Effects of Climatic Change on a Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer

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Seniority of authorship is shared. This research was partially supported by and is a contribution to the National Assessment of Climate Change, Agricultural Focus Group, supported by the U.S. Global Climate Change Office. The authors thank John Reilly for useful discussions. The views expressed are not necessarily those of the U.S. Department of Agriculture.

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Global climate change portends shifts in water demand and availability which may damage or cause intersectoral water reallocation in water short regions. This study examines the implications of some climate change projections for the San Antonio Texas, Edwards Aquifer (EA) region concentrating on the economy and the water use pattern.

The EA waters supply the needs of municipal, agricultural, industrial, military and recreational users. The EA is carstic aquifer which has many characteristics in common with a river. Annual recharge over the period 1934 -1996 averaged 658,200 acre feet (af) while discharge averaged 668,700 acre feet (USGS,1997). EA discharge is through pumping and artesian spring discharge. Pumping has rose by 1% a year in the 1970's-1980's (Collinge et al,1993) and now accounts for 70% of total discharge. Pumping in the Western EA is largely from agricultural (AG) whereas eastern pumping is mainly in municipal and industrial (M&I). Spring discharge, mainly from San Marcos and Comal springs in the East, supports a habitat for endangered species (Longley 1992), provides water for recreational use and serves as an important supply source for water users in the Guadalupe-Blanco river system. The aquifer is now under pumping limitations due to actions by the Texas Legislature (Texas Senate,1993) and because of a successful suit by the Sierra club to protect the endangered species (Bunton,1996). A number of efforts have examined economic, hydrological, and environmental issues regarding the EA (Dillion (1991), McCarl et al.(1993), Lacewell and McCarl (1995), Williams (1996), Keplinger et al.(1997,1998), McCarl et al. (1998), Schiable et al.(1999) and Watkins and McKinney (1999)).

Reduced water availability or increased water demand caused by climate change could exacerbate the regional problems which arise in dealing with water scarcity. This study utilizes an existing EA hydrological and economic systems model – EDSIM (McCarl et al. 1998) to examine the implications of climate induced changes in recharge, and water demand.

Climatic Change in the Edwards Aquifer Region

The U.S. Global Climate Change Research Program, National Assessment Team (USGCRP-NAT) has been working on an integrated multisectoral assessment of climate change and has selected two global circulation models as the primary source of future climate projections. These are the Canadian Climate Center Model (CCC) and the Hadley Center Model (HAD) run under the greenhouse gas and sulfate emission scenario proposed by the Intergovernmental Panel on Climate Change known as IPPC1992a. We drew the results for the EA region climate from the CCC and HAD models for use in this study. These yielded regional estimates of the changes in temperature and precipitation for the years 2030 and 2090 as listed in Table 1.

Changes in climatic conditions in the EA region would alter water demand and supply. An increase in temperature will cause an increase in water demand for irrigation and municipal use, but would also increase evaporation lowering runoff and in turn EA recharge. A decrease in rainfall would increase crop and municipal water demand, lower the profitability of dryland farming and reduce the available water for recharge. Each of these terms were independently estimated

Recharge implications

To project climatic change effects on EA recharge, a regression analysis was employed to estimate the effects of alternative levels of temperature and precipitation on historically observed recharge. Namely USGS estimates of historical recharge data by county were drawn from the Edwards Aquifer Authority annual reports for the years 1950 to 1996. County climate data for the same years were obtained from the Office of the Texas State Climatologist and a University of Utah web page.

The functional form we used was determined through examination of the statistical significance of the power transformation parameters associated with the dependent and independent variables via the Box Cox Transformation (Box and Cox 1964). A likelihood ratio test was used to test hypotheses about the value of these power transformation parameters. We concluded for this data set that the preferred regression model was a loglinear model. Thus monthly recharge was forecast as a loglinear function of temperature and precipitation. Because of the use of time series data, serial correlation could be a problem but the Durbin-Watson (DW) indicated no serial correlation. The significant recharge regressions coefficients all exhibited the expected sign. A table of the regression results is presented in Appendix A.

Summary measures of the effect of the projected climate changes on annual recharge for the years 2030 and 2090 under different climate scenarios is displayed in the top of Table 2 and shows a that climate change as projected cause large reductions amounting to (depending on climate scenario) from a 20.59 to 32.89 % recharge reduction for drought years and from 23.64 to 48.86 % for wet years.

Municipal water use implications

Griffin and Chang present estimates on how municipal water demand is shifted by changes in temperature and precipitation. In particular, they estimate an elasticity of climate for an increase in the municipal water demand for a one percent increase in the number of days that temperature exceeds 90 degrees and precipitation falls below 0.25 inches. To obtain the anticipated shifts for the 2030 and 2090 climate conditions, we took the daily climate record from 1950 to 1996 and adjust it by altering the original temperature and precipitation by the projected climate shifts from the climate simulators. In turn we then recomputed the municipal water demand accordingly. The results are given in Table 2 where we observe that the forecasted climate change increases municipal water demand by 1.5-3.5%.

