# *APPENDIX B*
# *Surface Water–Groundwater Interaction in the Central Carrizo-Wilcox Aquifer*

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## B-1.0 Introduction

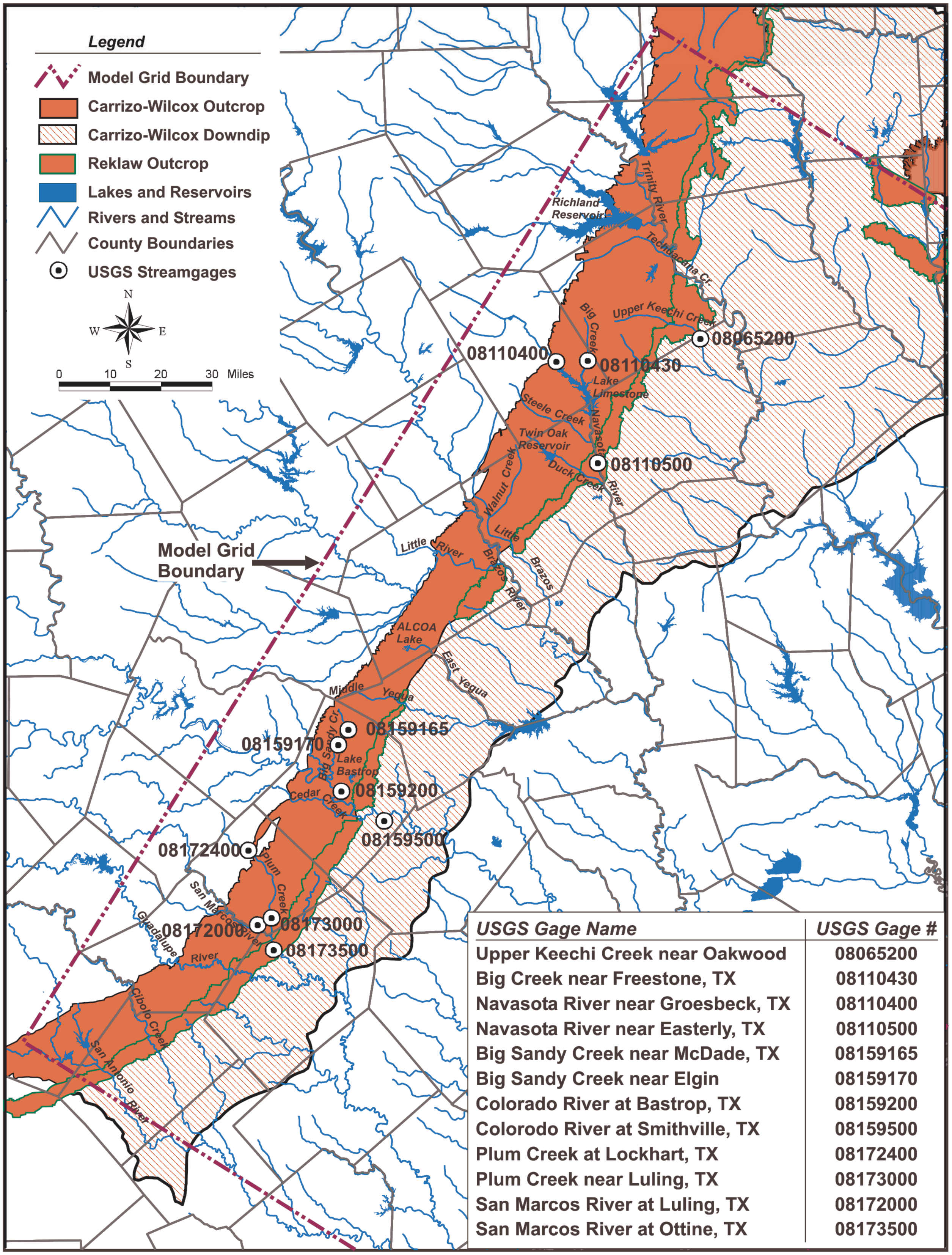
Herein we present the approach and findings of a study on the interaction between surface water and groundwater (SW/GW) in the central Carrizo-Wilcox aquifer and the simulation of this interaction in the Groundwater Availability Model (GAM). The geographic scope of this investigation focuses on the aquifer between the San Antonio River and the Trinity River. Rivers and streams were represented using the Stream Package of MODFLOW, while lakes and reservoirs were represented using the Reservoir Package of MODFLOW.

The following creeks and rivers were represented in the model (fig. B-1):

- San Antonio River
- Cibolo Creek
- Guadalupe River
- San Marcos River
- Plum Creek
- Cedar Creek
- Colorado River
- Big Sandy Creek
- Middle Yegua Creek
- East Yegua Creek
- Little River
- Brazos River
- Little Brazos River
- Walnut Creek
- Duck Creek
- Steele Creek
- Navasota River
- Big Creek
- Upper Keechi Creek
- Tehuacana Creek
- Trinity River

The following lakes and reservoirs were also represented in the model (fig. B-1):

- Braunig Lake
- Calaveras Lake
- Lake Bastrop
- Alcoa Lake
- Twin Oaks Reservoir
- Lake Limestone
- Richland-Chambers Reservoir
- Fairfield Lake
- Cedar Creek Reservoir




| USGS Gage Name | USGS Gage # |
|---|---|
| Upper Keechi Creek near Oakwood | 08065200 |
| Big Creek near Freestone, TX | 08110430 |
| Navasota River near Groesbeck, TX | 08110400 |
| Navasota River near Easterly, TX | 08110500 |
| Big Sandy Creek near McDade, TX | 08159165 |
| Big Sandy Creek near Elgin | 08159170 |
| Colorado River at Bastrop, TX | 08159200 |
| Colorodo River at Smithville, TX | 08159500 |
| Plum Creek at Lockhart, TX | 08172400 |
| Plum Creek near Luling, TX | 08173000 |
| San Marcos River at Luling, TX | 08172000 |
| San Marcos River at Ottine, TX | 08173500 |

Figure B-1. Central Carrizo GAM surface-water feature.

There are two primary goals of this investigation. The first is to compile physical data and to calculate parameters for all streams and reservoirs simulated and to incorporate these data and parameters into the model framework. The second is to estimate calibration/verification targets for SW/GW interaction within the model domain for use from 1980 through 2000. The methodology for these analyses is described in the following sections.

## B-2.0 Surface Water-Groundwater Interaction

### B-2.1 Physical Processes and Measurement

Streams and aquifers interact on the aquifer's outcrop. If the water table is above the streambed and slopes toward the stream, the stream is receiving groundwater from the aquifer and is called a gaining reach (i.e., it gains flow as it moves through the reach). If the water table is below the streambed and slopes away from the stream, the stream is losing water to the aquifer and is called a losing reach. In some cases, streams have an intermittent base flow, which is usually associated with wet winter conditions and dry, hot summer conditions. For large rivers such as the Colorado, Brazos, and Trinity, there are significant alluvium deposits that buffer the stream from direct connection with the regional aquifer. (The Brazos Alluvium is significant enough to be classified as one of the minor aquifers of the state.) Because of the regional scale of the GAM and because insufficient data were available to quantify the interaction between the Carrizo-Wilcox and the alluvium, the system was modeled as having direct interaction between the Carrizo-Wilcox and the stream.

As the Carrizo-Wilcox aquifer dips below the land surface and becomes confined, it loses the potential to interact with surface water; thus, all significant interaction occurs in the outcrop. We therefore represented streams only in the outcrop cells of the model, and data for consideration in the analysis were limited to sources located on or near the aquifer outcrop.

Results were applied to both gaged and ungaged watersheds in the outcrop cells of the model to develop targets for the model calibration.

Reservoirs also have a significant impact on the local groundwater regime. As reservoirs are filled, impounded water leaks into the underlying geologic formations until equilibrium between the reservoir water level and the surrounding water table is achieved.

### B-2.2 MODFLOW Representation of SW/GW Interaction

Both the stream package and the reservoir package in MODFLOW use similar algorithms to simulate interaction between groundwater and surface water. For a given model cell, a surface-water elevation is assigned to the stream or reservoir, and this water level is compared with the calculated head in the aquifer. If the water level in the stream or reservoir is greater than the head in the aquifer, water will flow from the surface-water body into the aquifer as a function of the conductance of the bed sediments and the difference in heads. If the head in the aquifer is greater than the water level of the surface-water body, water will flow from the aquifer to the stream (fig. B-2). The quantity of flow in either direction is calculated by

$$Q=C*dh \qquad (1)$$

where Q = discharge ($L^3/T$), C is conductance of streambed or reservoir sediments ($L^2/T$), and dh is difference in head between the surface water and groundwater (L). Conductance is a lumped parameter calculated by

$$C=KLW/M \qquad (2)$$

where K is hydraulic conductivity (L/T), L is length of stream (or reservoir) reach in grid cell (L), W is width of stream (or reservoir) reach in grid cell (L), and M is thickness of streambed or reservoir sediments (L).

