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Economic and Hydrologic Implications of Suspending Irrigation in Dry Years

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A dry year irrigation suspension has been proposed as a way of reallocating water when aquifer levels are low for the Texas Edwards Aquifer. Under this program, farmers would be paid to suspend irrigation to allow more spring flow or nonagricultural pumping. When irrigation is suspended in the east, spring flow response is markedly larger than when suspended in the western portions of the aquifer. Most acreage participates when a $90 per acre payment is offered before the cropping season. Considerably higher payments are needed and less water saved for a suspension program instituted during the cropping season.

Key words: drought management, hydrology, interruptible irrigation, stochastic programming, water policy

Introduction

The Edwards Aquifer (EA) stretches across 175 miles of south central Texas near San Antonio, providing water to agricultural, municipal, and industrial users while also supporting two large springs.[1] The EA exhibits rapid recharge, water movement, and pressure transmission compared with other aquifers. Water flow has been measured in places at rates of up to 145 miles per year (Jensen). Flows at artesian springs are directly related to aquifer elevation, which is dependent on recharge and pumping use.

Today a million and a half people and a considerable economy depend upon EA water. Pumping usage has been increasing at about 1.1% per year, and has led to decreased spring flow and greater annual aquifer level fluctuations (Collinge et al.). Recent pumping has averaged about 500,000 acre-feet, but exceeded 540,000 in 1988 and 1989. In the last 10 years, recharge has varied from 214,400 to 2,485,700 acre-feet, with an average of about 630,000 acre-feet. While the EA has tremendous storage capacity, maintaining artesian spring flows limits the level to which the aquifer can be lowered.

Most of the recharge occurs in the western reaches of the EA. Water generally flows from west to east. Use west of San Antonio is predominantly for crop irrigation. San

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[1] For further details, see the website page at www.eardc.swt.edu/edwards.

Antonio uses EA water to meet municipal and industrial demands. East of San Antonio, some water is pumped by municipal and industrial users, while a considerable portion is released as spring flow at Comal and San Marcos Springs. These springs provide habitat for several endangered and threatened species (Longley). Habitat quality is linked to spring flow volume.[2] The springs also support a recreational industry and supply from 30% to 70% of the Guadalupe River flow.

Recent dialogue regarding EA management has focused attention on ways to reduce pumping in order to augment spring flows. This interest has occurred within the context of low spring flows, years of litigation centered around spring flows, a 1996 drought, several lawsuit filings, the slow startup of the Edwards Aquifer Authority (EAA), and a federal court order to limit pumping (Keplinger; *Water Strategist* staff).

Much concern has focused on drought management. Proposals have surfaced for what is known regionally as the "Dry Year Option" (Texas Water Commission; Rothe Company, Inc.) or, most recently, the "Irrigation Suspension Program" (ISP) under which irrigators would be paid to suspend water use during dry years. The primary purpose of the research conducted for this study was to examine ISP features to determine: (*a*) how much pumping could be curtailed, (*b*) how much spring flow could be augmented, and (*c*) how much program cost would be incurred under alternative per acre payments and irrigation suspension dates.

The study is also designed to contribute to the broader water economics literature. Dry year ISPs have been suggested throughout the West (examples and citations are provided by McCarl and Parandvash; Hamilton, Whittlesey, and Halverson; Colby; and Michelsen and Young). We believe this research makes several contributions beyond those of studies currently found in the literature. First, the ISP program examined here encompasses groundwater usage, endangered species, and spring flow. Second, mid-year program implementation is considered with the program either entirely implemented during the cropping season, or announced as a possibility before the cropping season and implemented if the year is dry. Third, the study simultaneously considers stochastic water availability, groundwater and spring flow hydrology, pumping lift as it influences user participation, and irrigation strategy choice. Finally, the study integrates crop simulators, economic models, hydrological simulators, and regression-based response equations into the analytical framework.

Study Approach

The ISP reduces agricultural pumping under "dry" conditions. The resulting conserved water can be devoted either to augmenting spring flow or to increasing nonagricultural pumping while maintaining spring flow. Therefore, we seek to answer the following critical questions:

(1) How does spring flow respond to reduced agricultural pumping?
(2) Given particular program payment offers, how much might agricultural water use be reduced?

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[2] The U.S. Fish and Wildlife Service has determined that spring flow at Comal Springs of less than 200 cubic feet per second causes "takes" of the fountain darter, one of the federally listed endangered or threatened species associated with the aquifer.

(3) Given particular program payment offers, what is the projected program cost and the per unit cost of spring flow?
(4) How much will various offers allow San Antonio region industrial and municipal pumping to increase if this is done without reducing spring flow?

The questions are addressed using an EA region agricultural sector model and spring flow prediction equations.

