Edwards Aquifer Authority
San Antonio, Texas

Analysis of Recharge and Recirculation
Edwards Aquifer
Phase 1

September 2004

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San Antonio, Texas

ANALYSIS of RECHARGE and RECIRCULATION

EDWARDS AQUIFER

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Phase 1

Introduction

The concept of recharge and recirculation for the Edwards Aquifer embodies an integrated and coordinated approach to water management. This combines groundwater and surface water sources together with storage units, taking advantage of supply options to store water and thereby optimize the availability of water to pumpers using Edwards Aquifer water during drought periods and to accommodate water needs of endangered species at Comal Springs and San Marcos Springs.

To increase the volume of water stored in the Edwards Aquifer requires a source of water. Numerous possibilities have been suggested and discussed: transfers of water from nearby surface water bodies to the aquifer for recharge, including, for example, Canyon Lake, Lake Dunlap, and Medina Lake; recharge of water released from upstream Type 1 catchment dams; recharge of water from Type 2 recharge dams in the unconfined aquifer zone; and diversions of water from downstream rivers and streams back to the aquifer for recharge. Although not increasing storage, benefits are also possible by transferring water within the confined aquifer zone: pumping water in the western region, for example, to augment water levels and springflows in the east.

The feasibility of recharge and recirculation for the Edwards Aquifer depends upon the ability of the aquifer to retain (i. e., store) water for later use. If a major portion of groundwater flow occurs in highly permeable caverns or conduits, the pressure wave from recharged water may be rapidly dissipated and thereby void the opportunity for long-term storage. Conversely, if most subsurface water moves slowly through small cracks and fractures in the limestone, the retention may be sufficient to provide for long-term storage.

In recent studies, quantitative hydrogeologic conditions within the Edwards Aquifer have been evaluated using GWSIM IV, a numerical groundwater model. This has provided insight into the potential that the aquifer can serve as a storage unit. However, limitations of the model made unclear the accuracy that can be attributed to model results. Recognition of this situation led to a decision by the Edwards Aquifer Authority to support preparation of a new groundwater model employing the new and technically superior MODFLOW program developed by the U. S. Geological Survey, one that today is widely adopted and applied for groundwater investigations (Todd and Mays, 2004). After three years of effort a draft MODFLOW model of the Edwards Aquifer was released in May 2004 by the U. S. Geological Survey in cooperation with the Bureau of Economic Geology, the

University of Texas at Austin. The final model is scheduled for release in September 2004. It is most fortunate that this present recharge and recirculation study has this new model available as a basic tool for gaining an understanding of how the aquifer can be beneficially managed.

Plan of Study

This investigation is organized into four phases of which this report marks the completion of the first phase. The purpose of Phase 1 included several tasks:

1. Collect and review the several background studies and reports pertaining to recharge of the Edwards Aquifer that were conducted to increase water resources beneficially for well production and springflows.

2. Consult with interested water agencies in the San Antonio region.

3. Obtain, understand, and operate the new U. S. Geological Survey MODFLOW model of the Edwards Aquifer.

4. Conduct test runs of the model involving supplemental aquifer recharge to gain insight as to how the model should be operated to estimate water level and springflow responses.

5. Outline a series of recharge scenarios starting from known potential recharge sites to evaluate effects of location and water volume on the areal extent and duration of increased water levels.

6. Prepare a report summarizing the above tasks and serving as a proposal to the Edwards Aquifer Authority for work to be performed in Phase 2 of the study.

The Phase 2 study will focus on model runs selected in Phase 1, analysis of the results to understand how the Edwards Aquifer functions as an hydraulic mechanism, selection of recharge sites and rates that deserve further study, and preparation of a report summarizing Phase 2 work and serving as a proposal to the Edwards Aquifer Authority for work to be performed in Phase 3.

The Phase 3 study will evaluate selected recharge sites in terms of how they could augment springflows under drought conditions or increase water resources without impacting springs and provide estimates of relative costs based on previous investigations for specific facilities.

In Phase 4 results of the entire study will be summarized to form a comprehensive report that will serve as a basis for subsequent feasibility investigations.

Previous Investigations

Over the last thirty years there has been a concerted effort to understand the Edwards Aquifer in terms of its ability to store and transmit water not only because of its size and geologic uniqueness but also, and most importantly, because of its role as a source to meet major water supply demands and to maintain environmentally significant springflows. These diverse investigations can be generally grouped into

four categories: geologic structure, aquifer recharge, aquifer modeling, and aquifer management. References to key contributions are listed at the end of this report. What these results do is give us a good but not a perfect awareness of how the aquifer functions. We are therefore in a better position today to study aquifer management and optimization alternatives than ever before in history.

The San Antonio office of the U. S. Geological Survey has historically been the primary contributor of knowledge about the Edwards Aquifer. Much of this is summarized in Maclay (1995) followed by work of Barker and Ardis (1996) and Groschen (1996). Studies conducted elsewhere include work by Hovorka (1998) and Tomasko (2001) on details of aquifer permeability and hydraulic responses, respectively.

The availability of water from the aquifer clearly depends upon the magnitude of its recharge. First to look at natural recharge was Puente (1978) followed in more recent years by a series of studies on natural recharge and augmented recharge: HDR & Espey (1993) on the Guadalupe-San Antonio River Basin; HDR (1994a) on the Nueces River Basin; HDR (1998a) on the entire aquifer; HDR (1998c) on the Guadalupe River Basin; and lastly HDR (2002) on the Nueces and Blanco River Basins.

The ability to study the response of an entire aquifer to recharge and discharge became a reality beginning in the 1960s with development of computer models of aquifers. The first such pioneering effort on Edwards Aquifer was the work of Klemt, et al. (1979) on the GWSIM model for the then Texas Department of Water Resources. The U. S. Geological Survey revised and extended the model (Maclay and Land, 1988); subsequently Thorkildsen and McElhaney (1992) made further improvements for the Texas Water Development Board. Most recently refined simulations and travel time estimates of groundwater flow in the Edwards Aquifer were undertaken by U. S. Geological Survey personnel (Kuniansky and Holligan, 1994 and Kuniansky et al., 2001), respectively. However, all investigators recognized that the early models could not accurately reproduce historic water levels and springflows. In view of this limitation, together with an awareness that a new and improved groundwater model, MODFLOW, had been developed by the U. S. Geological Survey (McDonald and Harbaugh, 1988), plans were made to construct a MODFLOW model of the Edwards Aquifer. This effort by the U. S. Geological Survey in cooperation with the Bureau of Economic Geology, the University of Texas at Austin and the Edwards Aquifer Authority is scheduled for completion in September 2004 (Lindgren et al., 2004). As a result this study is the first to have the advantage of applying the new model to evaluate impacts of augmented recharge.

Within the last ten years a comprehensive Trans-Texas Water Program was undertaken by the Texas Water Development Board to determine projected water demands and supplies and to identify possible water supply alternatives to meet future needs. The West Central Study Area of this program embraced the Edwards

Aquifer within its 33-county coverage. As part of this program a series of studies, including how to manage the Edwards Aquifer by supplemental recharge, were completed by HDR Engineering (1994b, 1995, 1998b). In addition a specific study of springflow augmentation was undertaken at the University of Texas at Austin (McKinney and Sharp, 1995). Most recently the Texas Water Development Board completed a revised Texas Water Plan that for the Edwards Aquifer involves a regional water plan prepared by the South Central Texas Regional Water Planning Group (SCTRWPG, 2001a, b, c). Collectively these studies have included considerations for managing Edwards Aquifer by some form of artificial recharge that increases available water for wells and springs.