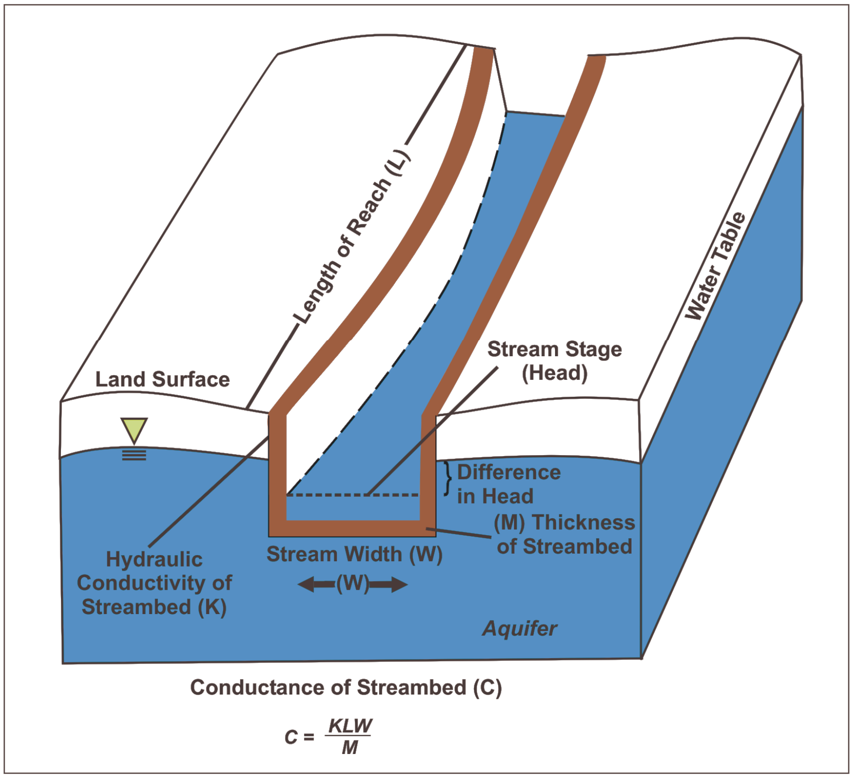



Figure B-2. MODFLOW representation of surface-water–groundwater interaction.

These parameters were assigned as follows. Length of individual stream reaches in each grid cell was measured on 1:24,000-scale USGS Topographic Quadrangle maps using an ArcView utility. Width was estimated using several methods. For major rivers, published USGS data on river width at gaging stations (Slade, 2002) was referenced; an average of the widths from the nearest upstream and downstream gages was used throughout the outcrop reach. For smaller streams, in which the width varied significantly throughout the reach, widths were increased from a few feet in the headwaters to a few tens of feet at the downstream end. Hydraulic conductivity and streambed thickness were initially estimated at 1 ft/d and 1 ft, respectively; however, it was anticipated that conductance values would be adjusted during calibration.

For reservoir simulation, any grid cell with more than half the cell area covered by surface water in TWDB GIS coverage was represented in the Reservoir Package. Reservoir representation assumes that the entire grid cell is subject to inundation (i.e., no partial inundation is simulated), so the length and width of reservoir cells default to the full dimensions of the grid cell. Average land-surface elevations were derived from topographic maps, while average water surface in the reservoirs was obtained from USGS hydrologic records.

## B-3.0 Methods to Estimate Interaction of Surface Water and Groundwater

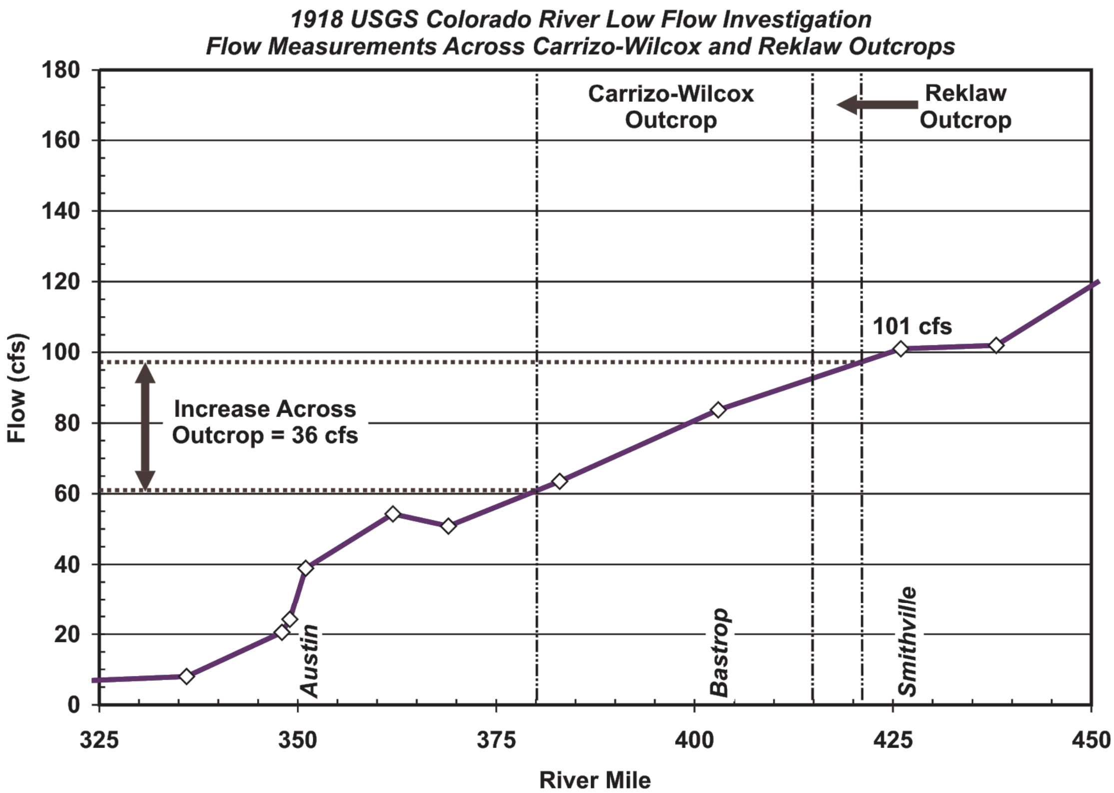
Two methods were employed to characterize SW/GW interaction in the model domain. In the first, details of historical low flow studies conducted on any streams across the Carrizo-Wilcox aquifer within the model domain were reviewed. In the second, data from stream gages located on the outcrop were analyzed using techniques of base-flow separation to obtain quantitative estimates of groundwater discharge to the streams.

B-3.1 Low-Flow Studies

The first method of investigation into Carrizo-Wilcox groundwater–surface-water interaction was to examine historical low-flow studies that had been conducted by the USGS or other agencies on rivers or streams that crossed the outcrop of the Carrizo-Wilcox aquifer. Low-flow studies involve performing flow measurements at many locations on a stream within a short period of time, when flows are low and no significant surface runoff is occurring in the study reach. One low-flow study was conducted on the Colorado River in 1918. Low-flow studies were conducted on Cibolo Creek in 1949, 1963, and 1968. Although, in most cases, the specific locations of the outcrop boundaries were not identified in the original data, comparison of recorded river mile data with known landmarks allowed identification of the approximate boundaries of the aquifer outcrop in these studies.

Figures B-3 and B-4 depict the results of these low-flow studies. In all four studies, the flow increased as the stream crossed the aquifer outcrop, indicating gaining conditions at the time the studies were performed.

