Limiting Pumping from the Edwards Aquifer: An Economic Investigation of Proposals, Water Markets and Springflow Guarantees

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Draft of paper appear in Water Resources Research, 35(4), 1257-1268, 1999.

Abstract

The Edwards Aquifer near San Antonio, Texas is both an important water source for pumping and springflow which in turn provides water for recreation and habitat for several endangered species. A management authority is charged with aquifer management and is mandated to reduce pumping, facilitate water markets, protect agricultural rights and protect the species habitat. This paper examines the economic dimensions of authority duties. A combined hydrologic/economic model is used in the investigation. The results indicate that proposed pumping limits are shown to have large consequences for agricultural usage and to decrease the welfare of current aquifer pumping users. However, the springflow habitat is found to be protected and the gains from that protection would have to exceed pumping user losses in order for the protection measures to increase regional economic welfare. Agricultural guarantees are shown to cause use value differences indicating the opportunity for emergence of an active water market. Fixed quantity pumping limits are found to be an expensive way of insuring adequate springflow.

The Edwards Aquifer (EA) near San Antonio, Texas is an important water source for agricultural, industrial, municipal, ecological and recreational uses. The San Antonio municipal area almost exclusively relies on EA water with 1995-7 annual municipal and industrial usage averaging close to 300,000 acre feet (af). Agricultural use, west of San Antonio, averages about 180,000 af [USGS,1997]. The EA also supports springs at San Marcos and New Braunfels (Comal Springs) which provide habitat for endangered species [Longley,1992]. In turn, the springflow supports recreation and downstream water usage. Average annual recharge is 637,000 af while mid 1990's average pumping is 480,000 af. The level of total pumping leaves only 150,000 af of water to support springflow which is much smaller than the historic 50 year average springflow (350,000 af). In recent years, pumping has frequently exceeded recharge [USGS,1997] .

The EA is a fractured limestone formation which recharges quickly. Pumping has grown at about 1.1% per year during the last 40 years [Collinge et al., 1993]. With increased pumping, the springflow share of recharge has fallen and springflow has twice been close to cessation during the last five years. Meanwhile aquifer level fluctuations have increased [Collinge et al.,1993].

There has been considerable concern regarding EA management (see the Water Strategist[1996] or the San Antonio Water System web page[1998] for a more detailed history). In the late 1950s, the Edwards Underground Water District was formed to manage the EA. In the late 1980s, the western agricultural counties seceded from the district due to disagreements about drought management plans. In the early 1990s, lawsuits were filed asserting that the EA should be declared an underground river and that endangered species in the springs should be protected by maintaining springflow. The Texas Water Commission declared the EA an underground river subject to surface water law during mid-1992, but this declaration was overturned by the courts during fall 1992. In early

1993, the district federal court upheld the endangered species lawsuit and ordered that pumping limits be imposed to protect springflow. Texas Senate Bill 1477 (SB1477)-[Texas Legislature, 1993]:

1) establishes the Edwards Aquifer Authority (EAA) to manage the aquifer;
2) requires the EAA to reduce pumping to 450,000 af in the near future and to 400,000 af by 2008;
3) mandates establishment of water rights;
4) provides for water sales and leases;
5) guarantees that the agricultural share will be a proportional share of historic use and a minimum of two af per acre;
6) limits off farm water leasing so that one af per acre must be retained for use in irrigation; and
7) charges the EAA to "protect terrestrial and aquatic life, domestic and municipal water supplies, the operation of existing industries and the economic development of the state".

The EAA formally began operation in fall 1996 and, as of this writing, is expending substantial efforts on water rights establishment. (EAA activities and charter are set out on the EAA home page http://www.e-aquifer.com).

This paper provides results from an analysis of issues regarding EAA duties. We report an economic evaluation of the 450,000 and 400,000 af pumping limits, agricultural guarantees and the associated imposition of water markets. Investigations are also performed on the costs of guaranteeing springflows to protect aquatic life.

The contribution of this paper is best viewed in terms of the total literature. Fundamentally, the paper will build upon prior economic analyses of water allocation and water markets involving multiple users as previously studied in the surface water context by authors such as Vaux and Howitt[1982], Howe, Schurmeier and Shaw [1986], McCarl and Parandvash[1988], Michelson and Young[1993], and Ward and Lynch[1997] extending the analysis to simultaneously treat multiple users, uncertainty and a groundwater case. Second, the model used unifies results from a grid cell based groundwater hydrology aquifer simulation (using the model described in Thorkildson and McElhaney[1992] which is similar in structure to that in Gharbi and Peralta[1994]) into an economic framework by using a regression summary of the ground water model results. Third, the case study provides information on the tradeoffs and considerations in the interesting Edwards Aquifer case which involves, to mention a few salient characteristics, ground water pumping by three economic sectors, endangered species, rapid recharge, springflow, groundwater pumping rights, water markets, and agricultural use guarantees (see the web page by Eckhardt [1998] for a wealth of material on the aquifer). Fourth, this paper is an outgrowth of ten years of work by the authors on Edwards aquifer issues. Compared to other journal articles involving the team, this is the first to treat nonagricultural and aquifer elevation / springflow endogenously [Keplinger et al.[1998] and Schaible, McCarl and Lacewell[1998] limit treatment to the agricultural sector]). This paper unifies work of the underlying dissertations Dillon[1991], Williams[1996], Keplinger(1996]. It extends an earlier bulletin on pumping limits [McCarl et al.,1993] analyzing new issues raised by the most recent legislation regarding the Edwards aquifer and using an improved analytical framework.

Water Use and Benefits with and without Pumping Limits

Before reporting empirical findings, a graphical economic exploration of pumping limits is presented. In particular, we consider three questions:

a) Why have pumping limits?
b) Should pumping limits be independent of water availability?
c) What are the welfare effects of pumping limits?

Why have pumping limits? A fundamental EA problem regarding efficient water use is the lack of transferrable water rights[1]. Currently individuals can use as much water as they can pump from beneath their land, although actions by the EAA will soon limit usage. However, the EA is an atypical aquifer. Water recharge is rapid as is flow. Users jointly determine aquifer elevation which determines pumping cost. Springflow users are residual claimants obtaining water left over after pumping usage. The basic economics of such a case are depicted in Figure 1 where: a) the curve DC gives the demand for consumptive use by pumping, after water lifting cost has been paid, by a party that can pump as much as desired; b) the supply curve AS is the aquifer supply of water; c) the demand curve DS is the demand for springflow (arising through demands for both endangered species existence and instream flows which in turn affect river ecology, recreation/tourism and downstream water users).

This graphic format can be used to evaluate the effects of treating springflow as a residual (as has been the case) versus actively considering springflow related demand. In the residual case, since available water (AS) is greater than the maximum pumping demand, then pumping users withdraw water until the marginal value product (MVP) of water use is zero (or the MVP at the surface is just equal to water lifting cost). Thus, pumping use is QA and the net water value is zero. In turn, unused water (AS-QA=QR) goes into springflow and that market yields a water value of MVPA. Such a situation yields a disparity between the value of water in springflow and pumping usage arising due to a classic market failure [Baumol and Oates,1975]. If somehow a market or other institutional mechanism confronted the value of displaced springflow on pumping user decisions, with WS being the excess supply curve of water after pumping use, then the market would clear at price P with QC consumed by pumping and QS being the amount of springflow.

