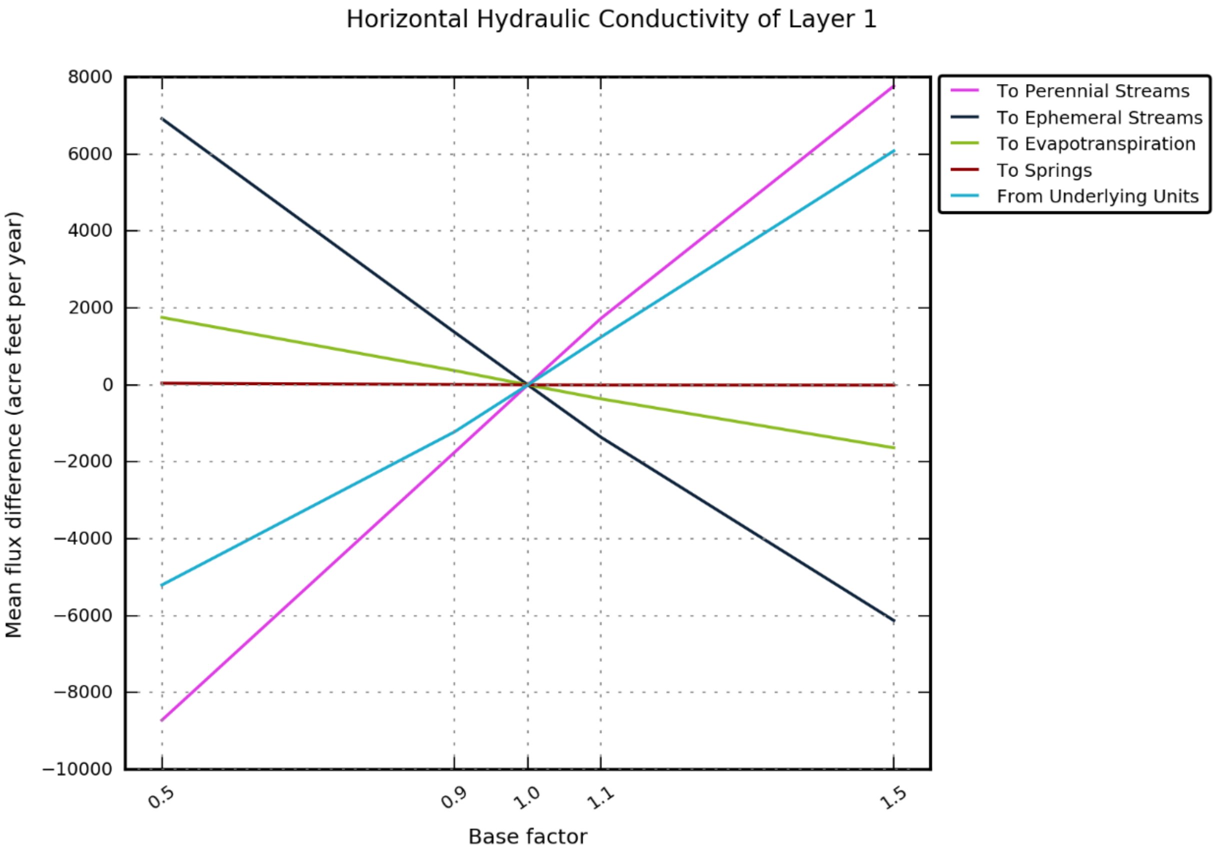

Figure 4.2.15 Flow sensitivity in acre-feet per year for the steady-state model to changes in horizontal hydraulic conductivity (Kh) of layer 1.

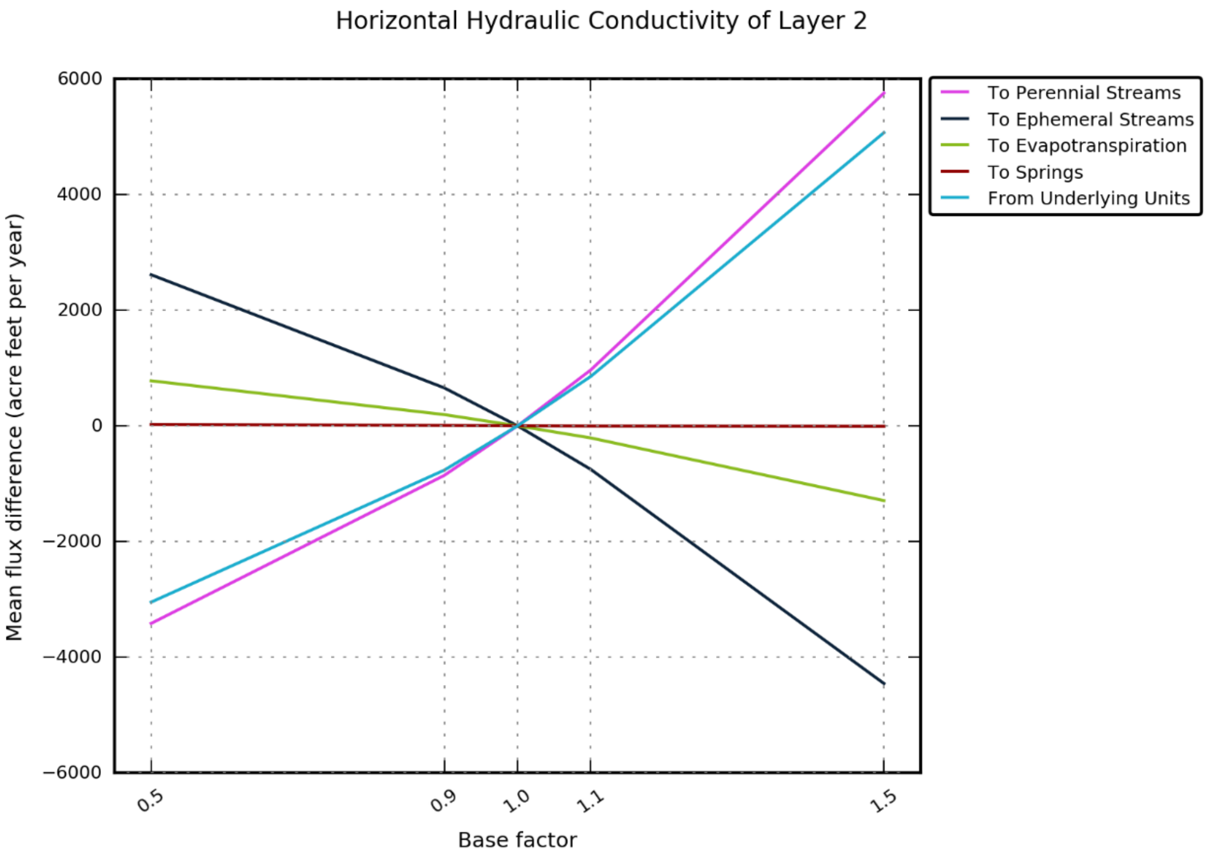

Figure 4.2.16 **Flow sensitivity in acre-feet per year for the steady-state model to changes in horizontal hydraulic conductivity (Kh) of layer 2.**

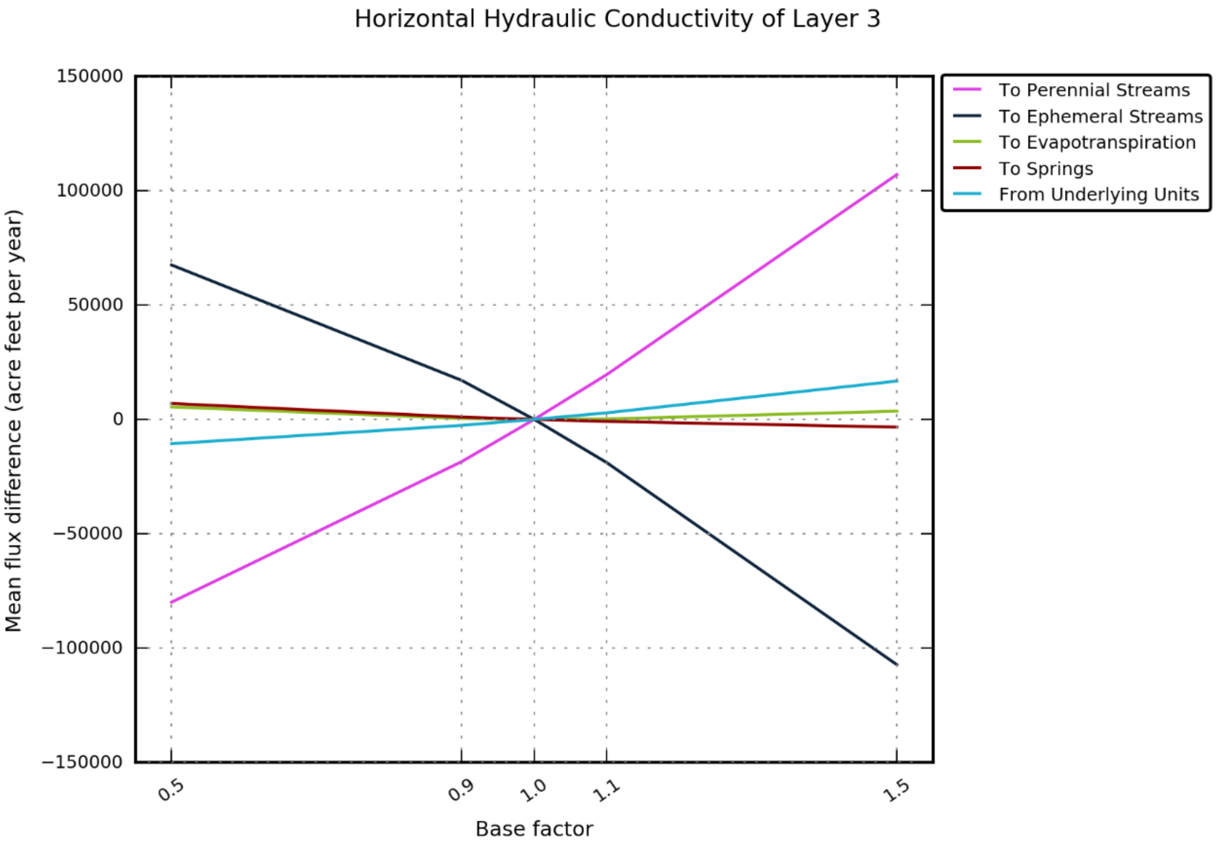

Figure 4.2.17 **Flow sensitivity in acre-feet per year for the steady-state model to changes in horizontal hydraulic conductivity (Kh) of layer 3.**

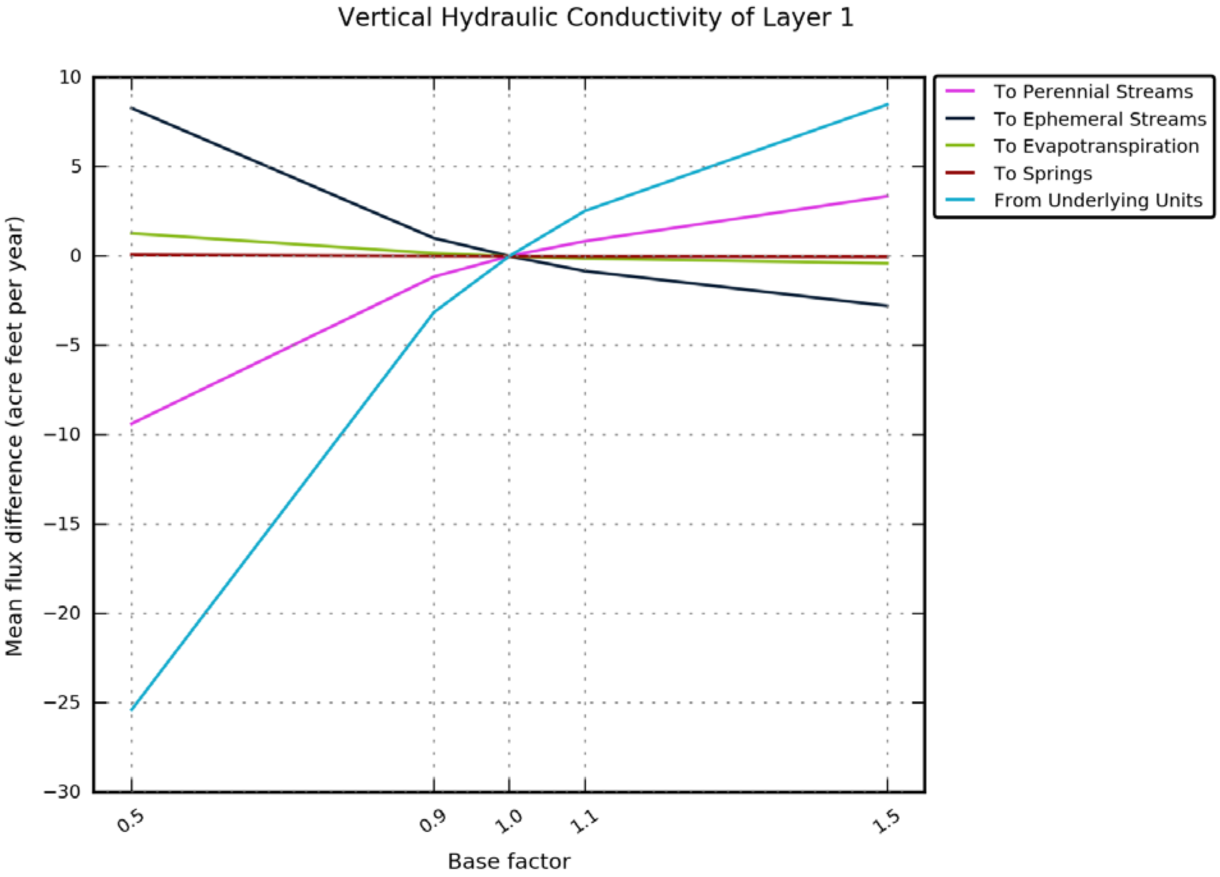

Figure 4.2.18 Flow sensitivity in acre-feet per year for the steady-state model to changes in vertical hydraulic conductivity (Kv) of layer 1.

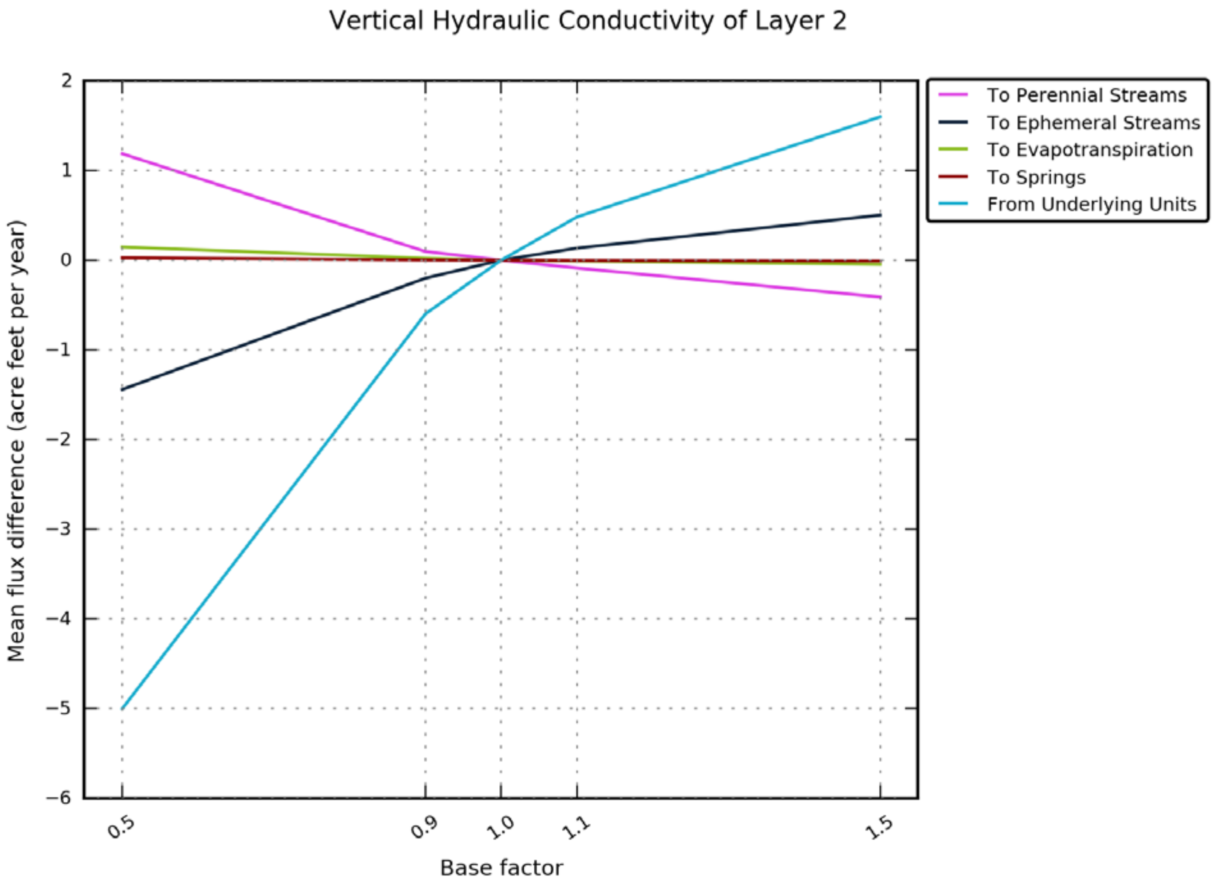

Figure 4.2.19 **Flow sensitivity in acre-feet per year for the steady-state model to changes in vertical hydraulic conductivity (Kv) of layer 2.**

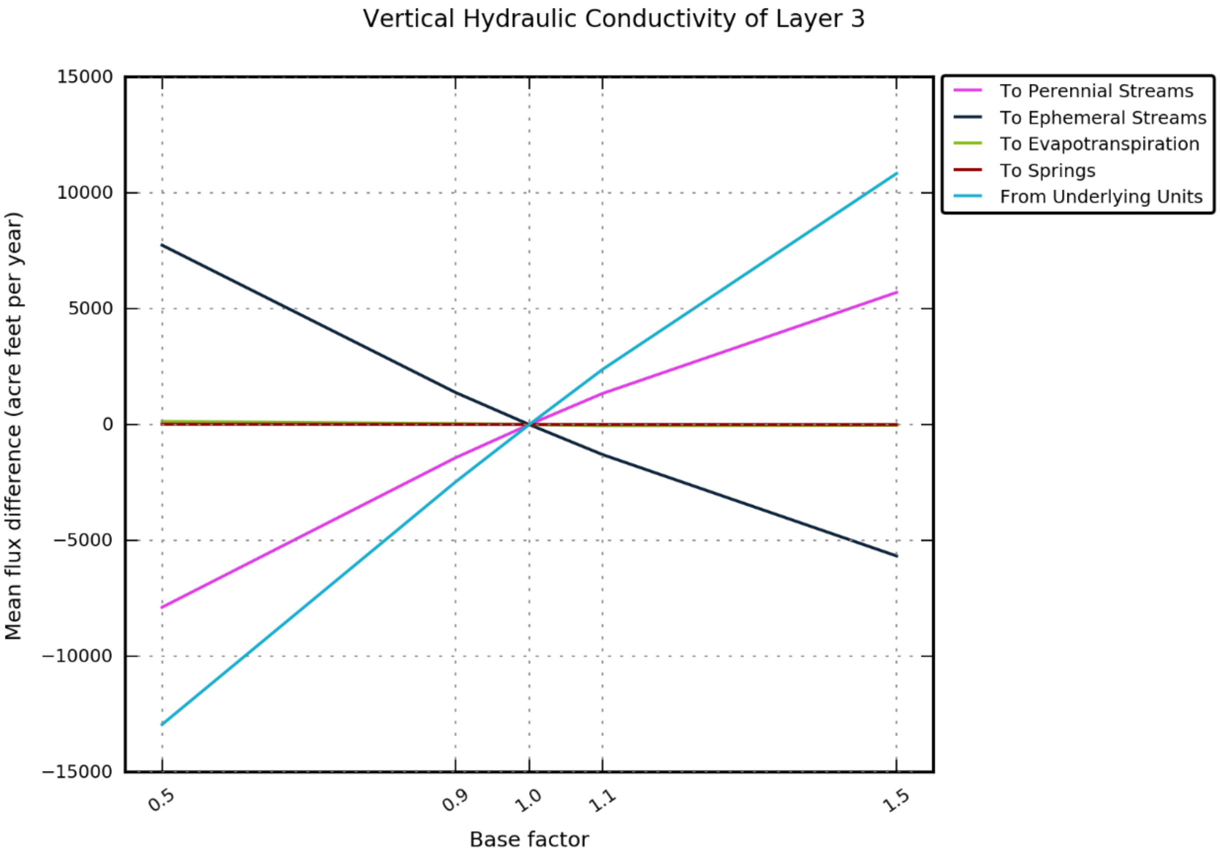

Figure 4.2.20 Flow sensitivity in acre-feet per year for the steady-state model to changes in vertical hydraulic conductivity (Kv) of layer 3.

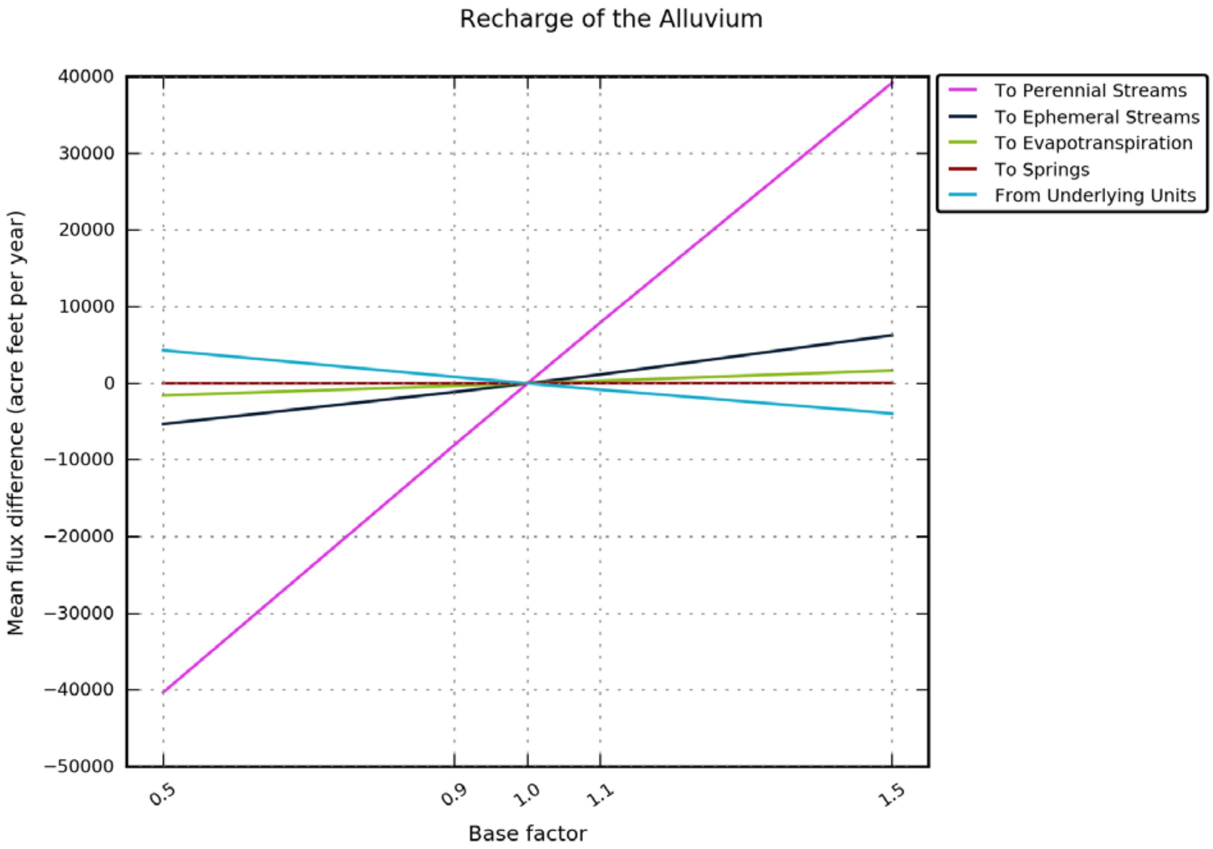

Figure 4.2.21 Flow sensitivity in acre-feet per year for the steady-state model to changes in recharge to the Brazos River Alluvium Aquifer.

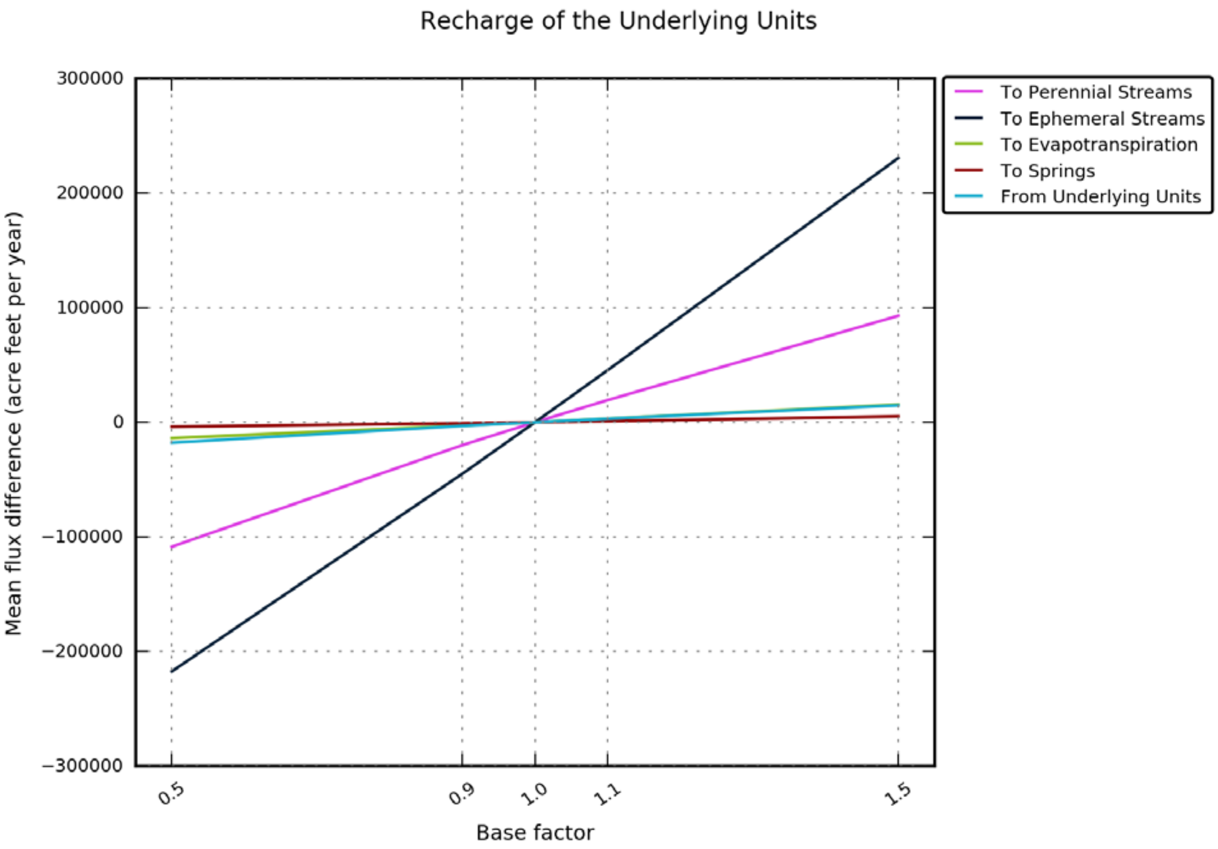

Figure 4.2.22 **Flow sensitivity in acre-feet per year for the steady-state model to changes in recharge to the underlying formations.**

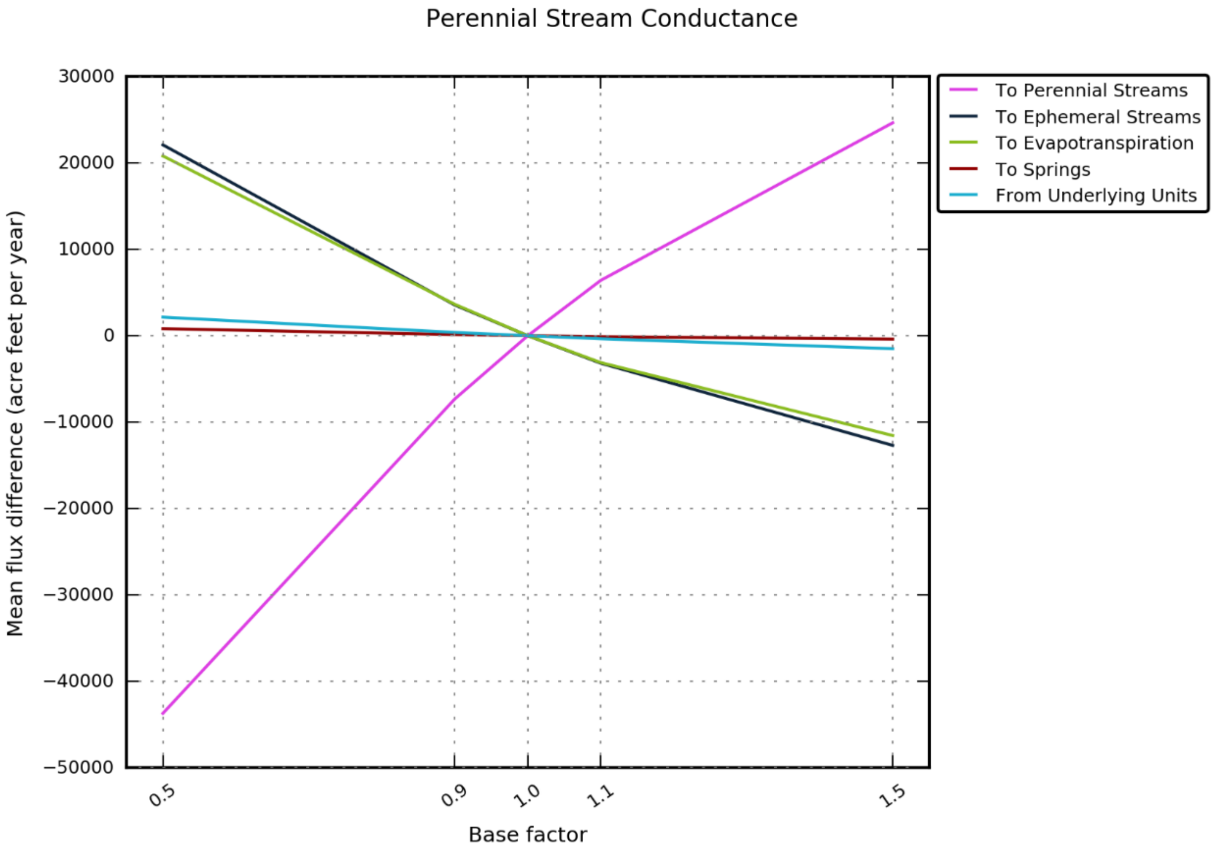

Figure 4.2.23 **Flow sensitivity in acre-feet per year for the steady-state model to changes in streambed conductance of perennial streams.**

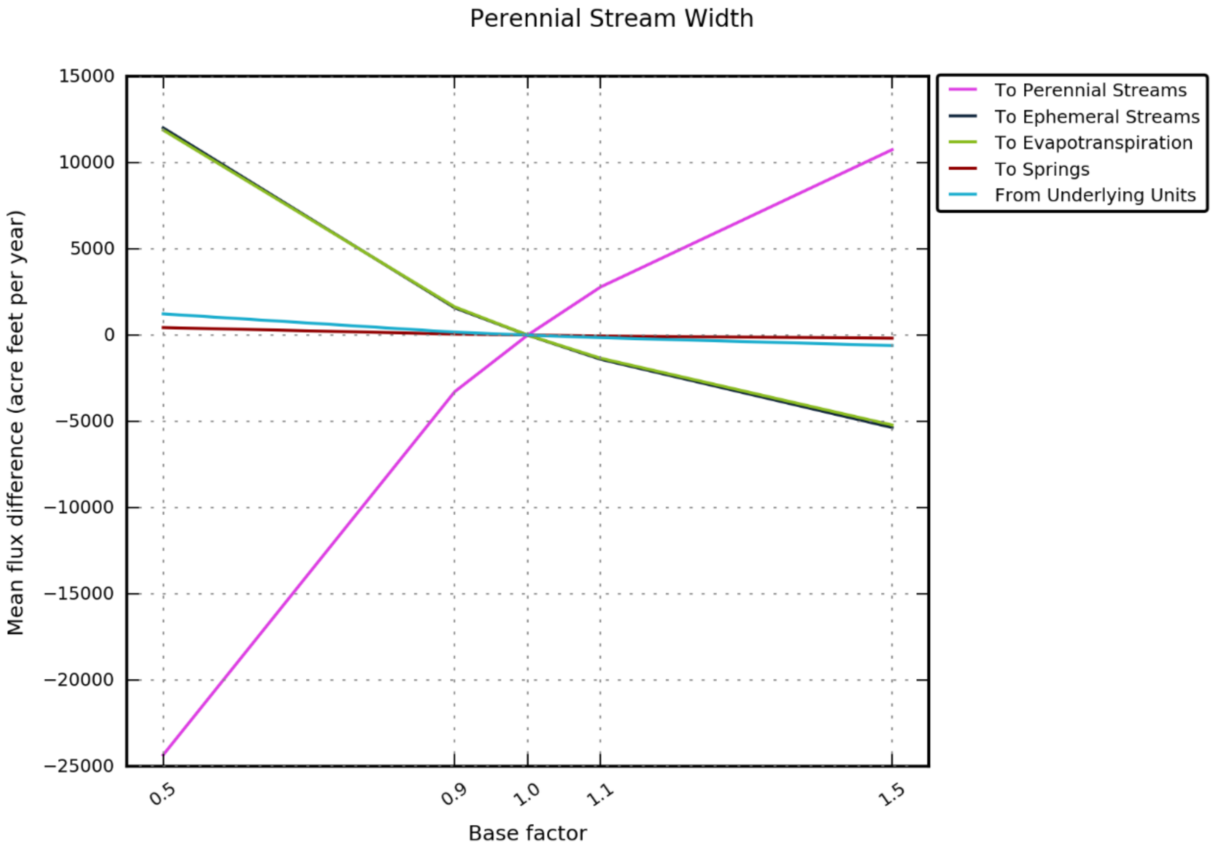

Figure 4.2.24 **Flow sensitivity in acre-feet per year for the steady-state model to changes in stream width for perennial streams.**

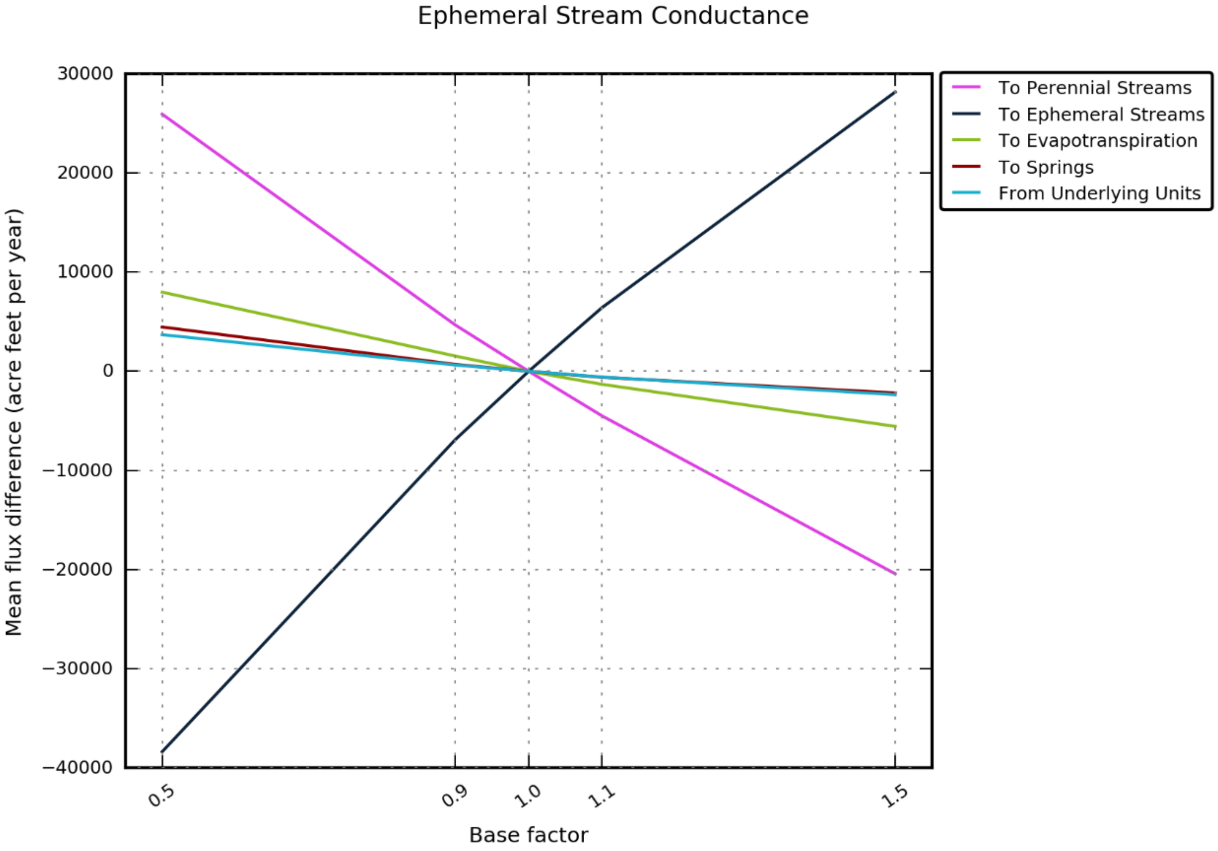

Figure 4.2.25 Flow sensitivity in acre-feet per year for the steady-state model to changes in streambed conductance for ephemeral streams.

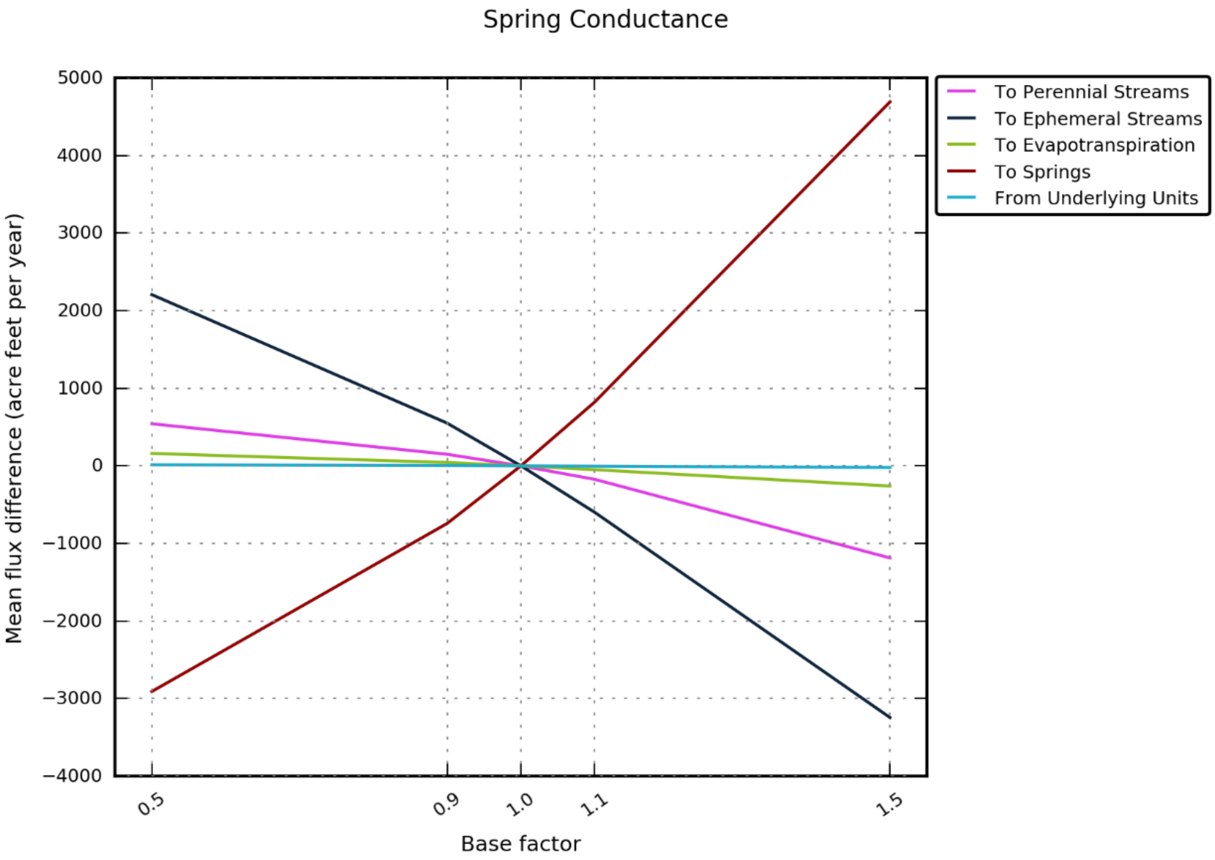

Figure 4.2.26 Flow sensitivity in acre-feet per year for the steady-state model to changes in spring conductance.

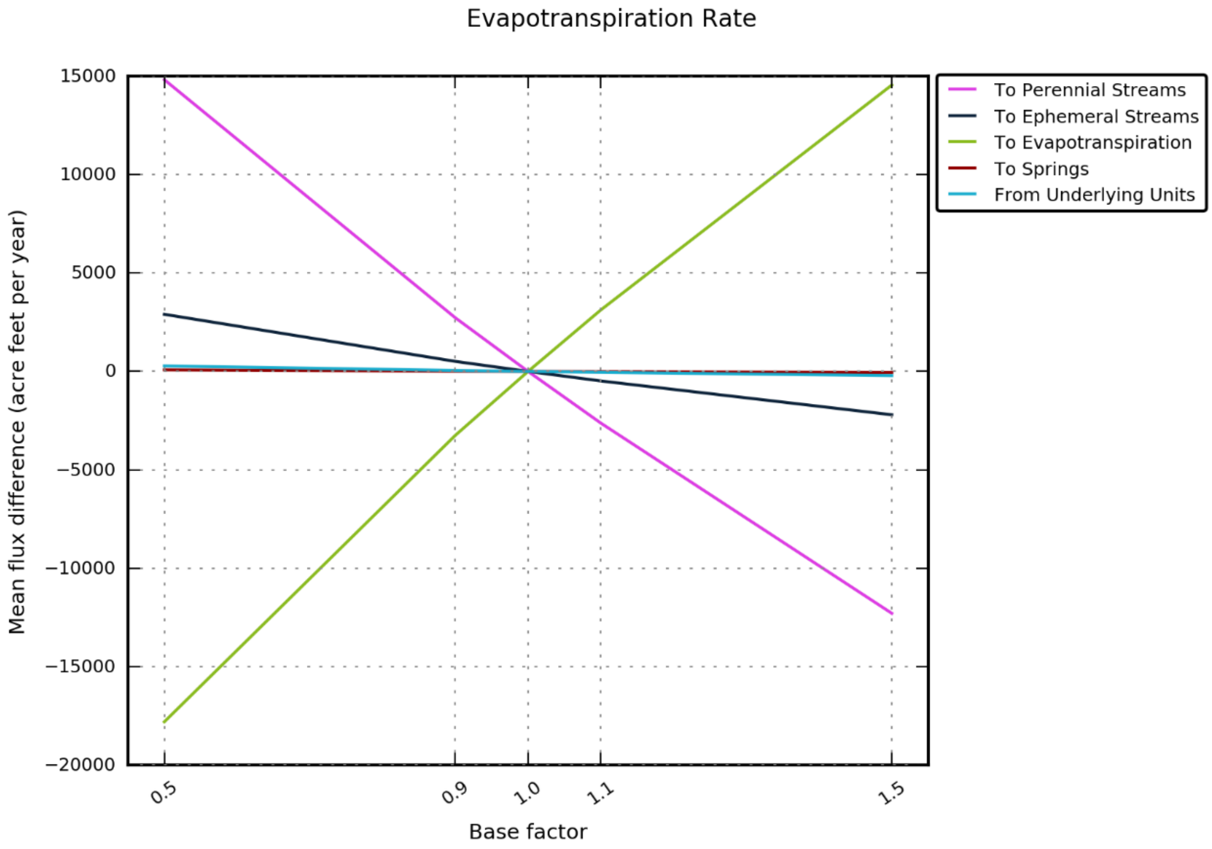

Figure 4.2.27 Flow sensitivity in acre-feet per year for the steady-state model to changes in the maximum evapotranspiration rate.

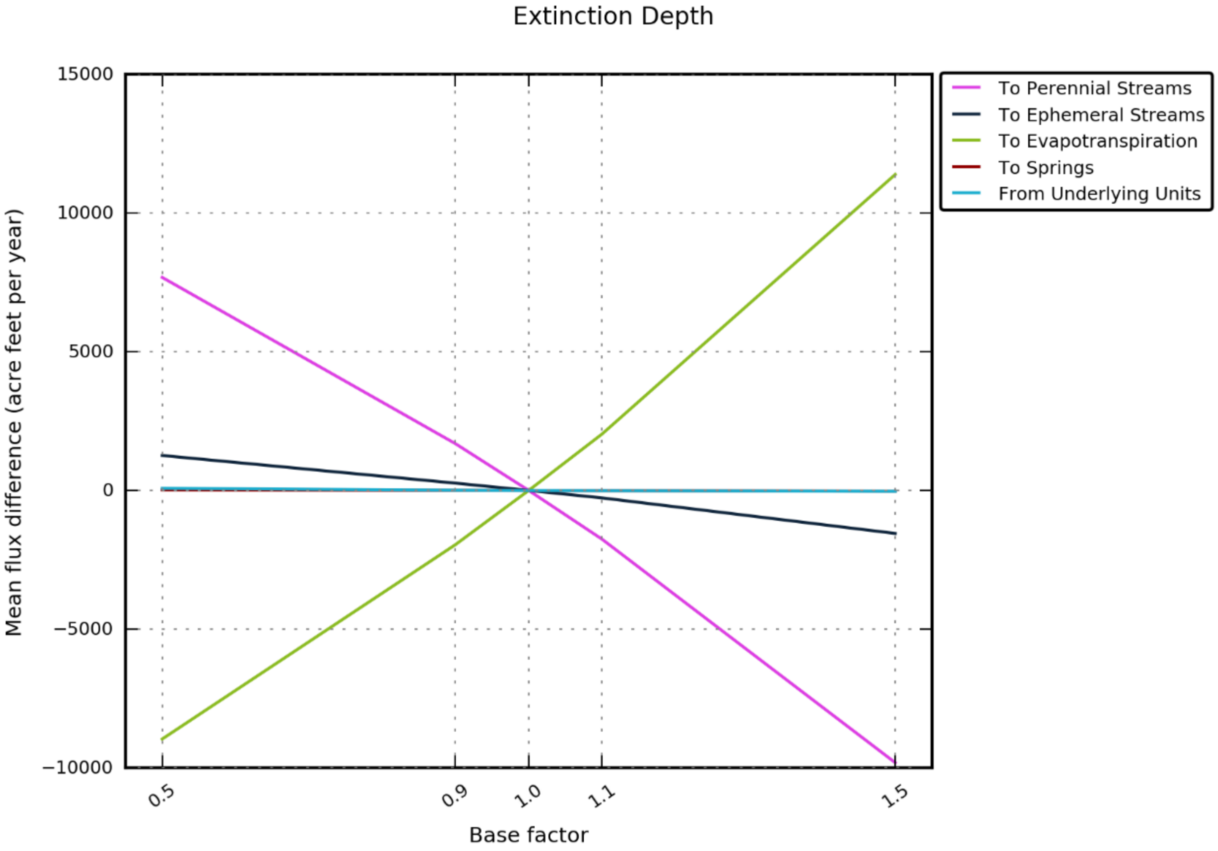

Figure 4.2.28 **Flow sensitivity in acre-feet per year for the steady-state model to changes in the extinction depth for evapotranspiration.**

4.2.2 Transient Sensitivities

In general, hydraulic head sensitivity responses for the transient model are generally very similar to the corresponding sensitivity responses for the steady-state model. Figures 4.2.29 through 4.2.34 for the transient model head sensitivity to horizontal and vertical hydraulic conductivity are very similar to Figures 4.2.1 through 4.2.6 for the steady-state model.