Crop yields and irrigation water use

Changes in climatic conditions influence crop yields for irrigated and dryland crops as well as irrigation crop water requirements. For this study the shift in water use and yield under the projected climate changes was estimated using the Blaney-Criddle (BC) procedure (Heimes and Luckey[1983]; Doorenbos and Pruitt[1977]) following Dillon[1991]. In particular we used the BC procedure to alter yields and water use for the 9 recharge/weather states of nature present in the EDSIM model. Summary measures of the resultant effects are presented in Table 2 which shows a decrease in crop and vegetable yields and an increase in water requirements. For example, under the Hadley climate simulator scenario in 2090, the irrigated corn yield decreases by 3.47% whereas the irrigation water requirement increases by 31.32%.

. Methods for Developing Regional Impact

Once we had estimates of the climate induced changes in water demand, and supply then we turned to a regional aquifer model to examine the implications of these changes. The model that we employed is an existing EA region economic and hydrological simulation model called EDSIM (McCarl et al 1998). EDSIM depicts pumping use by the agricultural, municipal, and industrial sectors while simultaneously calculating pumping lift, ending elevation, and springflow. EDSIM operates across a 9 state representation of the probability distribution of precipitation, EA recharge, and crop water demand/yield. The model computes regional welfare which is the sum of net farm income and municipal and industrial consumers' surplus. An algebraic representation of the fundamental relationships in EDSIM is in Appendix B, here we provide an overview.

EDSIM is the unification of cumulative developments by Dillon[1991]; McCarl et al.[1993]; Lacewell and McCarl[1995]; Keplinger et al.[1995]; Keplinger[1996] and Williams[1996]. EDSIM depicts pumping use by the agricultural, industrial and municipal sectors while simultaneously calculating pumping lift, ending elevation and springflow. EDSIM simulates choice of regional water use, irrigated versus dryland production and irrigation delivery system (sprinkler or furrow) such that overall regional economic value is maximized. Regional value is derived from a combination of perfectly elastic demand for agricultural products, agricultural production costs, price elastic municipal demand, price elastic industrial demand, and lift sensitive pumping costs. The municipal demand elasticity is drawn from Griffin and Chang[1991] while the industrial elasticity is from Renzetti[1988]. The quantity demanded by municipal users depends upon rainfall and climatic conditions following Griffin and Chang[1991]. Agricultural water use dependency on climate is developed using EPIC [Williams et al.,1989].

In terms of its implementation EDSIM is a mathematical programming model which employs a two-stage stochastic programming with recourse formulation. The multiple stages in the model depicts the uncertainty inherent in regional water use decision-making. Many water related decisions are made in advance of the time when water availability is known. For example the decision whether or not to irrigate a particular parcel of land and the choice of the crops to put on that parcel are decided early in the year whereas the true magnitude of recharge is not known until substantially later during the year[1].

Model Experimentation, Regional Results and Discussion

Five scenarios were considered in this study: 1) BASE without climatic change, 2) the change predicted by the Hadley model for the year 2030, 3) the change predicted by the Canadian model for the year 2030; 4) that predicted by Hadley for 2090, and that predicted by Canadian for 2090.

EDSIM produces results on the economic and hydrological effects of climate change (Table 3). Results under the BASE scenario are displayed as actual values whereas results under the other scenarios are displayed as a percentage change from the BASE results. The total water usage is held less than or equal to a 400,000 a.f pumping limit mandated by the Texas Senate for years after 2008. Under BASE condition agriculture uses 38% of total pumping while M&I pumping usage accounts for the rest. Total welfare is $355.69 million consisting of $11.39 million from agricultural farm income and $337.65 million from M&I surplus. Additionally, $6.64 million accrues to the EAA or the water use permits. This authority surplus can be viewed as the rents to water rights to use some of the 400,000 af available. Comal and San Marcos springflows are 379.5 and 92.8 thousand a.f., respectively and are greater than recent average historical levels.

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[1] This uncertainty is perhaps best illustrated by referring to the Irrigation Suspension Program implement by the EA authority a couple of years ago where early in the year an irrigation buyout was pursued but the year turned out to be quite wet in terms of recharge.

According to the results the strongest effect of climate change falls on springflow and the agricultural sector.   Under the climatic change scenarios the Comal (the most sensitive spring) springflows decrease by 10-16% in 2030 and 20-24% in 2090. This could require additional springflow protection as explored below. In terms of agriculture, the change moves water away from agriculture and adds to cost through higher pump lifts and irrigation requirements with lower yields causing a reduction in farm income ranging from 16-30% in 2030 and 30-45% in 2090. Regionally farmer income falls by 1.8 to 3.3 million dollars per year in 2030 and 3.5 to 5.1 million dollars in 2090. The shift in agricultural water to M&I indicates that the city users will buy out some agricultural usage through water markets.