Spring Flow Prediction

The historical data on spring flow do not provide a rich enough set of observations to allow estimating monthly spring flow prediction equations. Thus, we used a widely accepted EA hydrologic model (GWSIM-IV) to provide data for estimating spring flow equations (Thorkildsen and McElhaney).[3]

The GWSIM-IV model was run for 12 months, 57 recharge observations (1934–90), five pumping use alternatives for both eastern and western portions of the region, and eight EA initial aquifer levels. Regional pumping level alternatives were set at 50%, 75%, 100%, 125%, and 150% of 1989 levels. Initial aquifer levels were chosen to span the entire range of recorded aquifer elevations. This resulted in a data set with 136,800 simulated monthly spring flows.

Regression was used to develop predictions of monthly Comal and San Marcos spring flow during the ISP year. Spring flow was specified as a function of initial elevation in an eastern and western well (one in San Antonio, the other in Uvalde County), annual recharge, eastern pumping (in Medina, Bexar, Comal, and Hays Counties), and western pumping (in Uvalde and Kinney Counties). Further details are found in Keplinger and McCarl.

Table 1 lists regression coefficients, *t*-values, and R^2s for the estimated equations. Although monthly spring flow equations were used, given limited space, only data from annual models are presented since they summarize the major relationships found. High R^2s suggest the linear relationships satisfactorily explain the hydrologic relationships inherent in GWSIM-IV.[4]

One notable result arises—namely, for Comal Springs (the most sensitive spring), the coefficient for eastern pumping is −0.28, versus −0.04 for western pumping. Thus, pumping cutbacks in the eastern counties produce about seven times more additional spring flow compared to western cutbacks.[5] This response difference caused us to examine ISP implementation independently for the eastern and western regions.

Two facts help explain the response difference. First, the lower effect of western pumping and elevation is due to physical factors. In particular, between the western and eastern counties, a granite formation—known as the Knippa Gap—restricts transmission of water and hydrostatic pressure. Second, a one acre-foot usage reduction would not be expected to immediately increase spring flow by one acre-foot (for example,

[3] GWSIM-IV employs a 31 × 80 grid to simulate ending aquifer levels for each cell and artesian spring flows, using starting aquifer level, recharge, and pumping by cell as inputs.

[4] The *t*-values for the monthly equations are also high, with the exception of the western pumping coefficients in the San Marcos equation (which is expected to exhibit a weak relationship).

[5] Regressions done using actual 1934–90 spring flow and usage data confirm these results (Keplinger and McCarl).

Table 1. Regression Results for Comal and San Marcos Annual Spring Flow

Parameter	Dependent Variable: Comal Spring Flow (acre-feet)	Dependent Variable: San Marcos Spring Flow (acre-feet)
Intercept (acre-feet)	-1,924,677	-203,976
	(-259.15)	(-98.66)
San Antonio well starting elevation (feet above sea level)	2,651	412
	(89.93)	(133.55)
Sabinal well starting elevation (feet above sea level)	551	0
	(24.70)	—
Annual recharge (acre-feet)	0.08	0.024
	(100.42)	(108.99)
Western pumping (acre-feet)	-0.04	-0.0005
	(-5.91)	(-0.28)
Eastern pumping (acre-feet)	-0.28	-0.025
	(-116.15)	(-37.27)
R^2	0.93	0.77

Note: Numbers in parentheses are *t*-statistics.

summing the effect of one acre-foot of eastern curtailment for both springs predicts 0.28 + 0.025 = 0.305 more spring flow). The equations predict this year's spring flow as a function of this year's cutbacks. The water not escaping as spring flow at Comal and San Marcos contributes to higher ending aquifer elevation (aquifer storage), flows at smaller springs, and leakage to other aquifers.[6] Calculations of long-term effects of cutbacks show less disparate effects of eastern versus western pumping on total spring flow (see Keplinger and McCarl).[7]

Simulating Agricultural Response to an ISP Payment

A regional agricultural model was used to predict farmer response to ISP payments. We used the agricultural component of an EA regional model which has evolved through the efforts of Dillon; McCarl et al.; Williams; and Lacewell and McCarl. The model is a stochastic programming with recourse (SPR) representation of the agricultural sector (Dantzig; Boisvert and McCarl; McCarl and Parandvash).[8] A mathematical version of the model is presented in the appendix.

Activity in six counties is modeled. Production is depicted under nine recharge/ weather states of nature with unequal probabilities. These are based on a frequency

[6] While increases in aquifer elevation are of long-term benefit, the ISP is motivated by the potential to augment declining spring flow during the current "dry year."

[7] When elevation effects are taken into account and the long-run spring flow effect is computed, the total amount of spring flow generated by a one acre-foot cutback in pumping approaches one acre-foot. Leakage and flows at smaller springs account for the difference from one.

[8] This is also known as discrete stochastic programming (Cocks).

grouping of 1934–90 EA recharge and weather data. The model includes the major regional field, hay, and vegetable crops, depicting decisions regarding irrigated/dryland production choice, sprinkler/furrow delivery, irrigated crop mix, irrigation strategy (timing and quantity of water), and dryland crop mix for three groupings of producers based on pumping lift (hereafter these producer groupings are denoted "lift zones").

