The Effects of Recharge, Agricultural Pumping and Municipal Pumping on Springflow and Pumping Lifts Within the Edwards Aquifer:

A Comparative Analysis Using Three Approaches

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An ongoing project in the Department of Agricultural Economics at Texas A&M University involves investigating the consequences of selected pumping scenarios concerning the Edwards Aquifer. The prediction of springflow and aquifer elevation under alternative recharge and pumping scenarios is an integral component of this investigation. An investigation was conducted to develop explanatory models of the interrelationship between pumping, springflow, aquifer elevation, and pumping lift. This research follows a similar analysis by Dillon, McCarl and Williams but employs an updated GWSIM-IV Edwards Aquifer simulation model which uses monthly rather than an annual time steps. This analysis also estimates a regression analysis on historical data and performs a controlled experiment using the GWSIM-IV model. Another major difference is that this analysis employs a model specification which breaks out pumping by type of use, thereby allowing differential impacts of agricultural versus municipal pumping to be estimated.

The first part of the analysis is conducted on an annual basis. Three approaches were taken. First, historical data on aquifer attributes were used to develop response coefficients for recharge and pumping using regression analysis. Second, the groundwater simulation model (GWSIM-IV), as modified by the Texas Water Development Board (Thorkildsen and McElhaney), was used to generate data on springflow, elevation, and pumping lifts under different pumping and recharge scenarios. This data was subjected to regression analysis using the same model specification as that used for the real world model. Results based on the simulation were compared to regression results using historical data. Finally, the simulation model was used to perform controlled experiments on the effects of pumping and recharge over time. In order to account for seasonal variations in springflow, a monthly regression analysis was also conducted using data generated from the aquifer simulation model.

The purpose of this paper is to present the results of the various analyses and describe the estimation procedures. In the case of the annual analysis, results of the three procedures are compared.

Model of Springflow

Maintaining springflow is a major concern involving efforts to manage the Edwards Aquifer. Springflow at any given point in time is hypothesized to be a function of the hydrostatic pressure of the water in the area of spring orifices. Well head (elevation) is commonly used as a measure of hydrostatic pressure. Well head, or hydrostatic pressure for any given location in the aquifer, in turn is determined by the amount, timing and location of water entering and leaving the aquifer as determined by hydrologic influences such as transmissivity and anisotropy. The GWSIM-IV model, using monthly time steps and 2,480 grid locations, integrates hydrologic principles directly into the model thereby simulating the hydrologic process rather explicitly.

When dealing with discrete units of time, we hypothesize that springflow can be specified as a function of beginning aquifer elevation, as measured by well head, and pumping and recharge for the current period. Beginning aquifer elevation effectively captures the effects of pumping and recharge for all previous periods. We also hypothesize that ending aquifer elevation for the current period (t) can be specified as a function of pumping and recharge for the current period (t) as well as ending elevation of the previous time period (t-1).

Historic data on aquifer attributes is limited and does not permit an elaborate specification of numerous recharge and pumpage locations. However, a model can be formed to examine are the effects of agricultural and municipal pumping on springflows. Pumping user, in effect, serves as a proxy for pumping location since there is a very high correlation between type of pumping and pumping location. Virtually all agricultural pumping occurs in the western three counties of the Edwards Aquifer region, while virtually all municipal pumping occurs in the eastern three counties. A substantial portion of agricultural pumping also occurs over or west of the Knippa gap, an igneous protrusion into the Edwards limestone formation which may inhibit flows through the aquifer.

Springflow of the two largest springs fed by the Edwards Aquifer, Comal Springs and San Marcos springs, are of interest. The J17 well head level (in San Antonio) was used as a proxy for aquifer elevation in the eastern portion of the aquifer. A second well head level, located in Sabinal, was used to represent aquifer level in the western part of the aquifer. Sabinal is located in Uvalde county and overlies the Knippa gap.

The inclusion of more than one head level in the specification allows an estimation in which the aquifer does not have to respond as a unified whole to recharge and pumping, allowing these effects involve both time and place dimensions. Preliminary evidence suggested that the effects pumping on head level, or hydrostatic pressure, are more immediate, the closer the pumping is to the springs. In addition, the effects of pumping and recharge persist, at diminishing levels, over time. Both of these phenomena are captured by the inclusion of two head levels in the specification. In order to lend a more meaningful interpretation to the intercept term in the annual models, means of explanatory variables were subtracted from each value of the corresponding explanatory variable. The resulting intercept terms indicate the mean of the respective explanatory variables.

Comal and San Marcos springflow are thus specified as a recursive system of four linear equations as follows:

Comal = $"_0 + "_1\text{J17} + "_2\text{Sabinal} + "_3\text{Recharge} + "_4\text{AgPump} + "_5\text{ MunPump} + ,$

San Marcos = $\$_0 + \$_1\text{J17} + \$_2\text{Sabinal} + \$_3\text{Recharge} + \$_4\text{AgPump} + \$_5\text{ MunPump} + ,$

End J17 = $(_0 + (_1\text{J17} + (_2\text{Sabinal} + (_3\text{Recharge} + (_4\text{AgPump} + (_5\text{ MunPump} + ,$

End Sabinal = $*_0 + *_1\text{J17} + *_2\text{Sabinal} + *_3\text{Recharge} + *_4\text{AgPump} + *_5\text{ MunPump} + ,$

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 (mean adjusted), year i,
Sabinal = beginning elevation of Sabinal well (mean adjusted), year i,
Recharge = total recharge into the aquifer (mean adjusted), year i,
AgPump = total agricultural pumping from the aquifer (mean adjusted), year i,
MunPump = total municipal and industrial pumping from the aquifer (mean adjusted), year i,

the , are error terms, 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 priori hypotheses are that the coefficients for beginning head levels and for recharge are positive, while the coefficients agricultural and municipal pumping are negative. In addition, municipal pumping is expected to have a stronger effect on Comal springflow, San Marcos springflow and J17 ending head than agricultural pumping because most of municipal pumping occurs in the San Antonio area, which much closer to the springs and the J17 well than Uvalde and Medina counties, where almost all agricultural pumping occurs. Using the same reasoning, agricultural pumping is expected to have a stronger effect on Sabinal well's ending head than municipal 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 the Sabinal ending head equation.

Historical Analysis

Data

Annual starting head levels for the J17 well (located in San Antonio) and I-4-35 well (Sabinal well) were obtained from the Edwards Underground Water District (EUWD). In almost all cases these levels reflect measured levels as of January 1st. In a few cases, measured levels a few days later in the month were used if levels for the preceding days were unavailable. Ending head levels for the current year are considered beginning head levels for the previous year.

Pumping data as well as annual estimated recharge were obtained from the U.S. Geological Survey (USGS) (Brown, Petri and Nalley) and the EUWD (Bader and Walthour). The pumping data were broken out by four type of use: municipal, irrigation, industrial, and domestic, stock and miscellaneous use. Relative magnitudes of the four types of pumping for the years 1955-1993 are displayed in Figure 1.

For this analysis, municipal and industrial uses were combined while irrigation and 'domestic and stock' use were combined resulting in two pumpage series which are referred to as municipal and agricultural pumpage respectively. As noted earlier, type of usage correlates strongly with area of usage. In 1989, 97.6% of irrigation occurred in the western three counties overlying the aquifer (Kinney, Uvalde and Medina counties), whereas 95.5% of municipal pumping, 97.1% of industrial pumping, and 90.9% of domestic and stock use occurred in the eastern three counties overlying the aquifer (Bexar, Comal and Hays counties)[1].

