Regression Based Investigation of Pumping Limits and Springflow Within the Edwards Aquifer

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Within the Edwards Aquifer

In recent years, the Edwards Aquifer (EA) has become a focus of controversy as different interests vie for a limited water supply. Although the EA exhibits rapid recharge and is tremendously productive for its size, growing utilization of the aquifer, particularly among agricultural and municipal users, has caused annual pumping from the EA to become an ever greater percentage of average annual recharge. Much of the residual of EA recharge over pumping eventually becomes springflow,[1] the majority of which occurs in two large springs: Comal Springs in New Braunfels and San Marcos Springs in San Marcos.

Concern has been expressed about maintaining minimum levels of springflow at Comal and San Marcos Springs. This concern derives from three major sources: 1) the springs support several endangered species which require a minimum level of springflow to remain viable, 2) the presence of spring-based recreation industries which contribute to local economies, and 3) Comal and San Marcos springs feed the Guadalpe River which supplies water to downstream agricultural, municipal and domestic users. Consequently, the effect of pumping on springflow is an important element in the management of the EA.

With the intent of increasing springflow, recent legislation specifies annual pumping limits which are significantly less than levels witnessed in the majority of years of the last decade. The legislation, *per se*, however, does not specify how these limits are to be achieved, but delegates many of these decisions to a regional authority. This study will examine the effects of pumping location on springflow. In particular, hypothetical pumping allocations which distribute given levels of total pumping between eastern and western portions of the aquifer, are investigated. The analysis is based on regression studies of historical data and from the TWDB's Edwards Aquifer simulation model.

Background

The Edwards Aquifer has historically provided quantities of water to a crescent-shaped section of south central Texas located over the aquifer's recharge and reservoir areas. The aquifer, located in south central Texas, begins in Bracketville in Kinney County, runs east to San Antonio, then extends northeast through New Braunfels and San Marcos, finally terminating north of Kyle in Hays County. Naturally occurring springs emanating from the EA provided an abundant and high quality source of water to the early settlements of San Antonio, New Braunfels and San Marcos. In 1865, the first well was drilled into the EA and by 1900, wells had become the major source of water for the region. Steadily increasing pumping from the aquifer, combined with a severe drought during the 1950s resulted in the complete cessation of springflow at Comal Spring during a period in 1956. This event signaled the first major conflict between users of the aquifer and presaged the more recent legislative and legal battles over the aquifer.

Historical records provide a number of manifestation of the EA water problem. Growth in pumping, by type of use, is depicted in Figure 1. Pumping for industrial use, and 'domestic use and stock watering' have remained relatively steady since 1955 and constitute small percentages of total pumping. By contrast, municipal pumping has more than doubled, while agricultural pumping displays not only an upward trend, but increased variability in recent years. This growth in pumping has caused total pumping as a percent of average recharge to increase from 34% in 1960 to 72% in 1990. Aquifer recharge, average recharge and total pumping are portrayed in Figure 2. The volatility of annual recharge is readily apparent. Pumping and springflow, as a percentage of recharge, is portrayed in

Figure 3. Here, the inverse relationship between pumping and springflow is apparent.

Recent Legislative and Court Actions

In 1949, the Texas Legislature authorized the creation of underground water conservation districts, allowing the Texas Water Commission (TWC) to initiate the formation of districts in critical groundwater areas. In 1959, following the record drought of 1947-56, the Edwards Underground Water District (EUWD) was established pursuant to the enabling legislation. The EUWD originally consisted of five of the six counties overlying the recharge zone. An effort to strengthen the powers of the EUWD, however, was followed by the withdrawal of the western agricultural counties of Uvalde and Medina, each of which subsequently established their own underground water conservation districts.

In 1992, following an interpretation by the Attorney General of Texas that the EA was an underground river, the TWC attempted to assert control over the EA under the same regimen applying to surface water. A state judge, however, ruled that the intent of the legislature was that aquifer be treated as percolating groundwater and not as an underground river. Unlike surface water, which is regulated in accordance with the principle of prior appropriation, Texas courts have historically and consistently litigated disputes pertaining to percolating groundwater under the English common law doctrine of "free capture," also referred to as "right of capture" or "absolute ownership." (Kaiser) Under the "free capture" doctrine, a person owning land overlying the aquifer is entitled to pump an unlimited amount of water from the aquifer so long as the water is applied to a beneficial use. The absolute character of the "free capture" doctrine, in the main, disregards the affects of one's pumping on others' interests, and has often been cited as a key obstacle to attaining meaningful regulation of groundwater. In the case of the EA, the first interests to be substantially negatively impacted by unregulated pumping are those related to springflow, since springflow is the residual of recharge over pumping. These interests include the recreation industries of San Marcos and New Braunfels which are dependent upon the springs[2], environmental concern relating to the viability of endangered species which live in and around the springs, and pumpers in the portions of the San Marcos and Guadalupe Rivers downstream from the springs[3].

Using the Endangered Species Act as a springboard, the Sierra Club, backed by the Guadalupe-Blanco River Authority as plaintiff-intervenor, filed suit against the U.S. Fish and Wildlife Service (USFWS) in 1991, claiming that the USFWS and other government agencies were not adequately protecting endangered species that depend on springflow at Comal and San Marcos springs. Federal judge Lucius Bunton ruled in favor of the Sierra Club in January 1993, and ordered that a satisfactory plan be developed by the TWC by March 1, 1993. The judge also stipulated "that if the Legislature did not enact a regulatory plan to limit withdrawals from the Edwards by May 31, 1993, he would allow the plaintiff to return to seek regulation by the USFWS, and the aquifer could become subject to federal judicial control." (House Research Organization) In the following legislative session, State Senator Kenneth Armbrister and others introduced Senate Bill 1477 (SB1477), a comprehensive plan to manage the aquifer. On May 28, 1993, one day before judge Bunton's deadline, the Texas legislature passed the measure. SB1477 stipulated the replacement of the EUWD with a new agency, the Edwards Aquifer Authority (EAA), and endowed the new authority with strong powers to regulate pumping and maintain springflows. Key features of the bill include:

- an initial pumping limit of 450,000 AF annually, which is reduced to 400,000 AF in 2008[4],

- the granting of authority to the EAA to issue permits to most users which specify given amounts and rates of allowable pumping,

- a provision instituting limited water marketing, allowing permit holders of irrigation water to lease up to 50% of their initial water right.

