Chapter 4

Conjunctive Use of the Brazos River Alluvium Aquifer

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Introduction

This paper presents some basic hydrogeologic data describing the Brazos River Alluvium aquifer, culled from various published sources. This paper also presents the results of a groundwater model of a section of the Brazos River Alluvium that was developed to examine the conceptual feasibility of a managed enhanced recharge project. Much of this work was done for the Brazos G Regional Water Planning Group during the preparation of the 2002 State Water Plan.

Hydrogeologic Data

The Brazos River Alluvium is identified by the Texas Water Development Board (TWDB) as a minor aquifer in the State of Texas. The aquifer extends from Whitney Dam in the northwest to Fort Bend County in the southeast (Figure 4-1). The deposits of the Brazos River Alluvium are comprised of Quaternary-aged unconsolidated clay, silt, sand, and gravel deposited by flooding of the Brazos River and Little Brazos River. Older alluvial terrace deposits also occur contiguous with the alluvium. The thickness of the Brazos River Alluvium exceeds 100 feet in some isolated downstream areas but averages approximately 45 to 50 feet throughout its extent.

Within the model area, thickness of the aquifer is approximately 50 to 60 feet. The Brazos River Alluvium in the model area is underlain by older Cretaceous and Eocene-aged deposits (Figure 4-2), some of which comprise major or minor aquifers. In general, the piezometric heads in the underlying water-bearing formations are greater than the piezometric head in the Brazos River Alluvium, which indicates an unquantified amount of recharge to the alluvium from the underlying formations.

Groundwater in the aquifer occurs under water table conditions (that is, there is no contiguous confining layer located above the aquifer). Water table elevations slope toward the Brazos River, indicating that the Brazos is gaining flow supplied by aquifer discharge. It is unclear from published data whether the Little Brazos River is a gaining reach.

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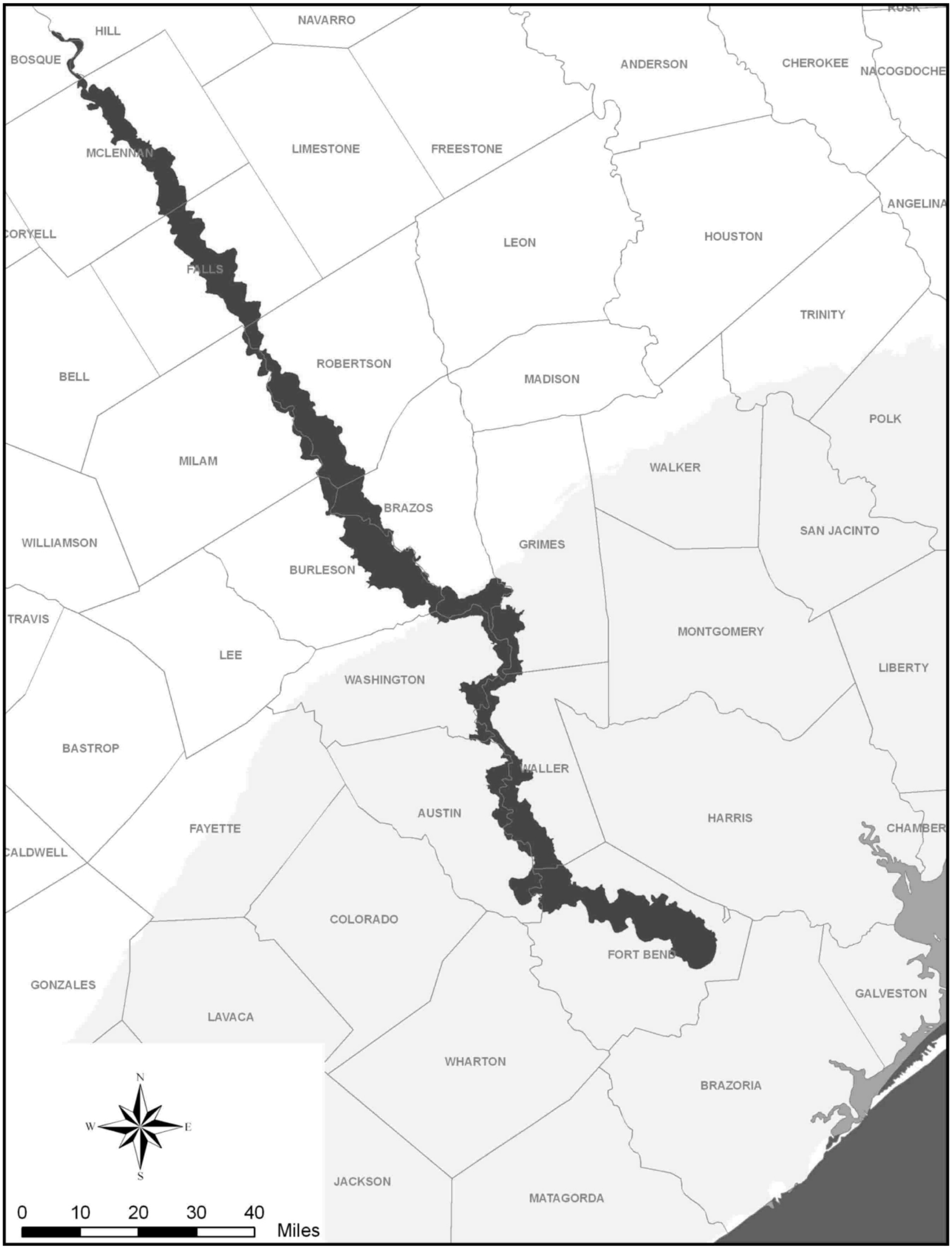

Figure 4-1. Brazos River Alluvium and Gulf Coast aquifers.