In the 1918 Colorado River study, the flow increased from about 61 to 97 cfs across the aquifer outcrop, an increase of 36 cfs (fig. B-3a). The flow at the Smithville gage during this study was 101 cfs. For comparison with historical flows, a flow-duration curve was generated for daily flows at the Smithville station (fig. B-3b), and the flow of 101 cfs is exceeded 99.9 percent of the time (in fact, only 16 daily flows out of 17,573 were lower than 101 cfs). This figure indicates that even during conditions of extremely low flow, the Colorado River is still a gaining reach across the outcrop of the Carrizo-Wilcox aquifer. The flow increase documented in the 1918 study may be compared with the results obtained from the model to estimate the low end of



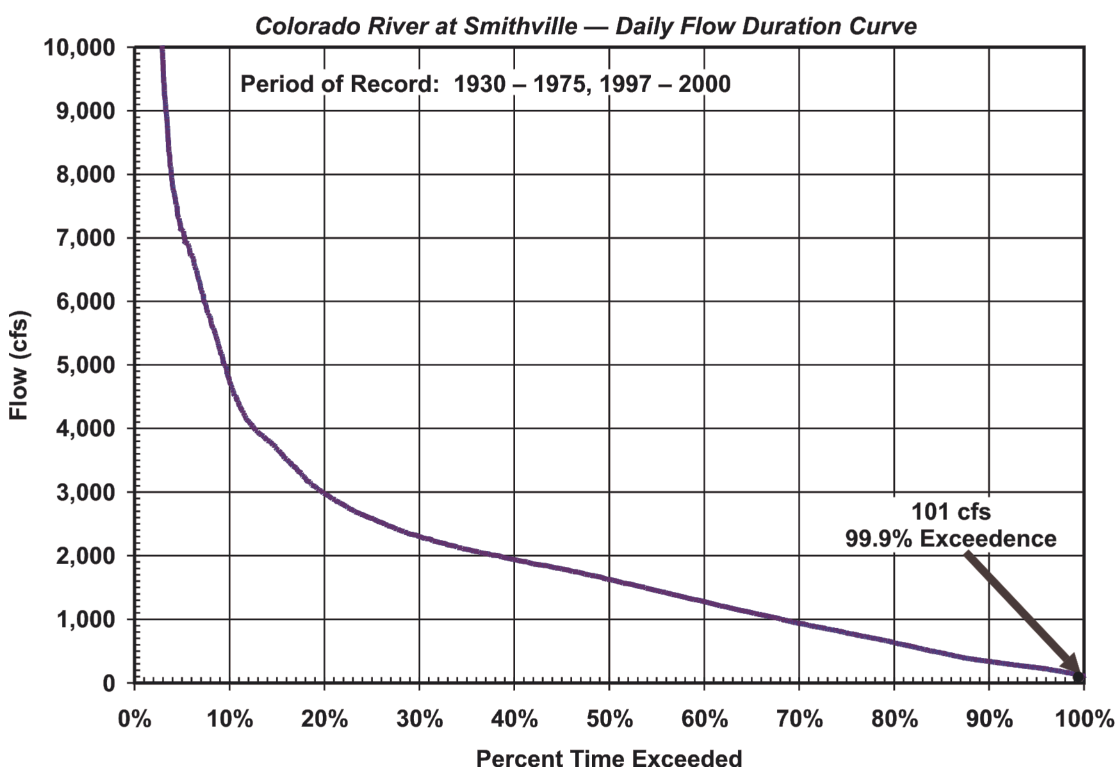
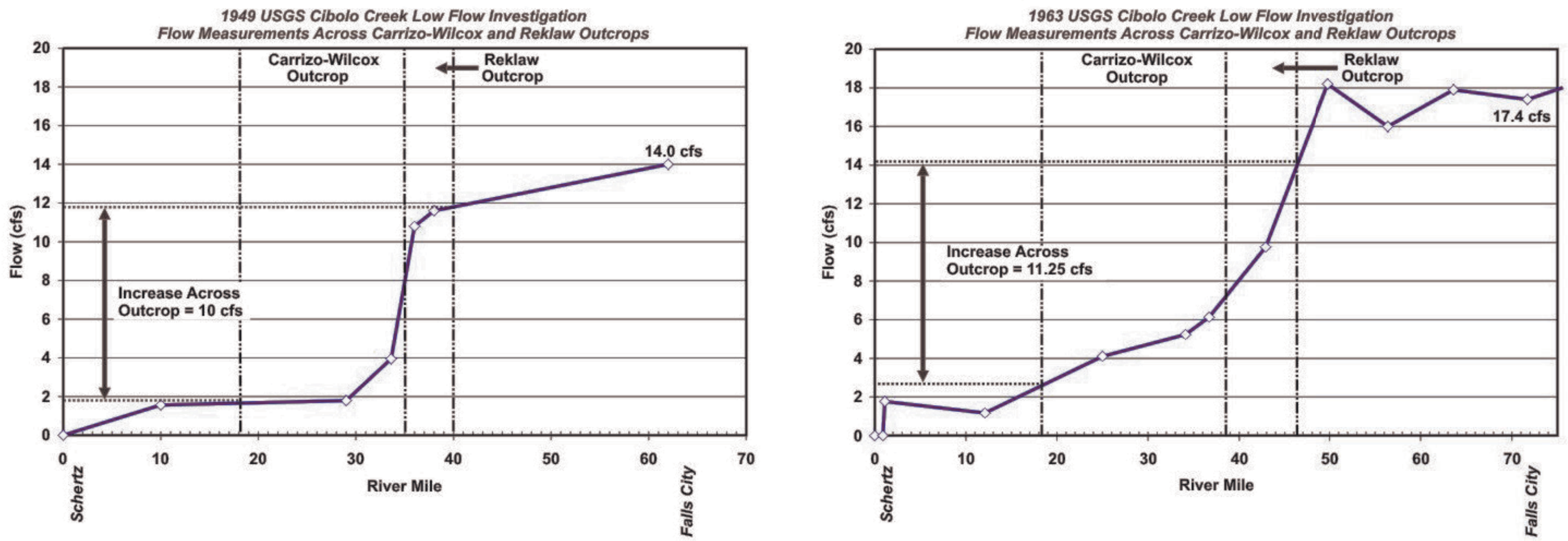




Figure B-3. Colorado River low-flow investigation.




Note: Variation between studies in Schertz – Falls City river distance reflects original data.

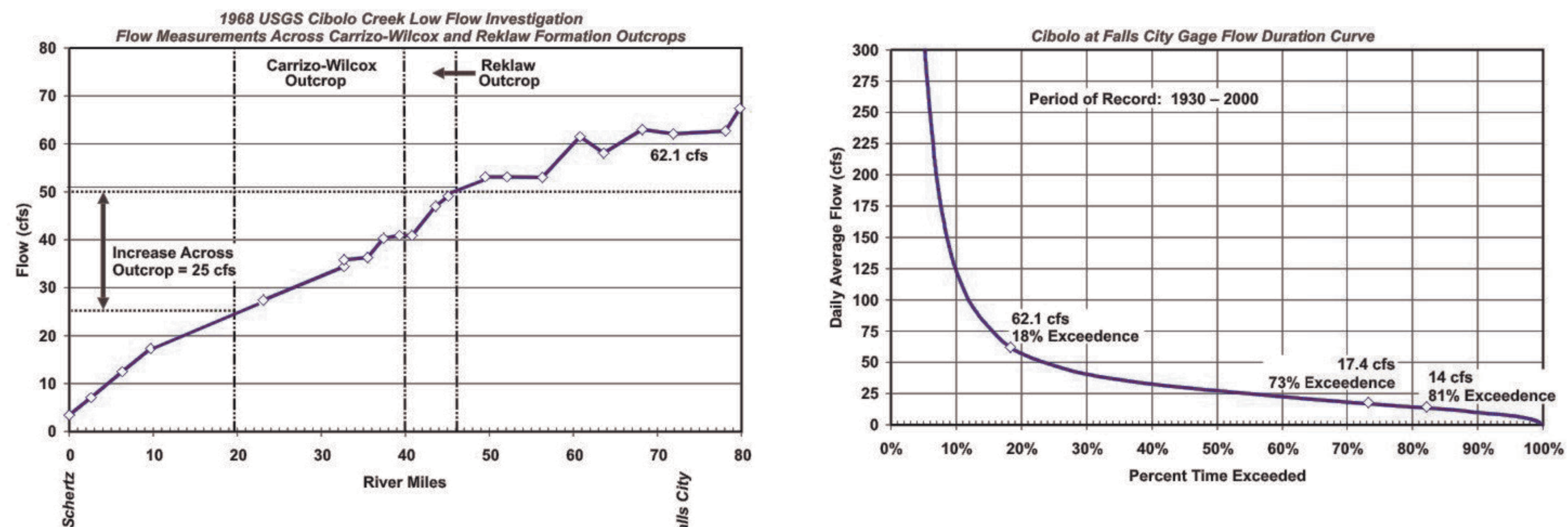



*Figure B-4. Cibolo Creek Low Flow Investigations* groundwater discharge in the Colorado River across the outcrop (i.e., few, if any, modeled aquifer discharge quantities should be less than this value).