Data describing yields and water use were developed using the Erosion Productivity Impact Calculator (EPIC) crop growth model (Williams et al.). The crops and vegetables included were corn, cotton, sorghum, oats, winter wheat, peanuts, cabbage, lettuce, spinach, carrots, cucumbers, cantaloupe, and onions. Simulations were run using nine years of actual weather data representative of the nine states of nature.

The automatic irrigation feature of EPIC was used to form data on irrigation strategy water use and yields. About 30 irrigation strategies were developed for each major crop and vegetable. These strategies involved soil moisture based triggers, irrigation ending dates (30 April, 30 May, 30 June, etc.), and irrigation methods (furrow and sprinkler). Dryland simulations were also conducted for relevant crops. The EPIC results were integrated with extension service budgets and then used as the production data in the sector model.

In the regional agriculture model, the first-stage decisions consist of crop mix, land allocation between irrigated and dryland production, and furrow/sprinkler choice. These decisions are constant across all states of nature (i.e., they are locked in before rainfall and recharge are known and are not subject to "recourse"). In the second stage, the weather is known and the irrigation water application strategy is chosen in accordance with the weather event by crop (i.e., these decisions are subject to "recourse"). Thus, irrigation intensity adjusts to specific weather events, but the crop acreage and furrow/sprinkler/dryland mix do not.

A key constraint is imposed to cause realistic crop mixes: dry and irrigated crop mixes must be convex combinations of prespecified crop mixes (following McCarl, and Önal and McCarl). These mixes are those historically observed on dry and irrigated acres by county from 1975–94, plus mixes reflecting farmer opinions about actions if the farm program were decoupled (which has occurred). The latter mixes were identified in a recent U.S. Department of Agriculture study conducted in the Edwards Aquifer area (Schaible).

Another consideration is pumping cost. Ceteris paribus, irrigators with higher pumping lifts incur higher pumping costs than those with lower lifts. Irrigators faced with higher costs would be more likely to participate in the ISP. Three lift zones are used to depict such reactions. (Keplinger provides additional model specification details.)

Definition of the Irrigation Suspension Program

Our analysis required a specific definition of the ISP. Several decisions were made relative to this definition. First, since EA water rights are not defined, payment is applied to acres of land removed from irrigation, rather than to water.

Second, we assumed the decision to suspend irrigation could be made before or during the cropping year based on aquifer level. Additionally, a mid-year ISP might arise if the aquifer water level was near, but above, critical levels in November, and then subsequently fell to an unacceptable level during a spring drought.

Third, to define the probability of a mid-year ISP implementation when the year was dry, we ran an analysis with an expanded regional economic model which included industrial, municipal, and agricultural usage (McCarl et al.). We examined differences in agricultural water use between cases when agriculture operated in complete self-interest, maximizing only its profits, versus a cooperative agriculture participating so that regional welfare, including that of municipal and industrial interests, was maximized. The comparison revealed that for the driest years (occurring 48% of the time), a cooperative agriculture sector would reduce water use relative to a self-interest maximizing sector (note that the western location of agriculture gives it first access to EA water and that water rights are not defined).

Based on the above considerations, the following three definitions were established for timing of the ISP. An ISP could be set up so that a payment is offered to irrigators when the program is announced:

(1) before the crop year (allowing farmers to establish crop mixes in reaction to their ISP participation)—identified hereafter as "1 Jan." ISP;
(2) during the cropping year with agricultural water use stopping after May—identified hereafter as "1 June unannounced" ISP; and
(3) as a possibility before the crop year (thus influencing crop mix) but implemented only if the spring is dry (48% of the time), with irrigation water use ceasing after May—identified hereafter as "1 June announced" ISP.

In turn, we simulated responses to alternative payment levels for each ISP scenario implemented independently in the eastern and western counties.

Estimating a Schedule of Responses and Program Cost

The alternative ISP definitions necessitated slightly different model setups. The 1 Jan. program simply involved specifying a per acre ISP payment. The 1 June unannounced ISP required constraining the annual crop mix and water use up to the end of May to be constant. When the 1 June announced ISP was simulated, the ISP payment was activated only in the driest years (occurring 48% of the time), but the crop mix could adjust.

A schedule of responses to ISP payments was developed by varying payments in $10 increments from $0 to $150 an acre. Monthly spring flow implications were computed using the regression equations, plugging in the pumping levels observed at each payment level. Program cost was calculated by multiplying participating acres times the payment for the years when the ISP is active. Cost per unit of additional water is total cost divided by water produced, while cost per unit of spring flow is total cost divided by spring flow increment.

Results

Selected results under the ISP scenarios are presented in figures 1–4. Comparing figures 1 and 2 reveals that as the ISP payment is increased, the number of acres reverting to dryland increases, but at a faster rate in eastern than western counties.