Annual data for springflow for San Marcos and Comal springs were obtained from the San Antonio office of USGS. Figure 2 illustrates the relative magnitudes, variations, and correlations between total recharge, total pumpage, San Marcos springflow and Comal springflow. The wide fluctuations in recharge are evident reflecting the highly stochastic year-to-year variation in precipitation. The upward trend in total pumpage is shown and a negative correlation between recharge and pumpage is also evident. The graph of Comal springflow roughly mirrors total pumpage reflecting the hypothesized negative relationship. San Marcos springflow, while less than that of Comal springs, displays somewhat less variation. Means, standard deviations, minimums and maximums of each variable in the model, as well as correlations between variables are provided in Table 1.

All values of the explanatory variables were available for the years 1957 through 1993 resulting in 37 observations. Ordinary least squares (OLS) regression analysis was performed on the 1957 through 1993 series using the specification in the preceding section.

Results

Table 2 portrays the regression results. The signs of the coefficients are as expected except for the coefficients for agricultural pumping in the J17 and Sabinal ending elevation equations and the municipal pumping coefficient in the San Marcos springflow equation. Positive coefficients for either agricultural or municipal pumping are counter to expectations. A possible explanation is the high degree of correlation between agricultural and municipal pumping (.64) as indicated in Table 1 and Figure 2.

The expected relationships with regard to the relative magnitude of agricultural versus municipal pumping are evident except in the San Marcos equation, while the expected relationships with regard to the magnitudes of the J17 versus Sabinal starting elevations are all as expected. R-squared values for the four equations ranged from .76 to .89 indicating that the linear specification succeeded in explaining the majority of variation of the dependent variables.

Interpretation of the coefficients for the Comal springflow equation are as follows. A one foot increase in the beginning elevation of well J17 increases Comal springflow by 1,569 acre feet, while a one foot increase in the beginning level of the Sabinal well increases Comal springflow by 711 acre feet for the current period. A one acre foot increase in recharge over the year increases Comal springflow by .06 acre feet for the current year, a one acre foot increase in agricultural pumpage over the year decreases Comal springflow by .01 acre feet for the current year, while a one acre foot increase in municipal pumping decreases Comal springflow by .33 acre feet for the current year. The intercept term suggests that when values for all explanatory variables are at their historical means for the 1957-1993 period, as given in Table 1, Comal Springs will flow at the rate of 209,456 acre feet per year.

The precision of the estimates can be determined from each coefficient's confidence interval. Confidence intervals can be determined at any level of significance from the coefficient's standard error, which can be found by dividing the coefficient of interest by its t-value. At the 90% confidence level, results imply that the effect of one acre foot of municipal pumpage on Comal springflow is between -.16 acre feet and -.49 acre feet.[2] The 90 percent confidence interval for the effect of agricultural pumping on Comal springflow is between -.18 and +.16. The precision of the estimates in the historical analysis is hampered by a relatively small number of observations (37) and a relatively high degree of multicollinearity among the independent variables as indicated by high values of simple correlation coefficients among the independent variables (see Table 1).

Of the 24 estimated coefficients in Table 2, 16 are significantly different from zero at the 10 percent significance level. Only one coefficient with a sign counter to expectations (Agricultural Pumping in the Sabinal Ending Elevation equation) is significantly different from zero at the 10 percent level.[3] Thus, while the results of the analysis on historic data generally support *a priori* hypotheses, estimated coefficients are imprecise, and often not significantly different from zero. Results of the historic analysis, however, are later used to test whether coefficients estimated on generated data are significantly different from historic coefficients, thus statistically testing the validity of the simulation model.

Analysis of Simulated Output

Generation of Data

The Edwards Aquifer Simulation Model (GWSIM-IV) is a finite difference groundwater simulation model incorporating 2,480 cell locations (31 rows by 80 columns) (Thorkildsen and McElhaney). The simulation model uses historical monthly pumping, recharge, and beginning head levels as input data, which are divided among the appropriate cell locations. The model's outputs include monthly springflows, ending head levels for each cell over the aquifer, and mass balance (amount of water in the aquifer).

The GWSIM-IV model was used to simulate values of Comal and San Marcos springflow, J17 and Sabinal well heads, and average pumping lifts (defined later). Agricultural and municipal pumping were varied independently thus overcoming the high degree of multicollinearity between agricultural pumping, municipal pumping and recharge evident in the historical data.

Three levels of municipal pumping and four levels of agricultural pumping were chosen. All combinations of agricultural and municipal pumping were simulated resulting in 12 pumping scenarios. In addition, 34 recharge levels and eight starting head levels were chosen. All combinations of pumping, recharge, and starting head scenarios were simulated resulting in a 39,168 record data set (12 pumping scenarios x 34 recharge levels x 8 starting head levels x 12 months). In order to conform to the historic analysis, springflow values were aggregated over each calendar year, resulting in a 3,264 record data set.

Pumping levels for 1989 were used as the base case scenario. Municipal pumping was simulated at 50%, 100%, and 150% of 1989 municipal pumping and while agricultural pumping was simulated at 25%, 75%, 100%, and 125% of 1989 agricultural pumping. A random component ranging between -5% and +5% was added to each pumping/recharge/head-level scenario. Recharge levels corresponding to the years 1957 to 1990 were simulated. These years match those used in the historical analysis with the exception of 1991 through 1993, for which distributed recharge information was not available. Starting head levels were chosen to reflect the range of starting head levels assuming 1989 pumping levels in conjunction with historical recharge for the years 1934 to 1990. High and low values chosen for starting head (for the cell representing the area containing the J17 well) were 698.0 and 553.2 feet above sea level, respectively. Six additional level were chosen between these levels at approximately 25 foot increments.

Finally, any scenario which produced an annual springflow at Comal springs of less than 91,060 acre feet were dropped from the data set, since this was the lowest springflow recorded in the historical data.[4] The elimination of these observations resulted in a data set representing 1,773 scenarios for different combinations of pumping, recharge, and starting head level. Means, standard deviations, minimums, and maximums for each variable as well as simple correlations between variables are provided in Table 3.

OLS regression analysis was performed on the simulated output using the same model specification as that used for the historical analysis. Two additional equations were also estimated: agricultural lift and municipal lift. Lift is defined as the distance between surface elevation and head level for a given well. The importance of lift to our analysis derives from the cost associated with pumping, which is an increasing function of lift. A weighted average value for agricultural lift was calculated by averaging lift values for all cells in the model associated with agricultural pumping, and weighting each value by the associated amount of agricultural pumping. The same approach was taken with respect to municipal pumping. The explanatory variables used in the two lift equation are identical to those specified for the other equations.

Results

Results of the regression analysis on the simulated data are presented in Table 4. The *a priori* hypotheses, as specified in the previous section, are used to evaluate regression results on the generated data. In addition, it is hypothesized that higher well levels (heads) for the J17 and Sabinal wells, and higher recharge will decrease lift; whereas higher levels of agricultural and municipal pumping increase lift. In addition, it is expected that the J17 head will have a larger influence on municipal lift than the Sabinal head, whereas the Sabinal head is expected to have a greater influence on agricultural lift than the J17 head. Also, agricultural pumping is expected to have a greater impact on agricultural lift than on municipal lift; and municipal pumping is expected to have a greater influence on municipal lift than on agricultural lift.