This graphical analysis provides the basic rationale for SB1477 pumping limits. Namely, in the absence of a market which reflects springflow value, then there is a less than economically efficient amount of water left after pumping use for springflow. One way of making sure that enough water is left for springflow is to impose a pumping limit at QC. The parties crafting SB1477 must have felt that an appropriate amount of pumping is somewhere around 400,000 af. Such a level of pumping leaves about 100,000 af more for springflow than is currently the case.

Should pumping limits be independent of water availability? EA recharge in the last 10 years has varied from 240,000 to 2.4 million af, while averaging about 630,000 af [USGS, 1998]. Figure 2 contains a second water supply/recharge level ASr considerably smaller than the original and leads to a different excess water supply curve (WSr). Under ASr price Pr should be charged and consumptive use should be QCr, whereas under “normal” recharge (AS) quantity QC should be pumped. Thus a fixed pumping limit may not be appropriate as recharge varies.

In the empirical work we evaluate the effects of constant 400,000 or 450,000 af pumping limits and of requiring springflow to exceed various critical levels. No attempt is made herein (nor do we know of any attempt that has ever been made) to specify a springflow demand equation and measure economic benefits as they relate to springflow due to immense data gaps.

<u>What are the welfare effects of pumping limits?</u> To examine this we return to our certainty world of Figure 1. Pumping user welfare without pumping limits is the sum of the areas marked a,b, and c, while springflow welfare is d+e+f. However, if the springflow and pumping markets are in equilibrium, then pumping welfare equals a, while welfare area b arises due to the pumping limit and accrues to water rights and/or whatever agency is charging water rates[2] while area c no longer accrues in the pumping sector. Simultaneously, springflow welfare increases by areas g+h. Thus, the overall net welfare gain would be g+h-c. However, if the analysis is here, h = c limited to the pumping sector (as we do below) then there will be a loss of welfare equaling area c, which is offset by unmeasured gains in the springflow sector. We develop estimates of area c which are a lower bound on what the water has to be worth when it is released as springflow if potential pareto optimality is to be achieved. Thus, welfare accruing to pumpers will fall under pumping limits. In Figure 1 pumpers lose areas b+c while b accrues to the water rights holders and water agencies who, in turn, may redistribute that in various forms to those in the region.

The Modeling Framework

The empirical counterpart of the Figure 1 analysis was implemented using an equilibrium year economic and hydrologic aquifer simulation model herein named EDSIM. EDSIM is the unification of cumulative developments by Dillon[1991]; Williams[1996]; McCarl et al.[1993]; Lacewell and

McCarl[1995]; Keplinger[1996] and Keplinger et al.[1995] with this being the first comprehensive publication. 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].

An algebraic representation of the fundamental relationships in EDSIM is presented below. A complete model specification is available in the source GAMS code. All variables are typed in upper case, while all the parameters are typed in lower case.

The unifying force in EDSIM is the objective function. EDSIM is a two stage stochastic programming with recourse model (Dantzig,1955). The model is solved as one simultaneous model, but includes variables at two “stages” of uncertainty. The first (“stage 1'') set of variables depicts decisions on irrigation investment and crop mix and are constant acrross all states of nature chosen based on average irrigation returns before anything is known about the weather event. The second (“stage 2'') set of variables are chosen with knowledge of state of nature (irrigation scheduling, crop sale and nonagricultural water use). Thus, following Dantzig, the objective function involves two types of terms, one where certain costs are borne regardless of the uncertain outcome and the other where stochastically based decisions are weighted by their probability.

The first stage which is constant across all stochastic outcomes appears in the first three lines of the objective function equation (1) and contains

a) the differential costs of irrigation development (costirr) by lift zone type (z) times acres developed (IRRLAND) in a place (p) for lift zone z and

b) the cost of establishing the crop mix times the acres in the mix (IRRMIX, DRYMIX) by place and irrigated or dryland crop (irracrecost, dryacrecost).

The second stage is defined for each state of nature (r) depicting alternative weather, recharge and irrigation demand conditions and is weighted by probability(prob) as derived from historical observations. The second stage objective terms include the following state of nature dependent components:

a) irrigation and dryland net income (irrincome, dryincome) by place, lift zone, crop(c) and irrigation strategy(s) times acres produced (IRRPROD, DRYPROD);

b) agricultural pumping cost involving per unit cost (AGPUMPCOST) times volume pumped (AGWATER) by month(m);

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

d) municipal and industrial pumping costs defined in an analogous manner to the above agricultural pump cost term (MIPCOST).

Objective Function: Algebraically the objective function is as follows:

(1)
$$
\begin{aligned}
\text{maximize}\ & -\sum_{p}\sum_{z} costirr_{z}\ IRRLAND_{pz} \\
& -\sum_{p}\sum_{k}\sum_{z} irracrecost_{pk}\ IRRMIX_{pzk} \\
& -\sum_{p}\sum_{k}\sum_{z} dryacrecost_{pk}\ DRYMIX_{pzk} \\
& +\sum_{r} prob_{r}\ \Big(\ \sum_{p}\sum_{z}\sum_{c}\sum_{s} irrincome_{rcs}\ IRRPROD_{pzrcs} \\
& \qquad +\sum_{p}\sum_{c} dryincome_{rc}\ DRYPROD_{prc} \\
& \qquad -\sum_{p}\sum_{z}\sum_{m} AGPCOST_{pzr}\ AGWATER_{pzrm} \\
& \qquad +\sum_{p}\sum_{m}\int mprc_{prm}(MUN_{prm})\, d\, MUN_{prm} \\
& \qquad +\sum_{p}\sum_{m}\int iprc_{prm}(IND_{prm})\, d\, IND_{prm} \\
& \qquad -\sum_{p}\sum_{z} MIPCOST_{pr}\ (\ MUN_{pr} + IND_{pr}\ )
\end{aligned}
$$

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

The above objective function (equation 1) is maximized subject to the constraints in equations 2-17 which link the stage 1 and stage 2 variables and constrain the stage 2 variables to be conditioned by the stage 1 variables (for example only allowing as much irrigation as the amount of installed irrigation equipment and requiring the irrigation schedule to be consistent with the irrigated crop mix)

Irrigation Water Use Accounting – irrigation water use is added up into the variable AGWATER by taking the water use per acre by each strategy times the acres produced (IRRPROD) by place(p), lift zone(z), state of nature(r) and irrigation strategy(s).

(2)

$$\sum_{c} \sum_{s} \text{wateruse}_{prcsm} \ \text{IRRPROD}_{pzrcs} - \text{AGWATER}_{pzrm} \leq 0, \text{ for all } p, z, r, m$$

The AGWATER variable is used in the hydrologically based accounting of aquifer elevation, pump lift, and springflow.

Total Farm Land Availability – total acreage irrigated (IRRLAND) plus that converted to dryland use (MAKEDRY) cannot exceed the total land historically irrigated by place p and lift zone z.

(3)

$$+ \quad \text{MAKEDRY}_{pz} + \text{IRRLAND}_{pz} \leq \text{landavail}_{pz} \text{ for all } p, z$$

Irrigated Land Availability – total acreage irrigated (IRRLAND) in a place and lift zone is set equal to irrigated production by crop and irrigation strategy (IRRPROD) in that place and lift zone. The land to be irrigated is the same across all states of nature (note IRRLAND does not have an r subscript) but the land can be assigned to different irrigation strategies depending on state of nature. Irrigated crop choice is constrained by equations 6 and 7.