In the Cibolo Creek studies, the flow increases across the outcrop were about 10 cfs (0.38 cfs/mi) in the 1949 study (fig. B-4a), 11.25 cfs (0.5 cfs/mi) in the 1963 study (fig. B-4b), and 25 cfs (1 cfs/mi) in the 1968 study (fig. B-4c). Examination of a daily-flow duration curve generated for the Falls City stream gage (fig. B-4d) indicates that these studies spanned a wide range of flow conditions. For example, in the 1949 study, flow at Falls City was 14.0 cfs, a daily value that is exceeded 81 percent of the time, indicating fairly low-flow conditions. By contrast, in the 1968 study, flow at Falls City was 62.1 cfs, a daily value that is exceeded only 18 percent of the time, indicating relatively higher flow conditions. Therefore, Cibolo Creek is consistently gaining on the outcrop over this wide range of flow conditions. Although no studies exist during extreme low-flow conditions (as on the Colorado), these data indicate that Cibolo Creek may be expected to be a gaining reach during most conditions, and the specific quantities of discharge from the aquifer to the stream documented in these studies may be compared to the results obtained from the model on Cibolo Creek to check for consistency.

### B-3.2 Base-Flow Studies

The portion of a stream's flow that is not directly influenced by runoff is considered to be its base flow. Unlike other water-budget components such as pumping, it is a cumulative result from a diffuse source over all the bed and banks of the stream in the watershed. It is therefore not directly measurable. Base flow is determined using graphical techniques for separation of base flow from the total stream flow. For this project, base-flow separation was performed on daily flow data using the Base Flow Index (BFI) program, jointly maintained by the USGS and U.S. Bureau of Reclamation (Wahl and Wahl, 2001). BFI uses the Standard Hydrologic Institute Method for base-flow separation; this method identifies sudden rises in the hydrograph typical of storm-induced runoff and separates the total stream flow into daily time series of base flow and storm flow for each gage. Figure B-5 presents an example of this process on data from Big Sandy Creek at McDade. It is important to note that this is an approximate method and that for any given day the program may under- or overpredict base flow, although the long-term accuracy of the method is commonly accepted.

In order to quantify the amount of groundwater discharge provided to streams by the Carrizo-Wilcox aquifer in the model domain, the following methodology was used. Stream-flow records were reviewed to determine all gages historically located on or near the aquifer outcrop. These data were narrowed to identify any combination of stream gages that specifically bracketed flow on the Carrizo-Wilcox outcrop. By isolating stream reaches located entirely on the outcrop, the influence of hydrologic factors external to the base flow from the Carrizo aquifer was minimized. Outcrop-specific stream reaches may be defined using one of three types of gage arrangements, as depicted in the schematic drawings in figure B-6. In Type 1, only one gage is necessary for a headwater watershed located on the outcrop (a, fig. B-6) (i.e., all of the contributing watershed area is above a single gage and is located on the outcrop, as in the case of Big Creek near Freestone and Upper Keechi Creek near Oakwood). In Type 2, two gages on the same stream may define an outcrop reach (b, fig. B-6) if both gages are located near the outcrop boundaries and all or most of the intervening drainage area is located on the outcrop, as in the case of Navasota River, Big Sandy Creek, and Plum Creek. Finally, in Type 3, three gages may