Signs and relationships of the estimated coefficients are as expected expecting the signs on the coefficients for Sabinal well level and Agricultural pumping in the San Marcos equation. These counter-hypothetical signs are attributed to the limitations imposed by the linear regression model, not to the actual response of the simulation model. This conclusion is supported by a relatively low R-square value for the San Marcos springflow equation of .64. In addition, t-values for these two coefficients were the lowest of the 36 coefficients generated. The conclusion drawn is that the effect of Sabinal well head on San Marcos springflow is positive but very small whereas the effect of agricultural pumping on San Marcos springflow is negative, but very small. The results of a controlled experiment, presented later in the paper, confirms this conclusion.

Regression coefficients are interpreted as before. For instance, 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 534 acre feet for the current period. A one acre foot increase in recharge over the year increases Comal springflow by .08 acre feet for the current year, a one acre foot increase in agricultural pumping decreases Comal springflow by .09 acre feet for the current year, while a one acre foot increase in municipal pumping decreases Comal springflow by .30 acre feet for the current year. The intercept term suggests that when values all explanatory variables are at their means, as provided in Table 3, Comal Springs will flow at the rate of 247,972 acre feet per year. These results suggest that municipal pumping has approximately three times the effect on springflow as does agricultural pumping during the calendar year of pumping; also, results suggest that changes in the J17 head level have approximately five times the effect on springflow as changes in the more distant Sabinal head level, for the current year.

T-values for regression coefficients are provided in Table 4 but should be interpreted only with caution. Data generated by the simulation model are deterministic (as determined by the model) not of a stochastic nature. Thus, tests of statistical significance cannot properly be made, nor can hypotheses be tested.[5] T-values (and standard errors, which can be found by dividing the coefficient by its t-value), however, may provide some insights regarding how well the regression model fit the generated output for different variables. Except for the San Marcos equation, R-squares range in value from .84 to .93 suggesting that a relatively simple linear specification can explain most of the variation in the vastly more complex hydrologic model.

Comparison of Historical Data and Simulated Data Regression Analyses

Results of the regression analyses of the two approaches are compared, with the aim of providing some insights into the validity of the simulation model. A comparison of the 20 coefficients (intercepts excluded[6]) between analyses in the four common equations reveals that 7 of the coefficients are within 20% of each other, while 11 of the 20 coefficients are within 35% of each other. A more scientific comparison involves statistical tests measuring whether the coefficients estimated using simulated data are significantly different from the corresponding coefficients estimated from historic data.

Null hypotheses are tested that the coefficients produced by the regression analysis on the simulated data are equal to corresponding coefficients estimated in the historic regression analysis . Since the simulation model is deterministic, coefficients on the simulated output are also considered to be deterministic. Thus, t-values, testing the above hypotheses, were developed by dividing the difference between each pair of corresponding coefficients by the standard error of the historic coefficient. Results are presented in Table 3.

Of the 20 null hypotheses tested, (4 equations times 5 explanatory variables), the null hypothesis that the coefficients from the two analyses are the same was rejected in only six cases, using a 10 percent significant level. Four of the six cases applied to coefficients for recharge. All four equations estimated on the simulated data were found to have recharge coefficients which were significantly different than the corresponding regression coefficients on the historic data. In addition, the coefficients for agricultural pumping were found to be significantly different in the J17 and Sabinal ending elevation equations. As indicated earlier, the signs on the values for these two coefficients do not meet *a priori* expectations in the "historic" analysis. This is attributed to either errors in the data, omitted variables or functional form misspecification.

In general, assuming that the functional form is reasonable specified, statistically significant differences in corresponding coefficients from the two analyses can be attributed either to 1) misspecification of the simulation model or 2) measurement errors of the explanatory and dependent variables. Thus, any conclusion regarding the validity of the simulation model is necessarily dependent on the accuracy of the historic data and, or course, the appropriateness of the functional form specified.

The differences between recharge coefficients are significantly different for all equations. It is noted, however, that t-values for the historic recharge coefficients are several times higher than those for the other explanatory variables, implying very small standard errors, making hypothesis rejection more likely. The recharge coefficient is significantly higher for the analysis on simulated data for the Comal springflow equation, and significantly lower in the San Marcos springflow, J17 ending elevation and Sabinal ending elevation equations. While the foregoing tests indicate statistically significant differences, of greater interest is the absolute amount of the difference.[7] Using the historic coefficients as a base, the coefficients for recharge for the analysis on simulated data differ by +35%, -54%, -35%, and -49% respectively for the Comal, San Marcos, J17 ending elevation and Sabinal ending elevation equations.[8]

Controlled experiment using GWSIM-IV

Procedure

The third approach used to determine the effects of pumping and recharge on springflows and ending elevations was to conduct a controlled experiment using the GWSIM-IV aquifer simulation model. The advantage to this approach is that the experiment produces precise results regarding the effects of the exogenous variable which is varied, thus eliminating specification error due to non-linearities in the regression analysis. A disadvantage of the approach is that model results are strictly applicable only to the particular scenario chosen. The regression analysis on simulated output summarizes many controlled experiments in a linear fashion although these relationships are not strictly linear. On the other hand, a particular controlled experiment strictly applies only for the values chosen. However, if results of the controlled experiment correspond to the predictions from the regression, then the linear equations are validated.

One hundred years were simulated in two separate runs using the same recharge and pumping scenarios for each year and the same initial starting heads, with the exception that in the first run, recharge was increased by 10% above recharge levels in the second run. From the second year onward, recharge levels were constant and identical between runs. Head levels were allowed to change from year to year thereby allowing the effects of recharge to persist over time. This procedure allowed the effects of recharge, over the 100 year period, to be developed by subtracting the effects of run one from run two, for the various years. The same analysis was performed for agricultural and municipal pumping.

Year 1989 agricultural and municipal pumping usage figures were used in the controlled experiment. Values for recharge and starting head level were chosen to reflect average conditions for recharge and head levels.[9] In order to develop partial derivatives comparable to regression results, the endogenous effects caused by the changes in the exogenous variable are divided by the amount of change.

Results

First year results of the controlled experiments are presented in Table 6. Results meet all *a priori* expectations as previously enumerated. Moreover, values of coefficients developed from the controlled experiments are very close to regression estimates (Table 4) with two exceptions. First, the effect of municipal pumping on San Marcos springflow is negative (as expected), rather than positive; second, the effect of recharge on Comal springflow is considerably less (less than half) of that predicted in the regression analysis on the simulated output. Both of these divergences are attributable to non-linear and/or interactive relationships inherent in the simulation model which are not captured in the linear specification.

The Effects of Recharge and Pumping Over Time

Regression estimates directly provide current year effects of recharge and pumping. In addition, effects for successive years can be developed by substitution into the recursive relationships previously described. Current recharge and pumping affects ending head, which in turn, affects next periods springflow. For the controlled experiment, the effects of pumping and recharge on successive years are found directly by simulating for several years and allowing head levels to adjust, as described in the previous section. Of particular interest are the aggregate effects of changes in pumping and springflow as well as their distribution over time. The aggregation of effects over time can also be considered "steady state" effects, since, in the steady state, a change in pumping would persist indefinitely into the past allowing all adjustments of the change to have taken place.