Although the bill was due to take effect on September 1, 1993, its implementation was held up by the federal preclearance procedure. Under sec. 5 of the federal Voting Rights Act, any change affecting voters or elections in certain states must be submitted to the U.S. Justice Department for preclearance. A local minority organization actively opposed preclearance. On November 9, 1993, the department's Civil Rights Division objected to the new law citing concerns that Hispanic voters in the district might not have the same opportunity to be represented on the appointed Edwards Aquifer Authority board as on the elected EUWD board. Unsuccessful attempts were made to challenge the ruling, or to allow the EUWD to exist alongside the EAA.

In the legislative void created by legal challenges, an Interlocal Agreement was entered into by the EUWD, the Medina County Underground Water Conservation District and the Uvalde County Underground Water Conservation District. A goal of the Interlocal Agreement is "to maintain springflows at levels necessary to comply with the Endangered Species Act." The West Texas District Court, however, maintained that the agreement contained neither the incentives nor the authority necessary to achieve this goal.

Meanwhile, the voting rights obstacle to implementing SB1477 was directly addressed by proposed legislation which would amended SB1477 by designating a 15 member elected board of directors. Not withstanding, in an order filed March 6, 1995, the District Court concluded that "Clearly the State will not have an adequate plan in place by this summer." To order to protect springflow, especially in case of drought, the District Court ordered the court-appointed Monitor to revise an Emergency Withdrawal Reduction Plan which would include trigger levels and enforceable mechanisms to reduce pumping. The March 6 order also scheduled an evidentiary hearing on May 19, 1995 to provide "an opportunity for those who oppose the plan to present evidence on disputable facts relevant to the plan." (Bunton) In response to the Order, the Monitor submitted a Revised Emergency Withdrawal Reduction Plan to Court on March 31. A central feature of the plan is a five stage withdrawal reduction schedule for municipalities, industries, and military installations, stage one being voluntary, while mandatory reductions are specified for the remaining four stages. Each stage is triggered by springflow rates at Comal Springs. The plan also specified mandatory reductions in agricultural pumping whenever the emergency plan is in effect.

At the May 19 evidentiary hearing, the Sierra Club argued that the Monitor's plan was not strict enough, while the city of San Antonio claimed "that the federal government's minimum springflow levels were arbitrary and too low [sic], and that the springs won't be near the danger levels predicted by [the Monitor] for this summer." (SAEN) "Irrigators argued that their pumping wouldn't affect the spring flow on the other side of the region," (SAEN) and would result in devastating economic losses. Upon completion of testimony, the judge appointed a five-member panel of lawyers, representing various interests, and invited them to promulgate their own recommendations and submit them to the Court by June 1.

The committee of lawyers prepared and submitted a compromise emergency withdrawal reduction plan on the appointed date which contained a three stage voluntary withdrawal reduction schedule for municipal water use. "Because crops had already been planted, substantial irrigation [had] already occurred, and no established regulatory mechanism [existed], mandatory limitation of irrigation [was] not considered feasible by the panel." (Hooper, et al.)

Meanwhile, on May 29, with less than 24 hours remaining in the legislative session and three days before the panel of lawyers submitted its emergency withdrawal reduction plan, the Texas Senate passed House Bill 3189 (HB3189) which amended SB1477 by designating a 15 member elected board of directors and defining 15 single-member election districts. The bill was signed into law by the governor on May 31. This legislation brought SB1477 into compliance with the Voting Rights Act thereby overcoming the existing legal challenge, and stipulated the establishment of a temporary EAA board to convene on August 28, 1995. Companion legislation, which would have changed dates in the two year old law as well as reinstate the EUWD was killed by a point of order raised by a state representative.

On June 14, the Court, noting that the EAA would not commence operation until August 28, barring legal challenges, issued an order on emergency withdrawal reductions for summer 1995. Although convinced of its authority to order the TNRCC to implement the emergency withdrawal reduction plan, the Court resolved to await voluntary responses to the Panel Report's proposed restrictions. Accordingly, the Court reiterated the Panel Report's voluntary emergency withdrawal reduction measures in its order and urged all pumper-parties to cooperate fully to implement the Panel Report's voluntary measures. Currently, establishment of the EAA has been delayed by legal challenges to SB1477 at the state level.

A Model to Study the Effects of Pumping Limits

Central to this analysis is the hypothesis that pumping from the western portion of the aquifer affects springflow differently than pumping from the eastern portion of the aquifer. This can be attributed to the fact that the western portion of the aquifer is farther from Comal Springs and San Marcos Springs than the eastern portion of the aquifer. Another factor is the Knippa gap, an igneous rock intrusion into the Edwards limestone formation located in eastern Uvalde County. Hydrological evidence suggests that the Knippa gap acts as a partial barrier to the flow of water from the western portion of the aquifer to the eastern portion. Consequently, the springflow models developed in this study specify eastern pumping and western pumping as two separate independent variables.

The effects of pumping on springflow over time were also of interest. The entire balance of recharge over pumping is not manifested as springflow during the current period. Storage and leakage are important elements in the hydrologic continuity equation (see endnote 1). The ability of the EA to store water enables recharge in the current period to contribute to springflow in future periods. The presence of leakage implies that the entire amount of recharge cannot be attributed to springflow or pumping even for all future periods. The presence of leakage between pumping locations and the Springs also implies that increased springflows due to a cutbacks in pumping will not equal the amount of the reduction, even over time.

Aquifer storage is not directly included in the model specifications used in this analysis but its important features are captured by including two aquifer head levels in the analysis, one representing the eastern portion of the aquifer, the other representing the western portion. Aquifer storage can, in fact, be expressed as a function of head levels over the aquifer, i.e., the hydrostatic surface. Head levels, however, are directly related to hydrostatic pressure which determines springflow. Moreover, including eastern and western head levels in the specification allows the differential effects of eastern versus western head level on springflow to be estimated over time.

The effects of changes on aquifer storage over time was captured in a recursive set of equations in the following manner. Comal and San Marcos springflows (current period) were specified as a functions of beginning head level for the eastern region of the aquifer, beginning head level of the western region of the aquifer, total recharge, eastern pumping and western pumping. Next, ending head levels for each region were specified as functions of beginning head levels for each region, total recharge, western pumping and eastern pumping. Since ending head levels for the current period are beginning head levels for period 2, they can be substituted into the springflow equations in order to develop an estimates for period 2 springflows. Through this iterative (recursive) process, the effects of pumping and recharge over time were estimated.