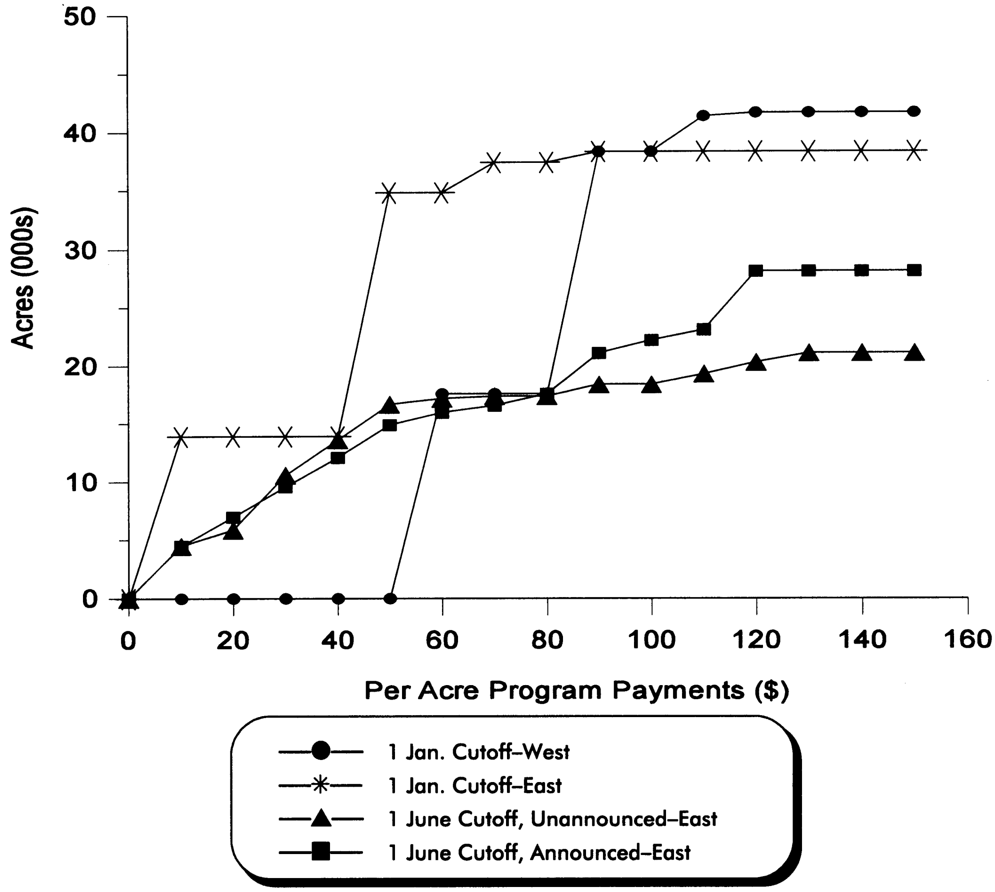

Figure 1. Acres suspending irrigation for alternative payment levels and programs

This is due to different crop mixes in the regions. Model results suggest furrow irrigation is only marginally profitable. A $10/acre payment combined with the profit obtainable from dryland agriculture causes about half of the eastern furrow-irrigated acreage (13,885 acres) to accept the ISP payment. Not until a payment level of $50/acre is reached do sprinkler-irrigated acres start to participate. When the payment is raised to $90/acre, virtually all the eastern irrigated acreage participates.

In the west, irrigated acres do not begin to participate until a payment of $60/acre is reached. At $60/acre, model results suggest that 17,618 acres in the west will accept the ISP offer. At $120/acre, all the western irrigated land converts to dryland.

Turning to spring flow, model results show that under a $10 eastern payment, irrigation pumping will be reduced by 37,011 acre-feet. The spring flow equations predict 15,034 acre-feet of increased spring flow at Comal and San Marcos Springs during the year. Most of the remaining water goes into storage, thereby raising aquifer elevation and future spring flows.

Spring flow response to western reductions is much less. For example, as a result of a $60 western payment, water use is reduced by 49,621 acre-feet, but spring flow only