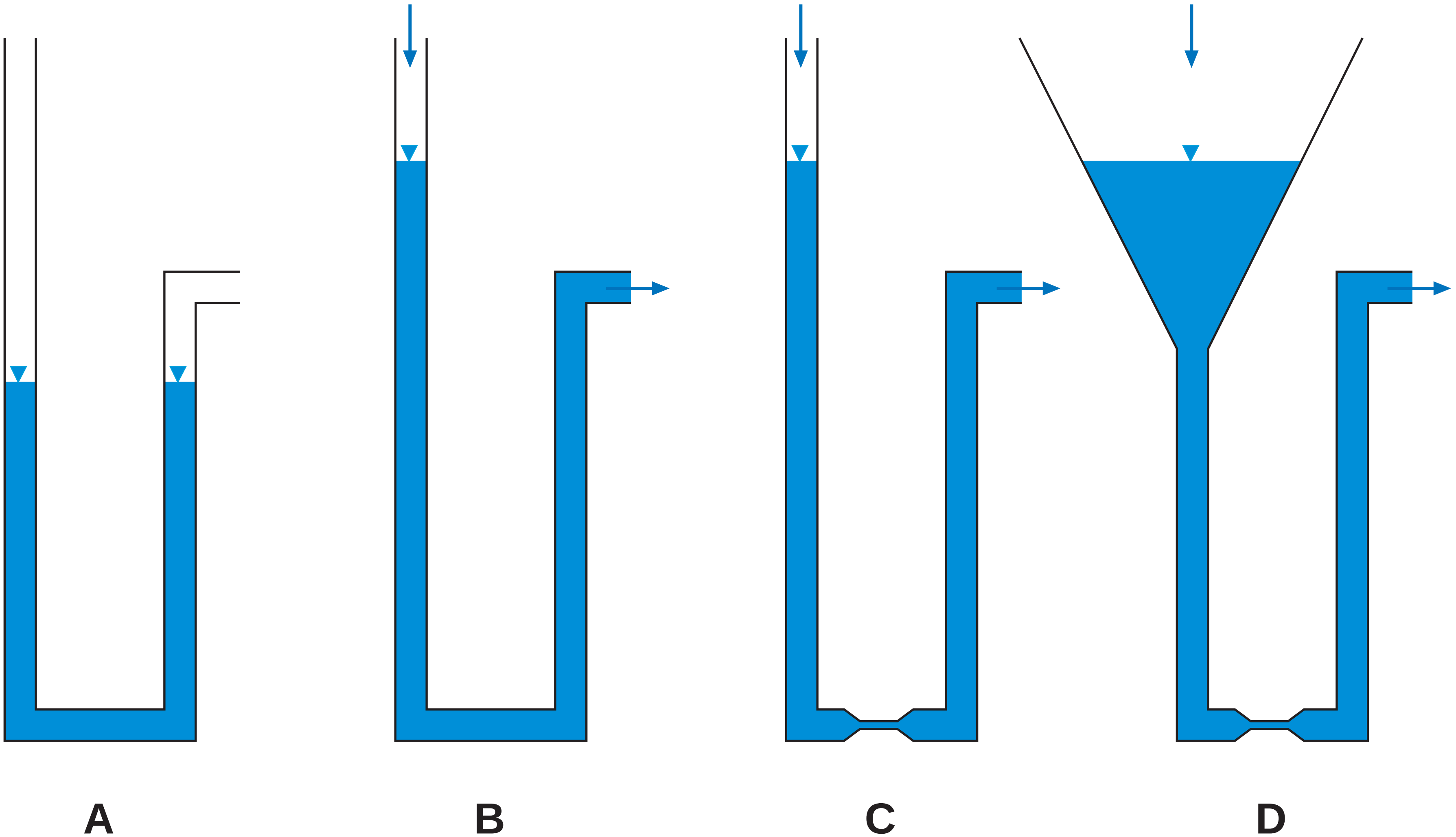
Physical Concept of Edwards Aquifer

The Edwards Aquifer is a karst aquifer that is characterized by the presence of sinkholes, sinking streams, caves, springs, and a well-integrated subsurface drainage system. It is one of the most productive groundwater systems in the United States, characterized by extremely productive water wells and high spring discharges. The aquifer exhibits extremely high (cavernous) porosity and permeability which are typical of many karst aquifers and enables groundwater levels to respond quickly to rainfall (recharge) events.

Development of the MODFLOW model for the Edwards Aquifer by the U. S. Geological Survey was based on defining how water is stored and flows through the aquifer system. Beginning with a water balance approach, the model design was initiated with the recognition that the total water recharging the aquifer minus the total water discharging from the aquifer must over a given time interval equal the change in water storage expressed as changes in water levels throughout the aquifer.

From a hydraulic standpoint it is useful to picture the aquifer as a modified form of a simple U-tube. Consider the static case of a U-tube shown in Figure 1A. A small volume of water poured into the left tube will partially flow into the right tube so as to exactly balance the levels in both tubes; in other words the water pressure is equal on the two sides and hence no flow of water occurs. For the dynamic case in Figure 1B water is poured into the left tube at a constant rate. Here the water level in the left tube stands above the outlet in the right tube; as a consequence the pressure difference causes water to discharge from the outlet. It follows that the flow rate entering the left tube exactly equals that discharging from the right tube.

In Figure 1C the U-tube is modified by placing a narrow neck in a portion of the tube, thereby constricting water flow from left to right. Water again flows at a constant rate through this U-tube; however, to maintain the same levels as in Figure 1B, it is apparent that the flow rate in Figure 1C will be smaller due to the restriction caused by the neck. Consider now the transient case in which inflows in Figure 1B and 1C are stopped at the same moment. Water discharging from the



September 2004	**Figure 1**
Todd Engineers Emeryville, California	**Illustrative U-Tube Flows**

Figure 1C tube will continue to flow for a longer period of time as a result of its slower flow rate.

Now with a further change in U-tube design, increase the size of the left tube as in Figure 1D. The flows in Figures 1C and 1D encounter the same flow restriction; therefore, flow rates will be equal if levels are maintained equal. In other words water pressure, or head, is defined by water level and is independent of water volume.

Finally, in the last of these hydraulic examples, let the inflows stop in the Figure 1C and 1D tubes at the same instant. It should be apparent that flow continues in the Figure 1D tube longer because of the greater water volume in storage. It is this concept of variable storage and flow in a U-tube that can by analogy be transposed to the Edwards Aquifer where maintenance of high groundwater levels by artificial recharge in the western portion of the aquifer, aided by the restricting influence of low permeability in Knippa Gap, located in southeastern Uvalde County, could help to sustain downstream springflows during drought periods.

Figure 2, applying the U-tube concept, presents a simplified hydraulic version of flow in the Edwards Aquifer from west to east. Water enters through various tributary recharge areas along the northern boundary, of which those in Kinney, Uvalde, and Medina Counties together constitute the major (68 percent) contribution. These western flows in the aquifer traverse southward, converge through the limited flow space existing in the Knippa Gap, a few miles west of Sabinal, and thence move eastward to discharge through wells and the major springs. Beyond San Marcos Springs groundwater flow approaches a no-flow divide marking the boundary where the Barton Springs portion of the aquifer begins. Note that springflows originate from a combination of water coming from west of Knippa Gap and from recharge areas much closer to the springs. It is the damming effect of Knippa Gap that offers the possibility of supporting springflows during drought periods. One question in this flow system is the role of Leona Springs, situated west of Knippa Gap, which could function as an upstream exit point for high water levels and remains to be examined in detail.

Clearly Figure 2 is a symbolic representation of the Edwards Aquifer. What the MODFLOW model does is to take this schematic format and transpose it into quantitative values of actual recharge, discharge, and water levels. The entire aquifer is in dynamic equilibrium, which means that all of the variables---recharge, springflows, and well pumpage—define water levels as a function of time. The model has been calibrated over a 60-year period embracing the drought of the 1950s as well as the wet years of the 1990s; therefore, it can reveal how given recharge efforts may supplement pumpage and springflows in times of drought.

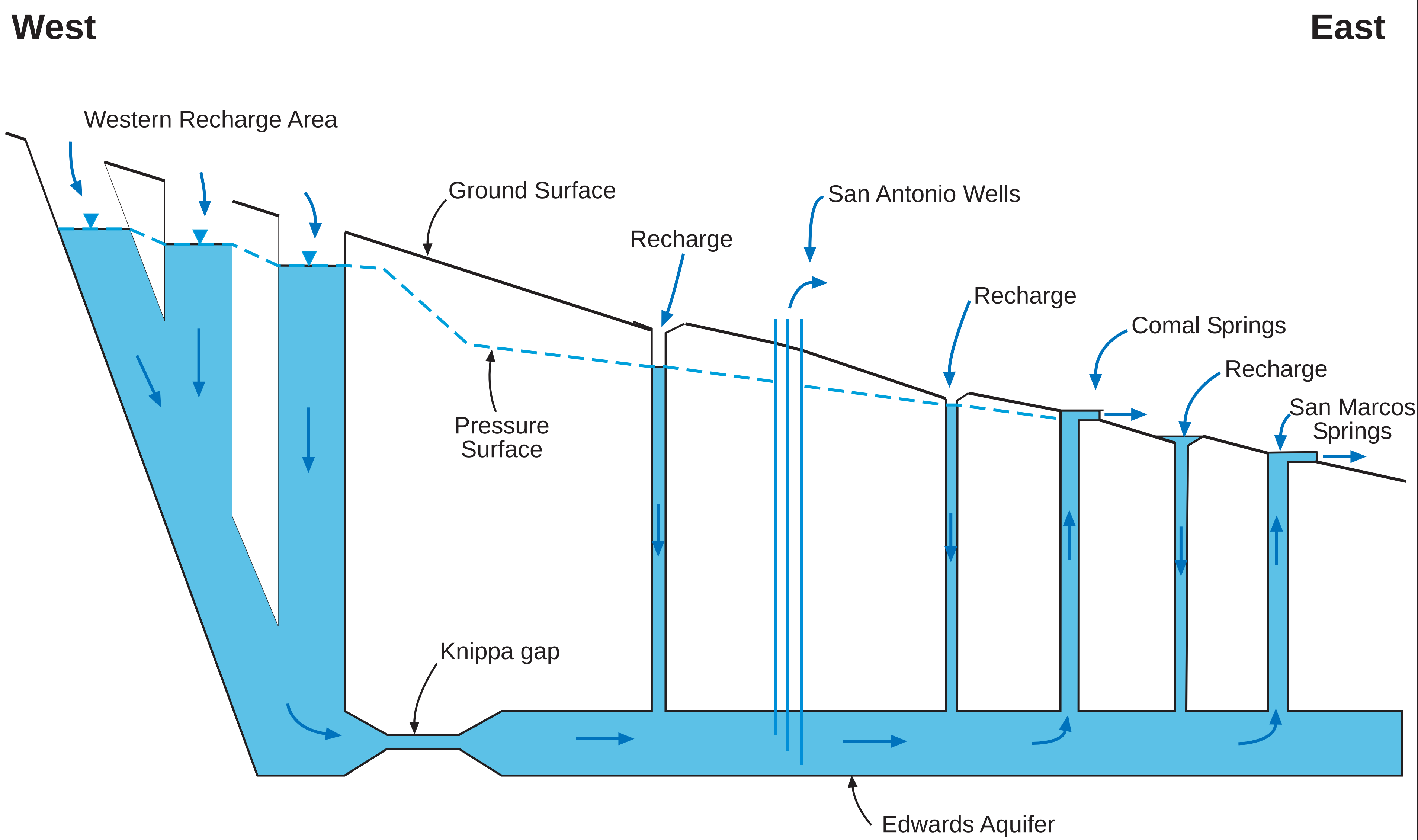


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Figure 2
Schematic Representation of Edwards Aquifer Flows

Sources of Recharge

To make more water available for wells and springs supplied by the Edwards Aquifer requires artificial recharge over and above that received by natural recharge. The largest source for such water is runoff from precipitation falling on the extensive drainage area located north of the Edwards Aquifer and flowing southeastward across the aquifer in accordance with the topography sloping downward toward the Gulf of Mexico. This area is shown in Figure 3 in relation to the recharge and confined zones of the aquifer.