Despite an increase in M&I water use, the M&I surplus decreases. This is because of an increase in pumping cost which result from an increase in pumping lift due to lower recharge. In contrast to the decrease in welfare of agricultural and non-agricultural pumping users the rents to the authority or water permits increases by 5-24%. Water use in the nonagricultural sector is less variable and a shift to that sector actually makes water use slightly greater with corresponding declines in springflow.

The great reduction in springflow would put the endangered species in the spring emergence areas in additional peril. Thus a smaller pumping limit may be required to protect the springs, endangered species and other environmental amenities. Table 4 presents the results of an examination of how much water use would need to be reduced to preserve the same level of the Comal and San Marcos springflows as in the current situation. This shows, the Edwards Aquifer pumping limit level needs to decrease by 35 to 50 thousand acre feet in 2030 and 55 to 80 thousand acre feet in 2090. Such further decreases in pumping impose substantial economic costs with welfare falling by between 0.5 and 0.9 million dollars in 2030 and 1.1-1.9 million in 2090. The additional pumping reduction causes great impact on agriculture and a substantial municipal cutback.

Concluding Remarks

Changes in climatic conditions cause a reduction in the available water resources as well as a demand increase in the San Antonio Edwards Aquifer region. The incidence of this change largely manifests itself in reduced springflows and a smaller regional agricultural sector and a regional welfare loss of 2.2 -6.8 million dollars per year. If spingflows are to be maintained at the currently desired level to protect endangered species, pumping must be reduced by 9 - 20% at an additional cost of .5 to 2 million dollars per year.

Table 1. Projected percentage Climate Changes for Edwards Region by Scenario

Climate Change Scenario	Temperature (^{0}F)	Precipitation (Inch)
Hadley 2030	3.20	-4.10
Hadley 2090	9.01	-0.78
Canadian 2030	5.41	-14.36
Canadian 2090	14.61	-4.56

Table 2. Selected Effects under the Climate Scenarios in terms of Percentage Changes from the BASE Scenario

	Hadley		Canadian	
	2030	2090	2030	2090
Recharge in drought year	-20.59	-32.89	-29.65	-31.96
Recharge in normal year	-19.68	-33.46	-28.99	-36.23
Recharge in wet year	-23.64	-41.45	-34.42	-48.86
Municipal Water demand	1.539	2.521	1.914	3.468
Irrigated Corn Yield	-1.93	-3.47	-4.26	-5.61
Irrigated Corn Water Use	11.95	31.32	23.47	54.03
Dryland Corn Yield	-3.93	-6.78	-8.17	-10.79
Irrigated Sorghum Yield	-1.75	-3.35	-2.79	-4.17
Irrigated Sorghum Water Use	15.12	38.16	42.65	79.36
Dryland Sorghum Yield	-5.93	-13.07	-10.82	-16.76
Irrigated Cotton Yield	-9.06	-15.82	-19.80	-24.64
Irrigated Cotton Water Use	16.88	40.82	34.58	71.50
Dryland Cotton Yield	-7.13	-11.60	-13.95	-17.76
Irrigated Cantaloupe Yield	-1.34	-2.33	-2.86	-3.58
Irrig. Cantaloupe Water Use	18.95	46.47	41.41	82.68
Irrigated Cabbage Yield	-5.57	-12.05	-9.63	-14.72
Irrigated Cabbage Water Use	14.80	30.95	36.36	71.30

Table 3. Aquifer Regional Results under Alternative Climate Change Scenarios

Variable	Units	BASE Value	2030 Hadley (%)	2030 Canadian (%)	2090 Hadley (%)	2090 Canadian (%)
AG Water Use[a]	1000 af	150.05	-0.89	-1.35	-2.4	-4.15
M&I Water Use[b]	1000 af	249.72	0.63	0.9	1.54	2.59
Total Water Use[c]	1000 af	399.77	0.06	0.06	0.06	0.06
Net AG Income[d]	Thousand Dollars	11391	-15.85	-29.41	-30.34	-44.97
Net M&I Surplus[e]	Thousand Dollars	337657	-0.2	-0.36	-0.58	-0.92
Authority Surplus[f]	Thousand Dollars	6644	3.76	7.07	12.73	21.6
Net Total Welfare[g]	Thousand Dollars	355692	-0.64	-1.16	-1.3	-1.93
Comal Flow[h]	1000 af	379.5	-9.95	-16.62	-20.15	-24.15
San Marcos Flow[i]	1000 af	92.8	-5.07	-8.3	-10.09	-12.06

[a] refers to agricultural water use.
[b] refers to municipal and industrial water use.
[c] refers to total water use including agricultural and non-agricultural water use.
[d] refers to net farmer income.
[e] refers to net municipal and industrial surplus.
[f] refers to surplus accruing to the pumping or springflow limit.
[g] refers to net total welfare including agricultural and non-agricultural welfare.
[h] refers to Comal springflow.
[i] refers to San Marcos springflow.