In addition to the parameter sensitivities considered in the steady-state model, the transient model adds additional parameters for perturbation including storage properties and pumping. Figure 4.2.35 shows the sensitivity in hydraulic heads to the specific yield of layer 1 with increases in specific yield resulting in increases in hydraulic heads for all three layers. Figure 4.2.36 shows a similar trend in sensitivity to the specific yield of layer 2 but the mean head differences are beneath the level of noise in head convergence. Increases in the specific yield of layer 3 results in decreases in hydraulic heads as depicted in Figure 4.2.37.

Figures 4.2.38 through 4.2.40 show that the model is very insensitive to storativity with all hydraulic head sensitivities below the level of noise in head convergence. This is not surprising because both the Brazos River Alluvium and the shallow flow system in the outcrops of the underlying formations are unconfined.

Figures 4.2.41 through 4.2.48 for the transient model head sensitivity to recharge and boundary conductance are very similar to Figures 4.2.7 through 4.2.14 for the steady-state model. Figure 4.2.49 illustrates the sensitivity of hydraulic heads to pumping, with increases in pumping resulting in decreases in hydraulic heads.

Figures 4.2.50 through 4.2.55 for the transient model flow sensitivity to horizontal and vertical hydraulic conductivity are generally similar to Figures 4.2.15 to 4.2.20 for the steady-state model with the exception of the vertical hydraulic conductivity of layer 1 in the transient model. Figure 4.2.53 shows a reversed trend for change in flow to perennial streams than Figure 4.2.18, but in both cases the change in flow is only a few acre-feet per year.

Figure 4.2.56 shows the sensitivity of boundary flows to changes in the specific yield of layer 1. Increasing specific yield increases flow to perennial streams, and to a far lesser degree, to ephemeral streams while decreasing flow from the underlying formations and to evapotranspiration. Figure 4.2.57 shows the sensitivity of boundary flows to changes in the specific yield of layer 2. Increasing specific yield increases flow to perennial streams while decreasing flow from the underlying formations and, to a lesser degree, to evapotranspiration and ephemeral streams. Figure 4.2.58 shows the sensitivity of boundary flows to changes in the specific yield of layer 3. Increasing specific yield decreases all of the boundary flows, particularly the flow to ephemeral and perennial streams.

Figure 4.2.59 shows the sensitivity of boundary flows to changes in the storativity of layer 1. Increasing storativity decreases flow to perennial streams, and to a far lesser degree, flow from the underlying formations. Figure 4.2.60 shows the sensitivity of boundary flows to changes in the storativity of layer 2. Increasing storativity increases flow to perennial streams, and to a lesser degree, to ephemeral streams while decreasing flow from the underlying formations and to evapotranspiration. Figure 4.2.61 shows the sensitivity of boundary flows to changes in the storativity of layer 3. Increasing storativity increases flow from the underlying units and decreases all of the other boundary flows, particularly the flow to ephemeral streams.

Figures 4.2.62 through 4.2.69 for the transient model flow sensitivity to recharge and boundary conductance are very similar in all cases to Figures 4.2.21 through 4.2.28 for the steady-state model.

Figure 4.2.70 depicts the sensitivity of boundary flows to changes in pumping with increases in pumping resulting in decreases in flows to perennial streams and, to a much lesser degree, to ephemeral streams and evapotranspiration. In contrast, flow from the underlying formations increases somewhat with increased pumping.

After reviewing the spider plots discussed to this point, sensitivity hydrographs were plotted for several key parameters. Wells were chosen from most counties where hydrographs were available. Figure 4.2.71 depicts the sensitivity of several hydrographs to changes in horizontal hydraulic conductivity in the Brazos River Alluvium Aquifer. Figure 4.2.72 shows the sensitivity of the same hydrographs to changes in recharge to the Brazos River Alluvium Aquifer. Figure 4.2.73 shows the sensitivity of the same hydrographs to changes in pumping within the Brazos River Alluvium Aquifer. Each of these hydrographs illustrate how changes to key model inputs affect the behavior of the numerical model.

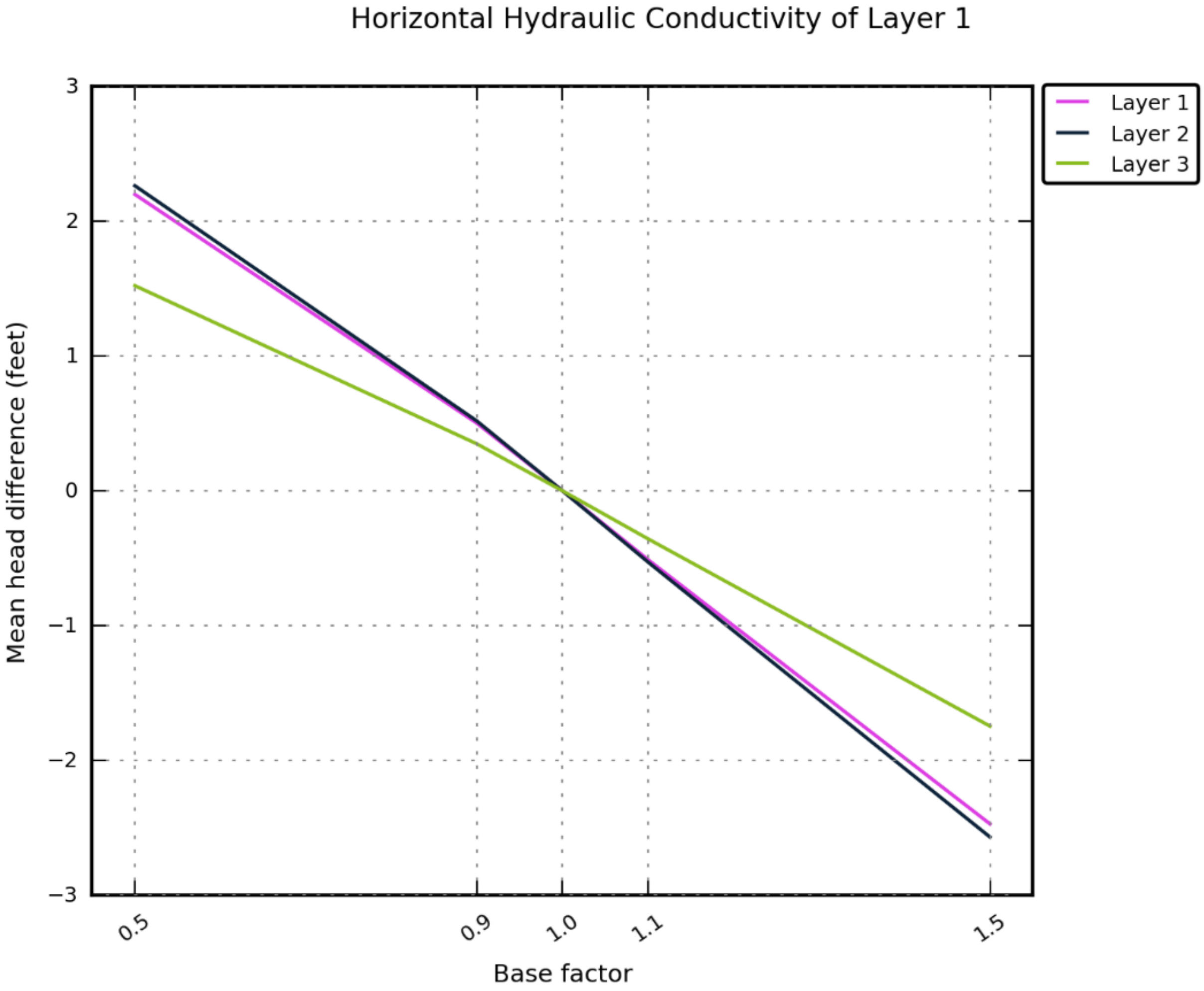

Figure 4.2.29 **Hydraulic head sensitivity in feet for the transient model to changes in horizontal hydraulic conductivity (Kh) of layer 1.**

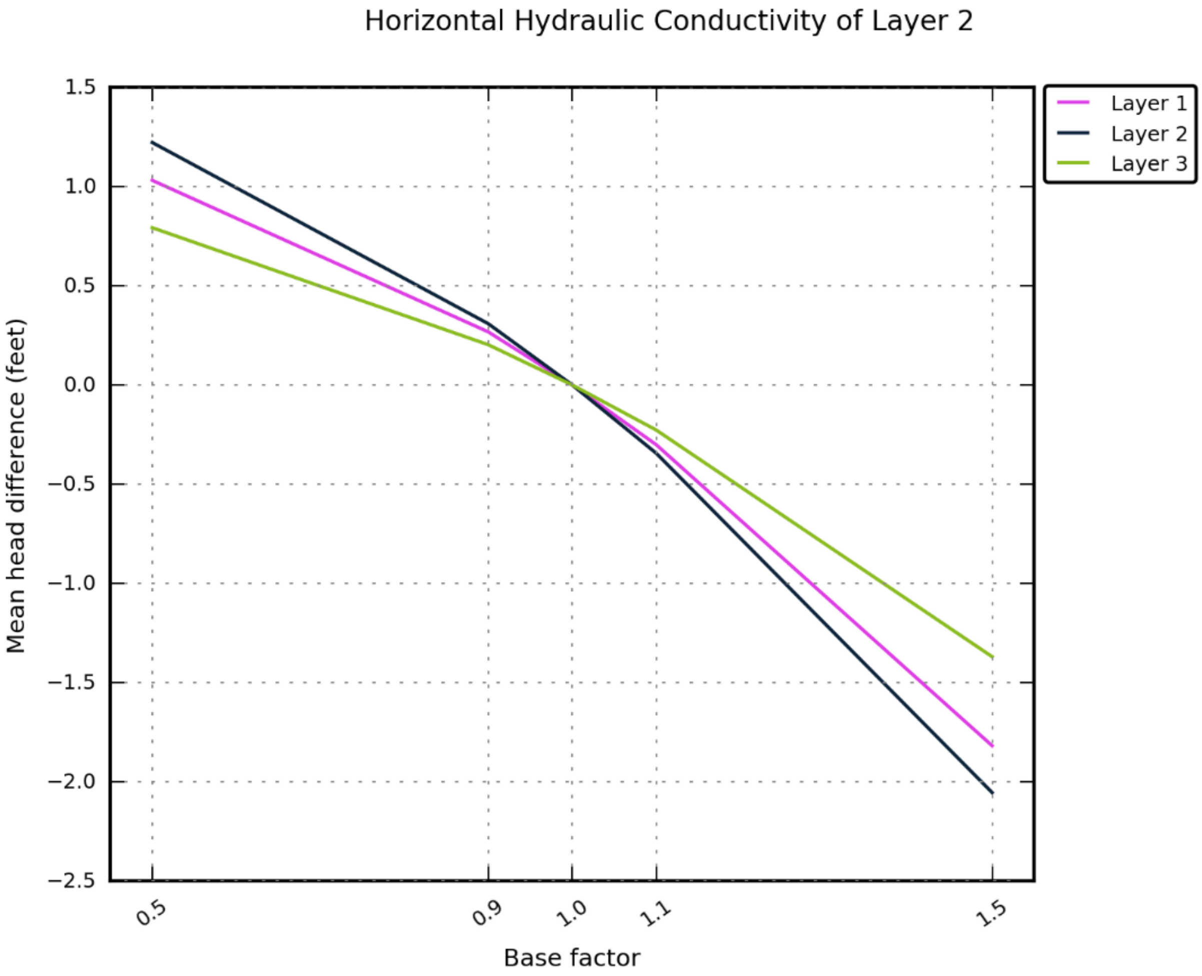

Figure 4.2.30 Hydraulic head sensitivity in feet for the transient model to changes in horizontal hydraulic conductivity (Kh) of layer 2.

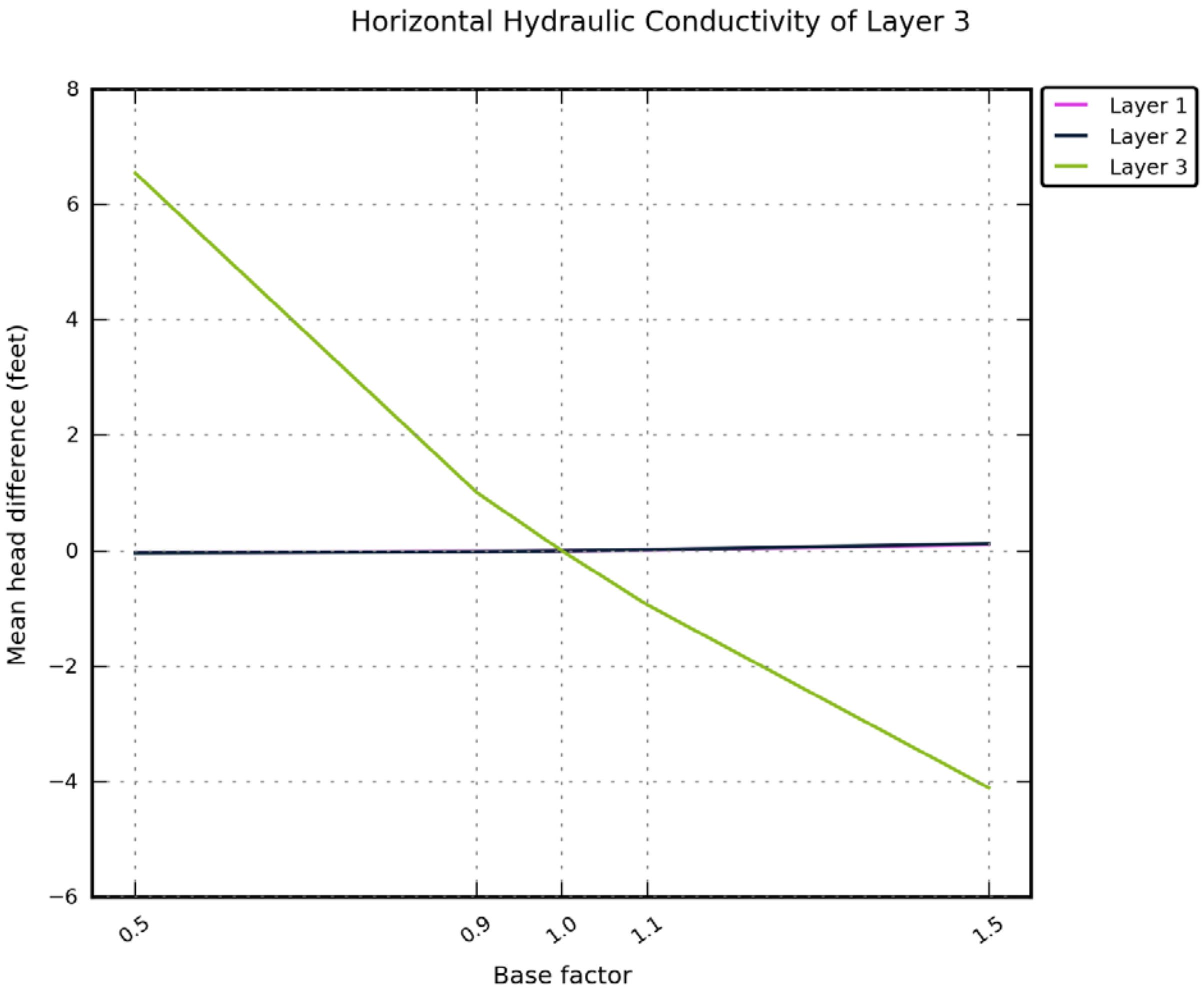

Figure 4.2.31 Hydraulic head sensitivity in feet for the transient model to changes in horizontal hydraulic conductivity (Kh) of layer 3.

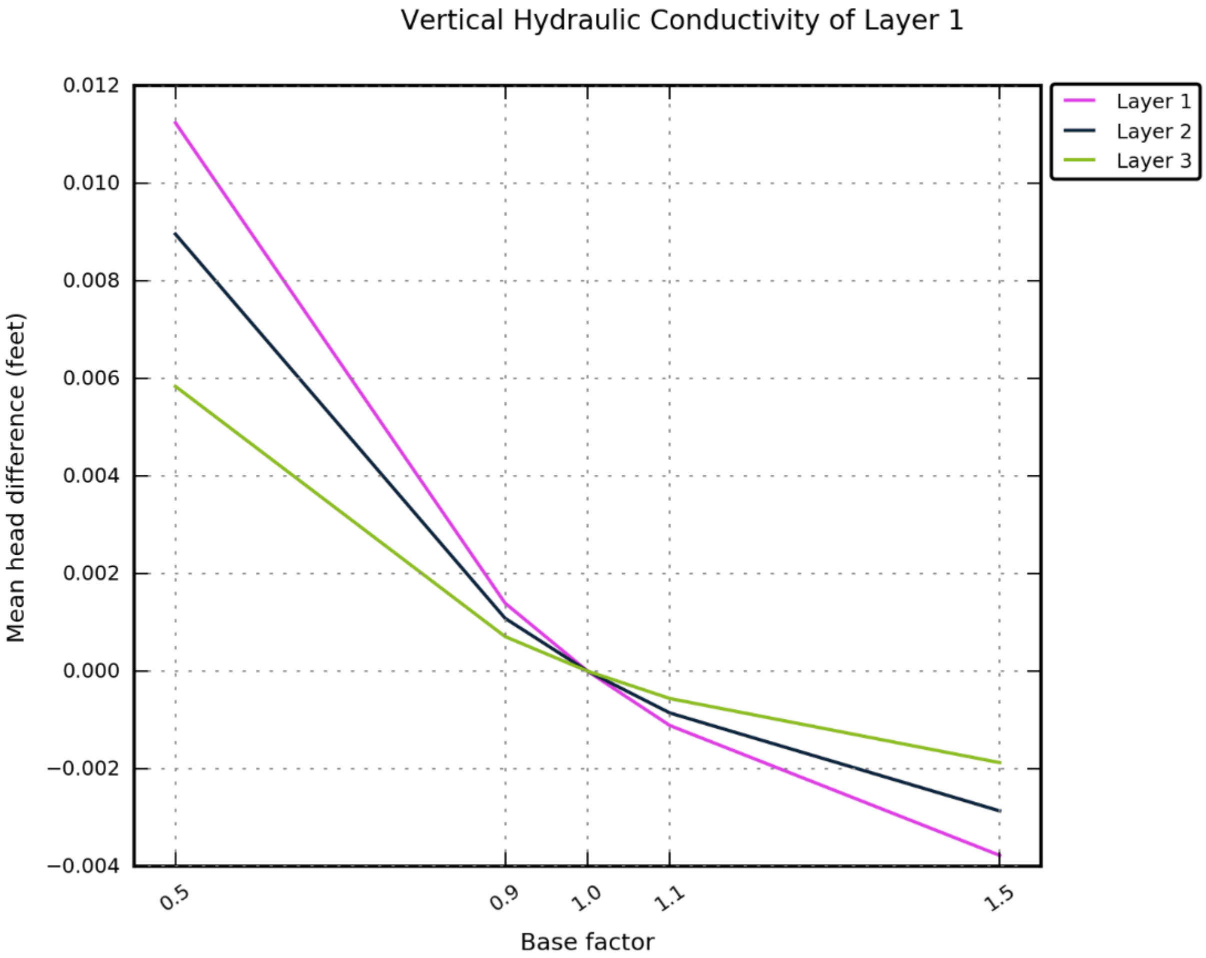

Figure 4.2.32 **Hydraulic head sensitivity in feet for the transient model to changes in vertical hydraulic conductivity (Kv) of layer 1.**

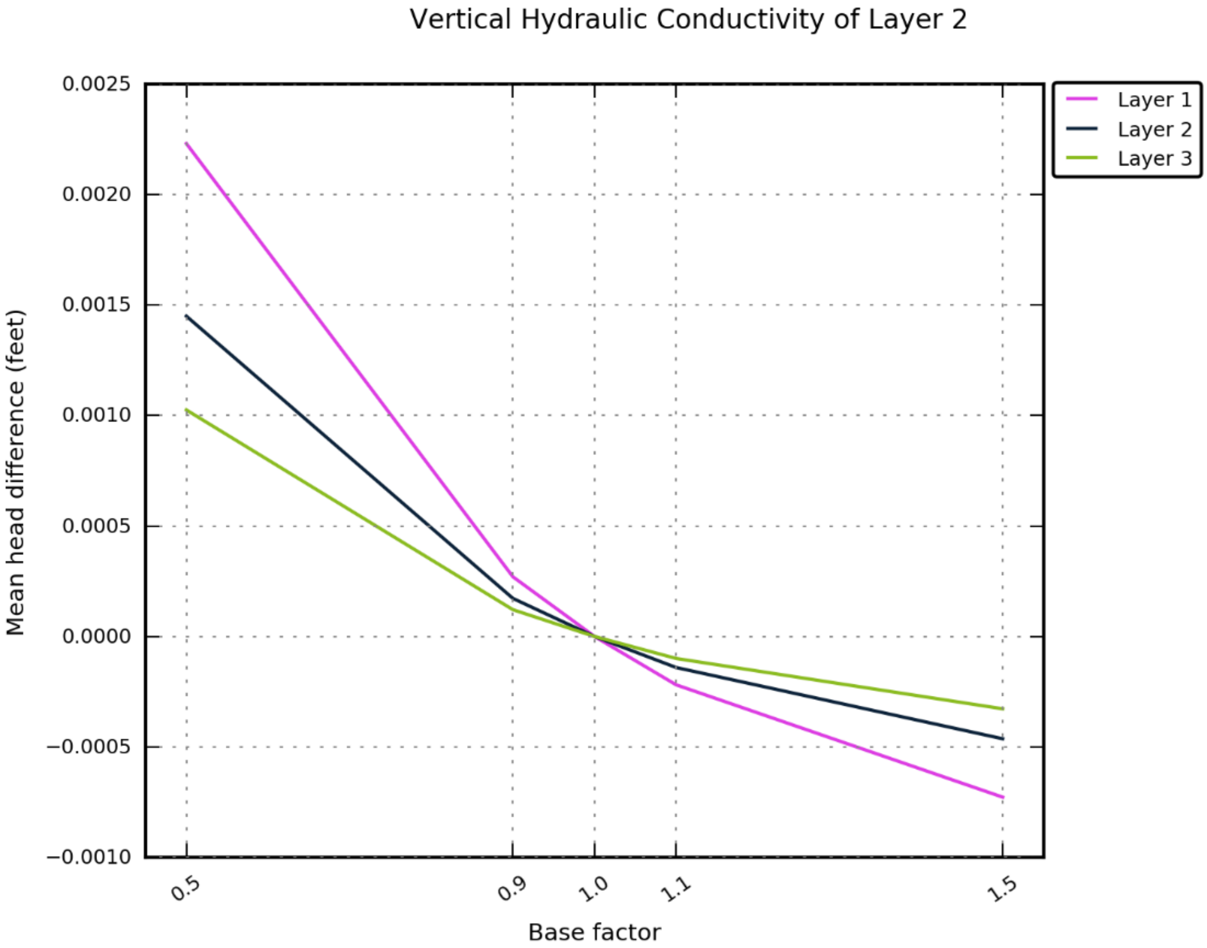

Figure 4.2.33 **Hydraulic head sensitivity in feet for the transient model to changes in vertical hydraulic conductivity (Kv) of layer 2.**

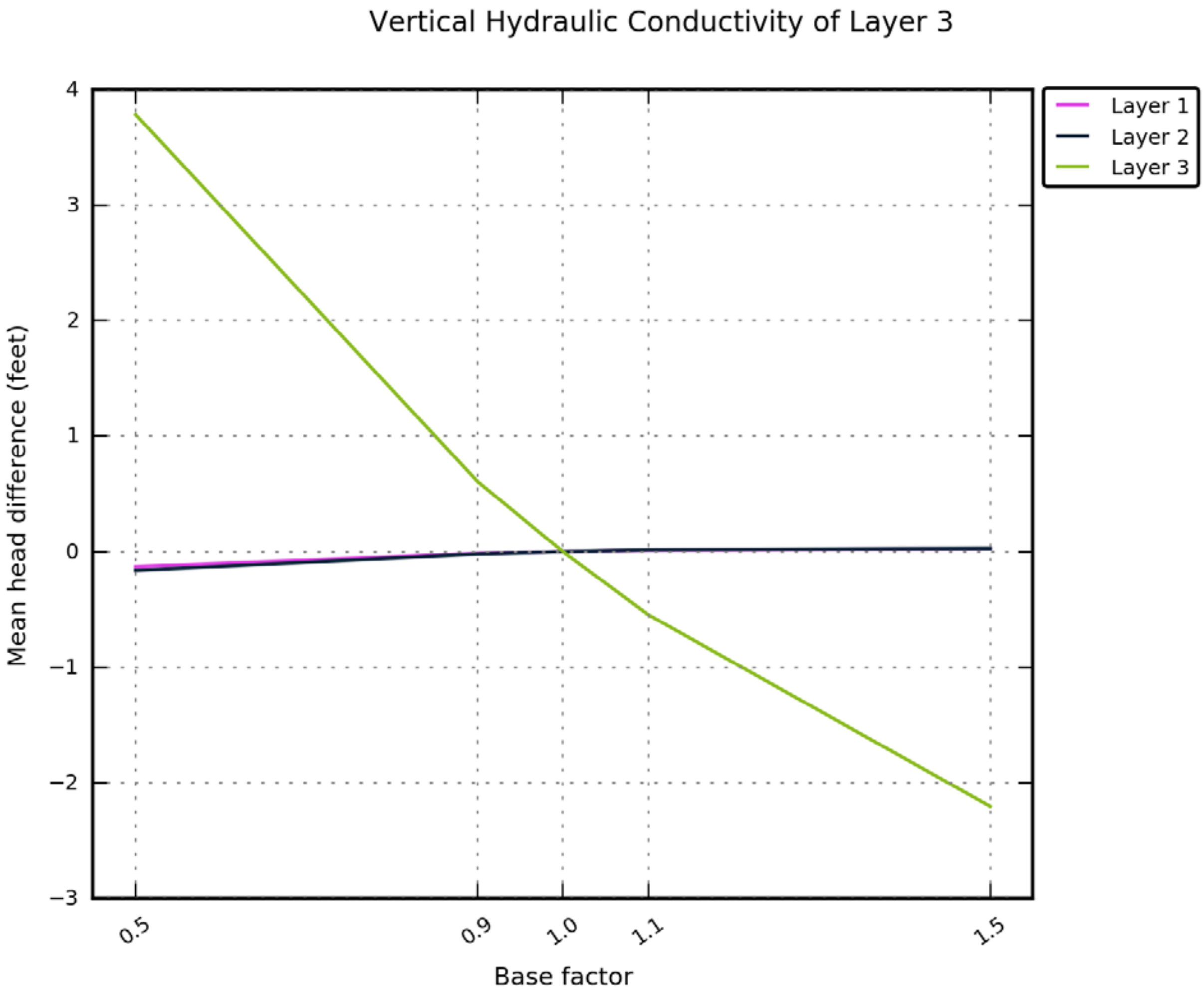

Figure 4.2.34 Hydraulic head sensitivity in feet for the transient model to changes in vertical hydraulic conductivity (Kv) of layer 3.

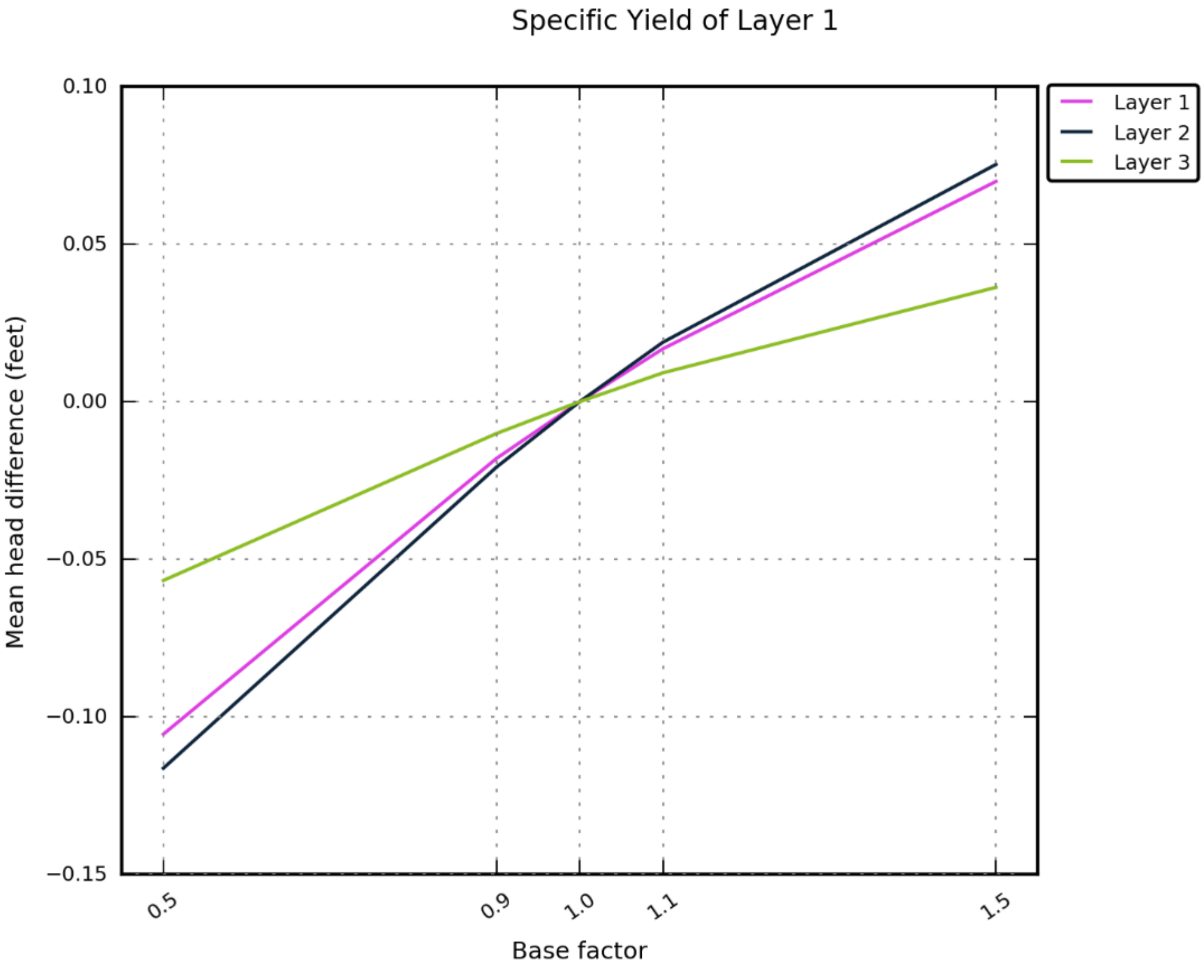

Figure 4.2.35 Hydraulic head sensitivity in feet for the transient model to changes in specific yield of layer 1.

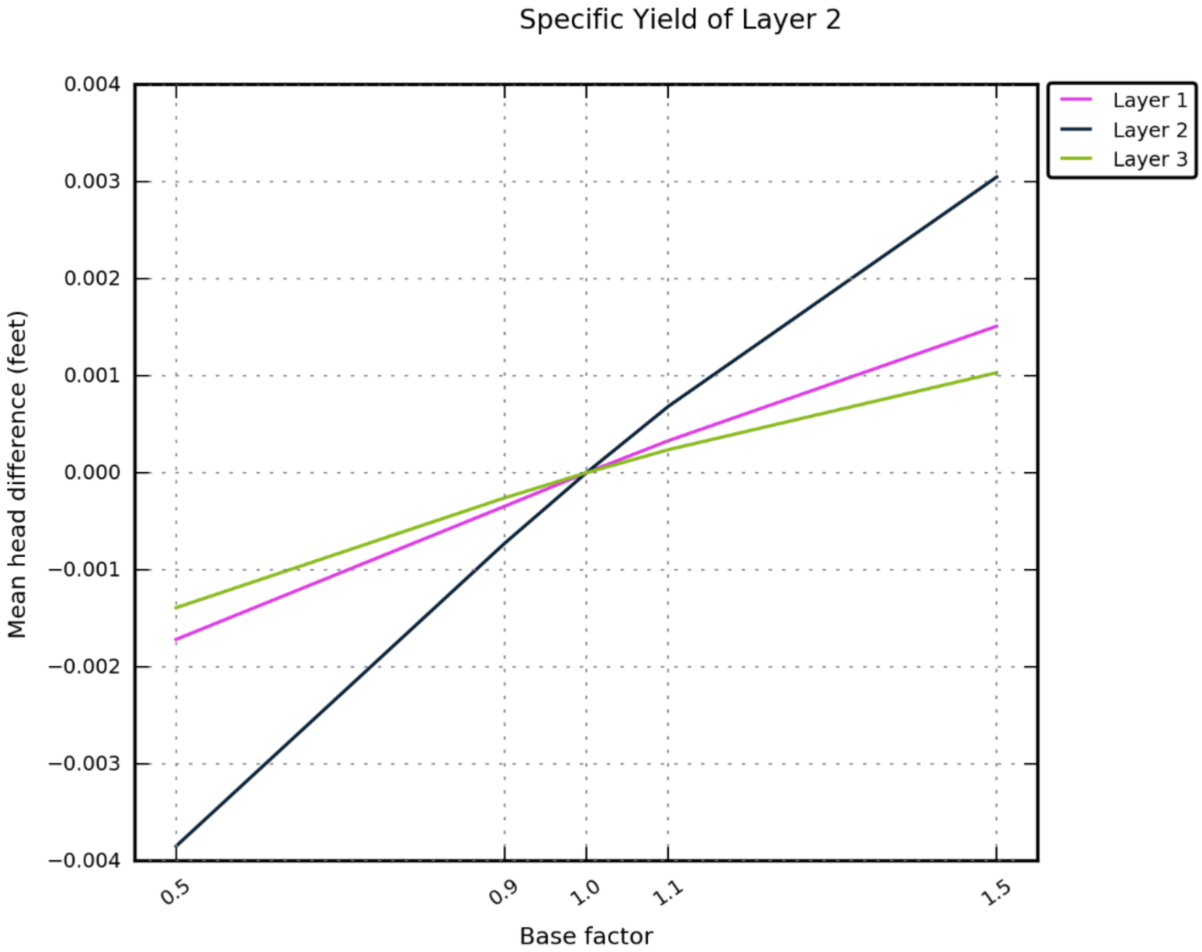

Figure 4.2.36 Hydraulic head sensitivity in feet for the transient model to changes in specific yield of layer 2.

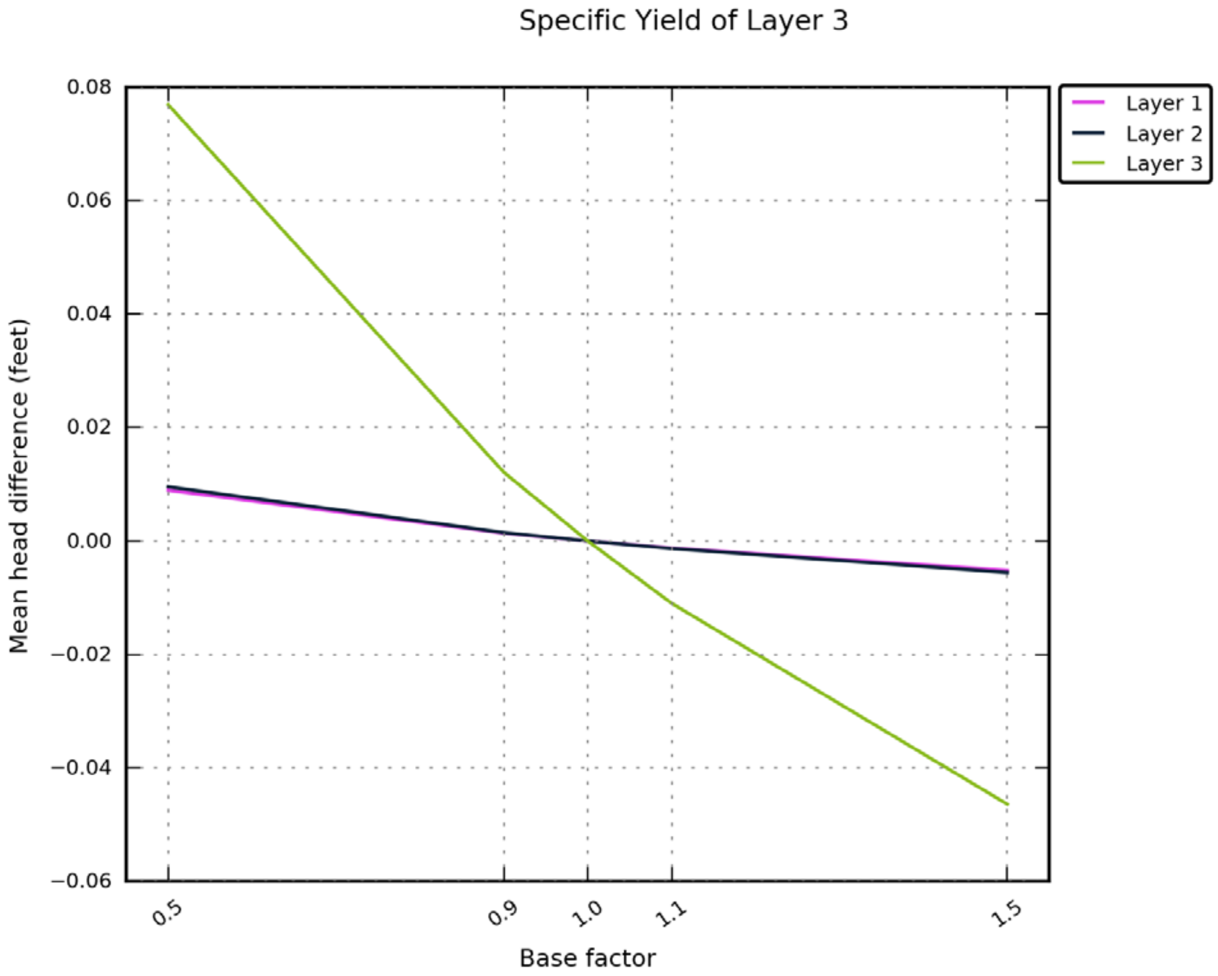

Figure 4.2.37 **Hydraulic head sensitivity in feet for the transient model to changes in specific yield of layer 3.**

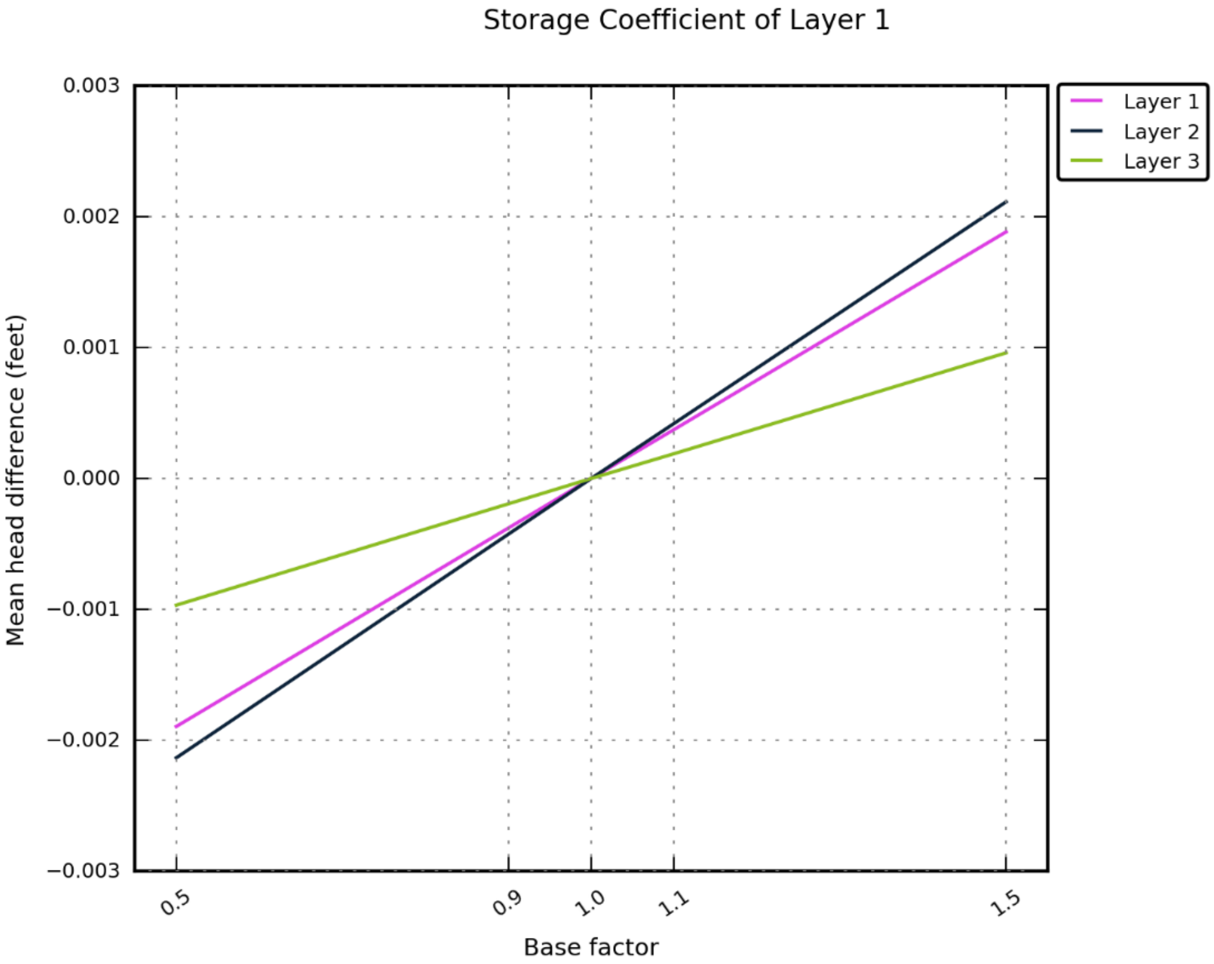

Figure 4.2.38 Hydraulic head sensitivity in feet for the transient model to changes in storativity of layer 1.

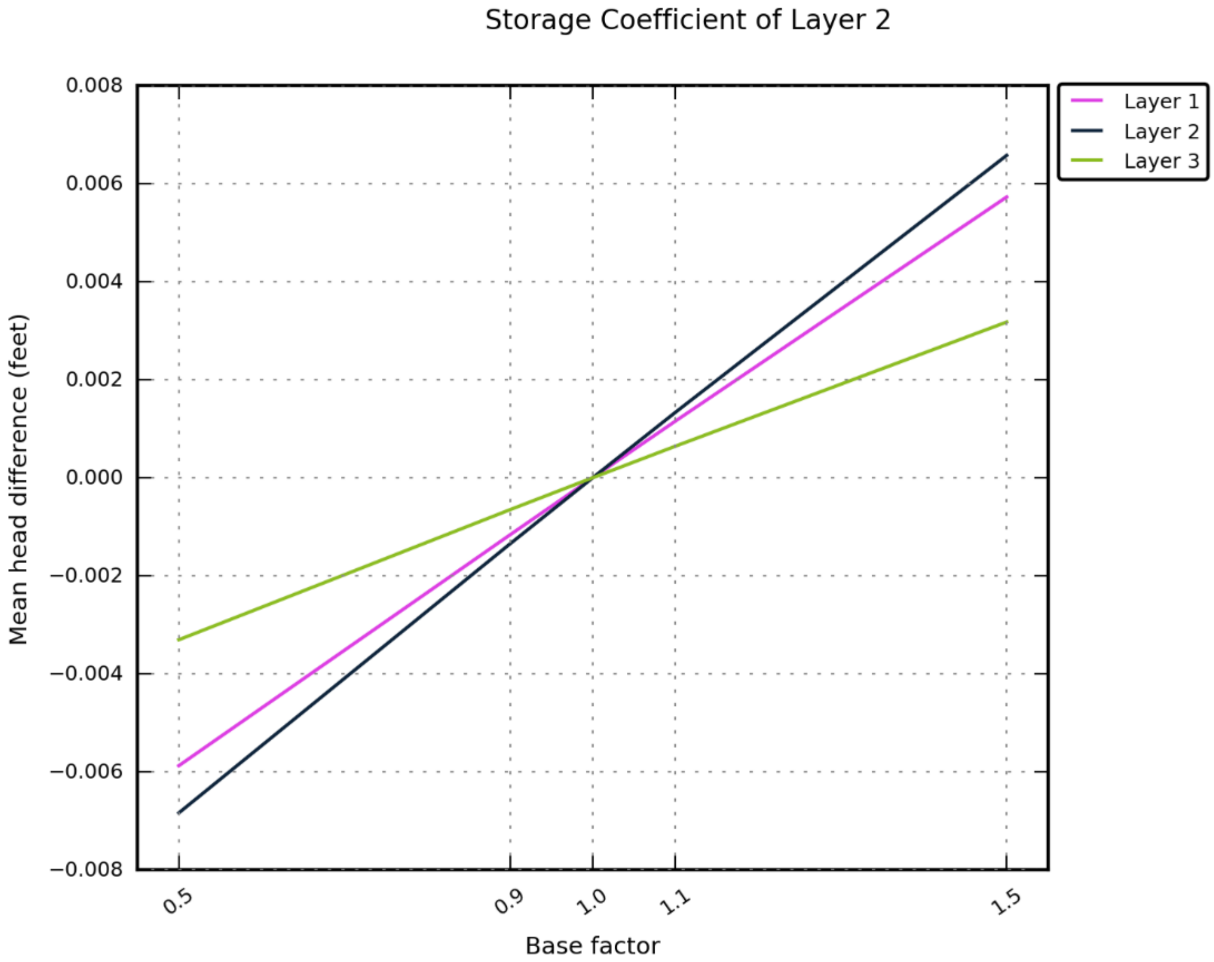

Figure 4.2.39 Hydraulic head sensitivity in feet for the transient model to changes in storativity of layer 2.