Annual effects of pumping and recharge on springflow, head levels, and lifts were calculated for 100 years forward (as described above), starting with the current year's effect, and summed to derive steady state effects. A 100 year period was used in order to assure that virtually all of the effect would be captured. Results are presented in Table 7.

Differences in steady state effects of pumping and recharge between the simulated data regression results versus the results of the controlled experiment are largely attributed to specification error in the regression model.[10] These differences are largest for the effects of recharge and suggest that a more sophisticated regression specification with respect to recharge would improve regression results. Differences between the two approaches employing the simulation model are also substantial for many of the effects attributed to agricultural pumping. For instance, the steady state effect of agricultural pumping on Comal springflow is -0.76 as determined by the controlled experiment, whereas it is only -0.46 as determined by the regression on the simulated data. At least for the particular scenario chosen, the controlled experiment results can be considered unambiguously better than the results based on regressions on the simulated data. It is noteworthy that all results produced by the controlled experiment comport with *a priori* expectations.

The validity of the results of both the controlled experiment and the regression on simulated output are dependent on the underlying specification of the simulation model. The historic analysis is free from potential misspecification in the simulation model, but suffers from the relative scantness of information as well as potential specification error of the regression model. In certain cases, such as the effect of municipal pumping on Comal springflow, the results of the three approaches are similar, lending validity to the estimated effect.

The effects of agricultural pumping, municipal pumping, and recharge over a ten year period are plotted in Figures 3 through 8. Each plot shows the time path of the effect for both the controlled experiment and the results based on the regression on simulated data. Where appropriate, results based on the historic regression results are also included.

An inspection of the plots reveals the persistent and often lagged nature of pumping and recharge on springflow. For instance, focusing on the simulated response, Figure 3.c. indicates that annual recharge has its greatest impact on Comal springflow in the year following the year of recharge.

Figure 3.a. indicates that agricultural pumping has almost the same effect on Comal springflow during the year following the current year as in the current year. Although the effect is very small, Figure 4.a. (simulated response) suggests that agricultural pumping has its greatest effect on San Marcos springflow during the second year following pumping (year 3).

The Effects of Agricultural Pumping, Municipal Pumping and Recharge on Comal Springflow

Of particular importance in developing an aquifer management plan are the effects of agricultural pumping, municipal pumping, and recharge on Comal springs. Maintaining springflow has been identified as a major objective in managing the Edwards aquifer. While both major springs are affected by aquifer elevation, Comal springs is the most vulnerable of the two springs to changes in aquifer elevation[11], which in turn is determined by pumping and recharge. Because of the correlation between pumping location and type of use, the effects of agricultural and municipal pumping have distinctly different effects on Comal springflow.

The effect of municipal pumping on Comal springflow is large and direct. Focusing on the controlled experiment, results suggest the current year effect of one acre-foot of municipal pumping is a decrease in springflow of 0.35 acre-feet. During the second year, the effect drops to 0.19 acre-feet, dropping to 0.07 acre-feet and 0.04 acre-feet respectively for the third and fourth years. The total or steady state effect of one acre-foot of municipal pumping is a decrease in springflow of 0.91 acre-feet. Eighty percent of the effect occurs during the first ten year period.

The effect of agricultural pumping on Comal springflow is somewhat smaller, in aggregate, and less direct. Results of the controlled experiment suggest the steady state effect of one acre-foot of agricultural pumping is a decrease in Comal springflow of .76 acre-feet, 62% of which occurs during the first 10 years.[12] The GWSIM-IV model suggests a first year decrease in springflow is 0.11 acre-feet, while the declines in springflow the second, third, and fourth years are 0.10 acre-feet, .06 acre-feet and .05 acre-feet respectively.

These results suggest municipal pumping has approximately three times the effect on springflow as agricultural pumping during the year of pumping. The effect of municipal pumping on springflow is approximately twice that of agricultural pumping the year follow pumping. By the fourth year, the effects of agricultural and municipal pumping are approximately equal, whereafter, the effects of agricultural pumping are somewhat higher. By the fourth year, however, and thereafter, the annual effect of one acre-foot of pumping for either agricultural or municipal purposes is less than 0.05 acre-feet.

Results of the controlled experiment suggest the effects of recharge on Comal springflow are delayed and very persistent. The steady state (100 year) effect of a one acre-foot increase in aquifer recharge is an increase in Comal springflow of .69 acre feet. However, the increase in Comal springflow over a ten year period is only .32 acre feet, thus, 56% (over half) of the effect of aquifer recharge (based on model results) occurs after the first ten years. The first year effect of a one acre-foot increase in recharge is an increase in Comal springflow of .030 acre-feet. Corresponding values of years two through six are .058, .042, .035, .032, and .029 respectively. Thus, the greatest effect of recharge on Comal springflow occurs during the year following the year of recharge, whereafter, the annual effect of recharge diminishes very slowly for succeeding years (see Figure 3.c.)

Monthly Analysis

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.

<u>The Model</u>

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. Comal springflow regression estimations used only those observations where Comal springflow was greater than zero. Two sets of monthly equations were estimated for San Marcos springflow. The first set of equations was estimated on records where springs was greater than zero; the second set of equations was estimated on the remainder of the observations (those observations for which Comal springflow equaled zero). In addition, it was found that breaking out recharge by zones within the aquifer significantly improved R-squares in some of the San Marcos equations. Two zones were specified: the first includes recharge from river basins in the west of the aquifer, the second zone is comprised of recharge from river basins in the east of the aquifer. The monthly relationships are specified as follows:

$$\text{Comal}_{ij} = "_{0ij} + "_{1ij}\text{J17}_j + "_{2ij}\text{Sabinal}_j + "_{3ij}\text{Recharge}_j + "_{4ij}\text{AgPump}_j + "_{5ij}\text{MunPump}_j + ,_{ij}$$

$$\text{San Marcos}_{ij} = \$_{0ij} + \$_{1ij}\text{J17}_j + \$_{2ij}\text{Sabinal}_j + \$_{3ij}\text{Recharge1}_j + \$_{4ij}\text{Recharge2}_j + \$_{4ij}\text{AgPump}_j + \$_{5ij}\text{MunPump}_j \;,_{ij}$$

$$\text{End J17}_j = (_{0j} + (_{1j}\text{J17}_j + (_{2j}\text{Sabinal}_j + (_{3j}\text{Recharge}_j + (_{4j}\text{AgPump}_j + (_{5j}\text{MunPump}_j + ,_j$$

$$\text{End Sabinal}_j = *_{0j} + *_{1j}\text{J17}_j + *_{2j}\text{Sabinal}_j + *_{3j}\text{Recharge}_j + *_{4j}\text{AgPump}_j + *_{5j}\text{MunPump}_j + ,_j$$

where Comal_{ij} = Comal Springflow, month i, data set j, year k,
San Marcos_{ij} = San Marcos Springflow, month i, data set j, year k,
End J17_{j} = ending elevation of well J17, data set j, year k,
End Sabinal_{j} = ending elevation of Sabinal well, data set j, year k,
J17_{j} = beginning elevation of well J17, data set j, year k,
Sabinal_{j} = beginning elevation of Sabinal well, data set j, year k,
Recharge_{j} = total recharge into the aquifer, data set j, year k,
Recharge1_{j} = recharge into the aquifer from the Nueces, West Nueces, Frio, Dry Frio, Sabinal and Medina river basins, and areas between the Sabinal and Medina basins and between Medina and Cibolo-Dry Comal Creek basins, data set j, year k
Recharge2_{j} = recharge into the aquifer from the Cibolo Creek, Dry Comal Creek, and Blanco river basins, data set j, year k,
AgPump_{j} = total agricultural pumping from the aquifer, data set j, year k,
MunPump = total municipal and industrial pumping from the aquifer, data set j, year k,

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

j = 1, if Comal springflow > 0,
2, if Comal springflow = 0,

j = 1, for Comal_{ij} equations,
j = 1,2 for all other equations,

the $,_{j}$ and $,_{ij}$ are error terms and the other Greek symbols represent regression coefficients to be estimated. As before, pumping, recharge and springflows are denominated in acre feet per year, while beginning and ending heads are represented in feet above sea level.