Table 4. Results of Analysis on Needed Pumping Limit to Preserve Springflows at Base, without Climate Change Levels

Variable	Units	BASE	2030		2090	
		Value	Hadley (%)	Canadian (%)	Hadley (%)	Canadian (%)
Pumping Limit	1000 af	400	365	350	345	320
AG Water Use	1000 af	150.05	-16.46	-22.74	-23.69	-46.08
M&I Water Use	1000 af	249.72	-4.03	-6.27	-7.7	-4.26
Total Water Use	1000 af	399.77	-8.7	-12.45	-13.7	-19.95
Net AG Income	Thousand Dollars	11391	-18.43	-33.44	-34.6	-58.28
Net M&I Surplus	Thousand Dollars	337657	-0.78	-1.3	-1.86	-1.88
Authority Surplus	Thousand Dollars	6644	32.33	52.53	73.66	68.34
Net Total Welfare	Thousand Dollars	355692	-0.78	-1.41	-1.62	-2.47
Comal Flow	1000 af	379.5	1.47	0.52	1.22	-1.06
San Marcos Flow	1000 af	92.8	-0.28	-1.13	-1.11	-2.48

Note: The pumping limit under each scenario represents the amount of water restriction in Edwards Aquifer regions.

References

Adams, R.M., B.H. Hurd, S. Lenhart, and N. Leary . "Effects of Global Climate Change on Agriculture: An Interpretative Review", *Climatic Research* 11:19-30 (1998).

Baumol W. J., and Oates, W. E. *The Theory of Environmental Policy: Externalities, Public Outlays, and the Quality of Life*. Prentice Hall, Englewood Cliffs, New Jersey (1975).

Box, G.E.P., and D.R. Cox, "An Analysis of Transformations.", *Journal of the Royal Statistical Society*, Series B, Vol. 26, 1964, P211-243.

Bunton, Lucius D. III (1996) *Order on the Sierra Club's Motion for Preliminary Injunction, Sierra Club, et al. v. Bruce Babbitt et al.* MO-91-CA-069, United States District Court, Western District of Texas, Midland-Odessa Division. August 23.

Collinge, R., P. Emerson, R. C. Griffin, B. A. McCarl, and J. Merrifield. *The Edwards Aquifer: An Economic Perspective*. Texas Water Resources Institute, Texas A&M University, College Station, Texas. TR-159, 1993

Dantzig , G.B., "Linear Programming Under Uncertainty", *Management Science*, 1(1955),197-206.

Dillon, C.R. *An Economic Analysis of Edwards Aquifer Water Management*. Ph.D. dissertation, Texas A&M University, College Station, Texas. 1991.

Doorenbos, J. and W. O. Pruitt. *Guidelines for Predicting Crop Water Requirements*. Food and Agriculture Organization of the United Nations. FAO Irrigation and Drainage Paper 33. Rome, 1977.

Eckhardt, G.A., *The Edwards Aquifer Home Page*, http://www.txdirect.net/users/eckhardt , 1998.

Edwards Aquifer Authority, *Homepage*, http://www.e-aquifer.com 1998.

Gharbi, A. and Peralta, R. C. "Integrated Embedding Optimization Applied to Salt Lake Valley Aquifers." *Water Resources Research*. 30(1994):817-832.

Griffin, R.C. and C. Chang. "Seasonality in Community Water Demand." *Western Journal of Agricultural Economics*. 16(1991):207-217.

Heimes, F. J. and R. R. Luckey. *Estimating 1980 Groundwater Pumpage for Irrigation on the High Plains in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.* USGS. Water Resources Investigation Report 83-4123. Denver, Colorado, 1983.

Howe, C. W., D. R. Schurmeier, and W. D. Shaw. Jr. "Innovative Approaches to Water Allocation: The Potential for Water Markets." *Water Resources Research.* 22(April 1986):439-45.

Keplinger, K. O. *An Investigation of Dry Year Options for the Edwards Aquifer*. Unpublished Ph.D. dissertation, Texas A&M University, College Station, Texas, 1996.

Keplinger, K. O. and B. A. McCarl. *Regression Based Investigation of Pumping Limits on Springflow within the Edwards Aquifer.* Unpublished manuscript. Department of Agricultural Economics, Texas A&M University, College Station, Texas (1995).

Keplinger, K., B. McCarl, M. Chowdhury, and R. Lacewell, "Economic and Hydrologic Implications of Suspending Irrigation in Dry Years", *Journal of Agricultural and Resource Economics*, 23(1998):191-205.