(4)

$$\sum_{c} \sum_{s} IRRPROD_{pzrcs} - IRRLAND_{pz} \le 0 \text{ for all } r, p, z$$

Dryland Availability – acres in each place converted to dryland (MAKEDRY) summed across lift zones are set equal to dry production by crop (DRYPROD). The acreage converted is a stage 1 variable and is therefore equal across all states of nature. Initially, dryland production is zero since we are only modeling the irrigated portion of the region. This equation, however, allows conversion to dryland if the cost of water makes the conversion profitable.

(5)

$$\sum_{c} DRYPROD_{prc} - \sum_{z} MAKEDRY_{pz} \le 0 \text{ for all } r, p$$

The acres converted to dryland are summed across the lift zones (since no pumping is done and thus lift zone is not an a cost factor for dryland production) and set them equal to total dryland cropping across all crops (c) for a place (p) and state of nature (r). The choice of dryland crop mix is controlled by equations 8-9.

Irrigated Crop Mix Restriction – These constraints require that the irrigated crop production for a place and lift zone be a convex combination of pre-specified allowable crop mixes (where IRRMIX 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 state of nature summed over 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. The mixes chosen can differ by place and lift zone. Constraint 6 insures that the acres chosen by crop across all irrigation strategies s for a state of nature r are a weighted average of the relative frequency of that crop in that region and lift zone where IRRMIX is the weights in the average. Equation 7 forces the acres in the average to equal the acres farmed.

(6)
$$\sum_{s} \mathrm{IRRPROD}_{pzrcs} - \sum_{k} \mathrm{imix}_{pck}\, \mathrm{IRRMIX}_{pzk} \le 0 \quad \text{for all } p,\ z,\ r,\ c$$

(7)
$$\sum_{c} \sum_{s} \mathrm{IRRPROD}_{pzrcs} - \sum_{c} \sum_{k} \mathrm{imix}_{pck}\, \mathrm{IRRMIX}_{pzk} = 0 \quad \text{for all } p,\ z,\ r$$

The mix data include historical and survey based mixes. The survey based mixes arose from a farm survey [Schiable,1996] which asked irrigators what crop mix changes they would employ if the farm program was eliminated. These constraints cause the solution to cause realistic crop mixes without requiring modeling of detailed farm level resource allocation as argued in McCarl(1982).

Dryland Crop Mix Restriction – This is the dryland counterpart of 6-7 above and requires that dryland production falls into a convex combination of previously observed dryland crop mixes by place. The DRYMIX variables are the weights in the convex combinations and multiply observed mixes. Constraint 9 requires that the total dryland acres in the mix equal the total dryland acres farmed.. The dryland crop mixes are developed from historical dryland acreage statistics for the region.

(8)
$$\mathrm{DRYPROD}_{pzrc} - \sum_{k} \mathrm{dmix}_{pck}\, \mathrm{DRYMIX}_{pzrk} \le 0 \quad \text{for all } p,\ z,\ r,\ c.$$

(9)
$$\sum_{c} \mathrm{DRYPRODpr} - \sum_{c} \sum_{k} \mathrm{dmix}_{pck}\, \mathrm{DRYMIXpk} = 0 \quad \text{for all } p,\ r$$

Agricultural Pumping Cost Determination – Per af agricultural pumping cost (AGPCOST) is set equal to a regression estimated linear function of lift (AGLIFT) by place, lift zone, and state of nature where agcosti is the intercept and agcostl is the slope.

(10)
$$-AGPCOST_{pzr} + agcosti + agcostl\ AGLIFT_{pzr} = 0 \quad \text{for all } p, z, r$$

Regional Base Pump Lift Equation – Base regional pumping lift is determined based on ending elevation. The base aquifer lift (LIFT) in a region is set equal to the difference between ending elevation (ENDWATER) and a zero lift level for each state of nature (r) and region (w).

(11)
$$-LIFT_{wr} + ENDWATER_{wr} = zero\ lift_{w} \quad \text{for all } w, r$$

Agricultural Lift Determination – The agricultural lift in a place and lift zone is set equal to the overall regional lift plus the agricultural lift difference (agdiff) for each state and lift zone.

(12)
$$-AGLIFT_{pzr} + LIFT_{wr} = -agdiff_{pz} \quad \text{for all } r, z, w, p \in reg(w)$$

The agdiff was calculated as a weighted average of the agricultural pumplift differential from the eastern are average lift in the GWSIMIV input data (Thorkildsen and McElhaney,1992) for lands falling in the three lift zones.

Nonagricultural Pumping Cost Calculation – The per acre foot municipal and industrial pumping cost (MIPCOST) is set equal to a regression estimated linear function of the calculated M&I lift (MILIFT) by place and state of nature where micosti is the intercept and micostl is the slope.

(13)

$$\& \; MIPCOST_{pr} + micosti \; \% \; micostl \; MILIFT_{pr} \; ' \; 0 \text{ for all } p \, , \, r$$

Nonagricultural Lift Determination – The municipal and industrial lift in place p falling in region w, is set equal to the overall regional lift level for state r plus the place dependent municipal and industrial lift difference.

(14)

$$\& \; MILIFT_{pr} \; \% \; LIFT_{wr} \; ' \; \& \; midiff_{p} \text{ for all } r \, , \, w \, , \, p0reg(w)$$

The midiff was calculated as a weighted average of the nonagricultural pumplift differential from the eastern area average lift in the in the GWSIMIV input data (Thorkildsen and McElhaney,1992) for pumping falling in a county.

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 endogenous initial water level (INITWAT) term, and a water use by region parameter (rendu) times summed municipal, industrial and agricultural use. Initial water level in both this and the adjacent eastern or western region affects this region’s ending water level. Thus, the subscript w2 is used to sum across both regions. The same is true for usage. 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 a section later in the paper.

(15)

$$
\begin{aligned}
ENDWAT_{wr} = {} & rendi_{w} \\
& + \sum_{m} rendr_{w}\, rech_{rm} \\
& + \sum_{w_2} rende_{ww_2}\, INITWAT_{w_2} \\
& + \sum_{w_2} rendu_{ww2} \sum_{p \in reg(w_2)} \sum_{m} \left(MUN_{prm} + IND_{prm} + \sum_{z} AGWATER_{przm} \right)
\end{aligned}
$$

$$\text{for all } w,\ r$$

Initial Elevation Balance – Initial elevation is set equal to the probability weighted average of ending elevation by region.

(16)

$$-INITWAT_{w} + \sum_{r} prob_{r}\, ENDWATER_{wr} = 0 \text{ for all } w$$

Springflow Equation - Flow for the two springs is predicted from a regression based forecast of similar structure to that used in the ending water level equation (15). The regression based forecast only considers the cumulative use and recharge summed over months m* which proceed a particular month (m). Thus, the regression equation for August will consider the initial water level and all pumping use in recharge from January through August. A linear equation is used that includes an intercept term (rsprni), a recharge parameter (rsprnr) times the state dependent exogenous level of recharge(rech), an initial water level parameter (rsprne) times the endogenous initial water level (INITWAT) term, and a water use by region parameter (rsprnu) times summed municipal, industrial and agricultural use. This equation is defined for each spring during each month for each state of nature. Equation estimation and resultant parameters is described in a section later in the paper.