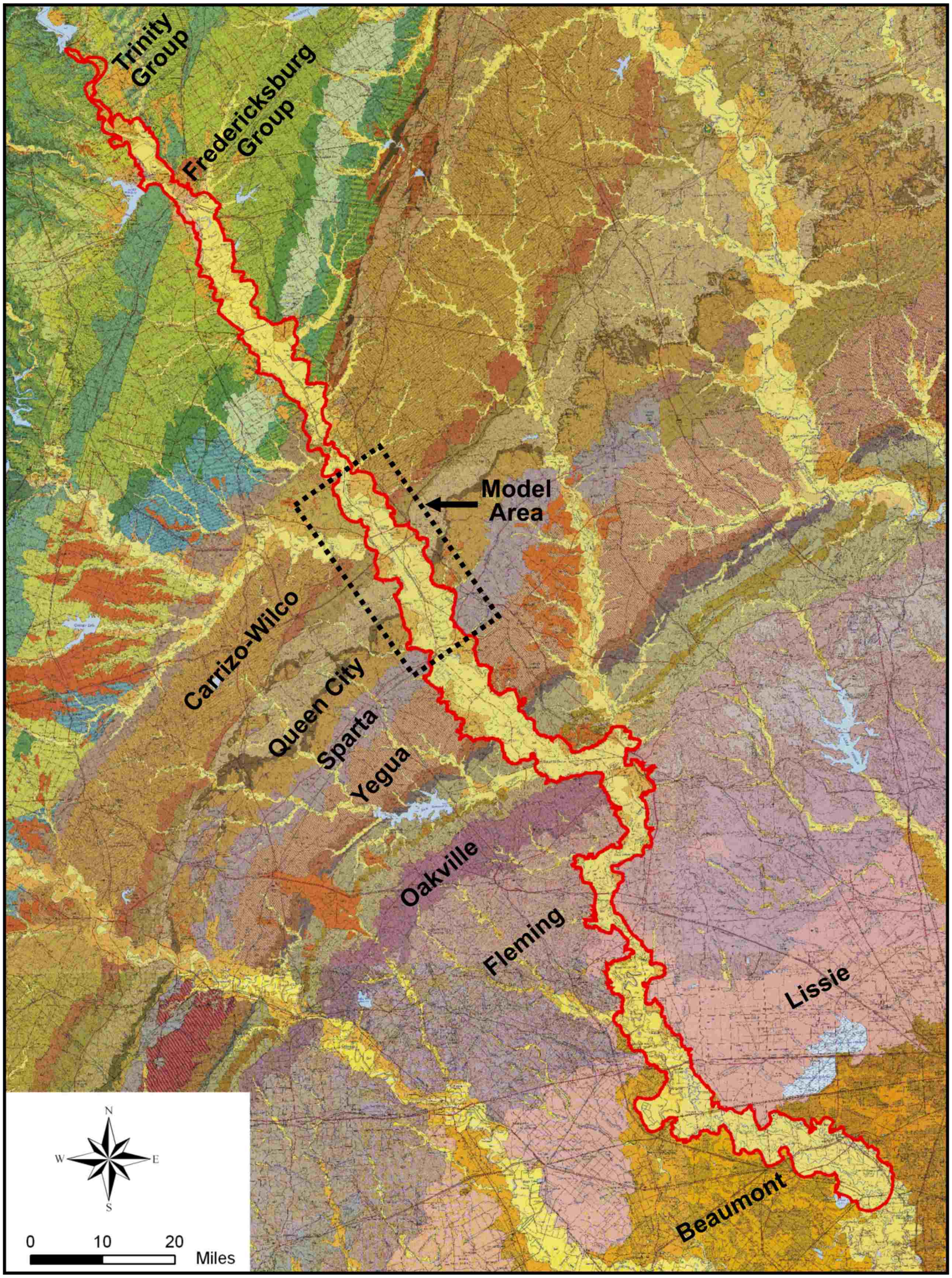

Figure 4-2. Geologic map with Brazos River Alluvium aquifer.

Recharge to the aquifer occurs primarily through direct precipitation onto the aquifer surface and subsequent percolation of a portion of this precipitation to the saturated zone of the alluvium. A minor amount of recharge may be supplied to the aquifer from upward vertical leakance from the underlying bedrock formations that are crossed by the alluvium. Discharge from the aquifer occurs through seepage into the Brazos River, evapotranspiration, and wells. The primary use of groundwater from the aquifer is for local irrigation. Recent estimates of groundwater use from the aquifer are approximately 25,000 acre-feet per year.

Following is a summary of reported data describing the hydrogeologic properties of the Brazos Alluvium aquifer from Cronin and Wilson (1967):

- Reported transmissivity estimates in the Brazos River Alluvium range from 50,000 gallons per day per foot (gpd/ft) to 300,000 gpd/ft.
- Reported laboratory permeability (hydraulic conductivity) values range from less than 1 foot per day up to 2,400 feet per day, with an average value of about 290 feet per day for 19 samples collected.
- Reported specific yield estimates range from 4 to 35 percent and average approximately 24 percent. A conservative estimate is probably 15 percent.
- Well yields from large irrigation supply wells located in thick portions of the alluvium are typically between 250 and 500 gallons per minute.
- Water quality varies widely throughout the aquifer, with total dissolved solids concentrations reported from less than 500 milligrams per liter to greater than 3,000 milligrams per liter (Figure 4-3).
- On the basis of reported saturated thickness and a storage value of 15 percent, it is estimated that nearly 3,000,000 acre-feet of water is in storage in the aquifer.

Groundwater Model Development

Background

During analysis of water management strategies for the 2001 State Water Plan, the feasibility of a conceptual conjunctive use project utilizing the Brazos River Alluvium was evaluated for Region G. Conjunctive use is proposed to be accomplished through enhanced recharge to the aquifer for temporary storage during times of adequate precipitation and river flow and subsequent recovery from the aquifer during times of low precipitation and reduced river flow. It should be noted that this project is conceptual in nature: no actual project is being pursued on the ground at present. As part of the analysis, a groundwater model was developed to evaluate hydrologic conditions associated with operation of the project. The purpose of this model is to assess the potential for conjunctive use of surface water from the Brazos River and groundwater from the alluvial aquifer. The model is used to examine the response of the aquifer system to enhanced recharge, to monitor the movement of this recharge water through the system, to evaluate potential water losses from the system, and to determine an appropriate operational cycle for recharge and recovery (that is, long-term drought-proofing vs. fixed seasonal operation

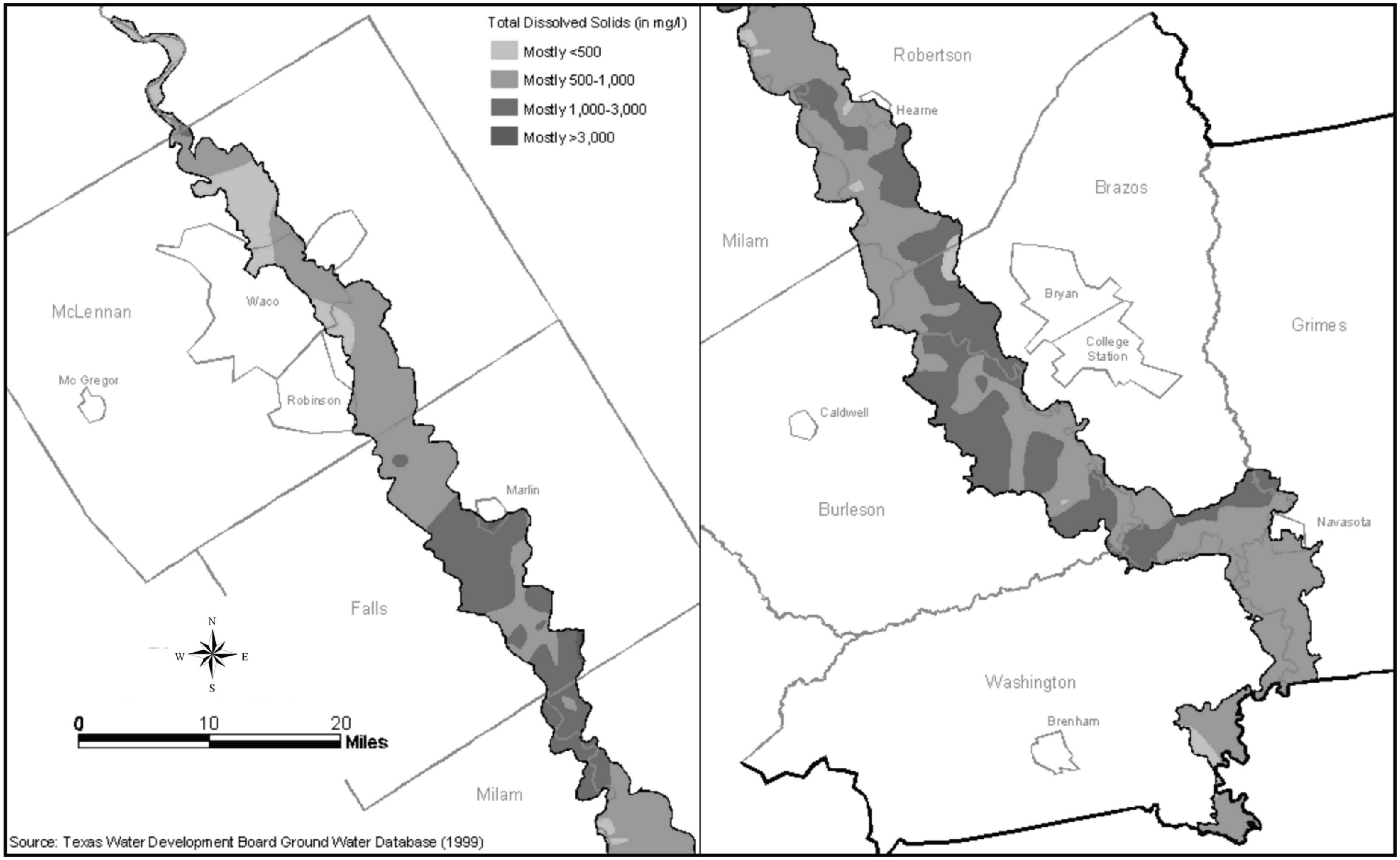

Figure 4-3. Groundwater quality in the Brazos River alluvium aquifer.

schedule). The area of the aquifer identified for this study is located in Robertson, Milam, Burleson, and Brazos counties between the city of Calvert and State Highway 21 (Figure 4-2).

Structure

The Brazos River Alluvium, which is actually comprised of numerous interfingering layers of sand, silt, clay, and gravel, was represented as a single hydrogeologic layer. The model was restricted to a single layer for simplicity. Reliable data regarding flow between the alluvium and the underlying Carrizo-Wilcox aquifer is difficult to obtain and would have introduced an extra calibration variable with no observed data to calibrate to.