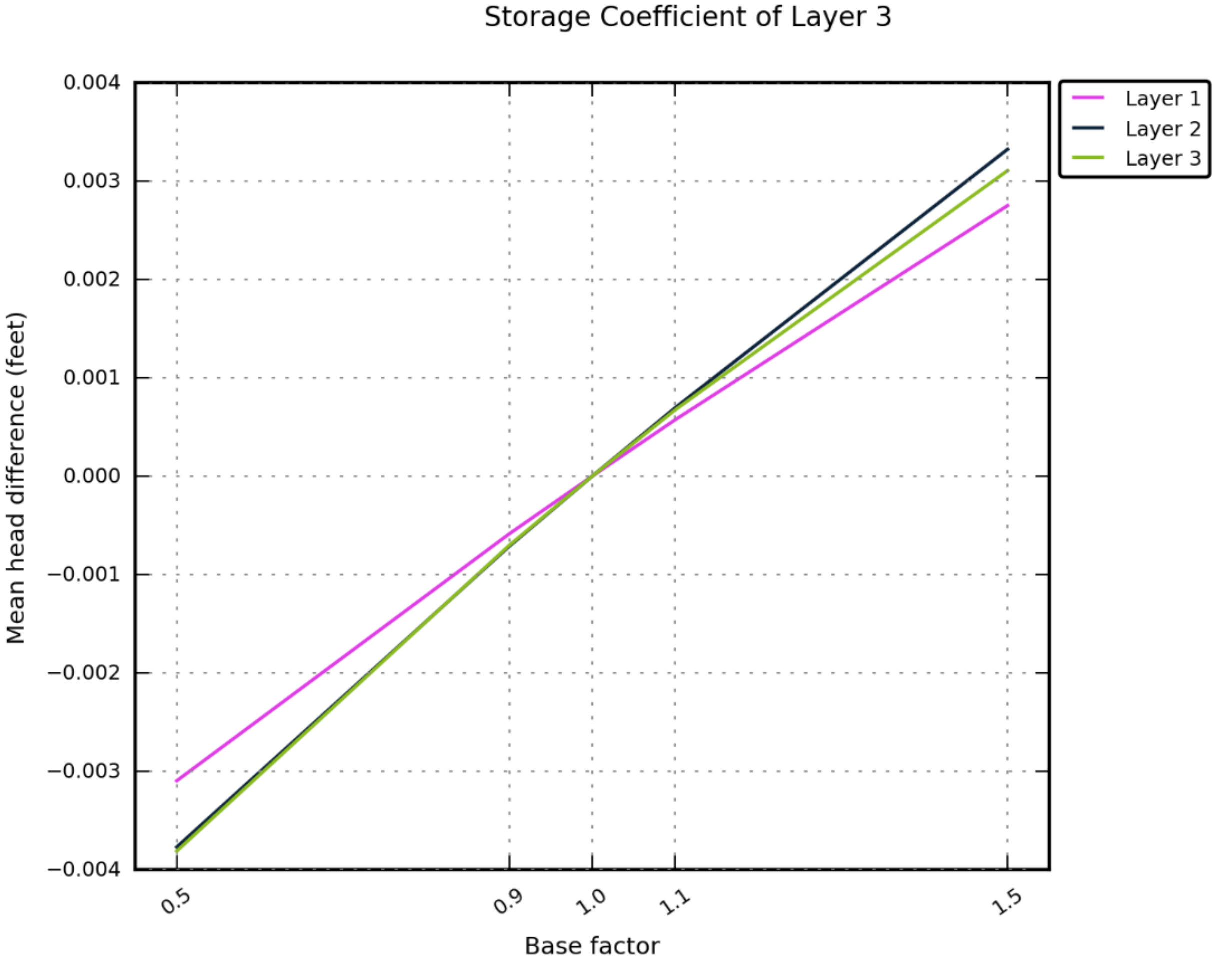

Figure 4.2.40 Hydraulic head sensitivity in feet for the transient model to changes in storativity of layer 3.

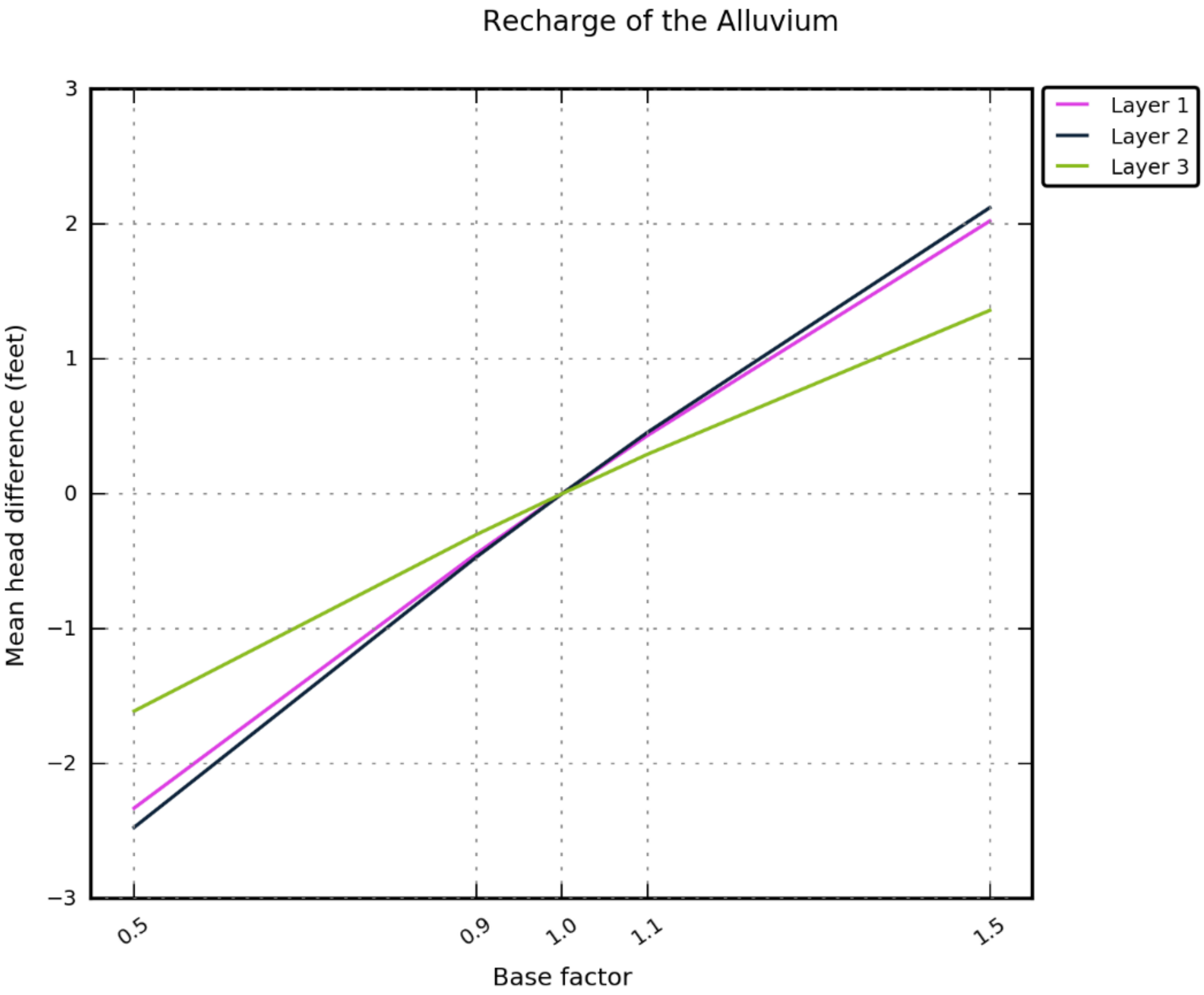

Figure 4.2.41 Hydraulic head sensitivity in feet for the transient model to changes in recharge to the Brazos River Alluvium Aquifer.

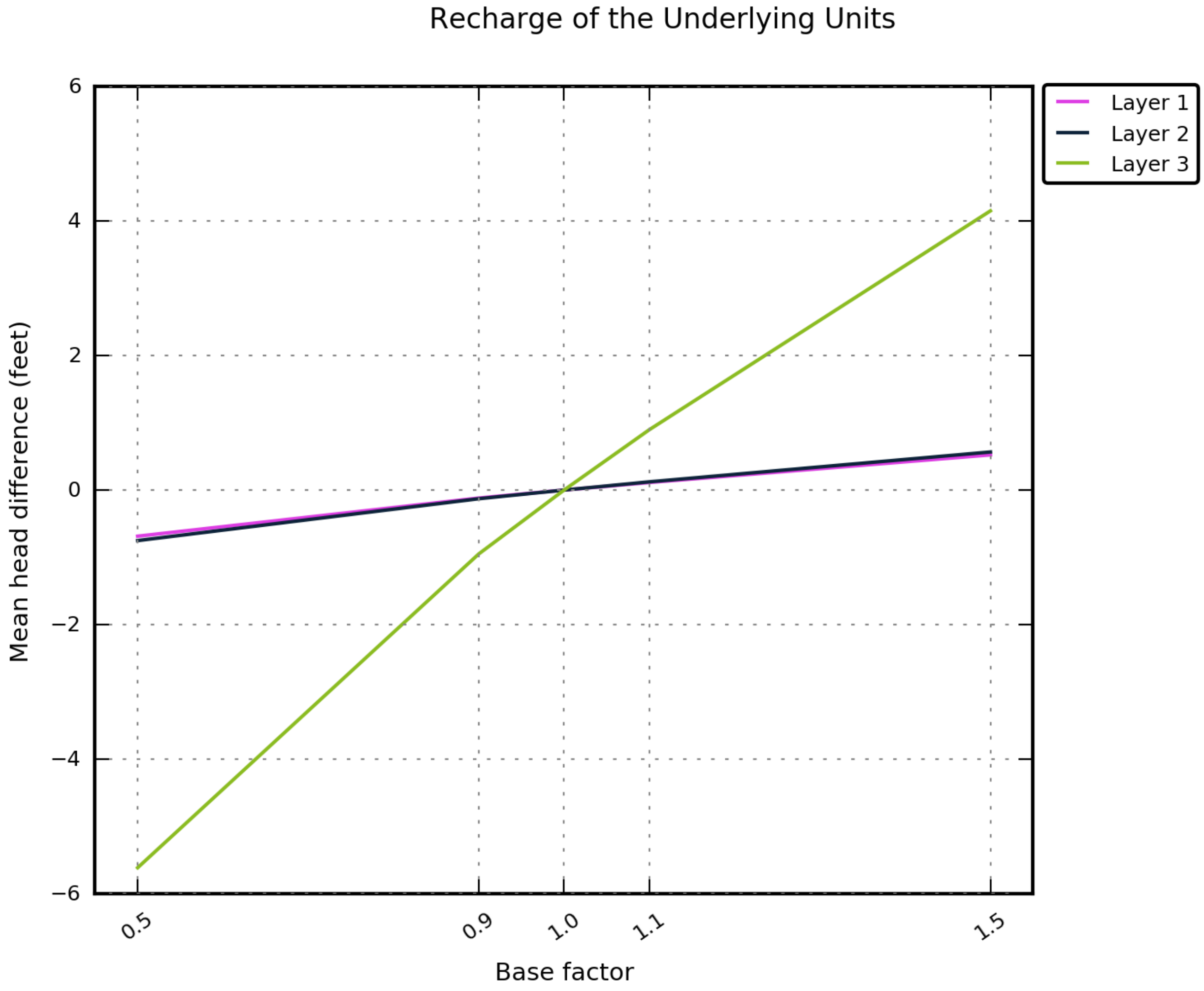

Figure 4.2.42 Hydraulic head sensitivity in feet for the transient model to changes in recharge to the outcrops of the underlying formations.

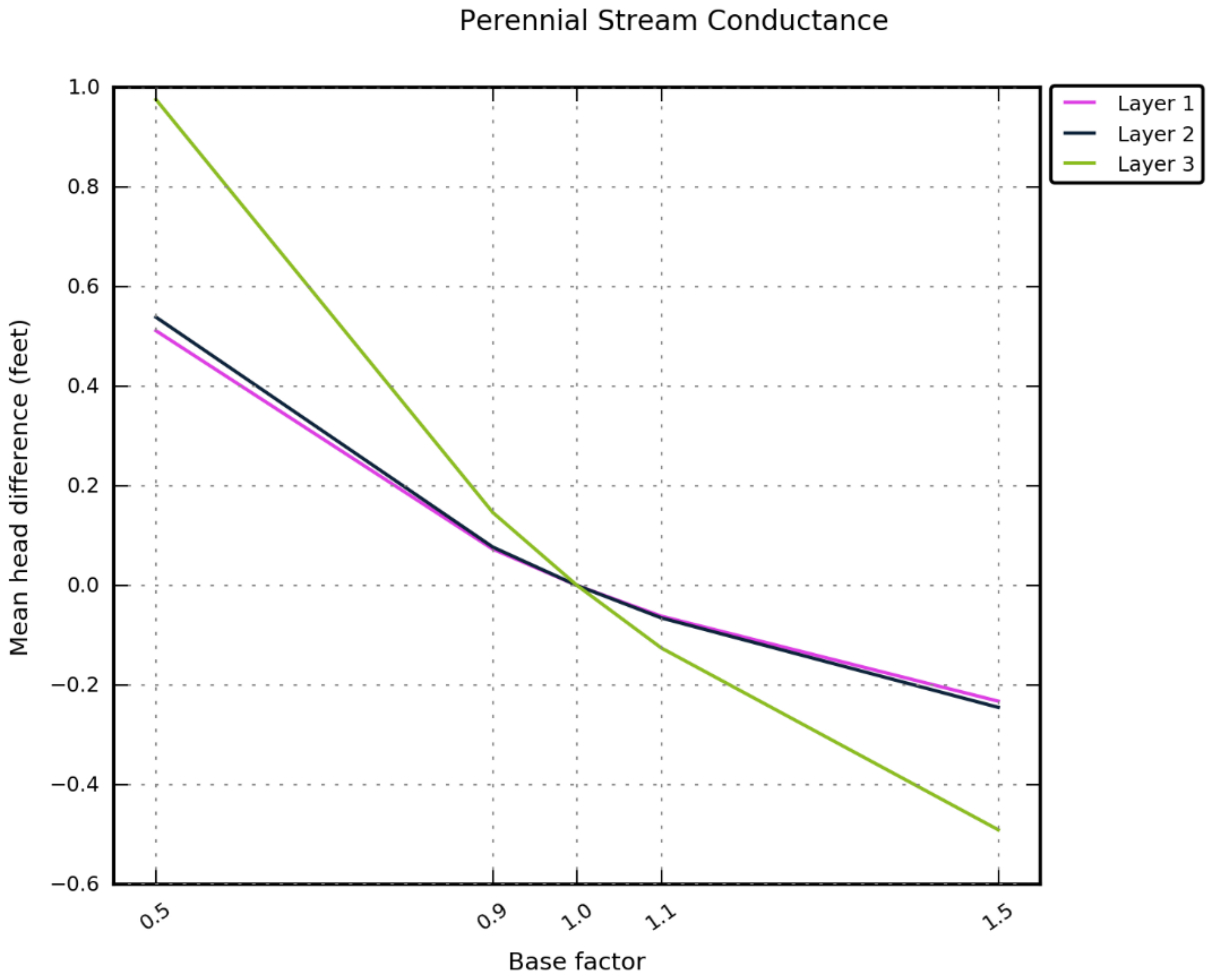

Figure 4.2.43 Hydraulic head sensitivity in feet for the transient model to changes in streambed conductance of perennial streams.

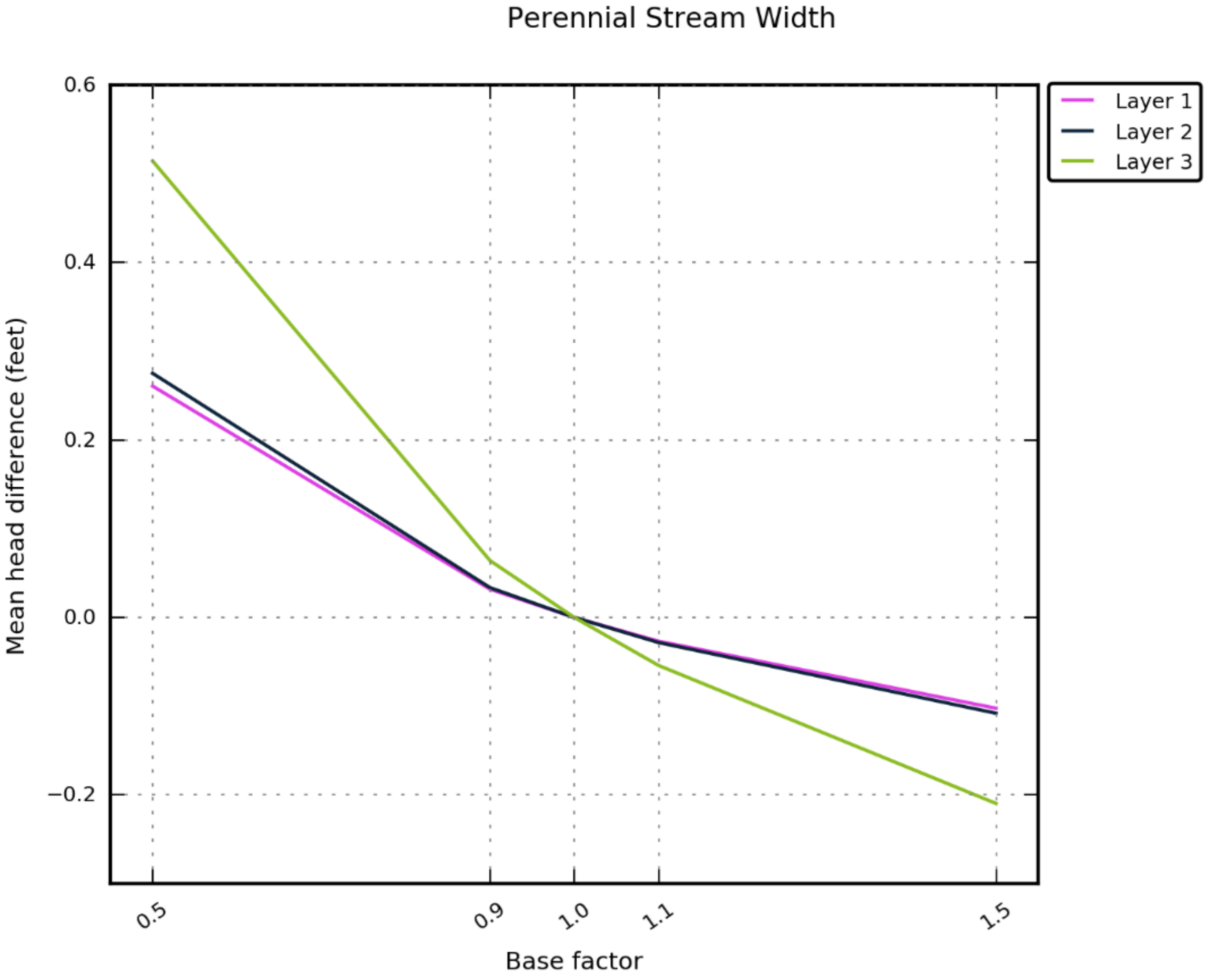

Figure 4.2.44 Hydraulic head sensitivity in feet for the transient model to changes in stream width of perennial streams.

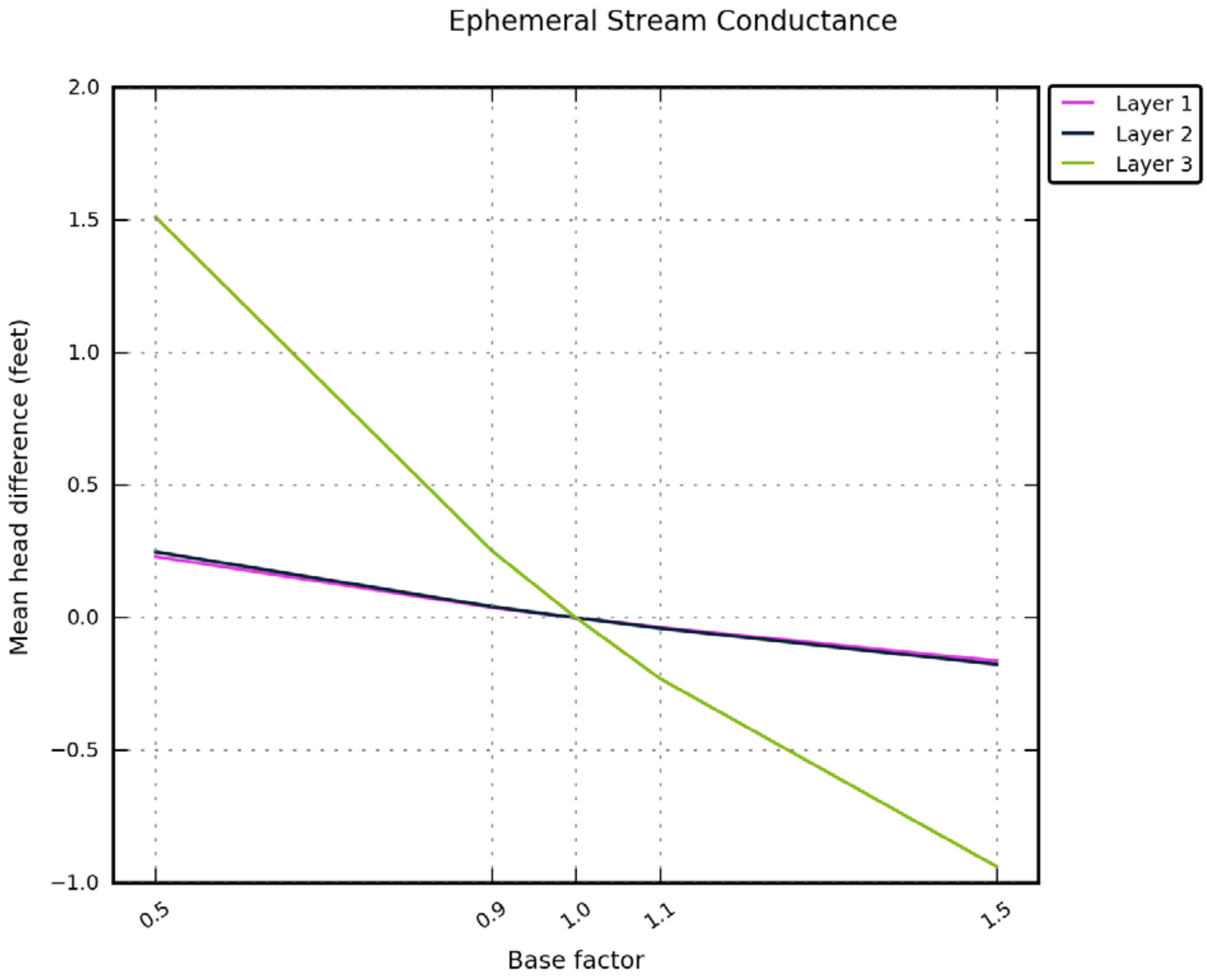

Figure 4.2.45 Hydraulic head sensitivity in feet for the transient model to changes in streambed conductance of ephemeral streams.

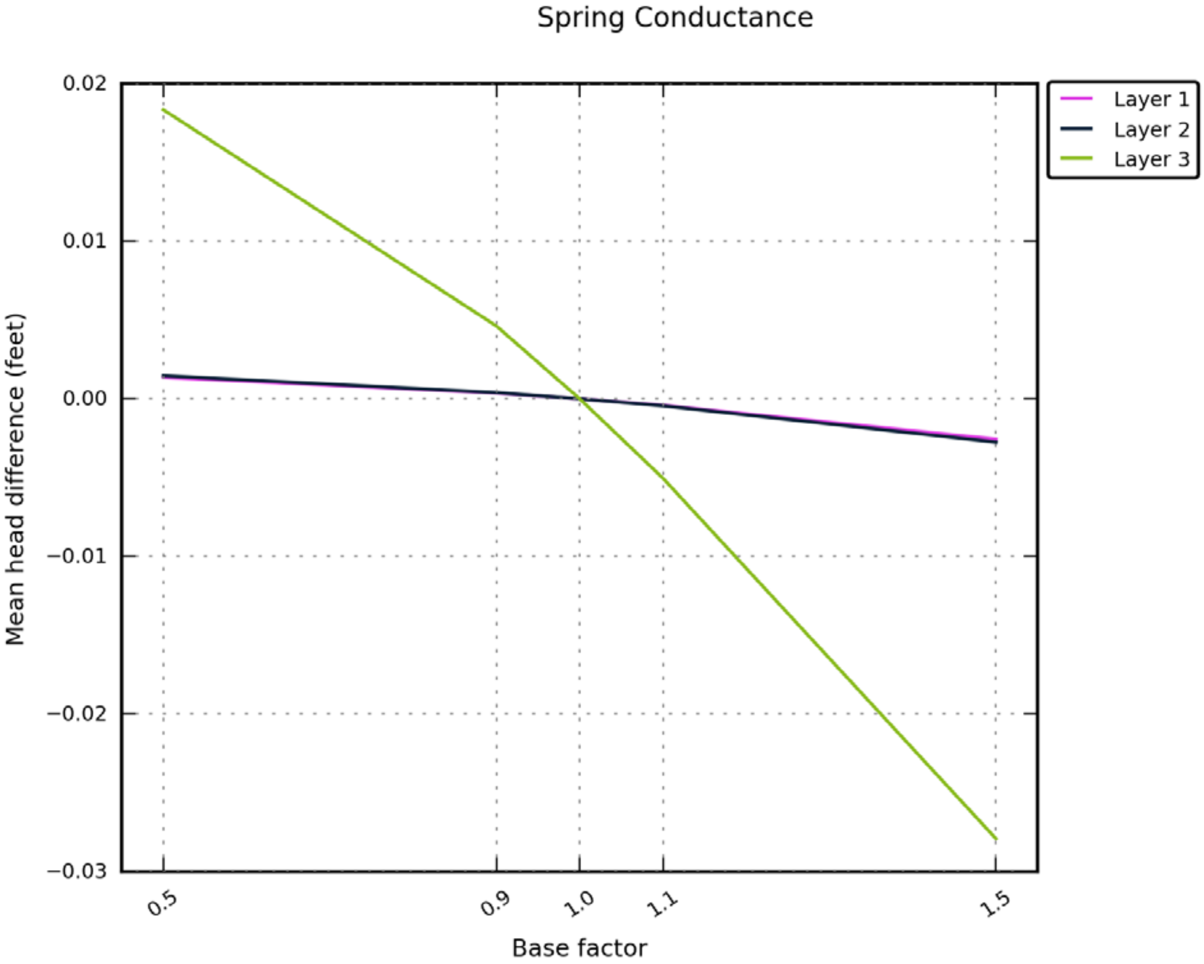

Figure 4.2.46 Hydraulic head sensitivity in feet for the transient model to changes in spring conductance.

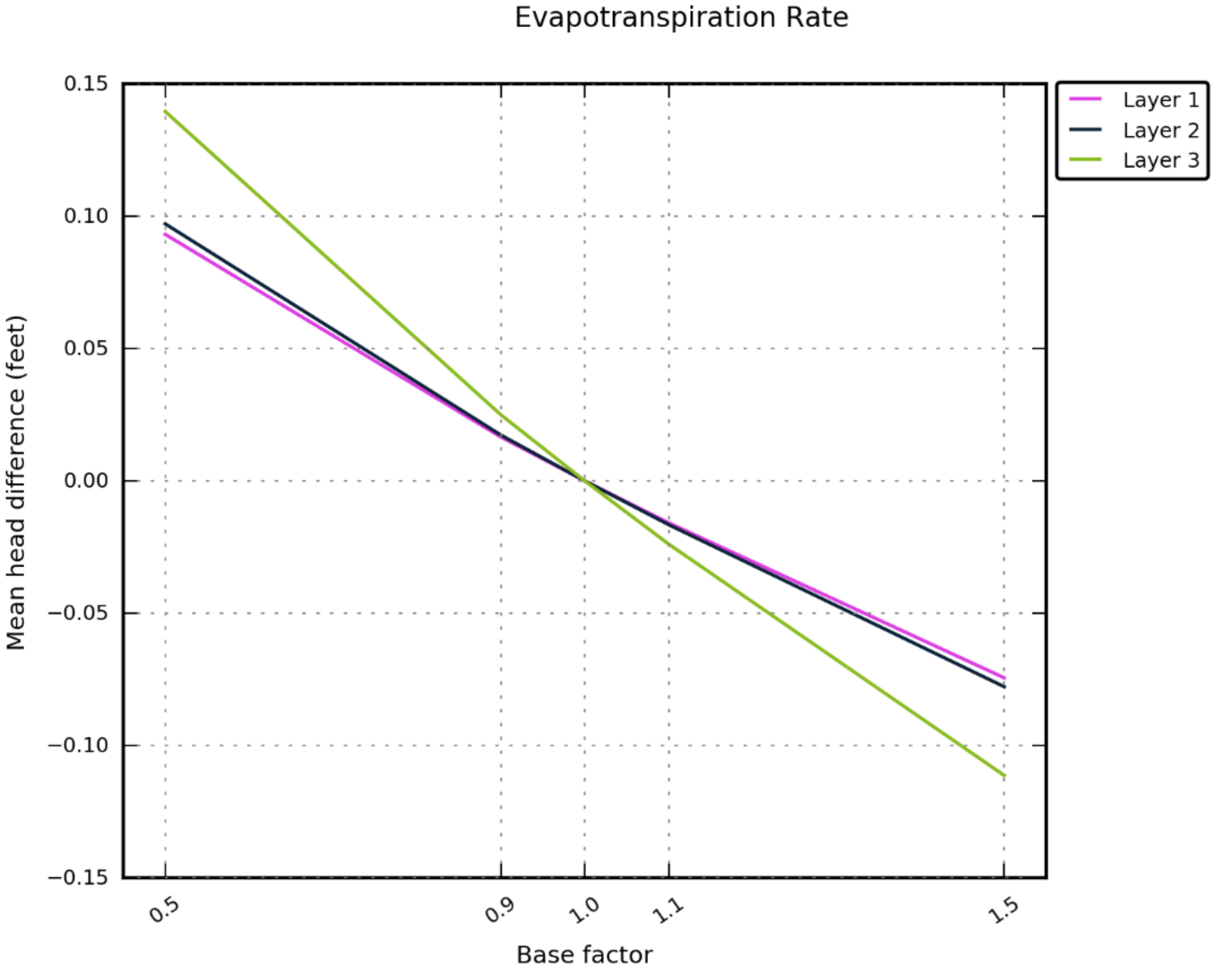

Figure 4.2.47 Hydraulic head sensitivity in feet for the transient model to changes in the maximum evapotranspiration rate.

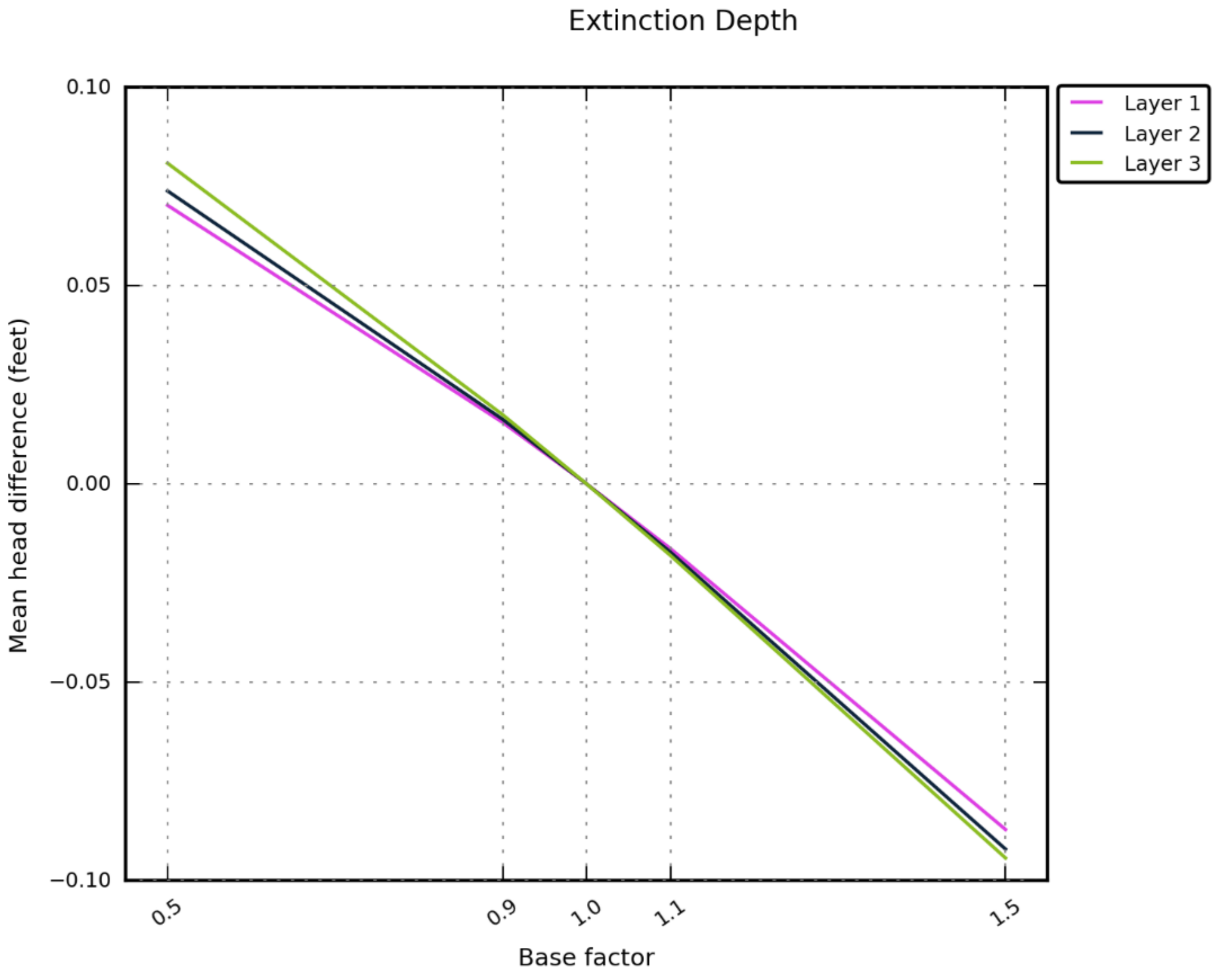

Figure 4.2.48 **Hydraulic head sensitivity in feet for the transient model to changes in the extinction depth for evapotranspiration.**

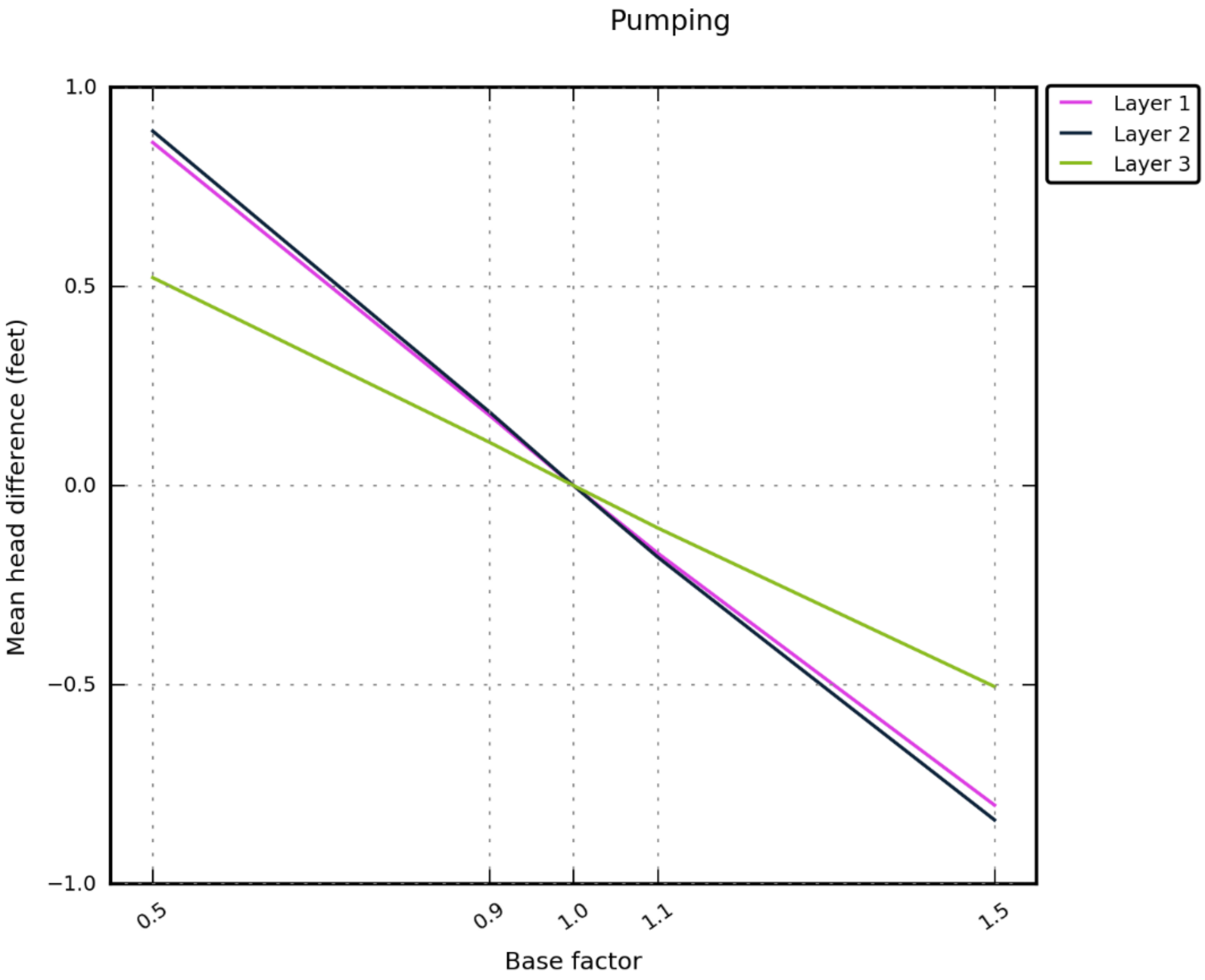

Figure 4.2.49 Hydraulic head sensitivity in feet for the transient model to changes in pumping.

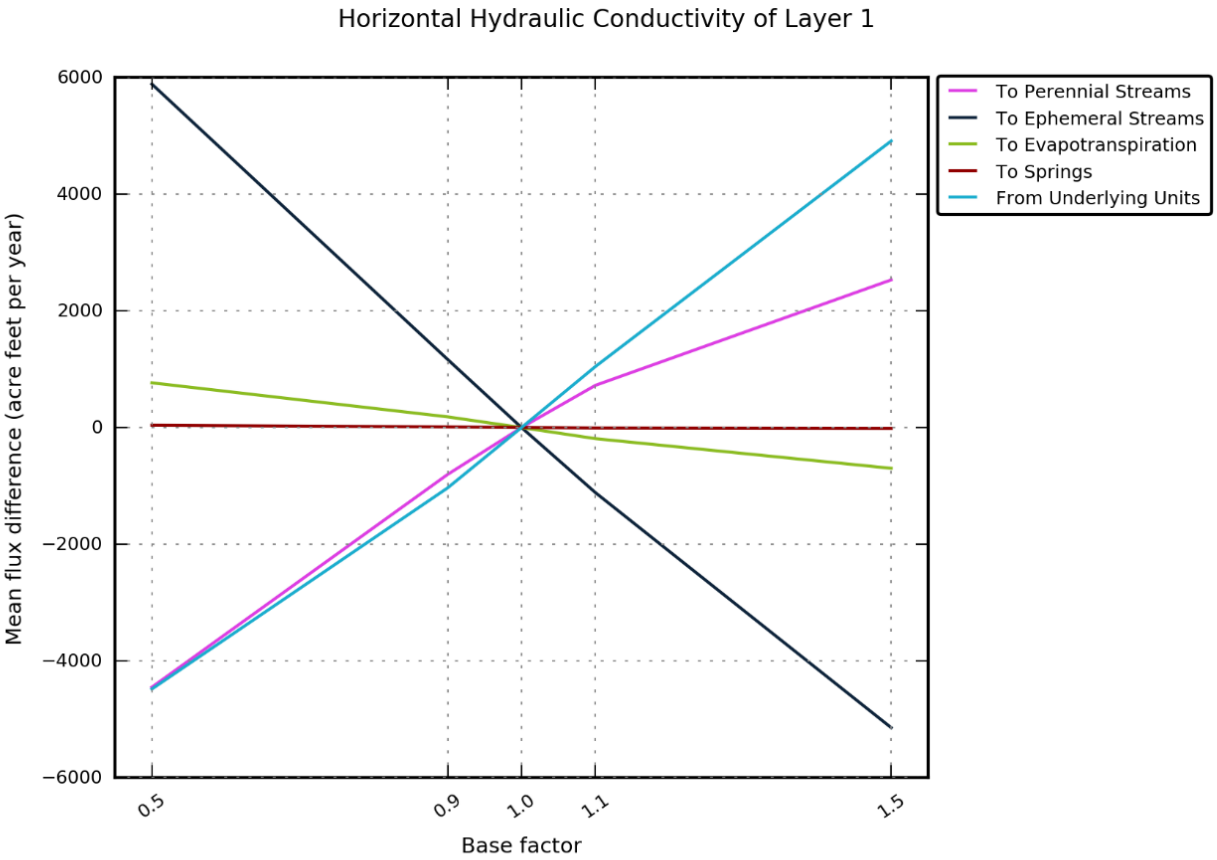

Figure 4.2.50 Flow sensitivity in acre-feet per year for the transient model to changes in horizontal hydraulic conductivity (Kh) of layer 1.

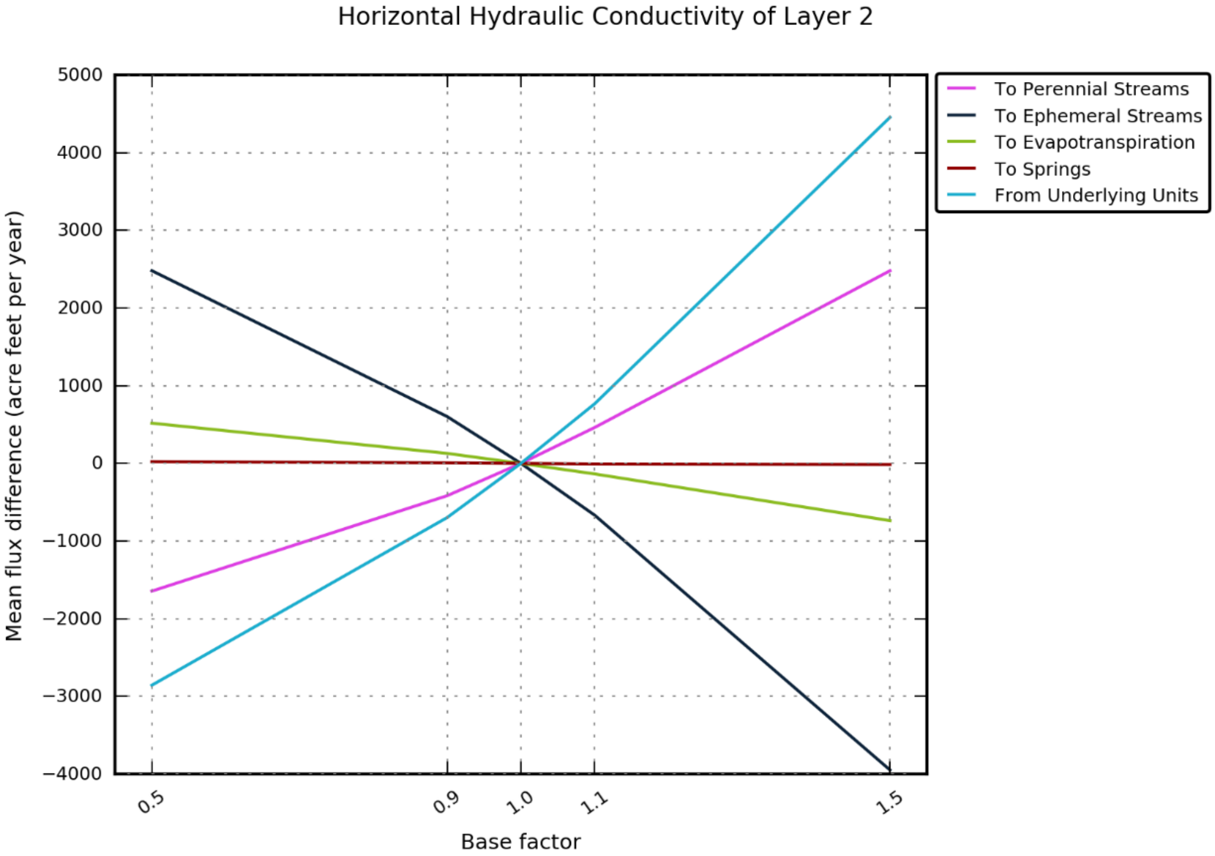

Figure 4.2.51 Flow sensitivity in acre-feet per year for the transient model to changes in horizontal hydraulic conductivity (Kh) of layer 2.

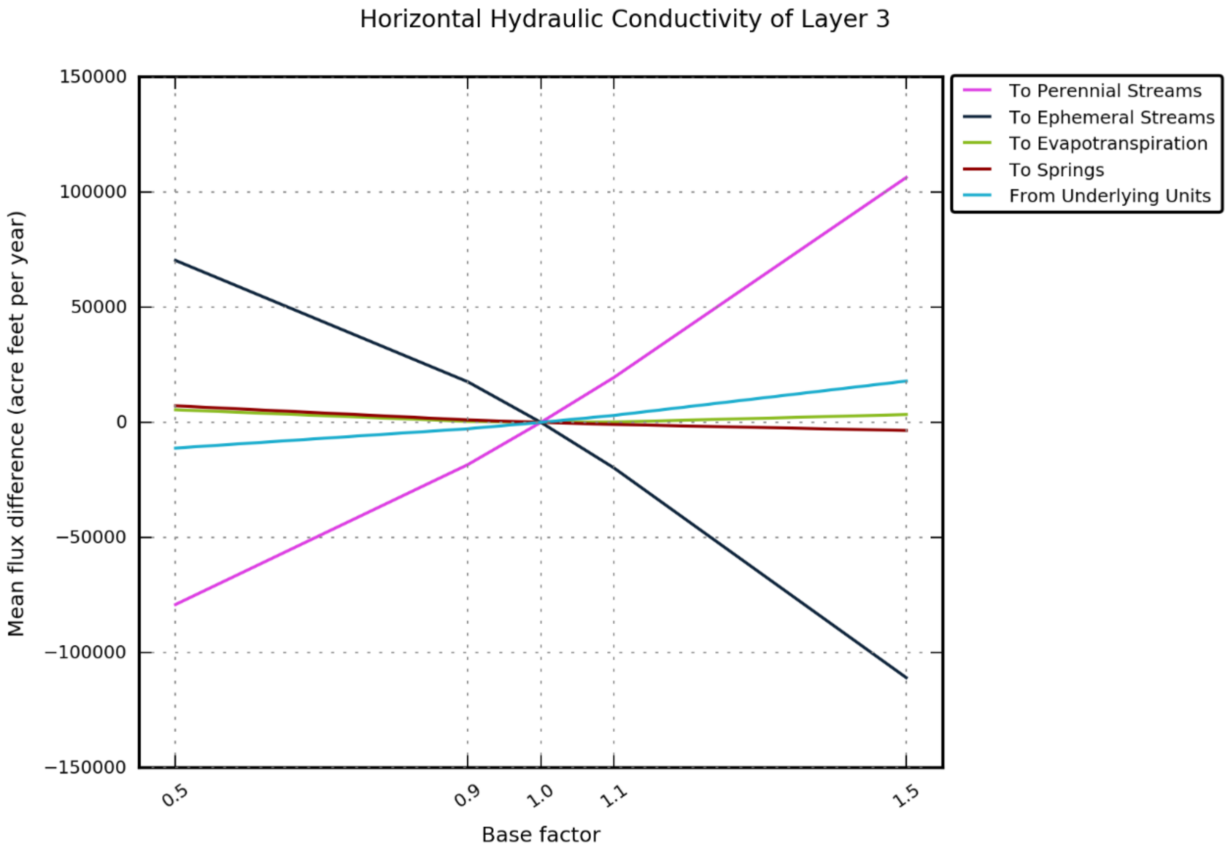

Figure 4.2.52 Flow sensitivity in acre-feet per year for the transient model to changes in horizontal hydraulic conductivity (Kh) of layer 3.