The drainage basins comprising the tributary area consist, from west to east, of the following streams: Nueces River, Dry Frio River, Frio River, Sabinal River, Seco Creek, Hondo Creek, Medina River, Leon Creek, San Antonio River, Salado Creek, Cibolo Creek, Dry Comal Creek, Guadalupe River, and Blanco River, as shown in Figure 4. It is important to recognize that the large northern drainage area supplies water to a relatively narrow recharge zone where the aquifer outcrops at ground surface before dipping southward beneath relatively impermeable overlying geologic strata. In the western area of Kinney and Uvalde Counties, the recharge zone is largest and exceeds the area of the confined zone (see Figure 5). In the central area of Medina and Bexar Counties, the recharge zone is small with the confined zone being large. In the eastern region the recharge zone predominates while the confined zone reduces to an extremely narrow strip.

The magnitudes of annual recharge to Edwards Aquifer have been reported by the U. S. Geological Survey since 1934 (Hicks et al., 2002) based on streamflow gaging data for stations shown in Figure 4. To indicate the relative magnitude of these recharge sources, maximum, minimum, and median annual values are listed in Table 1. Note the wide variability between wet year maxima and drought year minima. The maxima are generally several times greater than even the medians, an exception being Medina River Basin where Medina Lake provides a regulatory effect on flows.

The series of studies by HDR Engineering on recharge to Edwards Aquifer (see References for a listing) provides detailed information as to quantities of augmented water and costs that can be expected from structures constructed to intercept and recharge streamflows from the tributary drainage area. Two kinds of dams were proposed, as illustrated in Figure 5: Type 1 structures on stream channels in the drainage area and Type 2 structures on stream channels within the recharge area. Water collected behind a Type 1 structure would be held for subsequent release at a rate permitting it to be infiltrated downstream in the recharge area. In contrast a Type 2 structure would be designed to hold streamflow for direct infiltration so that it does not continue past the confined zone where it could not reach the aquifer. Locations of proposed recharge enhancement projects are presented in Figure 6 based on work of SCTRWPG (2001c). Clearly, the more

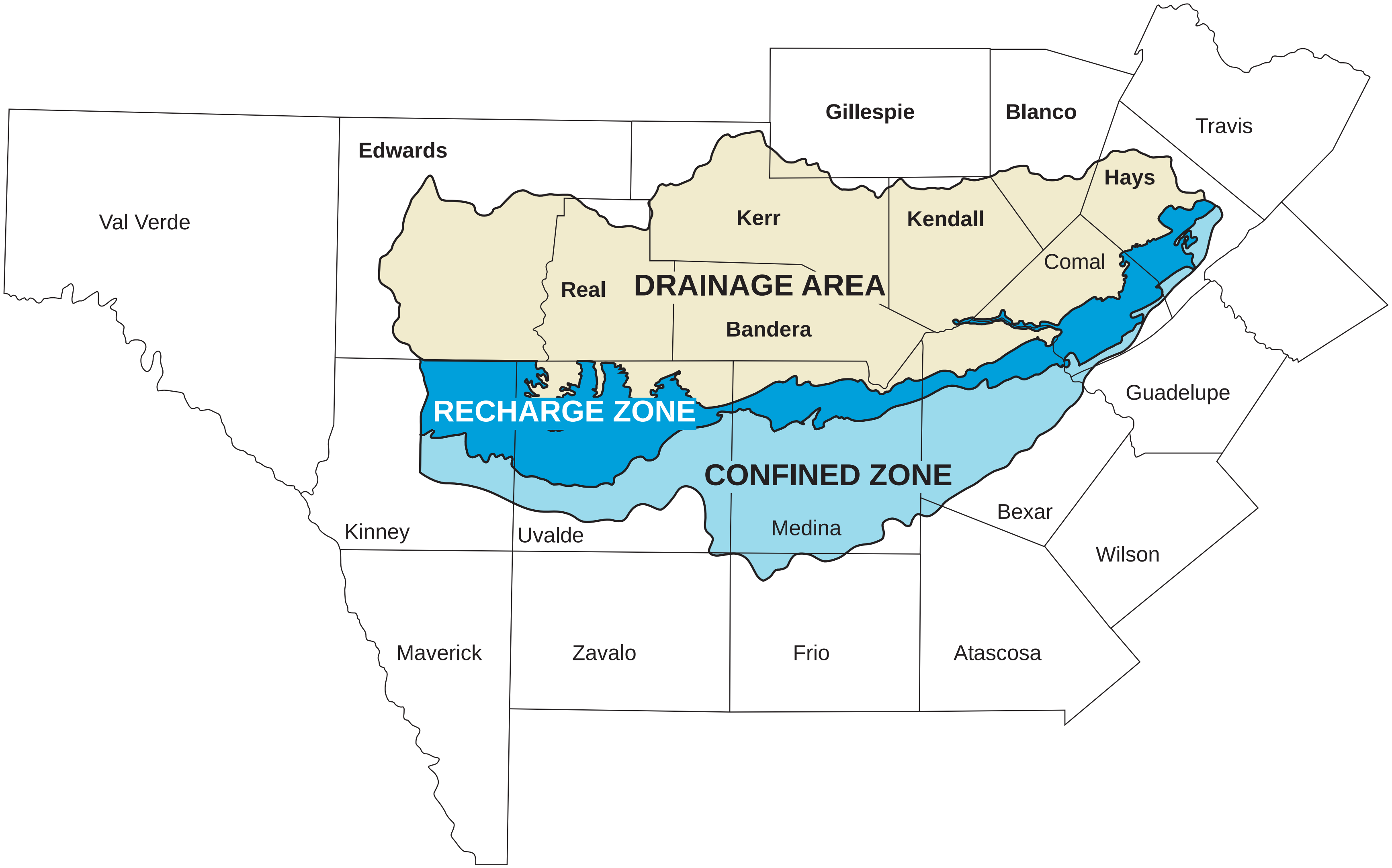

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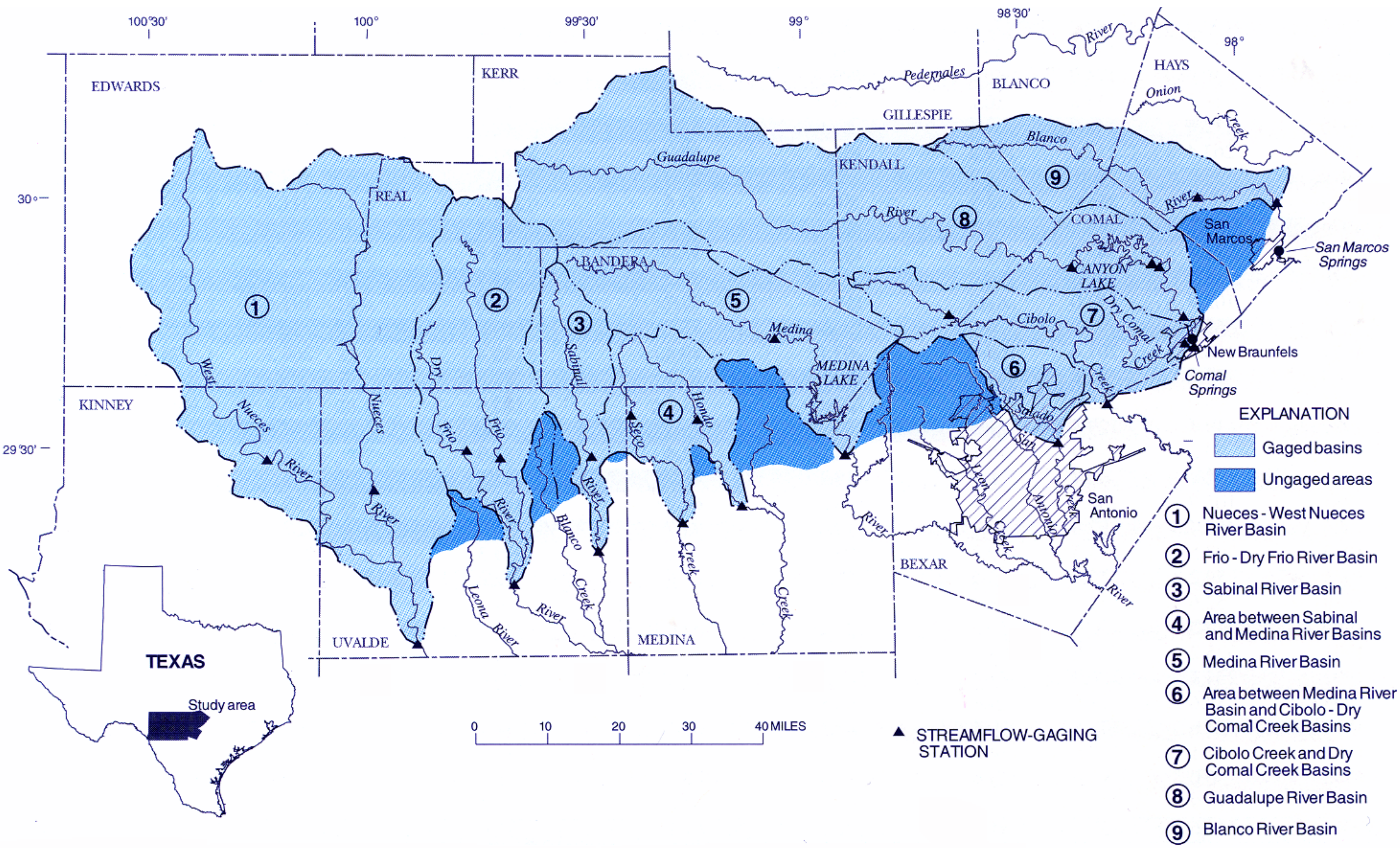
Figure 3
Edwards Aquifer and Drainage Area



After: U.S. Geological Survey.