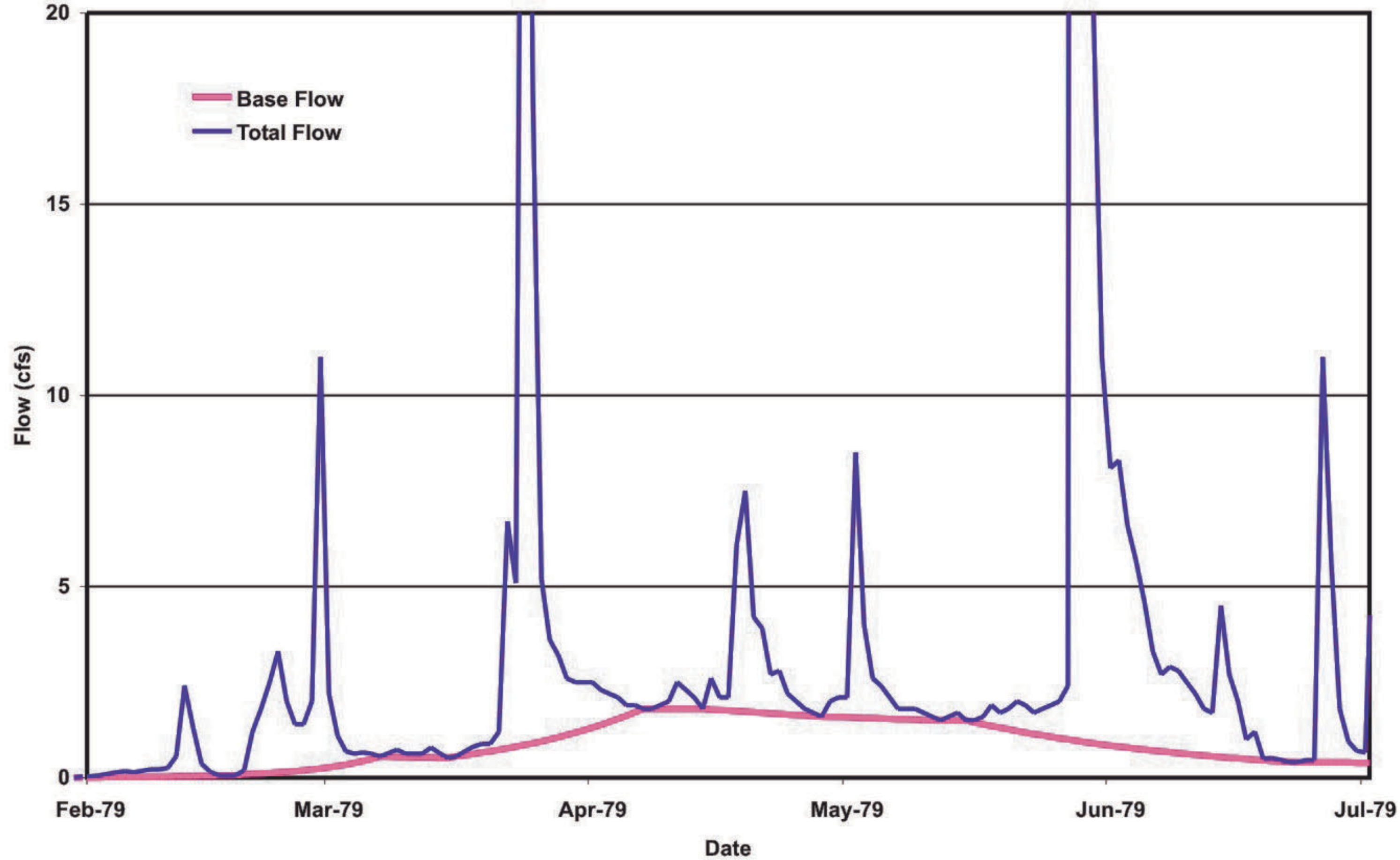



*Figure B-5. Baseflow Separation — Big Sandy Creek near McDade, TX*

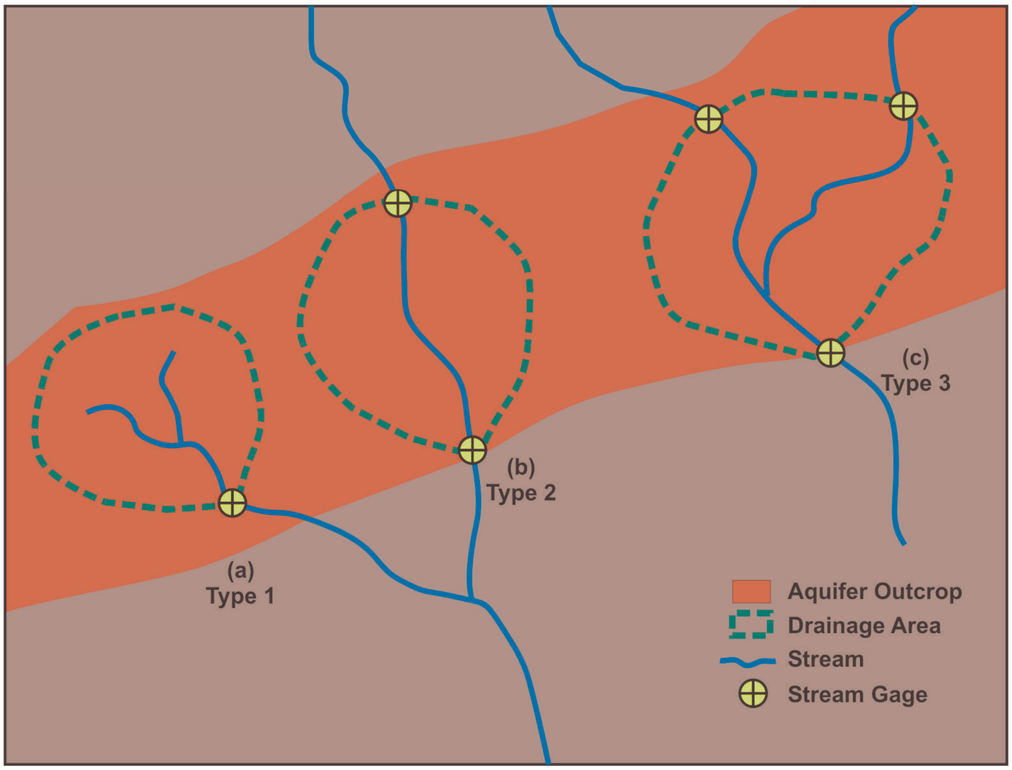



Figure B-6. Schematic stream-gage configurations for estimating base flow.

be used (c, fig. B-6) if all three reaches of a stream confluence are gaged, as in the case of the San Marcos River/Plum Creek confluence.

The stream gages used to define the study reaches are summarized in table B-1, and presented in figure B-1. The study reaches identified that meet the previously described criteria to estimate base-flow gains and losses on the Carrizo-Wilcox outcrop are presented in table B-2.

A brief description of the unique aspects of each reach and its associated gages analyzed within the framework of this investigation follows.

- Upper Keechi Creek (Type 1). Gage #08065200: Upper Keechi near Oakwood, TX. Period of record May 1962–September 2000. This reach has its headwater drainage located entirely on the outcrops of the Carrizo-Wilcox and Reklaw Formations. It is an intermittent stream. The gage is located near the downstream extent of the Reklaw Formation.

- Big Creek (Type 1). Gage #08110430: Big Creek near Freestone, TX. This reach has its headwaters on the Carrizo-Wilcox outcrop and is an intermittent stream. This gage was established to monitor inflows into Lake Limestone from Big Creek.

- Navasota River (Type 2). Upstream Gage #08110400: Navasota River near Groesbeck, TX. Downstream gage #08110500: Navasota River near Easterly, TX. The Easterly gage is located near the downstream edge of the Reklaw Formation. The Groesbeck gage is located near the upstream extent of the aquifer. It was discontinued and moved farther upstream in 1979 in association with the construction of the dam that created Lake Limestone.

Table B-1. Stream-gage summary.

| USGS gage name | USGS gage number | Drainage area ($mi^2$) | Gage datum (fsl) | Period of record |
|---|---|---|---|---|
| Upper Keechi Ck near Oakwood, TX | 08065200 | 150 | 240.11 | 5/1/62-9/30/01 |
| Big Ck near Freestone, TX | 08110430 | 97 | 362.94 | 7/1/78-9/30/00 |
| Navasota Rv near Groesbeck, TX | 08110400 | 311 | 358.84 | 3/1/65-4/30/79 |
| Navasota Rv near Easterly, TX | 08110500 | 968 | 271.46 | 4/1/24-9/30/00 |
| Big Sandy Ck near McDade TX | 08159165 | 39 | 422 | 7/13/1979-9/30/85 |
| Big Sandy Ck near Elgin, TX | 08159170 | 64 | 392 | 7/12/79-9/30/85 |
| Colorado Rv at Bastrop, TX | 08159200 | 28576 | 307.38 | 3/1/60-9/30/00 |
| Colorado Rv at Smithville, TX | 08159500 | 28968 | 270.14 | 8/1/30-9/24/75, 10/6/97-9/30/00 |
| Plum Ck at Lockhart, TX | 08172400 | 112 | 431.19 | 5/1/59-9/30/01 |
| Plum Ck near Luling, TX | 08173000 | 309 | 321.27 | 4/1/30-9/30/01 |
| San Marcos Rv at Luling, TX | 08172000 | 838 | 322.05 | 5/1/39-9/30/01 |
| San Marcos Rv at Ottine, TX | 08173500 | 1249 | 285.20 | 7/1/15-1/31/43 |

Table B-2. Stream reaches used in base-flow study.

| ***Reach name*** | ***Reach type*** | ***USGS gage number*** | | ***Outcrop in drainage area ($mi^2$)*** | ***Common period of record*** |
|---|---|---|---|---|---|
| | | ***Upstream*** | ***Downstream*** | | |
| Upper Keechi Creek | 1 | NA [1] | 08065200 | 150 | 5/28/62-9/30/00 |
| Big Creek | 1 | NA | 08110430 | 97 | 7/1/78-9/30/00 |
| Navasota River | 2 | 08110400 | 08110500 | 566 | 3/1/65-4/30/79 |
| Big Sandy above McDade | 1 | NA | 08159165 | 64 | 7/13/1979-9/30/85 |
| Big Sandy above Elgin | 1 | NA | 08159170 | 39 | 7/13/1979-9/30/85 |
| Colorado River | 2 | 08159200 | 08159500 | 394 | 3/1/60-9/24/75,<br>10/6/97-9/30/00 |
| Plum Creek | 2 | 08172400 | 08173000 | 142 | 5/1/59-9/30/93 |
| San Marcos River/Plum Creek | 3 | 08173000<br>08172000 | 08173500 | 96 | 5/1/39-1/31/43 |
| Notes: [1]NA = Not applicable. Type 1 reaches are headwaters defined by a single gage. | | | | | |

- Big Sandy Creek (Type 1). Upstream gage #08159165: Big Sandy Creek near Elgin, TX. Downstream gage #08159170: Big Sandy Creek near McDade, TX. These gages were temporarily operated from 1979 through 1985, or 6 years. Big Sandy Creek is an intermittent stream, located primarily on the Calvert Bluff Formation. For this study, each gage was considered independently as a Type 1 headwater gage to avoid inaccuracies associated with subtraction of daily rating-derived flow estimates.
- Colorado River (Type 2). Upstream gage #08159200: Colorado River at Bastrop, TX. Downstream gage #08159500: Colorado River at Smithville, TX. The Smithville gage is actually located slightly downstream from the top of the Reklaw Formation, which is in turn obscured by the Colorado River alluvial deposits. However, because of the close proximity of the gage to the outcrop edge and the connective effect of the alluvium, a simplifying assumption was made that the intervening drainage area was in the outcrop. These time-series data had the additional complicating factors of being influenced by major releases from the Highland Lakes for deliveries to rice farmers during the growing season, approximately March through September. Identifying and analyzing only periods of time when no reservoir releases were being made and no significant precipitation was occurring minimized the effect of these releases.
- Plum Creek (Type 2). Upstream gage #08172400 (Plum Creek at Lockhart, TX). Downstream gage #08173000 (Plum Creek near Luling, TX). Just downstream from the Lockhart gage, the stream passes over a small outcrop area that is part of the underlying Midway Formation then reenters the Carrizo-Wilcox outcrop.
  Plum Creek is an intermittent stream.

- San Marcos River (Type 3). Upstream gages #08172000 (San Marcos at Luling, TX) and #08173000 (Plum Creek near Luling, TX). Downstream gage #08173500 (San Marcos River at Ottine, TX). These three gages define a reach of the San Marcos River where it is receives flow from Plum Creek, a major tributary on the outcrop of the Carrizo-Wilcox aquifer. Daily data exist for all three of these gages for approximately 3.5 yr.

Base-flow separation was performed on the data for all identified stream gages with common periods of record. The difference in base flow between the upstream and downstream gages is used as an estimate of the amount of groundwater discharge from the aquifer to the stream in the reach between the two gages. Data from Water Availability Models (WAM) prepared for the TNRCC were reviewed to identify any significant water rights or return flows located between the gages; accordingly, base-flow estimates were adjusted for the Colorado and Navasota Rivers, but in neither case was this adjustment significant when compared with the total base flow.