Since historical data is limited, springflow data was generated using a simulation modal as described in the next section. A regression based model of springflow was then developed to explain springflow as a function of recharge, western pumping and eastern pumping using the generated data set. Finally, estimated regression coefficients were used to calculate the effects of pumping limits on springflow under different pumping scenarios. In particular, the effects of cutbacks of western pumping on springflow were compared to equal cutbacks of eastern pumping on springflow.

Generation of Data

The TWDB's Edwards Aquifer Simulation Model (GWSIM-IV) was employed to generate simulated values of springflow and head level under various recharge, pumping, and starting head scenarios. The model incorporates a finite difference methodology using 2,480 cell locations (31 rows by 80 columns) (Thorkildsen and McElhaney). Historical monthly pumping, recharge, and beginning head levels are used as input data, which are divided among the appropriate cell locations. The model's outputs include monthly springflows and ending head levels for each cell over the aquifer.

Monthly pumping was divided into two regions, eastern pumping and western pumping based roughly on the region's relationship to the Knippa gap and results of an investigation using GWSIM-IV to determine the effect of each county's pumping on Comal springflow. Results indicated that the effect of pumping from Medina County on Comal Springs was hydrologically more similar to the effect of pumping from Bexar County, than to the effect of pumping from Uvalde County. Consequently, pumping from Kinney and Bexar Counties was designated as western pumping, while pumping from the four eastern counties (Medina, Bexar, Comal, and Hays) was designated as eastern pumping.

Eastern and western pumping were then varied independently using five pumping scenarios for each region. The five scenarios chosen were: 50%, 75%, 100%, 125%, and 150% of 1989 pumping, which served as the base case scenario. All combinations of eastern and western pumping were simulated resulting in 25 pumping scenarios. In addition, 57 historical recharge levels corresponding to the years 1934-90, and eight starting head levels were chosen.

The eight starting head sets (the beginning head level for each recharge or aquifer cell in the model) developed using a mixture of data and model outputs. Although the hydrostatic surface of the aquifer can take many forms, there is generally a high correlation among head levels in different regions of the aquifer. The head level of the cell representing the area containing the J17 well was used as the criterion for selection of starting head level sets. Only three sets of estimated historical head levels were available. Several other sets were developed by simulating from 1947 to 1990 using historical recharge, but 1989 pumping levels for every year. The results, therefore, are indicative of head levels which might occur assuming a repetition of historical recharge under current (1989) pumping levels. The head level sets chosen reflect the range of aquifer levels, based on the J17 cell, which might occur given this scenario. Based on this criteria, the high and low values chosen for the J17 cell were 698.0 and 553.2 feet above sea level, respectively. Six additional level were chosen between these levels at approximately 25 foot increments. In addition to the three historical head level sets, five simulated sets of starting head levels, as described above, were used in the analysis.

All combinations of pumping, recharge, and starting head scenarios were simulated. In order to maintain the full range of starting head scenarios, starting head levels were reset to their original values at the end of each year of simulation. The procedure resulted in a 136,800 record data set (25 pumping scenarios x 57 recharge levels x 8 starting head levels x 12 months). In order to perform an annual analysis, monthly pumping, recharge, and springflows were aggregated by year resulting in a 11,400 record data set.

Model Estimation

Annual Model

Two sets of regressions were performed, one on the annual simulated data and the other on the monthly data. Annual estimates for Comal and San Marcos springflow were initially specified as a recursive system of four linear equations as follows:

$$\text{Comal} = \alpha_0 + \alpha_1 \text{J17} + \alpha_2 \text{Sabinal} + \alpha_3 \text{Recharge} + \alpha_4 \text{WestPump} + \alpha_5 \text{EastPump} + \varepsilon$$

$$\text{San Marcos} = \beta_0 + \beta_1 \text{J17} + \beta_2 \text{Sabinal} + \beta_3 \text{Recharge} + \beta_4 \text{WestPump} + \beta_5 \text{EastPump} + \varepsilon$$

$$\text{End J17} = \gamma_0 + \gamma_1 \text{J17} + \gamma_2 \text{Sabinal} + \gamma_3 \text{Recharge} + \gamma_4 \text{WestPump} + \gamma_5 \text{EastPump} + \varepsilon$$

$$\text{End Sabinal} = \delta_0 + \delta_1 \text{J17} + \delta_2 \text{Sabinal} + \delta_3 \text{Recharge} + \delta_4 \text{WestPump} + \delta_5 \text{EastPump} + \varepsilon$$

where Comal = Comal Springflow, year i,
San Marcos = San Marcos Springflow, year i,
End J17 = ending elevation of well J17, year i,
End Sabinal = ending elevation of Sabinal well, year i,
J17 = beginning elevation of well J17, year i,
Sabinal = beginning elevation of Sabinal well, year i,
Recharge = total recharge into the aquifer, year i,
WestPump = total pumping from the western portion of the aquifer, year i,
EastPump = total pumping from the eastern portion of the aquifer, year i,
ε = an error term,

and the other Greek symbols represent regression coefficients to be estimated. Pumping, recharge and springflows are denominated in acre feet per year, while beginning and ending heads are represented in feet above sea level. A previous analysis (Keplinger and McCarl) used a similar specification, except that agricultural and municipal pumping were specified as independent variables in place of eastern and western pumping. Agricultural and municipal pumping variables capture much of the same phenomena as the eastern pumping and western pumping variables since type of pumping is highly correlated with region: most agricultural pumping occurring in the western portion of the aquifer while most municipal pumping occurs in the eastern portion of the aquifer. Comparing the results of both groupings indicates that the east-west breakdown is the better grouping, as evidenced by higher R-squares and smaller standard errors.

A priori hypotheses are that the coefficients for beginning head levels and for recharge are positive, while the coefficients eastern and western pumping are negative. In addition, eastern pumping is expected to have a stronger effect on Comal springflow, San Marcos springflow and J17 ending head than western pumping because of the proximity of eastern pumping to the springs and the J17 well. Using the same reasoning, western pumping is expected to have a stronger effect on Sabinal well's ending head than eastern pumping. Also, because of its proximity, J17 starting head is expected to have a stronger influence on Comal springflow, San Marcos springflow and on J17 ending head than Sabinal starting head, while the opposite relation is expected for Sabinal ending head.