(17)

$$
\begin{aligned}
SPRNFLO_{srm} = \; & rsprni_{sm} \\
& + \sum_{m^* \leq m} rsprnr_{smm^*} \; rech_{rm^*} \\
& + \sum_{w} rsprne_{smw} INITWAT_{w} \\
& + \sum_{w} \sum_{p \in reg(w)} \sum_{m^* \leq m} rsprnu_{smwm^*} (MUN_{prm^*} + IND_{prm^*} + \sum_{z} AGWATER_{przm^*})
\end{aligned}
$$

for all s , r , m

Model Component Elaboration

There are several key characteristics of the EDSIM framework which merit discussion. First, EDSIM is a price endogenous optimization model following McCarl and Spreen[1980]. Water is allocated to the highest and best use in terms of generating greatest net economic value. Thus, EDSIM is not constrained to simulate current use, but rather simulates best use in an economic sense. However, when run without pumping limits under current water demand, the EDSIM water use solution corresponds closely to water use in the current unrestricted pumping environment where the marginal water value is basically driven to zero as in Figure 1. When EDSIM is executed with the pumping or springflow limits imposed, the results simulate the "best" total regional economic outcome under that limitation as well as permitting comparison with the existing situation.

Second, EDSIM incorporates uncertainty. The uncertain phenomena involves recharge and associated climate. The handling of uncertainty in EDSIM is based upon discrete stochastic programming or stochastic programming with recourse (Dantzig[1955]; McCarl and Parandvash[1988]; Ziari, McCarl and Stockle[1995]). Decision making is modeled as a 2 stage process.   In stage 1, decisions on irrigated acreage, furrow versus sprinkler irrigation and crop mix are made which are state of nature independent. In stage 2, water use decisions are made which depend upon the state of nature. EDSIM maximizes average regional welfare over the recharge events and their probabilities[3]. This uncertainty model depicts an important fact coloring the agricultural production environment. Namely, the amount of agricultural irrigated acreage, the choice of furrow verus sprinkler and the crop mix are generally chosen before the weather is revealed and persist as fixed decisions once the weather is known. However, the use of water is dependent on recharge and climate after their characteristics become known. Thus, municipal demand, industrial demand and choice of irrigation strategy depend upon water available.

Third, EDSIM incorporates hydrological processes based upon a regression summary of the Texas Water Development Board's EA simulation model [Thorkildson and McElhaney,1992]. The estimated regression equations are directly incorporated as EDSIM equations in equations 15 and 17. Regression equations were estimated for monthly springflow and ending elevation at two wells (one in Uvalde county and one in San Antonio) during the year at hand.

Fourth, EDSIM depicts economic competitive equilibrium water use by municipal, industrial and agricultural interests. The agricultural submodel assumes farmers are profit maximizers choosing between dryland and irrigated cropping under 1996 commodity prices. The irrigation strategy depends on the recharge/weather situation, pumping lift, crop mix and installed irrigation system. Three pumping lift zones and two irrigation delivery systems (furrow and sprinkler) are considered. The municipal and industrial submodels derive an economic equilibrium by intersecting explicit demand curves for water with their water supply prices. The supply price equals the pumping cost plus any water opportunity cost stimulated by pumping or springflow restrictions. Thus, EDSIM allocates water among sectors so that, to the extent allowed by the scenario, marginal productivity is equalized and the overall level of economic activity is maximized.

Fifth, EDSIM is run under year 2000 demand projections. The year 2000 conditions assume municipal and industrial demands expand according to growth based, regional forecasts by the Texas Water Development Board.

Sixth, the EDSIM data evolved over time from efforts by Dillon[1991]; McCarl et al.[1993]; Williams[1996]; Lacewell and McCarl[1995]; and Keplinger[1996]. The agricultural part was largely specified using EPIC and extension service regional budgets (Lacewell and McCarl[1995]; Keplinger[1996]).

Seventh, EDSIM is a single equilibrium year model. It starts from a single initial elevation across all recharge states. This initial elevation is set equal to the probabilistic weighted average of the ending elevations via equation 16. This means that the model always returns to an average initial elevation and does not account for decision making that would occur in a period of multiyear drought.

Hydrologic Regressions

The hydrologic regressions have large influences on the results and thus merit discussion. Equations were estimated that predict monthly springflow at two springs and ending elevation at two wells. The monthly springflow equations predict flow in month m during this year as a simple linear function of beginning year (January) well elevations, water pumping between January and month m, and recharge in months up to month m following a linear functional form. The same functional form was used for the ending elevations, but only a end of December equation was estimated. The response function equations were estimated from the results of 136,800 monthly observations from the single layer, porous medium, aquifer simulation model documented in Thorkildson and McElhaney[1992]. These observations arose from model runs under all combinations of 57 recharge states, 25 pumping alternatives and 8 initial water levels observing 12 monthly results for each case. Annual versions of all equations are given in Table 1. Note, because the simulation model was the data source we do not have a true underlying random distribution. Thus, t statistic significance levels are not presented as they cannot be interpreted as valid statistical tests. We do however provide R squared as a measure of fit.

The equations fit the simulated data well and contain expected results in terms of pumping, elevation and recharge effects on the springflow and ending elevation. Two features of the regression results merit discussion. First, western pumping and elevation have much smaller effects than their eastern counterparts. This is due to a granite intrusion (called the Knippa Gap) that separates the east and west EA regions restricting flows and hydraulic pressure transmission. This finding manifests itself in later results.[4] Second, the springflow regression results do not fit the flows at San Marcos Springs as well as at Comal Springs but Comal is the critical spring[5].

Base Model Results

The base model results appear in Table 2. Agricultural water use averages about 170,000 af with nonagricultural water use averaging around 330,000 af. Maximum agricultural water use is about 190,000 af and nonagricultural water use about 350,000 af for a total of 540,000 af. This corresponds closely to historic maximum water use [USGS,1997]. The smallest monthly springflow at Comal, the most sensitive spring, is zero, an expected result given that a very dry year is in the data set. In terms of welfare, agricultural net income averages $6.4 million with municipal consumers' surplus about $471 million (being so large since it comes from a constant elasticity demand curve which goes asymptotic to the axis) and industrial surplus about $2.8 million. Rents to water rights/agencies (area b from above) are around $7 million. Total average welfare, the model maximand, is $487 million across all sectors. All available acreage is irrigated (only acres irrigated in 1992 are included as land available in the model). Agricultural income has a 44.55% coefficient of variation. The optimal beginning (January) elevation for the J17 reference well in San Antonio is 642 ft. However, under dry conditions the ending elevation is as low as 626 ft.

Model Based Policy Analysis

We are now in a position to investigate issues regarding EAA duties. We begin by examining the implications of the two SB1477 pumping limits, then follow that with an investigation of the pumping levels needed to maintain selected springflow levels. Lastly, we turn attention to the implications of agricultural guarantees and associated water marketing.

SB1477 Pumping Limits

As stated above, SB1477 imposes pumping limits of 450,000 af in the near future and 400,000 af in the longer term. We simulate this by bounding the sum of the IND, MUN and AGWATER variables to not exceed the pumping limit. The second and third columns of Table 2 give results from EDSIM under those pumping limits. The total loss in regional welfare (equivalent to area c in Figure 1) is $300,000 per year under the 450,000 af limit and \$1.1 million (0.23%) under the 400,000 acre limit. Under the 400,000 af limit agriculture loses \$1.2 million or 18.7% of base income level while municipal surplus is reduced by \$4.3 million (about 1%) (Note municipal surplus percent change is small because we are dealing with a constant elasticity demand curve). Industrial surplus falls by \$130,000 dollars or 4.6% . Simultaneously, an additional \$4.55 million dollars a year accrues to water agencies or water rights holders. Thus, the pumpers lose \$5.68 million dollars a year (areas b & c above) whereas the agencies and rights holders gain \$4.55 million leaving a net regional loss of \$1.13 million. As shown in the theoretical section above, for society to gain as a whole, this \$1.13 million must be recouped through the value of the additional activities stimulated by the increased springflow. Thus, if total net benefit is the standard for making decisions, then at least \$1.13 million dollars must be gained annually through the value of the continued existence of the endangered species, the increased aquifer elevation, and the benefits of increased springflows including the improved ecological characteristics in the rivers fed by springflows, the increased recreational and other social values stimulated by expanded instream flows, and the value of additional downstream water consumption permitted by the increased springflows.