A finite difference grid consisting of 100 rows and 300 columns was developed and aligned so that model rows were approximately parallel to the Brazos and Little Brazos rivers. Grid cells were sized to be 500 feet square in order to capture groundwater movement at a local scale. The model grid area is displayed on Figure 4-4.

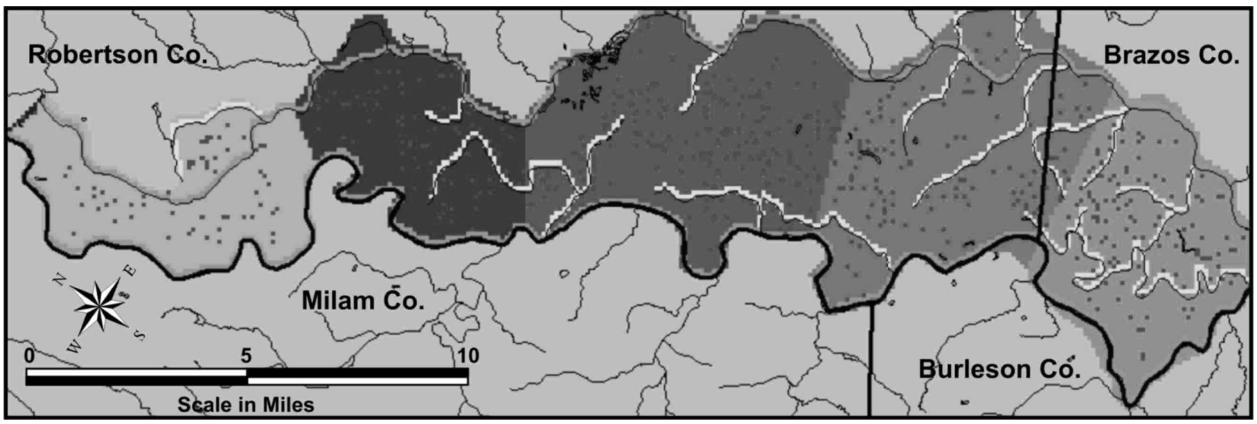

Figure 4-4. Groundwater model area with hydraulic conductivity zones

Digital elevation data from the U.S. Geological Survey were used to determine land surface elevations, and the data was imported using ArcView GIS software to populate the model grid cells with appropriate values. Structure maps from Cronin and Wilson (1967) were used to determine the elevation of the base of the alluvium. Ten-foot contours of this data were digitized and imported into the model using Ground Water Vistas, and an internal kriging procedure was utilized to populate all model gird cells with appropriate values.

Boundary Conditions

The following section describes boundary conditions adopted for the groundwater model development:

- No-flow boundaries were imposed in all non-alluvium cells.
- A constant head boundary of 300 feet was defined at the northern upgradient edge of the model (near Calvert).

- The MODFLOW General Head Boundary (GHB) package was used to simulate the southeastern downgradient edge of the model (near Highway 21) with an assigned head of approximately 205 feet above mean sea level.
- The Brazos River and the Little Brazos River were represented using MODFLOW's River Package. A free water surface two feet higher than the stream bed surface elevation was assigned in both rivers.
- MODFLOW's Drain Package was used to simulate small ephemeral creeks on the alluvium surface that might be supplied by discharge from the alluvium under high water table conditions.
- MODFLOW's Well Package was used to simulate existing irrigation wells within the model area as well as the enhanced recharge and recovery operations.
- MODFLOW's Recharge package was used to simulate direct recharge to the aquifer surface from precipitation. An initial estimate of eight percent of precipitation based on Cronin and Wilson (1967) was reduced to four percent of precipitation during model calibration.
- Evapotranspiration was simulated using MODFLOW's ET Package.

Aquifer Parameters

Hydraulic conductivity was represented using five different zones, varying from 100 to 200 feet per day, based on examination of well test data available in Cronin and Wilson (1967) (Figure 4-4).

A storage coefficient (specific yield) of 0.15 was used for the model. This is a typical storage coefficient used to represent water table conditions and is corroborated by Cronin and Wilson (1967).

Well pumpage values for the irrigation supply wells in the model were generated by evaluating aquifer use totals by county and then applying a typical irrigation use pattern with adjustments made for unusual precipitation conditions. A basic monthly water use distribution for the Brazos River Basin was modified to take into account rainfall totals during the calibration period. In months where the actual rainfall received was significantly less than the average rainfall for that month, the pumpage distribution factor for that month was increased to allow for greater pumpage. Conversely, in months where the actual rainfall received was significantly greater than the average rainfall for that month, the pumpage distribution factor for that month was decreased.

As mentioned previously, recharge was initially assigned a value of eight percent of precipitation measured at the College Station rain gage. This value was adjusted downward to four percent of precipitation during calibration.

Evapotranspiration rates used for the model area were derived from the Priestly-Taylor method, and an annual time series of twelve monthly values was applied to the model for the runs. Evaporation rates varied from approximately 5.2×10^{-3} feet per day (1.6 millimeters per day) to 2.6×10^{-2} feet per day (8 millimeters per day). The extinction depth was set at 15 feet.

The river package in MODFLOW simulates hydrologic interaction between rivers and the surrounding aquifer. Flow to and from the rivers is based on head differences between the river stage and the groundwater level in the model cell containing the river. Data required are the elevation of the stream bed, the stage elevation of the stream, the thickness of the river bed, and hydraulic conductivity of the stream bed sediments. River bed conductance is a calculated parameter which controls the flux rate of water between the river and the aquifer. The Brazos and Little Brazos rivers were represented as having a river stage of two feet during the course of the model runs. Initial estimates of conductance ranged from 2.0×10^4 to 2.0×10^5 square feet per day and were adjusted during calibration.

The drain package in MODFLOW allows water to be drained from the model through other mechanisms. This package may be used to represent a variety of physical situations. For this model, the drain package was used to represent the occurrence of high groundwater table conditions recharging ephemeral stream beds, whereupon the water lost from the aquifer would flow from these stream beds into the larger river system.

Model Calibration

Once the basic data sets were assembled, a steady state version of the model was run. Average data values were used for all packages which had annual time series (well, recharge, and evapotranspiration). The purpose of this model run was to develop "average" starting heads for use in transient simulations and to perform initial calibration prior to the start of the transient calibration runs.

After the steady-state model had been successfully run, a transient model was developed which utilized monthly stress periods so that the seasonal irrigation patterns of groundwater pumpage and recharge could be simulated. The calibration period selected for this model was from January 1987 to December 1992. This period was selected because groundwater pumpage data, well water level data, precipitation data, and streamflow data were readily obtainable. In addition, during this time period, a majority of the wells within the study area displayed a decreasing water level from the period 1987 to 1990 and then an increasing water level from 1990 to 1992. It was determined that this cycle (a decreasing water level rebounding in the latter part of the calibration period) would provide an opportunity to calibrate the model to both rising and falling water level conditions.

Eleven wells in the model area, which are regularly monitored for water levels by the TWDB, were selected as calibration targets. Water-level data were obtained from the database available on the TWDB Web page. These wells are broadly spaced and represent a reasonably homogeneous spatial distribution within the model area. Calibration target well locations are shown in Figure 4-5. Each of these wells had between four and seven recorded water levels during the calibration period for a total of 121 separate calibration target water levels.