Lacewell, R. D., and B.A. McCarl. *Estimated Effect of USDA Commodity Programs on Annual Pumpage from the Edwards Aquifer*. Final report submitted to the U.S. Department of Agriculture, Natural Resource Conservation Service, Temple, Texas (1995).

Lewandrowski, J., and D. Schimmelpfennig. "Economic Implications of Climate Change for U.S. Agriculture: Assessing Recent Evidence." *Land Economics* 75(February 1999):39-57.

Longley, G. "The Subterranean Aquatic Ecosystem of the Balcones Fault Zone Edwards Aquifer in Texas - Threats from Overpumping." *Proceedings of the First International Conference on Ground Water Ecology*. Ed. J.A. Stanford and J.J. Simons. Tampa, Florida, April 26-29, 1992, pp. 291-300.

McCarl, B.A. "Cropping Activities in Agricultural Sector Models: A Methodological Proposal." *American Journal of Agricultural Economics,* 64(1982):768-72.

McCarl, B.A. and T.H. Spreen. "Price Endogenous Mathematical Programming as a Tool for Sector Analysis." *American Journal of Agricultural Economics*. 62(1980):87-102.

McCarl, B.A. K.O. Keplinger, C. Dillon, and R.L.Williams , "Limiting Pumping from the Edwards Aquifer: An Economic Investigation of Proposals, Water Markets and Springflow Guarantees", *Water Resources Research* , 35(4), 1257-1268, 1998.

McCarl, B.A. and G.H. Parandvash. "Irrigation Development versus Hydroelectric Generation: Can Interruptible Irrigation Play a Role?" *Western Journal of Agricultural Economics*. 13(1988):267-276.

McCarl, B. A., W. R. Jordan, R. L. Williams, L. L. Jones and C. R. Dillon. *Economic and*

Hydrologic Implications of Proposed Edwards Aquifer Management Plans. Texas Water Resources Institute, Texas A&M University, College Station, Texas. TR-158, 1993.

Michelsen, A. R. and Young, R. A. Optioning Agricultural Water Rights for Urban Water Supplies During Drought. *American Journal of Agricultural Economics.* 75(November 1993):1010-20.

Office of the Texas State Climatologist ****

Renzetti, S. "An Economic Study of Industrial Water Demands in British Columbia, Canada." *Water Resources Research*. 24(1988):1569-1573.

San Antonio Water System, *Environmental Homepage*, http://www.saws.org/other.htm, 1998.

Schaible, G. D. Summary/interpretation: Three County Irrigation Survey of Irrigators in the EA Area. Appendix II in *Biological Evaluation of USDA Farmer Assistance and Rural Development Programs Implemented in Bexar, Medina, and Uvalde Counties, Texas on EA Threatened and Endangered Aquatic Species*, Natural Resources Conservation Service, USDA, Temple, TX, March 1996.

Schaible,G.D. B. A. McCarl and R. D. Lacewell, “The Edwards Aquifer’s Water Resource Conflict: Do USDA Farm Programs Increase Irrigation Water-Use?” forthcoming Water Resources Research, 2000.

Texas Legislature, *Senate Bill No.1477*, 73rd Session, Austin Texas, May 1993.

Thorkildsen, D. and P.D. McElhaney. *Model Refinement and Applications for the Edwards (Balconies Fault Zone) Aquifer in the San Antonio Region, Texas*. Texas Water Development Board, Report 340. Austin, Texas. July 1992.

United States Fish and Wildlife Service, *San Marcos/Comal Recovery Plan*, Albequerque New Mexico, 1995.

United States Geological Survey, *Recharge to and Discharge from the Edwards Aquifer in the San Antonio Area, Texas*, Austin,TX, various issues, the1997 report is on http://tx.usgs.gov/reports/district/98/01/index.html.

University of Utah web page http://climate.usu.edu/free/default2.htm

Vaux, H. J., and R. E. Howitt. “Managing Water Scarcity: An Evaluation of Interregional Transfers.” *Water Resources Research.* 20(September 1984):785-92.

Ward, F. A., and Lynch, T. P. “Is Dominant use Management Compatible with Basin-Wide

Economic Efficiency." *Water Resources Research*. 33(1997):1165-70.

Williams, R.L. "Drought Management and the Edwards Aquifer: An Economic Inquiry." Unpublished Ph.D. dissertation, Texas A&M University, College Station, Texas. 1996.

Williams, J. R., C. A. Jones, J. R. Kiniry, and D. A. Spaniel. "The EPIC Crop Growth Model." *Transactions of The American Society of Agricultural Engineers*. 32 (1989):497-511.

Water Strategist. Newsletter entitled *On Groundwater Control and Markets: Managing the Edwards Aquifer*. Volume 10, Number 3 , Fall 1996.