Correct interpretation of resulting coefficients is not obvious and requires careful analysis. Springflow for January is specified as a function of head levels as of January 1st, and annual recharge and pumping. Since future recharge and pumping cannot influence springflow, only January recharge and pumping actually affects springflow. Levels of pumping and recharge for January, however, constitute only a fraction of corresponding annual levels. Therefore, coefficients for pumping and recharge incorporate the fraction of annual pumping and recharge occurring in January. Thus, monthly distributions (over the year) of pumping and recharge are incorporated into regression coefficients.

The pumping scenarios used to generate data for the monthly analysis employed only 1989 levels of agricultural and municipal pumping and adjusted these levels either upward or downward. The distribution of pumping over the aquifer, as well as over the 12 months of the year, however, was maintained. Therefore, regression coefficients for pumping strictly apply only for the 1989 distribution of pumping over the 12 month period. On the other hand, generated data include recharge scenarios corresponding to each year of the 1934 through 1990 period. Thus, the average distribution of recharge over the 12 months of the year for the 1934 through 1990 period is incorporated into regression coefficients for recharge.

As in the case for January, springflow model specifications for February employ annual pumping and recharge as independent variables. For February models, however, recharge and pumping during *January and February* is expected to affect springflow since starting head levels in the models indicate starting heads as of the beginning of the year.[13] As before, distributions of pumping and recharge (over the year) are implied in the regression coefficients. Since the summation of January's and February's recharge and pumping is greater than that of January's alone, we would, in general, expect coefficients for February to be larger than those for January.

Similar interpretations can be made for succeeding months. Coefficients for pumping and recharge for June equations, for instance, incorporate the first six months of pumping and recharge, which is a larger fraction of total annual pumping and recharge than for succeeding months. Sums of each coefficient over 12 months are made for each variable in the Comal and San Marcos springflow equations. These values represent annual effects for each variable and are similar in value to the coefficients derived in the annual regression analysis on simulated output.

Generation of Data

The GWSIM-IV Edwards Aquifer simulation model was used to generate data for the monthly analysis, as previously described. The data set employed for the monthly analysis differs from that used in the annual analysis in that springflow data for Comal and San Marcos springs was not summed by year. In addition, 57 recharge scenarios were employed. This resulted in a data set of 65,664 records (4 agricultural pumping levels x 3 municipal pumping levels x 57 recharge scenarios x 8 starting head levels x 12 months), 5,472 records applying to each month.

Results

Results of the monthly analysis are presented in Table 8. In the great majority of cases, signs on the coefficients and relationships between various coefficients meet *a priori* expectations. Cases where they do not are attributed to the limitations of the relatively simple linear specifications. T-values of coefficients with counter-intuitive signs are almost always very low.

Summary and Conclusions

This analysis investigates the effects of agricultural pumping, municipal pumping, and recharge on aquifer springflows and pumping lifts. The mechanism, through which the persistent effects of recharge and pumping are manifest, is changes in aquifer elevation. Three approaches were taken in the investigation: 1) regression analysis on historic aquifer data, 2) regression analysis on a data set of simulated aquifer values, and 3) a controlled experiment using the aquifer simulation model directly.

The advantage of the first approach is the 'real world' nature of the data. The major problem, however, is the relatively scant amount of information contained in the historic data set. This is manifest in the relatively modest number of observations available (37), and the high degree of multicollinearity contained in the data. The most important result of the historic analysis is the consistency of those results with the results from the simulation model.

The second approach employs the aquifer simulation model to generate data on springflows, aquifer elevations, and pumping lifts. Agricultural pumping, and municipal pumping were varied independently thus overcoming the scantness of information and multicollinearity problems manifest in the historic data. Thirty-four historic recharge scenarios which matched those of the historic analysis were used. Regression analysis were performed on the simulated data set, and results were compared to the historic regression analysis, both in magnitude, and for statistically significant differences. These comparisons generally supported the validity of the GWSIM-IV aquifer simulation model although statistically significant differences were found in the recharge coefficients.

The regression analysis on simulated data can be considered a linear summary of the more complex relationships inherent in the aquifer simulation model. High R-square values suggests the specified relationships are 'more or less' linear although a more sophisticated model specification would improve results.

In order to eliminate misspecification in the regression analysis and to evaluate the goodness of fit with regard to each variable in the regression analysis, a controlled experiment was run using the aquifer simulation model directly. Two 100 year runs were conducted: the first increased either agricultural pumping, municipal pumping, or recharge the first year, setting it back to the base level for following years, the second run kept all exogenous variables at their base levels for the entire 100 year period. The effect of the varied variable was calculated for each year by subtracted the effects of run two from run one. The validity of the results of the controlled experiment depends solely on the validity of the GWSIM-IV model itself. Results of the three approaches, in many cases, were similar, lending corroborative support to the simulation model as well as to the estimated relationships.

A prime consideration in managing the Edwards Aquifer is maintaining a certain level of springflow at any given time during the year. A yearly analysis does not indicate the distribution of springflow within any given year. Thus, a monthly analysis was conducted in order to estimate springflow on a monthly basis, thereby increasing the ability to determine springflow at any time during the year.

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ENDNOTES

1. Of the combined pumpages, 95.6% of municipal and industrial pumping occurred in the eastern three counties while 83.2% of agricultural pumping (combined irrigation and domestic and stock pumping) occurring in the western three counties. Almost all of the variation in agricultural pumping, however, occurs in the western three counties.

2. The approximate value of the Student's t-distribution greater than .90 (10 percent confidence level) is 1.3054. The standard error for the municipal pumping coefficient is .325005/2.58 = .125971. Thus, the endpoints for the 90 percent confidence interval for the municipal pumping coefficient equals -.325005 (+ or -) (1.3054 x .125971), or -.160562 and -.489448.

3. At the 10 percent significance level, 10 percent of coefficients which are truly zero will appear to be significant. Thus, it is entirely reasonable that the significance of coefficients with counter-hypothetical signs can be attributed to statistical error.

4. In addition to more accurately matching the historical data, the elimination of low and zero levels of Comal springflow prevents serious non-linearities from occurring which a linear OLS estimation technique cannot accurately estimate. In addition to the level of springflow having a lower bound of zero, the evidence suggests that the response of the aquifer to various scenarios significantly differs when Comal springflow is low or non-existent.