During calibration, the initial recharge estimate was reduced from eight percent to four percent of precipitation. The initial estimate of 8 feet for evapotranspiration extinction depth was increased to 15 feet, which is consistent for values used in sandy soils in other Central Texas

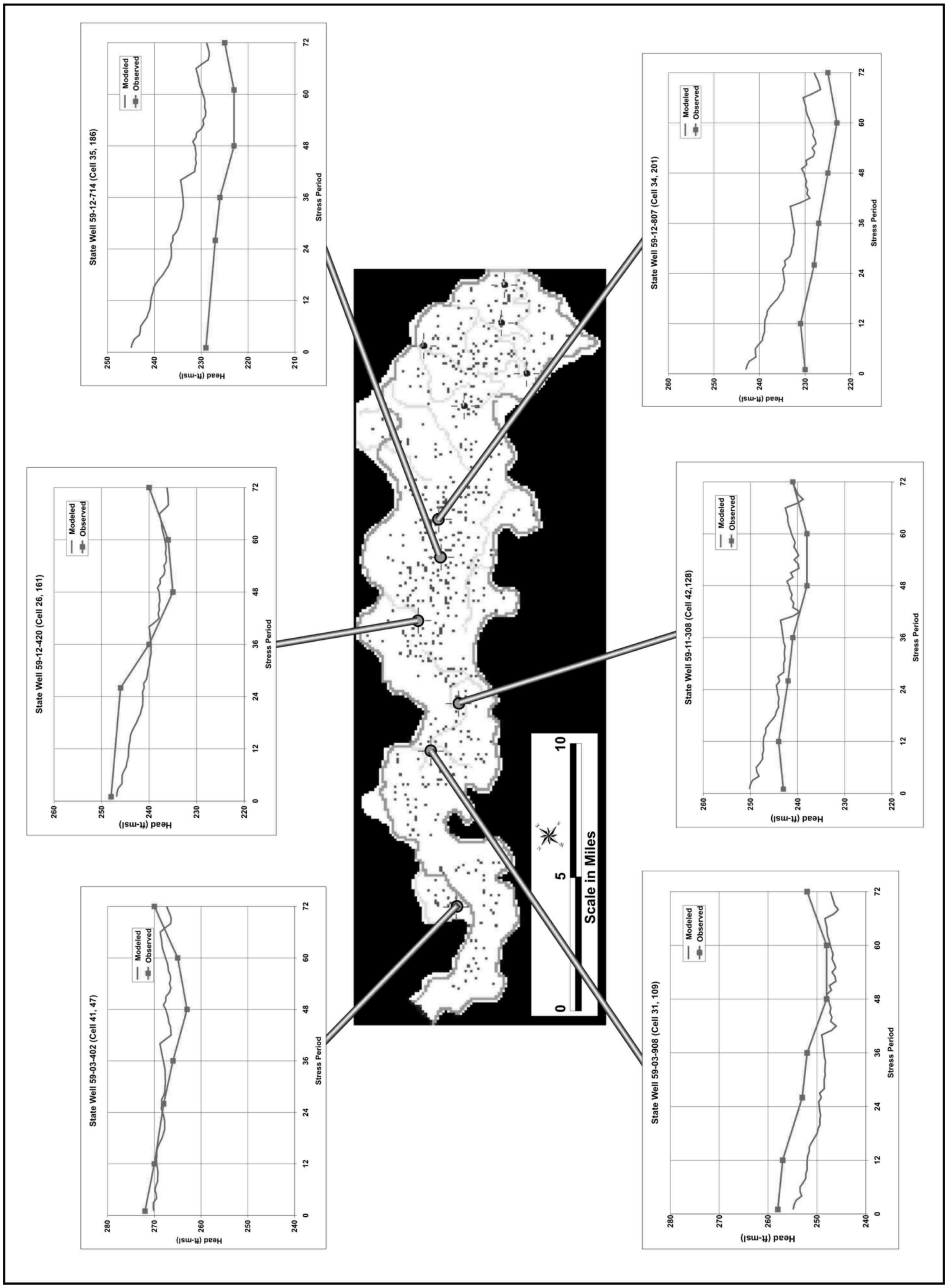

Figure 4-5. Calibration hydrographs.

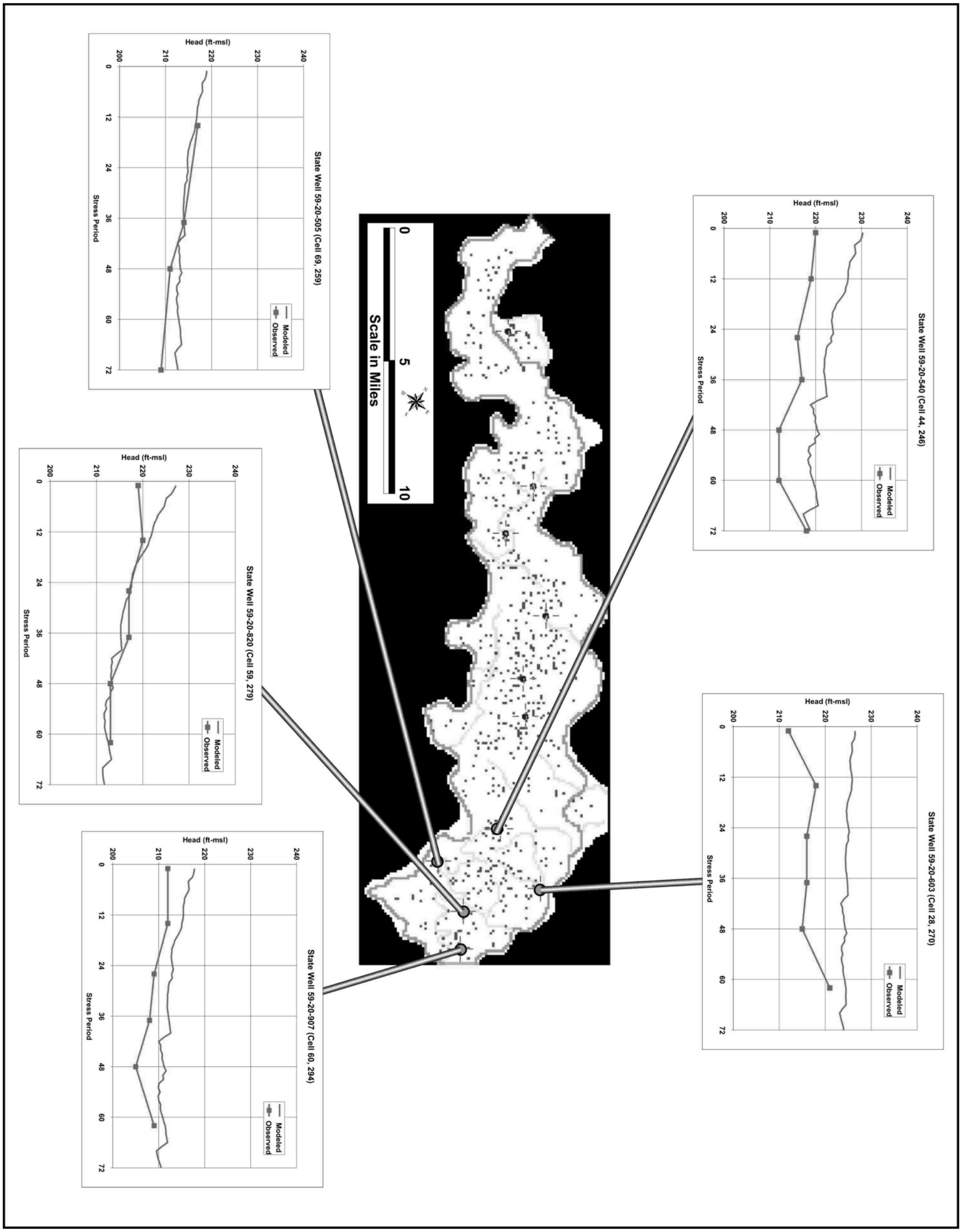

Figure 4-5. Continued.

groundwater models. The values for river bed conductance, which originally ranged from 2.0×10^4 to 2.0×10^5 square feet per day, were adjusted upward during calibration.

Calibration is often guided by examination of the total residuals of the model run. A residual is the difference between the field measurement and the model-computed value. A summary of the residual statistics for the Brazos River Alluvium model calibration is presented in Table 4-1. The mean residual for all 121 calibration targets was -3.4 feet. A plot of observed versus simulated heads is displayed in the upper plot of Figure 4-6. For reference, the diagonal line drawn across the graph represents a perfect match between observed and computed head values. This graph displays a reasonable correspondence between the observed and model-computed values. The lower plot in Figure 4-6 presents another representation of the calibration results, plotting observed head values versus the corresponding residual value. This graph makes it apparent that most of the calibration residuals are negative, indicating that, for the most part, the computed values are higher than field-measured values.

Table 4-1. Residual statistics for the Brazos River Alluvium model calibration.