Ziari, H.A., McCarl, B.A., and Stockle, C.A "Nonlinear Mixed Integer Program Model for Evaluating Runoff Impoundments for Supplemental Irrigation" *Water Resources Research* 31(1995) 1585-1594.

Appendix A: Regression Results for the Edwards Aquifer Recharge prediction

Variables	Units	Kinney County	Uvalde County	Medina County	Bexar County	Comal County	Hays County
January:							
Intercept		5.91	15.47*	16.19*	26.49*	31.40*	13.12*
		(0.89)[a]	(2.06)	(2.29)	(2.86)	(1.95)	(1.99
Temperature	ºF	-1.30	-3.32*	-3.62*	-6.30*	-7.93*	-3.12*
		(0.77)	(1.74)	(2.01)	(2.67)	(1.92)	(1.82)
Precipitation	Inch	0.12*	0.10*	0.10*	0.20*	0.11	0.05
		(1.99)	(1.55)	(1.66)	(2.26)	(0.76)	(1.08)
R-Square		0.1261	0.1549	0.1862	0.2464	0.0934	0.0911
February:							
Intercept		5.14	20.35*	18.05*	13.97	-0.09	8.29
		(1.52)	(2.92)	(2.02)	(1.09)	(0.01)	(1.14)
Temperature	ºF	-3.40*	-4.48*	-3.99*	-3.02	0.25	-1.75
		(1.45)	(2.58)	(1.79)	(0.95)	(0.12)	(0.96)
Precipitation	Inch	0.06*	0.03	0.02	0.09	0.069	0.10*
		(1.45)	(0.90)	(0.45)	(0.85)	(1.47)	(2.79)
R-Square		0.1365	0.2101	0.1046	0.0481	0.0469	0.1751
March:							
Intercept		9.72	10.55	16.14*	17.78	-3.82	20.42
		(0.42)	(1.29)	(1.84)	(1.28)	(0.17)	(0.87)
Temperature	ºF	-2.10	-1.94	-3.40	-3.88	1.10	-4.75
		(0.39)	(0.98)	(1.60)	(1.15)	(0.20)	(0.83)
Precipitation	Inch	0.27	0.22*	0.20*	0.53*	0.30*	0.09
		(1.23)	(2.91)	(2.48)	(3.84)	(3.32)	(0.82)
R-Squared		0.0515	0.2344	0.2336	0.3036	0.2047	0.0367

Appendix A: Regression Results for the Edwards Aquifer Recharge prediction (continued.)

Variables	Units	Kinney County	Uvalde County	Medina County	Bexar County	Comal County	Hays County
April:							
Intercept		6.28	46.32*	44.10*	10.61	-44.68	-3.07
		(0.16)	(3.37)	(3.00)	(0.51)	(0.75)	(0.11)
Temperature	ºF	-1.33	-10.32*	-9.87*	-2.19	10.56	1.02
		(0.14)	(3.19)	(2.86)	(0.45)	(0.75)	(0.15)
Precipitation	Inch	0.05	0.10*	0.12*	1.15*	0.21	0.09
		(0.35)	(1.80)	(2.06)	(6.43)	(1.33)	(1.06)
R-Square		0.0038	0.2636	0.2492	0.5024	0.0554	0.0250
May:							
Intercept		51.80*	73.77*	77.00*	88.80*	71.10	21.05
		(2.99)	(4.63)	(4.51)	(3.34)	(1.29)	(1.27)
Temperature	ºF	-11.69*	-16.39*	-17.17*	-20.13*	-16.39	-4.51
		(2.93)	(4.47)	(4.36)	(3.29)	(1.29)	(1.18)
Precipitation	Inch	0.07	0.01	-0.04	0.53*	0.50*	0.15*
		(1.56)	(0.33)	(1.00)	(2.68)	(3.57)	(2.36)
R-Square		0.2284	0.3386	0.3277	0.4365	0.2710	0.1515
June:							
Intercept		92.41	113.80*	116.13*	64.88*	26.11	-15.09
		(1.12)	(4.77)	(4.37)	(1.67)	(0.32)	(0.31)
Temperature	ºF	-20.84	-25.22*	-25.81*	-14.32	-5.74	3.76
		(1.11)	(4.66)	(4.29)	(1.63)	(0.31)	(0.34)
Precipitation	Inch	0.05	0.06	0.01	0.57*	0.14	0.10
		(0.34)	(1.25)	(0.28)	(3.35)	(1.21)	(1.24)
R-Square		0.0452	0.4424	0.3580	0.3243	0.0374	0.0365

Appendix A: Regression Results for the Edwards Aquifer Recharge prediction (continued.)