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. Intercepts are excluded because they are a function of the means of the explanatory variables, since they are mean adjusted. In the regression analysis on generated data, agricultural and municipal pumping were intentionally manipulated, thus, their means are not historical means.

7. Two values may be statistically significantly different, although the absolute difference may be very small and not significant from a practical standpoint.

8. Results of a controlled experiment, described in the next section, indicate that the effect of recharge on Comal springflow is significantly *smaller* (for the scenario chosen) than the effect estimated using the historic data. The relatively large difference here between the results of the controlled experiment and those of the regression on simulated output can be attributed to specification error of the regression model.

9. Year 1976 levels of recharge and 1947 starting heads as determined by the TWDB were used to represent "more or less" normal aquifer conditions.

10. This must be the case since the simulated data is, in essence, a series of controlled experiments involving the same underlying assumptions of the same simulation model. It would not be expected that the relatively crude specification of the regression model would capture the entirety of the hydrologic processes inherent in a sophisticated hydrologic simulation model.

11. Coefficients in Table 2 suggest that J17 well level has 7 times influence on Comal Springflow as on San Marcos springflow. Moreover, in an emergency withdrawal reduction plan for the Edwards Aquifer (Moore and Votteler), the authors indicate their belief (based on historical relationships) that an emergency withdrawal reduction plan which maintained minimum levels at Comal Springs to avoid "takes" of endangered species would also be sufficient to ensure adequate springflow at San Marcos Springs to protect endangered species found there.

12. These results are consistent with those published in the Texas Water Development Board Report 340 (Thorkildsen and McElhaney). Their results, also using the GWSIM-IV aquifer simulation model, indicate a 34% increase in springflow and Comal and San Marcos springs due to a decrease in pumpage in Uvalde County and a 67% increase in springflow when pumpage in Medina County. Much of the remainder of the water flow balance was accounted for intertransformational flow from the model, increased aquifer storage in the western part of the aquifer and renewed flow at the cell representing Leona springs (in the case of a decrease in Uvalde County pumping).

Increased flow percentages at Comal and San Marcos springs in the TWDB study represent the increase after 10 years of pumping at reduced rates. This corresponds to the aggregate 10 year effect of pumping in this study using the controlled experiment approach. The corresponding value for a decrease in agricultural pumping over a ten year period using this study's methodology is an increase in springflow at Comal and San Marcos springs of 49% (46.7% of the increase occurring at Comal springs, 2.2% occurring at San Marcos springs).

The current study suggests that another 33% of decreased agricultural pumping can be accounted for in increased springflow after the aquifer has fully adjusted, i.e., over a 100 year period.

13. As given in the theoretical model, pumping and recharge are hypothesized to influence head levels, which, in turn, are hypothesized to influence springflow. Thus, coefficients for recharge and springflow represent any effects they may have after the time head levels are specified in the model, since head levels incorporate all prior effects of pumping and recharge.

Table 1. Statistics on Dependent and Independent Variables, Historical Data.

Variable	Mean	Standard Dev.	Minimum	Maximum
Dependent Variables				
Comal Springflow	209460.	57011.	91060.	324200.
San Marcos Springflow	123900.	36827.	70010.	248900.
J17 Ending	671.89	13.192	643.90	692.63
Sabinal Ending	770.22	31.477	701.69	826.85
Independent Variables				
J17 Starting	670.74	14.491	634.81	692.63
Sabinal Starting	766.90	35.638	666.20	826.85
Recharge	844000.	519270.	170700.	2485700.
Agricultural Pumping	141950.	51402.	61900.	242300.
Municipal Pumping	219350.	56076.	138790.	308100.

Correlation Matrix of Variables

	Comal	San Marcos	J17 End	Sabinal End	J17 Start	Sabinal Start	Recharge	Ag. Pumping	Mun. Pumping
Comal Springflow	1.00000								
San Marcos Springflow	.80544	1.0000							
J17 Ending	.80629	.76284	1.00000						
Sabinal Ending	.87249	.74816	.79688	1.0000					
J17 Starting	.75667	.38138	.52917	.67219	1.0000				
Sabinal Starting	.54452	.15000	.30541	.63372	.83490	1.00000			
Recharge	.46776	.79563	.63267	.56640	-.02103	-.16857	1.0000		
Agricultural Pumping	-.31654	-.46769	-.34802	-.03896	-.10061	.34644	-.37950	1.0000	
Municipal Pumping	-.10002	-.03026	-.15555	.23790	.00789	.41980	.06335	.64266	1.0000

Table 2. Estimated Coefficients, T-Values and R-Squares of Edwards Aquifer Relationships, Historical Data.

	Well Level			Pumping			
Equation	J17	Sabinal	Recharge	Agricultural	Municipal	Intercept	R-Square
Comal	1569.1234*	711.4789*	0.062331*	-0.010650	-0.325005*	209455.8037*	
Springflow	(1.77)	(1.78)	(6.45)	(-0.08)	(-2.58)	(52.60)	.8445
San Marcos	866.7641*	47.0955	0.052663*	-0.126529	0.009436	123900.3115*	
Springflow	(1.37)	(0.17)	(7.63)	(-1.27)	(0.10)	(43.55)	.8099
J17 Ending	0.2597	0.1232	0.000020*	0.000036	-0.000103*	671.8925*	
Elevation	(1.03)	(1.08)	(7.14)	(0.91)	(-2.85)	(589.88)	.7625
Sabinal Ending	0.3991	0.5518*	0.000045*	0.000098*	-0.000099*	770.2235*	
Elevation	(0.99)	(3.04)	((10.32)	(1.54)	(-1.72)	(425.57)	.8947

* indicates statistical significance at the 10% level (one-tailed test).

Table 3. Statistics on Dependent and Independent Variables, Simulated Data.

Variable	Mean	Standard Dev.	Minimum	Maximum
Dependent Variables				
Comal Springflow	247970.	84823.	91770.	483320.
San Marcos Springflow	84698.	15033.	53242.	137640.
J17 Ending	656.12	17.137	613.67	684.12
Sabinal Ending	784.57	23.274	704.40	847.91
Independent Variables				
J17 Starting	672.49	21.732	600.20	698.00
Sabinal Starting	790.58	29.267	688.20	831.00
Recharge	823760.	442730.	170760.	2003600.
Agricultural Pumping	145660.	77965.	39389.	255370.
Municipal Pumping	291490.	122480.	134970.	464490.

Correlation Matrix of Variables

	Comal	San Marcos	J17 End	Sabinal End	J17 Start	Sabinal Start	Recharge	Ag. Pumping	Mun. Pumping
Comal Springflow	1.00000								
San Marcos Springflow	.75578	1.0000							
J17 Ending	.84057	.56797	1.00000						
Sabinal Ending	.86194	.59968	.71761	1.0000					
J17 Starting	.68447	.28833	.40023	.68080	1.0000				
Sabinal Starting	.59901	.17565	.38272	.75958	.82353	1.0000			
Recharge	.29188	.64460	.23834	.28018	-.17963	-.17669	1.0000		
Agricultural Pumping	-.04795	.02850	-.11890	-.22610	.04165	.04312	.00653	1.0000	
Municipal Pumping	-.31355	-.17499	-.70837	-.10892	.14698	.14541	-.01441	.00502	1.0000

Table 4. Estimated Coefficients, T-Values and R-Squares of Edwards Aquifer Relationships, Simulated Output.