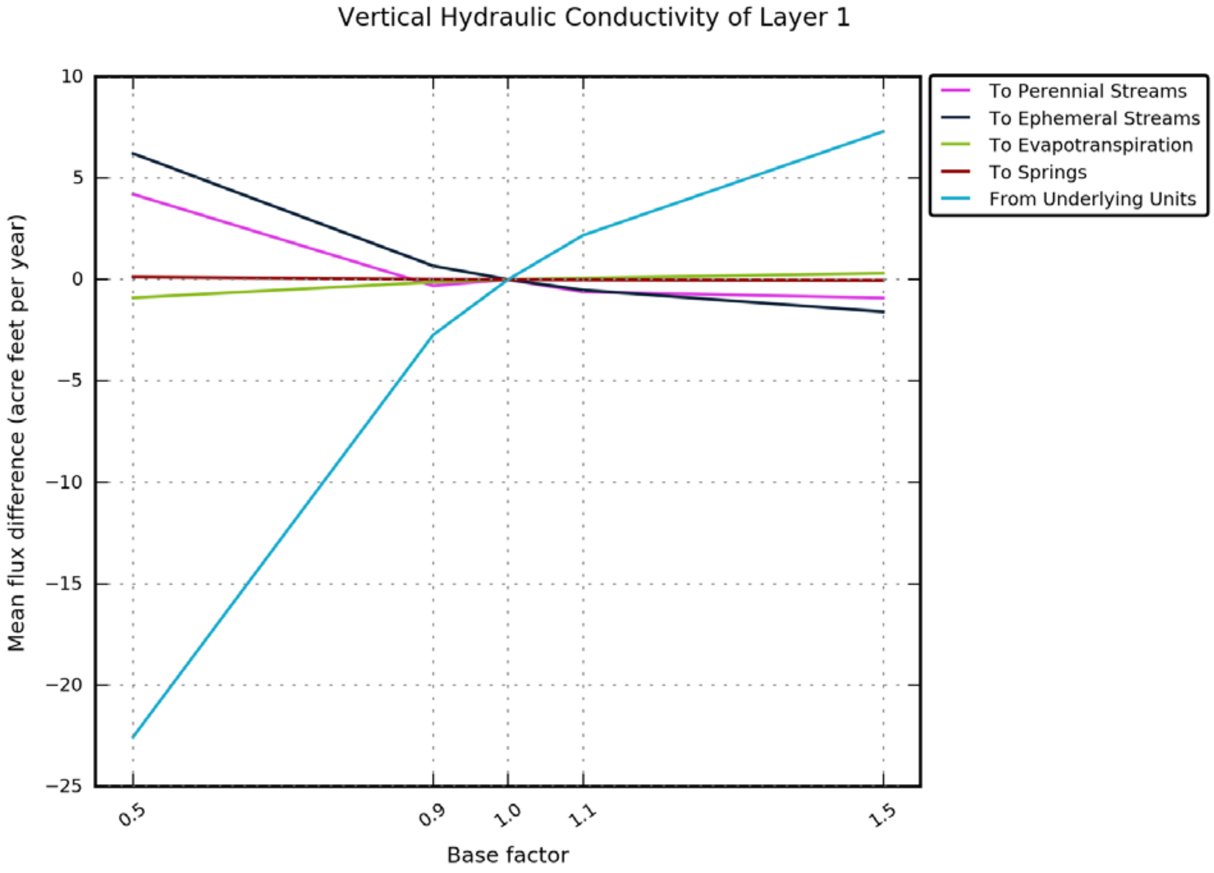

Figure 4.2.53 Flow sensitivity in acre-feet per year for the transient model to changes in horizontal hydraulic conductivity (Kv) of layer 1.

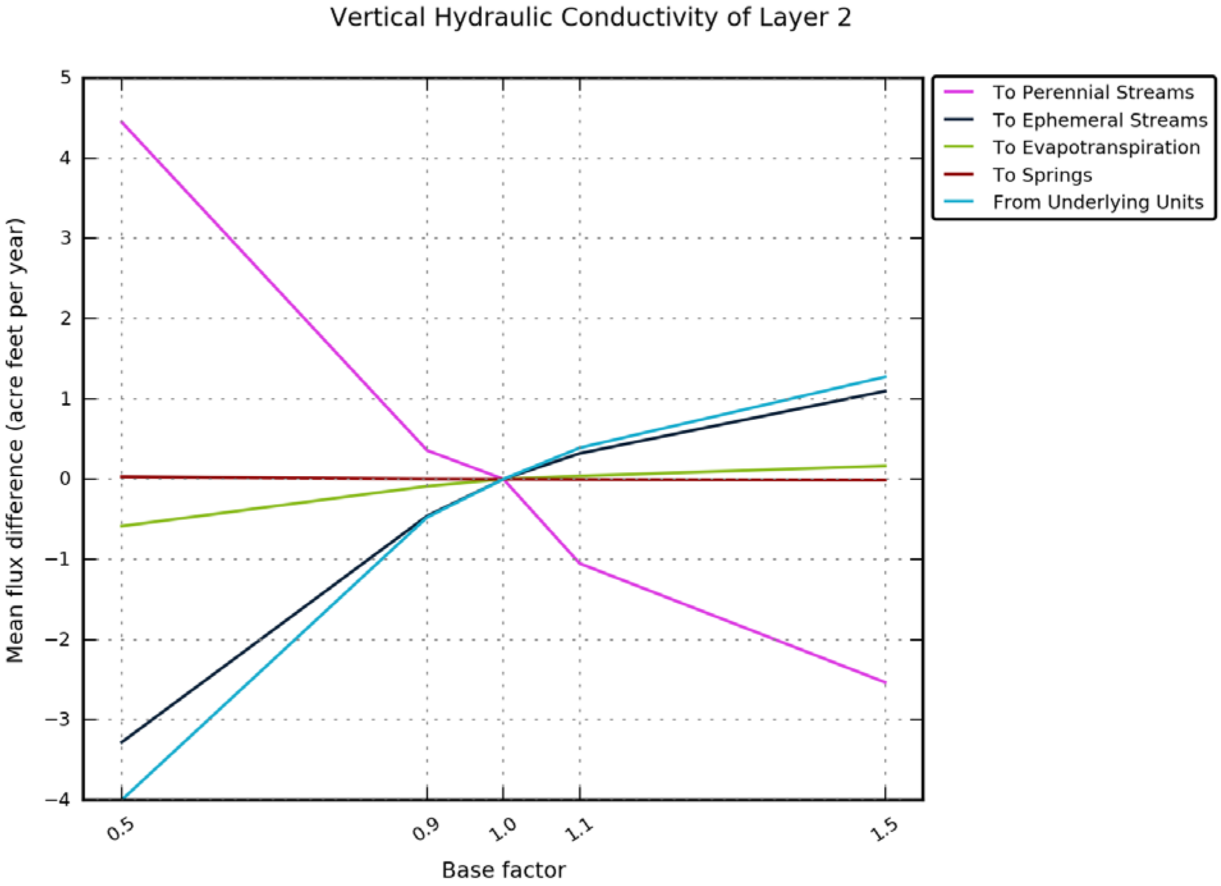

Figure 4.2.54 Flow sensitivity in acre-feet per year for the transient model to changes in horizontal hydraulic conductivity (Kv) of layer 2.

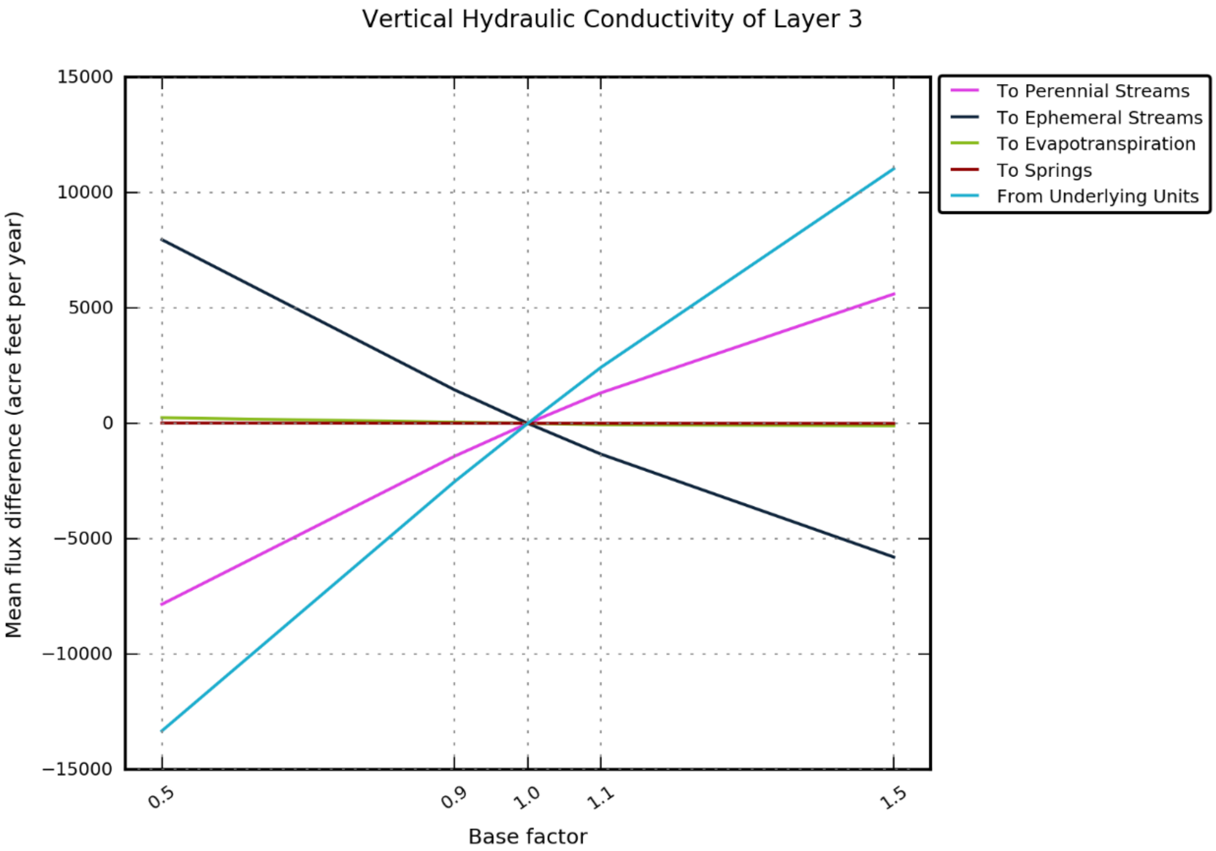

Figure 4.2.55 Flow sensitivity in acre-feet per year for the transient model to changes in horizontal hydraulic conductivity (Kv) of layer 3.

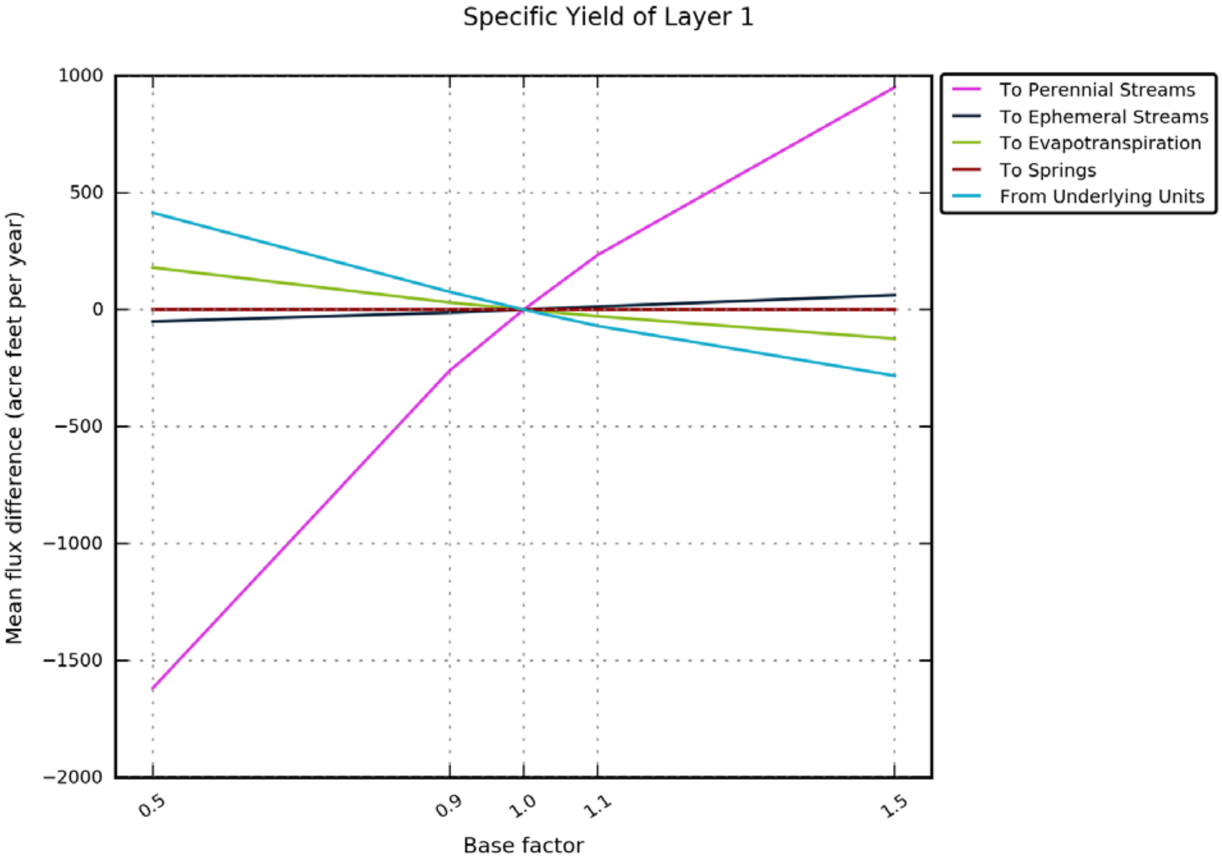

Figure 4.2.56 Flow sensitivity in acre-feet per year for the transient model to changes in specific yield of layer 1.

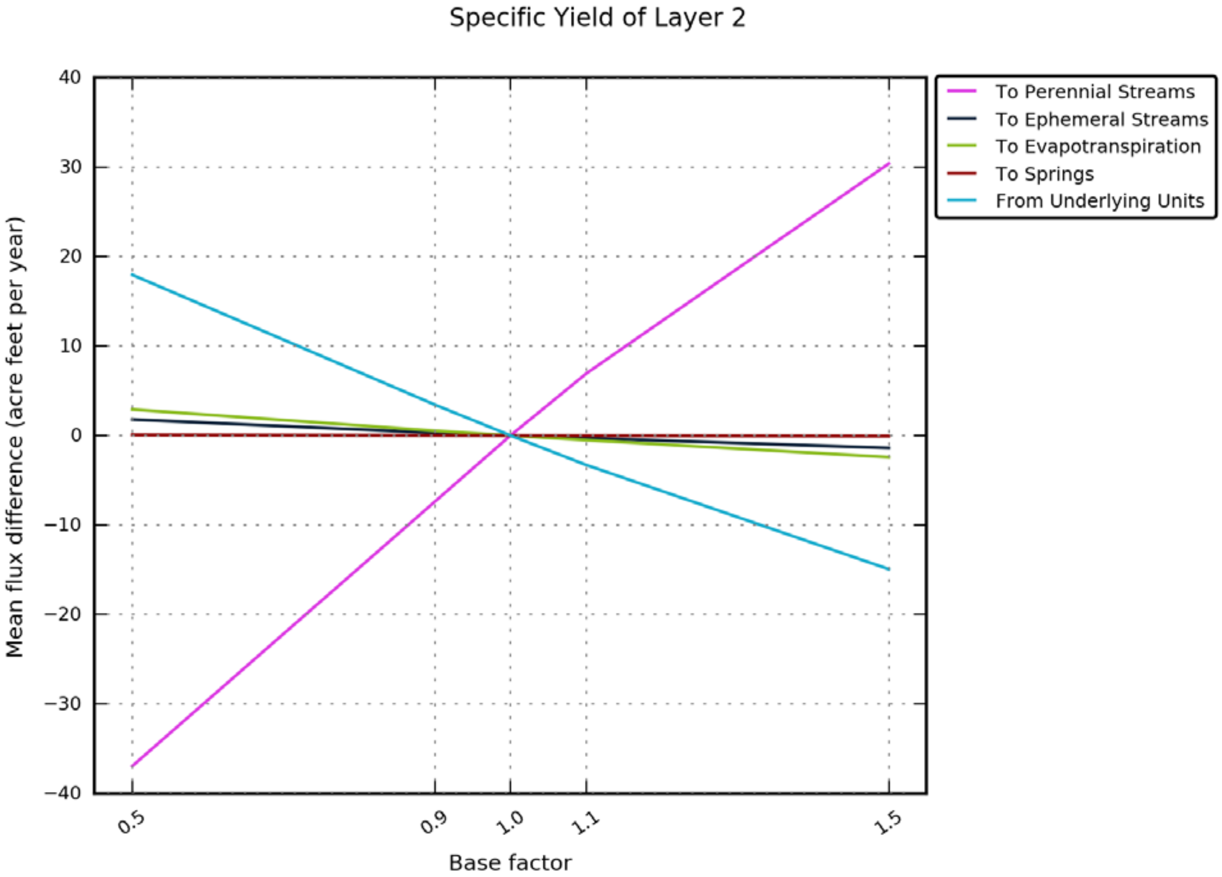

Figure 4.2.57 Flow sensitivity in acre-feet per year for the transient model to changes in specific yield of layer 2.

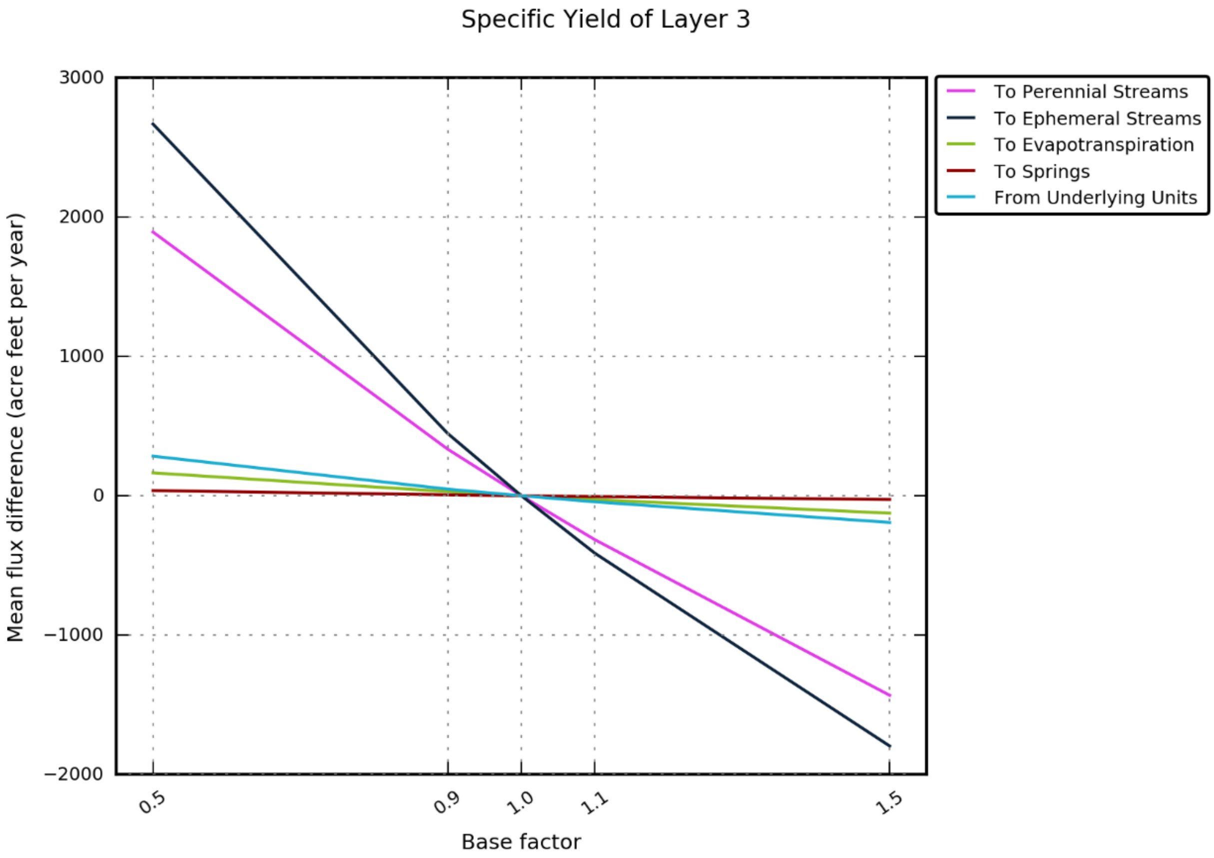

Figure 4.2.58 Flow sensitivity in acre-feet per year for the transient model to changes in specific yield of layer 3.

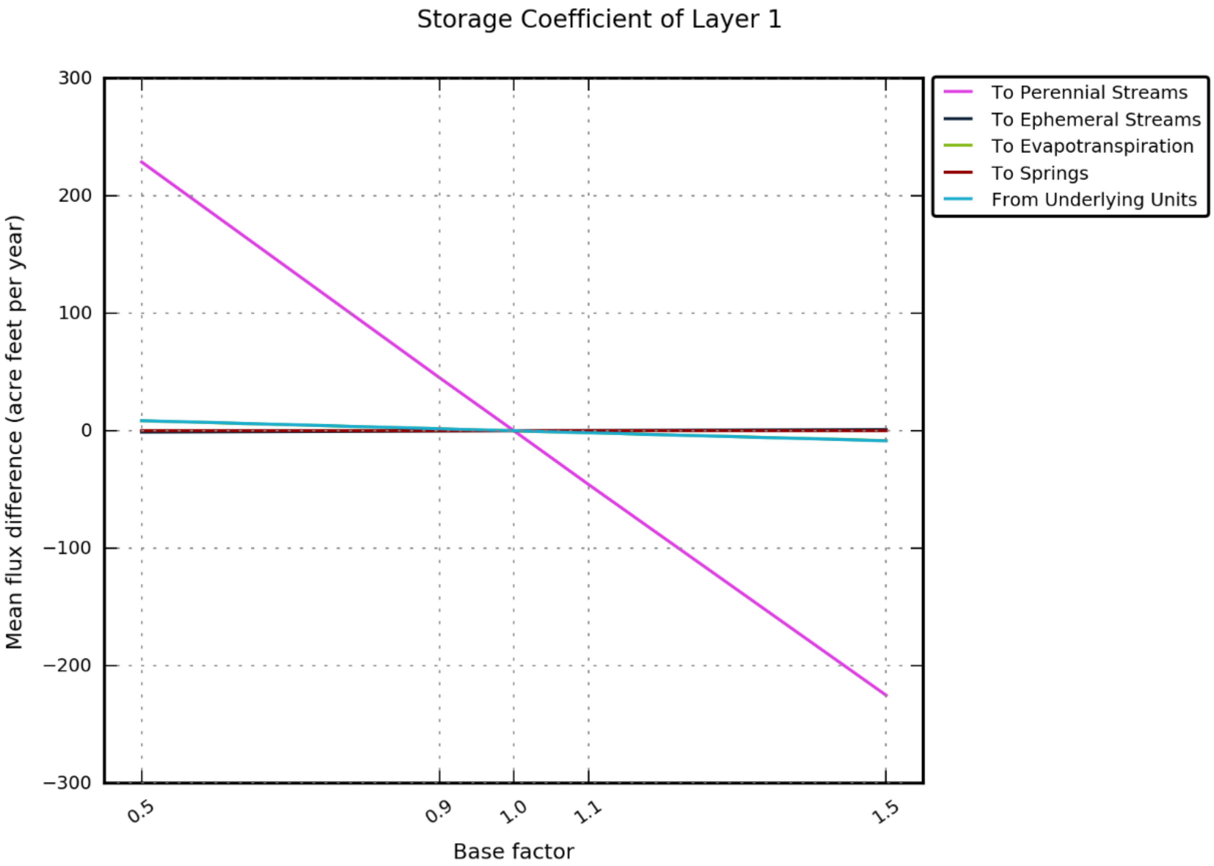

Figure 4.2.59 **Flow sensitivity in acre-feet per year for the transient model to changes in storativity of layer 1.**

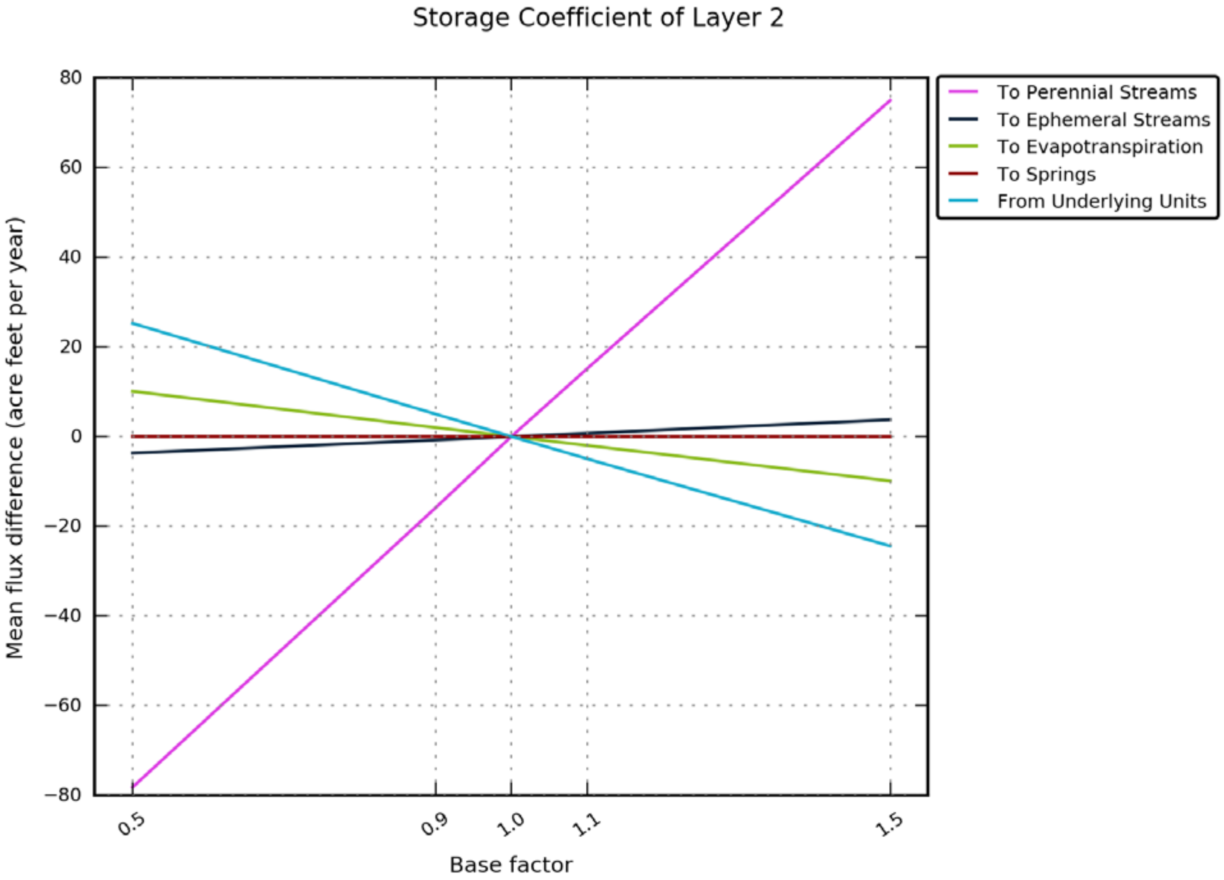

Figure 4.2.60 Flow sensitivity in acre-feet per year for the transient model to changes in storativity of layer 2.

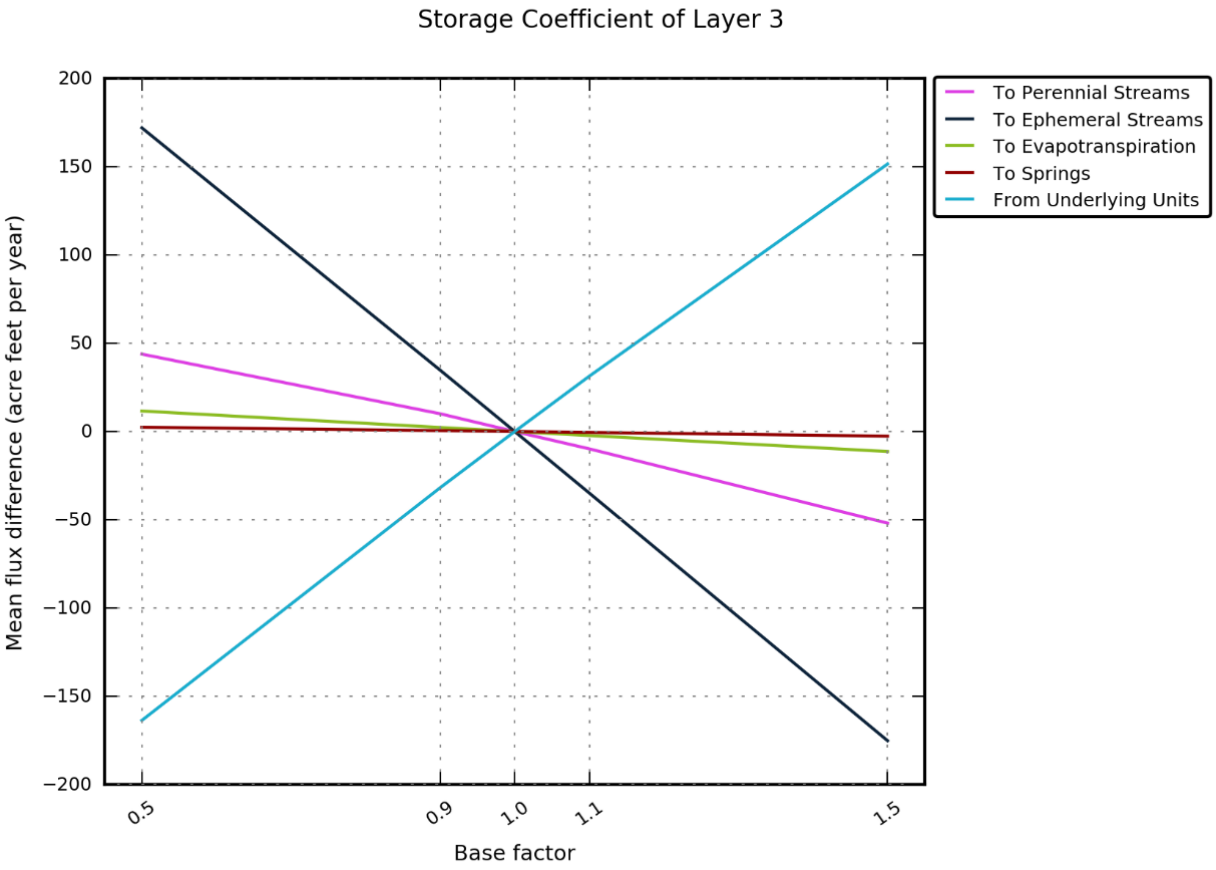

Figure 4.2.61 **Flow sensitivity in acre-feet per year for the transient model to changes in storativity of layer 3.**

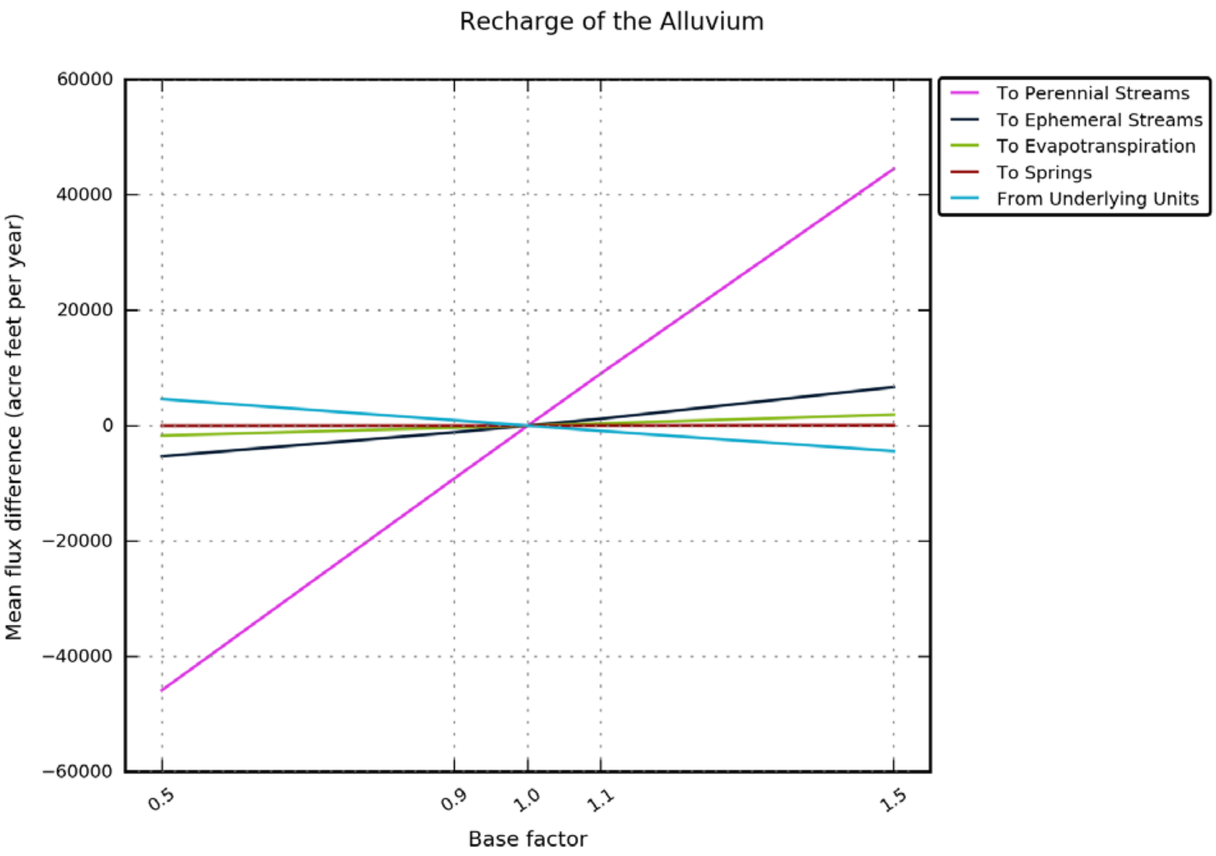

Figure 4.2.62 **Flow sensitivity in acre-feet per year for the transient model to changes in recharge to the Brazos River Alluvium Aquifer.**

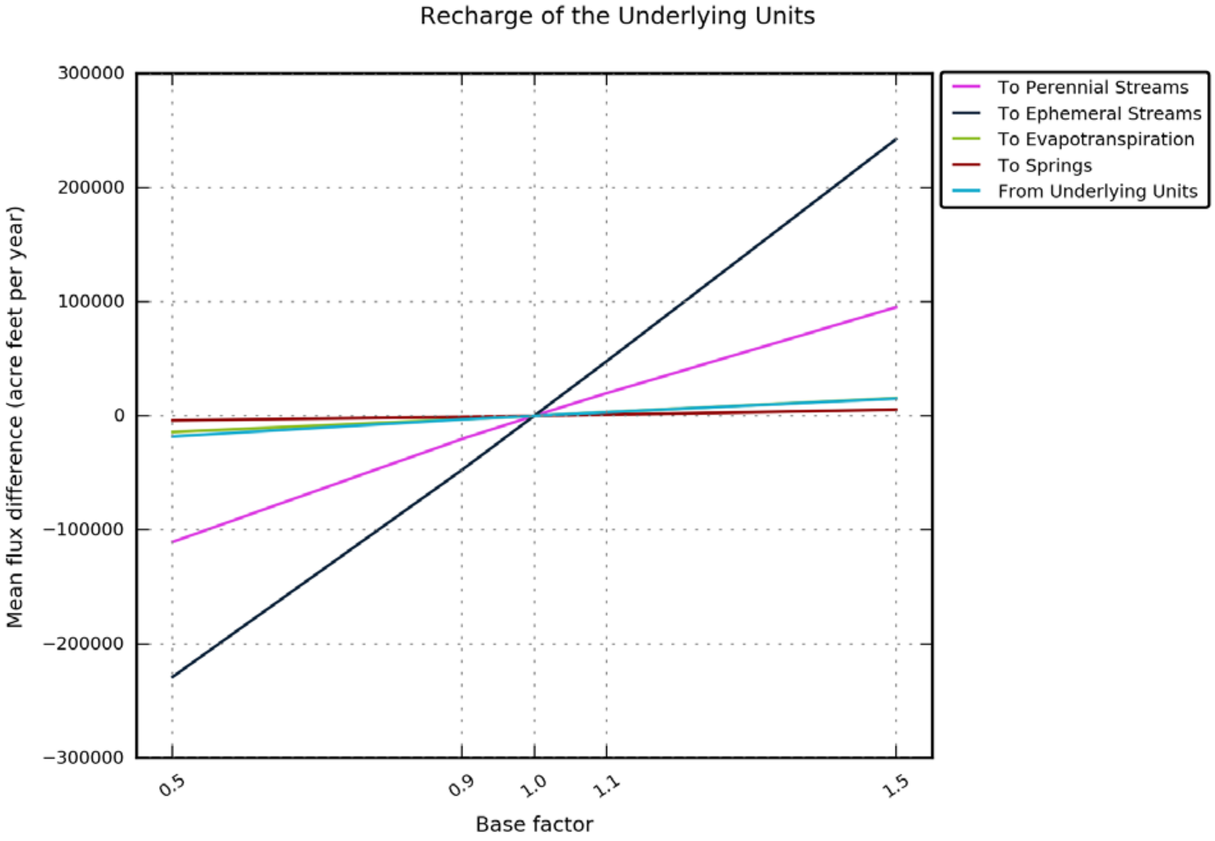

Figure 4.2.63 **Flow sensitivity in acre-feet per year for the transient model to changes in recharge to the outcrops of the underlying formations.**

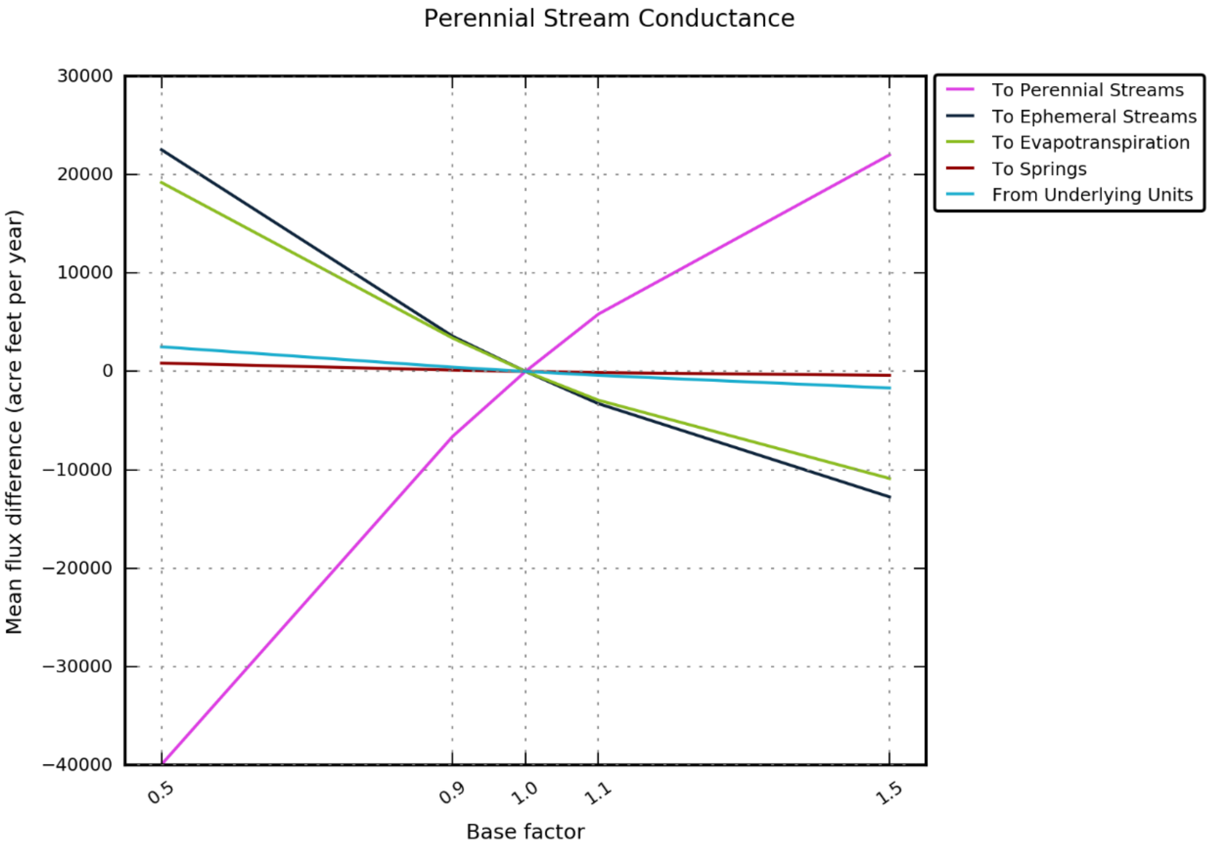

Figure 4.2.64 Flow sensitivity in acre-feet per year for the transient model to changes in streambed conductance of perennial streams.