Results

OLS regression analysis was performed on the annual data set on observations where Comal springflow was positive. Results of the regression analysis on the simulated data are presented in Table 1. Signs and relationships of the estimated coefficients were as expected expect for the signs on the coefficients for Sabinal well level in the San Marcos equation. This counter-hypothetical sign is attributed to the limitations imposed by a relatively simple linear model, not to the actual response of the simulation model. Thus, the variable for Sabinal well level was dropped for the San Marcos springflow equation and the equation was re-estimated.

Regression coefficients are interpreted as follows. Focusing on the Comal springflow equation, a one foot increase in the beginning elevation of well J17 increases Comal springflow by 2,651 acre feet, while a one foot increase in the beginning level of the Sabinal well increases Comal springflow by 551 acre feet. A one acre foot increase in recharge distributed over the year increases Comal springflow by .05 acre feet for the current year, a one acre foot increase in western pumping decreases Comal springflow by .04 acre feet for the current year, while a one acre foot increase in eastern pumping decreases Comal springflow by .28 acre feet for the current year. These results suggest that eastern pumping has approximately seven times the effect on springflow as does western pumping during the calendar year of pumping; also, results suggest that changes in the J17 head level have approximately five times the effect on Comal springflow as changes in the more distant Sabinal head level, for the current year.

T-values for regression coefficients are provided in Table 1 but should be interpreted only with caution. Data generated by the simulation model are deterministic, not stochastic or probabilistic. Thus, tests of statistical significance cannot properly be made, nor can hypotheses be tested[5]. The magnitude of T-values, however, may provide some insights regarding the relative importance of the variables in the model. R-squares range in value from .77 to .96 suggesting that a relatively simple linear specification can explain most of the variation in the vastly more complex hydrologic model.

<u>Monthly Model</u>

A monthly analysis was conducted in order to estimate monthly variations in springflow. Of particular interest to our analysis is the ability to predict periods of low or zero flow at Comal Springs.

Regression coefficients on annual data provide only annual responses and provide no insights regarding the distribution of the response throughout the year. A monthly analysis allows monthly responses in springflow to be estimated, thus significantly reducing the length of the time period for which low flow conditions can be predicted.

Specification of the monthly models were motivated by the ability to easily implement results into an Edwards Aquifer optimization model with an annual time step. As before, Comal and San Marcos springflow are specified as a recursive system of linear equations. The monthly specification, however, includes a springflow equation for each month. Recharge, eastern pumping and western pumping are aggregated from January to the month of springflow for each monthly springflow equation. As before, regression estimation was performed on those observations where Comal springflow was greater than zero. The monthly relationships were initially specified as follows:

$$\text{Comal}_i = \alpha_{0i} + \alpha_{1i}\text{J17} + \alpha_{2i}\text{Sabinal} + \alpha_{3i}\text{Recharge}_i + \alpha_{4i}\text{WestPump}_i + \alpha_{5i}\text{EastPump}_i + \varepsilon_i$$

$$\text{San Marcos}_i = \beta_{0i} + \beta_{1i}\text{J17} + \beta_{2i}\text{Sabinal} + \beta_{3i}\text{Recharge}_i + \beta_{4i}\text{WestPump}_i + \beta_{5i}\text{EastPump}_i + \varepsilon_i$$

$$\text{End J17} = \gamma_0 + \gamma_1\text{J17} + \gamma_2\text{Sabinal} + \gamma_3\text{Recharge}_{12} + \gamma_4\text{WestPump}_{12} + \gamma_5\text{EastPump}_{12} + \varepsilon$$

$$\text{End Sabinal} = \delta_0 + \delta_1\text{J17} + \delta_2\text{Sabinal} + \delta_3\text{Recharge}_{12} + \delta_4\text{WestPump}_{12} + \delta_5\text{EastPump}_{12} + \varepsilon$$

where Comal_i = Comal Springflow, January to month i, year k,
San Marcos_i = San Marcos Springflow, January to month i, year k,
End J17 = ending elevation of well J17, year k,
End Sabinal = ending elevation of Sabinal well, year k,
J17 = beginning elevation of well J17, year k,
Sabinal = beginning elevation of Sabinal well, year k,
Recharge_i = total recharge into the aquifer, January to month i, year k,
WestPump_i = total western pumping from the aquifer, January to month i year k,
EastPump_i = total eastern pumping from the aquifer, January to month i, year k,

i = January, February, ... , December,

the ε and ε_i are error terms and the other Greek symbols represent regression coefficients to be estimated. As before, the Sabinal well head is dropped from the San Marcos springflow equations due to counter-hypothetical signs. Pumping, recharge and springflows are denominated in acre feet per year, while beginning and ending heads are represented in feet above sea level.

Results

Results of the monthly regression analysis are presented in Table 2. Signs of estimated coefficients are as expected except for three signs in the San Marcos equations: the J-17 well level coefficient in the January equation and the western pumping coefficient in the June and September equations. Low t-values for coefficients with counter hypothetical signs, again, support the conclusion that these results were due to the limitations imposed by a relatively simple regression specification, rather than to attributes of the aquifer simulation model.

Historical Data Estimation

The accuracy and validity of model results depend on 1) the validity of the GWSIM-IV aquifer simulation model and 2) on the ability of the models specified in the regression equations to capture the processes inherent in the simulation model. Thus a comparison of the regression analysis produced in this investigation was compared to regression results using historical data on Edwards Aquifer variables. This comparison, however, was hampered by the relatively small number of data points available (60 years), and the fact that many variables of interest were highly correlated. The simple correlation between eastern and western pumping, for instance, was .77. Consequently, the historical data, did not contain sufficient independent variation of eastern and western pumping to separate out their individual effects on springflow. Signs of the historical coefficients, however, were as expected except for the coefficients of the western pumping variable (in all equations) and the coefficient of the Sabinal well head variable in the San Marcos springflow equation.

In a previous analysis, pumping was broken out into two grouping: agricultural pumping and municipal pumping (Keplinger and McCarl). These grouping were less highly correlated. Regression analyses were also run on simulated data using the same methodology as in this paper except that pumping was broken out by type (agricultural and municipal) rather than by region (western and eastern). In many cases, coefficients produced from the historical data were very close to those estimated using the simulated data. Moreover, the differences between pumping coefficients between the historical and simulated regressions were not statistically significant. This evidence generally supports the validity of the coefficients produced in this analysis.