Once the quantification of base-flow change was completed for each of the seven stream reaches on the outcrop of the Carrizo-Wilcox aquifer, this discharge was then converted to unit values by dividing the base-flow change by the intervening drainage area on the outcrop between the gages. This calculation yielded a value of change in base flow per unit area (af/yr/mi$^2$) of Carrizo-Wilcox outcrop drained. A summary of these data is presented in figure B-7. A flow duration curve was generated from the unit daily values, showing the percentage of time that each flow value was exceeded during the period of record. The flow duration curves for all seven study reaches are presented in figure B-8. Basic flow statistics, including maximum, minimum,

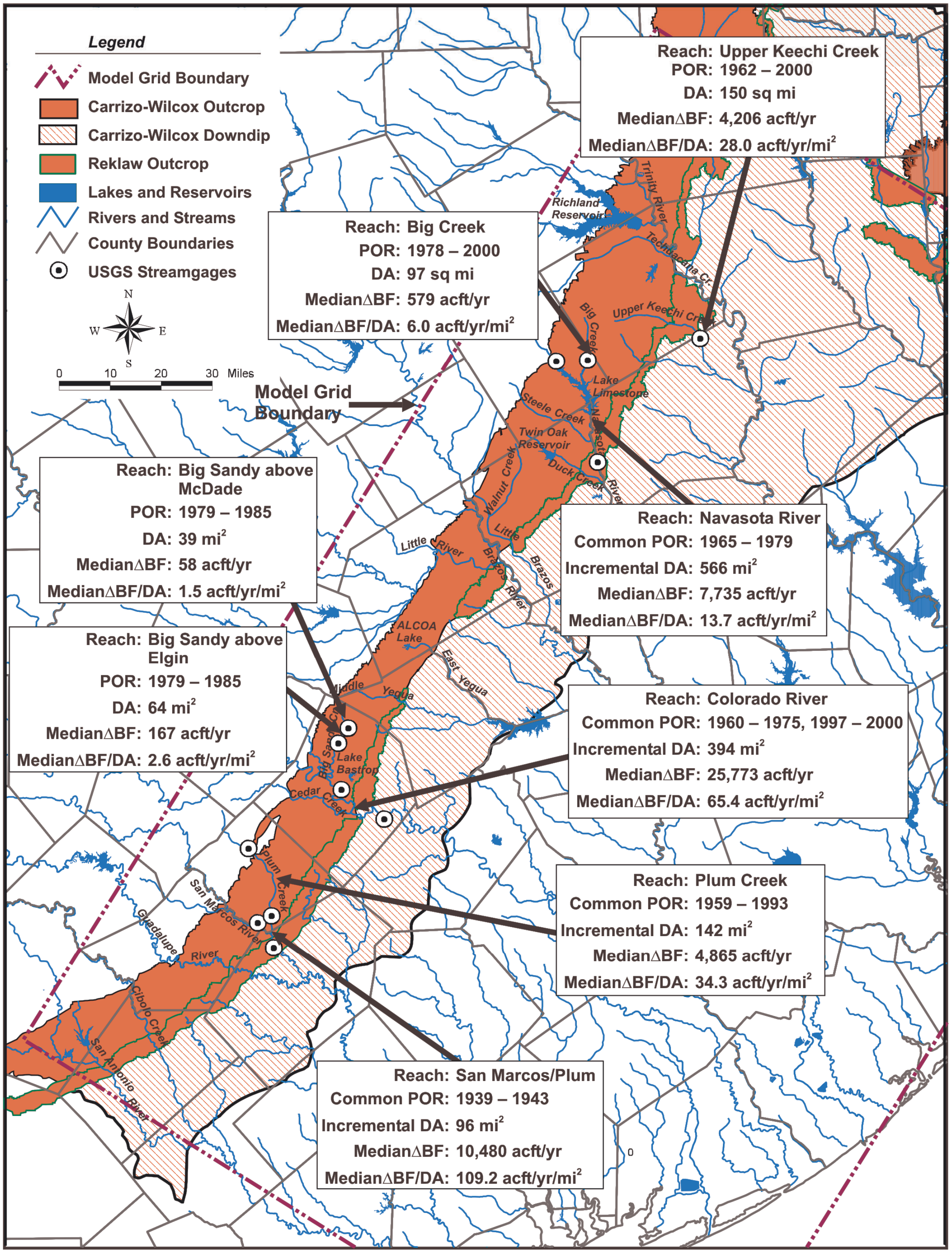



Figure B-7. Base-flow separation analysis results.

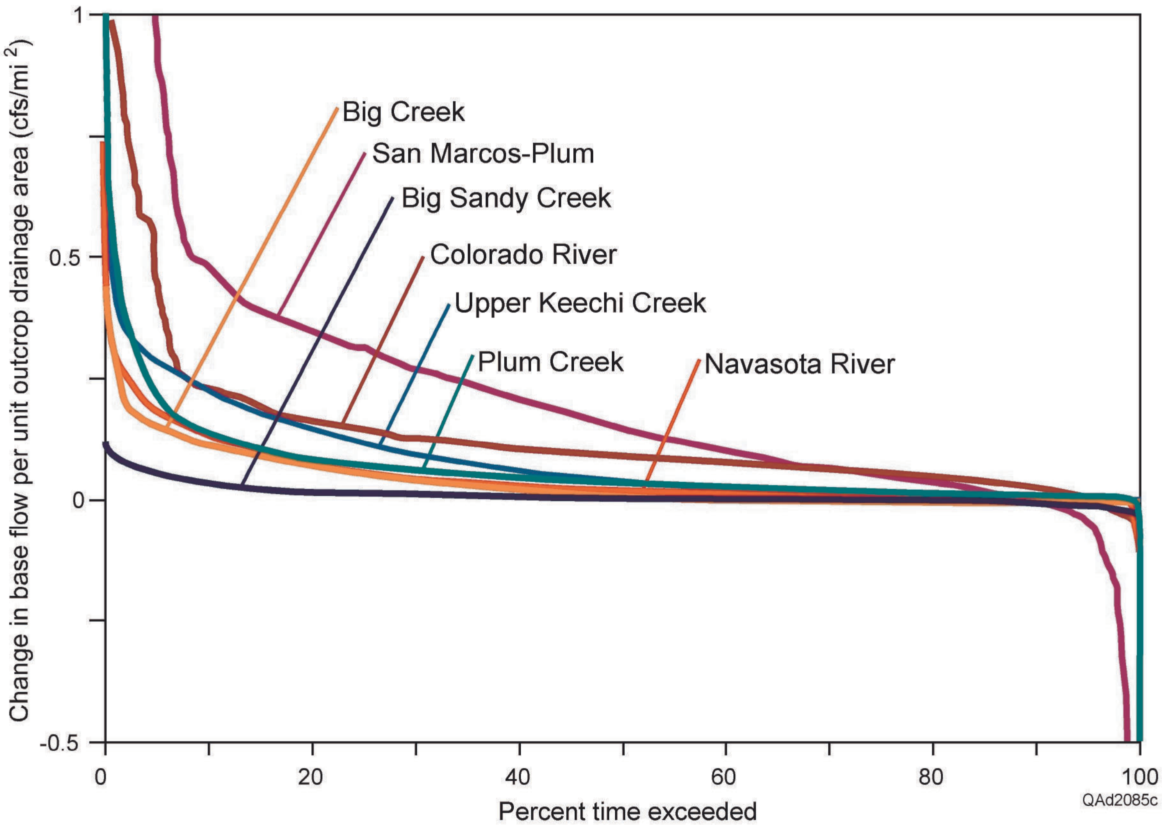



Figure B-8. Base-flow increase across the Carrizo–Wilcox outcrop, unitized by area of drainage basin in the outcrop. Base-flow increase assumed to reflect the discharge of groundwater from the Carrizo–Wilcox aquifer. Most of the discharge is from the Simsboro and Carrizo Formations.

median, and flows from the 10th and 90th percentiles, were calculated and are presented in table B-3. The application of these values is described in the Section B-4.

## B-4.0 Model Application

As discussed previously, the physical processes of aquifer discharge are variable in quantity, diffuse in source, and cumulative in nature. The ultimate purpose of the data analysis described in Section B-3 is to develop specific numerical targets of groundwater flux between the aquifer and the streams for use during model calibration. Calibration targets for both the steady-state and the transient models are needed. We satisfied this requirement using the methods described in subsections B-4.1 and B-4.2.