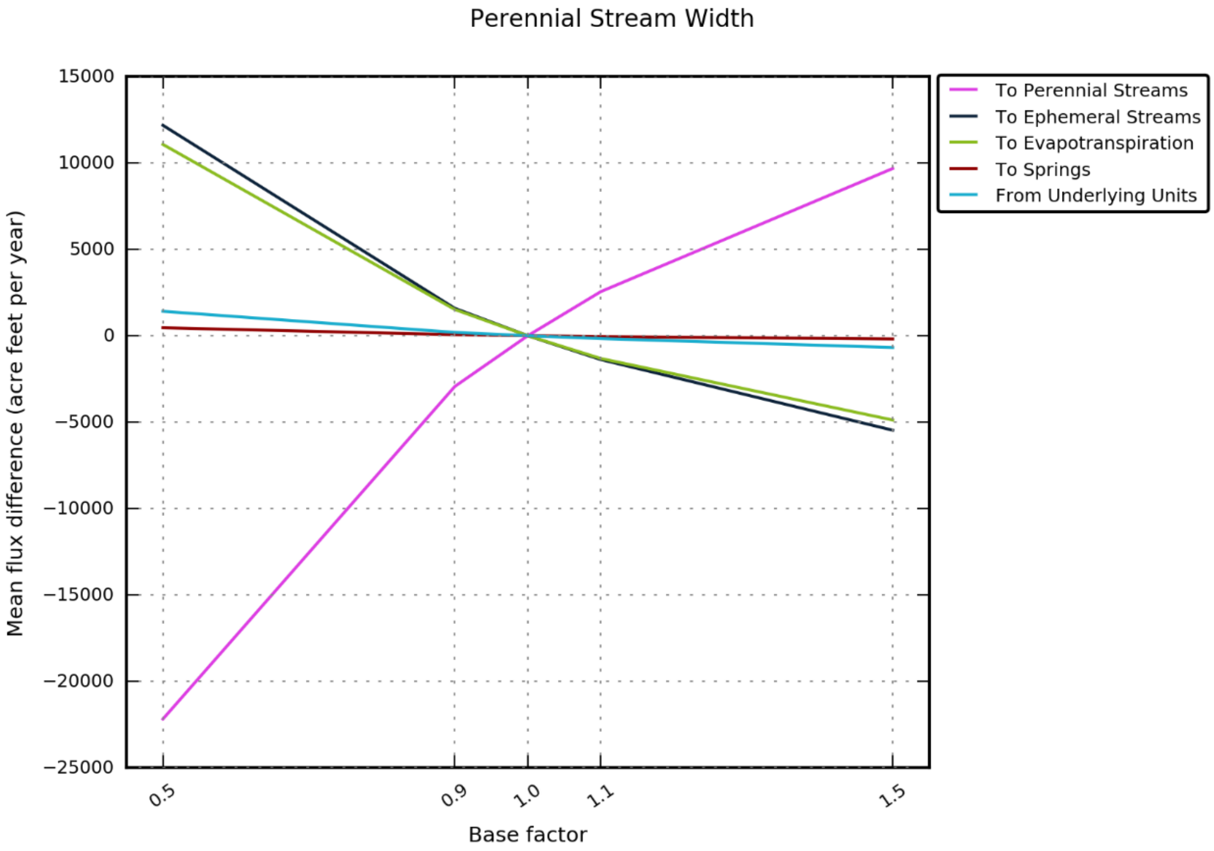

Figure 4.2.65 **Flow sensitivity in acre-feet per year for the transient model to changes in stream width of perennial streams.**

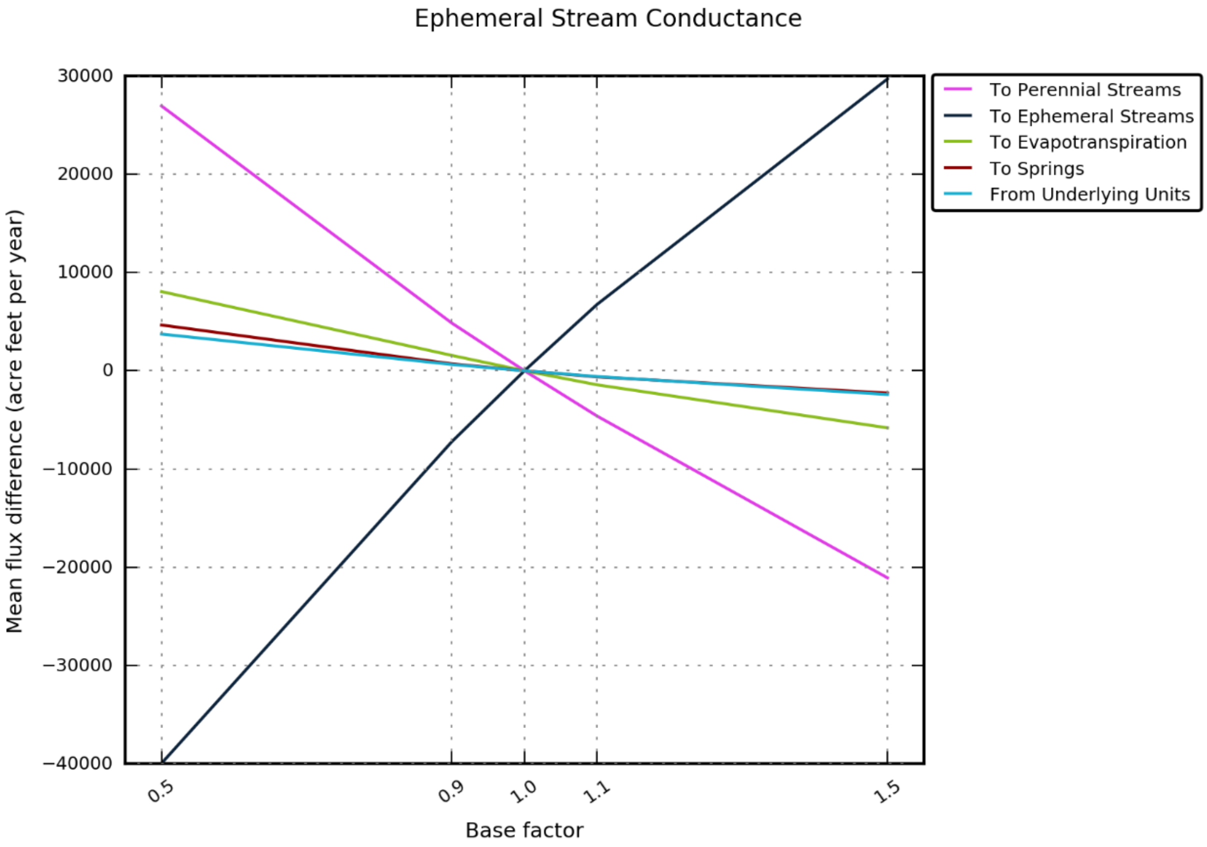

Figure 4.2.66 **Flow sensitivity in acre-feet per year for the transient model to changes in streambed conductance of ephemeral streams.**

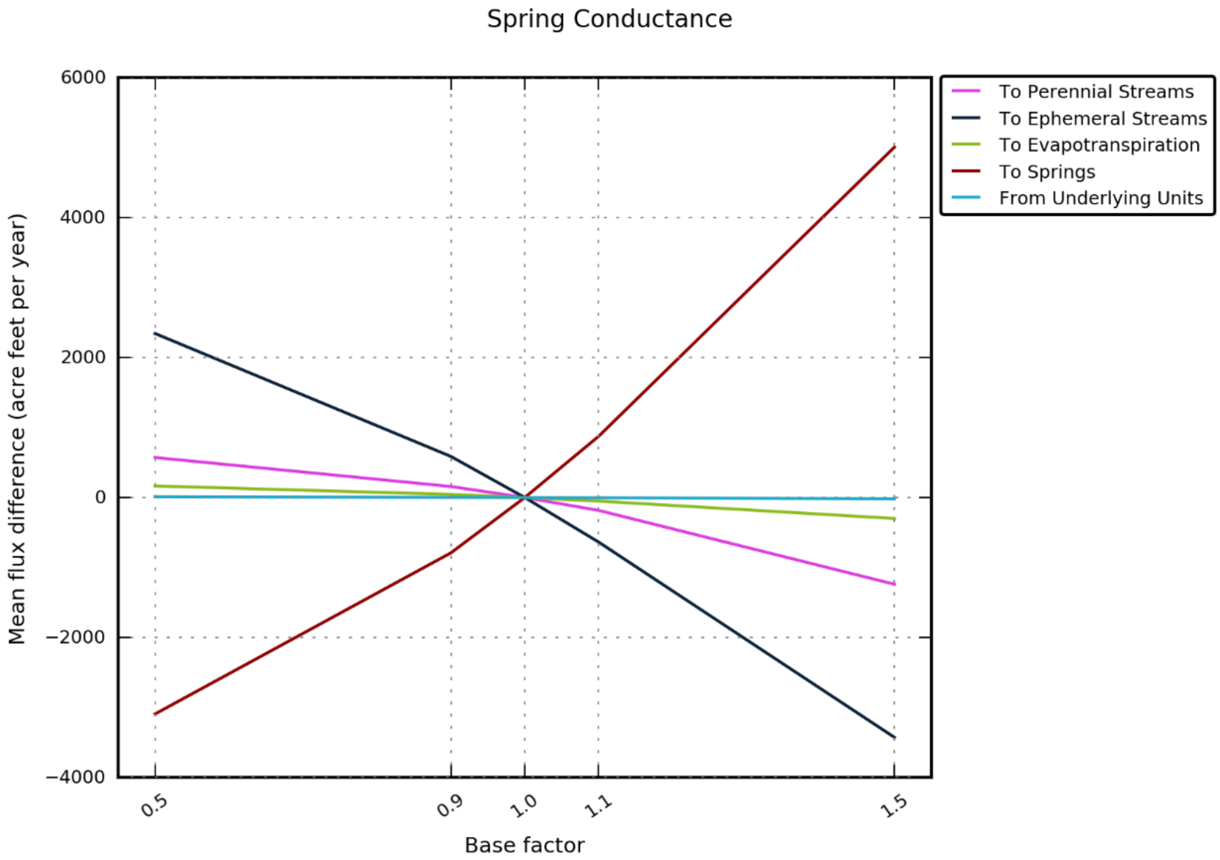

Figure 4.2.67 **Flow sensitivity in acre-feet per year for the transient model to changes in spring conductance.**

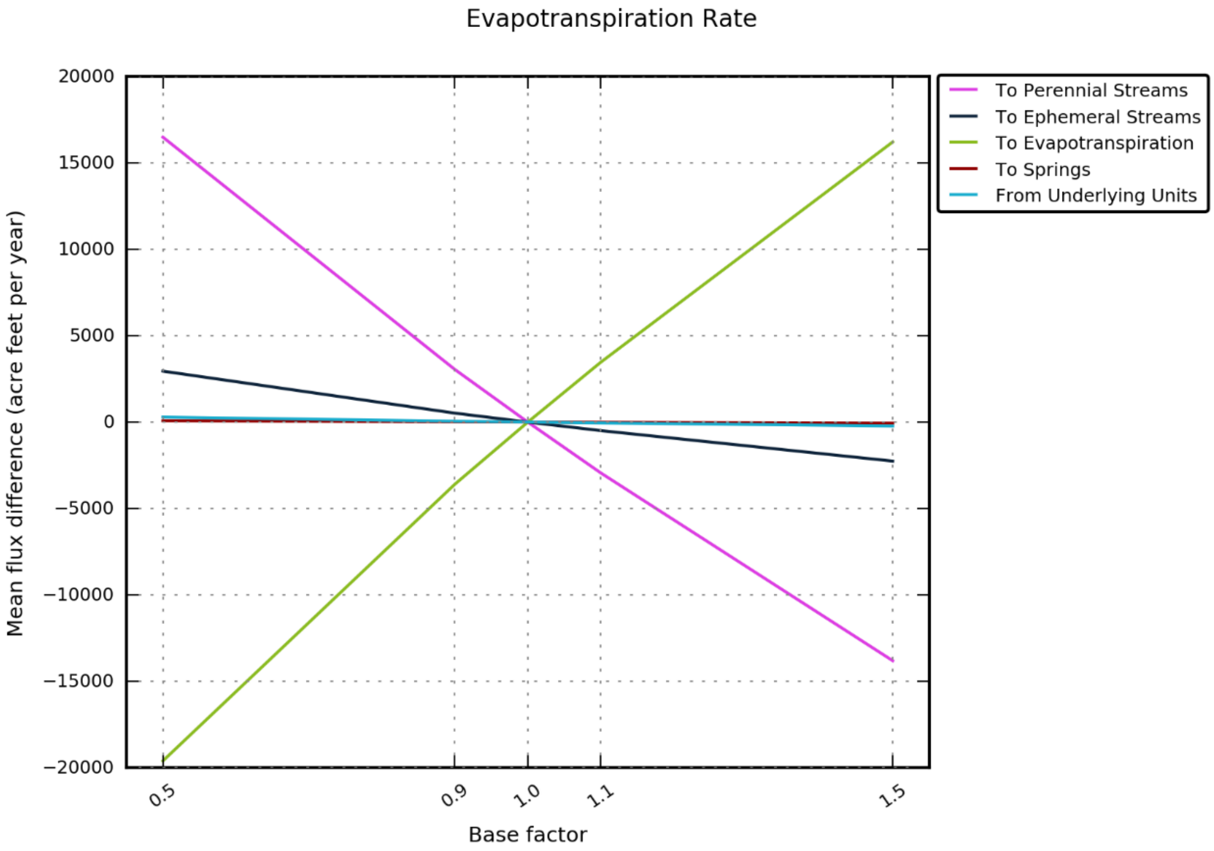

Figure 4.2.68 **Flow sensitivity in acre-feet per year for the transient model to changes in the maximum evapotranspiration rate.**

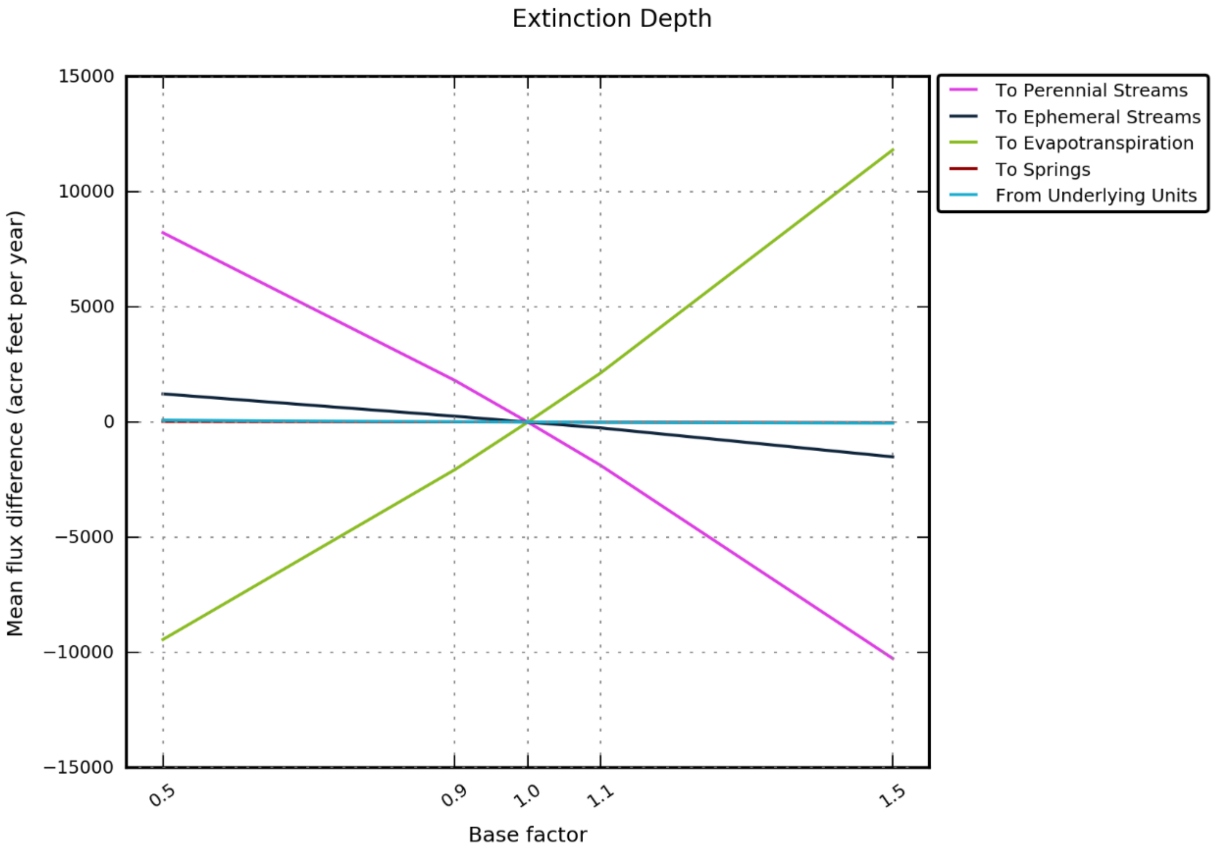

Figure 4.2.69 Flow sensitivity in acre-feet per year for the transient model to changes in extinction depth for evapotranspiration.

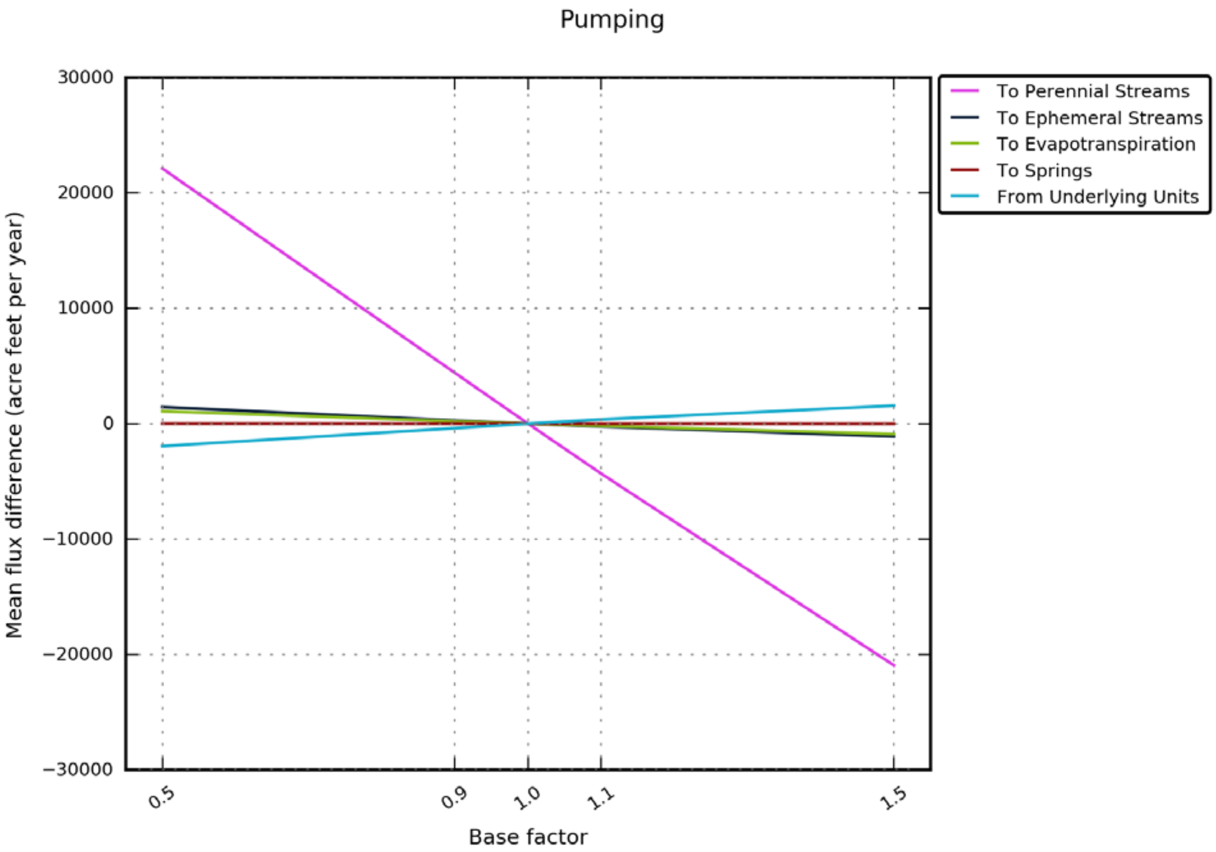

Figure 4.2.70 Flow sensitivity in acre-feet per year for the transient model to changes in pumping.

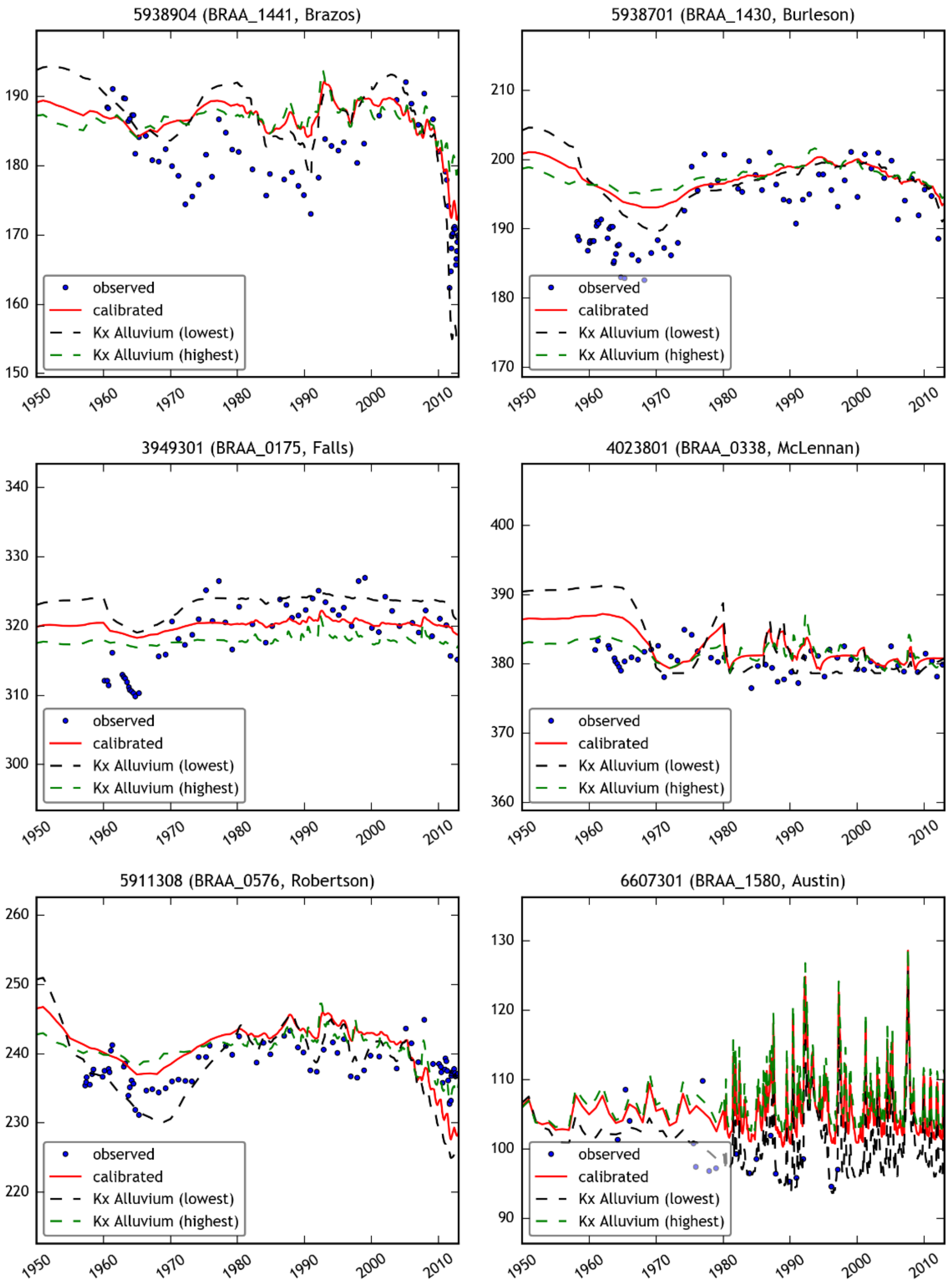

Figure 4.2.71 Example hydrographs showing sensitivity of heads (feet above mean sea level) to changes in the horizontal hydraulic conductivity of the Brazos River Alluvium Aquifer.

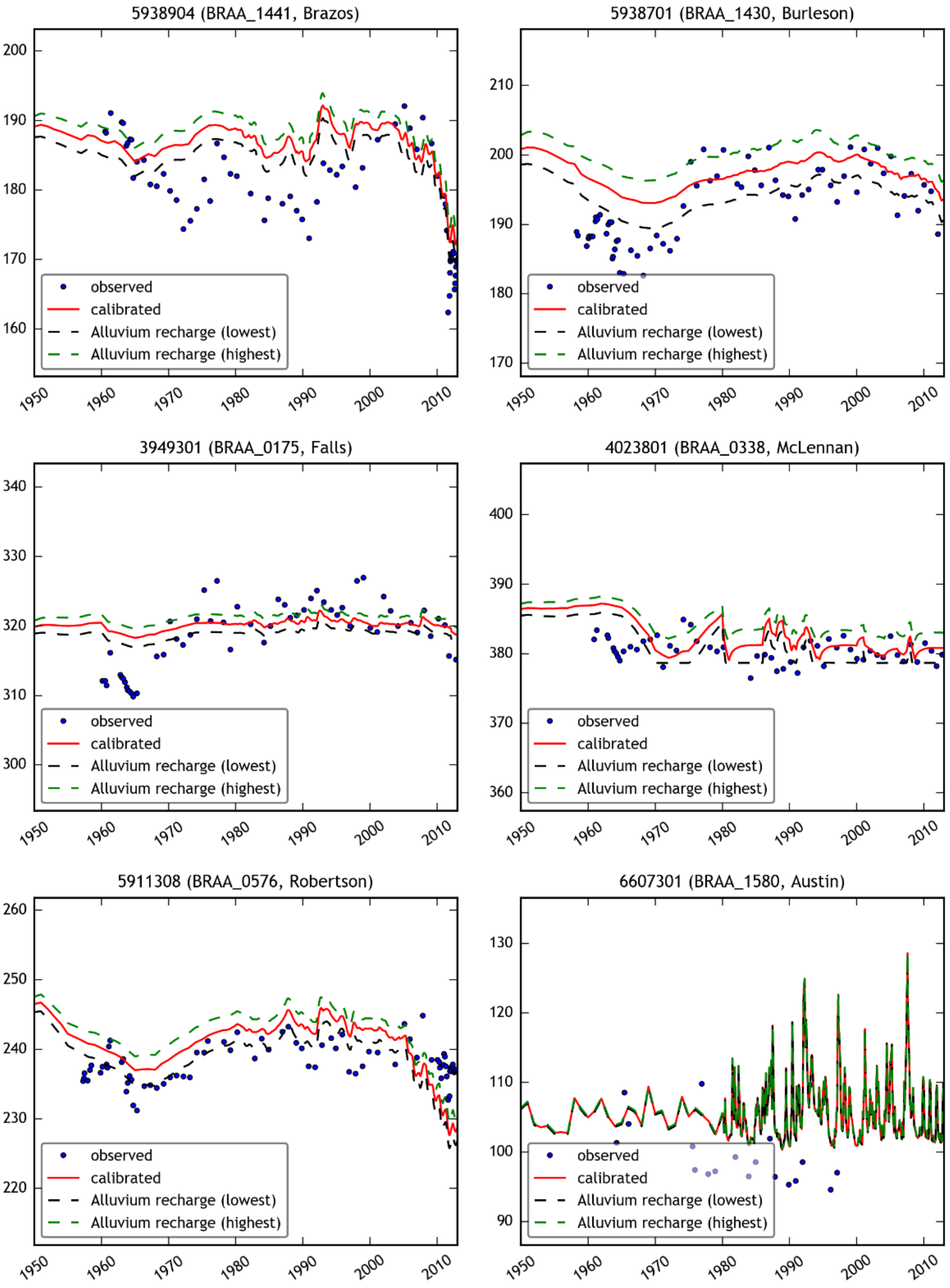

Figure 4.2.72 Example hydrographs showing sensitivity of heads (feet above mean sea level) to changes in recharge to the Brazos River Alluvium Aquifer.

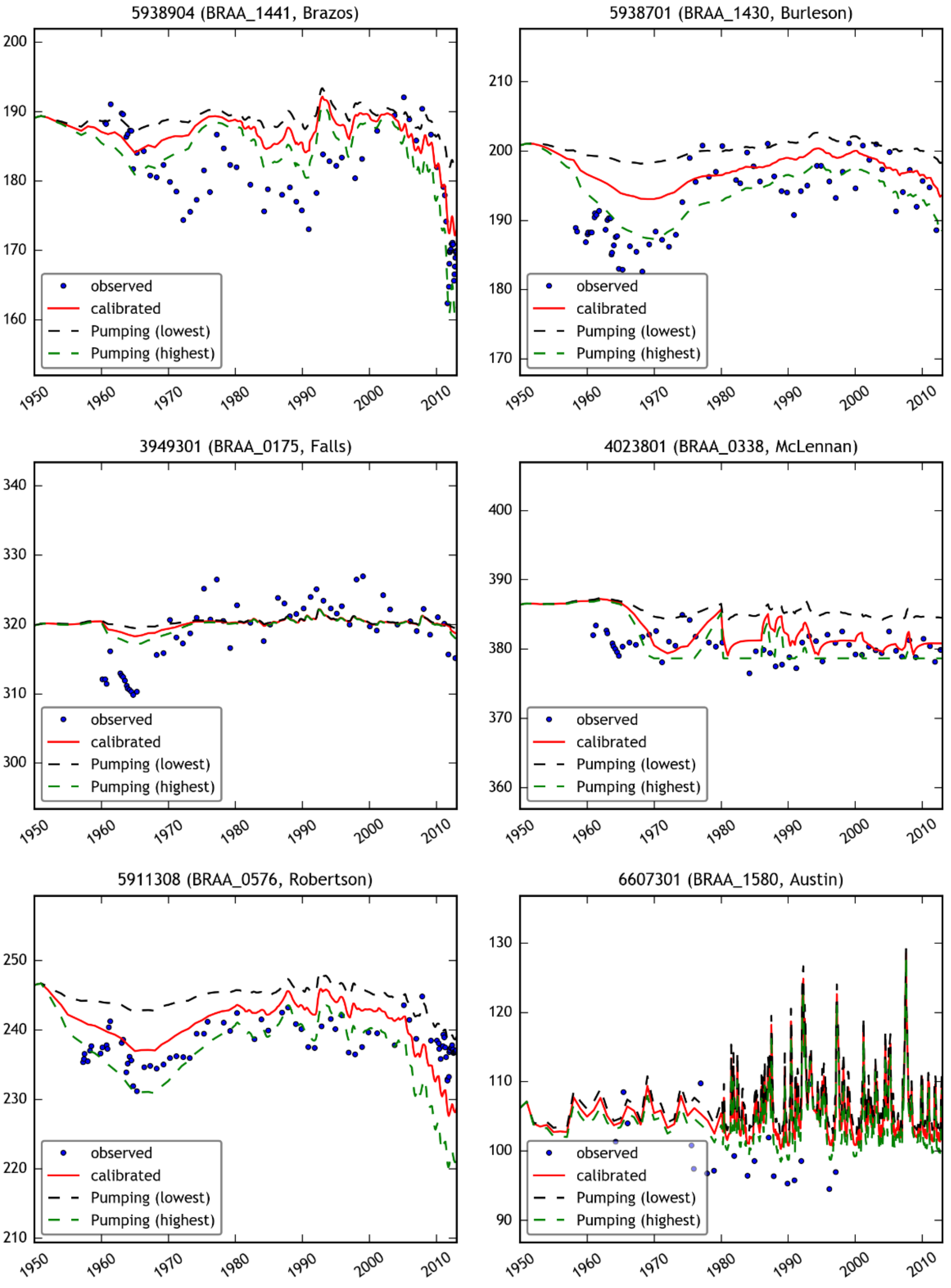

Figure 4.2.73 Example hydrographs showing sensitivity of heads (feet above mean sea level) to changes in pumping in the Brazos River Alluvium Aquifer.

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5.0 Model Limitations

A model can be defined as a representation of reality that attempts to explain the behavior of some aspect of it, but is always less complex than the real system it represents (Domenico, 1972). As a result, limitations are intrinsic to models. Model limitations can be grouped into several categories including: (1) limitations in the data supporting a model, (2) limitations in the implementation of a model which may include assumptions inherent to the model application, and (3) limitations regarding model applicability. The limitations of this modeling study are discussed in the following paragraphs consistent with the groupings above.

5.1 Limitations of Supporting Data

Development of the supporting data for a regional model of the size and complexity of the Brazos River Alluvium Aquifer groundwater availability model is a challenge. The primary limitations in the supporting data for the model are:

- Limited hydraulic head targets spatially and temporally in portions of the aquifer,
- Limited applicability of stream gain/loss estimates,
- Limited hydraulic conductivity data for portions of the aquifer,
- Limited data quantifying cross-formational flow between the aquifer and the underlying formations,
- Uncertain estimates of pumping in the aquifer.

Each of these data limitations is discussed briefly below.

The primary type of calibration target used in most models, including this groundwater availability model, is hydraulic head. Wells in the Brazos River Alluvium Aquifer tend to be concentrated spatially within the aquifer which leaves portions of the aquifer less constrained by available data.

The Brazos River is regulated through a series of dams throughout the extent of the aquifer. Because dam capture and releases obfuscate the natural streamflow in the river, gain/loss estimates along the Brazos River are prone to enough error to preclude them from providing a quantifiable metric with which to constrain a groundwater model. Unregulated streams within the Brazos River Basin can provide a quantitative, long-term gain/loss estimate of stream-aquifer interaction but are more uncertain on time scales less than a decade. One or two-day measurement periods for gain/loss estimates, which yield gaining and losing results at different times do not provide information that can be used to assess model performance, which is judged on annual or monthly stress periods. The spring flow estimates are typically only taken once, and are often uncertain due to crude measurement methods.

Cross-formational flow from underlying formations, which can have serious implications both for water quality and water availability in the Brazos River Alluvium Aquifer, is difficult to measure at the local scale and nearly impossible to measure at the regional scale. While the model predicts that cross-formational flow is important to the overall water budget, it is primarily constrained by the recharge applied to the outcrops of the underlying formations within the Brazos River Basin with estimates of recharge being constrained by long-term estimates of baseflow to streams. The lack of empirical verification of the model estimates of cross-formational flow is, therefore, a limitation to the model.

Pumping, which is increasingly a large source of discharge from the model, is uncertain because estimates of pumping are dependent on secondary sources, such as crop areas and application rates, which are themselves uncertain. Although some metering or more direct use reporting has occurred in recent years (for example, Brazos Valley Groundwater Conservation District), the lack of historical data results in the pumping being uncertain over the historic period of record.

5.2 Assessment of Assumptions

Many small assumptions are made about the hydrogeologic system during construction and calibration of a groundwater model. However, two assumptions stood out during construction and calibration of the model, that may impact the predictions made by the model.

- Hydraulic conductivity is constant when water levels change
- Irrigation return flow can be aggregated with overall recharge

Even though the Brazos River Alluvium Aquifer is modeled as two layers, the hydraulic conductivity is considered to be constant throughout the vertical profile of the aquifer. There is no available data to quantifiably discriminate between the upper and lower portions of the aquifer. In reality, the hydraulic conductivity varies vertically within the aquifer profile. If there are significant trends in the hydraulic conductivity (for example, if materials are far coarsergrained at the bottom of portions of the aquifer), they are not being captured in the model. Under these example conditions, if water levels decline significantly within the aquifer, these coarser materials will have a higher effective conductivity than when the water was flowing throughout the entire vertical profile.

The conceptualization of recharge for the model included estimates of pre-development recharge rates, and post-development recharge rates. The increase in recharge in some areas is due to agricultural activity, which can both change vegetative and soil characteristics (make percolation more likely from precipitation) and increase the availability of percolation water because of irrigation return flow. The study included estimates of increased recharge beneath irrigated cropland in the transient historic period.

The approach implemented in the numerical model assumed that the post-development recharge rates represented the current condition, whereby irrigation return flow increased recharge in areas of verifiable irrigation. This approach is appropriate for calibrating the model in the historical period. However, this increased recharge cannot, with the current evidence, be divided between enhanced natural recharge from precipitation, and irrigation return flow. If it is primarily irrigation return flow, then it will decrease over time since agricultural practices have become much more efficient from the 1950s to the current day.

In addition, some areas show no evidence of enhanced recharge having occurred, but may show such evidence in the future. If a predictive simulation is run decades into the future, then either this eventual enhanced recharge must be estimated or assumed, or conservatively left out of the calculation. This topic has further discussion in Section 7.0 where model improvements are discussed.

5.3 Limitations of Model Applicability

The purpose of the TWDB groundwater availability model program is the development of models to determine how regional water availability is affected on a large scale by water resource development. While the current model uses a 1/8-mile square grid throughout the entirety of the Brazos River Alluvium Aquifer, its applicability is representative at a larger scale, such as miles. The model should not be used to predict drawdown at a particular well. The model may be applicable at the scale of a large wellfield, depending on the data support that was available in that area of the model.

The mean absolute error for calibration of the model to observed heads ranged from approximately 5 to 6 feet. This means that, on average, simulated heads deviate from observed heads by this amount. However, the model performs better in some areas and worse in others, so care must be taken in using the model to estimate absolute head elevation. As a predictive tool, the model will be better at predicting changes in heads due to changes in stresses than absolute head values.

While the overall mean error of the model for the Brazos River Alluvium Aquifer was less than 2 feet, the mean error for a given county at the end of the historical period may be up to 15 feet. Because the Brazos River Alluvium Aquifer is unconfined, this 15 feet can translate to large volumes of water when estimating future availability. Predictive simulations with the model may want to include at least a partial accounting of mean errors in starting head surfaces.

The Brazos River Alluvium Aquifer groundwater availability model should be used to estimate water availability for the Brazos River Alluvium Aquifer that is represented in the model but not for the surficial portions of the underlying aquifers and formations included in the model.

6.0 Summary and Conclusions

This report documents the development of a numerical groundwater model of the Brazos River Alluvium Aquifer, which consists of the Brazos River Alluvium Aquifer and the shallow portions of the formations that underlie it within the Brazos River Basin.

Development of a numerical model includes model design and construction, model calibration, and sensitivity analyses. The development of the numerical model documented in this report was based on the conceptual model development documented in Ewing and others (2016). The purpose of the model is to provide a tool for groundwater planning in the State of Texas.

The code used to implement the numerical model was MODFLOW-USG. The model consists of three layers, with the Brazos River Alluvium Aquifer comprising layers 1 and 2 and the formations underlying the Brazos River Alluvium Aquifer within the Brazos River Basin as layer 3. The model grid is composed of variably spaced square grid cells whereby the cells are one-eighth of a mile squares over the entirety of the Brazos River Alluvium Aquifer footprint and increase to one-mile squares in a quadtree, expanding fashion to the extents of the Brazos River Basin. The model simulates the time period from 1950 to 2012, with an initial steady-state stress period that represents pre-development conditions.

The model was primarily calibrated to observed heads in the Brazos River Alluvium Aquifer. It was calibrated to both steady-state and transient conditions. Both the steady-state and transient calibration statistics are well within acceptable ranges. The primary parameters modified during calibration were horizontal hydraulic conductivities, as well as recharge to the outcrops of the underlying formations. The model was also calibrated to observed steady-state heads in the formations underlying the Brazos River Alluvium Aquifer and the calibration statistics are well within acceptable ranges. Additionally, the model was calibrated to long-term baseflow estimates in streams within the study area within acceptable ranges.

In the steady-state calibration, recharge is the major source of inflow to the Brazos River Alluvium Aquifer with cross-formational flow from the underlying formations also being appreciable, and discharge to perennial streams is the largest source of outflow. In the transient model, recharge and cross-formational flow from the underlying units continue to dominate the inflow portions of the water balance but, in recent years, pumping has become an increasingly large component of outflow at approximately 50,000 acre-feet per year. Discharge to perennial streams is highly variable from year to year because of the variability in flows within the Brazos River. A simple trend analysis indicates that discharge from the Brazos River Alluvium Aquifer to perennial streams is decreasing over time.

A sensitivity analysis was performed, which indicated that the horizontal hydraulic conductivity of the Brazos River Alluvium Aquifer was the most important parameter for the Brazos River Alluvium Aquifer followed by recharge to the aquifer. Heads in the Brazos River Alluvium Aquifer were insensitive to the vertical hydraulic conductivity of the aquifer.

7.0 Future Improvements

To use models to predict future conditions requires a commitment to improve the model as new data become available or when modeling assumptions or implementation issues change. This groundwater availability model is no different. Through the modeling process, one generally learns what can be done to improve the model's performance or what data would help better constrain the model calibration. Future improvements to the model, beyond the scope of the current groundwater availability model, are discussed below.

7.1 Additional Supporting Data or Studies

Several types of data could be collected to better support future enhancement of the Brazos River Alluvium Aquifer groundwater availability model. These data limitations have been discussed in Section 5.1. Any studies that help to improve the quality and availability of these data could be used to provide additional constraint for future model updates.

Improving estimates of pumping data would be especially helpful. Although older historical pumping estimates cannot be easily revised, decades of remote-sensing data are now available that could help refine both earlier estimates of irrigated acreages and application rates. Recent advances in cloud-based Landsat image processing have made this type of analysis practical on a large scale with far fewer resources than previously required.

An additional study that attempts to answer some of the questions about agriculturally-enhanced recharge could both help constrain recharge estimates for future model updates, and allow better techniques for predicting future recharge. The current model has generated estimates of where and when agriculturally enhanced recharge has occurred. The next step would be to perform large-scale vadose zone flow and transport modeling to help evaluate the processes that drive the timing and occurrence of this recharge. The predictive estimates from this vadose zone flow and transport model could then be used as input for predictive estimates of water availability.

7.2 Future Model Implementation Improvements

Analysis of the model water budget indicated that a relatively large rate of flux occurs between the formations underlying the Brazos River Alluvium Aquifer and the aquifer. This cross-formational interaction can vary considerably along the length of the aquifer within the numerical model but is not well-constrained by available data. Any future proximal wells completed in both the alluvium and the underlying formations could provide a valuable source of information regarding cross-formational flow between the Brazos River Alluvium Aquifer and the formations underlying it.

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Appendix A

Water Budgets by County, Groundwater Conservation District, and Aquifer/Layer

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The tables of this appendix summarize the water budget for the Brazos River Alluvium Aquifer in terms of volume in acre-feet per year for the steady-state model, for the stress period representing December, 1980 in the transient model, and for the stress period representing December, 2012 in the transient model. Water budgets are presented for the Brazos River Alluvium Aquifer portion of the model and broken into counties and groundwater conservation districts. All values are reported in acre-feet per year. Negative numbers indicate flow out of the county or groundwater conservation district. In all tables, the abbreviation ET is evapotranspiration. In Tables A.4.1 through A.6.2, the abbreviation UWCD is underground water conservation district, GCD is groundwater conservation district, WD is water district, and SD is subsidence district. Note that most counties are only partially contained within the model boundary. Only Coryell, McLennan, Bell, Falls, Milam, Robertson, Burleson, Brazos, and Waller counties are entirely contained within the active model boundary. Williamson, Washington, and Austin counties are almost entirely contained within the active model boundary.

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Table A.1.1 **Water budget for the Brazos River Alluvium Aquifer by county for the steady-state model.**

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Lateral	Cross-Formational
Austin	2,816	-19	0	-7,780	-3	1,306	3,680
Bosque	499	0	0	-606	0	26	81
Brazos	10,293	-3,869	0	-15,228	-138	3,151	5,790
Burleson	10,995	-2,214	-122	-13,006	-465	-2,682	7,493
Falls	10,148	-3,636	0	-9,248	-500	610	2,625
Fort Bend	28,706	0	0	-27,513	-2,758	359	1,206
Grimes	5,068	-535	0	-8,848	-83	1,506	2,892
Hill	368	0	-94	-328	0	-6	60
McLennan	6,257	-1,137	0	-4,948	-208	-520	556
Milam	2,041	-547	0	-5,947	-232	2,644	2,040
Robertson	9,213	-1,872	-19	-12,434	-351	-4,712	10,176
Waller	6,156	-9	-3	-7,876	-81	-1,752	3,565
Washington	3,784	-568	0	-8,661	-30	70	5,405

Table A.1.2 Water budget for the underlying formations by county for the steady-state model.

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Lateral	Cross-Formational
Austin	27,806	0	-20	-11,208	-14,391	1,493	-3,680
Bastrop	4,342	0	-29	0	-1,401	-2,913	0
Bell	12,110	-23	-66	-6,028	-4,173	-1,821	0
Bosque	1,548	-68	0	-838	-504	-56	-81
Brazoria	275	0	0	0	-313	38	0
Brazos	33,807	-4,078	0	-17,097	-2,756	-4,086	-5,790
Burleson	43,688	-2,194	-1,100	-9,320	-24,244	663	-7,493
Burnet	11,582	0	0	-858	-5,530	-5,194	0
Colorado	2,540	0	0	0	-1,871	-669	0
Coryell	13,130	0	-3	-8,448	-4,724	45	0
Falls	22,934	-1,596	0	-5,855	-13,152	294	-2,625
Fort Bend	11,858	0	0	-2,794	-7,276	-581	-1,206
Freestone	1,179	0	0	0	-1,365	185	0
Grimes	27,930	-2,357	0	-14,033	-11,985	3,337	-2,892
Hamilton	136	0	0	26	0	-162	0
Harris	20,727	0	-1	0	-22,553	1,828	0
Hill	5,706	-228	0	-3,219	-982	-1,217	-60
Lampasas	14,332	0	0	-7,999	-10,276	3,943	0
Lee	27,790	-1,899	-149	-17,110	-13,724	5,090	0
Leon	36,890	-1,656	-321	-16,947	-11,707	-6,259	0
Limestone	17,536	-441	0	-3,763	-11,153	-2,179	0
Madison	4,575	-452	0	-3,692	-193	-239	0
McLennan	6,316	-428	0	-3,092	-3,387	1,146	-556
Milam	86,768	-1,711	-10	-44,690	-49,058	10,739	-2,040
Mills	414	0	0	-98	0	-316	0
Montgomery	6,499	0	0	0	-8,419	1,919	0
Robertson	66,308	-1,861	-130	-20,919	-42,257	9,035	-10,176
Travis	108	0	0	0	0	-108	0
Waller	8,101	0	0	0	-2,506	-2,029	-3,565
Washington	40,422	-1,135	-579	-8,864	-19,661	-4,778	-5,405
Wharton	6,323	0	0	0	-7,616	1,292	0
Williamson	20,007	-87	-117	-1,248	-10,115	-8,440	0

Table A.2.1 Water budget for the Brazos River Alluvium Aquifer by county for year 1980 of the transient model.

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Wells	Storage	Lateral	Cross-Formational
Austin	2,996	-25	0	-13,829	-38	-971	6,735	1,277	3,854
Bosque	496	0	0	-590	0	-45	63	-6	82
Brazos	12,046	-3,843	0	-17,102	-142	-4,248	5,747	1,693	5,849
Burleson	14,043	-2,077	-122	-13,313	-352	-5,805	1,906	-2,014	7,734
Falls	13,000	-3,578	0	-10,541	-526	-3,420	1,821	618	2,625
Fort Bend	28,651	-1	0	-35,718	-2,469	-3,982	11,645	371	1,503
Grimes	5,263	-614	0	-10,753	-88	-404	2,372	1,309	2,916
Hill	367	0	-88	-117	0	-305	67	15	60
McLennan	7,611	-1,161	0	-6,302	-259	-999	1,112	-555	553
Milam	2,203	-536	0	-4,546	-233	-36	836	357	1,954
Robertson	12,412	-1,180	-27	-8,106	-182	-15,495	3,298	-1,641	10,920
Waller	6,253	-35	-6	-16,760	-113	-1,278	9,622	-1,501	3,817
Washington	3,960	-602	0	-15,495	-32	-71	6,597	77	5,565

Table A.2.2 Water budget for the underlying formations by county for year 1980 of the transient model.

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Deep Flow	Storage	Lateral	Cross-Formational
Austin	27,515	0	-17	-11,151	-14,430	-1,999	2,490	1,445	-3,854
Bastrop	4,291	0	-35	0	-1,420	7	93	-2,935	0
Bell	11,824	-23	-66	-6,400	-4,188	0	665	-1,811	0
Bosque	1,442	-68	0	-1,411	-501	0	677	-56	-82
Brazoria	265	0	0	0	-313	0	9	39	0
Brazos	33,761	-4,150	0	-17,172	-2,870	-12	440	-4,148	-5,849
Burleson	42,362	-2,230	-1,175	-9,295	-24,936	-53	2,462	598	-7,734
Burnet	11,339	0	0	-872	-5,604	0	366	-5,229	0
Colorado	2,515	0	0	0	-1,565	-1,106	801	-645	0
Coryell	12,879	0	-4	-9,872	-4,754	0	1,707	44	0
Falls	22,752	-1,600	0	-5,901	-13,232	16	309	282	-2,625
Fort Bend	11,685	0	0	-3,582	-6,676	-1,223	1,968	-668	-1,503
Freestone	1,185	0	0	0	-1,379	20	-19	193	0
Grimes	27,875	-2,526	0	-14,287	-12,129	-1,141	1,767	3,358	-2,916
Hamilton	135	0	0	25	0	0	2	-162	0
Harris	20,806	0	-2	0	-19,217	-12,162	8,794	1,781	0
Hill	5,681	-231	0	-2,912	-1,015	0	-236	-1,228	-60
Lampasas	14,204	0	0	-8,065	-10,447	0	330	3,979	0
Lee	27,359	-2,005	-161	-17,366	-13,997	-32	1,069	5,132	0
Leon	34,479	-1,690	-351	-17,192	-12,055	-46	3,182	-6,327	0
Limestone	17,401	-449	0	-3,802	-11,257	136	180	-2,207	0
Madison	4,571	-520	0	-3,602	-199	-1	-4	-245	0
McLennan	6,088	-445	0	-3,693	-3,390	0	837	1,156	-553
Milam	85,928	-1,749	-11	-47,773	-50,243	33	5,105	10,664	-1,954
Mills	410	0	0	-100	0	0	8	-319	0
Montgomery	6,439	0	0	0	-7,278	-4,021	2,939	1,922	0
Robertson	64,769	-1,891	-134	-21,245	-43,001	-12	3,000	9,432	-10,920

Table A.2.2, continued

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Deep Flow	Storage	Lateral	Cross-Formational
Travis	107	0	0	0	0	0	4	-111	0
Waller	8,017	0	0	0	-1,804	-7,847	7,312	-1,861	-3,817
Washington	40,275	-1,160	-596	-8,803	-20,046	-125	983	-4,962	-5,565
Wharton	6,253	0	0	0	-7,287	-783	504	1,312	0
Williamson	19,116	-95	-117	-2,234	-10,158	14	1,899	-8,423	0

Table A.3.1 Water budget for the Brazos River Alluvium Aquifer by county for 2012 of the transient model.

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Wells	Storage	Lateral	Cross-Formational
Austin	2,983	-46	0	13,750	-17	-781	-20,915	1,647	3,379
Bosque	511	0	0	-91	0	-49	-269	-189	82
Brazos	11,452	-3,693	0	24,716	-58	-33,770	-14,012	7,781	7,584
Burleson	12,740	-2,129	-129	24,687	-225	-27,778	-10,398	-5,070	8,303
Falls	11,526	-3,709	0	4,528	-579	-7,203	-7,572	285	2,723
Fort Bend	29,490	-1	0	7,072	-1,697	-5,729	-30,940	231	1,575
Grimes	5,278	-581	0	-4,066	-88	-174	-3,513	410	2,734
Hill	378	0	-94	305	0	-519	-312	182	60
McLennan	6,967	-1,341	0	5,518	-215	-4,453	-6,537	-521	580
Milam	2,129	-578	0	12,378	-219	-1,575	-5,276	-8,145	1,286
Robertson	11,061	-421	0	23,541	-22	-49,352	-9,210	8,897	15,507
Waller	6,374	-100	-7	21,074	-117	-1,114	-27,729	-1,464	3,084
Washington	3,920	-635	0	13,094	-30	-327	-16,935	-4,044	4,958

Table A.3.2 Water budget for the underlying formations by county for year 2012 of the transient model.