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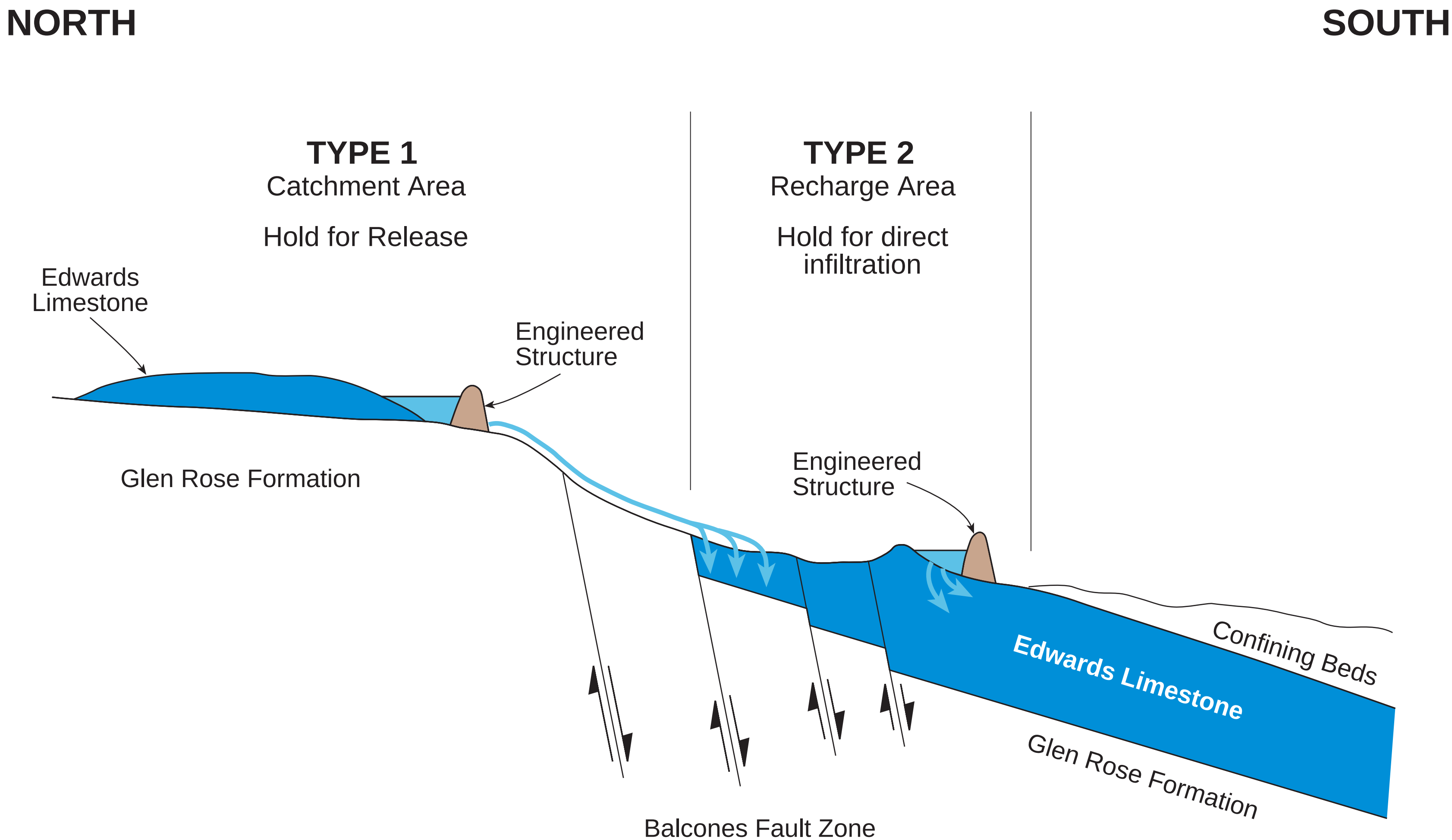
Figure 4
Drainage Basins Supplying Edwards Aquifer



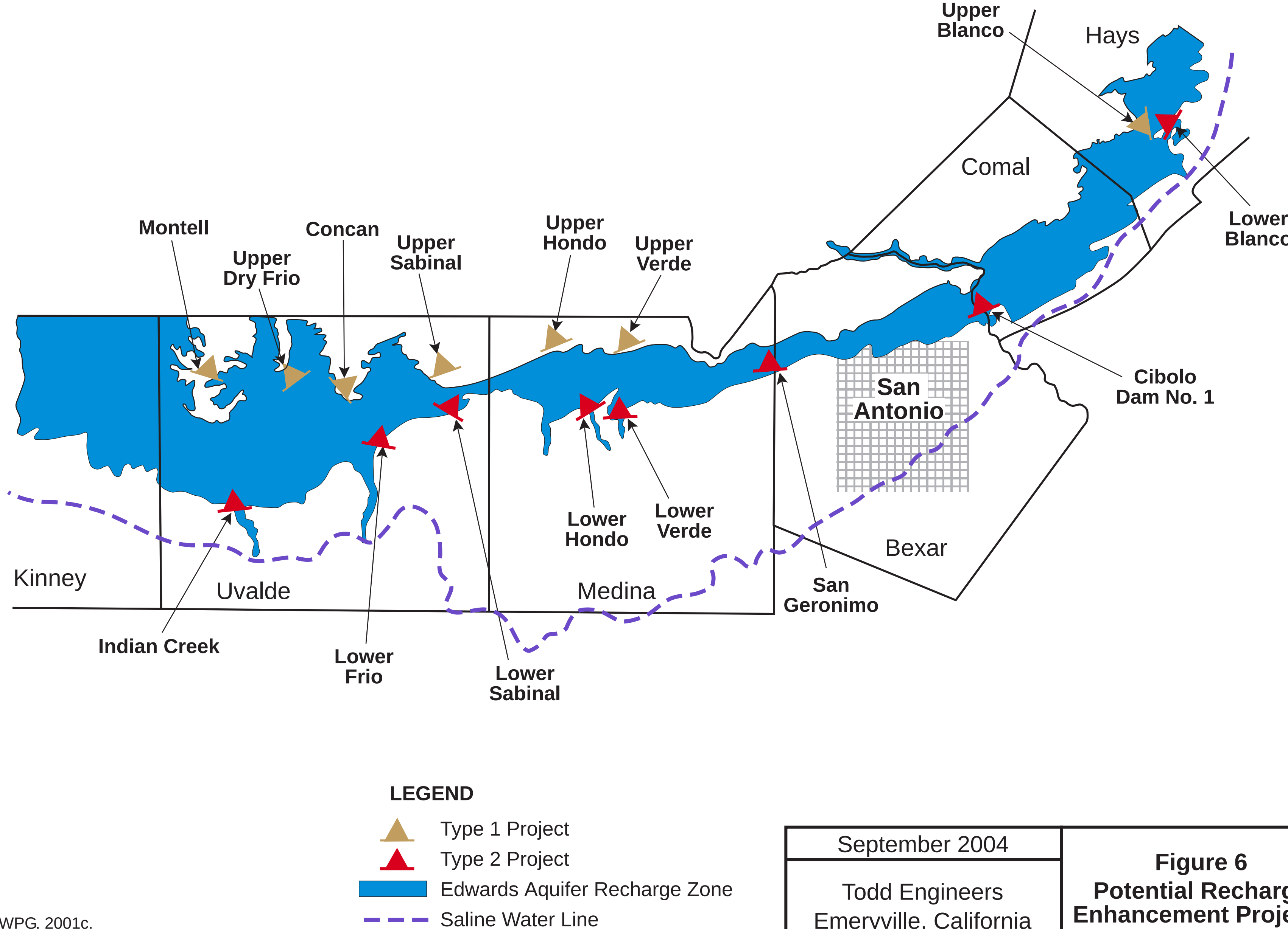
After: HDR Engineering, Inc.

September 2004	**Figure 5**
Todd Engineers Emeryville, California	**Types of Recharge Reservoirs**

Table 1. Estimated Annual Recharge
Contributing to Edwards Aquifer, 1934-2001*
(Thousands of acre-feet)

Basin or Ungaged Area	Maximum	Minimum	Median
Nueces River / West Nueces River Basin	479	9	102
Frio River / Dry Frio River Basin	587	4	123
Sabinal River Basin	224	1	31
Area Between Sabinal River and Medina River Basin	566	4	78
Medina River Basin	104	6	60
Area Between Medina River and Cibolo Creek / Dry Comal Creek Basin	291	4	50
Cibolo Creek / Dry Comal Creek Basin	398	2	77
Blanco River Basin	229	8	34

*Data source: U.S. Geological Survey and Edwards Aquifer Authority



Ref: SCTRWPG, 2001c.