Residual Mean	-3.43
Res. Std. Dev.	4.65
Sum of Squares	2301
Abs. Res. Mean	4.57
Min. Residual	-15.98
Max. Residual	5.01
Head Range	67.00
Std/Head Range	6.94%

Conjunctive Use Testing Applications

Once the model was sufficiently calibrated to represent observed groundwater levels, model simulations were set up to test the feasibility of a conjunctive use project in the aquifer system. The conjunctive use project that was simulated was designed to be consistent with the water supply project outlined in Chapter 5.19 of the 2001 Brazos G Regional Water Plan, “Conjunctive use of the Brazos River alluvium” (HDR Engineering and others, 2001). The referenced chapter summarizes the project description, design calculations, cost estimates, and environmental implications of a project that would divert high river flows from the Brazos River to a series of infiltration basins or injection wells on the alluvium surface.

A note should be made regarding the semantics of the following discussion. The project as proposed recommends using infiltration basins to enhance recharge to the aquifer. In the model, however, the enhanced recharge is simulated using injection wells in the well package. This was done simply because it is easier to use the well package than the recharge package to create and manipulate the necessary MODFLOW data files. It is irrelevant to the model whether the well package or recharge package is used—the water is delivered either way. For the purposes of this report, however, enhanced recharge will heretofore be referred to as “injection” and recovery will be referred to as “extraction”.

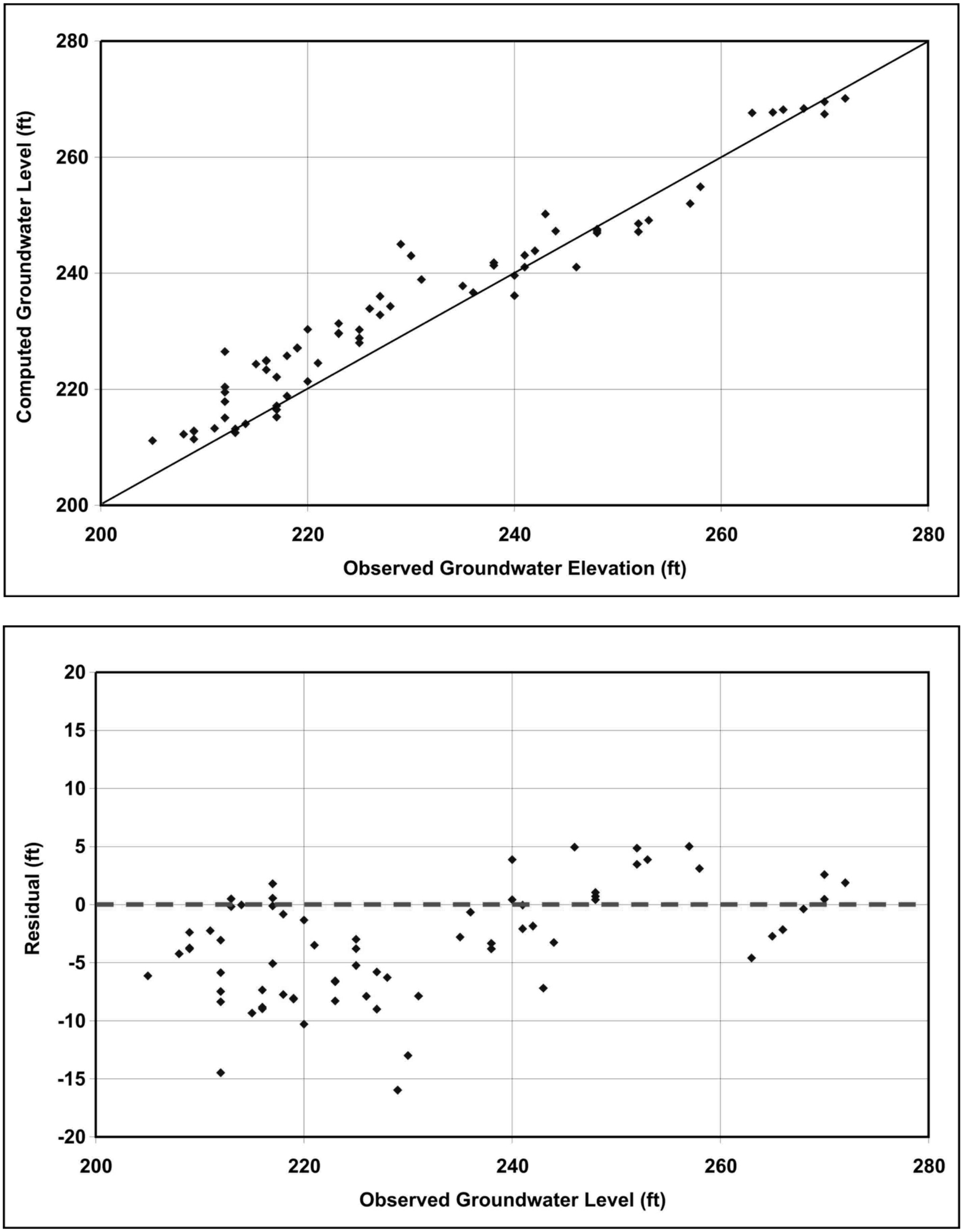

Figure 4-6. Observed water levels versus residuals.

In the proposed project, it was conservatively estimated that infiltration ponds could accept water at 0.5 inches per hour. If the ponds were sized to be one acre, this is equivalent to injection of one acre-foot per day for each pond built. It was proposed that 90 such ponds be built to handle the full project as designed, resulting in delivery to the aquifer of approximately 90 acre-feet per day, or 2,700 acre-feet per month. Ninety acre-feet per day were injected into the model using the well package over a total of 45 cells located slightly south of the center axis of the alluvium between the two rivers. This assumed two acres of pond in each cell (the model cells are approximately 5.7 acres). An equivalent number of extraction wells were then placed between the injection wells along the same sinuous axis. The conceptual layout is presented in Figure 4-7.

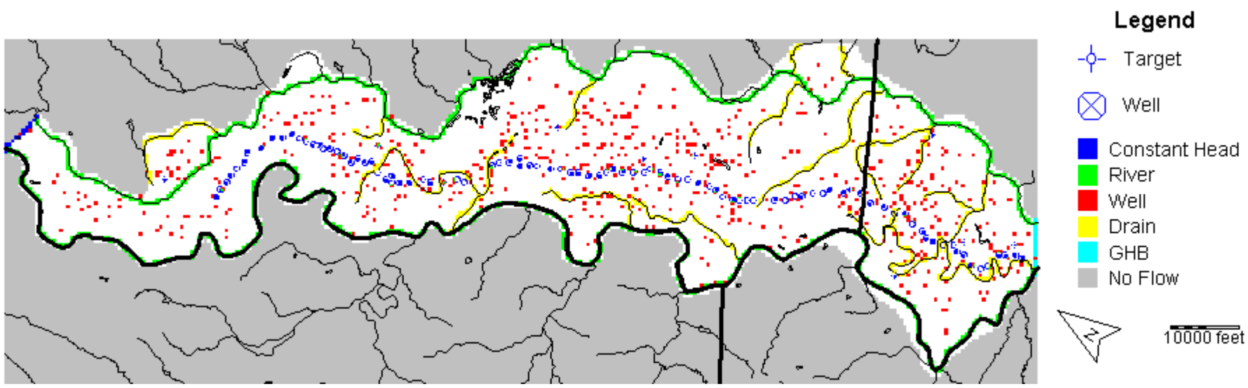

Figure 4-7. Conceptual layout of infiltration ponds and extraction wells.

The calibrated transient model was used as a baseline for comparison of the effect of the project. All project simulation runs were compared to this baseline run for assessment.

For an initial analysis of the response of the alluvial aquifer system to injected recharge, a simulation was depicted wherein 90 acre-feet of water were injected daily into the aquifer for the first three months of the model simulation, and no corresponding recovery cycle was simulated. This was done to examine the movement of the injected water through the system if no recovery was implemented. The water budget in the model output was then examined month by month to determine the difference between the project run and the baseline run in losses to the aquifer due to discharge to the rivers and streams, evapotranspiration, and flow across the model boundaries. Loss to drains represents high water table conditions resulting in flowing water in ephemeral streams, ultimately being delivered to the larger streams and rivers. Therefore, discharge to drains was added to rivers. Loss of flow across the general head boundary at the downgradient extreme of the aquifer model was measurable, but not significant when compared to other losses, and will not be discussed further.