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Deep Flow	Storage	Lateral	Cross-Formational
Austin	28,459	0	-12	-10,129	-14,355	-2,833	987	1,261	-3,379
Bastrop	4,428	0	-34	0	-1,379	-292	178	-2,902	0
Bell	12,217	-23	-66	19,166	-4,200	0	-25,071	-2,022	0
Bosque	1,534	-68	0	576	-501	0	-1,403	-56	-82
Brazoria	275	0	0	0	-312	0	-3	40	0
Brazos	33,927	-4,176	0	-16,043	-2,975	-9	617	-3,757	-7,584
Burleson	44,639	-2,254	-1,132	-8,979	-24,767	95	413	289	-8,303
Burnet	11,792	0	0	-885	-5,640	0	-29	-5,237	0
Colorado	2,602	0	0	0	-1,320	-1,349	713	-646	0
Coryell	13,304	0	-4	-4,080	-4,784	0	-4,480	44	0
Falls	23,173	-1,597	0	-5,836	-13,240	-235	137	320	-2,723
Fort Bend	11,898	0	0	-416	-6,607	16	-2,647	-670	-1,575
Freestone	1,201	0	0	0	-1,174	-722	517	178	0
Grimes	28,529	-2,558	0	-13,733	-11,260	-4,774	3,032	3,498	-2,734
Hamilton	138	0	0	25	0	0	0	-163	0
Harris	21,251	0	-1	0	-19,242	13	-3,789	1,768	0
Hill	5,718	-234	0	-1,553	-1,141	0	-1,496	-1,233	-60
Lampasas	14,628	0	0	-8,128	-10,538	0	49	3,989	0
Lee	28,328	-1,948	-154	-17,203	-13,669	-1,548	1,376	4,818	0
Leon	37,609	-1,661	-313	-16,611	-11,612	-541	-673	-6,198	0
Limestone	17,863	-391	0	-3,456	-10,678	-3,177	1,954	-2,115	0
Madison	4,588	-546	0	-3,373	-202	-1	-225	-241	0
McLennan	6,363	-473	0	-171	-3,391	0	-2,909	1,161	-580
Milam	87,877	-1,457	-10	-9,763	-45,361	-15,645	-23,840	9,484	-1,286
Mills	420	0	0	-101	0	0	1	-319	0
Montgomery	6,654	0	0	0	-7,153	-314	-1,017	1,831	0
Robertson	67,527	-1,847	-130	-20,308	-39,963	-2,986	2,365	10,848	-15,507
Travis	111	0	0	0	0	0	1	-112	0

Table A.3.2, continued

County	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Deep Flow	Storage	Lateral	Cross-Formational
Waller	8,296	0	0	0	-1,622	-310	-1,556	-1,724	-3,084
Washington	41,275	-1,178	-604	-7,794	-20,164	-1,161	-302	-5,114	-4,958
Wharton	6,364	0	0	0	-7,075	-954	338	1,327	0
Williamson	20,182	-96	-117	609	-9,913	-1,207	-1,110	-8,348	0

Table A.4.1 Water budget for the Brazos River Alluvium Aquifer by groundwater conservation district for the steady-state model.

Groundwater Conservation District	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Lateral	Cross-Formational
Bluebonnet GCD	14,041	-563	-3	-24,505	-167	1,059	10,137
Brazos Valley GCD	19,505	-5,740	-19	-27,662	-489	-1,561	15,966
Fort Bend Subsidence	28,706	0	0	-27,513	-2,758	359	1,206
Middle Trinity GCD	499	0	0	-606	0	26	81
Post Oak Savannah GC	13,037	-2,762	-122	-18,953	-697	-38	9,533
Prairielands GCD	368	0	-94	-328	0	-6	60
Southern Trinity GCD	6,257	-1,137	0	-4,948	-208	-520	556

Table A.4.2 Water budget for the underlying formations by groundwater conservation district for the steady-state model.

Groundwater Conservation District	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Lateral	Cross-Formational
Bluebonnet GCD	63,837	-2,357	-20	-25,241	-28,883	2,801	-10,137
Brazoria County GCD	275	0	0	0	-313	38	0
Brazos Valley GCD	100,117	-5,940	-130	-38,016	-45,013	4,949	-15,966
Central Texas GCD	11,582	0	0	-858	-5,530	-5,194	0
Clearwater UWCD	12,110	-23	-66	-6,028	-4,173	-1,821	0
Coastal Bend GCD	6,323	0	0	0	-7,616	1,292	0
Colorado County GCD	2,540	0	0	0	-1,871	-669	0
Fort Bend Subsidence	11,858	0	0	-2,794	-7,276	-581	-1,206
Fox Crossing Water D	414	0	0	-98	0	-316	0
Harris-Galveston Coa	20,727	0	-1	0	-22,553	1,828	0
Lone Star GCD	6,499	0	0	0	-8,419	1,919	0
Lost Pines GCD	32,132	-1,899	-177	-17,110	-15,124	2,178	0
Mid-East Texas GCD	42,644	-2,108	-321	-20,639	-13,264	-6,312	0
Middle Trinity GCD	14,678	-68	-3	-9,286	-5,228	-12	-81
Post Oak Savannah GC	130,462	-3,905	-1,109	-54,010	-73,302	11,402	-9,533
Prairielands GCD	5,706	-228	0	-3,219	-982	-1,217	-60
Saratoga UWCD	14,332	0	0	-7,999	-10,276	3,943	0
Southern Trinity GCD	6,316	-428	0	-3,092	-3,387	1,146	-556

Table A.5.1 Water budget for the Brazos River Alluvium Aquifer by groundwater conservation district for year 1980 of the transient model.

Groundwater Conservation District	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Wells	Storage	Lateral	Cross-Formational
Bluebonnet GCD	14,512	-674	-6	-41,342	-239	-2,652	18,729	1,085	10,587
Brazos Valley GCD	24,459	-5,023	-27	-25,208	-323	-19,743	9,045	52	16,768
Fort Bend Subsidence	28,651	-1	0	-35,718	-2,469	-3,982	11,645	371	1,503
Middle Trinity GCD	496	0	0	-590	0	-45	63	-6	82
Post Oak Savannah GC	16,246	-2,613	-122	-17,859	-584	-5,841	2,742	-1,657	9,688
Prairielands GCD	367	0	-88	-117	0	-305	67	15	60
Southern Trinity GCD	7,611	-1,161	0	-6,302	-259	-999	1,112	-555	553

Table A.5.2 Water budget for the underlying formations by groundwater conservation district for year 1980 of the transient model.

Groundwater Conservation District	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Deep Flow	Storage	Lateral	Cross-Formational
Bluebonnet GCD	63,408	-2,526	-17	-25,438	-28,363	-10,987	11,569	2,941	-10,587
Brazoria County GCD	265	0	0	0	-313	0	9	39	0
Brazos Valley GCD	98,531	-6,040	-134	-38,417	-45,871	-24	3,440	5,284	-16,768
Central Texas GCD	11,339	0	0	-872	-5,604	0	366	-5,229	0
Clearwater UWCD	11,824	-23	-66	-6,400	-4,188	0	665	-1,811	0
Coastal Bend GCD	6,253	0	0	0	-7,287	-783	504	1,312	0
Colorado County GCD	2,515	0	0	0	-1,565	-1,106	801	-645	0
Fort Bend Subsidence	11,685	0	0	-3,582	-6,676	-1,223	1,968	-668	-1,503
Fox Crossing Water D	410	0	0	-100	0	0	8	-319	0
Harris-Galveston Coa	20,806	0	-2	0	-19,217	-12,162	8,794	1,781	0
Lone Star GCD	6,439	0	0	0	-7,278	-4,021	2,939	1,922	0
Lost Pines GCD	31,650	-2,005	-197	-17,366	-15,417	-25	1,161	2,197	0
Mid-East Texas GCD	40,234	-2,211	-351	-20,794	-13,633	-26	3,159	-6,379	0
Middle Trinity GCD	14,321	-68	-4	-11,283	-5,255	0	2,384	-12	-82
Post Oak Savannah GC	128,290	-3,979	-1,186	-57,067	-75,179	-20	7,567	11,262	-9,688
Prairielands GCD	5,681	-231	0	-2,912	-1,015	0	-236	-1,228	-60
Saratoga UWCD	14,204	0	0	-8,065	-10,447	0	330	3,979	0
Southern Trinity GCD	6,088	-445	0	-3,693	-3,390	0	837	1,156	-553

Table A.6.1 **Water budget for the Brazos River Alluvium Aquifer by groundwater conservation district for year 2012 of the transient model.**

Groundwater Conservation District	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Wells	Storage	Lateral	Cross-Formational
Bluebonnet GCD	14,635	-727	-7	30,757	-222	-2,069	-52,156	592	9,196
Brazos Valley GCD	22,513	-4,114	0	48,257	-80	-83,122	-23,223	16,678	23,090
Fort Bend Subsidence	29,490	-1	0	7,072	-1,697	-5,729	-30,940	231	1,575
Middle Trinity GCD	511	0	0	-91	0	-49	-269	-189	82
Post Oak Savannah GC	14,869	-2,707	-129	37,064	-444	-29,352	-15,674	-13,215	9,589
Prairielands GCD	378	0	-94	305	0	-519	-312	182	60
Southern Trinity GCD	6,967	-1,341	0	5,518	-215	-4,453	-6,537	-521	580

Table A.6.2 Water budget for the underlying formations by groundwater conservation district for year 2012 of the transient model.

Groundwater Conservation District	Recharge	ET	Springs	Perennial Streams	Ephemeral Streams	Deep Flow	Storage	Lateral	Cross-Formational
Bluebonnet GCD	65,284	-2,558	-12	-23,862	-27,237	-7,917	2,463	3,036	-9,196
Brazoria County GCD	275	0	0	0	-312	0	-3	40	0
Brazos Valley GCD	101,453	-6,024	-130	-36,350	-42,938	-2,995	2,982	7,092	-23,090
Central Texas GCD	11,792	0	0	-885	-5,640	0	-29	-5,237	0
Clearwater UWCD	12,217	-23	-66	19,166	-4,200	0	-25,071	-2,022	0
Coastal Bend GCD	6,364	0	0	0	-7,075	-954	338	1,327	0
Colorado County GCD	2,602	0	0	0	-1,320	-1,349	713	-646	0
Fort Bend Subsidence	11,898	0	0	-416	-6,607	16	-2,647	-670	-1,575
Fox Crossing Water D	420	0	0	-101	0	0	1	-319	0
Harris-Galveston Coa	21,251	0	-1	0	-19,242	13	-3,789	1,768	0
Lone Star GCD	6,654	0	0	0	-7,153	-314	-1,017	1,831	0
Lost Pines GCD	32,757	-1,948	-189	-17,203	-15,047	-1,839	1,554	1,916	0
Mid-East Texas GCD	43,397	-2,207	-313	-19,984	-12,988	-1,264	-381	-6,260	0
Middle Trinity GCD	14,838	-68	-4	-3,503	-5,285	0	-5,883	-12	-82
Post Oak Savannah GC	132,518	-3,711	-1,142	-18,742	-70,128	-15,550	-23,428	9,773	-9,589
Prairielands GCD	5,718	-234	0	-1,553	-1,141	0	-1,496	-1,233	-60
Saratoga UWCD	14,628	0	0	-8,128	-10,538	0	49	3,989	0
Southern Trinity GCD	6,363	-473	0	-171	-3,391	0	-2,909	1,161	-580

Appendix B

Observed and Simulated Hydrographs

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Due to the relatively large volume of transient hydraulic head data available for wells in the study area, all observed and simulated hydrographs were not presented in the main body of this report. Therefore, this appendix was created to show additional hydrographs. The hydrographs included here show observed and simulated water-level (hydraulic head) data for wells identified as being completed in the Brazos River Alluvium Aquifer. Not all of the transient hydraulic head data available for wells in the study area were plotted as hydrographs and included here. Data for wells with fewer than ten measurements were not included. Hydrographs are sorted alphabetically by county and by the number of available measurements.

Each hydrograph includes a title that consists of a well identifier and the county in which the well is located. For wells with a Texas state well number, the well identifier is the state well number. For wells without a state well number, a well identifier was developed to associate the well with the data source (such as a groundwater conservation district). In some cases, an internal identification was given to a well, which can be cross-referenced with the master well database included as part of the electronic delivery with this work.

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B.1 Brazos River Alluvium Aquifer Hydrographs

This section contains the observed and simulated hydrographs for the Brazos River Alluvium Aquifer.

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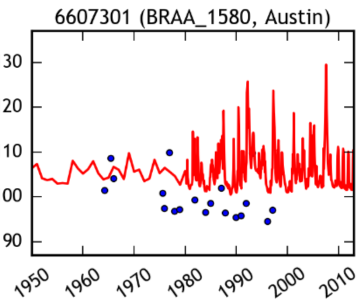
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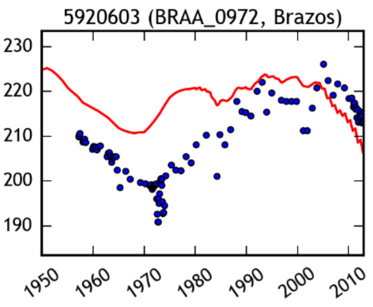
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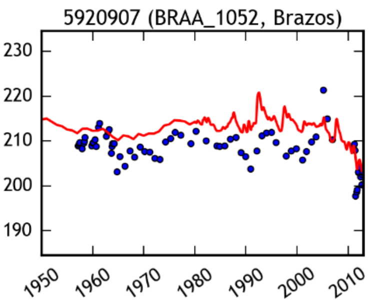
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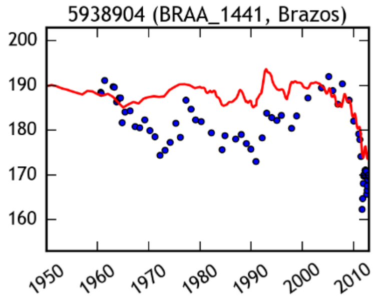
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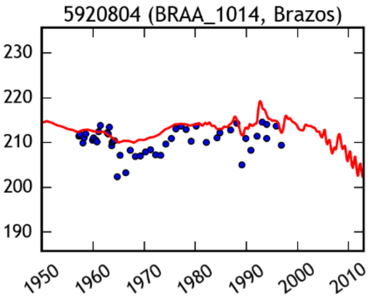
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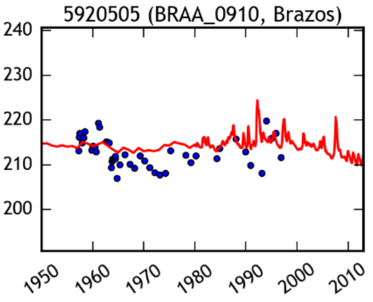
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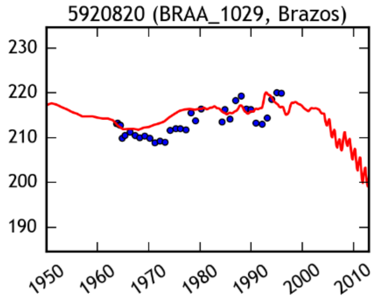
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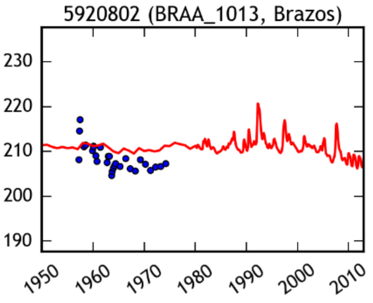
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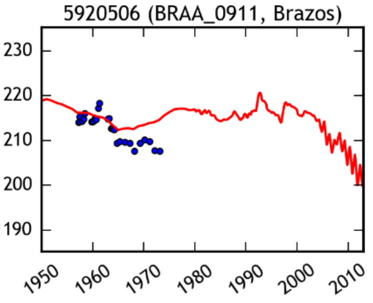
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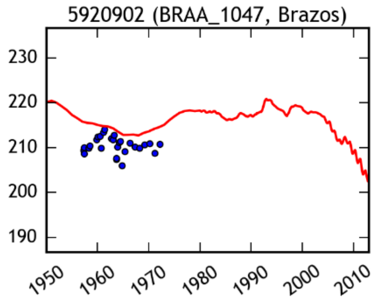
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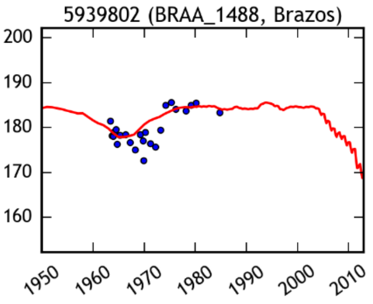
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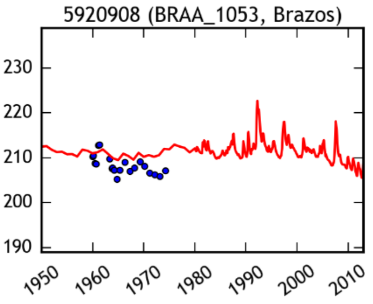
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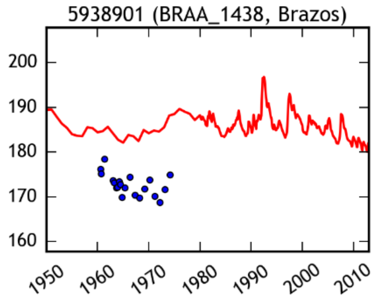
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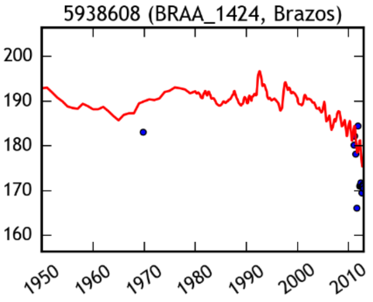
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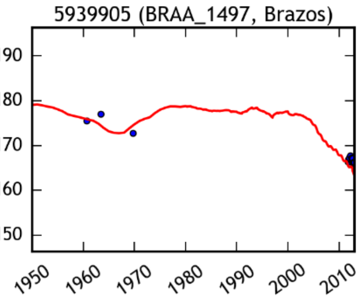
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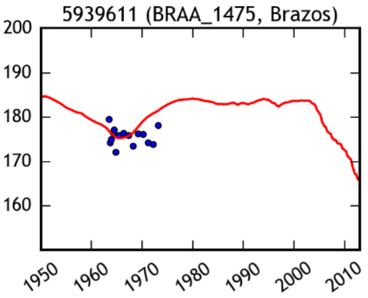
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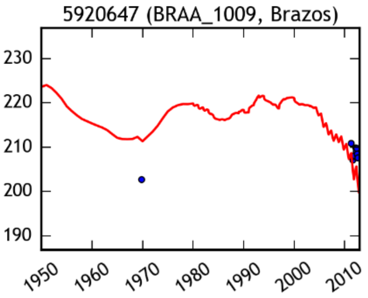
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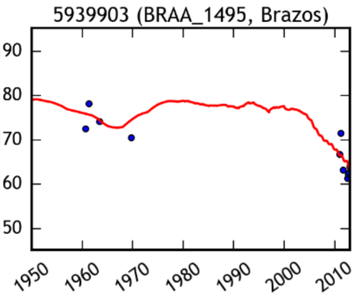
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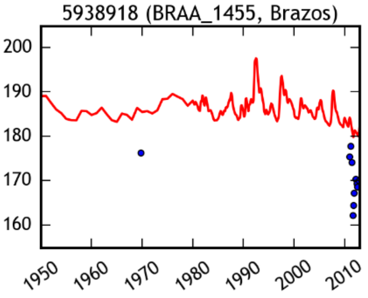
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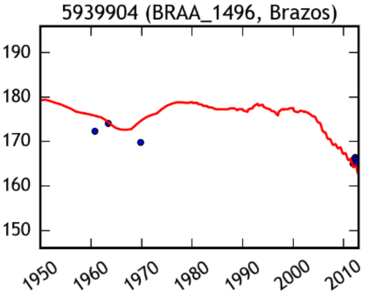
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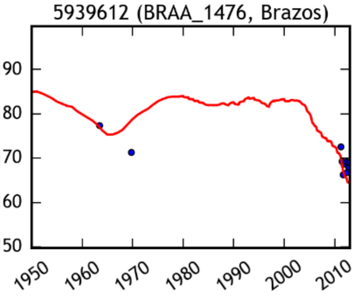
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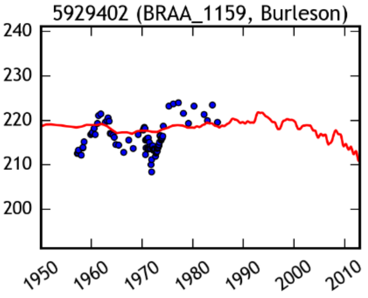
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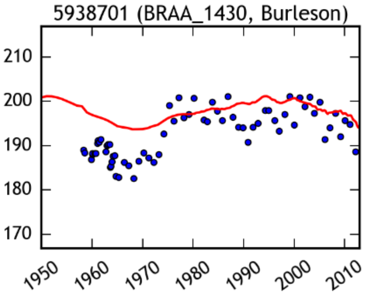
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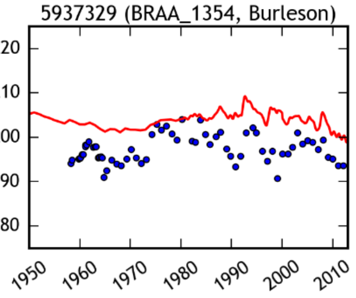
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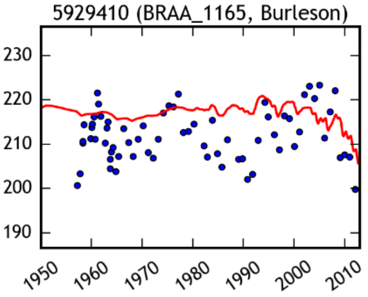
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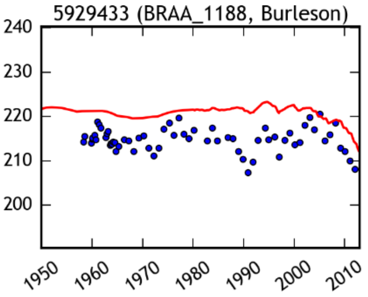
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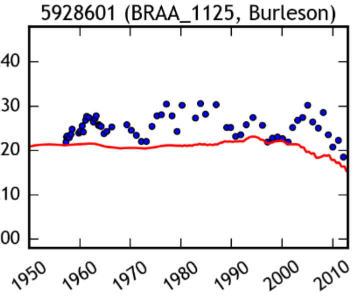
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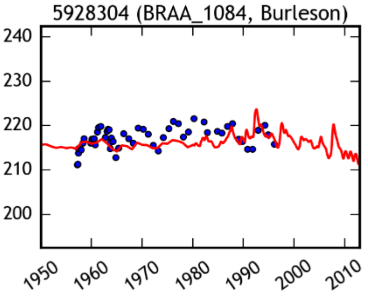
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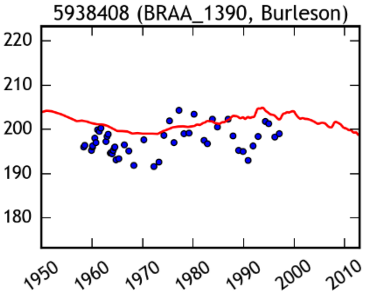
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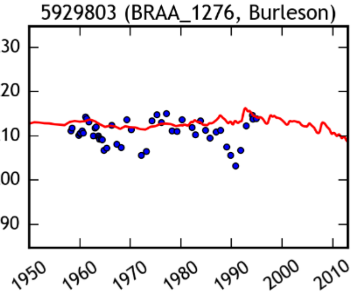
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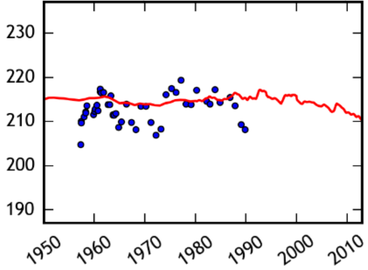
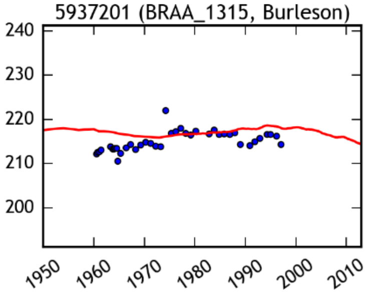
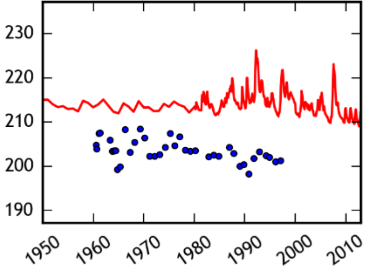
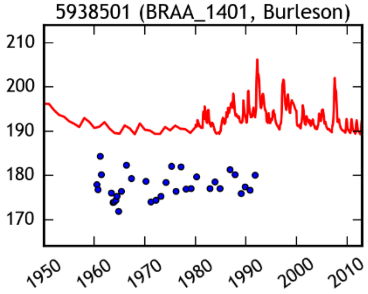
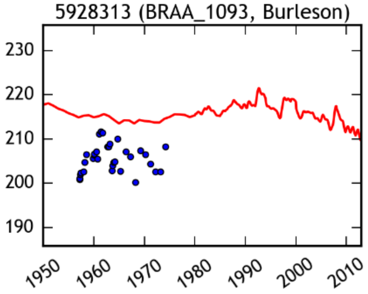
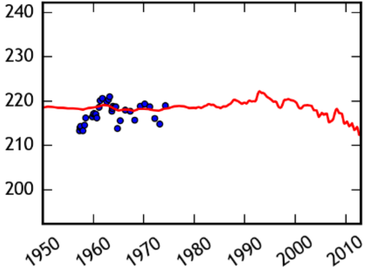

5929801 (BRAA_1274, Burleson)

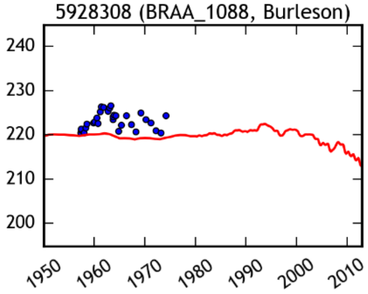

5937201 (BRAA_1315, Burleson)

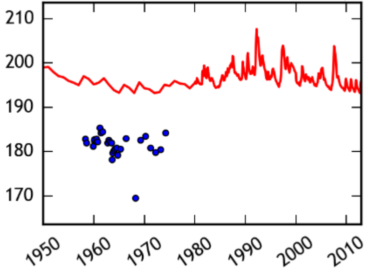

5928310 (BRAA_1090, Burleson)

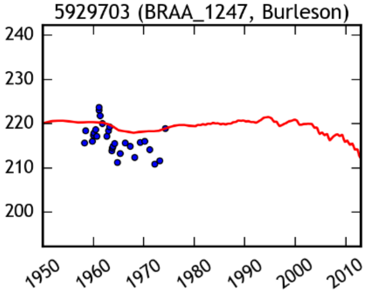

5938501 (BRAA_1401, Burleson)

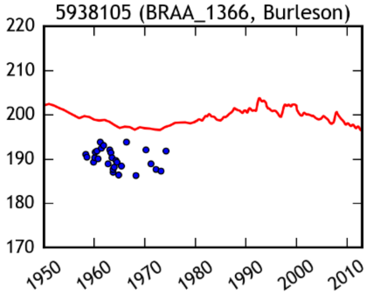

5928313 (BRAA_1093, Burleson)


5928306 (BRAA_1086, Burleson)


5928308 (BRAA_1088, Burleson)


5938106 (BRAA_1367, Burleson)


5929703 (BRAA_1247, Burleson)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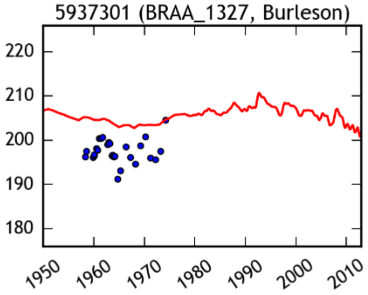
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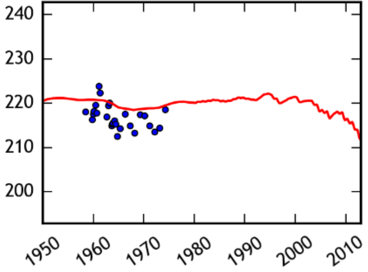
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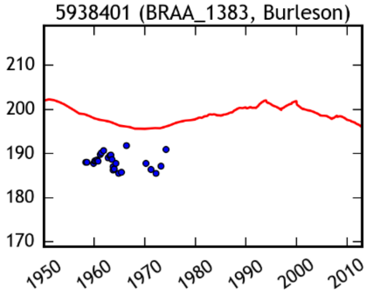
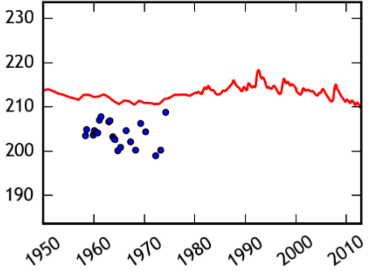

5938401 (BRAA_1383, Burleson)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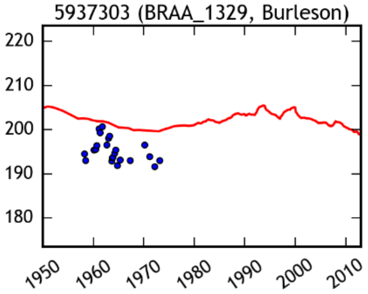
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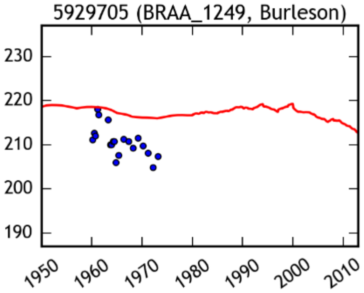
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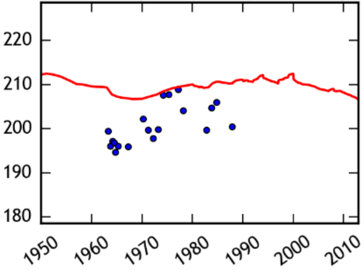
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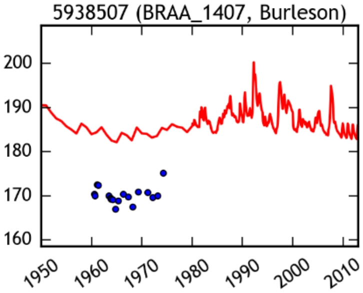
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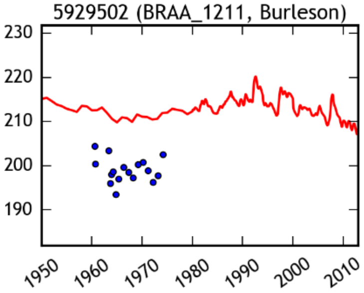
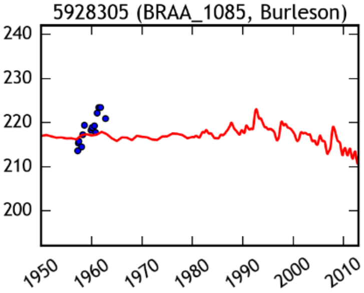

5929502 (BRAA_1211, Burleson)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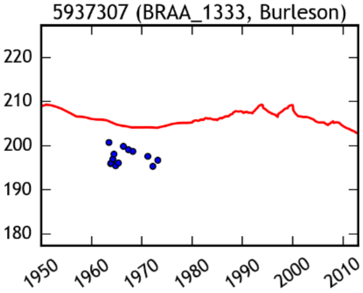
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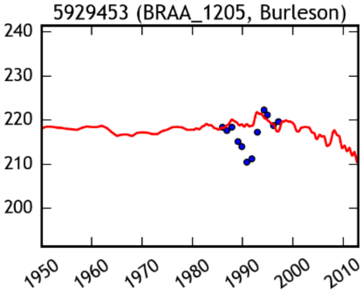
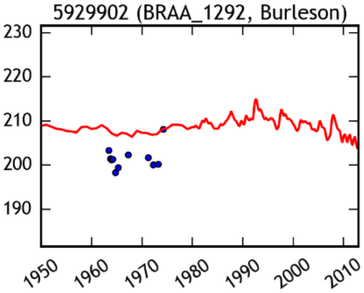

5929453 (BRAA_1205, Burleson)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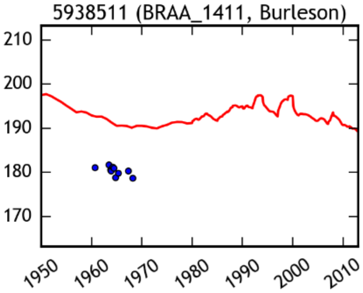
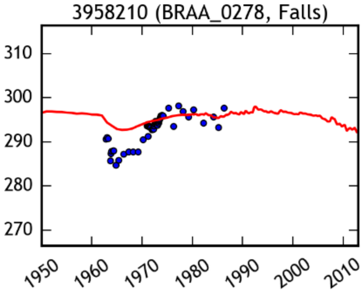
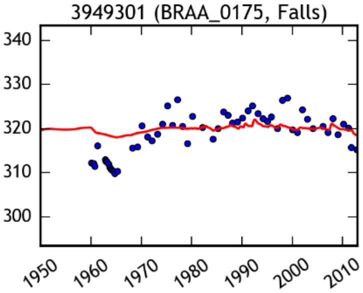
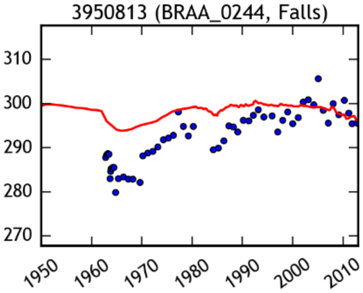
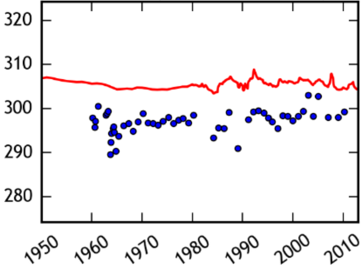
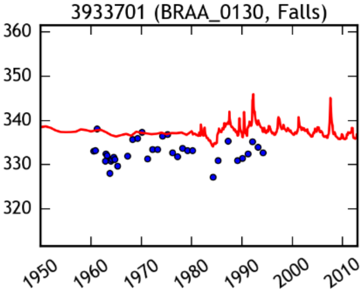

5938511 (BRAA_1411, Burleson)

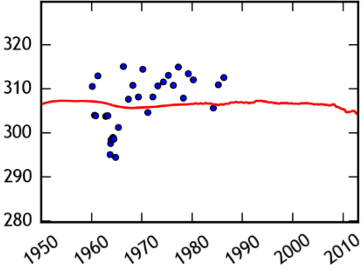

3958210 (BRAA_0278, Falls)


3949301 (BRAA_0175, Falls)

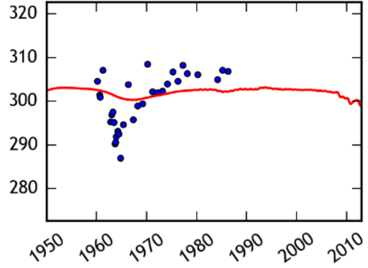

3950813 (BRAA_0244, Falls)


3950408 (BRAA_0199, Falls)

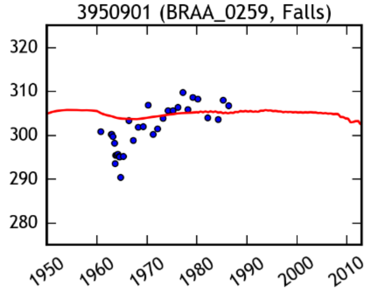

3933701 (BRAA_0130, Falls)


3950802 (BRAA_0233, Falls)

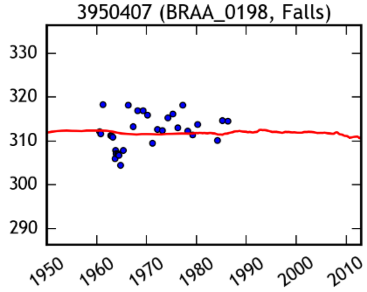
3950904 (BRAA_0262, Falls)



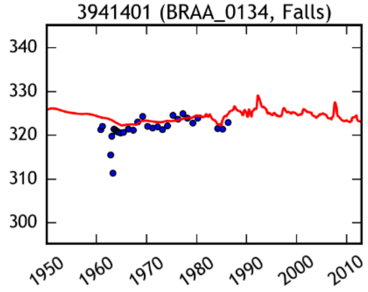
3950901 (BRAA_0259, Falls)



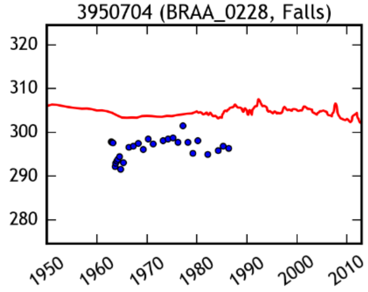
3950407 (BRAA_0198, Falls)



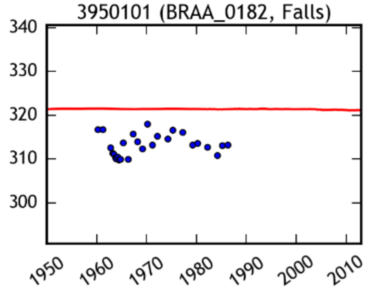
3941401 (BRAA_0134, Falls)



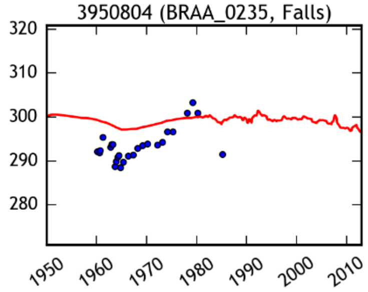
3950704 (BRAA_0228, Falls)



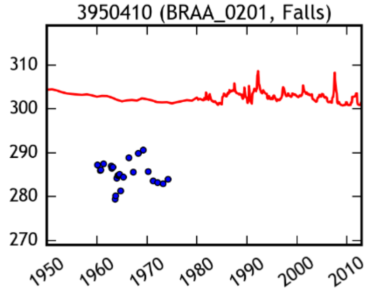
3950101 (BRAA_0182, Falls)



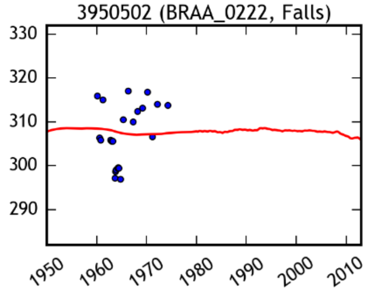
3950804 (BRAA_0235, Falls)



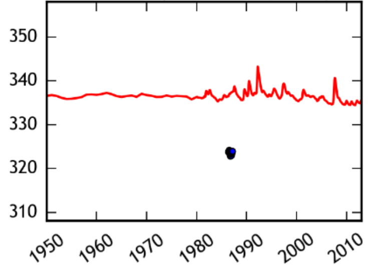
3950410 (BRAA_0201, Falls)



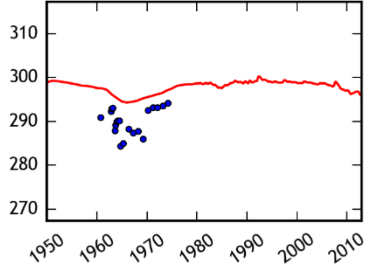
3950502 (BRAA_0222, Falls)



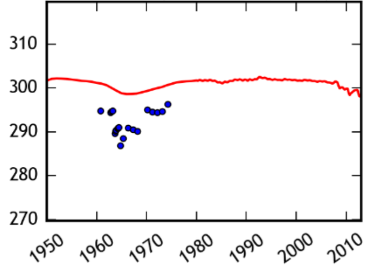
3941102 (BRAA_0132, Falls)



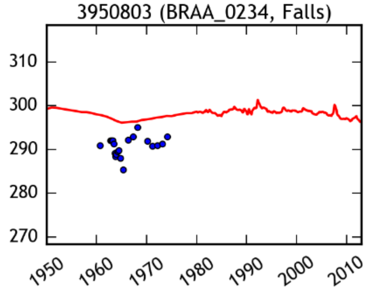
3950812 (BRAA_0243, Falls)



3950808 (BRAA_0239, Falls)



3950803 (BRAA_0234, Falls)



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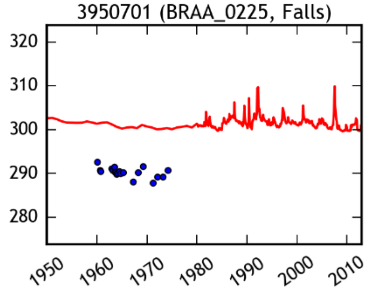

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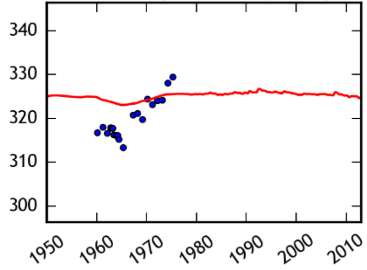

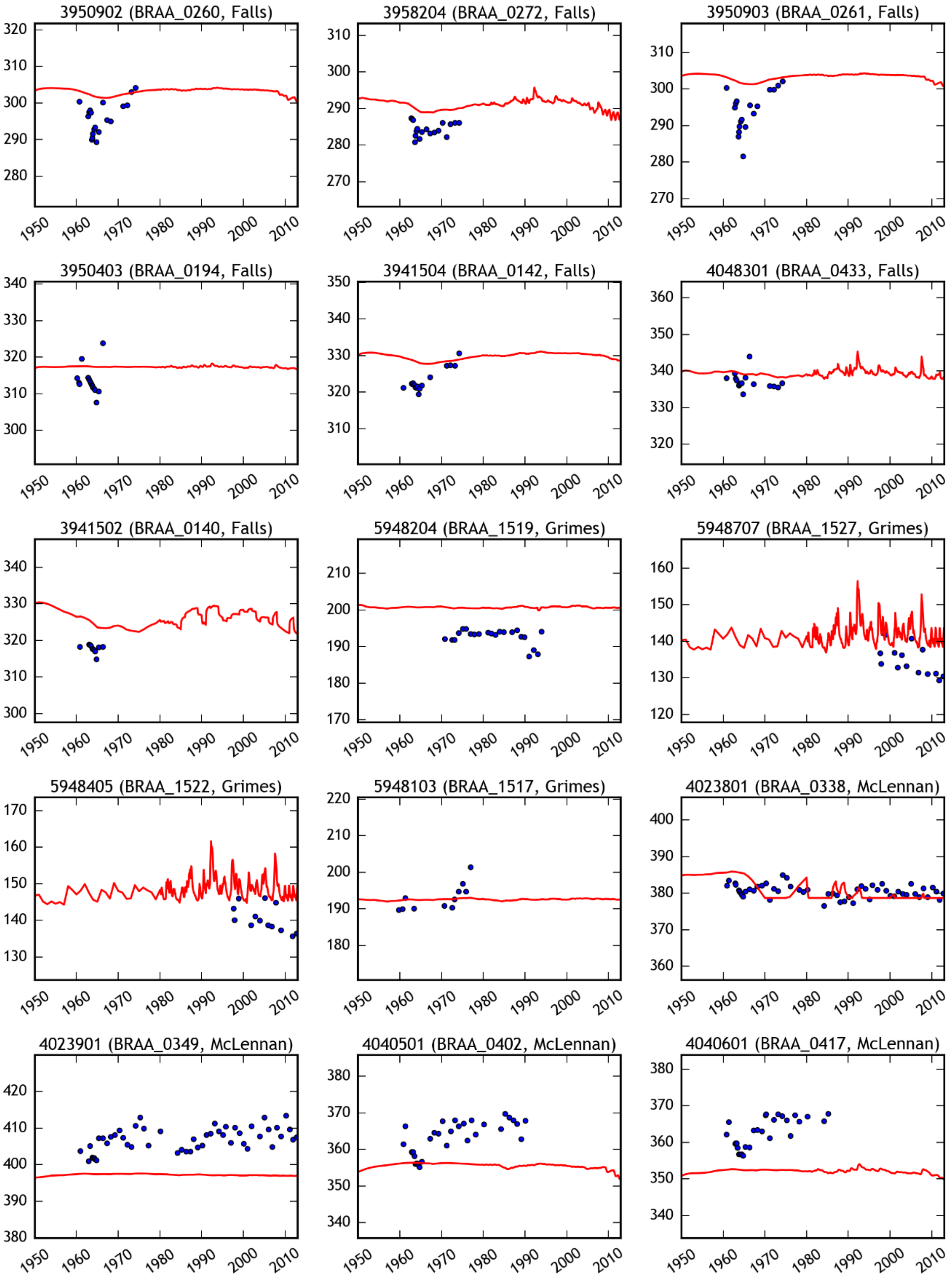
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3950403 (BRAA_0194, Falls)
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3941504 (BRAA_0142, Falls)
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4048301 (BRAA_0433, Falls)
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3941502 (BRAA_0140, Falls)
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5948204 (BRAA_1519, Grimes)
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5948707 (BRAA_1527, Grimes)
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5948405 (BRAA_1522, Grimes)
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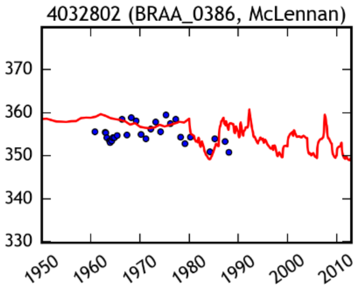
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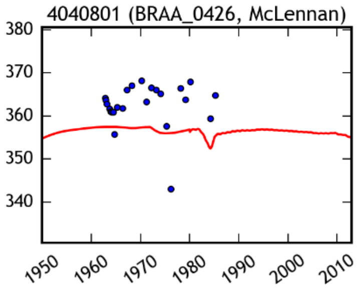
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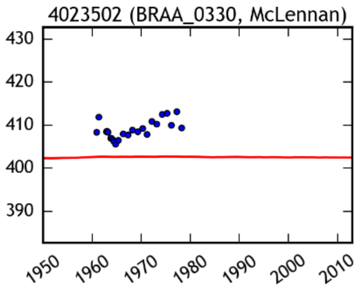
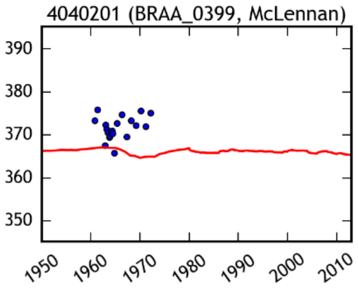
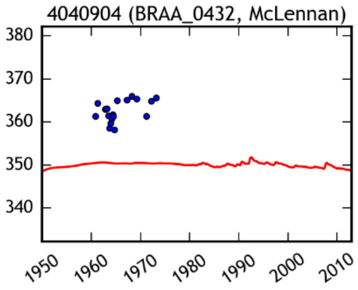
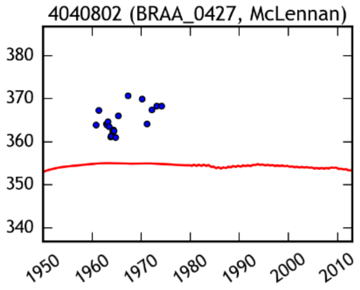