Investigation of the Effects of Pumping Allocations on Springflow

Estimated regression coefficients were used to develop estimates of the effects of limiting pumping on springflow. Specifically, a base case scenario was developed based on average pumping and recharge values for the 1980-1989 decade. Various pumping scenarios were then developed where total pumping was 1) reduced to correspond to limits set in SB1477, and 2) divided between eastern pumping and western pumping. Results of each scenario were then subtracted from corresponding values in the base case to yield springflow responses to cutbacks in eastern pumping, western pumping, or combinations of cutbacks in eastern and western pumping. The differential impacts of eastern versus western pumping were then analyzed.

Recent Pumping and Proposed Pumping Limits

During a recent decade (1980-1989), total pumping from the EA averaged 467,800 acre feet, well above both targets specified in the legislation. Approximately 22.1 percent of total pumping, (or an average annual withdrawal of 103,384 acre feet) occurred in Uvalde and Kinney counties, while the remainder, 87.9 percent (or an average annual withdrawal of 364,416 acre feet) occurred in the eastern four counties. In round figures, then, average annual withdrawals for the period amounted to approximately 475,000 acre feet, 100,000 acre feet of which was pumped in the western region of the aquifer, while the remainder, or 375,000 acre feet, was withdrawn in the eastern portion of the aquifer.

Total pumping, on average, then, must decrease by about 25,000 acre feet, from 475,000 acre feet to 450,000 acre feet in order to comply with the first phase of pumping restrictions designated in SB1477. In order to achieve the target of 400,000 acre feet as set forth in the second phase of pumping restrictions, total pumping must be cut back approximately 75,000 acre feet from the decade average. These cutbacks can be achieved by cutting back only western pumping, only eastern pumping, or by distributing the required reductions between both eastern and western pumping. Simulated effects of the foregoing management strategies on Comal and San Marcos springflow are developed in the following investigation.

Methodology

Estimated regression coefficients, described in the previous section, were used to evaluate various pumping allocation scenarios. The first set of scenarios is based on a total annual pumping limit of 450,000 acre feet, the target set in SB1477 which would immediately go into effect upon implementation of the legislation. The second set of scenarios uses an annual pumping limit of 400,000 acre feet, the target which SB1477 designates as going into effect in the year 2008. Under both sets of scenarios, total pumping and the implied pumping reductions, are distributed between eastern pumping and western pumping.

The foregoing scenarios are simulated using both the annual and monthly sets of equations. Starting head levels for the variables representing the two wells are initially set at their mean values for the 1980-89 period. For the first set of scenarios (total pumping of 450,000 acre feet), western pumping is cut back 25,000 acre feet in the first run (from the 100,000 acre feet average to 75,000 acre feet). In the second run, eastern pumping is cut back 25,000 acre feet (from 375,000 to 350,000 acre feet).

For the second set of scenarios, cutbacks of 75,000 acre feet (the amount need to achieve the 2008 target) are distributed between western and eastern pumping. For the first run, western pumping is cut back the entire 75,000 acre feet. In the second run, western pumping is cut back 50,000 acre feet while eastern pumping is cut back 25,000 acre feet. In the third run, western pumping is cut back 25,000 acre feet and eastern pumping is cut back 50,000 acre feet, while for the fourth run, eastern pumping was cut back the entire 75,000 acre feet.

For both sets of scenarios, the simulation is run for five years. Starting heads for each successive year are reset with the values produced by the J17 and Sabinal well equations, while the same pumping scenarios are assumed for the five year period. Recharge is simulated at the 1980-1989 decade average of 762,568 acre feet annually for each year of the five year period. For the monthly analysis, monthly values for pumping and recharge are derived from the average monthly distribution of pumping and recharge for the 1980-89 period.

Next, employing the same methodology, a base springflow scenario was developed for a five year period. The base case was chosen to reflect average pumping and recharge rates for the 1980-1989 decade as described in the previous section. Thus, western pumping is set at 100,000 acre feet, eastern pumping is set at 375,000 acre feet, while total recharge is set at 762,568 acre feet (the average for the decade). Simulated base case springflow estimates were then subtracted from springflow estimates under each of the scenarios involving pumping reductions, as described above. The resultant differences represent the increases in springflow attributable to a cutbacks in pumping thereby allowing springflow responses to various pumping cutback scenarios to be compared.

Results

Results of the foregoing simulations using the annual equations are presented in Table 3. The table displays Comal and San Marcos springflow, as generated by the model, as well as the inputs: J17 and Sabinal starting heads, recharge, and western and eastern pumping. Section A of Table 3, shows the results of annual simulations which achieve the 450,000 acre feet pumping limit. In the first five year run, western pumping is cut back 25,000 acre feet from the 100,000 acre feet historical level. In the next run, eastern pumping is cut back 25,000 acre feet. Results suggest that eastern pumping has a significantly greater effect on Comal springflow than western pumping implying that cuts in eastern pumping result in a greater increase in Comal springflow than cuts in western pumping. For instance, Table 3, Section A. indicates that after five year of reducing western pumping by 25,000 acre feet, Comal springflow in increased by 9,160 acre feet. However, reducing eastern pumping by 25,000 acre feet for five years results in an increase of Comal springflow of 23,209 acre feet, over twice the effect of the corresponding western reduction scenario. The differential impact between eastern pumping and western pumping is even more marked for a one year period. When western pumping is cut back 25,000 acre feet for one year, Comal springflow increases by 1,022 acre feet for the current year. Whereas if eastern pumping is cut back by 25,000 acre feet, springflow at Comal Springs is increased by 6,942 acre feet, almost a seven fold increase of the one year effect of western pumping. San Marcos springflow is affected in a similar manner. The increase in San Marcos springflow due to pumping cutbacks is considerably less than that of Comal Springs, however, the relative difference in magnitude between the effects of an equal cutback in western versus eastern pumping is greater.

Section B of Table 3 displays the results of simulations using a 400,000 acre feet pumping limit.

The general conclusion inferred from Section A also applies to section B results. When western pumping is reduced 75,000 acre feet over a five year period, springflow at Comal Springs is increased by 27,481 acre feet in year five, whereas, if eastern pumping is reduced 75,000 acre feet over a five year period, Comal springflow is increased by 69,627 acre feet.