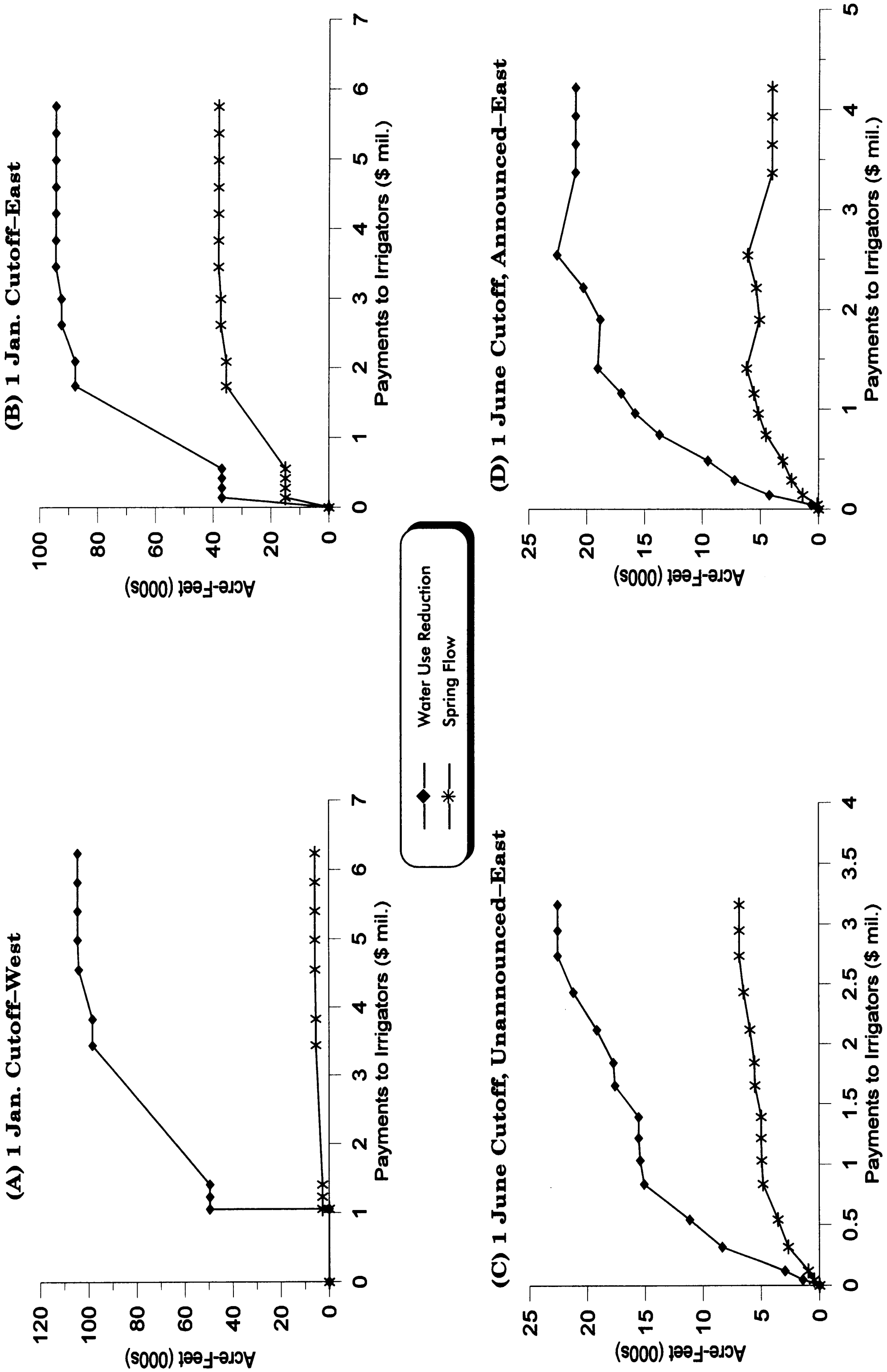

Figure 2. Water use reduction and added spring flow for program alternatives

increases by 2,789 acre-feet. The disparity in the pumping/spring flow relationship occurs because of the differing regression coefficients which arise largely because of the flow-constricting rock formation. Because spring flow effects are so much less in the western than in the eastern region, we do not report results for ISP scenarios 2 and 3 for the western region.

Cost schedules for additional spring flow and water produced in the years when the ISP is active, assuming nonirrigation pumping remains constant, are presented in figure 2. Here, water use reduction refers to the amount irrigation pumping is reduced during the year the ISP is implemented. Panels A and B of figure 2 graphically show the disparity between the cost of water and spring flow due to pumping reductions in the two regions under the 1 January ISP. Panels C and D show the cost of additional water and spring flow for the ISP, mid-year. The per unit costs of water are much higher for the mid-year ISP scenarios. This is because (*a*) considerable irrigation water use occurs before 1 June, when the mid-year ISP begins; and (*b*) by 1 June, resources have already been committed and it is costly to change the irrigation schedule. At high payment levels, Panel D shows a "backward-bending" water supply curve—because we are graphing the response in terms of conserved water, not participating land (which does monotonically increase). Under the 1 June announced ISP, when payments are high enough, the model shifts to crops that use less water after 1 June, but use more water before 1 June. Thus, the slight backward bend occurs.

Instead of dedicating water to spring flow as implied in figure 2, the agricultural water use reduction could be offset by nonagricultural pumping increases while leaving spring flow unaffected. In such a case, the quantity of additional water available for San Antonio pumping (located in the east where most of the nonagricultural water is used) is identical to the reduction in eastern agriculture water use. However, when water use is curtailed in the western region, and one wishes to hold spring flow constant, then the possible amount of additional eastern use is only one-seventh of the western water use reduction.