### B-4.1 Steady-State Model Calibration

For the steady-state model, the following approach was used to develop calibration targets. Because there is no variation in heads or storage in a steady-state simulation, a single value was necessary for each calibration target location on outcrop streams. Initially it was determined that for the steady-state calibration, calibration targets would be located at the downstream edge of the outcrop, thereby incorporating all tributary contribution to the stream prior to leaving the outcrop. Ultimately, calibration targets were developed for all modeled streams, and for each modeled stream, a “reference stream” was selected from the seven study reaches analyzed. This “reference stream” is the analyzed stream reach that most closely approximates the ungaged, modeled stream in size and location. Steady-state targets were derived by multiplying the median values of base-flow increase per unit area of the reference stream times the outcrop drainage area for the modeled stream at the target location. For example, of the seven streams analyzed, the Brazos River (which did not have adequate gage

Table B-3. Statistics from base-flow analysis of selected stream reaches (acre-feet/yr/mi$^2$). Results based on median increase in base flow in the reach in the outcrop.

| | Big Sandy above McDade | Big Sandy above Elgin | Big Creek | Upper Keechi |
|---|---|---|---|---|
| Period of record | 1979-1985 | 1979-1985 | 1978-2000 | 1962-2000 |
| Median | 1.50 | 2.61 | 5.97 | 28.04 |
| Maximum | 46.77 | 54.47 | 320.95 | 492.32 |
| Minimum | 0 | 0 | 0 | 0 |
| 10th Percentile | 0 | 0 | 0 | 0.10 |
| 90th Percentile | 22.45 | 20.77 | 82.25 | 163.48 |

| | Navasota River | Plum Creek | Colorado River | San Marcos-Plum |
|---|---|---|---|---|
| Period of record | 1965-1979 | 1959-1993 | 1960-1975, 1997-2000 | 1939-1943 |
| Median | 14.33 | 34.26 | 65.72 | 109.17 |
| Maximum | 618.61 | 1028.90 | 754.97 | 7082.08 |
| Minimum | -92.62 | -1245.59 | -48.50 | -1347.62 |
| 10th Percentile | 1.38 | 6.12 | 18.98 | 0 |
| 90th Percentile | 110.21 | 136.58 | 166.05 | 349.22 |

data for the analysis) most closely resembles the Colorado River. Therefore, the median unit base-flow value for the Colorado (66 af/yr/mi$^2$) was multiplied by the outcrop drainage area for the Brazos River (380 mi$^2$) to obtain a steady-state calibration target for the farthest downstream cell of the Brazos River. In this way, the appropriate unit base-flow increase calculated during the previous analysis may be applied to any ungaged stream and watershed within the model domain to produce a reasonable calibration target. (Although included in the study analysis, the data for the San Marcos River-Plum Creek confluence were ultimately not used as a reference stream because of both the relative brevity of the period of record [3.5 yr] and the ambiguity associated with apportioning the calculated base flows between the two tributary streams.) A summary of steady-state calibration targets developed in this process is presented in table B-4.

### B-4.2 Transient Model Calibration

Because transient models simulate multiple stress periods in which heads, flux, and storage change with time, they require more extensive calibration targets than steady-state simulations. This GAM was calibrated and verified to the historical period of 1980 through 2000. The analysis presented in Section B-3 resulted in two separate approaches to developing transient calibration targets. The first involves matching time-specific data from the analysis at particular stream-gage locations for any of the study streams that had data within the 1980 through 2000 calibration period. The second involves using the base-flow duration statistics generated during the analysis as a guide for evaluating the time series at streams for which no specific data within the 1980 through 2000 time period was known. The following paragraphs discuss these approaches.

Table B-4. Steady-state conditions of calibration targets for selected watersheds.

| River name | Calibration target cell [1] | | | Outcrop in drainage area ($mi^2$) | Reference stream [2] | Estimated base-flow increase across outcrop (af/yr) [3, 4] |
|---|---|---|---|---|---|---|
| | Layer | Row | Column | | | |
| San Antonio River | 2 | 22 | 5 | 208 | Colorado | 13,700 |
| Cibolo Creek | 2 | 27 | 16 | 196 | Plum Creek | 6,700 |
| Guadalupe River | 2 | 36 | 41 | 202 | Colorado | 13,300 (10,900)[4] |
| San Marcos River | 2 | 39 | 49 | 367 | Colorado | 24,100 (11,100)[4] |
| Colorado River | 1 | 39 | 85 | 495 | Colorado | 32,500 (26,100)[4] |
| Middle Yegua Creek | 2 | 33 | 112 | 151 | Plum | 5,200 |
| East Yegua Creek | 3 | 33 | 125 | 65 | Plum | 2,200 |
| Brazos River | 1 | 36 | 151 | 380 | Colorado | 25,000 (20,000)[4] |
| Little Brazos River | 1 | 37 | 153 | 234.5 | Navasota | 3,400 |
| Duck Creek | 3 | 40 | 178 | 164 | Plum | 2,200 |
| Navasota River | 2 | 43 | 181 | 566 | Navasota | 8,100 |
| Upper Keechi Creek | 3 | 39 | 218 | 134 | Upper Keechi | 3,800 |
| Tehuacana Creek | 1 | 29 | 231 | 329 | Navasota | 4,700 |
| Trinity River | 1 | 39 | 229 | 651 | Colorado | 42,800 (17,800)[4] |
| **Total** | | | | | | **187,700 (135,900)**[4] |

Notes:

[1] Target cell at extreme downstream location of stream on outcrop.

[2] Reference stream is one of the seven streams quantitatively analyzed that most resembles the modeled stream in location and area.

[3] Estimate obtained by multiplying median unit base-flow increase of reference stream by outcrop drainage area of modeled stream.

[4] The estimated base flow for the Colorado has been revised from 32,500 acre-ft/yr to 26,100 acre-ft/yr, which corresponds to the value of 36 cfs of the 1918 low flow study (Fig. B-3). As a consequence, all stream flows derived from the Colorado River data, except the San Antonio River, have been multiplied by a correction factor of 26100/32500~0.8: new estimated base flows for Guadalupe and Brazos Rivers are 11,100 acre-ft/yr and 20,000 acre-ft/yr, respectively. In addition, it was observed that the Simsboro and Carrizo Formations contribute most to the stream base flow, whereas the Hooper, Calvert Bluff, and Reklaw Formations contribute very little. Approximately 25 percent of the Colorado drainage basin is located on the Simsboro and Carrizo Formations. The same is true of the Guadalupe and Brazos Rivers. However, the San Marcos and Trinity Rivers need an additional correction because the Simsboro and Carrizo Formations cover only 14 and 12 percent of the river drainage area, respectively. The new estimated base-flow increase for the San Marcos and Trinity Rivers is then 24,100 x 0.8 x 0.14/0.25 ~11,100 acre-ft/yr and 42,800 x 0.8 x 0.12/0.25 ~17,800 acre-ft/yr, respectively (multiplications not exact because of rounding).

The first calibration target approach simply applies annual base-flow increases calculated during the study. Of the seven streams examined in the quantity analysis, five (all but Navasota and San Marcos Rivers) have at least some data in the calibration period. For those streams, the annual median change in base flow attributed to each stream reach was used as an annual calibration target for any year in which data existed. These calibration targets are presented in table B-5.

Several of the modeled streams have no specific data in the 1980 through 2000 time period. In these instances, the second calibration target approach was used. We derived transient calibration targets by trying to match the duration curve statistics generated for the appropriate reference stream. Only base flows between 10 and 90 percent were considered for calibration statistics because many outliers are included in the extremes owing to (1) gage inaccuracies, (2) time lag for propagation of flow between upstream and downstream gages, and (3) inaccuracies in the base-flow program. Flows from the 10th percentile ($Q_{10}$) were used to estimate the minimum quantity of discharge from the aquifer to the streams, and flows from the 90th percentile ($Q_{90}$) were used to estimate the maximum of base-flow discharge from the aquifer to the streams. The median was selected instead of the average as a representative value of the middle range of flows to diminish the influence of extreme outliers in the data set. Therefore, after an appropriate reference stream is selected (as with the steady-state targets), the median, $10^{th}$, and $90^{th}$ percentile unitized base-flow increases from the reference stream are multiplied times the outcrop area for any modeled stream to produce estimates for the median, minimum, and maximum groundwater flux expected between the aquifer and the stream at any target location. This is not a “hard” calibration target in the traditional sense; there is no specific numerical target associated with a particular stress period. However, it defines a target base-flow

Table B-5. Calculated 1980–2000 annual base-flow increases for selected study reaches.