The results show, under the 400,000 af limit, that average Comal springflow almost triples increasing by 184,000 af from the base level of 97,000 af. Further, the smallest monthly Comal springflow under the worst case recharge (approximately 50,000 af) has risen from zero to 250 cubic feet per second(cfs) which is above the US Fish and Wildlife Service (USFWS) take and jeopardy levels which are 200 and 150 cfs, respectively as described in the next section [USFWS, 1995].

Irrigated acres are reduced under the 400,000 af pumping limit by 27,000 acres (almost 33%). Eastern agricultural water use falls by over 75% whereas western use falls by about 17% due to higher pump lifts. Municipal use is reduced by 1,000 af in the west and 22,000 af in the east. Total average water use falls from 501,000 af down to the 400,000 af limit. The elevation of the San Antonio reference well rises by 44 feet in the typical year.

The pumping limit causes agriculture relative to municipal and industrial uses to experience larger water and percentage welfare adjustments, particularly in the east. This occurs because: 1) the regression shows eastern usage has more profound implications for eastern pumping lifts; 2) use of a less profitable overall crop mix in the east (which is congruent with historic observation) and 3) agricultural use values are smaller than municipal and industrial use values on the margin. Annual welfare reductions to the pumping users are almost a million dollars less under the 450,000 than the 400,000 af limit. Considerable revenues could accrue to those allocating the rights under the pumping limit which might need to be dissipated if a public utility were involved.

Consideration of Springflow Limits

The EAA is charged with maintaining springflow. The USFWS has estimated that Comal flows less than 200 cfs, the "take" level, will result in unsuitable habitat for the endangered fountain darter species, while finding 150 cfs is the Comal "jeopardy" level. In order to investigate the implications of maintaining springflow we ran four minimum springflow scenarios placing a lower bound on the monthly SPRNFLOW variable from equation 17. These scenarios require 50, 100, 150, and 200 cfs of Comal flow during each and every month. Some of these levels are underneath the USFWS take and jeopardy levels. However, during August of 1996 springflow fell to 79 cfs even though the USFWS levels had been announced.

The results show that relatively small adjustments can guarantee the lower springflow minima. However, the 200 cfs minimum requires relatively larger adjustments. The welfare lost by pumping users to achieve this level of springflow is only about half as much as that implied under the 400,000 af limit because the use of water generating spring flows above those needed is not allowed even if available. In particular, a 200 cfs limit reduces pumping user welfare by about a half million dollars a year. This rises through welfare losses of about $0.5 million to agriculture, $3 million to municipal interests and $80 thousand to industrial interests, but a $3.2 million increase in the welfare account accruing to water rights and agencies. In terms of irrigation, irrigated acreage falls by about 25%. Again the most substantial adjustment is in eastern water use by agriculture and municipal interests again because of the Knippa gap as discussed above.

These adjustments are stimulated by a pumping pattern which adjusts to climate as implied in Figure 2. Table 3 details water use under the 200 cfs and 450,000 af scenarios. The 200 cfs column shows that when recharge is low, usage approaches 400,000 af. However, as recharge grows, so initially does usage until at high levels demand is reduced by abundant rainfall. The reductions in usage relative to the base are greater the dryer the year. This result implies that pumping limit or water cost policies which vary with aquifer water supply would be desirable to take advantage of plentiful or scarce water.

Agricultural Water Use Guarantees

The above results arise from a scheme which allocates limited EA water so as to maximize total regional welfare. The EDSIM structure allocates water in a manner that implies that agriculture would forego pumping to allow higher valued users access to water. In practice, that would be unlikely without compensation. Further, most of the agricultural use is west of the municipal use and EA water flows from west to east. Thus, agriculture generally has first access to the water.

Here we explore the implications of agriculture being guaranteed the amounts suggested in SB1477. Namely, agricultural water use will be no less than either: 1) the base unrestricted level of usage adjusted down proportionally; or 2) two acre feet per acre irrigated. These minima are imposed on all acres in all counties in all lift zones as a lower bound on the AGWATER variable. Also for now we do not allow agriculture to sell or lease water.

Table 4 presents the agricultural guarantee results under the 400,000 af limit. The optimal column gives EDSIM results under the pumping limit when agricultural water use is not guaranteed. The next two columns give the results under the proportional and 2 af guarantees. (The two market columns will be discussed in the next section.)

The results demonstrate water use and welfare tradeoffs between sectors. Under guarantees, average agricultural welfare is 22-35% higher. These welfare gains occur due to 15 to 50% higher agricultural water use associated with the guarantee particularly in the east. However, total welfare is reduced by $0.3 to $3 million with the agricultural gains achieved at the expense of nonagricultural users. Equivalently, without an agricultural guarantee, the gains by nonagricultural users are achieved at agriculture's expense (in the absence of compensation for reduced water use).

The results show the choice of guarantees involves more than a million dollars annually at a 400,000 af limit. There the 2 acre foot guarantee has a million dollar greater annual welfare effect.

Water Markets

The results under the agricultural pumping guarantees show there is room for the establishment of water markets. EDSIM, in effect, simulates water use under an idealized water market with no transactions cost. We examine the effects of not having a water market by imposing water usage minimums by parties who do not freely participate in water sales by placing lower bounds on the AGWATER variable. Then through comparison with the unrestricted model, we evaluate the economic implications of market presence.

Two market forms are considered, temporary (lease) and permanent (sale) markets. We examined potential trades between agricultural and non agricultural interests under the 400,000 af limit. In particular, we develop our discussion from results of four water marketing related scenarios under the 400,000 af limit.

1) Agriculture does not trade any water and is guaranteed its proportional share. (the second column in Table 4).
2) Agriculture is deeded its proportional share and can sell water to nonagricultural interests, but the same amount of water is required to be transferred across all states of nature simulating a permanent water sale of a given number of af (the next to last column in Table 4).
3) Agriculture realizes the guarantees of case 2 but must retain usage of one af per acre following a restriction appearing in SB1477 (the last column in Table 4).
4) Agriculture sells whatever it wants with the volume sold varying by state of nature (the first column in Table 4).

Table 5 presents results on water marginal value product (MVP), derived as a weighted average of monthly and recharge dependent shadow prices for water less the pumping cost under these scenarios. In the absence of a water transfer mechanism, there is about a $70 per af difference in MVPs. Allowing permanent sales reduces the MVP disparity to about $4 ($41.64-$37.55) per af in the east or about $5 in the west. When leasing is allowed, the MVPs are almost equal with slight differences due to seasonality in water use intensities.[6] The data in Table 4 for the water market scenarios show that most of the losses in the municipal and industrial areas can be mitigated by water markets. However, these results do not consider the magnitude of the transaction costs involved in the parties finding each other or factor in the agricultural and municipal welfare implications of water payments. Hence, we conclude that the emergence of an active market is likely.