The monthly patterns of water use reductions and spring flow increases are important. Figures 3 and 4 show monthly pumping reductions and Comal spring flows when an eastern ISP payment of $150/acre is implemented and dedicated to spring flow. Focusing on the eastern 1 January cutoff scenario, most of the water use reduction occurs in April, May, and June, whereas the greatest impact on Comal spring flow occurs in June, July, August, and September (the most critical months). Note the mid-year ISPs are not nearly as effective. Also note the announced mid-year ISP causes an increase in water use in the April-May period as the model shifts cropping patterns to depend less on water after 1 June.

Concluding Comments

Growing aquifer demands, interests in maintaining spring flow, and the incidence of droughts have made Edwards Aquifer waters scarce. One proposal to reduce demand during dry years is an irrigation suspension program whereby irrigators are paid to not pump. Two important factors in designing the irrigation suspension program are when and where the program is implemented.

This study examines two timing scenarios for implementing an irrigation suspension program: a cutoff of 1 January and a cutoff of 1 June. The effects of implementing a

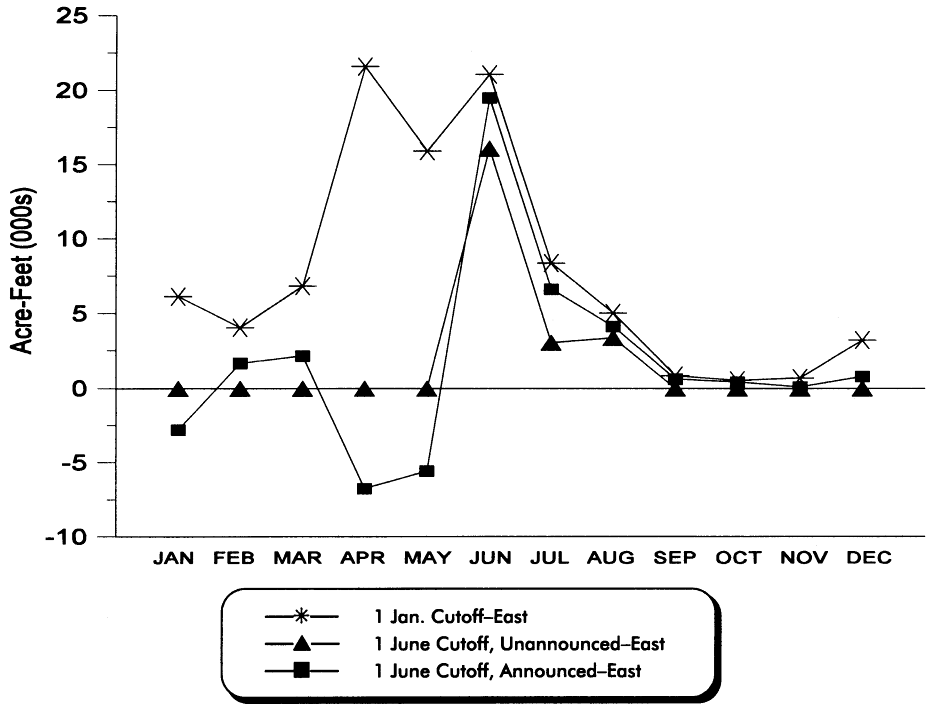

Figure 3. Potential monthly water use reduction from implementing irrigation suspension

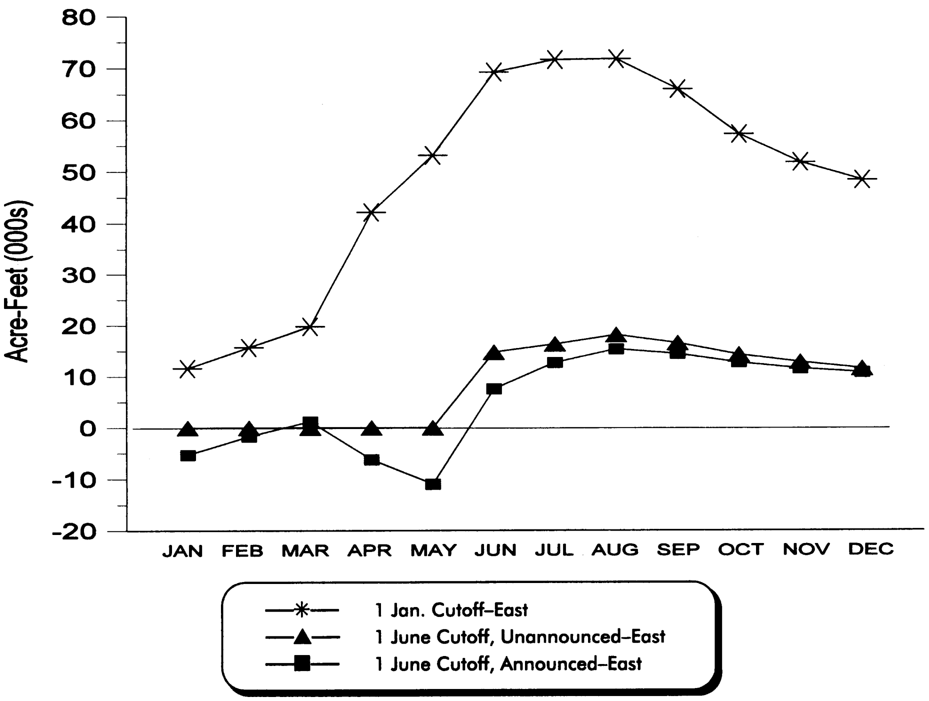

Figure 4. Monthly increase in Comal spring flow from implementing irrigation suspension