| ***Stream*** | ***Upper Keechi Creek*** | ***Plum Creek*** | ***Big Creek*** | ***Big Sandy Creek*** | ***Colorado River*** |
|---|---|---|---|---|---|
| ***Target cell (L, R, C)*** | ***3, 39, 218*** | ***4, 33, 55*** | ***4, 27, 201*** | ***4, 26, 96*** | ***(Reach between 1, 32, 88 and 1, 39, 85)*** |
| 1980 | 8,900 | 3,100 | 1,800 | 384 | * |
| 1981 | 3,300 | 5,500 | 900 | 329 | * |
| 1982 | 6,200 | 4,600 | 1,600 | 286 | * |
| 1983 | 10,600 | 4,000 | 2,800 | 780 | * |
| 1984 | 6,000 | 2,900 | 1,800 | 239 | * |
| 1985 | 8,000 | 9,200 | 3,000 | 835 | * |
| 1986 | 7,200 | 13,800 | 1,900 | * | * |
| 1987 | 7,300 | 11,700 | 3,300 | * | * |
| 1988 | 3,300 | 4,000 | 1,700 | * | * |
| 1989 | 4,500 | 2,100 | 900 | * | * |
| 1990 | 9,300 | 1,900 | 1,800 | * | * |
| 1991 | 20,700 | 800 | 6,300 | * | * |
| 1992 | 19,900 | 30,000 | 7,700 | * | * |
| 1993 | 16,400 | 14,800 | 3,600 | * | * |
| 1994 | 11,100 | * | 2,400 | * | * |
| 1995 | 13,700 | * | 3,800 | * | * |
| 1996 | 2,000 | * | 1,000 | * | * |
| 1997 | 9,100 | * | 3,100 | * | * |
| 1998 | 12,400 | * | 4,600 | * | 132,750 |
| 1999 | 11,200 | * | 2,200 | * | 80,514 |
| 2000 | 3,900 | * | 500 | * | 56,551 |
| | 8,900 | 4,300 | 2,200 | 357 | |

range to compare against the range of flux values calculated by the model. Calibration targets developed using this method are summarized in table B-6.

## B-5.0 Discussion

The methodology developed to quantify the interaction between groundwater and surface water attempts to develop specific numerical estimates of quantities that are not directly measurable. Simplifying assumptions were made in order to facilitate the analysis. Several factors may affect the accuracy of the estimates. This section briefly discusses these factors.

The estimates provided by the base-flow methodology may somewhat underestimate aquifer discharge because stream-channel losses due to evaporation and transpiration are occurring between the two gages' measuring points. What is actually measured using this methodology is groundwater discharge from the aquifer minus evapotranspiration losses in the intervening reach. However, this is a valid target for model calibration, when considering a model design that represents evapotranspiration.

In addition, this statistical approach may overestimate the seasonal and year-to-year variability of groundwater discharge to streams. If viewed as a simple system in the context of Darcy's Law, with groundwater flow direction perpendicular toward the stream, the quantity of discharge (Q) to the stream is

$$Q=KiA \tag{3}$$

where: K is hydraulic conductivity, i is hydraulic gradient of groundwater flow, and A is cross-sectional area of flow. Of these factors, hydraulic conductivity and cross-sectional area of flow remain constant with time. The hydraulic gradient is a factor of lateral flow distance (x-direction), which remains constant, and the vertical head (z-direction), which changes. However, groundwater level fluctuations in the outcrop are generally only on the order of 5 to 10 ft, and

Table 6. Calibration targets for transient conditions (acre-feet/yr)

| River Name | Calibration Target Cell [1] | | | Outcrop in Drainage Area ($mi^2$) | Reference Stream [2] | Minimum flow increase across outcrop [3] | Median flow increase across outcrop [4] | Maximum flow increase across outcrop [5] |
|---|---|---|---|---|---|---|---|---|
| | Layer | Row | Column | | | | | |
| San Antonio River | 2 | 22 | 5 | 208 | Colorado | 4,000 | 13,700 | 34,500 |
| Cibolo Creek | 2 | 27 | 16 | 196 | Plum Creek | 1,200 | 6,700 | 26,900 |
| Guadalupe River | 2 | 36 | 41 | 202 | Colorado | 3,800 | 13,300 | 33,500 |
| San Marcos River | 2 | 39 | 49 | 367 | Colorado | 7,000 | 24,200 | 60,900 |
| Plum Creek [6] | 4 | 36 | 52 | 142 | Plum Creek | 900 | 4,800 | 19,500 |
| Cedar Creek | 1 | 36 | 84 | 255 | Plum Creek | 1,500 | 8,700 | 34,900 |
| Colorado River | 1 | 39 | 85 | 495 | Colorado | 9,400 | 32,700 | 82,200 |
| Big Sandy Creek | 4 | 28 | 91 | 64 | Big Sandy Ck | 0 [7] | 100 | 1,500 |
| Middle Yegua Creek | 2 | 33 | 112 | 151 | Plum Creek | 900 | 5,100 | 20,700 |
| East Yegua Creek | 3 | 33 | 125 | 65 | Plum Creek | 400 | 2,200 | 8,900 |
| Little River | 1 | 34 | 150 | 245 | Navasota | 200 | 3,400 | 27,000 |
| Brazos River | 1 | 36 | 151 | 380 | Colorado | 7,200 | 25,100 | 63,100 |
| Little Brazos River | 1 | 37 | 153 | 234.5 | Navasota | 200 | 3,300 | 25,800 |
| Walnut Creek | 1 | 28 | 159 | 135 | Plum Creek | 800 | 4,600 | 18,500 |
| Duck Creek | 3 | 40 | 178 | 164 | Plum Creek | 1,000 | 5,600 | 22,500 |
| Steele Creek | 3 | 39 | 184 | 160 | Plum Creek | 1,000 | 5,400 | 21,900 |
| Navasota River | 2 | 43 | 181 | 566 | Navasota | 600 | 7,900 | 62,300 |
| Big Creek | 4 | 29 | 196 | 94 | Big Creek | 0 | 600 | 7,700 |
| Upper Keechi | 3 | 39 | 218 | 134 | Upper Keechi | 0 | 3,800 | 21,800 |
| Tehuacana Creek | 1 | 29 | 231 | 329 | Navasota | 300 | 4,600 | 36,200 |
| Trinity River | 1 | 39 | 229 | 651 | Colorado | 12,400 | 43,000 | 108,100 |

1. Target cell located at farthest downstream location of stream on outcrop, except as noted.
2. Reference stream is the one of the seven streams quantitatively analyzed which most resembles the modeled stream in location and area.
3. Obtained by multiplying median unitized base-flow increase of reference stream by outcrop drainage area of modeled stream. See text for details.
4. Obtained by multiplying 10th percentile unitized base-flow increase of reference stream by outcrop drainage area of modeled stream. See text for details.
5. Obtained by multiplying 90th percentile unitized base-flow increase of reference stream by outcrop drainage area of modeled stream. See text for details.
6. Stream name in bold indicates that target cell location is coincident with USGS gage location rather than farthest downstream location.
7. Reported minimum estimates of zero reflect 10th percentile flows from analyzed streams. Annual average minimum flows will likely be greater than zero.

with all other factors essentially remaining constant, it may be argued that the quantity of aquifer discharge does not vary as markedly as indicated from the base-flow methodology presented here. In addition, a succession of large storms would tend to increase the base-flow estimate if there were not adequate time between storms for the hydrograph recession limb to return to its prestorm level.

In addition, the relative altitude of a stream gage or the degree of incision of a river channel may affect the amount of groundwater discharge because a deeply incised channel will offer a cross-sectional area through which groundwater may enter the river that is larger than a gently sloping floodplain with no significant incision. There is no consideration of factors such as gage altitude or stream incision in this analysis.

An additional factor that is lost in the context of annual stress periods is the seasonal variability of stream flow. As previously mentioned, several of the streams modeled in this GAM are intermittent, going dry during the hottest summer months but maintaining flow through the winter. Although the intermittent streams analyzed have smaller values of groundwater flux than perennial streams, this variability is not represented in an annual model; future work that incorporates shorter stress periods should attempt to simulate this seasonal variability.

It has been suggested that recent groundwater development would result in values of groundwater discharge that are lower than historical, predevelopment values. However, the unit annual values calculated during the base-flow analysis were examined and revealed no evidence of a decreasing trend with time. As discussed previously, seasonal variability in base flow for perennial streams may not fluctuate as significantly as indicated by the base-flow analysis results.

## B-6.0 Reference

Wahl, T. L., and Wahl, K. L., 2001, BFI Version 4.12, A Computer Program for Computing an Index to Base Flow: U.S. Bureau of Reclamation and U.S. Geological Survey.