Concluding Comments

The economic impacts of Texas Senate Bill 1477 provisions which deal with management of the Edwards Aquifer were investigated using a multi-user, stochastic, linked economic-hydrologic simulation model. The results indicate that the near term consequences of a 450,000 af total pumping limit plan are not large (around $300,000 per year). The simulations show the 400,000 af limit will cause the springs to flow above the endangered species critical limits. However, as the limit is reduced to 400,000 af some users show almost a 75% drop in water use, particularly Eastern irrigators. This reduces total agricultural income by 18.7%. Simultaneously, the plan decreases municipal and industrial sector welfare by about $4.6 million (1%), but generates a $4.5 million return to water rights, agencies or permit holders. Overall, a 400,000 af pumping limit reduces pumping user welfare by $1.1 million per year. Such losses would be offset through gains from increased springflows at Comal and San Marcos Springs and higher ending aquifer elevation . For the springflow limitation to the yield and economic gain for society the gains from these other sources would have to exceed the $1.1 million annual loss borne by Edwards Aquifer pumping users.

The results also indicate that an active water market is likely to arise under the tighter pumping limits. For example, when historic levels of agricultural use are guaranteed, then the study results show water use value differences of more than $70 per acre foot. An active water market can reduce this difference thereby benefitting both sectors.

Finally, the results indicate that minimum springflow can be achieved at a higher level of pumping than the 400,000 af limit, but that total allowed water use needs to be sensitive to weather and recharge with less water consumed under the dryer events. This would require implementation of a more complex water use management regime such as the seniority system used for Western water rights.

Endnotes

1. The current lack of property rights inhibits a market solution also rendering the Edwards Aquifer a common property pool. Provisions in Texas Senate Bill 1477 [Texas Legislature, 1993] provide a way for pumping interests to acquire and trade rights but do not provide a way for springflow interests to acquire rights. Rather, a reduction in total use is envisioned leaving the residual for springflow users.
2. A large portion of the water rights are likely to be assigned to agencies such as the San Antonio Water System who in turn would need to develop a pricing scheme that would cause an appropriate level of water use. That might lead to such agencies accruing significant amounts of funds which would need to be redistributed since they are public utilities. In the rest of this paper this component of welfare will be referred to as welfare to water rights and agencies.
3. The recharge distribution used herein is a 9 event representation of the recharge and climate distribution observed from 1934-1992. Dillon[1991] discusses its initial development and statistical characteristics.
4. These results have large implications for regional water use when springflow is to be protected. Thus, we decided to try to verify the results using historical (rather that simulated) data. Annual regressions over historical data yielded essentially the same east/west results although multicollinearity did not permit estimation of the exact same equation. (See Keplinger and McCarl[1995] for details).
5. Also as a reviewer pointed out, the GWBSIM model has more difficulty in predicting San Marcos springflows.
6. Note the MVPs are usage weighted averages across all states of nature and months. So in cases differences arise between agricultural and nonagricultural values due to the fact

that these are a composite of 108 differentially weighted shadow prices across months and recharge years. The water value differs slightly due to place and time of diversion.

Acknowlegments

McCarl is Professor of Agricultural Economics, Texas A&M University; Dillon is Associate Professor of Agricultural Economics, University of Kentucky; Keplinger is Research Economist, Tarlton State University; and Williams is Assistant Professor, California State University, Fresno. Thanks to Ron Griffin, Ron Lacewell, Manzoor Chowdhury, Perry New, Wayne Jordan and two anonymous reviewers for contributions and comments. This research project was sponsored by the Texas Water Resources Institute and the Texas Agricultural Experiment Station. This manuscript was done in association with the USDA NRCS cooperative agreement and with Texas A&M University entitled Natural Resource Modeling and Policy Analysis. McCarl is senior author. The other authors all contributed equally.

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Table 1. Regression Coefficients for Annual Comal and San Marcos Springflow

Parameter	Dependent Variable			
	Comal Springflow (acre feet)	San Marcos Springflow (acre feet)	J17 Ending Elevation (feet above sea level)	Sabinal Ending Elevation (feet above sea level)
J17 Starting Elevation (feet above sea level)	2,651	412	0.542	0.348
Sabinal Starting Elevation (feet above sea level)	551	0.0	0.155	0.583
Annual Recharge (acre feet)	0.080	0.024	0.000019	0.000023
Western Pumping (acre feet)	-0.04	-0.0005	-0.000028	-0.000091
Eastern Pumping (acre feet)	-0.28	-0.025	-0.000136	-0.000059
Intercept	-1924677	-203976	225.41	102.22
R-Square	0.93	0.77	0.95	0.96

Table 2. Comparison of Welfare Effects of Alternative Water Management Plans

		Base	Pumping Limits in af		Springflow Limits in Cubic Feet per Second			
			450,000	400,000	50	100	150	200
			-------------------- change from Base Scenario ---------------------					
<u>Average Welfare Measures</u>								
Ag Income	$(10^6\ \$)$	6.36	-0.40	-1.19	-0.08	-0.24	-0.27	-0.49
percent change			-6.33	-18.69	-1.20	-3.82	-4.28	-7.73
Mun Surplus	$(10^6\ \$)$	471.20	-1.90	-4.36	-0.26	-0.43	-1.90	-3.16
percent change			-0.40	-0.93	-0.06	-0.09	-0.40	-0.67
Ind Surplus	$(10^6\ \$)$	2.77	-0.06	-0.13	0.00	0.00	-0.05	-0.08
percent change			-1.99	-4.61	-0.22	-0.36	-1.67	-2.78
Authority Surplus	$(10^6\ \$)$	6.99	2.06	4.55	0.32	0.61	2.03	3.26
percent change			29.48	65.10	4.63	8.74	29.08	46.70
Total Surplus	$(10^6\ \$)$	487.32	-0.30	-1.13	-0.02	-0.07	-0.19	-0.47
percent change			-0.06	-0.23	-0.005	-0.01	-0.04	-0.10
<u>Agricultural Activity Measures</u>								
Irrigated land	$(10^3$ ac$)$	79.89	-13.89	-26.98	-4.16	-11.19	-13.89	-18.64
Dryland Usage	$(10^3$ ac$)$	0	13.89	26.98	4.16	11.19	13.89	18.64
Ag. Inc. Coef var.	(%)	44.56	-1.84	-0.93	-1.41	-3.74	-4.36	-4.57
<u>Water Use Measures</u>								
East Agricultural	$(10^3$ af$)$	81.85	-32.85	-63.41	-9.35	-24.81	-32.55	-44.23
West Agricultural	$(10^3$ af$)$	87.41	-8.82	-14.08	0.03	0.79	0.37	-1.33
East Non Agricl	$(10^3$ af$)$	322.00	-9.92	-22.49	-1.47	-2.42	-10.50	-16.89
West Non Agricl	$(10^3$ af$)$	9.73	-0.48	-1.01	-0.01	-0.01	-0.12	-0.20
Total Use	$(10^3$ af$)$	500.99	-52.08	-100.99	-10.80	-26.44	-42.80	-62.65

Hydrologic Result

Comal Spr flow	(10^3 af)	97.56	93.12	183.91		21.83	54.49	86.17	123.55
San Marcos flow	(10^3 af)	64.16	9.88	19.56		2.34	5.85	9.25	13.25
J17 Well End Elev.	(ft)	641.83	22.25	44.01		5.18	12.90	20.58	29.57
Min. Comal Sprflow	(cfs)	0	139.72	250.56		50.00	100.00	150.00	200.00

Table 3: Total Pumping Usage under Alternative Scenarios

Typical Weather Year[1]	Probability	Recharge	Base Usage	450,000 af pumping limit	Usage when Springflow $200 cfs
		--------------------------- 1000 acre feet ---------------------------			
1956	0.018	43.7	537.8	450.0	401.8
1951	0.018	140.1	535.1	450.0	433.6
1963	0.089	170.8	526.9	450.0	442.4
1989	0.143	214.5	521.0	450.0	440.0
1980	0.214	406.3	519.6	450.0	461.5
1974	0.214	658.4	497.8	450.0	445.5
1976	0.214	894.1	463.9	445.8	412.2
1958	0.071	1701.2	487.7	450.0	434.9
1987	0.018	2003.6	454.3	439.8	409.8
Average	--	626.9	501.0	448.9	438.3

[1] These weather years provide the states of nature used in the model.