program are examined for two regions: eastern and western. A regression study shows the effect of eastern pumping reductions on near-term spring flow at the sensitive spring is approximately seven times greater than the effect of curtailed western pumping. In turn, economic results indicate that the generated spring flow costs less per unit when obtained from the eastern as opposed to the western region.

Simulations of mid-year suspensions show substantially higher payments are required due to committed production decisions, already completed water applications, and yield penalties when reducing water use. Early announcement of the possibility of a mid-year ISP if drought occurs raises costs even further because producers shift to crops that use more water before the cutoff date.

Our findings suggest that large reductions in agricultural water use can be obtained for a relatively small per acre-foot cost. The simulated effects of offering eastern irrigators $50 to suspend irrigation results in 91% of total acreage participating. Assuming no offsetting increase in pumping, spring flow at Comal Springs during August (a month often experiencing low flows) increases by an estimated 67 cubic feet per second (almost one-third the U.S. Fish and Wildlife Service's "take" level). Total cost of this program would be $1.7 million, which amounts to $20 per acre-foot of reduced pumping or $49 per acre-foot of additional spring flow. This is relatively inexpensive compared with other possible spring flow solutions.[9]

The irrigation suspension program also has certain advantages over other methods of preserving spring flow. First, costly conveyance systems are not needed. Second, the program provides a management option that can be used while the Edwards Aquifer Authority is completing water rights assignment. Third, the program can be implemented as needed, based on aquifer levels. Fourth, the cost of obtaining additional water through an irrigation suspension program is likely less than obtaining water by many other methods. Fifth, the program does not appear to cause environmental damage. Finally, a program carried out while this article was in review reveals that such an ISP is practically feasible; farmers were willing to sell (10,000 acres participated) and regional water supply systems were willing to fund the program (Keplinger).

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[9] McKinney and Sharp evaluated several techniques for EA spring flow augmentation. Total estimated capital costs of injection wells or addition of water to the spring lakes are $200 million, while annual operating expenses are $32 million. Water transferred from other river basins is anecdotally felt to cost in excess of $200/acre-foot annually.

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Appendix

An algebraic representation of the economic model ignoring the sprinkler/furrow features is presented below. Variables are typed in all caps/italics, while parameters are typed in lower case/nonitalics.

(A1) Objective Function:

$$\begin{aligned}\text{maximize} \sum_r \text{prob}_r \Bigg(& \sum_p \sum_z \sum_c \sum_s \text{irrincome}_{rcs} \, IRRPROD_{pzrcs} \\ & + \sum_p \sum_c \text{dryincome}_{rc} \, DRYPROD_{prc} \\ & - \sum_p \sum_z \sum_m \text{pumpcost}_{pzr} \, AGWATER_{pzrm} \\ & + \sum_p \sum_z \text{janprice}_p \, JANBUY_{pz} \\ & + \sum_p \sum_z \text{junprice}_{pr} \, JUNBUY_{pzr} \Bigg),\end{aligned}$$

where irrincome_{rcs} is the irrigated production net income excluding pumping cost and ISP payments under recharge state r for crop c using strategy s; $IRRPROD_{pzrcs}$ is the acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; dryincome_{rc} is dryland production net income under recharge state r for crop c; $DRYPROD_{prc}$ is acres of dryland production in county p under recharge state r for crop c; pumpcost_{pzr} is cost of lifting one acre-foot of water in county p, lift zone z, under state r; $AGWATER_{pzrm}$ is agricultural water use in county p, lift zone z, under recharge state r in month m; janprice_p is ISP payment offer in county p for 1 Jan. program; $JANBUY_{pz}$ is acres in 1 Jan. ISP in county p, lift zone z; junprice_{pr} is 1 June ISP payment in county p in recharge state r; and $JUNBUY_{pzr}$ is acres in 1 June ISP in county p, lift zone z, under recharge state r. The objective function maximizes expected net profits to irrigators over a distribution of weather conditions (from very wet to very dry). Net profits equal net income from irrigated and dryland production minus the cost of pumping plus the value of any payment from the ISP.