Variables	Units	Kinney County	Uvalde County	Medina County	Bexar County	Comal County	Hays County
July:							
Intercept		-52.77	149.60*	125.13*	95.14	28.21	10.36
		(0.48)	(5.23)	(4.88)	(1.58)	(0.35)	(0.51)
Temperature	ºF	11.97	-33.21*	-22.78*	-21.10	-6.26	-2.09
		(0.48)	(5.14)	(4.80)	(1.55)	(0.34)	(0.45)
Precipitation	Inch	0.21*	0.01	0.01	0.40*	0.37*	0.12*
		(1.70)	(0.47)	(0.63)	(4.14)	(3.69)	(2.68)
R-Square		0.0715	0.4955	0.4073	0.3913	0.2437	0.1749
August:							
Intercept		129.87	93.42*	97.51*	259.38*	81.88	20.58
		(0.89)	(3.65)	(4.64)	(2.35)	(0.99)	(1.11)
Temperature	ºF	-29.32	-20.58*	-21.56*	-58.28*	-18.47	-4.43
		(0.77)	(3.56)	(4.55)	(2.34)	(0.99)	(1.06)
Precipitation	Inch	0.03	0.14*	0.01	0.32*	0.55*	0.88*
		(0.18)	(2.81)	(0.40)	(1.74)	(3.39)	(1.99)
R-Square		0.0766	0.4874	0.4180	0.2258	0.2505	0.1148
September:							
Intercept		25.40	26.59	36.20*	100.08*	-48.74	1.15
		(0.36)	(1.02)	(2.10)	(1.68)	(0.52)	(0.28)
Temperature	ºF	-5.85	-5.59	-7.84*	-23.00*	10.88	-0.008
		(0.37)	(0.94)	(1.99)	(1.69)	(0.51)	(0.008)
Precipitation	Inch	0.93*	0.54*	0.31*	1.66*	0.58	0.09*
		(2.11)	(3.27)	(2.10)	(3.83)	(0.92)	(2.04)
R-Square		0.1208	0.2666	0.2942	0.3296	0.0217	0.0873

Appendix A: Regression Results for the Edwards Aquifer Recharge prediction (continued.)

Variables	Units	Kinney County	Uvalde County	Medina County	Bexar County	Comal County	Hays County
October:							
Intercept		52.30	31.12*	40.27*	61.69	-46.62	34.76*
		(0.85)	(2.02)	(2.91)	(1.58)	(1.14)	(2.24)
Temperature	°F	-12.35	-6.69*	-8.97*	-14.25	10.90	-7.96*
		(0.85)	(1.85)	(2.76)	(1.55)	(1.13)	(2.18)
Precipitation	Inch	0.60*	0.14*	0.10*	0.46*	0.42*	0.04
		(3.45)	(3.35)	(2.64)	(2.67)	(2.18)	(1.08)
R-Square		0.2468	0.2792	0.2802	0.1668	0.1222	0.1100
November:							
Intercept		57.30	0.16	13.86	11.94	89.29*	9.63
		(1.52)	(0.01)	(1.29)	(0.68)	(2.12)	(0.96)
Temperature	°F	-13.98	0.54	-2.91*	-2.60	-21.90*	-2.06
		(1.51)	(0.15)	(1.11)	(0.61)	(2.13)	(0.84)
Precipitation	Inch	0.01	0.05	0.05	0.37*	0.61*	0.13*
		(0.10)	(1.09)	(1.13)	(3.82)	(4.25)	(2.97)
R-Square		0.0579	0.0291	0.0840	0.2726	0.3110	0.1852
December:							
Intercept		2.82	-0.21	-1.64	4.25	10.81	1.01
		(0.32)	(0.02)	(0.18)	(0.40)	(0.66)	(0.10)
Temperature	°F	-0.50	0.68	0.94	-0.64	-2.55	-0.05
		(0.22)	(0.27)	(0.41)	(0.24)	(0.61)	(0.02)
Precipitation	Inch	0.10*	0.11*	0.13*	0.64*	0.15*	0.14*
		(2.54)	(2.47)	(3.25)	(4.26)	(1.71)	(2.29)
R-Square		0.1520	0.1337	0.2107	0.2941	0.0698	0.1109

Asterisk (*) indicates significance at the 0.10 level

[a] Absolute t-ratio values in parentheses.

Appendix B EDSIM Algebraic Structure

This appendix summarizes the structure of EDSIM. All variables are typed in upper case and parameters are typed in lower case. Additional details can be found in McCarl et al (1998).