Table 4. Welfare Effects of Agricultural Guarantees and Water Markets 400,000 Pumping Limit

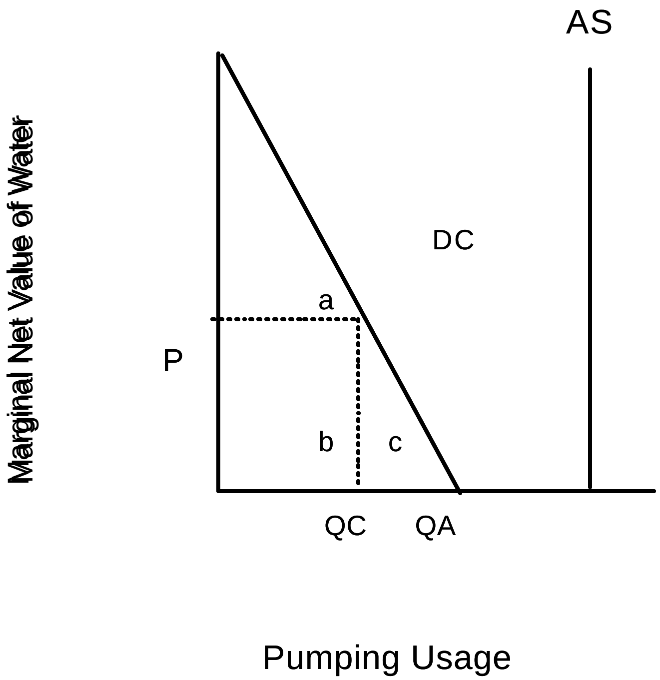
			Guarantee			
		Optimal	Proportion	2 acre ft	Proportion	Prop/1af
					with Market	
Average Welfare Measures			--------------Change from Optimal			---------------------
Ag Income	(10^6 $)	5.17	1.14	1.82	0.18	0.62
percent change			22.04	35.13	3.46	12.05
Mun Surplus	(10^6 $)	466.84	-9.89	-16.57	-1.18	-5.03
percent change			-2.12	-3.55	-0.25	–1.08
Ind Surplus	(10^6 $)	2.64	-0.26	-0.43	-0.03	-0.13
percent change			-9.83	-16.41	-1.07	-5.09
Authority Surplus	(10^6 $)	11.54	7.92	13.09	0.97	4.08
percent change			68.66	113.46	8.38	35.34
Total Surplus	(10^6 $)	486.20	-1.09	-2.09	-0.06	-0.47
percent change			-0.22	-0.43	-0.01	-0.10
Agricultural Measures						
Irrigation Develop	(10^3 acres)	52.91	17.39	26.31	2.76	14.65
Dryland Usage	(10^3 acres)	26.98	-17.39	-26.31	-2.76	-14.65
Water Use						
Ag. East	(10^3 acre feet)	18.44	42.79	55.59	6.20	28.55
Ag. West	(10^3 acre feet)	73.33	-3.50	4.64	-0.92	-6.79
Nonag East	(10^3 acre feet)	299.51	-38.04	-58.31	-5.13	-21.08
Nonag West	(10^3 acre feet)	8.72	-1.25	-1.92	-0.15	-0.69
Hydrological Measures						
Comal Spr flow	(10^3 af)	281.47	-9.16	-1.79	-1.82	-11.16
San Marcos Spr flow	(10^3 af)	83.72	-0.97	-0.06	-0.20	-1.26
Ending Elevation j17	(ft)	685.84	-1.38	0.79	-0.31	-2.17
Min. Comal Spr flow	(cfs)	250.56	-5.31	1.85	-1.06	-7.64

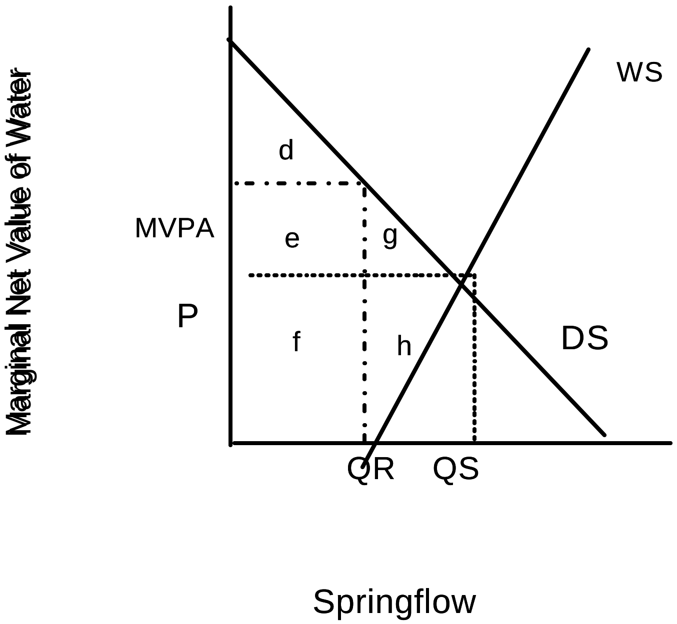
Note the scenario definitions are as follows: Proportion means agriculture gets its proportional share; 2 acre feet indicate no more than 2 acre feet of water can be used per acre (as opposed to 2.12 in the base scenario), with market means that permanent sale of water is allowed and prop/1 af means that agricultural gets its proportional share but must retain use of at least one af per acre.

Table 5. Marginal Value of Water under Three Water Marketing Scenarios at the 400,000 af Limit

		Base 400-- No Guarantee (Leasing)	No Market	Permanent Sale
Ag Water Value East	($/af)	38.23	26.15	37.55
Non-Ag Water Value East	($/af)	37.66	99.93	41.64
Ag Water Value West	($/af)	30.21	21.23	28.02
Non-Ag Water Value West	($/af)	30.28	90.93	33.73

Note that the Base 400–No guarantee scenario allows agriculture to vary water sold across state of nature while the Permanent Sale scenario depicts the same amount of water sold by agriculture in each and every state of nature.


AS
Marginal Net Value of Water
DC
a
P
b
c
QC
QA
Pumping Usage


Marginal Net Value of Water
WS
d
MVPA
e
g
P
f
h
DS
QR
QS
Springflow

Appendix

An algebraic representation of the fundamental relationships in the dry year option model is presented below. A complete model specification is available in the source GAMS code. All variables are typed in upper case, while all the parameters are typed in lower case.