4023502 (BRAA_0330, McLennan)


4040201 (BRAA_0399, McLennan)


4040904 (BRAA_0432, McLennan)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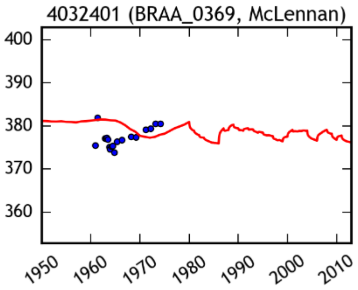
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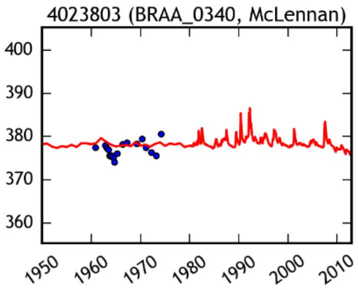
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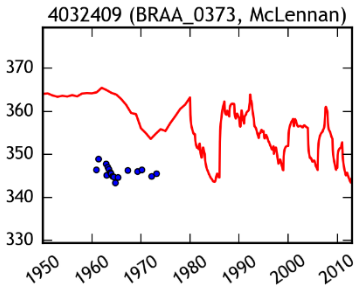
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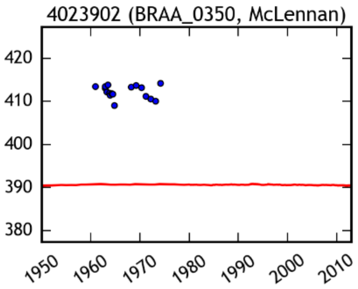
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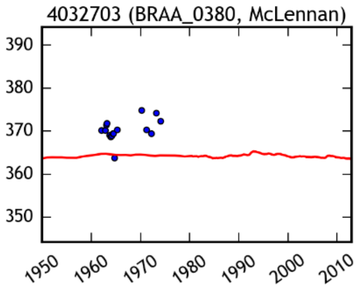
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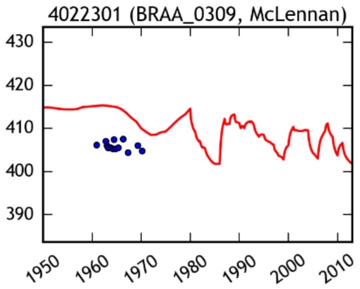
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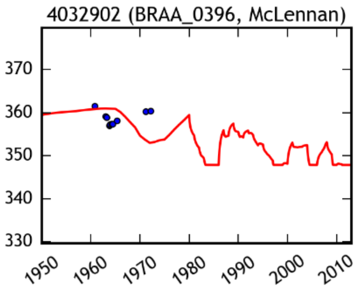
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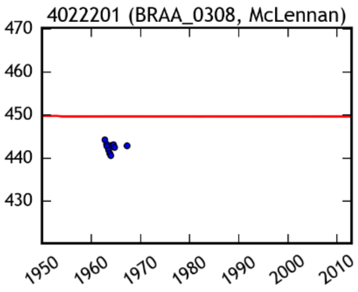
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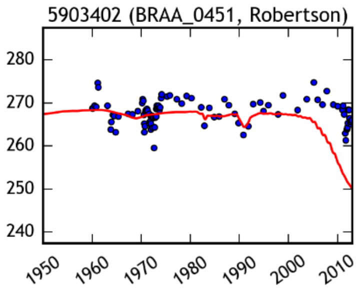
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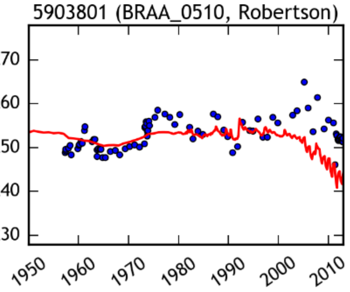
5903801 (BRAA_0510, Robertson)



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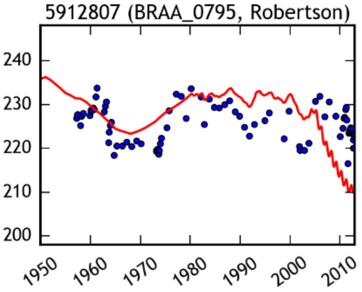

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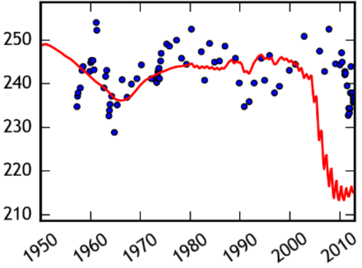

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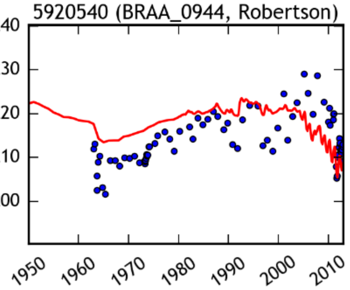

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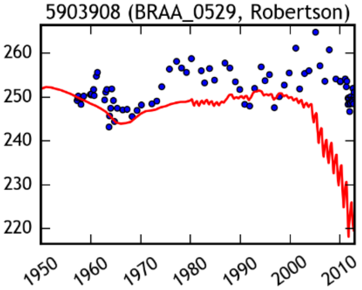

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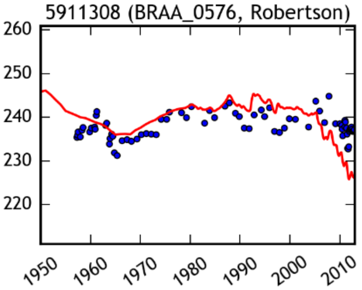

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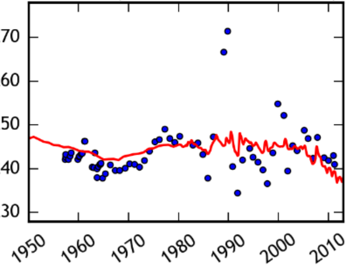

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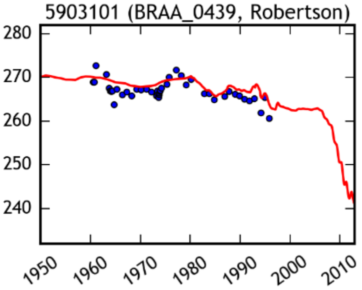

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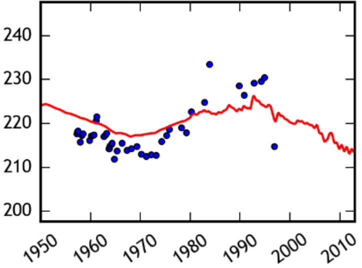

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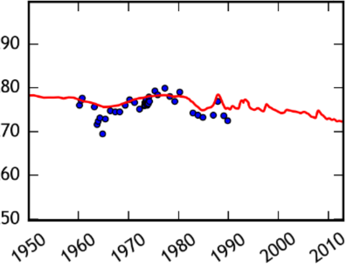

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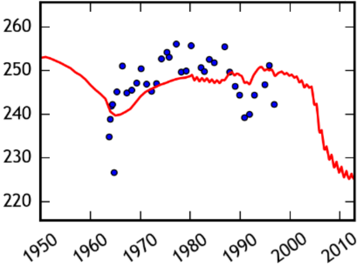

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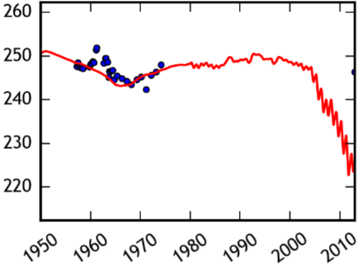

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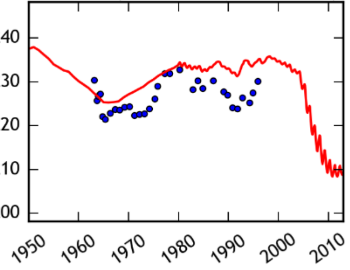

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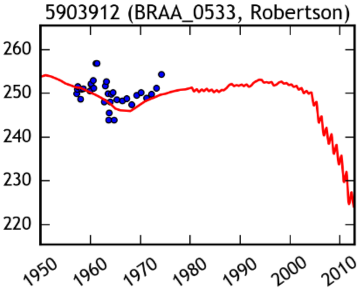

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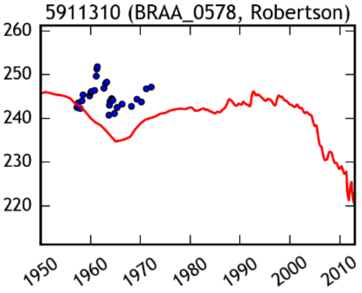

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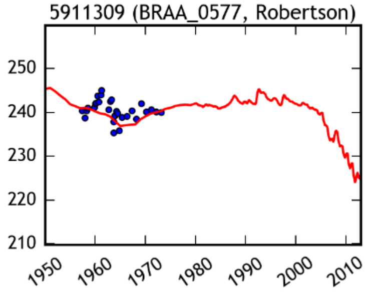

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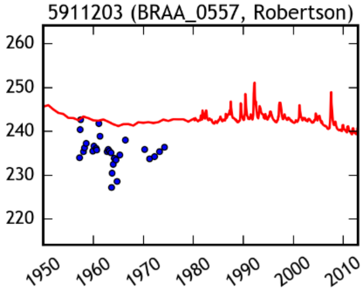

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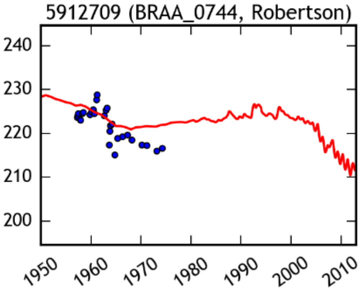

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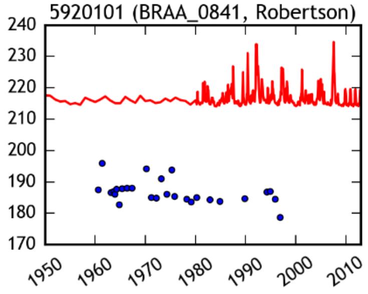

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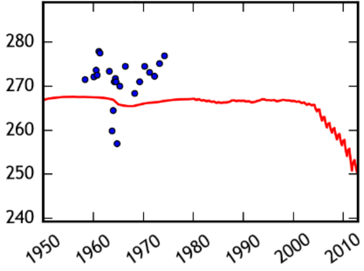

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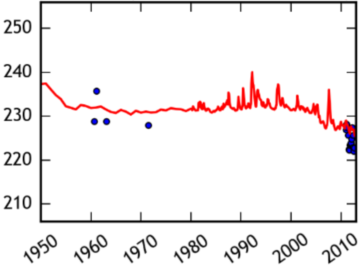

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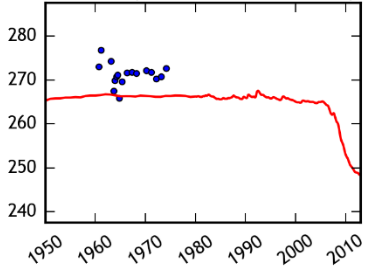

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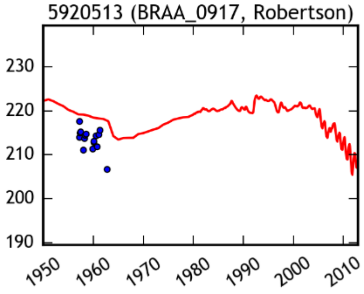

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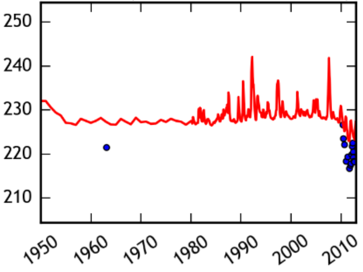

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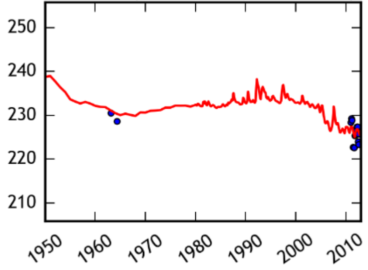

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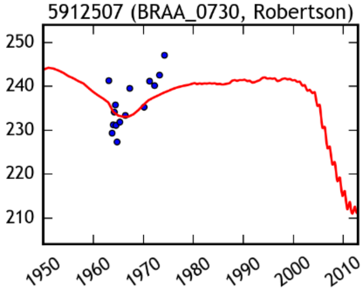

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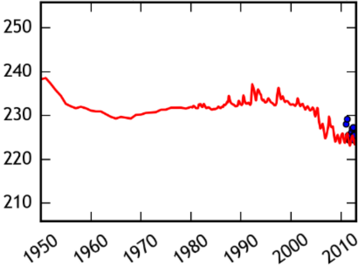

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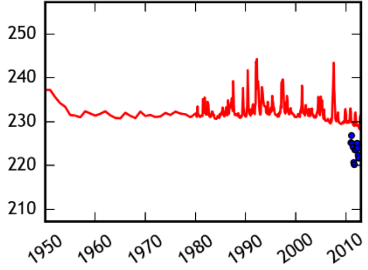

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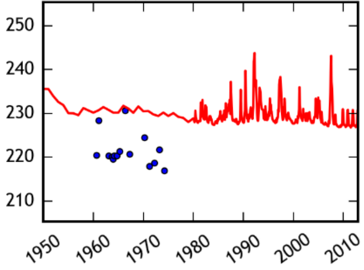

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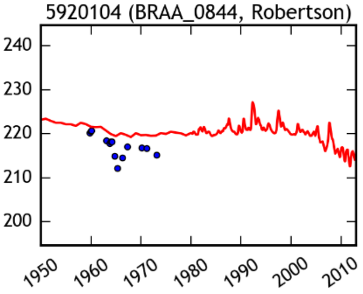

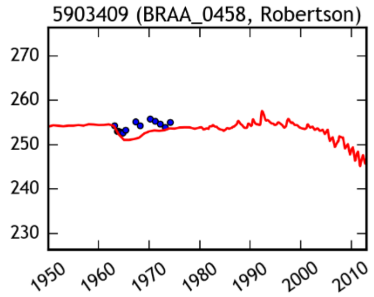
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250
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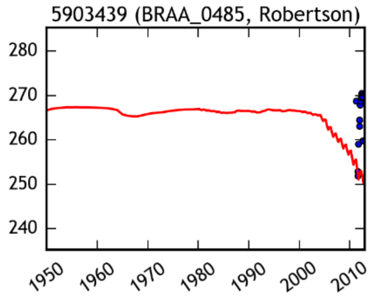
230
1950
1960
1970
1980
1990
2000
2010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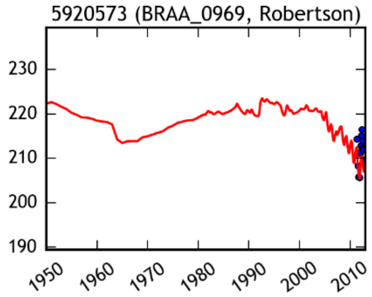
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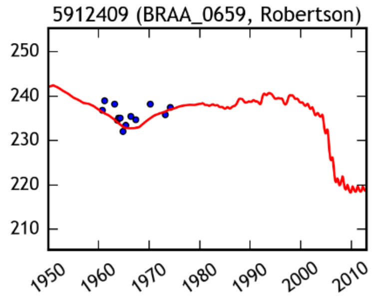
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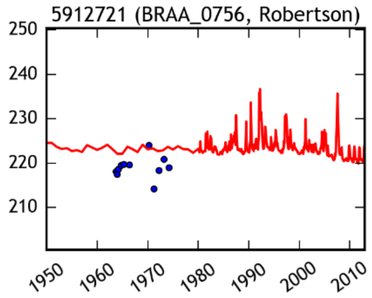
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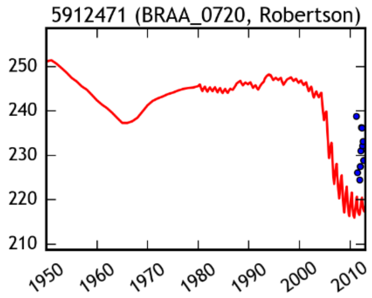
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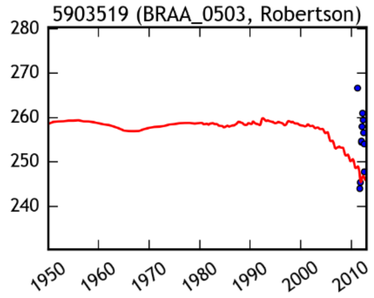
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240
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1990
2000
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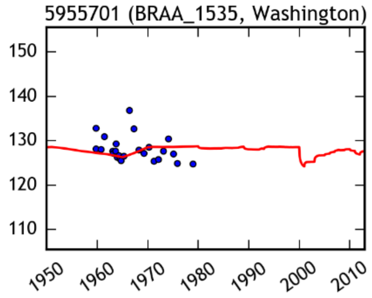
5955701 (BRAA_1535, Washington)
150
140
130
120
110
1950
1960
1970
1980
1990
2000
2010

Appendix C

Total Pumping by County and Stress Period

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The tables of this appendix provide the total pumping by county and stress period in terms of volume in acre-feet per year for the period from 1950 to 2012. Pumping values are for the Brazos River Alluvium Aquifer.

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Table C.1.1 Pumping in the Brazos River Alluvium Aquifer in acre-feet per year by County and Stress Period.

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
2	58	0	55	164	145	144	105	19	51	4	183	62	22
3	107	0	1,326	1,377	546	547	132	18	60	5	2,597	163	31
4	155	0	2,597	2,590	947	950	160	18	69	6	5,011	264	40
5	203	48	3,868	3,802	1,347	1,353	187	18	30	8	7,424	365	49
6	252	50	5,139	5,015	1,748	1,756	214	17	37	9	9,838	466	58
7	290	51	6,341	6,297	2,149	2,159	242	17	44	10	12,252	577	67
8	329	52	7,538	7,584	2,550	2,562	269	17	52	12	14,665	687	76
9	397	53	8,778	8,827	2,951	2,964	296	17	59	13	17,079	768	85
10	445	55	10,111	9,979	3,352	3,367	324	16	66	14	19,493	869	93
11	477	56	10,985	11,097	3,866	3,242	316	25	74	22	20,990	874	104
12	526	57	11,868	12,207	4,381	3,116	308	33	81	29	22,487	862	114
13	574	59	12,759	13,313	4,897	2,996	302	42	89	37	23,983	854	125
14	559	30	13,637	14,433	5,413	2,877	296	52	126	44	25,479	909	136
15	562	31	14,514	15,554	5,929	2,757	291	61	134	52	26,974	948	146
16	597	31	15,423	16,642	6,445	2,637	285	70	142	60	28,470	952	157
17	659	32	13,813	16,291	6,145	3,055	304	131	302	56	25,606	962	135
18	670	32	12,187	15,955	5,844	3,473	324	192	461	53	22,742	1,022	112
19	655	33	10,563	15,619	5,544	3,890	343	254	621	50	19,878	1,109	90
20	782	34	8,954	15,266	5,243	4,308	363	315	781	47	17,014	1,054	67

21	700	34	7,333	14,925	4,943	4,726	382	376	941	44	14,151	1,206	45
22	738	35	6,261	13,661	4,961	4,526	355	353	928	45	14,165	1,224	46
23	743	36	5,215	12,379	4,978	4,355	333	329	915	46	14,160	1,276	47
24	771	37	4,168	11,098	4,995	4,185	311	305	901	48	14,154	1,305	49
25	900	38	3,122	9,817	5,011	4,014	290	281	888	49	14,149	1,233	50
26	895	39	2,076	8,535	5,024	3,844	268	257	875	54	14,143	1,296	51
27	923	40	2,153	8,589	4,590	3,764	281	223	753	45	13,656	1,242	50
28	916	41	2,230	8,642	4,153	3,685	295	189	631	40	13,169	1,225	49
29	894	42	2,313	8,689	3,715	3,605	308	155	509	35	12,682	1,222	48
30	868	43	2,390	8,742	3,324	3,526	322	121	387	29	12,149	1,223	47
31	914	44	2,467	8,795	2,879	3,446	335	87	265	24	11,670	1,152	46
32	648	45	4,248	5,805	3,356	753	264	191	1,023	36	9,279	258	71
33	676	45	4,248	5,805	3,356	753	264	191	1,023	36	9,137	258	71

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
34	676	45	4,248	5,805	3,356	753	264	191	1,023	36	9,137	258	71
35	627	45	4,248	5,805	3,356	753	264	191	1,023	36	8,996	258	71
36	930	45	4,248	5,805	3,512	6,097	600	534	1,023	36	14,677	2,176	71
37	1,528	45	4,248	5,805	3,506	8,102	600	534	1,023	36	24,028	2,393	71
38	1,484	45	4,248	5,805	3,509	8,102	600	534	1,023	36	23,872	2,438	71
39	1,464	45	4,248	5,805	3,510	8,102	600	362	1,023	36	22,484	2,457	71
40	1,446	45	4,248	5,805	3,511	8,102	600	362	1,023	36	22,471	2,476	71
41	1,129	45	4,248	5,805	3,356	2,757	264	362	1,023	36	17,788	1,525	71
42	795	45	4,248	5,805	3,356	2,757	264	191	1,023	36	15,399	575	71
43	458	45	4,248	5,805	3,356	753	264	191	1,023	36	8,906	258	71
44	463	45	4,248	5,805	3,356	753	264	191	1,023	36	8,902	258	71
45	476	49	4,287	6,282	3,779	818	245	147	1,198	37	8,775	273	71
46	483	49	4,287	6,282	3,779	818	245	147	1,198	37	8,782	273	71
47	478	49	4,287	6,282	3,779	818	245	147	1,198	37	8,774	273	71
48	760	49	4,287	6,282	3,918	6,328	658	405	1,198	40	13,924	1,810	71
49	1,340	49	4,287	6,282	3,918	8,395	658	405	1,198	40	23,125	2,466	71
50	1,478	49	4,287	6,282	3,907	8,395	658	405	1,198	40	23,007	2,328	71
51	1,457	49	4,287	6,282	3,906	8,395	658	276	1,198	37	21,867	2,349	71
52	1,379	49	4,287	6,282	3,911	8,395	658	276	1,198	37	21,814	2,428	71

53	1,126	49	4,287	6,282	3,779	2,884	245	276	1,198	35	17,701	1,669	71
54	1,184	49	4,287	6,282	3,779	2,884	245	147	1,198	37	16,012	800	71
55	918	49	4,287	6,282	3,779	818	245	147	1,198	37	10,103	273	71
56	684	49	4,287	6,282	3,779	818	245	147	1,198	37	9,715	273	71
57	596	52	5,444	6,777	4,204	915	226	105	1,371	39	9,576	290	63
58	556	52	5,444	6,777	4,204	915	226	105	1,371	39	9,508	290	63
59	542	52	5,444	6,777	4,204	915	226	105	1,371	39	9,485	290	63
60	831	52	5,444	6,777	4,325	6,591	715	276	1,371	44	13,972	1,857	63
61	1,473	52	5,444	6,777	4,317	8,720	715	276	1,371	44	22,242	2,392	63
62	1,449	52	5,444	6,777	4,316	8,720	715	276	1,371	44	22,131	2,416	63
63	1,435	52	5,444	6,777	4,314	8,720	715	190	1,371	39	21,034	2,430	63
64	1,382	52	5,444	6,777	4,318	8,720	715	190	1,371	39	20,987	2,483	63
65	1,098	52	5,444	6,777	4,204	3,044	226	190	1,371	34	17,364	1,724	63
66	807	52	5,444	6,777	4,204	3,044	226	105	1,371	39	15,418	952	63
67	527	52	5,444	6,777	4,204	915	226	105	1,371	39	9,813	290	63

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
68	611	56	6,592	7,244	4,707	1,004	206	62	1,517	120	9,587	307	62
69	825	56	6,592	7,244	4,707	1,004	206	62	1,519	120	9,647	307	62
70	864	56	6,592	7,244	4,707	1,004	206	62	1,519	120	9,731	307	62
71	911	56	6,592	7,244	4,824	6,846	773	147	1,570	127	13,907	1,904	62
72	1,250	56	6,592	7,244	4,823	9,037	773	147	1,574	127	22,069	2,468	62
73	1,249	56	6,592	7,244	4,824	9,037	773	147	1,570	127	21,834	2,469	62
74	1,225	56	6,592	7,244	4,826	9,037	773	105	1,567	120	20,641	2,493	62
75	1,232	56	6,592	7,244	4,826	9,037	773	105	1,568	120	20,636	2,487	62
76	1,011	56	6,592	7,244	4,707	3,195	206	105	1,539	113	16,720	1,707	62
77	771	56	6,592	7,244	4,707	3,195	206	62	1,537	120	14,806	921	62
78	533	56	6,592	7,244	4,707	1,004	206	62	1,537	120	8,662	307	62
79	527	56	6,592	7,244	4,707	1,004	206	62	1,533	120	8,580	307	62
80	526	60	7,190	7,243	5,193	1,060	172	19	1,566	123	8,581	309	61
81	511	60	7,107	7,181	5,193	1,060	172	19	1,556	123	8,508	309	61
82	564	60	7,013	7,160	5,193	1,060	172	19	1,542	123	8,509	309	61
83	773	60	8,090	7,694	5,313	6,568	815	19	2,059	133	13,505	1,937	61
84	1,233	60	9,049	8,157	5,312	9,072	815	19	2,100	133	22,198	2,575	61
85	1,231	60	9,048	8,141	5,312	9,072	815	19	2,057	133	21,961	2,577	61
86	1,228	60	8,827	8,096	5,311	9,072	815	19	2,012	123	20,663	2,580	61

87	1,221	60	8,816	8,102	5,311	9,072	815	19	2,008	123	20,666	2,587	61
88	958	60	7,407	7,748	5,193	4,565	172	19	1,529	114	16,624	1,783	61
89	800	60	7,600	7,824	5,193	3,564	172	19	1,464	123	14,984	937	61
90	600	60	6,320	7,609	5,193	1,060	172	19	1,386	123	8,987	309	61
91	721	60	6,272	7,687	5,193	1,060	172	19	1,362	123	9,092	309	61
92	771	64	6,107	6,411	2,761	1,088	182	140	1,404	121	9,271	297	52
93	688	64	6,096	6,411	2,761	1,088	182	140	1,402	121	9,243	297	52
94	810	64	6,123	6,411	2,761	1,088	182	140	1,410	121	9,439	297	52
95	784	64	6,759	6,427	2,869	4,759	451	388	2,535	237	13,959	2,160	52
96	941	64	7,262	6,426	2,866	5,807	451	388	2,620	234	22,003	2,692	52
97	924	64	7,263	6,425	2,867	5,807	451	388	2,536	235	21,681	2,709	52
98	892	64	7,182	6,424	2,869	5,807	451	264	2,453	229	20,483	2,741	52
99	875	64	7,183	6,424	2,869	5,807	451	264	2,453	230	20,473	2,758	52
100	719	64	6,703	6,411	2,761	2,136	182	264	1,613	113	16,724	1,838	52
101	593	64	6,778	6,411	2,761	2,136	182	140	1,527	121	15,184	901	52

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
102	515	64	6,336	6,411	2,761	1,088	182	140	1,441	121	9,366	297	52
103	780	64	6,342	6,411	2,761	1,088	182	140	1,440	121	9,618	297	52
104	629	57	6,339	5,558	1,755	1,178	187	202	252	119	8,984	322	53
105	774	57	6,371	5,558	1,755	1,178	187	202	252	119	9,293	322	53
106	588	57	6,383	5,558	1,755	1,178	187	202	252	119	8,962	322	53
107	649	57	6,817	5,571	1,823	4,693	456	574	252	193	11,601	1,693	53
108	1,035	57	7,270	5,571	1,822	5,698	456	574	252	192	16,674	2,163	53
109	1,090	57	7,265	5,570	1,816	5,698	456	574	252	186	16,511	2,107	53
110	1,050	57	7,200	5,569	1,818	5,698	456	388	252	182	15,743	2,147	53
111	1,007	57	7,204	5,569	1,821	5,698	456	388	252	185	15,688	2,191	53
112	880	57	6,815	5,558	1,755	2,182	187	388	252	112	13,454	1,491	53
113	783	57	6,895	5,558	1,755	2,182	187	202	252	119	12,723	791	53
114	678	57	6,524	5,558	1,755	1,178	187	202	252	119	9,320	322	53
115	899	57	6,561	5,558	1,755	1,178	187	202	252	119	9,553	322	53
116	772	40	6,472	6,418	1,679	1,163	166	202	689	108	8,874	303	55
117	772	40	6,472	6,418	1,679	1,163	166	202	689	108	8,764	303	55
118	772	40	6,472	6,418	1,679	1,163	166	202	689	108	8,874	303	55
119	781	40	6,472	6,418	1,680	4,154	433	573	689	113	8,954	1,771	55
120	784	40	6,476	6,418	1,683	5,009	433	573	689	119	9,090	2,161	55

121	798	40	6,474	6,418	1,680	5,009	433	573	689	115	9,092	2,147	55
122	798	40	6,474	6,418	1,680	5,009	433	388	689	112	9,070	2,147	55
123	798	40	6,474	6,418	1,680	5,009	433	388	689	112	9,070	2,147	55
124	789	40	6,474	6,418	1,679	2,017	166	388	689	108	8,981	1,413	55
125	731	40	6,477	6,418	1,679	2,017	166	202	689	114	8,766	695	55
126	687	40	6,472	6,418	1,679	1,163	168	202	689	108	8,316	303	55
127	699	40	6,472	6,418	1,679	1,163	170	202	689	108	8,235	303	55
128	725	37	6,972	5,049	1,694	1,348	139	303	419	143	9,549	311	45
129	688	37	6,892	5,049	1,694	1,348	139	303	419	143	9,435	311	45
130	715	37	6,814	5,049	1,694	1,348	137	303	419	143	9,387	311	45
131	861	37	9,801	5,129	1,784	6,611	333	874	419	261	13,189	2,258	124
132	1,202	37	12,523	5,129	1,784	7,927	333	874	419	352	20,188	2,927	124
133	1,212	37	12,443	5,128	1,783	7,927	333	874	419	349	19,838	2,917	124
134	1,211	37	11,970	5,128	1,782	7,927	333	589	419	320	18,778	2,917	124
135	1,202	37	11,976	5,127	1,783	7,927	333	589	419	321	18,764	2,927	123

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
136	998	37	9,009	5,049	1,694	2,663	134	589	419	204	15,484	1,964	123
137	778	37	9,556	5,049	1,694	2,663	134	303	419	234	14,358	999	45
138	558	37	6,863	5,049	1,694	1,348	134	303	419	143	9,107	311	45
139	591	37	6,850	5,049	1,694	1,348	134	303	419	143	9,199	311	45
140	578	36	5,298	5,163	3,337	1,232	134	43	703	117	8,713	299	76
141	639	36	5,298	5,163	3,337	1,232	134	43	703	117	8,765	299	76
142	649	36	5,298	5,163	3,337	1,232	138	43	703	117	8,783	299	76
143	882	36	5,298	5,163	3,404	5,680	173	100	703	200	11,880	1,483	76
144	1,335	36	5,359	5,163	3,398	7,348	173	100	703	255	17,212	1,924	76
145	1,368	36	5,350	5,163	3,389	7,348	173	100	703	238	17,038	1,892	76
146	1,348	36	5,355	5,163	3,394	7,348	173	72	703	231	16,312	1,911	76
147	1,319	36	5,357	5,163	3,396	7,348	173	72	703	236	16,266	1,940	76
148	1,113	36	5,359	5,163	3,337	2,900	145	72	703	162	13,902	1,371	76
149	889	36	5,360	5,163	3,337	2,900	150	43	703	179	13,103	792	76
150	653	36	5,298	5,163	3,337	1,232	155	43	703	117	9,383	299	76
151	631	36	5,298	5,163	3,337	1,232	156	43	703	117	9,371	299	76
152	623	39	6,670	6,808	5,246	1,367	172	46	919	100	9,964	302	74
153	655	39	6,641	6,808	5,246	1,367	172	46	919	100	10,072	302	74
154	874	39	6,675	6,808	5,246	1,367	172	46	919	100	10,569	302	74

155	1,066	39	7,929	6,962	5,340	6,371	172	108	919	209	15,361	1,830	104
156	1,379	39	9,218	6,933	5,324	8,247	172	108	919	271	23,322	2,312	100
157	1,379	39	9,212	6,920	5,324	8,247	172	108	919	271	23,012	2,312	96
158	1,379	39	9,109	6,898	5,329	8,247	172	77	919	265	21,983	2,312	94
159	1,333	39	9,122	6,900	5,332	8,247	172	77	919	272	21,912	2,358	93
160	1,137	39	8,392	6,776	5,246	3,244	172	77	919	173	18,363	1,619	93
161	937	39	8,501	6,796	5,246	3,244	172	46	919	188	17,116	864	74
162	719	39	7,559	6,797	5,246	1,367	172	46	919	100	11,712	302	74
163	673	39	7,455	6,798	5,246	1,367	172	46	919	100	11,618	302	74
164	1,015	39	4,479	7,830	1,233	1,630	184	47	624	101	11,938	311	75
165	1,015	39	4,479	7,830	1,233	1,630	184	47	624	101	11,971	311	75
166	899	39	4,479	7,830	1,233	1,630	184	47	624	101	11,784	311	75
167	1,055	39	4,479	7,912	1,316	5,779	184	109	624	198	15,888	1,738	75
168	1,136	39	4,559	7,909	1,313	7,335	184	109	624	275	22,909	2,135	75
169	1,136	39	4,557	7,908	1,312	7,335	184	109	624	272	22,603	2,135	75

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
170	1,084	39	4,560	7,911	1,315	7,335	184	78	624	264	21,596	2,187	75
171	1,061	39	4,561	7,912	1,315	7,335	184	78	624	265	21,586	2,210	75
172	945	39	4,562	7,830	1,233	3,186	184	78	624	169	18,172	1,497	75
173	759	39	4,563	7,830	1,233	3,186	184	47	624	186	16,883	807	75
174	742	39	4,479	7,830	1,233	1,630	184	47	624	101	11,919	311	75
175	790	39	4,479	7,830	1,233	1,630	184	47	624	101	12,162	311	75
176	1,214	39	3,219	5,979	1,898	1,538	234	46	979	107	13,411	320	74
177	1,214	39	3,219	5,979	1,898	1,538	234	46	979	102	14,186	320	74
178	1,214	39	3,219	5,979	1,898	1,538	234	46	979	102	14,186	320	74
179	1,324	39	3,219	5,990	1,909	4,423	234	108	979	127	14,740	1,643	74
180	1,545	39	3,233	5,992	1,911	5,505	234	108	979	145	15,714	2,085	74
181	1,545	39	3,232	5,991	1,910	5,505	234	108	979	142	15,670	2,085	74
182	1,528	39	3,235	5,994	1,913	5,505	234	77	979	122	15,453	2,102	74
183	1,460	39	3,239	5,999	1,918	5,505	234	77	979	130	15,357	2,170	74
184	1,129	39	3,246	5,979	1,898	2,620	234	77	979	102	14,090	1,576	74
185	707	39	3,251	5,979	1,898	2,620	234	46	979	153	13,325	967	74
186	267	39	3,219	5,979	1,898	1,538	234	46	979	125	10,812	320	74
187	297	39	3,219	5,979	1,898	1,538	234	46	979	127	10,529	320	74
188	327	39	4,890	4,776	1,997	1,566	336	50	1,143	131	6,458	323	47

189	398	39	4,890	4,776	1,997	1,566	336	50	1,143	131	6,458	323	47
190	534	39	4,890	4,776	1,997	1,566	336	50	1,143	131	6,458	323	47
191	791	39	4,890	4,776	1,997	5,242	373	121	1,143	176	6,458	1,290	47
192	1,199	39	4,890	4,776	1,997	6,621	373	121	1,143	176	6,458	1,738	47
193	1,163	39	4,890	4,776	1,997	6,621	373	121	1,143	176	6,458	1,774	47
194	1,141	39	4,890	4,776	1,997	6,621	373	85	1,143	131	6,458	1,796	47
195	1,116	39	4,890	4,776	1,997	6,621	373	85	1,143	131	6,458	1,821	47
196	802	39	4,890	4,776	1,997	2,945	295	85	1,143	85	6,458	1,350	47
197	498	39	4,890	4,776	1,997	2,945	290	50	1,143	131	6,458	868	47
198	202	39	4,890	4,776	1,997	1,566	288	50	1,143	131	6,458	323	47
199	228	39	4,890	4,776	1,997	1,566	285	50	1,143	131	6,458	323	47
200	244	42	6,729	8,511	3,866	1,498	274	50	993	172	9,895	329	60
201	259	42	6,659	8,511	3,866	1,498	272	50	993	173	9,829	329	60
202	321	42	6,588	8,512	3,866	1,498	268	50	993	173	9,831	329	60
203	629	42	7,136	8,608	3,932	16,934	434	121	993	264	13,007	1,529	75

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
204	1,347	42	7,821	8,632	3,927	24,137	434	121	993	315	19,205	2,090	75
205	1,343	42	7,808	8,633	3,928	24,137	434	121	993	318	18,888	2,094	75
206	1,315	42	7,704	8,622	3,930	24,137	434	85	993	236	18,089	2,123	75
207	1,304	42	7,695	8,627	3,932	24,137	434	85	993	240	18,053	2,134	76
208	999	42	7,011	8,531	3,866	12,818	251	85	993	150	15,170	1,534	77
209	800	42	7,070	8,550	3,866	8,702	249	50	993	241	14,283	899	60
210	571	42	6,202	8,516	3,866	1,498	246	50	993	174	9,589	329	60
211	751	42	6,175	8,517	3,866	1,498	244	50	993	173	9,811	329	60
212	902	48	6,748	9,853	4,503	1,510	245	87	1,225	212	9,653	343	60
213	781	48	6,731	9,836	4,503	1,510	243	87	1,225	214	9,447	343	60
214	857	48	6,741	9,912	4,503	1,510	242	87	1,225	210	9,773	343	60
215	927	48	10,851	15,398	4,544	17,538	486	231	1,225	287	12,624	1,429	151
216	975	48	15,133	20,330	4,545	25,019	486	231	1,225	330	16,672	1,724	150
217	975	48	15,046	20,161	4,544	25,019	486	231	1,225	329	16,471	1,724	149
218	968	48	14,432	19,399	4,547	25,019	486	159	1,225	207	15,909	1,731	149
219	975	48	14,436	19,402	4,547	25,019	486	159	1,225	207	15,915	1,724	149
220	931	48	10,691	14,675	4,503	13,264	246	159	1,225	119	13,850	1,191	149
221	836	48	11,211	14,813	4,503	8,990	246	87	1,225	260	13,130	669	60
222	759	48	6,972	10,057	4,503	1,510	247	87	1,225	215	9,392	343	60

223	754	48	6,916	9,954	4,503	1,510	247	87	1,225	217	9,267	343	60
224	738	28	7,050	10,016	3,459	1,632	237	86	1,185	294	9,883	386	61
225	708	28	6,980	9,951	3,459	1,632	235	86	1,185	295	9,802	386	61
226	691	28	6,915	9,898	3,459	1,632	234	86	1,185	294	9,812	386	61
227	894	28	12,111	16,420	3,550	19,961	477	228	1,185	430	14,705	1,458	180
228	1,309	28	17,793	22,546	3,550	28,515	477	228	1,185	520	24,130	2,205	180
229	1,316	28	17,670	22,335	3,548	28,515	477	228	1,185	515	23,696	2,198	181
230	1,308	28	16,829	21,378	3,548	28,515	477	157	1,185	292	22,624	2,207	181
231	1,296	28	16,827	21,376	3,548	28,515	477	157	1,185	292	22,622	2,219	181
232	1,131	28	11,772	15,394	3,459	15,073	224	157	1,185	156	18,643	1,653	181
233	897	28	12,502	15,694	3,459	10,186	224	86	1,185	374	17,456	1,130	61
234	704	28	6,817	10,010	3,459	1,632	224	86	1,185	285	10,574	386	61
235	854	28	6,879	10,146	3,459	1,632	224	86	1,185	278	11,143	386	61
236	892	33	3,417	4,305	2,782	1,403	254	112	1,482	130	9,900	353	62
237	908	33	3,417	4,305	2,782	1,403	254	112	1,505	123	10,521	353	62

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
238	908	33	3,417	4,305	2,782	1,403	254	112	1,533	123	10,521	353	62
239	1,146	33	3,417	4,305	2,783	12,859	504	304	1,545	177	10,562	1,242	62
240	1,177	33	3,419	4,306	2,783	18,205	504	304	1,546	177	10,635	1,703	62
241	1,177	33	3,419	4,306	2,783	18,205	504	304	1,544	177	10,631	1,703	62
242	1,177	33	3,419	4,306	2,783	18,205	504	208	1,543	123	10,623	1,703	62
243	1,177	33	3,419	4,306	2,783	18,205	504	208	1,543	123	10,623	1,703	62
244	916	33	3,419	4,305	2,782	9,804	262	208	1,533	69	10,588	1,270	62
245	840	33	3,419	4,305	2,782	6,749	267	112	1,533	123	10,579	841	62
246	764	33	3,417	4,305	2,782	1,403	270	112	1,533	123	10,493	353	62
247	788	33	3,417	4,305	2,782	1,403	272	112	1,519	124	10,379	353	62
248	1,084	34	4,118	3,974	2,800	1,504	274	112	1,435	222	11,817	364	63
249	1,084	34	4,118	3,974	2,800	1,504	274	112	1,435	224	11,659	364	63
250	1,084	34	4,118	3,974	2,800	1,504	275	112	1,435	216	12,289	364	63
251	1,347	34	4,118	4,022	2,847	21,222	602	304	1,435	321	14,972	1,375	63
252	1,327	34	4,220	4,076	2,851	30,424	602	304	1,435	382	19,942	1,932	63
253	1,298	34	4,223	4,080	2,853	30,424	602	304	1,435	390	19,609	1,961	63
254	1,280	34	4,226	4,083	2,854	30,424	602	208	1,435	231	18,941	1,979	63
255	1,268	34	4,228	4,085	2,855	30,424	602	208	1,435	234	18,909	1,991	63
256	907	34	4,231	4,031	2,800	15,964	277	208	1,435	124	16,067	1,485	63

257	905	34	4,230	4,031	2,800	10,706	275	112	1,435	292	15,286	943	63
258	1,084	34	4,118	3,974	2,800	1,504	273	112	1,435	234	10,742	364	63
259	1,084	34	4,118	3,974	2,800	1,504	272	112	1,435	234	10,726	364	63
260	1,017	27	3,916	1,304	1,681	1,365	295	65	1,040	232	10,377	385	63
261	941	27	3,916	1,304	1,681	1,365	294	65	1,040	234	10,217	385	63
262	869	27	3,916	1,304	1,681	1,365	294	65	1,040	236	10,018	385	63
263	1,208	27	3,916	1,358	1,735	12,022	636	161	1,040	350	13,270	1,234	63
264	1503	27	4027	1415	1736	16996	636	161	1040	408	19111	1827	63
265	1490	27	4029	1416	1737	16996	636	161	1040	411	18766	1841	63
266	1480	27	4031	1418	1738	16996	636	113	1040	243	18066	1850	63
267	1470	27	4032	1419	1739	16996	636	113	1040	244	18053	1860	63
268	1029	27	4034	1362	1681	9181	292	113	1040	130	14958	1449	63
269	788	27	4036	1363	1681	6339	290	65	1040	307	14059	1033	63
270	548	27	3916	1304	1681	1365	288	65	1040	249	8911	385	63
271	538	27	3916	1304	1681	1365	285	65	1040	250	8815	385	63

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
272	531	35	5,575	9,741	1,894	1,470	142	44	565	241	8,836	421	288
273	522	35	5,575	9,670	1,894	1,470	139	44	565	242	8,740	421	288
274	577	35	5,575	9,609	1,894	1,470	139	44	565	242	8,703	421	288
275	1,034	35	5,692	15,456	1,958	14,527	249	93	565	355	12,731	1,344	288
276	1,524	35	6,118	20,705	1,958	20,621	249	93	565	418	19,739	2,041	288
277	1,541	35	6,115	20,411	1,957	20,621	249	93	565	414	19,369	2,023	288
278	1,521	35	6,118	19,646	1,957	20,621	249	68	565	241	18,537	2,043	288
279	1,513	35	6,121	19,635	1,957	20,621	249	68	565	241	18,538	2,051	288
280	1,034	35	6,005	14,194	1,894	11,045	139	68	565	130	15,099	1,591	288
281	773	35	6,007	14,329	1,894	7,563	139	44	565	306	14,237	1,134	288
282	788	35	5,575	9,344	1,894	1,470	139	44	565	238	9,120	421	288
283	775	35	5,575	9,357	1,894	1,470	139	44	565	238	9,087	421	288
284	937	30	5,330	8,455	1,392	1,612	154	107	903	338	10,363	414	219
285	937	30	5,330	8,610	1,392	1,612	154	107	903	335	10,632	414	219
286	937	30	5,330	8,610	1,392	1,612	154	107	903	321	11,890	414	219
287	1,426	30	5,330	8,753	1,497	9,649	303	279	903	478	18,064	1,369	219
288	1,449	30	5,650	8,895	1,498	13,668	303	279	903	589	29,530	1,859	219
289	1,435	30	5,657	8,897	1,500	13,668	303	279	903	597	28,859	1,872	219
290	1,409	30	5,660	8,894	1,501	13,668	303	193	903	335	27,426	1,899	219

291	1,394	30	5,661	8,891	1,501	13,668	303	193	903	335	27,426	1,914	219
292	923	30	5,660	8,686	1,392	7,640	154	193	903	177	21,571	1,399	219
293	817	30	5,664	8,635	1,392	5,630	154	107	903	444	20,104	947	219
294	794	30	5,330	8,466	1,392	1,612	154	107	903	333	10,802	414	219
295	937	30	5,330	8,610	1,392	1,612	154	107	903	327	11,313	414	219
296	522	29	5,484	8,801	2,005	1,026	145	185	887	392	11,978	436	222
297	522	29	5,484	8,793	2,005	1,026	145	185	887	392	11,987	436	222
298	522	29	5,484	8,723	2,005	1,026	145	185	887	394	11,798	436	222
299	1,012	29	5,503	9,809	2,140	8,688	251	513	887	583	20,434	1,416	222
300	1,012	29	5,964	10,788	2,142	12,170	251	513	887	725	35,422	1,906	222
301	1,012	29	5,971	10,735	2,143	12,170	251	513	887	730	34,165	1,906	222
302	1,012	29	5,964	10,606	2,142	12,170	251	349	887	395	32,422	1,906	222
303	1,012	29	5,971	10,600	2,143	12,170	251	349	887	398	32,375	1,906	222
304	522	29	5,957	9,467	2,005	5,901	145	349	887	207	24,814	1,416	222
305	522	29	5,962	9,438	2,005	4,508	145	185	887	543	23,346	926	222