September 2004	**Figure 6**
Todd Engineers Emeryville, California	**Potential Recharge Enhancement Projects**

of these projects completed, the more supplemental water becomes available to the aquifer.

Besides the tributary drainage area, water can also be brought to Edwards Aquifer from other outside surface water sources. Investigations have considered transporting, for example, water from Canyon Lake and Lake Dunlap to the aquifer for recharge. Another possibility is that of intercepting water from the Guadalupe River Basin downstream from Comal and San Marcos Springs and recirculating it to the recharge zone of the aquifer as suggested by Figure 7. Such sources, as well as more distant ones, depend not only on the physical availability of water but also on economic, water quality, and water rights considerations.

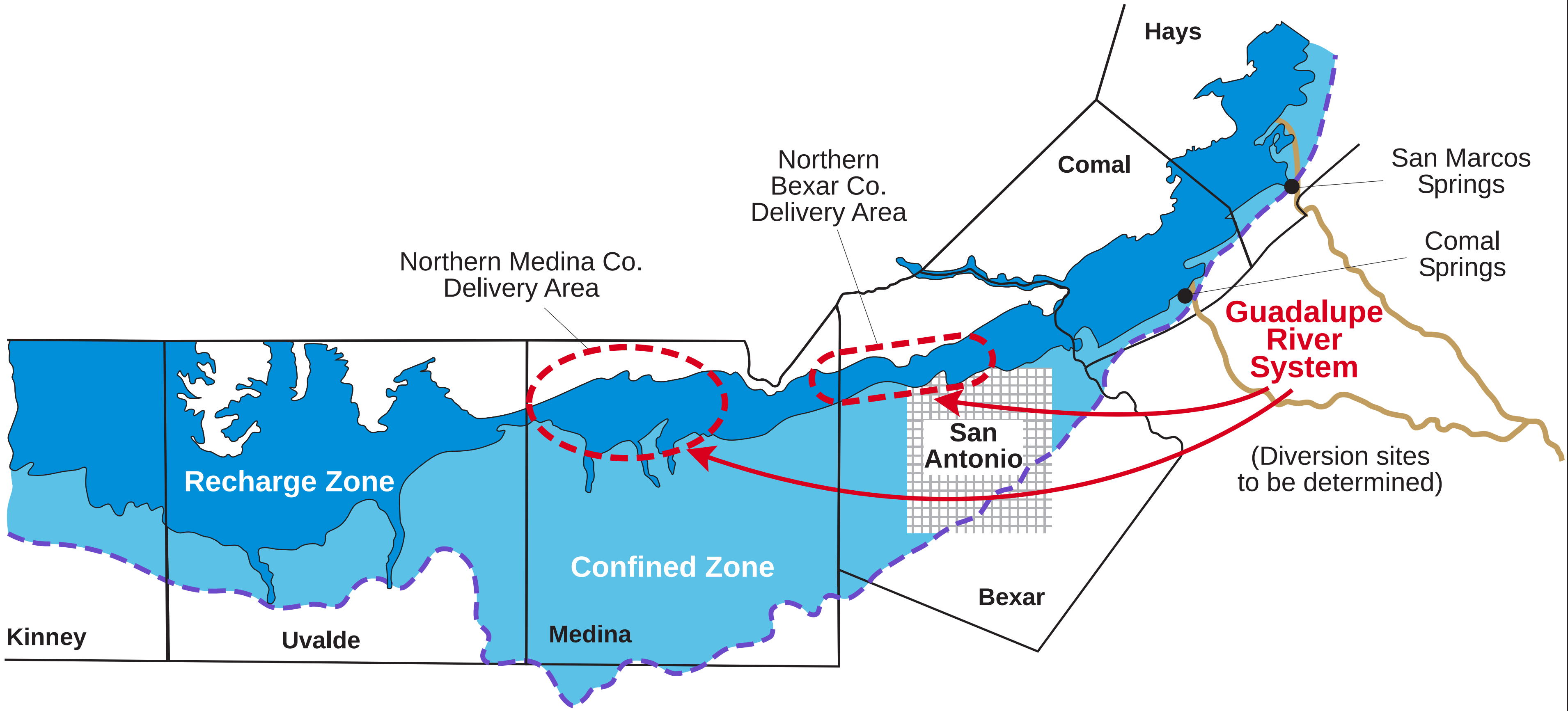
The MODFLOW Model

The Edwards Aquifer model was developed by the U. S. Geological Survey and the Texas Bureau of Economic Geology. It will be published as a Water Resources Investigation Report (Lindgren, 2004). The simulation is a finite difference model based on MODFLOW 2000 (Harbaugh, et al., 2000) and the pre- and post-processor Groundwater Vistas 3. Incorporating the latest information and conceptualization of the Edwards Aquifer, the conceptual model was developed by a panel of advisors, the Ground-Water Model Advisory Panel (GWMAP) composed of representatives from local, regional, and state agencies; consultants with direct experience modeling the Edwards Aquifer; and national and international experts on karst hydrology. Constructed with a goal to provide an improved understanding of the basin, the model will enable hydrologic responses to be evaluated for a variety of alternative aquifer operational proposals.

Initially the USGS reviewed previous models constructed for the same area, used some of the same information, and made improvements as appropriate. Key features added by the new model include:

- **A user-interface**
- **An updated model code**
- **A finer grid resolution**
- **Less restrictive boundary conditions**
- **Improved discretization of hydraulic conductivity**
- **Better estimates of well pumpage**
- **A longer period of record**
- **Refined aquifer conduits**
- **A better simulation of known hydraulic heads**
- **An expanded study area**

The model simulated the period 1946 through 2000. The first year was modeled as a steady state simulation using input water levels based on the average for the period 1939-1946 with no changes to inflows or outflows of groundwater. The remainder of the model, 1947-2000, was a transient simulation in which inflows,



After: HDR Engineering.

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Figure 7
Conceptual Diagram
Springflow Recirculation

pumpage, and springflows varied each month. The stress period for input data to the model was one month; however, the time step for model output was one day so as to define daily changes in the aquifer.

Model Grid

The USGS model grid covers over 10 million acres and contains 259,000 cells (370 rows by 700 columns). All cells are squares measuring one-quarter mile on a side (1,320 ft by 1,320 ft). A single layer represented the aquifer to reduce complexity and uncertainty concerning the location of geologic units at depth. The grid was rotated 35º counterclockwise as shown in Figure 8 to align cells with the general direction of regional geologic structure.

Model Boundaries

Boundaries of the model were selected, where possible, at physical limits of the aquifer. The northern boundary of the model is the northern physical limit of the Edwards Aquifer. To account for inflow from the underlying Glen Rose Limestone of the Trinity aquifer, a head-dependent boundary was applied in the steady-state simulation. This boundary allows the volume of water flowing into the model to vary in concert with groundwater levels in the northern portion of the aquifer. During the transient simulation the MODFLOW well package was used to specify flow coming into the model area. This specified flow boundary was adopted because it assumes fluctuations of levels in the Trinity and Edwards Aquifers along the boundary are similar and the head gradient remains constant.

In the east the model extends to the Colorado River, a regional sink for the aquifer, and therefore a natural boundary. The southern boundary is the fresh water/saline water interface at the10,000 mg/L concentration contour, treated as a no flow boundary. This boundary was simulated as a no flow boundary under the assumption that lateral flow between fresh and saline water is minimal.

A groundwater divide exists in the western area of the Edwards Aquifer near Brackettville in Kinney County. Although poorly defined, it serves as the western boundary for lack of a clearer natural boundary. Flow across the divide is assumed to be minimal so that a no-flow boundary could be assigned. During calibration the northern part of the western boundary was changed to a specified flow boundary based on a matching of measured hydraulic heads near the boundary.

Faults and Conduits

The Edwards Aquifer in the Balcones Fault Zone contains an extensive series of parallel faults with a northeast-southwest orientation. Some of these undoubtedly impede groundwater flow, while others serve as primary groundwater flow paths. Impedance faults were simulated using MODFLOW's horizontal-flow barrier package. Here barriers were applied between cells of simulated porous media and assigned relatively low hydraulic conductivities. These barriers were placed in the model based on an areal map of faults in the aquifer and on the assumption that fault displacements of more than 50 percent would serve as flow barriers. Barrier