(A2) Irrigation Water Use:

$$\sum_c \sum_s \text{wateruse}_{pzrcsm} \, IRRPROD_{pzrcs} - AGWATER_{pzrm} \le 0, \quad \forall\, p, z, r, \text{and } m,$$

where wateruse_{pzrcsm} is use in county p, lift zone z, during month m under recharge/weather state r when irrigating crop c under irrigation strategy s; $IRRPROD_{pzrcs}$ is the acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; and $AGWATER_{pzrm}$ is agricultural water use in county p, lift zone z, under recharge state r in month m. Water use across all crops and irrigation strategies is summed into $AGWATER$. In the objective function, this variable is multiplied by per acre-foot pumping costs to account for total pumping costs.

(A3) Irrigated Land:

$$\sum_c \sum_s IRRPROD_{pzrcs} + JANBUY_{pz} \le \text{irrland}_{pz}, \quad \forall\, r, p, \text{and } z,$$

where $IRRPROD_{pzrcs}$ is acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; $JANBUY_{pz}$ is acres in 1 Jan. ISP in county p, lift zone z; and irrland_{pz} is an inventory of irrigable land in county p falling in lift zone z. The model limits irrigated production to land available and allows the ISP to move land to dryland use.

(A4) Dryland:

$$\sum_{c} DRYPROD_{prc} - \sum_{z} JANBUY_{pz} \leq 0, \quad \forall\, r \text{ and } p,$$

where $DRYPROD_{prc}$ is acres of dryland production in county p under recharge state r for crop c, and $JANBUY_{pz}$ is acres in 1 Jan. ISP in county p, lift zone z. Dryland production is limited to land converted from irrigation to dryland use.

(A5) Irrigated Mix:

$$\sum_{s} IRRPROD_{pzrcs} - \sum_{k} \text{imix}_{pck} IRRMIX_{pzk} \leq 0, \quad \forall\, p, z, r, \text{ and } c;$$

(A6) Irrigated Mix:

$$\sum_{c} \sum_{s} IRRPROD_{pzrcs} - \sum_{c} \sum_{k} \text{imix}_{pck} IRRMIX_{pzk} = 0, \quad \forall\, p, z, \text{ and } r,$$

where $IRRPROD_{pzrcs}$ is acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; imix_{pck} is the proportion of crop c in irrigated mix alternatives k, county p; and $IRRMIX_{pzk}$ is acres under irrigated crop mix k for county p, lift zone z. Irrigated crop mixes are required to be a convex combination of historical and farm survey-based irrigated crop mixes.

(A7) Dry Mix:

$$DRYPROD_{prc} - \sum_{k} \text{dmix}_{pck} DRYMIX_{pk} \leq 0, \quad \forall\, p, r, \text{ and } c;$$

(A8) Dry Mix:

$$\sum_{c} DRYPROD_{prc} - \sum_{c} \sum_{k} \text{dmix}_{pck} DRYMIX_{pk} = 0, \quad \forall\, p \text{ and } r,$$

where $DRYPROD_{prc}$ is acres of dryland production in county p under recharge state r for crop c; dmix_{pck} is the proportion of crop c in dryland mix alternative k in county p; and $DRYMIX_{pk}$ is acres under dryland crop mix k for county p. Dryland crop mixes are required to be a convex combination of historical and farm survey-based dryland crop mixes.

(A9) June Buyout:

$$\sum_{c} \sum_{s} \text{elig}_{pcs} IRRPROD_{pzrcs} - JUNBUY_{pzr} \leq 0, \quad \forall\, p \text{ and } z,$$

where elig_{pcs} equals one for crop irrigation strategies that use water after the end of May, zero otherwise; $IRRPROD_{pzrcs}$ is acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; and $JUNBUY_{pzr}$ is acres in 1 June ISP in county p, lift zone z, under recharge state r. Only irrigation alternatives that use water in June and beyond are eligible for a June ISP.

(A10) Limit June Adjustment:

$$IRRPROD_{pzrcs} = \text{fixir}_{pzrcs}, \quad \forall\, p, z, \text{ and } r, \text{ along with all } c, s \text{ systems}$$

$$\text{where elig}_{pcs} = 0 \text{ with the June unannounced policy used,}$$

where $IRRPROD_{pzrcs}$ is acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; and fixir_{pzrcs} denotes irrigated acres that have finished irrigation by 1 June.

All cropping decisions for crops harvested as of the first of June are held fixed for the case of the mid-year ISP.

(A11) Hold Acres–June:

$$\sum_{s} IRRPROD_{pzrcs} = \text{ifix}_{pzc}, \quad \forall\, p, z, c, \text{ and } r, \text{ with the June unannounced policy used,}$$

where $IRRPROD_{pzrcs}$ is acres of irrigated production in county p, lift zone z, recharge state r, crop c, using irrigation strategy s; and ifix_{pzc} is acres of crops chosen in the base model for crop c, lift zone z, in county p. The mix of crops under the unannounced June ISP is held the same; i.e., we preclude going back earlier in the year and adjusting to a more desirable crop mix when simulating the June announcement without prior warning. The model is restricted to the crop mix chosen when an ISP is not in place.