Selected results of simulations using the monthly equation set are presented in Table 4. Regression results as well as historical data indicated that Comal Springs typically reaches its lowest flow in September, suggesting that it is this month, on average, that Comal Springs is most vulnerable to pumping. Thus, September springflow effects are presented in Table 4. Here, the input values for recharge, western pumping and eastern pumping reflect aggregated monthly values from January to September as described in the "Monthly Model" section of the paper.

Table 4, Section A results suggest that September springflows are vulnerable to total pumping as well as to location of pumping. When western pumping was cut back 25,000 acre feet per year, September Comal springflow increased by 145 acre feet in the first year and 730 acre feet in year five. When eastern pumping was cut back the same amount, Comal springflow increased by 943 acre feet in the current year and by 2,112 acre feet by the fifth year. As in the annual analysis, the monthly analysis suggests that cutbacks in eastern pumping are more effective in achieving springflow than cutbacks in western pumping. Section B results of Table 4, which set total pumping at 400,000 acre feet and distributes a 75,000 acre feet cutback between western and eastern pumping, also confirm these general findings.

Conclusions

In sum, all of the simulated results suggest that cutbacks in eastern pumping are significantly more effective in achieving increases in springflow than cutbacks in western pumping, even over the five year period considered.[6] Results also indicate that cutbacks in eastern pumping result in increased springflow more immediately than cutbacks in western pumping. Thus, two general conclusions can be drawn: 1) the effects on springflow of changes in eastern pumping are manifested sooner than the effects of changes in western pumping and 2) the total, or steady state, effect on springflow of changes in eastern pumping is considerably greater than the total, or steady state, effect of changes in western pumping. Both conclusions are consistent with hydrologic theory and favor reductions in eastern pumping over western pumping from both a timing and steady state standpoint.

Unaddressed in this analysis is the value of water by various parties. Efficient water use, from an economic perspective involves both hydrology, or technical considerations, and economic valuations. Consequently, policy makers may wish to consider both economic and hydrologic information in the formulation of policy designed to protect springflows by reducing pumping. The hydrologic analysis developed in this study provides a base upon which further analysis can be conducted.

ENDNOTES

1. Aquifer "leakage" also plays a role in maintaining the balance in the hydrologic continuity equation:

Change in Aquifer Storage(t) =
Aquifer Storage(t) - Aquifer Storage(t-1) =
recharge(t) - Pumping(t) - Leakage(t) - Springflow(t).

2. An estimated 6% of economic activity and 5% of employment in Comal and Hays counties are attributable to Comal and San Marcos Springs (McKinney and Watkins).

3. Comal and San Marcos Springs supply approximately 30% of the base flow of the Guadalupe River under normal conditions and up to 70% of the base flow in times of drought (EUWD).

4. Exceptions to the pumping limits of 450,000 acre feet annually until January 1st, 2008, and 400,000 acre feet thereafter are contained in subsection (d), (f), and (h) of section 1.14 of SB1477. Subsections (d) and (f) allow for the increase of maximum withdrawals, dependent upon well levels. Subsection (g) provides authority to implement and enforce management practices to ensure that "not later than December 31, 2012, continuous minimum springflows of the Comal Springs and the San Marcos Springs are maintained to protect endangered and threatened species to the extent required by federal law." (SB1477)

5. T-values for regression coefficients could be significantly increased simply by generating more observations from the simulation model. This demonstrates arbitrariness of t-values in such a context.

6. Historical comparison generally supports the validity of the simulated results although the iterative procedure, using regression coefficients, used to estimate springflows for several years does not always produce comparable results to those produced directly from the simulation model (Keplinger and McCarl). A more precise analysis can be performed by employing the simulation model directly to develop outputs for the various scenarios considered, although this approach is considerably more computer intensive. The advantage of employing a model based on regression estimates to simulate springflow is its relative simplicity, ease of operation, and the ability to integrate the results in more comprehensive modeling schemes such as models which optimize the value of water withdrawn from the aquifer. In such contexts, employing the aquifer simulation model directly is infeasible. In these more comprehensive models, hydrological relationships are an essential element in determining outcomes, although they comprise only a small piece of the entire model.

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Table 1. Regression Coefficients, T-Values, and R-Squares for Edwards Aquifer Variables, Annual Analysis.

Regression Coefficients:

	J17	Uvalde	Recharge	West Pump	East Pump	Intercept
Comal	2650.7015	551.1829	.079621	-.040886	-.277668	-1924676.6102
San Marcos	412.2016	.0000	.024274	-.000540	-.025025	-203976.0737
J17 End Elev	.3437	.1739	.000015	-.000024	-.000113	321.1665
Sabinal End Elev	.2842	.5725	.000022	-.000088	-.000050	149.7165

T-Values and R-Squares:

	J17	Uvalde	Recharge	West Pump	East Pump	Intercept	R-Square
Comal	88.9300	24.7000	100.420000	-5.910000	-116.150000	-259.1500	.9284
San Marcos	133.5500	.0000	108.990000	-.280000	-37.270000	-98.6600	.7696
J17 End Elev	65.2200	44.0800	107.570000	-19.390000	-267.650000	244.6100	.9479
Sabinal End Elev	41.2100	110.8800	122.430000	-55.020000	-90.530000	87.1300	.9568

Table 2. Regression Coefficients, T-Values, and R-Squares for Edwards Aquifer Variables, Monthly Analysis.

Equation: Comal Springflow:
Regression Coefficients:

Month	J17	Uvalde	Recharge	West Pump	East Pump	Intercept
1	180.3684	121.2104	.010618	-.001728	-.116318	-191449.0800
2	280.2459	50.2790	.016243	-.008347	-.085650	-201927.1400
3	288.6519	41.4842	.017419	-.007245	-.071472	-200907.8200
4	279.8861	39.7958	.017648	-.007284	-.064956	-194209.8200
5	265.3099	39.6351	.017979	-.007090	-.059910	-185087.0900
6	247.6505	39.0824	.013393	-.007330	-.054482	-172110.8900
7	233.1974	40.3336	.013688	-.007653	-.052424	-163895.5400
8	221.9370	41.5496	.013216	-.007365	-.049567	-157862.7100
9	210.8783	41.8924	.011903	-.007358	-.043705	-150994.4500
10	199.1030	43.0783	.010761	-.007120	-.038932	-144158.2000
11	187.1714	44.2342	.010374	-.006842	-.033852	-137434.8500
12	176.1384	44.4788	.010000	-.006170	-.031558	-130588.8400