Figure 4-8 displays the increase over baseline in losses from the aquifer to the river under the previously described conditions. This increase in delivery of water from the aquifer to the river is assumed to be a direct result of the injected water providing increasing driving head to the system and the slug of injected water itself traveling through the system from the injection wells to the points of discharge along the river. The peak of this additional discharge to the river occurs approximately 12 months after the initial injection of recharge water. This indicates that the center of the slug of injected water has reached the river by 12 months after injection. These results indicate, therefore, that this system would be most efficiently operated on a seasonal

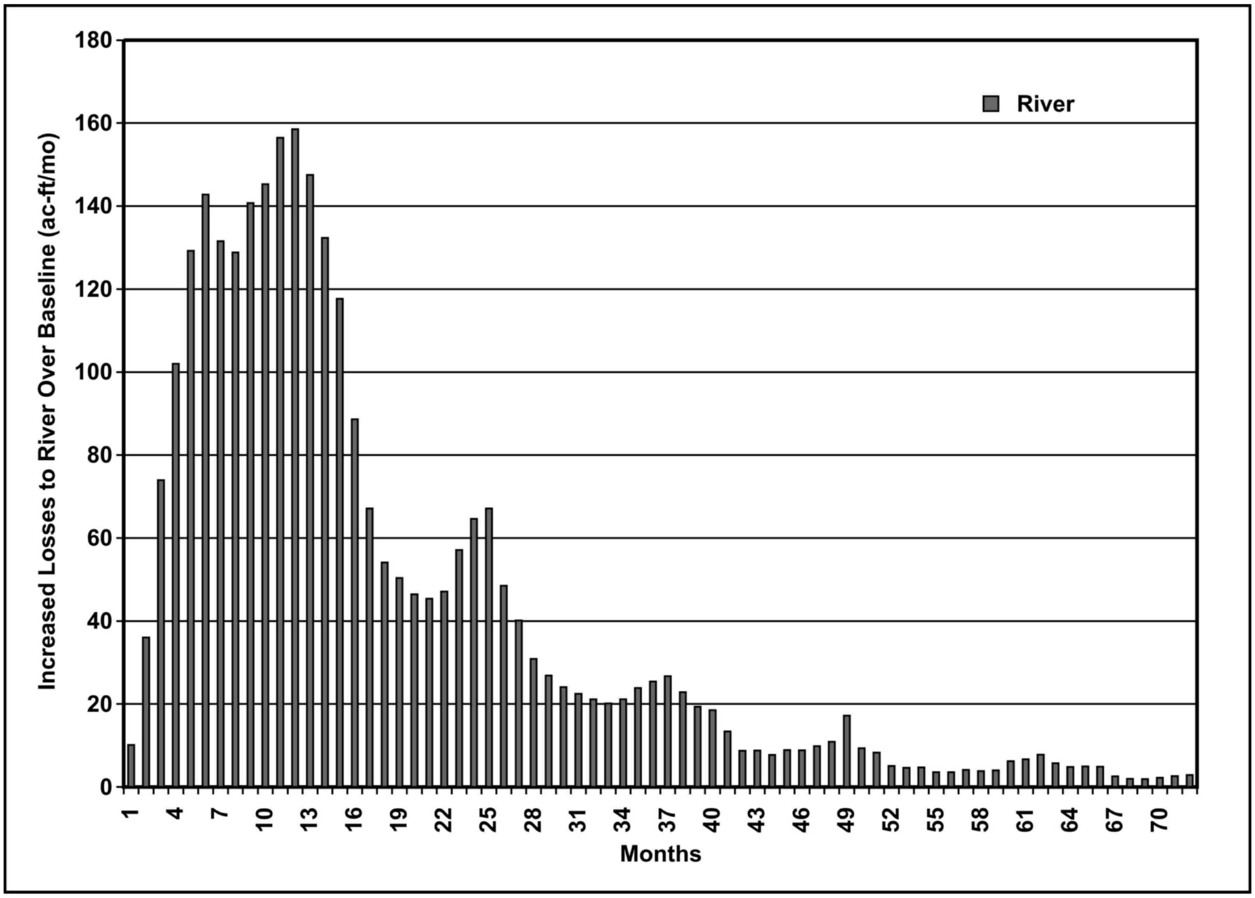

Figure 4-8. Increased river losses due to enhanced recharge slug.

basis, injecting water during the spring and extracting it for delivery during the summer of the same year. If the injected water were not recovered in this time frame, it would gradually be lost to the surrounding natural system. This finding indicates that this conjunctive use project would not be appropriate for long-term storage to be recovered during periodic drought conditions.

Figure 4-9 displays the increase over baseline in losses from the aquifer to evapotranspiration. The injected water raises the water table locally, subjecting it to greater losses from evapotranspiration than would otherwise occur. Note that evapotranspiration losses are cyclical, peaking in the hot summer months and becoming less during the winter. An interesting result that was encountered during initial evapotranspiration tracking runs concerned the location of the injection/extraction well system. Initially the injection/extraction wells were placed in the approximate center of the widest area of the alluvium with the expectation that maximizing the distance from the rivers would be most efficient for preventing losses to the river. However, this resulted in evapotranspiration losses five to six times greater than those represented in Figure 4-9. Upon further inspection of the model graphics and underlying geologic data, it was noted that although the initial well placement maximized distance from the rivers, depth to water was shallower in this area than it was further southwest, closer to the Brazos River. In many instances the initial depth to water prior to injection was fifteen feet or less. Since the depth of influence of evapotranspiration in the model is fifteen feet, this resulted in essentially all of the injection

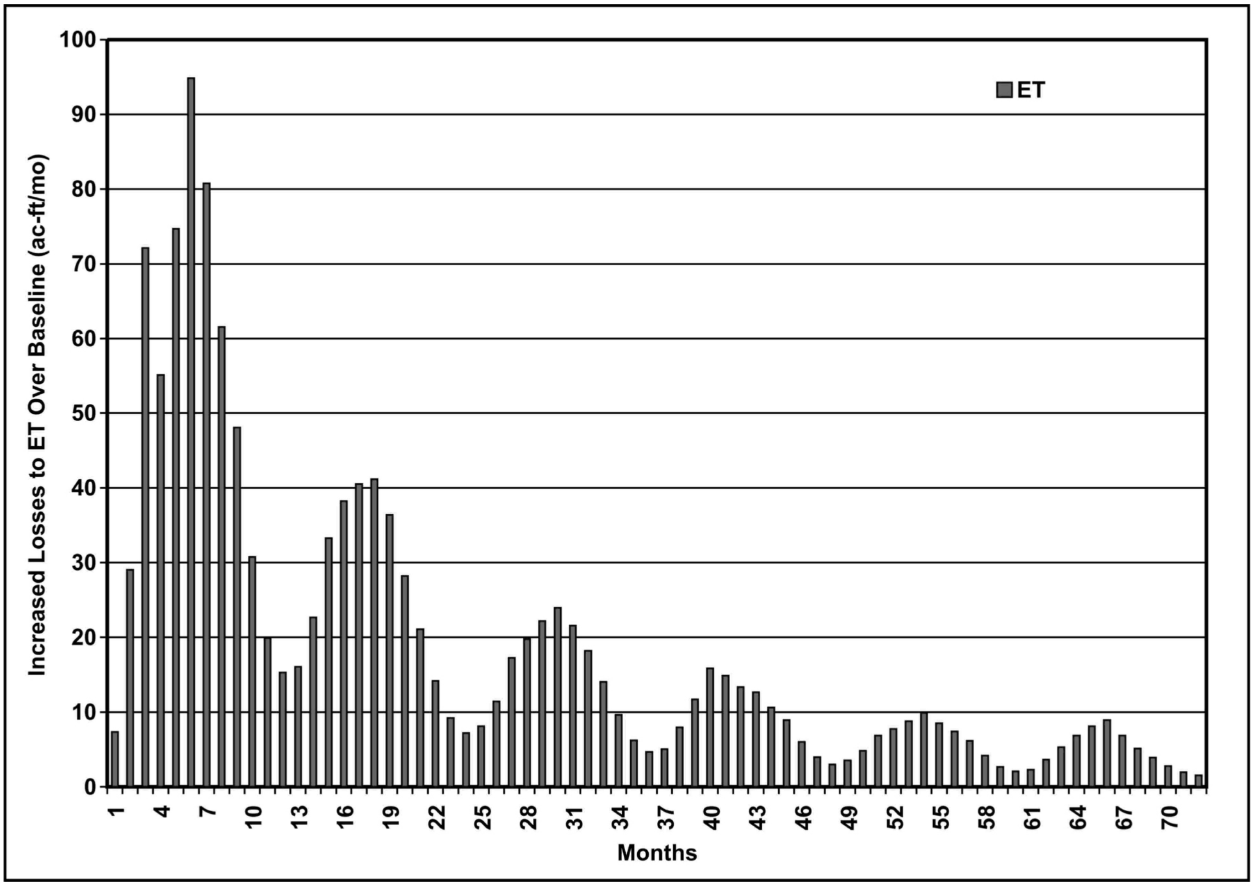

Figure 4-9. Increased evapotranspiration losses due to enhanced recharge slug.