Objective Function:

The unifying force in EDSIM is the objective function. It is a two stage stochastic programming with recourse model (Dantzig; Boisvert and McCarl). The model is solved as one simultaneous model, but includes variables at two “stages” of uncertainty. The first (“stage 1") set of variables depicts crop mix decisions which are constant across an initial elevation and all states of nature (weather conditions including precipitation and temperature) chosen based on average returns before the weather event is known. The second (“stage 2") set of variables (irrigation scheduling, crop sale and nonagricultural water use) are chosen with knowledge of state of nature.

$$
\begin{aligned}
(1)\quad \text{maximize}\;\; & -\sum_{p}\sum_{k}\sum_{q} acrecost_{pkq}\; AGMIX_{pkq} \\
& +\sum_{r} prob_{r}\,\Big[\;\sum_{p}\sum_{c}\sum_{s}\sum_{q} netaginc_{rcsq}\; AGPROD_{prcs} \\
& \qquad +\sum_{p}\sum_{m}\int mprc_{prm}(MUN_{prm})\,d\,MUN_{prm} \\
& \qquad +\sum_{p}\sum_{m}\int iprc_{prm}(IND_{prm})\,d\,IND_{prm}\Big]
\end{aligned}
$$

where the d MUN and d IND indicate the variables being integrated over.

The first stage contains decision variables which are constant across all stochastic outcomes and appears in the first line of the equation and depicts the cost (acrecost) of establishing the crop mix times acres (AGMIX) by place (p),mix choice (k) and irrigated or dryland choice (q). The second stage contains decision variables defined by state of nature (r) and are weighted by the associated recharge state of nature probability:

a. agricultural net income (netaginc) exclusive of the first stage costs by place, crop (c), irrigated/dryland (q) and, if not dryland, irrigation strategy (s) times acres produced (AGPROD); and

b. integrals under the municipal and industrial demand curves (the terms with MUN, IND) by place;

Total Farm Land Availability:

Total acreage allocated to irrigated or dryland use cannot exceed the total land historically irrigated at place p.

(2)
$$\sum_{q} AGLAND_{pq} \le landavail_{p} \quad \text{for all } p$$

Crop Mix Restriction:

The crop mix for a place for irrigated or dryland acres must be a convex combination of pre-specified allowable crop mixes (where MIX gives the weight in the combination and selects from k multi crop mix possibilities) following McCarl[1982]. The crop mix variables are stage 1 activities and do not differ by state of nature. The constraints require that the crops in each stage 2 over (if not dryland) irrigation schedule (s) equal the stage1 crop mix chosen. Thus, the model can adjust the water use strategy to the climate, but the crop mix is chosen before exact weather conditions are known. Constraint 8 controls acreage by crop. Equation 9 forces the acres in the mix to equal the acres farmed.

(3)
$$\sum_{s} AGPROD_{prcsq} - \sum_{k} mixdata_{pckq}\, MIX_{pzkq} \le 0 \quad \text{for all } p, r, c, q$$

(4)
$$\sum_{c} \sum_{s} AGPROD_{prcsq} - \sum_{c} \sum_{k} mixdata_{pckq}\, MIX_{pkq} = 0 \quad \text{for all } p, r, q$$

Regional Ending Elevation Determination:

The ending aquifer elevation by region (ENDWAT) is computed through a linear equation that includes an intercept term (rendi), a recharge parameter (rendr) times the state dependent exogenous level of recharge (rech), an initial water level parameter (rende) times the initial water level (INITWAT) term, and a water use by region parameter (rendu) times summed municipal, industrial and agricultural use. Initial water level and usage by eastern or western region affects a region's ending water level. Thus subscript w2 also depicts region. The rend terms in the equation are regression response surface estimates over the entire set of results from a wide variety of aquifer hydrology model runs as described in McCarl et al.

$$(5)\quad ENDWAT_{wr} = rendi_{w} + \sum_{m} rendr_{w}\, rech_{rm} + \sum_{w_2} rende_{ww_2}\, INITWAT_{w_2} + \sum_{w_2} rendu_{ww2} \sum_{p \in reg(w_2)} \sum_{m} \Big(MUN_{prm} + IND_{prm} + \sum_{c} \sum_{s} wateruse_{prcsm}\ AGPROD_{prcs1} \Big)$$

for all w , r

In EDSIM-DP the ending water level is set equal to a constant which is systematically varied in generating information for the dynamic program. Note ending water level is state of nature the dependent, so the aquifer will attain different levels depending upon recharge, initial elevation and pumping use.

(6)
$$ENDWAT_{wr} \geq \overline{ENDWAT_{w}} \text{ for all } w \ \& \ r$$

Note the ending elevation for each state of nature is required to end at or above the same ending level.

Initial Elevation Balance:

Initial elevation is set to constant which is systematically varied in generating information for the dynamic program.

(7)
$$INITWAT_{w} = \overline{INITWAT_{w}} \text{ for all } w$$

Other Features and Equations:

While not explained here there are a number of other features EDSIM which are used here (see McCarl et al for a full description). These include equations that determine spring flow which are identical in form to the ending elevation equation above. There are also equations that determine pumping lifts and associated costs for agricultural, municipal and industrial pumping users. Three pumping lift zones and two irrigation delivery systems (furrow and sprinkler) are considered. In the model the region is differentiated by county.