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
306	522	29	5,484	8,296	2,005	1,026	145	185	887	402	11,051	436	222
307	522	29	5,484	8,392	2,005	1,026	145	185	887	399	11,362	436	222
308	697	23	6,397	9,435	3,653	1,175	150	97	804	525	10,245	459	151
309	697	23	6,362	9,429	3,653	1,175	150	97	804	526	10,146	459	151
310	697	23	6,351	9,497	3,653	1,175	150	97	804	524	10,400	459	151
311	1,084	23	9,684	16,410	3,747	8,897	181	248	804	895	16,097	1,414	220
312	1,095	23	13,441	22,605	3,748	12,758	181	248	804	992	26,681	1,801	221
313	1,095	23	13,366	22,307	3,748	12,758	181	248	804	992	25,829	1,801	222
314	1,092	23	12,867	21,390	3,749	12,758	181	173	804	530	24,572	1,804	222
315	1,076	23	12,859	21,385	3,749	12,758	181	173	804	532	24,552	1,819	223
316	675	23	9,536	15,108	3,653	6,967	150	173	804	162	19,245	1,244	224
317	702	23	9,864	15,132	3,653	5,036	150	97	804	628	18,300	846	151
318	669	23	5,837	9,016	3,653	1,175	150	97	804	533	9,560	459	151
319	631	23	5,761	8,951	3,653	1,175	150	97	804	534	9,402	459	151
320	640	31	6,997	9,883	2,777	1,179	155	109	1,690	920	13,848	474	157
321	840	31	6,958	9,918	2,777	1,179	155	109	1,685	919	13,944	474	157
322	839	31	6,942	9,976	2,777	1,179	155	109	1,688	918	13,981	474	157
323	1,277	31	18,518	23,000	3,077	6,404	191	281	3,065	1,438	33,073	1,485	393
324	1,472	31	30,830	34,566	3,076	8,778	191	281	3,134	1,733	67,279	1,924	393

325	1,472	31	30,585	34,041	3,072	8,778	191	281	2,929	1,717	64,669	1,924	392
326	1,472	31	28,959	32,370	3,075	8,778	191	195	2,862	913	60,749	1,924	391
327	1,472	31	28,970	32,365	3,076	8,778	191	195	2,863	917	60,697	1,924	391
328	1,017	31	18,228	21,171	2,777	4,504	155	195	1,844	399	44,239	1,326	391
329	913	31	19,391	21,276	2,777	3,554	155	109	1,780	1,221	41,174	942	157
330	939	31	7,205	10,514	2,777	1,179	155	109	1,714	916	14,228	474	157
331	962	31	7,308	10,787	2,777	1,179	155	109	1,721	908	14,985	474	157
332	797	35	8,677	10,476	2,988	866	226	83	1,527	1,304	18,716	512	135
333	797	35	8,729	10,536	2,988	866	226	83	1,527	1,303	18,789	512	135
334	797	35	8,794	10,642	2,988	866	226	83	1,527	1,301	18,994	512	135
335	1,156	35	27,832	20,263	3,464	7,409	273	207	1,527	2,074	48,848	1,381	529
336	1,178	35	48,107	28,773	3,466	10,680	273	207	1,527	2,559	103,566	1,740	529
337	1,178	35	47,713	28,427	3,467	10,680	273	207	1,527	2,564	99,237	1,740	530
338	1,171	35	44,940	27,041	3,469	10,680	273	145	1,527	1,317	92,954	1,747	531
339	1,178	35	44,920	27,042	3,466	10,680	273	145	1,527	1,312	93,035	1,740	532

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
340	819	35	26,889	18,165	2,988	5,773	233	145	1,527	544	66,631	1,219	533
341	768	35	28,826	18,434	2,988	4,137	234	83	1,527	1,801	61,687	884	135
342	699	35	8,186	9,847	2,988	866	233	83	1,527	1,321	17,163	512	135
343	678	35	8,068	9,736	2,988	866	232	83	1,527	1,322	17,044	512	135
344	455	34	7,578	10,629	4,120	1,093	254	62	926	1,358	16,703	553	120
345	455	34	7,480	10,565	4,120	1,093	252	62	926	1,359	16,604	553	120
346	455	34	7,381	10,499	4,120	1,093	250	62	926	1,360	16,500	553	120
347	750	34	24,663	25,592	4,594	6,459	609	62	926	2,182	47,175	1,291	476
348	750	34	43,453	39,074	4,594	8,936	609	62	926	2,655	101,785	1,585	477
349	750	34	43,092	38,361	4,595	8,936	609	62	926	2,657	97,505	1,585	478
350	750	34	40,576	36,325	4,595	8,936	609	62	926	1,361	91,327	1,585	478
351	750	34	40,568	36,320	4,595	8,936	609	62	926	1,362	91,318	1,585	479
352	455	34	24,117	22,823	4,120	4,808	249	62	926	541	64,776	1,143	480
353	455	34	25,886	23,157	4,120	3,569	249	62	926	1,839	59,992	848	120
354	455	34	6,845	10,068	4,120	1,093	249	62	926	1,364	16,113	553	120
355	455	34	6,779	10,005	4,120	1,093	249	62	926	1,365	16,046	553	120
356	484	36	6,795	6,007	2,067	1,022	183	56	873	1,230	15,804	480	102
357	484	36	6,775	6,007	2,067	1,022	183	56	873	1,232	15,651	480	102
358	484	36	6,778	6,007	2,067	1,022	183	56	873	1,230	15,801	480	102

359	691	36	24,408	7,919	2,517	6,571	380	56	873	1,928	45,817	998	467
360	691	36	42,951	9,442	2,512	9,132	380	56	873	2,360	98,011	1,205	465
361	691	36	42,604	9,404	2,506	9,132	380	56	873	2,335	94,120	1,205	462
362	691	36	40,140	8,998	2,499	9,132	380	56	873	1,186	88,626	1,205	458
363	691	36	40,204	8,981	2,502	9,132	380	56	873	1,191	88,548	1,205	455
364	484	36	24,450	7,129	2,067	4,864	183	56	873	499	64,211	894	452
365	484	36	26,273	7,478	2,067	3,583	183	56	873	1,636	59,608	687	102
366	484	36	8,491	5,991	2,067	1,022	183	56	873	1,208	17,887	480	102
367	484	36	8,374	5,992	2,067	1,022	183	56	873	1,214	17,325	480	102
368	503	36	7,952	10,261	5,701	878	172	246	1,196	1,244	18,056	523	97
369	503	36	7,795	10,055	5,610	878	176	246	1,196	1,247	17,809	523	97
370	503	36	7,655	9,962	5,551	878	179	246	1,196	1,248	17,740	523	97
371	828	36	23,490	18,227	8,346	5,545	317	617	1,196	1,937	50,699	1,336	420
372	828	36	40,774	25,571	9,089	8,057	317	617	1,196	2,582	109,251	1,661	421
373	828	36	40,451	25,229	8,864	8,057	317	617	1,196	2,591	104,722	1,661	421

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
374	828	36	38,172	24,085	8,856	8,057	317	432	1,196	1,405	98,155	1,661	422
375	828	36	38,159	24,081	8,850	8,057	317	432	1,196	1,409	98,139	1,661	423
376	503	36	22,969	16,474	6,054	4,468	182	432	1,196	719	69,972	1,173	424
377	503	36	24,546	16,756	5,612	3,391	180	246	1,196	1,921	64,362	848	97
378	503	36	6,862	9,431	5,251	878	178	246	1,196	1,258	16,788	523	97
379	503	36	6,764	9,395	5,209	878	176	246	1,196	1,258	16,710	523	97
380	454	41	7,185	10,640	5,192	918	169	153	2,690	1,209	16,384	530	88
381	454	41	7,090	10,633	5,147	918	169	153	2,683	1,210	16,294	530	88
382	454	41	6,994	10,623	5,115	918	169	153	2,677	1,210	16,274	530	88
383	787	41	26,704	26,183	6,819	9,705	169	266	6,627	1,869	49,571	1,361	487
384	787	41	49,530	40,649	7,212	14,099	169	266	7,022	2,447	108,875	1,694	488
385	787	41	49,127	39,942	7,090	14,099	169	266	6,427	2,450	104,381	1,694	488
386	787	41	46,320	37,878	7,089	14,099	169	210	6,228	1,292	97,911	1,694	489
387	787	41	46,316	37,872	7,087	14,099	169	210	6,227	1,293	97,902	1,694	489
388	454	41	27,621	23,972	5,396	7,822	169	210	3,241	635	69,534	1,195	489
389	454	41	29,646	24,416	5,273	5,311	169	153	3,049	1,777	64,415	863	88
390	454	41	6,855	10,934	5,142	918	169	153	2,660	1,201	17,212	530	88
391	454	41	6,939	10,960	5,156	918	169	153	2,662	1,202	17,123	530	88
392	571	44	7,417	10,162	5,496	791	151	235	1,795	1,415	19,441	632	114

393	571	44	7,381	10,027	5,441	791	151	235	1,795	1,417	19,211	632	114
394	571	44	7,319	9,917	5,399	791	151	235	1,795	1,418	19,118	632	114
395	934	44	30,338	22,094	9,111	8,617	187	442	1,795	2,163	60,912	1,541	572
396	934	44	56,465	33,375	10,113	12,530	187	442	1,795	2,990	136,018	1,904	573
397	934	44	56,003	32,860	9,808	12,530	187	442	1,795	2,993	130,376	1,904	573
398	934	44	52,781	31,188	9,808	12,530	187	338	1,795	1,622	122,248	1,904	574
399	934	44	52,775	31,186	9,807	12,530	187	338	1,795	1,623	122,244	1,904	574
400	571	44	30,959	20,134	6,231	6,940	151	338	1,795	879	86,629	1,359	575
401	571	44	33,255	20,684	5,806	4,704	151	235	1,795	2,233	80,114	995	114
402	571	44	7,099	10,244	5,439	791	151	235	1,795	1,408	20,088	632	114
403	571	44	7,207	10,298	5,455	791	151	235	1,795	1,409	20,010	632	114
404	826	50	7,842	10,723	2,371	851	163	153	3,417	1,853	22,765	647	153
405	807	50	8,051	10,604	2,371	851	163	153	3,418	1,855	22,544	647	153
406	783	50	8,313	10,506	2,371	851	163	153	3,415	1,856	22,483	647	153
407	1,190	50	34,835	26,036	3,112	10,859	187	174	8,422	2,919	73,314	1,624	673

Table C.1.1 Pumping by county, continued

Stress Period	Austin	Bosque	Brazos	Burleson	Falls	Fort Bend	Grimes	Hill	McLennan	Milam	Robertson	Waller	Washington
408	627	45	4,248	5,805	3,356	753	264	191	1,023	36	8,996	258	71
409	930	45	4,248	5,805	3,512	6,097	600	534	1,023	36	14,677	2,176	71
410	1,528	45	4,248	5,805	3,506	8,102	600	534	1,023	36	24,028	2,393	71
411	1,484	45	4,248	5,805	3,509	8,102	600	534	1,023	36	23,872	2,438	71
412	1,464	45	4,248	5,805	3,510	8,102	600	362	1,023	36	22,484	2,457	71
413	1,446	45	4,248	5,805	3,511	8,102	600	362	1,023	36	22,471	2,476	71
414	1,129	45	4,248	5,805	3,356	2,757	264	362	1,023	36	17,788	1,525	71
415	795	45	4,248	5,805	3,356	2,757	264	191	1,023	36	15,399	575	71
416	458	45	4,248	5,805	3,356	753	264	191	1,023	36	8,906	258	71
417	463	45	4,248	5,805	3,356	753	264	191	1,023	36	8,902	258	71
418	476	49	4,287	6,282	3,779	818	245	147	1,198	37	8,775	273	71
419	483	49	4,287	6,282	3,779	818	245	147	1,198	37	8,782	273	71
420	478	49	4,287	6,282	3,779	818	245	147	1,198	37	8,774	273	71
421	760	49	4,287	6,282	3,918	6,328	658	405	1,198	40	13,924	1,810	71
422	1,340	49	4,287	6,282	3,918	8,395	658	405	1,198	40	23,125	2,466	71
423	1,478	49	4,287	6,282	3,907	8,395	658	405	1,198	40	23,007	2,328	71
424	1,457	49	4,287	6,282	3,906	8,395	658	276	1,198	37	21,867	2,349	71
425	1,379	49	4,287	6,282	3,911	8,395	658	276	1,198	37	21,814	2,428	71
426	1,126	49	4,287	6,282	3,779	2,884	245	276	1,198	35	17,701	1,669	71

427	1,184	49	4,287	6,282	3,779	2,884	245	147	1,198	37	16,012	800	71

No pumping is simulated in Bastrop, Bell, Brazoria, Burnet, Colorado, Coryell, Freestone, Hamilton, Harris, Lampasas, Lee, Leon, Limestone, Madison, Mills, Montgomery, Travis, Wharton, or Williamson counties in the BRAA from stress periods 2 to 427.

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Appendix D

Comments and Responses
for
Review of "Draft Numerical Model for the Brazos River Alluvium Aquifer Groundwater Availability Model" Report and deliverables for TWDB Contract No. 1348301620 dated March 2016

Comments and Responses
for
Review of "Draft Numerical Model for the Brazos River Alluvium Aquifer Groundwater Availability Model" Report and deliverables for TWDB Contract No. 1348301620 dated March 2016

Attachment 1

The following report and data review comments shall be addressed and included in the final deliverables due August 31, 2016.

Draft Numerical Model Report comments:

Specific comments to be addressed

1. Section 1.1, Paragraph 2, Page 1-1 and Figure 1.0.3, Page 1-5: The text in Section 1.1 describes Figure 1.0.3 by referencing counties; therefore, please update the figure with county labels so text and figure agree.
   Done.
2. Section 2.1, Pages 2-5 to 2-6: Per the Contract Exhibit A, Page 15 of 180 (page 10 of the SOQ), paragraph 3, a flux would be estimated from the existing models for the relevant aquifers below the Brazos River Alluvium and the flux would be applied to the boundary of layer 3. A code for automating the process would be supplied to the TWDB. Please elaborate on justification for making the base of the model a no-flow boundary and please elaborate on implications and limitations of this assumption.
   Additional text and figures have been added to these sections discussing how the assumption of a no-flow boundary appears to be adequate for the historical period of this model based on analyses of downdip flow in the underlying GAMs being a minimal component of the historical water balance. This assumption may not be valid for predictive scenarios involving increased pumping. A tool has now been provided to the TWDB that accounts for the impacts of flow between the shallow and deep portions of the underlying formations. The tool extracts flows from the three underlying GAMs and adds them to the well package for the BRAA GAM.
3. Table 2.2.1, Page 2-19: the model files indicate stress period 1 (steady-state) was 10 days however Table 2.2.1 indicates stress period 1 was 1 day. Please adjust table so it agrees with the model.
   Table updated.
4. Figures 2.2.2a and 2.2.2b, Pages 2-26 and 2-27: it is difficult to distinguish between colors used and when photocopied it is even more difficult. Per Exhibit B, Attachment 3, Page 3 of 8, Section 2.2.2: please adjust the color scale or use grayscale with variation or patterns to distinguish units.

The figures have been converted to grayscale and the bounds adjusted to better distinguish units.

5. Table 2.3.2, Page 2-31: Please verify the following values in the table and adjust if necessary:
    a. Kh mean for layer 3, we get 17.7 feet per day (not 23.8),
    A different analyst with a brand new script confirmed INTERA's calculation of 23.8 feet per day. We can reproduce TWDB's calculation of 17.7 feet per day if we don't account for model grid cell size by doing a simple arithmetic average.
    b. Kv min for layer 3 we get 1.307e-03 (not 1.67e-03),
    The new script confirms TWDB's calculation of 1.307e-03 feet per day.
    c. Kv max for layer 3 we get 1.607e-01 (not 2.41e-01), and
    The new script confirms TWDB's calculation of approximately 1.607e-01 feet per day (we get 1.608e-01 this time).
    d. Kv mean for layer 3 we get 1.725e-02 (not 2.38e-02).
    The new script confirms INTERA's calculation of approximately 2.38e-02 feet per day (we get 2.34e-02 this time). We can reproduce TWDB's calculation of 1.725e-02 feet per day if we don't account for model grid cell size by doing a simple arithmetic average. The layer 3 hydraulic conductivities have been altered per TWDB request following submittal of the Draft Numerical Model Report and Table 2.3.2 has been updated appropriately. Since the new script agrees with one or the other of the independent calculations, it has been used to populate the revised table.
6. Table 2.3.2 and Figures 2.3.3, 2.3.4, 2.3.6, and 2.3.7: Horizontal and vertical conductivity values appear to match exactly in layers 1 and 2. Per Exhibit B, Attachment 1, Page 11 of 33, Section 3.2.1: to simulate the vertical flow in the alluvium, at least two numerical layers should be used. Previous presentations, discussions, and conceptual model (Figures 2.2.6a to 2.2.6e) indicated a fining upward trend; however the properties in the model do not reflect this conceptualization and data. Please expand Section 2.3.2 to discuss reasoning for maintaining two layers and using the same properties in both layers.
Additional text has been added to Section 2.3.2 to explain how we could find no quantitative basis to discriminate between the properties in layers 1 and 2 from either water level data or well logs. The use of two layers allows for the simulation of vertical gradients within the Brazos River Alluvium Aquifer in the regions (predominantly near the Brazos River) where vertical gradients are likely to exist.
7. Table 2.3.2 (Page 2-31), Figure 2.3.2, Figure 2.3.4, and Figure 2.3.5 (Pages 2-33 to 2-36):
    a. The text discusses adjustments to hydraulic conductivity because the bulk of the underlying aquifers were not modeled. Properties used in the underlying units (layer 3) in the draft model do not reflect previous models, data from the conceptual model, nor the differences between confining units and aquifers. At a minimum please adjust the model so the values for confining units are significantly lower than the aquifers.
    The hydraulic properties of the underlying formations have been altered from those in the draft numerical model report based on comments to better reflect

a hierarchical distinction between confining units and aquifers. As such, sub-catchment area recharge had to be adjusted such that baseflow targets were met while, at the same time, flooding in layer 3 cells was kept within an acceptable range.

b. Please provide justification in the text for adding the alluvial channels to the hydraulic properties for the underlying units as noted in Figure 2.3.2. These were not shown in the conceptual model report and may act as high flow conduits in the model as the cells are 200 feet thick. Please re-evaluate and adjust as needed in the report and model.
Text to justify considering alluvium in layer 3 has been added to Section 2.3.1. A composite hydraulic conductivity that includes the properties of both the alluvium and the underlying formation was used. This is considered an improvement in the numerical model compared to that described in the conceptual model.

c. The purpose of this model is to analyze the availability of groundwater under various predictive scenarios. Please provide sufficient supporting documentation that the model can be used as intended or re-calibrate the model as needed so the objective and purpose of the model can be achieved.
A tool has been provided to the TWDB that accounts for the impacts of flow between the shallow and deep portions of the underlying formations. The tool extracts flows from the three underlying GAMs and adds them to the well package for the BRAA GAM. This has a small impact on the BRAA GAM during the historical period. If predictive simulations involve significant pumping in the underlying aquifers, this tool should be used to account for that impact on the BRAA GAM. Section 2.4.5 has been added to the report to discuss this tool. In addition, the revised hydraulic properties of the underlying units reflect a marked difference between “aquifer” and “confining unit” values (see revised Figures 2.3.5 and 2.3.8). This should eliminate concerns of the “confining units” inaccurately capturing pumping from the deeper portions of the underlying aquifers. Additional text has been added to section 2.3 to describe the approach to defining aquifer properties.

8. Figure 2.3.2, Page 2-33, Property Zones: Please order legend in stratigraphic (age) order rather than alphabetical order.
Done.

9. Sections 2.4.3 and 2.4.4, Pages 2-42 to 2-43:
   a. Please clarify if prior to using the cropland dataset that an analysis of reviewing TWDB Groundwater database for capped, unused, and second[ary] water use of wells was performed for additional well locations.
   We did not use capped or unused wells in distributing pumping.
   b. Please update the report with the reasoning for using a 10-mile radius (versus any other distance) for well locations for cropland as that seems to be an excessive distance to build a pipeline for irrigation purposes.
   Additional text and rationale for using a 10-mile radius for assigning crop types to irrigation wells was added to the report. The intention is not to suggest that a 10-mile pipeline has been built anywhere but rather that

proximity to known crop types is as good of a method as any to assign crop types to a given irrigation well.

c. Please clarify if a buffer was used around the Brazos River or other perennial streams when assigning pumping irrigation using the cropland dataset approach. Please clarify if any assumptions were explored or used such as assuming croplands near the rivers used surface water or some other buffer analysis using irrigation water right locations.

   No buffer was used. Pumping was applied to wells of a given use type. If not enough wells were found to handle the production rates without drying out, the excess pumping was spread out beneath irrigated cropland based on saturated thickness at very small cell-by-cell rates of less than 1 acre-foot per year. Because the rates were so small, we were not concerned further about location. We had no way to distinguish between surface water or groundwater irrigated land and proximity to the river was not considered a guarantee of surface water irrigation.

d. Please clarify if pumping for irrigation from 1980 to 2012 assumed cropland distribution as noted in 2008 (Figure 2.4.2) for the additional well locations analyses or if other years of cropland datasets were used (if so please provide years and references).

   The cropland coverage from 2008 was the earliest year available and was assumed the most representative of the historical period. This single distribution was used for all stress periods.

e. For municipal pumping, please confirm that an attempt to call the municipal users to confirm well locations was performed prior to using centroid of cities.

   At its highest, municipal pumping constitutes less than 1% of the pumping in the aquifer. We deemed that resources could be better spent on other, more important aspects of the model than the precise location of municipal pumping. If the municipal wells were in the TWDB groundwater database, they were used. If not, we considered the city centroid adequate.

f. Per the well file provided, no pumping was applied outside the Brazos River Alluvium in Layer 3. Please discuss the reasoning for this in the report and any implications for predictive simulations for the desired future condition process.

   Water levels in the outcrops of the underlying aquifers have not declined historically. Accordingly, the effect of shallow pumping on the BRAA can be considered negligible. Additional text was added to the report to explain this. The effect of deep pumping in the underlying aquifers is accounted for in the tool provided as part of the Final Numerical Model. This tool should be used for predictive simulations.

10. Figures 2.4.1 and 2.4.2, Pages 2-44 and 2-45: per Exhibit B, Attachment 3, Page 3, Section 4.0 (Citations and references) of the contract, please update figures 2.4.1 and 2.4.2 with the associated citation of source and please update the reference section as required and needed.

    Done.

11. Figure 2.4.3, Page 2-46:

   a. Please discuss pumping distributed to injection well(s) in the text and please confirm an injection well was completed in the relatively shallow Brazos River Alluvium Aquifer and adjust figure as needed.
      We did not distribute any pumping to injection wells since there was no injection use in the water use survey. The injection wells have been removed from the dataset and the figure.
   b. Please provide citation and reference for the well locations.
      Done.

12. Section 2.5, Paragraph 1, Page 2-55:
   a. Text refers to Figure 2.1.4[a-e] for locations of drains; however, the legend in these figures does not reference drains. So that text and figures agree, please update figure legends or captions to note that: Springs/ DRN, Evapotranspiration/ EVT, Perennial Stream/ SFR, and Ephemeral Stream/ RIV.
      Done.
   b. Please clarify in text the justification for lowering drain elevations by 10 feet as opposed to lowering the elevation by 1 to 20 feet. For example, a DEM analysis was performed, DEM elevations were compared to topographic elevations, or another approach was used (please provide associated datasets in the geodatabase).
      The choice of 10 feet is on the same order of magnitude as the mean absolute error (6.5 feet) for the steady-state model in the Brazos River Alluvium Aquifer. This clarification was added to Section 2.5.
13. Section 2.6.1, Page 2-57: Text states distribution of steady state recharge was not altered from the conceptual model; however, the pattern and volume of recharge from Figure 4.3.10 (Ewing and others, 2016) does not match Figure 2.6.1 in the numerical model report. For example, the conceptual model shows pre-development recharge in the Brazos River Alluvium in Fort Bend County is between 0.5 to 1.5 inches per year in two zones and the numerical model has one zone with 2 to 3 inches per year. Please update text to discuss adjustments to recharge for pre-development.
    The steady-state recharge was adjusted in both the Brazos River Alluvium and the underlying formations from the estimates in the conceptual model to match stream baseflow targets. The text in the report has been corrected to reflect this.
14. Section 2.6.2, Page 2-57, Transient Recharge: Please elaborate on the method for adjusting transient recharge. The descriptions in this section are brief and unclear. For example, please expand on the implementation of the step function (was it applied every stress period until Figure 4.3.11 in the conceptual model was achieved), please discuss implementation of focused recharge due to mining (discussed in the conceptual model report), and please discuss how temporal and step function application of irrigation return flow and focused recharge due to mining were implemented. Since we cannot just use average recharge from the transient calibration or use average precipitation to develop predictive files, the assumptions used must be fully understood and the process transparent.
    A significant amount of additional text has been added to Section 2.6.2 to clarify how recharge was distributed temporally in the transient model and how the impacts of focused recharge from mining and irrigation return flow were incorporated.

Specifically, the portions of recharge resulting from precipitation, mining, and irrigation return flow are broken out so that a consistent method can be used to develop predictive recharge rates.

15. Section 2.9, Page 2-67, and Figure 2.9.1:
    a. The text states that the maximum evapotranspiration rate is based on the coverage provided in the TWDB study (Scanlon and others, 2005). Figure 4.10 from that study shows maximum evapotranspiration estimates for Texas ranging from 19 to 66 inches per year. However, Figure 2.9.1 of this report gives a range of less than one to 65 inches per year for the estimates of maximum evapotranspiration. Please clarify the reasoning for adjustments to the Scanlon and others (2005) estimates or please discuss in the text of the report the basis for the maximum evapotranspiration estimates.
    The maximum evapotranspiration rate in a given model cell was area-weighted based on the various vegetation types in that cell. If no vegetation was present in a portion of a cell, the maximum evapotranspiration rate for that cell would be expected to be less than the value for a given vegetation type. Additional text was added to Section 2.9 to clarify this.
    b. The conceptual model discusses evapotranspiration and crops (pages 2.1-5 to 2.1-8, Figures 2.1.14 to 2.1.16). The land cover distribution (Figure 2.1.14) shows very little "forest" along the stream channels although the text states authors assumed areas adjacent to streams are assumed locations of riparian zones. Please discuss in Section 2.9 of the numerical model report the reasoning for not applying EVT to crops as detailed in the conceptual report. Several of the hydrographs indicated water levels were within 5-10 feet of land surface.
    The average depth to water in the Brazos River Alluvium is approximately 20 feet. It tends to be deeper than that in the inter-stream topographical highs and nearer to land surface in the topographical lows where the riparian EVT cells and other surficial boundary conditions for perennial and ephemeral streams are present. The vegetation types shown in Figure 2.1.14 of the conceptual model were used to define the area-weighted maximum evapotranspiration rates (a product of PET and crop coefficients) and rooting depths for the riparian EVT cells. Additional text was added to Section 2.9 to clarify this. Crops are conceptualized to involve primarily vadose zone ET with excess infiltration conceptualized as irrigation return flow as documented in the recharge section of the conceptual model report. Accordingly, no ET was applied to cells containing irrigated cropland conceptualized to recharge the aquifer. This approach is consistent with the conceptual model.
16. Section 3.2, Page 3-7, Paragraph 2, Sentence 3: Please discuss in more detail why transient targets were not used for the underlying formations.
    Additional text has been included in Section 3.2 discussing the rationale for not including transient targets for the underlying formations.
17. Figure 3.2.2, Page 3-13: Please clarify in the text of the report why targets located in Freestone County that appear outside the active model were used.
    The targets were used because they actually are inside the active model area. If one does a "select by location" using the "Active Model Area" coverage in ArcGIS using

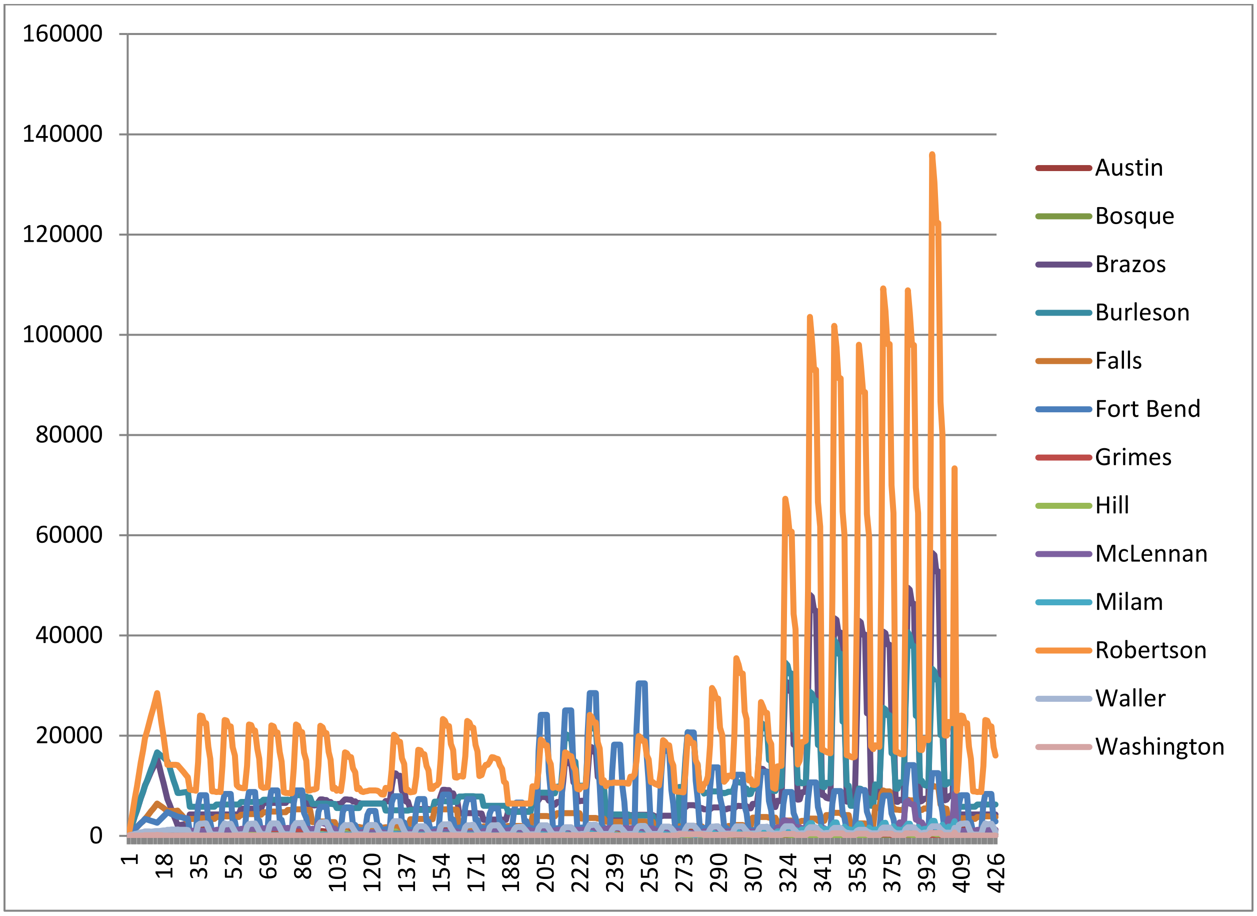
the MXD file provided as part of the data model, this should be apparent. No changes to the text were made.

18. Figure 3.2.15, Page 3-26: Scatter plot for 1980 to 2012 suggest bias in Burleson and Brazos counties with low heads and high heads in Fort Bend County.
    You actually have it backwards (low versus high) but the small locational bias is noted. Model calibration requires that hydraulic properties remain constant throughout time (barring subsidence which is not an issue in this model). Recharge was varied temporally about a steady-state average based on variations in precipitation. These biases are relatively small and not apparent in the 1950 to 1979 period which has significantly more targets than the 1980 to 2012 period (3,732 versus 1,346 targets). This suggests the calibrated properties are honoring measured data in the best way possible (targets were weighted equally in PEST and were unbiased) and there is no reason to suggest temporal bias in the model.
19. Figures 3.2.24 and 3.2.25, Pages 3-35 to 3-36: Please update caption with baseline year (steady-state) for the change in water level elevations.
    Done.
20. Section 3.3.1, Page 3-39, Paragraph 1: Section 4.4.2, Page 4.4-20 of the Conceptual Model Report states of the thirteen springs located in the extent of the Brazos River Alluvium, 11 of them have flow data available. Please discuss in the text of the Numerical Model Report the reasoning for only using 3 or 5 of the 11 springs as targets.
    The Conceptual Model Report counted springs labeled as "former spring" or "trickle" as having 1 measurement when there actually was no measurement. The text in Section 4.4.2 and Table 4.4.15 of the Conceptual Model Report have been corrected. There are actually only 5 springs in the Brazos River Alluvium that have flow measurements in the historical period of the model. Two of the springs have proximal locations and it is difficult to distinguish their locations as being separate in Figure 3.3.2. One spring was missing in the draft version of the figure and has been added back. Additional text has been added to Section 3.3.1 to clarify this.
21. Figure 3.3.2, Page 3-42 and Figure 3.3.4, Page 3-44: Figure 3.3.2 shows 3 locations of springs; however Figure 3.3.4 shows 5 springs. Please clarify in the text of the report the number of springs used as targets.
    There are 5 springs in the Brazos River Alluvium that have flow measurements in the historical period of the model. Two of the springs have proximal locations and it is difficult to distinguish their locations as being separate in Figure 3.3.2. One spring was missing in the draft version of the figure and has been added back. Additional text has been added to Section 3.3.1 to clarify this.
22. Section 3.3.2 Cross-Formational Flow, Page 3-40: The model primarily indicates upward flow into the Brazos River Alluvium from the units below; however, the underlying units do not include pumping and the base of layer 3 is a no-flow boundary so the effects of deeper pumping are not accounted for. One of the stated objectives of the research project from the project RFQ was:
    > *"In addition, any interactions with underlying aquifers should be assessed and modeled accordingly. One of the objectives for the model is to be able to accurately predict different pumping scenarios and how large pumping in one of the hydraulically connected aquifers may affect the system."*

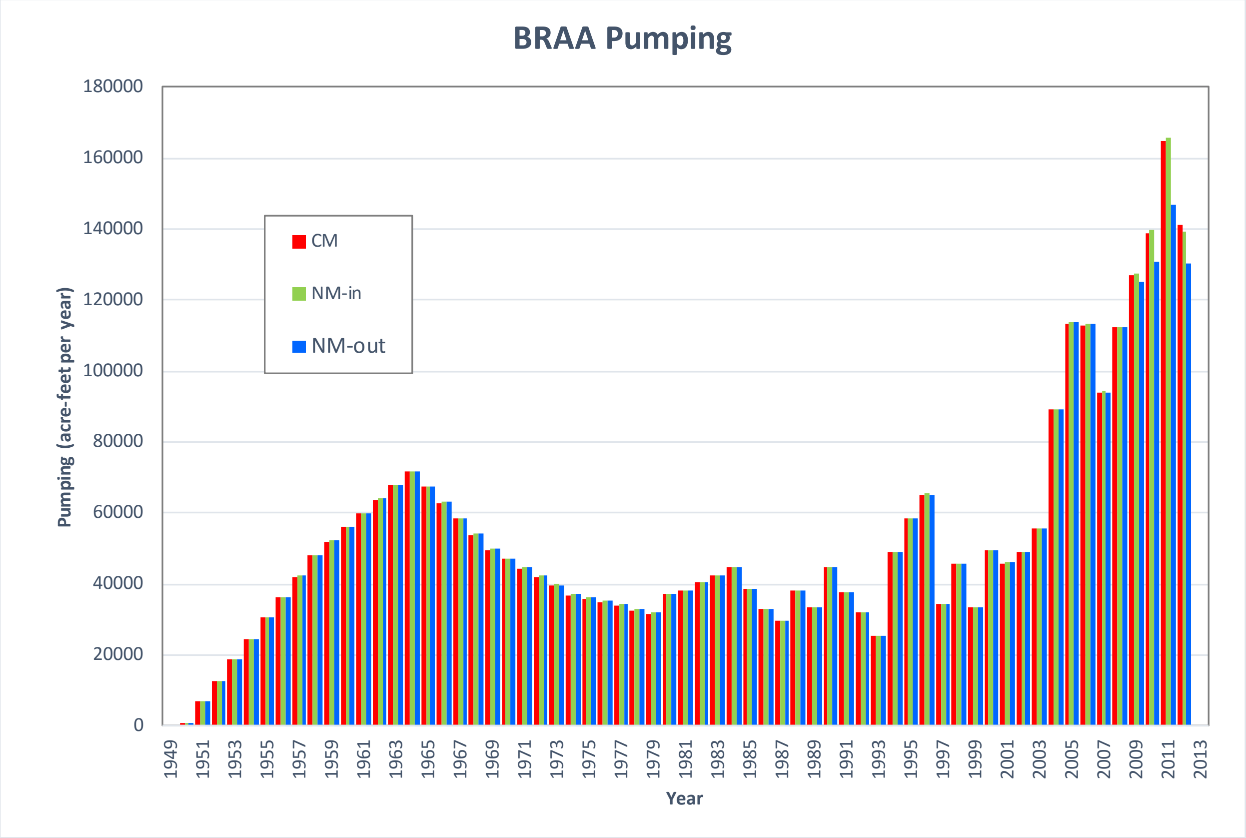
Please discuss in the text how this objective is addressed. In addition, please discuss why lateral flow was not part of the model design. Layers 1 and 2 only exchange flow at the base of the cells according to the model files.
See response to comment 8.d and response to comment 17. Based on the results of running the tool to incorporate downdip fluxes from the underlying models as flow through the base of layer 3, downdip pumping has had a minimal impact on flow through the base of layer 3 during the historical period. Additionally, there is no evidence of significant drawdown in the surficial portions of the underlying formations to warrant pumping in layer 3 during the historical period. As noted in the responses to the aforementioned comments, text has been added to the report to clarify these conditions.

23. Section 3.4.1, Page 3-52, Paragraph 1: Please update references to Figure 3.4.1b for the steady-state for the area around Bryan-College Station, TX to Figure 3.4.1c.
    Text has been changed to refer to the south-central region of the model shown in Figure 3.4.1c.
24. Section 3.5, Tables 3.5.2, 3.5.3, and 3.5.4 Transient Water Budgets: According to the water budget the largest percentage of discharge from the system is to ephemeral streams in the underlying formations, followed by discharge to perennial streams in the underlying formations. Please review the stream conductance values and the hydraulic conductivity values under the ephemeral streams in layer 3 to verify that they are reasonable and adjust as needed.
    The stream conductances were assigned based on widths applied in a hierarchical manner based on Strahler order and are consistent to each other in this respect. The BRAA is only 6% of the areal footprint of the model and streams are the major avenue of discharge for groundwater in the Brazos River Basin. It is, therefore, no surprise that discharge to streams in layer 3, which constitutes 94% of the areal footprint in the model, is the largest component of outflow in the model-wide water balance. This is why we provided separate water balance tables for the BRAA, which is the focus of this study.
25. Section 5.2, pages 5-2 and 5-3:
    a. Please discuss the limitations of assuming a no-flow boundary at the base of the model and please discuss the limitations of assuming no effects from pumping in the underlying formations.
       See responses to comments 8.d, 17 and 23. Additional text has been included in this section to clarify the minimal impacts of these assumptions to the transient model. To be clear, there is no longer a no-flow boundary at the base of the model. A tool to connect the BRAA with the underlying formations has been built and provided as part of the final model.
    b. Please discuss any limitations as it relates to statutory required modeling, such as water budgets for groundwater conservation districts, total estimated recoverable storage, estimating modeled available groundwater from desired future conditions (and application of pumping in layer 3).
       By providing a tool with which to include additional predictive pumping to both the shallow and deep portions of the underlying formations, there should be no significant limitations to meeting these requirements. Additional text has been added to the report to reflect this.

26. Tables A.1.2, A.2.2, and A.2.3, Appendix A: Please note all counties that are partially contained with the model.
    Additional text was added to the introductory paragraph to clarify which counties are fully contained within the model.
27. Appendix C: Review of the pumping in the model looks unusual from stress period 323 to 406. Please confirm units and please clarify if this pumping appears reasonable. Pumping does not match conceptual model figures for pumping.



The main reason the rates look different from the conceptual model in the plot above is that monthly stress periods were used from 1980 through 2012 and growing/irrigation seasons were considered in the model. This means that months during the growing season have higher than average pumping while other months have lower than average pumping. When pumping is averaged annually as in the chart below, the conceptual model (CM) and numerical model (NM-in and NM-out) are in agreement. The NM-in values are extracted from the WEL package and the NM-out values are extracted from the LST file. Noticeable deviations occur only in the NM-out values for the high pumping rates in the last four years of the historical period where the automatic flow reduction option in MODFLOW-USG curtailed pumping when the simulated heads were near the bottom of the model layer at pumping locations. This reduction was a maximum of 10% in 2011 which is considered acceptable given the uncertainty in pumping estimates.



Draft Numerical Model comments:

28. The attributed model grid file only contained information for the uppermost cells. TWDB staff re-evaluated the grid attributes to include all grid cells, which was necessary for the review process. Please use the TWDB attributed grid file for all model analysis.
    Request confirmed.
29. Per Exhibit B, Attachment 1, Page 11 of 33, Section 3.2 Model Architecture of the Contract: the final model shall be fully compatible with Groundwater Vistas. As noted in the “Notes on importing USG into GWV.docx” delivered with the Groundwater Vistas files, it appears the transition of MODFLOW files into Groundwater Vistas was not fully successful. Please coordinate with TWDB staff as they have successfully implemented the MODFLOW-USG code into Groundwater Vistas for the groundwater availability model for the minor aquifers in the Llano Uplift Area. In addition, staff has implemented all packages except for SFR into Groundwater Vistas for the draft Brazos River Alluvium model. Transferring the files takes up to a week and another week for verification.
    INTERA contacted TWDB staff immediately following the discovery of the issues regarding the inability of Groundwater Vistas to import its own exports for MODFLOW-USG along with other major deficiencies in Groundwater Vistas

regarding MODFLOW-USG and prior to delivering the Draft Numerical Model. Subsequent to submittal of the draft report, TWDB staff were successful in importing the model into Groundwater Vistas.

30. Please provide groundwater vistas map files: BrazosAlluvium.map, Extent.map, and AlluviumExtent.map
    Done.
31. Please load transient and steady-state targets into Groundwater Vistas.
    Done.

Final Conceptual Model comments:

32. Per Article III, item 5 (A) of the contract, 4 printed copies of the final conceptual report will be delivered to the TWDB no later than the Study Completion Date. We did not receive any printed copies of the final conceptual report.
    We provided electronic copies of the Final Conceptual Model Report on March 31, 2016 and will provide printed copies on August 31, 2016 along with the printed copies of the Final Numerical Model Report.
33. Section 4.6: Per Exhibit A (SOQ), Page 19 of 180 of the contract, National Agricultural Statistics Service (NASS) imagery will be used to distribute irrigation pumping .Please explain in either the conceptual model report or in the numerical model report whether the imagery was used to distribute irrigation pumping. If the imagery was not used please explain why not. If the imagery was used please clearly note this and please use the appropriate references.
    Reference to the National Agricultural Statistics Service (2015) has been added to the figure caption for Figure 2.4.2 as well as the references section of the report. This coverage was used in applying crop types to irrigation wells when adjusting seasonal pumping during monthly stress periods in the numerical model.

Final geodatabase comments to be addressed

34. Please include feature datasets within the NumericalModelSrc feature class and their associated metadata or please remove the feature class.
    All feature datasets are included in the NumericalModelFigure feature class and the NumericalModelSrc feature class has been removed.
35. Please include raster datasets within the NumericalModelRasters raster catalog and their associated metadata or please remove the raster catalog.
    The NumericalModelRasters raster catalog has been removed. All figures now reference datasets in the NumericalModelFigure feature class.
36. Please provide metadata including field descriptions and units of measure as applicable for the br_ssobs_xy_0315_0802 feature dataset.
    Done.
37. Please provide metadata including field descriptions and units of measure as applicable for the br_trobs_xy_0315_0802 feature dataset.
    Done.
38. Please provide metadata including field descriptions and units of measure as applicable for the br_trobs_xy_1950_1979 feature dataset.

Done.

39. Please provide metadata including field descriptions and units of measure as applicable for the br_trobs_xy_2012_0315_0930 feature dataset.
    Done.
40. Please provide metadata including field descriptions and units of measure as applicable for the braa_grid_bas_dis_lpf feature dataset.
    Done.
41. Please provide metadata including field descriptions and units of measure as applicable for the braa_grid_drn feature dataset.
    Done.
42. Please provide metadata including field descriptions and units of measure as applicable for the braa_grid_evt feature dataset.
    Done.
43. Please provide metadata including field descriptions and units of measure as applicable for the braa_grid_rch feature dataset.
    Done.
44. Please provide metadata including field descriptions and units of measure as applicable for the braa_grid_riv feature dataset.
    Done.
45. Please provide metadata including field descriptions and units of measure as applicable for the braa_grid_sfr feature dataset.
    Done.
46. Please provide metadata including field descriptions and units of measure as applicable for the BrazosRiverFlux feature dataset.
    Done.
47. Please provide metadata including field descriptions and units of measure as applicable for the Centroids_w_Well_Info feature dataset.
    Done.
48. Please provide metadata including field descriptions and units of measure as applicable for the crops_grid feature dataset.
    Done.
49. Please provide metadata including field descriptions and units of measure as applicable for the crops_grid2 feature dataset.
    Done.
50. Please provide metadata including field descriptions and units of measure as applicable for the dry_flooded_grid feature dataset.
    Done.
51. Please provide metadata including field descriptions and units of measure as applicable for the dry_flooded_grid2012 feature dataset.
    Done.
52. Please provide metadata including field descriptions and units of measure as applicable for the FlowInOutStreams feature dataset.
    Done.
53. Please provide metadata including field descriptions and units of measure as applicable for the hds_sswl_braa_contour feature dataset.
    Done.

54. Please provide metadata including field descriptions and units of measure as applicable for the hds_sswl_l3_contours feature dataset.
    Done.
55. Please provide metadata including field descriptions and units of measure as applicable for the hds_wl_1960_contours feature dataset.
    Done.
56. Please provide metadata including field descriptions and units of measure as applicable for the hds_wl_1980_contours feature dataset.
    Done.
57. Please provide metadata including field descriptions and units of measure as applicable for the l3_ssobs_xy_0315_0802 feature dataset.
    Done.
58. Please provide metadata including field descriptions and units of measure as applicable for the Lyr3_property_zones feature dataset.
    Done.
59. Please provide metadata including field descriptions and units of measure as applicable for the NorthernXSection feature dataset.
    Done.
60. Please provide metadata including field descriptions and units of measure as applicable for the PilotPoints feature dataset.
    Done.
61. Please provide metadata including field descriptions and units of measure as applicable for the SouthernXSection feature dataset.
    Done.
62. Please provide metadata including field descriptions and units of measure as applicable for the SpringCellPts feature dataset.
    Done.
63. Please provide metadata including field descriptions and units of measure as applicable for the WellsNode_GAM feature dataset.
    Done.
64. Please provide metadata including field descriptions and units of measure as applicable for the XFormationalFlow feature dataset.
    Done.
65. Please remove redundant feature datasets unless there is a difference between the crops_grid and crops_grid2 or between the dry_flooded_grid and dry_flooded_grid2012.
    Done.
66. Please provide River Ware Model time series flow data used for model calibration along with metadata that includes units and key field to join with spatial feature datasets within the SurfaceHydro feature class
    Done. As described in Section 2.7.1, this flow data was used as input to the SFR package. It was not used as calibration data.

General suggestions for Final Draft geodatabase

67. Please consider providing an additional folder of mxd files associated with the final draft geodatabase for comparison of figures in the final numerical model report to the data in the geodatabase for the NumericalModelFig feature class.
    Done.

Public Comments:

We did not receive any public comments.

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