	Well Level			Pumping			
Equation	J17	Sabinal	Recharge	Agricultural	Municipal	Intercept	R-Square
Comal	2650.6627	534.1348	0.084441	-0.092354	-0.300155	247971.7738	
Springflow	(40.85)	(11.09)	(46.05)	(-9.02)	(-45.55)	(311.05)	.8438
San Marcos	374.8525	-56.8585	0.024415	0.001379	-0.028012	84697.5474	
Springflow	(21.48)	(-4.39)	(49.51)	(0.50)	(-15.81)	(395.07)	.6404
J17 Ending	0.2921	0.1520	0.000013	-0.000032	-0.000111	656.1232	
Elevation	(29.16)	(20.46)	(46.53)	(-20.00)	(-109.38)	(5332.99)	.9089
Sabinal Ending	0.2611	0.5431	0.000023	-0.000080	-0.000045	784.5672	
Elevation	(17.89)	(50.15)	(56.47)	(-34.66)	(-30.31)	(4375.93)	.8951
Agricultural Lift	-0.3035	-0.3967	-0.000018	0.000079	0.000046	134.0641	
	(-25.97)	(-45.75)	(-55.65)	(42.82)	(38.75)	(933.83)	.9055
Municipal Lift	-0.3096	-0.1539	-0.000014	0.000033	0.000105	129.9590	
	(-34.96)	(-23.42)	(-57.06)	(23.59)	(117.22)	(1194.39)	.9258

Table 5. T-Values of Hypothesis that Real World Coefficients are Different than Coefficients on Simulated Output.

	Well Level			Pumping	
Equation	J17	Sabinal	Recharge	Agricultural	Municipal
Comal Springflow	1.22	-0.44	2.29*	-0.61	0.20
San Marcos Springflow	-0.78	-0.38	-4.09*	1.28	-0.40
J17 Ending Elevation	0.13	0.25	-2.50*	-1.72*	-0.22
Sabinal Ending Elevation	-0.34	-0.05	-5.05*	-2.80	0.94

* indicates statistical significance at the 10% level (two-tailed test).

Table 6. Edwards Aquifer Relationships, Controlled Experiment.

		Pumping	
	Recharge	Agricultural	Municipal
Comal Springflow	0.02984	-0.10839	-0.34685
San Marcos Springflow	0.03228	-0.00111	-0.03181
J17 Ending Elevation	0.000012	-0.000044	-0.000140
Sabinal Ending Elevation	0.000024	-0.000086	-0.000044
Agricultural Lift	-0.000020	0.000088	0.000049
Municipal Lift	-0.000012	0.000041	0.000123

Table 7. Total Effects of Pumping and Recharge, Three Approaches.

			Pumping	
		Recharge	Agricultural	Municipal
Comal Springflow	Historic Data	0.2468	*	-0.9370
	Simulated Data	0.2096	-0.4649	-0.9523
	Controlled Experiment	0.6917	-0.7569	-0.9076
San Marcos Springflow	Historic Data	0.1040	*	*
	Simulated Data	0.0369	-0.0354	-0.1040
	Controlled Experiment	0.0912	-0.0374	-0.0786
J17 Ending Elevation	Historic Data	0.000051	*	-0.000206
	Simulated Data	0.000033	-0.000094	-0.000203
	Controlled Experiment	0.000180	-0.000173	-0.000198
Sabinal Ending Elevation	Historic Data	0.000146	*	-0.000405
	Simulated Data	0.000069	-0.000229	-0.000214
	Controlled Experiment	0.000445	-0.000468	-0.000304
Agricultural Lift	Simulated Data	-0.000056	0.000198	0.000193
	Controlled Experiment	-0.000436	0.000461	0.000274
Municipal Lift	Simulated Data	-0.000035	0.000097	0.000201
	Controlled Experiment	-0.000173	0.000165	0.000188

* indicates that one or more of the regression coefficients used to generate the total effect was contrary to *a priori* hypotheses.

Table 8. Estimated Coefficients, T-Values and R-Squares of Edwards Aquifer Relationships, Monthly Analysis.

Coefficients: Comal Springflow (Comal Springflow > 0)

	Starting Head Level			Pumping			
Month	J17	Sabinal	Recharge	Agricultural	Municipal	Intercept	R-Square
Jan	179.6977	121.5242	.00037694	-.00081980	-.00840612	-191275.04	
Feb	279.1811	48.9021	.00129615	-.00134069	-.01140768	-199980.95	
Mar	286.9427	38.5477	.00229926	-.00258167	-.01496698	-197155.24	
Apr	278.3065	36.1406	.00333875	-.00395901	-.01911019	-189848.81	
May	261.6719	34.7905	.00524866	-.00527391	-.02325570	-178441.83	
Jun	243.7887	36.1801	.00801114	-.00830986	-.02593695	-168765.67	
Jul	230.3826	39.2029	.01011086	-.01082970	-.03130907	-163188.51	
Aug	219.6110	41.2386	.01058962	-.01352553	-.03559087	-158143.89	
Sep	208.0299	42.8022	.01012196	-.01400677	-.03598852	-151589.93	
Oct	196.7429	44.0088	.00996394	-.01364162	-.03569625	-144951.40	
Nov	185.9604	45.4085	.01013378	-.01270258	-.03328836	-139072.07	
Dec	174.5755	45.4241	.00999738	-.01136210	-.03377146	-131558.94	
Total	2744.8908	574.1705	.08148844	-.09835324	-.30872815	-2013972.28	

T-values and R-Squares: Comal Springflow (Comal Springflow > 0)

Jan	75.96	67.20	5.64	-2.27	-36.66	-255.36	.9629
Feb	91.32	21.08	15.14	-2.89	-38.77	-215.33	.9461
Mar	78.74	14.03	22.72	-4.71	-42.92	-185.45	.9284
Apr	68.54	11.86	29.77	-6.52	-49.40	-165.41	.9130
May	50.73	9.02	36.88	-6.82	-46.80	-124.02	.8590
Jun	42.06	8.36	50.39	-9.51	-45.69	-105.63	.8227
Jul	43.76	9.99	70.03	-13.60	-60.32	-111.97	.8516
Aug	47.38	11.96	82.58	-19.11	-76.96	-118.39	.8754
Sep	49.49	13.69	86.96	-21.71	-85.13	-125.13	.8881
Oct	49.16	14.78	90.17	-22.30	-88.74	-129.20	.8938
Nov	48.04	15.75	95.66	-21.72	-86.53	-134.12	.8983
Dec	43.52	15.21	91.37	-18.82	-84.92	-126.05	.8877

Coefficients: San Marcos Springflow (Comal Springs > 0)