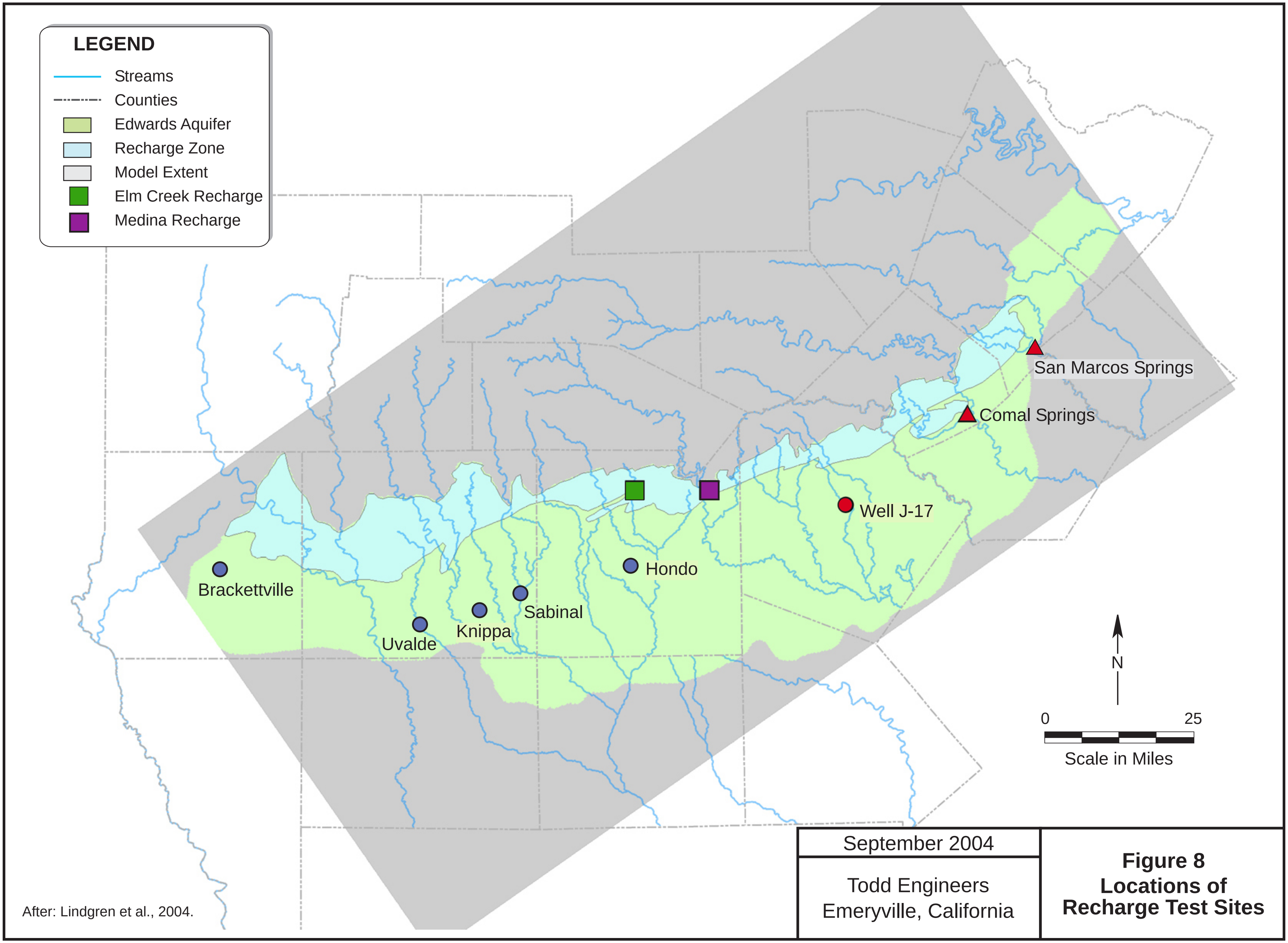

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Figure 8
Locations of Recharge Test Sites

hydraulic conductivities varied with displacement of individual faults and were estimated and revised during calibration.

Because the Edwards Aquifer is a karst formation, it contains interconnected conduits that are indicated by the presence of unique subterranean biology, large production wells, rapid responses to rainfall events, and the formation of extremely large springs. To represent these the model includes a discrete network of conduits (see Figure 9) represented by a series of interconnected high transmissivity cells. Worthington et al. (2004) defined conduit locations based on the presence of troughs in the potentiometric surface, known geological structure, and water chemistry variations. Each conduit was simulated as a one-cell wide line of high hydraulic conductivity, ranging from 5,000 ft/d to 300,000 ft/d. An exception was a short conduit two cells wide approaching Comal Springs. Conductivities of the conduits and some locations were revised during the calibration process.

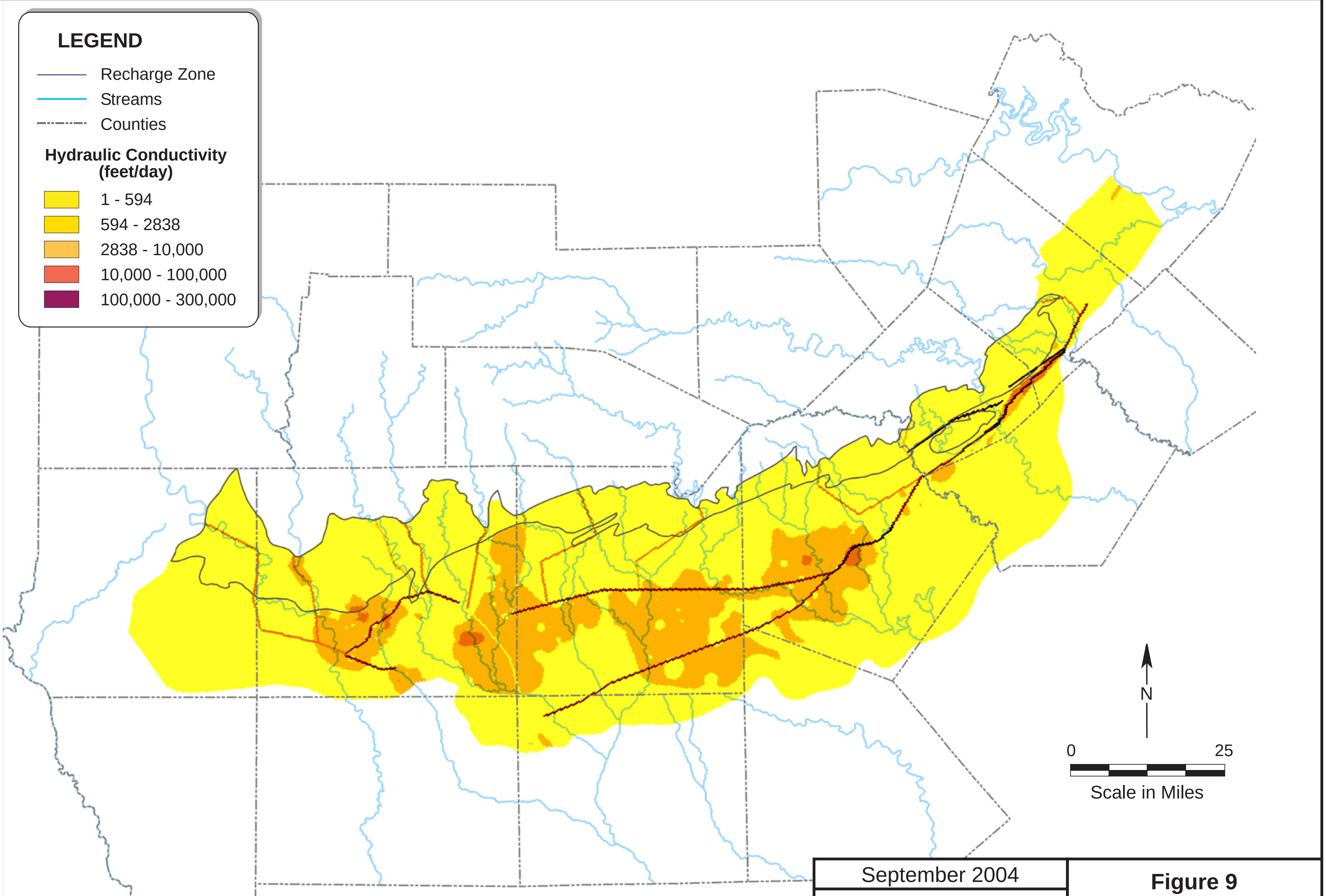
Aquifer Properties

Aquifer properties of hydraulic conductivity and storativity were applied to every active cell. The transmissivity of a cell is the product of the thickness of the aquifer and its conductivity; each cell value is calculated within the model. The hydraulic conductivity distribution within the model was developed by Painter et al. (2002) based on geostatistics and is illustrated in Figure 9. The high hydraulic conductivity of conduits was superimposed on this distribution, which modified Painter's values in the vicinity of each conduit. The storativity of each model cell was applied during transient simulation; initially uniform values were assigned and then revised as the model was calibrated.

Recharge and Discharge

The model simulates water inflows and outflows of the Edwards Aquifer. Most inflow occurs by recharge, primarily (85 percent) by subsurface inflow from surface runoff generated on the tributary streams to the north of the aquifer (see Figure 4). Stream seepage was based on monthly recharge rates calculated by the USGS. Recharge also occurs from infiltration of precipitation on the recharge zone; none is assumed to occur over the confined portion of the aquifer.

Discharge from the Edwards Aquifer occurs from pumping wells and springflows. Pumping rates from wells were compiled on a county basis for municipal, irrigation, and industrial purposes for the period 1939-2000. Pumping for mining, livestock, and power were excluded as these represent less than 3 percent of total groundwater use in most counties. Springflows simulated in the model included Comal, San Marcos, Leona, San Antonio, and San Pedro Springs. Barton and Las Moras Springs were also simulated in the model but were not used for calibration. These seven springs were simulated as drains: if the groundwater level in the cell containing the spring reaches above a set level, water discharges from the spring at a rate based on local groundwater level and conductance of the drain (head loss between the aquifer and the spring).



After: Lindgren et al., 2004.

September 2004	**Figure 9**
Todd Engineers Emeryville, California	**Hydraulic Conductivity of Edwards Aquifer Model**

Calibration

The model was calibrated by assigning various targets across the model, excluding the Barton Springs segment. Targets represent monitoring wells or other wells with known hydraulic head information. A target could also be a spring. Computed heads at these targets were then compared to measured heads to determine if the model were matching correctly. The USGS selected 144 well targets and flows for five springs for the steady state simulation, enabling reasonable revisions to be made to adjust the fit between computed and measured heads. For the transient simulation 172 wells and five spring flows served as targets. Changes made during the transient simulation included revisions to recharge rate, hydraulic conductivity, storativity values, conduit locations, drain conductances, and drain elevations.