being immediately subject to evapotranspiration losses. In fact, the thickness of the alluvial deposits in the valley is asymmetric, with the deposits considerably thicker near the Brazos River than the Little Brazos River. By moving the injection wells just a little closer to the Brazos River, where there was more “freeboard” between the land surface and the water table, evapotranspiration losses were significantly reduced. Another significant finding is implied in Figure 4-9. As mentioned previously, the evapotranspiration losses from the conjunctive use system are highest during the summer months. However, these are the same months when the extraction wells would be recovering water from the aquifer for delivery to the river. Extraction cycles would reduce the water table in the area, thus reducing evapotranspiration losses during these months.

Conjunctive Use Operational Simulations

To test the effect of operating a conjunctive use project of the Brazos River and the Brazos River Authority, a test case was set up in which the same amount of water (90 acre-feet per day) was injected in the first three months of each year. Extractions were scheduled to take place during June, July, and August of each year. Considering the supply of water in the Brazos River Alluvium and the conjunctive use project, potentially more water may be recovered from the system than was initially injected, due to the presence of pre-existing groundwater reserves at the project site and to the dynamic nature of the natural recharge processes. To evaluate the behavior of the system under different extraction schedules, four test runs were made in which 90 percent, 100 percent, 110 percent, and 125 percent of the amount injected was extracted. These runs are referred to as Tests 1, 2, 3, and 4.

To demonstrate the general effect of the conjunctive use storage and recovery cycles on water levels within the model area, water levels were monitored in two wells during the baseline simulation and with the four test projects. Test 3, where extractions were 110 percent of injections, was chosen as being representative of the general response of the aquifer to a conjunctive use project. The comparative hydrographs for the two wells (59-20-820 and 59-11-308) are displayed in Figure 4-10. In both cases, the results indicate that the cyclical operations would cause short-term water level fluctuations above and below the baseline levels by no more than one to two feet in most cases. Water levels which are elevated above the baseline during the injection cycle are routinely pulled below the baseline levels during the extraction cycle.

Figure 4-11 demonstrates the change in losses to the aquifer over time as compared to the baseline conditions. It is analogous to Figure 4-8, except that the model run simulated six successive years of recharge and recovery cycles. The primary y-axis represents the change over the baseline run in losses to the aquifer system expressed as a percentage of the quantity of water injected. The cycles of injection and extraction are depicted on the secondary y-axis for a time reference. The primary message of this figure is that the greatest losses of this system, and thus the peak inefficiency, occur in the first year of operation when the change in losses over the baseline are over 13 percent of the total quantity injected. This occurs when the project is introducing a large amount of water to an aquifer system that was previously in relative equilibrium and when the water levels were relatively high. With each succeeding year, the losses are reduced as the system moves toward a new stable equilibrium until losses stabilize at approximately two percent of the quantity injected at the end of the 6-year simulation. This “equilibrium efficiency” was lower for the model runs with greater extraction quantities, ranging from five percent for the Test 1 scenario to nearly zero percent for the Test 4 scenario. In other words, the losses form the most aggressive extraction schedule were the closest to the losses calculated in the baseline run. Of course, in the test runs that extracted greater amounts of water, a greater amount of groundwater is removed from storage, and resulting water levels are slightly lower. However, all achieved approximate equilibrium by the end of the six-year run.

Table 4-2 compares the effect of the various test scenarios on cumulative water budget values in comparison to the baseline calculated losses. Note that as the volume of water extracted in the test runs increases, the losses to evapotranspiration and river leakage decrease. This is indicative of the fact that the extraction wells are capturing a quantity of water that otherwise would be lost from the system and is a partial explanation of the phenomenon previously described, wherein higher extraction rates lead to lesser losses from the aquifer in comparison to the baseline.

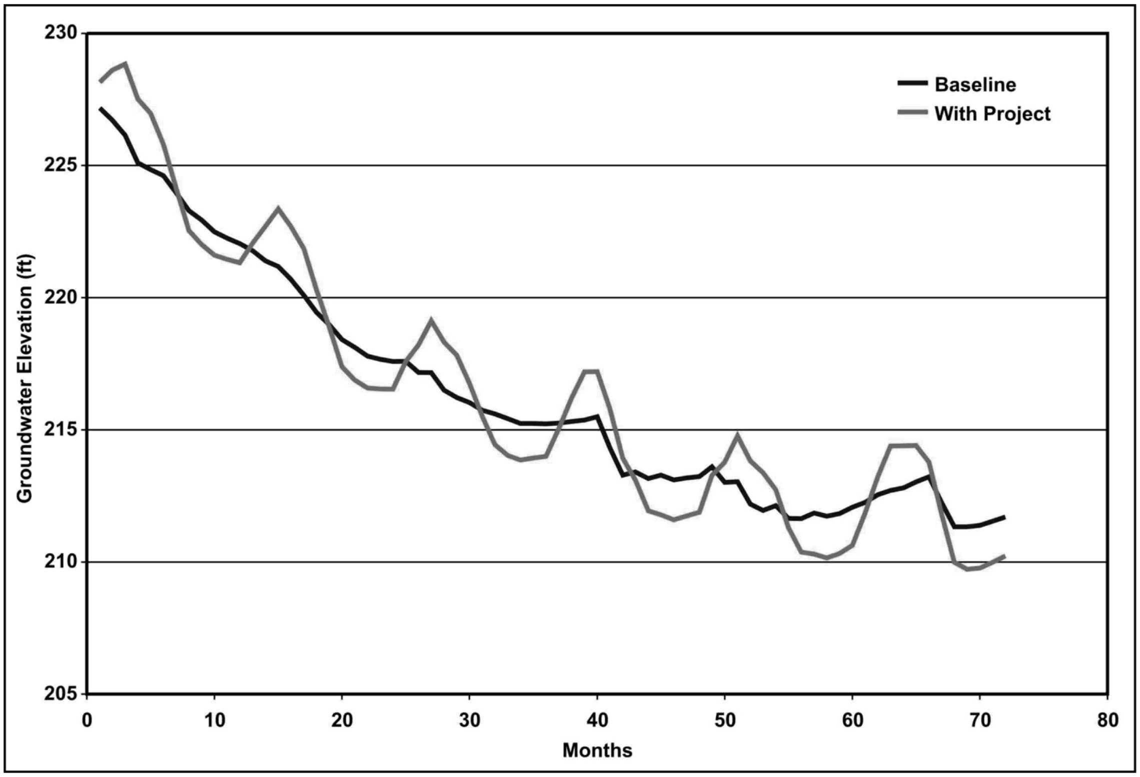

Figure 4-10a. Well 59-20-820 hydrograph with and without project.