T-Values and R-Squares:

Month	J17	Uvalde	Recharge	West Pump	East Pump	Intercept	R-Square
1	113.16	99.54	20.77	-.19	-53.82	-378.87	.9651
2	149.17	35.26	50.10	-1.19	-63.58	-351.51	.9578
3	146.61	27.94	80.48	-2.22	-82.13	-347.48	.9568
4	135.10	25.57	97.91	-3.19	-101.26	-326.60	.9527
5	99.87	19.94	105.58	-3.13	-97.03	-246.11	.9222
6	70.94	15.01	96.68	-3.74	-84.98	-176.18	.8665
7	70.17	16.30	117.64	-5.87	-106.13	-175.26	.8777
8	73.63	18.52	130.21	-7.64	-132.18	-179.49	.8922
9	75.60	20.17	132.26	-9.37	-140.78	-183.12	.8974
10	71.25	20.73	128.06	-9.92	-138.80	-178.28	.8923
11	67.86	21.54	131.69	-10.11	-133.26	-181.65	.8928
12	63.35	21.48	130.74	-9.29	-132.10	-175.96	.8876

Equation: San Marcos Springflow
Regression Coefficients:

Month	J17	Uvalde	Recharge	West Pump	East Pump	Intercept
1	-3.5255	.0000	.019929	-.001563	-.020095	7801.6400
2	26.9574	.0000	.013144	-.000570	-.011730	-12055.3300
3	34.6762	.0000	.007744	-.000235	-.008365	-16990.8400
4	36.4454	.0000	.006765	-.000321	-.006683	-18067.0500
5	38.3235	.0000	.007148	-.000159	-.005189	-19563.3300
6	42.5959	.0000	.008937	.000080	-.004991	-23253.6600
7	39.1549	.0000	.003921	-.000107	-.004465	-20287.2900
8	36.8948	.0000	.002312	-.000017	-.003704	-18519.7300
9	34.5880	.0000	.001809	.000019	-.003391	-16957.1100
10	33.1755	.0000	.002539	-.000079	-.003034	-16262.3000
11	31.8748	.0000	.001985	-.000028	-.002720	-15288.1200
12	31.3705	.0000	.001764	-.000035	-.002682	-14911.7900

T-Values and R-Squares:

Month	J17	Uvalde	Recharge	West Pump	East Pump	Intercept	R-Square
1	-5.90	.00	48.77	-.21	-11.63	19.33	.2633
2	57.13	.00	73.18	-.15	-15.71	-37.87	.5386
3	91.51	.00	81.08	-.16	-21.78	-66.60	.6592
4	58.27	.00	52.97	-.20	-14.70	-42.92	.4412

5	64.64	.00	79.27	-.13	-15.87	-49.19	.5574
6	58.91	.00	130.38	.08	-15.73	-48.21	.7157
7	83.78	.00	101.00	-.24	-27.09	-65.16	.6691
8	115.97	.00	94.51	-.07	-40.97	-87.42	.7272
9	91.36	.00	65.88	.08	-35.81	-67.40	.6082
10	53.75	.00	59.54	-.22	-21.32	-39.67	.4335
11	81.09	.00	72.75	-.12	-30.93	-58.55	.5779
12	83.15	.00	67.96	-.16	-33.11	-59.52	.5692

Table 2. Regression Coefficients, T-Values, and R-Squares for Edwards Aquifer Variables, Monthly Analysis (continued).

Note: T-values displayed under coefficients.

	J17	Uvalde	Recharge	West Pump	East Pump	Intercept	R-Square
J17 End Elev	.3210	.1650	.000014	-.000022	-.000106	341.5700	
	(68.32)	(47.14)	(105.26)	(-19.19)	(-261.65)	(272.34)	.9400
Sabinal End Elev	.2863	.5677	.000022	-.000087	-.000049	151.5800	
	(40.23)	(107.09)	(113.58)	(-51.16)	(-79.34)	(79.79)	.9400

Table 3. Simulated Values for Comal and San Marcos Springflow Response Under Various Pumping Cutback Scenarios, Annual Analysis.

A. Pumping Limit Set at 450,000 Acre Feet Implying a 25,000 Acre Foot cutback.

	West	East	Total
Pumping	75000.	375000.	450000.
Cutback	25000.	0.	25000.

Year	Comal	SanMarcos	J17	Sabinal	Recharge	West Pump	East Pump
1	1022.15	13.50	670.26	780.39	762567.80	75000.00	375000.00
2	3825.17	260.82	654.51	778.40	762567.80	75000.00	375000.00
3	6174.11	503.53	648.75	772.79	762567.80	75000.00	375000.00
4	7913.19	689.45	645.79	767.94	762567.80	75000.00	375000.00
5	9160.43	824.03	643.93	764.32	762567.80	75000.00	375000.00

	West	East	Total
Pumping	100000.	350000.	450000.
Cutback	0.	25000.	25000.

Year	Comal	SanMarcos	J17	Sabinal	Recharge	West Pump	East Pump
1	6941.70	625.63	670.26	780.39	762567.80	100000.00	350000.00
2	15118.91	1790.09	656.73	777.45	762567.80	100000.00	350000.00
3	19105.78	2279.93	651.57	771.93	762567.80	100000.00	350000.00
4	21553.67	2557.13	648.84	767.30	762567.80	100000.00	350000.00
5	23208.97	2738.93	647.09	763.87	762567.80	100000.00	350000.00

Table 3. Simulated Values for Comal and San Marcos Springflow Response Under Various Pumping Cutback Scenarios, Annual Analysis (continued).

B. Pumping Limit Set at 400,000 Acre Feet Implying a 75,000 Acre Foot cutback.

	West	East	Total
Pumping	25000.	375000.	400000.
Cutback	75000.	0.	75000.

Year	Comal	SanMarcos	J17	Sabinal	Recharge	West Pump	East Pump
1	3066.45	40.50	670.26	780.39	762567.80	25000.00	375000.00
2	11475.52	782.46	655.71	782.80	762567.80	25000.00	375000.00
3	18522.33	1510.58	651.13	780.05	762567.80	25000.00	375000.00
4	23739.57	2068.35	649.07	777.17	762567.80	25000.00	375000.00
5	27481.29	2472.09	647.87	774.94	762567.80	25000.00	375000.00

	West	East	Total
Pumping	50000.	350000.	400000.
Cutback	50000.	25000.	75000.