Results

The model matched measured heads better in some areas than others. Generally, computed heads in wells completed in the confined portion of the aquifer matched measured heads better than those in and near the recharge zone. Better fits occurred in the eastern counties as compared to those in the west. Springflows generally matched measured values although simulated high discharge rates for Comal Springs in 1958-61 and the late 1980's were somewhat greater than measured. Simulated flow at Leona Springs was generally greater than measured, especially after large recharge events; however, there is evidence of significant flow in the Leona Gravels that bypass the aquifer system. Overall the model simulated known hydraulic heads and spring discharges remarkably well over the 54-year period of the model.

Model Limitations

It is important to remember that the Edwards Aquifer model is a regional model designed to evaluate variations in springflows, regional water level changes, and relative comparisons of water management scenarios. The model cannot provide information locally, for example: drawdown effects of a single pumping well. Simulation of conduits as one-cell wide has considerable local scale effects. Locations of conduits are uncertain, hence local effects of conduits in the model may inaccurately simulate the natural system. Conduits simulated in the model as one cell wide (1,320 ft) are in all likelihood 50 times larger than the estimated width of actual conduits.

The Edwards Aquifer model is a porous media model with inputs modified to simulate a karst system; therefore, the model cannot simulate turbulent flow that may occur in conduits. By the same token the model can predict variations in water levels and springflows but cannot predict the rate of transport of contaminants.

Because the model provides a better simulation of the confined zone than the recharge zone, its application may be limited in predictions of heads in the recharge area. The hydrogeology of the recharge zone is not well known and data for model

construction were limited. During calibration storativity values in the recharge zone were adjusted to low values to better match the springflows and hydraulic heads in the confined area of the model; however, this change lessened the match of heads in the recharge zone. This area, like the rest of the aquifer, is karstic and Lindgren et al. (2004) has suggested that a multi-layered aquifer with differing porosities may at some time be required to better simulate this recharge zone.

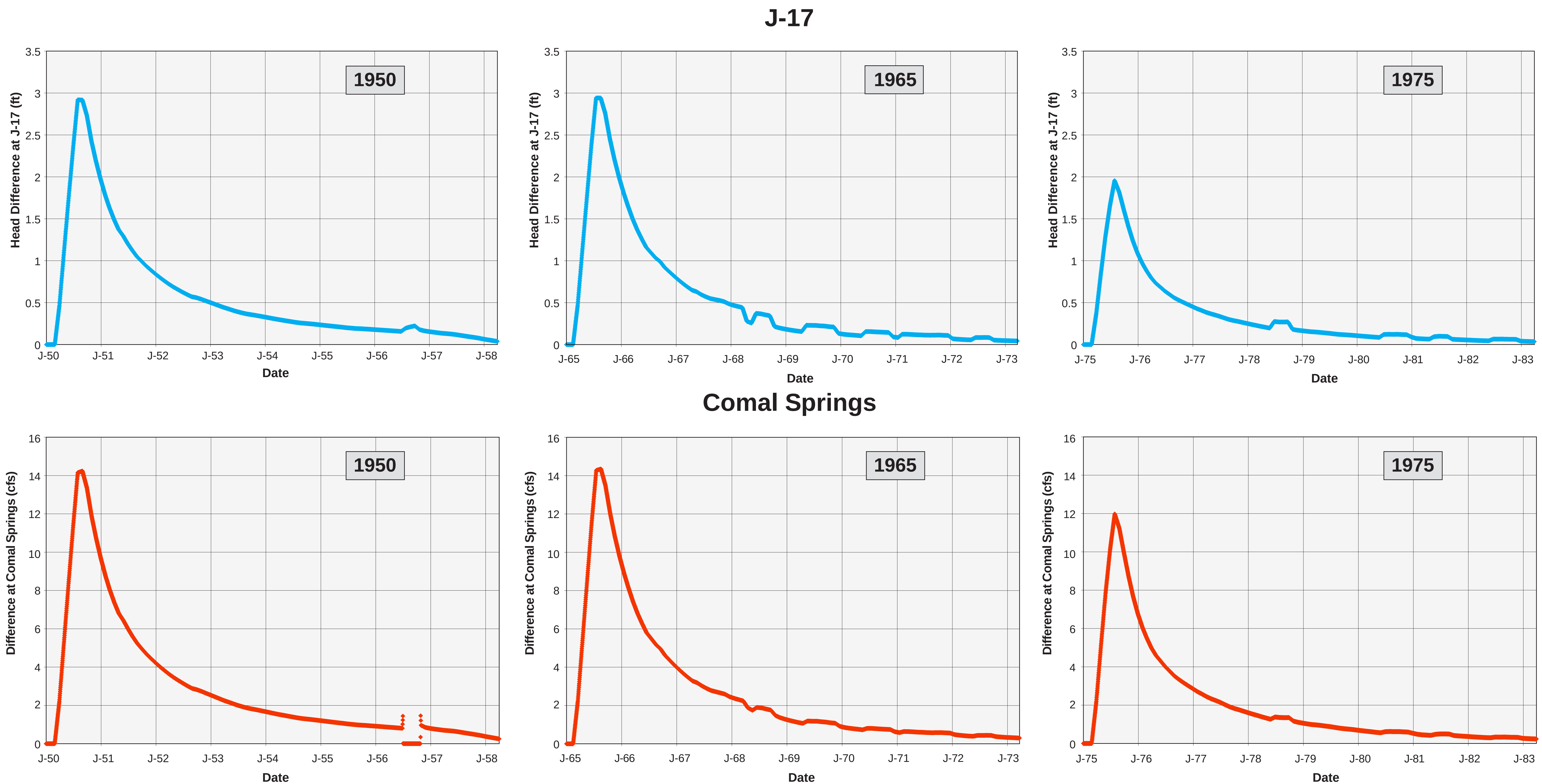
Preliminary Model Applications

Upon receipt of the draft Edwards Aquifer MODFLOW model from the Edwards Aquifer Authority, it was installed on our computer and run to demonstrate its operation. Initially a few discrepancies were noted but were quickly corrected after consultation with USGS personnel who prepared the draft model.

Effects of supplemental recharge were studied at two locations: well J-17 in San Antonio and Comal Springs. Well J-17 has a long and excellent record and is indicative of the magnitude of municipal pumping in the area. Comal Springs is the largest spring supplied by the aquifer and is most critical in terms of its potential to go dry. Furthermore, calibration of the model had shown reasonably accurate representations of water levels at well J-17 and flows from Comal Springs. First test runs were planned to study cause and effect relations based on a single isolated recharge event. It was assumed that 25,000 AF of water were recharged into the unconfined aquifer zone along Medina River below Medina Lake in northeastern Medina County. Location of the recharge site is indicated on Figure 8. Hypothetical supplemental water, over and above that occurring under actual conditions, entered the aquifer at a uniform rate of 5,000 AF per month from March through July 1950, a year when natural recharge in the Medina River Basin was only 23,600 AF as compared to a median value of 60,000 AF. To study the effect of variations in natural runoff, the same 25,000 AF of recharge were applied in a similar manner to the years 1965 when natural runoff in the basin was 54,600 AF and 1975 when runoff was 93,400 AF. For convenience each model run covered one half of the entire 54-year record; however, data were plotted for only the first eight years after recharge based on the small impacts of recharge found thereafter on well J-17 and Comal Springs.

Hydrographs of the responses expressed as differences from actual conditions are shown in Figure 10 for water levels in J-17 and flows in Comal Springs. Differences rather than true levels and flows are presented not only to emphasize the impacts but also to eliminate any discrepancy in the model, which should be constant for actual and supplemental modeled recharges. Table 2 summarizes comparative data on peak rises and times to peak in J-17 levels, the peak flow increases and times to peak in Comal Springs, and the volume and percentage of recharged water that appeared within eight years in Comal Springs.

To further explore recharge responses, another set of individual isolated recharge events were selected at a slightly more western site. As in the previous runs



Recharge of 25,000 AF in
March - July 1950, 1965, and 1975.

September 2004	**Figure 10**
TODD ENGINEERS Emeryville, California	**Responses to Medina River Recharge**

Table 2. Summary of Test Run Responses to Recharge

Medina Lake Basin

25,000 acft (5,000 acft/month)

		J-17		Comal Springs			
	Dates Added	Peak Head Difference (ft)	Date Occurred	Peak Spring Flow Difference (cfs)	Date Occurred	Total Volume Added to Spring Flow after 8 years (ac-ft)	% Recharge
Run 1	3/50 - 7/50	2.92	Jul-50	14.21	Aug-50	16,905	67.6%
Run 2	3/65 - 7/65	2.94	Aug-65	14.23	Aug-65	15,554	62.2%
Run 3	3/75 - 7/75	1.96	Jul-75	11.93	Aug-75	12,208	48.8%

Rio Hondo Basin - Elm Creek

25,000 acft (5,000 acft/month)

		J-17		Comal Springs			
	Dates Added	Peak Head Difference (ft)	Date Occurred	Peak Spring Flow Difference	Date Occurred	Total Volume Added to Spring Flow after 8 years (ac-ft)	% Recharge
Run 4	3/50 - 7/50	0.83	Jan-52	4.17	Jan-52	14,202	56.8%
Run 5	3/65 - 7/65	0.88	Nov-66	4.45	Sep-66	13,393	53.6%
Run 6	3/75 - 7/75	0.61	Jul-76	3.96	Jul-76	10,990	44.0%