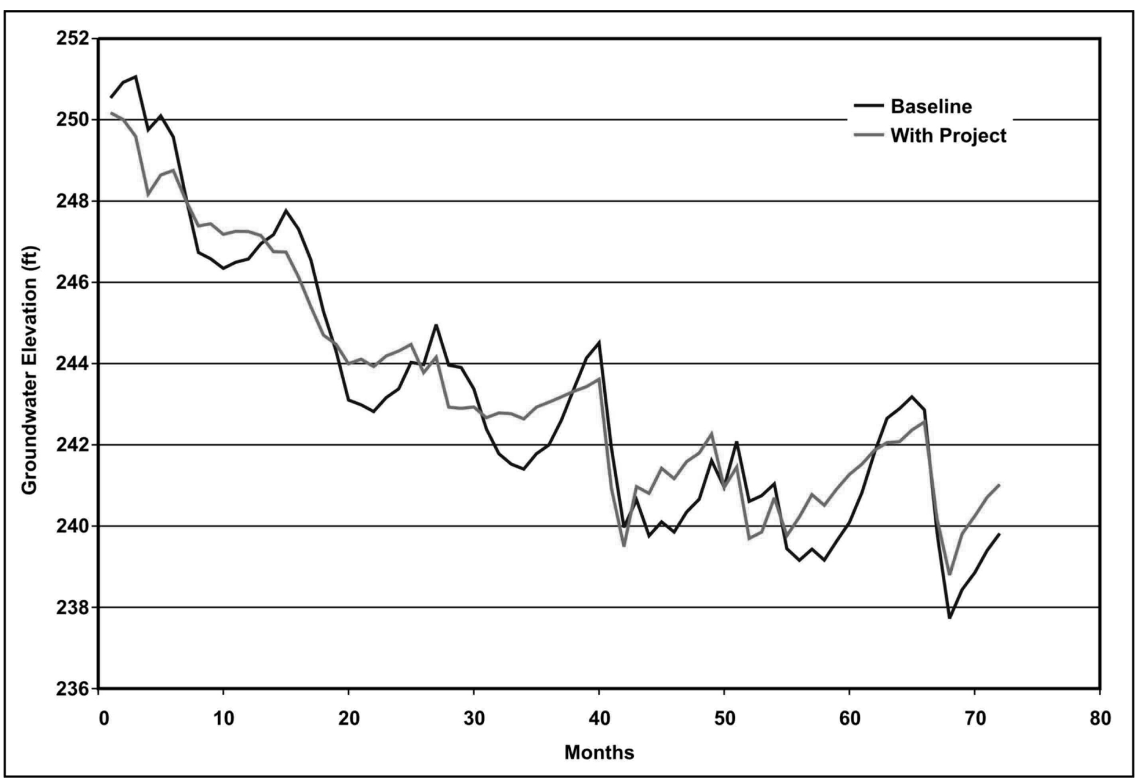

Figure 4-10b. Well 59-11-308 hydrograph with and without project.

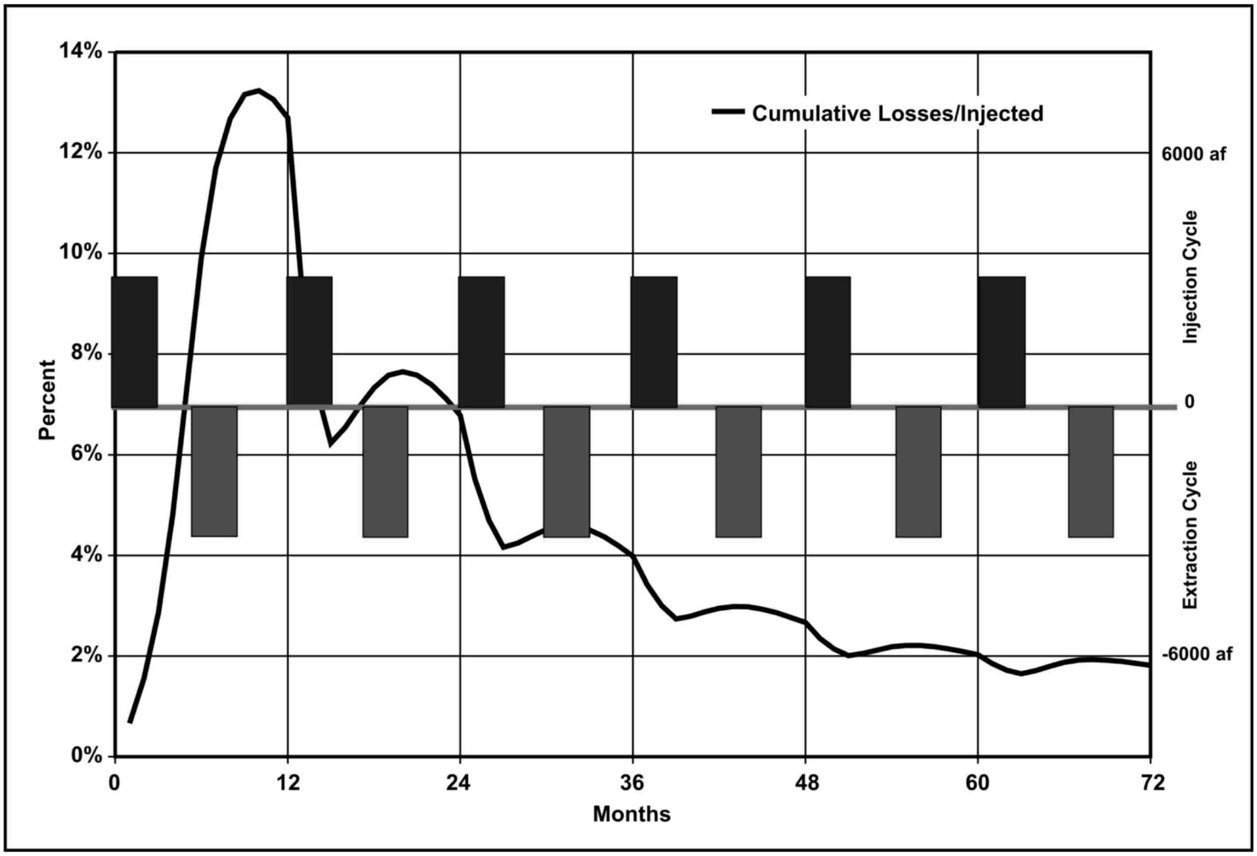

Figure 4-11. Operational losses of enhanced recharge water to natural system.

Table 4-2. A comparison of cumulative water budget values from model test scenarios to baseline calculated values.

	Baseline	Test 1	Test 2	Test3	Test 4
Injection	0	48600	48600	48600	48600
Extraction	0	43740	48600	53460	60750
Evapotranspiration	193414	1136	900	707	528
River Leakage	39851	1570	843	280	-234
Drains	323	17	10	4	-2
Upgradient Boundary	1570	0	0	0	0
Downgradient Boundary	2729	-19	-58	-98	-157
Notes:					
All values in acre-feet, and values are cumulative at end of six-year test period.					
+ indicates greater than baseline.					
- indicates less than baseline.					

Conclusions

The modeling analysis of conjunctive use projects in the Brazos River Alluvium aquifer conducted for this report indicates that the groundwater system studied appears to be suitable for use as a site for a conjunctive use water supply project in the future. Specific findings produced by the model are:

- The travel time for water placed into aquifer storage at the locations indicated in this report is on the order of one year. Thus, the storage/recovery operational cycles should be timed to recover water on a seasonal basis (that is, perform recovery operations less than one year after the storage injection takes place). This will prevent unnecessary losses from the system through leakage to the river.
- Evapotranspiration losses were significantly greater if the infiltration ponds and supply wells were located over areas with shallow water table than a deeper water table. Greater efficiency is obtained from the system by placing wells in areas which maximize "freeboard," or unsaturated zone thickness, rather than by placing them in areas which maximize distance between infiltration ponds and the zones of discharge along the river.
- If extraction and recovery are performed on a seasonal basis, there is little long-term effect on water levels. Temporary fluctuations of water levels due to injection/extraction cycles were only a few feet above and below baseline conditions, even when extraction rates exceeded injection rates.
- The system tends toward greater stability and efficiency with repeated operation. The initial flux of injection water induces a condition of disequilibrium on an aquifer system that was previously in equilibrium. Within the six-year period, the system re-achieves stable equilibrium efficiency. In fact, this efficiency is higher for the recovery schedules which extracted greater quantities of water than were injected, partly due to the capture of water that otherwise would be lost to evapotranspiration and river leakage during the summer months.

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