Year	Comal	SanMarcos	J17	Sabinal	Recharge	West Pump	East Pump
1	8986.00	652.63	670.26	780.39	762567.80	50000.00	350000.00
2	22769.26	2311.74	657.93	781.85	762567.80	50000.00	350000.00
3	31454.00	3286.98	653.95	779.19	762567.80	50000.00	350000.00
4	37380.05	3936.03	652.12	776.53	762567.80	50000.00	350000.00
5	41529.84	4386.99	651.03	774.49	762567.80	50000.00	350000.00

	West	East	Total
Pumping	75000.	325000.	400000.
Cutback	25000.	50000.	75000.

Year	Comal	SanMarcos	J17	Sabinal	Recharge	West Pump	East Pump
1	14905.55	1264.75	670.26	780.39	762567.80	75000.00	325000.00
2	34062.99	3841.01	660.16	780.90	762567.80	75000.00	325000.00
3	44385.66	5063.38	656.78	778.33	762567.80	75000.00	325000.00
4	51020.52	5803.71	655.16	775.89	762567.80	75000.00	325000.00
5	55578.38	6301.88	654.19	774.04	762567.80	75000.00	325000.00

	West	East	Total
Pumping	100000.	300000.	400000.
Cutback	0.	75000.	75000.

Year	Comal	SanMarcos	J17	Sabinal	Recharge	West Pump	East Pump
1	20825.10	1876.88	670.26	780.39	762567.80	100000.00	300000.00
2	45356.73	5370.28	662.38	779.95	762567.80	100000.00	300000.00
3	57317.33	6839.77	659.60	777.47	762567.80	100000.00	300000.00
4	64661.00	7671.38	658.21	775.25	762567.80	100000.00	300000.00
5	69626.92	8216.78	657.35	773.59	762567.80	100000.00	300000.00

Table 4. Simulated Values for September Springflow Response for Comal and San Marcos Springs Under Various Pumping Scenarios.

A. Pumping Limit Set at 450,000 Acre Feet Implying a 25,000 Acre Foot cutback.

	West	East	Total
Pumping	75000.	375000.	450000.
Cutback	25000.	0.	25000.

Year	Month	Comal	San Marcos	J17	Sabinal	Recharge	West Pump	East Pump
1	9	145.08	-.37	670.26	780.39	587489.10	59150.17	323755.88
2	9	349.64	18.25	654.64	778.75	587489.10	59150.17	323755.88
3	9	519.85	36.63	649.35	773.34	587489.10	59150.17	323755.88
4	9	643.50	50.45	646.76	768.76	587489.10	59150.17	323755.88
5	9	730.41	60.25	645.17	765.42	587489.10	59150.17	323755.88

Observations: Comal > 0 Recharge = 762567.8

	West	East	Total
Pumping	100000.	350000.	450000.
Cutback	0.	25000.	25000.

Year	Month	Comal	San Marcos	J17	Sabinal	Recharge	West Pump	East Pump
1	9	943.31	73.18	670.26	780.39	587489.10	78866.90	302172.15
2	9	1551.06	164.53	656.74	777.79	587489.10	78866.90	302172.15
3	9	1832.56	200.77	651.97	772.44	587489.10	78866.90	302172.15
4	9	2000.69	220.65	649.56	768.04	587489.10	78866.90	302172.15
5	9	2112.11	233.43	648.05	764.84	587489.10	78866.90	302172.15

Table 4. Simulated Values for September Springflow Response for Comal and San Marcos Springs Under Various Pumping Scenarios (continued).

B. Pumping Limit Set at 400,000 Acre Feet Implying a 75,000 Acre Foot cutback.

	West	East	Total
Pumping	25000.	375000.	400000.
Cutback	75000.	0.	75000.

Year	Month	Comal	San Marcos	J17	Sabinal	Recharge	West Pump	East Pump
1	9	435.24	-1.10	670.26	780.39	587489.10	19716.73	323755.88
2	9	1048.92	54.75	655.71	783.09	587489.10	19716.73	323755.88
3	9	1559.54	109.89	651.49	780.46	587489.10	19716.73	323755.88
4	9	1930.50	151.35	649.70	777.76	587489.10	19716.73	323755.88
5	9	2191.23	180.76	648.68	775.72	587489.10	19716.73	323755.88

	West	East	Total
Pumping	50000.	350000.	400000.
Cutback	50000.	25000.	75000.

Year	Month	Comal	San Marcos	J17	Sabinal	Recharge	West Pump	East Pump
1	9	1233.48	72.45	670.26	780.39	587489.10	39433.45	302172.15
2	9	2250.34	201.03	657.82	782.13	587489.10	39433.45	302172.15
3	9	2872.26	274.03	654.11	779.56	587489.10	39433.45	302172.15
4	9	3287.69	321.55	652.49	777.04	587489.10	39433.45	302172.15
5	9	3572.93	353.93	651.56	775.14	587489.10	39433.45	302172.15

	West	East	Total
Pumping	75000.	325000.	400000.
Cutback	25000.	50000.	75000.

Year	Month	Comal	San Marcos	J17	Sabinal	Recharge	West Pump	East Pump
1	9	2031.71	145.99	670.26	780.39	587489.10	59150.17	280588.43
2	9	3451.76	347.30	659.92	781.17	587489.10	59150.17	280588.43
3	9	4184.97	438.17	656.73	778.66	587489.10	59150.17	280588.43
4	9	4644.89	491.76	655.29	776.31	587489.10	59150.17	280588.43

5	9	4954.64	527.11	654.44	774.57	587489.10	59150.17	280588.43

	West	East	Total
Pumping	100000.	300000.	400000.
Cutback	0.	75000.	75000.

Year	Month	Comal	San Marcos	J17	Sabinal	Recharge	West Pump	East Pump
1	9	2829.94	219.54	670.26	780.39	587489.10	78866.90	259004.70
2	9	4653.18	493.58	662.02	780.21	587489.10	78866.90	259004.70
3	9	5497.69	602.32	659.35	777.75	587489.10	78866.90	259004.70
4	9	6002.08	661.96	658.08	775.59	587489.10	78866.90	259004.70
5	9	6336.34	700.28	657.32	774.00	587489.10	78866.90	259004.70