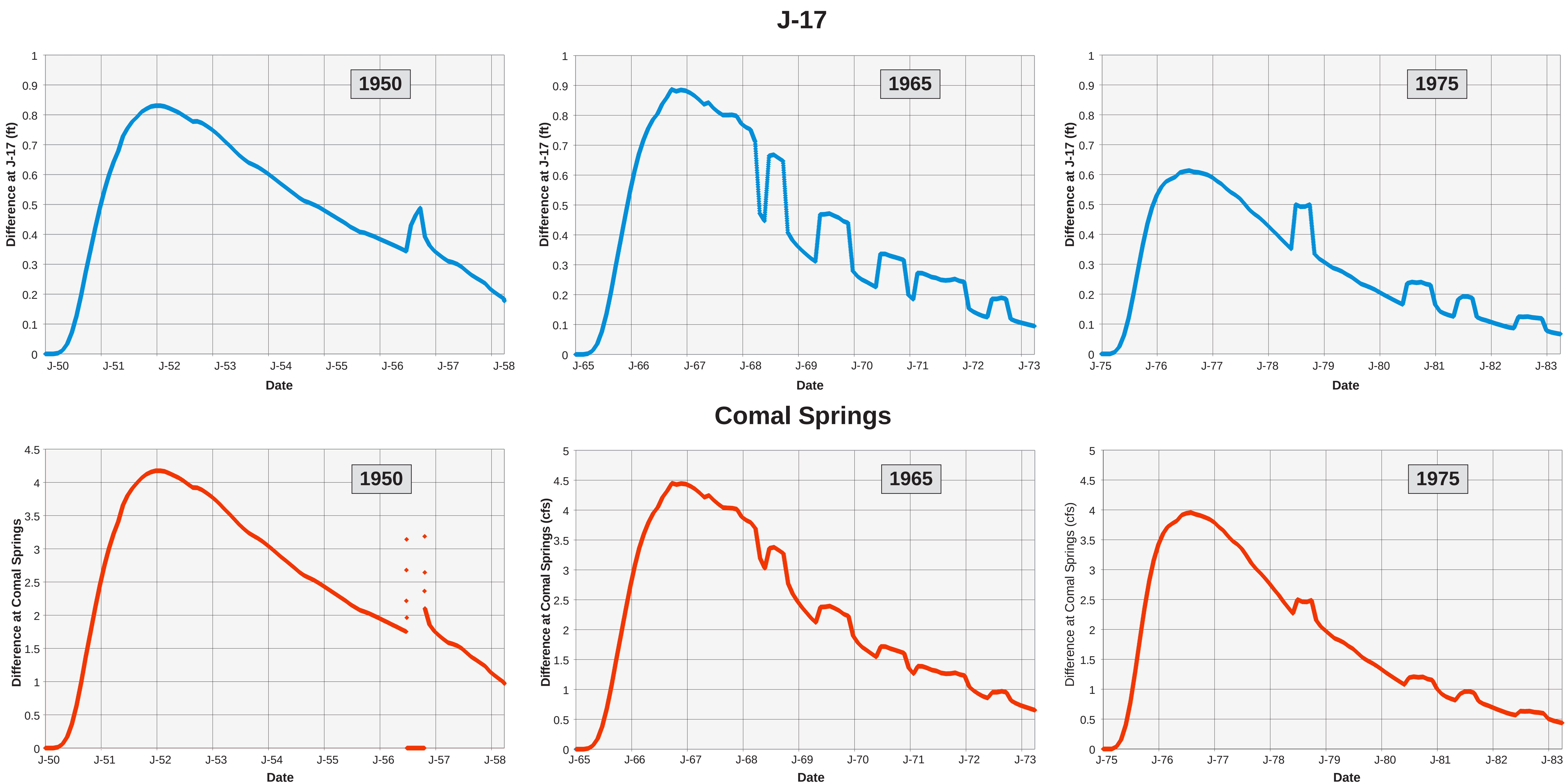
25,000 AF were recharged into the unconfined aquifer zone along Elm Creek, a tributary of Hondo Creek in northern Medina County (see Figure 8). The same three years for recharge were employed as for the Medina River site. Responses for well J-17 and Comal Springs are shown graphically in Figure 11 and Table 2 summarizes the differences from actual conditions.

<u>Interpretation of Recharge Results</u>

First it should be noted that the new USGS model functions properly, appears to give meaningful results, and operates remarkably efficiently considering that it embraces an aquifer some 150 miles long. This new tool offers considerable promise for illuminating how water is stored and moves within the Edwards Aquifer. The few preliminary test runs undertaken so far suggest that subsequent phases of this research program should lead to useful information as to how this extensive water body can be managed.

The first test runs of the new Edwards Aquifer model demonstrate that recharge of water into the aquifer from locations to the west of well J-17 can positively impact water levels and springflows over time. For the Medina River site response to recharge was nearly instantaneous (see Figure 10), suggesting that a pressure transfer occurred, analogous to unrestricted U-tube flow, at well J-17, 25 miles distant, and at Comal Springs, some 50 miles away. The model conduit in the Medina River along the recharge area facilitated the rapid adjustment of water levels from this location. The amplitude of responses decreased to ten percent of the maximum within about four years. Approximately two-thirds of the recharge volume appeared in Comal Springs within eight years, the remainder presumably going into storage or to other springs but not into pumpage, which is fixed in the model. Only in the 1975 period of high runoff was the benefit to the spring reduced, in all likelihood due to the larger natural inflows that diverted more supplemental water to other outlets.

Results for the Elm Creek recharge site, which is located only 15 miles west of the Medina River site, reveal smaller initial responses but more extended periods of transfer of water to the well and the spring. Here the peak responses occur about two years after recharge followed by a decline to ten percent of peak values some eight or more years later. The volume of water reaching Comal Springs is only slightly less than that from the Medina River site, and again the wet year of 1975 produced the smallest spring yield. An explanation for the slower response at Elm Creek may be due to two factors. The first is that there is no apparent conduit in the Elm Creek drainage; this suggests that recharged groundwater is flowing through a vast network of small openings in the aquifer, much as a porous media, without the accelerating benefit of a large pipeline-like channel. The second is that the recharge site is farther west so that the fault structure of the aquifer may cause some of the water to be deflected southward through Knippa Gap, a known restricted flow area, thereby delaying migration of water eastward.



Recharge of 25,000 AF in
March - July 1950, 1965, and 1975.

September 2004	**Figure 11**
TODD ENGINEERS Emeryville, California	**Responses to Elm Creek Recharge**

A recent study by members of the U. S. Geological Survey (Kuniansky et al. 2001) estimated travel times of water in Edwards Aquifer using simulated groundwater levels, published maps of aquifer thickness, and adjusted porosities based on geochemical measurements. They reported a travel time from Hondo Creek to Comal Springs (for a given drop of water) to be 49 to 600 years, much longer than the response times shown in Figure 11 for the same distance. This suggests that a pressure wave, delayed by a tortuous travel path through the aquifer, is responsible for supplemental springflow reaching Comal within a period of only a few years.

A major portion of natural recharge to Edwards Aquifer occurs in and is stored in the area west of Knippa Gap. In our tests so far conducted the delay found in Elm Creek recharge benefiting Comal Springs as compared to that from Medina River foreshadows what may be accomplished by increasing western recharge. Certainly this western area deserves careful study in order to learn how best to place artificial recharge in order to gain assurance that a drought, perhaps measured in months, need not adversely affect flows and critical species in Comal Springs. In connection with this, the role of Leona Springs needs to be explored. Located upstream of Knippa Gap, these springs serve as a ready and convenient outlet for water, particularly when levels are high, and could hamper benefits achieved by placing more water underground in the western region.

It is worth noting in Figures 10 and 11 that irregularities occur in well J-17 levels and Comal Springs flows during the middle of the year 1956. Because this was the time of historic drought causing the spring to go dry, the model was incapable of defining flows when levels fell below the lip of the spring, causing erroneous values to be generated. Similarly, fluctuations in Elm Creek recharge responses for years 1965 and 1975, amounting to a fraction of one foot or a fraction of one cubic foot per second, can be attributed to seasonal fluctuations in the overall aquifer.

Phase 2 Scope of Work

Based on the encouraging model test results from Phase I of this research program, efforts in Phase 2 will be focused on evaluating differing quantities, locations, and durations of recharge to Edwards Aquifer and how they impact water levels represented by well J-17 and flows of Comal Springs. Recharge locations will conform to those sites considered for development by SCTRWPG (2001c). As part of the Phase 2 study impacts of pumping limits will be considered. It is also anticipated that the model should be able to reveal illustrative flow paths of recharge water; these should provide insight as to the role of barrier faults and conduits in directing groundwater flow in various regions of the confined zone. Emphasis will be on recharge effects within the aquifer regardless of the original exterior source of supplemental water.

The proposed scope of work for Phase 2 of this four-part study will consist of the following tasks:

1. Conduct individual single-year model recharge applications at Type 1 and Type 2 recharge sites as defined by SCTRWPG (2001c) as shown in Figure 6.

2. Conduct model recharge applications as in (1) above assuming one or more sites have a constant annual recharge from 1946 to 2000.

3. Conduct model recharge applications as in (2) above assuming continuous annual recharge proportional to annual natural recharge from 1946 to 2000.

4. Determine for representative recharge sites how much recharge water emerges at the five major springs.

5. Study flow paths of recharge water in the vicinity of Balcones Fault Zone and Knippa Gap.

6. Evaluate the effect of recharge when annual pumpage is reduced to selected upper limits.

7. Analyze results of the above model investigations and determine sites and amounts of recharge that appear to be most promising in sustaining well J-17 levels and Comal Springs flows.

8. Prepare a report summarizing the above tasks and serving as a proposal to Edwards Aquifer Authority for work to be performed in Phase 3.

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