	Starting Head Level		Recharge		Pumping			
Month	J17	Sabinal	West	East	Agricultural	Municipal	Intercept	R-Square
Jan	-59.1948	48.0007	.00090833	.00112492	.00000414	-.00156946	7460.85	
Feb	19.5201	5.4816	-.00000756	.00595072	-.00002570	-.00181424	-11143.06	
Mar	39.2782	-4.8266	.00037415	.00604929	.00000457	-.00196948	-16358.73	
Apr	46.4795	-7.9619	-.00243988	.01524643	-.00004082	-.00211918	-18347.47	
May	48.7128	-10.4426	.00058276	.00667277	.00003702	-.00218111	-17815.17	
Jun	50.2691	-9.9966	.00542511	.00539631	.00000675	-.00246916	-21052.34	
Jul	49.9620	-9.6621	.00284398	.00309963	-.00006295	-.00290164	-20342.66	
Aug	48.4799	-9.5453	.00112269	.00397523	-.00006361	-.00292158	-19006.50	
Sep	47.0709	-9.2802	.00029037	.00594599	-.00004754	-.00319452	-18231.69	
Oct	45.9972	-8.5213	.00069669	.00897375	-.00007778	-.00319125	-18486.90	
Nov	44.2628	-8.0363	.00006184	.00909027	-.00017824	-.00298282	-17523.59	
Dec	42.5102	-7.4466	.00001620	.00825421	-.00021225	-.00306877	-16715.39	
Total	423.3480	-32.2375	.00987467	.07977952	-.00065640	-.03038322	-187562.65	

T-Values and R-Squares: San Marcos Springflow (Comal Springs > 0)

Jan	-34.10	36.18	9.50	3.69	.02	-9.33	13.58	.3446
Feb	11.07	4.10	-.08	19.36	-.10	-10.69	-20.79	.3681
Mar	28.93	-4.72	5.07	25.73	.02	-15.16	-41.26	.6016
Apr	24.91	-5.69	-24.40	48.31	-.15	-11.92	-34.70	.5676
May	19.93	-5.71	4.51	16.47	.10	-9.26	-25.99	.3613
Jun	16.12	-4.29	33.58	10.59	.01	-8.09	-24.30	.5601
Jul	29.25	-7.59	32.21	11.08	-.24	-17.23	-42.67	.6269
Aug	43.84	-11.61	19.52	21.69	-.38	-26.48	-59.24	.7011
Sep	41.10	-10.90	4.88	31.19	-.27	-27.74	-54.90	.6685
Oct	24.94	-6.21	7.33	29.43	-.28	-17.21	-35.54	.5411
Nov	40.34	-9.84	1.10	50.52	-1.08	-27.35	-59.28	.7368
Dec	36.58	-8.61	.27	43.59	-1.21	-26.64	-54.96	.6908

Table 8. Estimated Coefficients, T-Values and R-Squares of Edwards Aquifer Relationships, Monthly Analysis (continued).

Coefficients and T-Values (Comal Springflow > 0)

	Starting Head Level			Pumping			
Equation	J17	Sabinal	Recharge	Agricultural	Municipal	Intercept	R-Square
J17 Ending	.3138	.1667	.00001350	-.00003537	-.00011708	341.40	
Elevation	(45.55)	(32.49)	(71.86)	(-34.12)	(-171.45)	(190.50)	.9406
Sabinal Ending	.2809	.5686	.00002223	-.00008225	-.00004679	152.91	
Elevation	(27.40)	(74.50)	(79.53)	(-53.31)	(-46.05)	(57.34)	.9507
Agricultural	-.3266	-.4377	-.00001776	.00008165	.00004726	689.22	
Lift	(-36.54)	(-65.76)	(-72.85)	(60.69)	(53.34)	(296.38)	.9510
Municipal	-.3208	-.1627	-.00001431	.00003591	.00010908	449.06	
Lift	(-52.85)	(-35.99)	(-86.45)	(39.31)	(181.29)	(284.37)	.9512

Coefficients: San Marcos Springflow: Comal Springs = 0

	Starting Head Level		Recharge		Pumping			
Month	J17	Sabinal	West	East	Agricultural	Municipal	Intercept	R-Square
Jan	-.0620	68.4820	.00088500	.00109449	-.00000063	-.00144460	-43822.60	
Feb	12.5794	51.4032	-.00002939	.00578576	.00000511	-.00149605	-39664.58	
Mar	28.5775	31.5906	.00038894	.00545015	-.00001282	-.00174393	-35808.45	
Apr	15.0813	46.3737	-.00208495	.01357178	-.00005782	-.00220227	-37423.93	
May	63.5896	-11.3330	.00038433	.00630343	-.00009553	-.00216222	-26778.83	
Jun	65.5289	-11.9214	.00377792	.00878829	-.00008230	-.00260156	-29012.72	
Jul	63.4960	-10.4623	.00213408	.00482944	-.00010783	-.00321120	-28114.19	
Aug	61.2739	-8.3187	.00064070	.00514428	-.00019261	-.00341746	-27725.75	
Sep	58.2922	-7.5972	.00010572	.00624499	-.00033135	-.00372006	-26359.68	
Oct	57.9724	-6.8304	.00084275	.00904163	-.00058107	-.00399107	-26978.33	
Nov	58.9985	-7.0554	.00009415	.01001210	-.00051040	-.00416323	-27152.98	
Dec	56.9698	-5.4585	.00021959	.00896519	-.00058785	-.00448911	-26841.43	
Total	542.2974	128.8726	.00735884	.08523152	-.00255510	-.03464275	-375683.47	

T-Values and R-Squares: San Marcos Springflow: Comal Springs = 0

Jan	.00	1.96	10.14	3.93	.00	-9.41	-7.96	.6797
Feb	.33	1.18	-.27	16.52	.02	-7.75	-5.77	.5841
Mar	1.05	1.03	5.00	21.83	-.06	-12.68	-7.35	.7356
Apr	.37	.99	-17.29	34.08	-.18	-10.49	-5.04	.5940
May	6.19	-1.06	2.26	10.87	-.22	-7.46	-16.58	.3797
Jun	6.81	-1.26	18.54	12.47	-.16	-7.69	-21.11	.5706
Jul	12.52	-2.16	18.76	12.37	-.38	-16.92	-40.84	.6685
Aug	23.59	-3.46	10.48	25.11	-1.27	-33.19	-84.18	.8412
Sep	19.02	-2.71	1.44	25.67	-1.83	-29.99	-71.03	.7799
Oct	10.87	-1.40	6.55	21.21	-1.86	-18.49	-41.77	.6076
Nov	20.28	-2.60	1.36	43.26	-3.05	-35.97	-72.47	.8324
Dec	16.34	-1.68	2.65	32.12	-2.94	-32.18	-59.87	.7682

Table 8. Estimated Coefficients, T-Values and R-Squares of Edwards Aquifer Relationships, Monthly Analysis (continued).

Coefficients and T-Values (Comal Springflow = 0)

	Starting Head Level			Pumping			
Equation	J17	Sabinal	Recharge	Agricultural	Municipal	Intercept	R-Square
J17 Ending	.7507	.1862	.00002700	-.00006644	-.00019611	76.22	
Elevation	(32.25)	(8.60)	(90.67)	(-49.83)	(-211.15)	(25.64)	.9721
Sabinal Ending	.0710	.9190	.00002418	-.00009751	-.00007203	40.11	
Elevation	(5.69)	(79.20)	(151.47)	(-136.43)	(-144.66)	(25.17)	.9900
Agricultural	.1980	-1.1056	-.00002177	.00010152	.00007536	834.39	
Lift	(24.90)	(-149.52)	(-214.01)	(222.89)	(237.51)	(821.61)	.9955
Municipal	-.6963	-.1974	-.00002607	.00006311	.00017774	688.95	
Lift	(-31.31)	(-9.54)	(-91.65)	(49.54)	(200.29)	(242.57)	.9707