Objective Function

$$
\begin{aligned}
\text{maximize} \sum_r prob_r \Big(& \sum_p \sum_z \sum_c \sum_s irrincome_{rcs}\, IRRPROD_{pzrcs} \\
& + \sum_p \sum_c dryincome_{rc}\, DRYPROD_{prc} \\
& - \sum_p \sum_z \sum_m AGPCOST_{pzr}\, AGWATER_{pzrm} \\
& + \sum_p \sum_m \int mprc_{prm}(MUN_{prm})\, d\, MUN_{prm} \\
& + \sum_p \sum_m \int iprc_{prm}(IND_{prm})\, d\, IND_{prm} \\
& - \sum_p \sum_z MIPCOST_{pr}\, (\, MUN_{pr} + IND_{pr}\,)
\end{aligned}
\tag{A1}
$$

$$
\begin{aligned}
\text{where}\quad irrincome_{rcs} &= irryield_{rcs}\, (price_c - harvcost_c) - acrecost_{cs} \\
dryincome_{rc} &= dryyield_{rc}\, (price_c - harvcost_c) - acrecost_{c0}
\end{aligned}
$$

The objective function maximizes expected net profits to agriculture plus the integral underneath the demand curves for municipal and industrial pumping. Net agricultural profits are defined as net income from irrigated and dryland production minus the cost of pumping. This function operates over the distribution of weather/recharge conditions (from very wet to very dry). The objective function is maximized subject to the following constraints.

Irrigation Water Use

(A2) $$\sum_{c} \sum_{s} wateruse_{prcsm} \; IRRPROD_{pzrcs} - AGWATER_{pzrm} \leq 0, \text{ for all } p\,,\ z\,,\ r \text{ and } m$$

This equation accounts for irrigated water use. Water use across all crops and irrigation strategies is summed into the AGWATER variable for each county, pumping lift zone, recharge and month combination. This variable is multiplied by per acre foot pumping costs in the objective function to account for total pumping costs.

Irrigated Land

(A3) $$\sum_{c} \sum_{s} IRRPROD_{pzrcs} + MAKEDRY_{pz} \leq irrland_{pz} \text{ for all } r,p \text{ and } ,z$$

This equation limits irrigated production to the irrigated land available but allows land to move to dry land use.

Dry Land

(A4) $$\sum_{c} \mathrm{DRYPROD}_{prc} - \sum_{z} \mathrm{MAKEDRY}_{pz} \le 0 \text{ for all } r \text{ and } p$$

This equation limits dry land production to land converted from irrigation to dry land use. Initially, dry land production is zero since we are only modeling the irrigated portion of the region. This equation, however, allows conversion to dry land if the cost of water makes the conversion profitable.

Irrigated Mix

(A5) $$\sum_{s} \mathrm{IRRPROD}_{pzrcs} - \sum_{k} \mathrm{imix}_{pck} \mathrm{IRRMIX}_{pzk} \le 0 \text{ for all } p, z, r, c$$

(A6) $$\sum_{c} \sum_{s} \mathrm{IRRPROD}_{pzrcs} - \sum_{c} \sum_{k} \mathrm{imix}_{pck} \mathrm{IRRMIX}_{pzk} = 0 \text{ for all } p, z, r$$

This constraint along with the next one requires that the irrigated crop mixes to be a convex combination of historical crop mixes found over the past twenty years. Mix data include crop mixes obtained during a farm survey indicating what would happen if the farm program was eliminated.

Dry Mix

$$\mathrm{DRYPROD}_{pzrc} - \sum_{k} \mathrm{dmix}_{pck} \mathrm{DRYMIX}_{pzr} \le 0 \text{ for all } p, z, r, c.$$

(A7)

$$\sum_{c} \text{DRYPROD} - \sum_{c} \sum_{k} \text{dmix}_{pck}\, \text{DRYMIX} = 0 \quad \text{for all } p,\ r. \tag{A8}$$

This is the dry land counterpart of A5-6 above and requires that dry land production fall into a convex combination of previously observed dry land crop mixes. The dry land crop mixes are developed from historical dry land acreage statistics for the region.

Agricultural Pumping Cost

$$- \text{AGPCOST}_{pzr} + \text{agcosti} + \text{agcostl}\ \text{AGLIFT}_{pzr} = 0 \quad \text{for all } p,z,r \tag{A9}$$

Agricultural pumping cost is set equal to a quantity that’s independent of lift plus lift times cost per foot the water is lifted.

Lift

$$- \text{LIFT}_{wr} + \text{ENDWATER}_{wr} = \text{zero lift}_{w} \tag{A10}$$

The pumping lift is set equal to the zero lift level minus the ending water level for each recharge state (r) and region (w).

Agricultural Lift

(A11)

$$\& \ AGLIFT_{pzr} \ \% \ LIFT_{wr} \ ' \ \& \ agdiff_{pz} \ \text{for all } r, z, w, p0reg(w)$$

The agricultural lift in a county and lift zone is set equal to the regional average lift plus the agricultural lift difference for each recharge state (r).

Nonagricultural Pumping Cost

(A12)

$$\& \ MIPCOST_{pr} \ + micosti \ \% \ micostl \ MILIFT_{pr} \ ' \ 0 \ \text{for all } p,r$$

The per acre foot municipal and industrial pumping cost is set equal to constant plus a term times lift by county (p) and recharge state (r).

Nonagricultural Lift

(A13)

$$\& \ MILIFT_{pr} \ \% \ LIFT_{wr} \ ' \ \& \ midiff_{p} \ \text{for all } r,w,p0reg(w)$$

The municipal and industrial lift in county p falling in region w, is set equal to the regional lift plus the county municipal and industrial lift difference for recharge state r.

Ending Elevation

(A14)

$$\mathrm{NDWAT}_{w\,r} \;+\; \mathbf{j}_{w_2}\; \mathrm{rende}_{w\,w_2}\; \mathrm{INITWAT}_{w_2}$$

$$+\; \mathbf{j}_{w_2}\; \mathrm{rendu}_{w}\mathrm{w}_2\; \mathbf{j}_{p0reg(w_2)}\; \mathbf{j}_{m}\; (\; \mathrm{MUN}_{prm} \;+\; \mathrm{IND}_{prm} + \;\mathbf{j}_{z}\; \mathrm{AGWATER}_{p}$$

$$'\qquad -\; \mathrm{rendi}_{w} \;-\; \mathbf{j}_{m}\; \mathrm{rendr}_{w}\; \mathrm{rech}_{rm} \quad \text{for all } w,r$$

The ending elevation is set by region equal to a regression based equation that includes an intercept, a recharge term, an initial water level term and a water use by region term. Notice here that the initial level in both this and the adjacent region effects this regions ending water level. The same is also true for usage. The usage is total usage in a region by region (w) and recharge state.

Initial Elevation

(A15)

$$\&\mathrm{INITWAT}_{w} \;\%\; \mathbf{j}_{r}\; \mathrm{prob}_{r}\; \mathrm{ENDWATER}_{w\,r} \;'\; 0 \quad \text{for all } w$$

Initial elevation is set equal to the probability weighted average of ending elevation by region.

Springflow

(A16)

$$\mathrm{SPRNFLO}_{srm} \;+\; \mathbf{j}_{w}\; \mathrm{rsprne}_{smw}\mathrm{INITWAT}_{w}$$

$$+\; \mathbf{j}_{w}\; \mathbf{j}_{p0reg(w)}\; \mathbf{j}_{m^{(}\#\, m}\; \mathrm{rsprnu}_{smwm^{(}}(\mathrm{MUN}_{prm^{(}} + \mathrm{IND}_{prm^{(}} + \;\mathbf{j}_{z}\; \mathrm{AGWATER}_{przr}$$

$$'\qquad -\; \mathrm{rsprni}_{sm} - \;\mathbf{j}_{m^{(}\#\, m}\; \mathrm{rsprnr}_{smm^{(}}\; \mathrm{rech}_{rm^{(}} \quad \text{for all } s,r,m$$

Springflow is set equal to regression based forecast of similar structure to that used in the ending water level equation where the regression based forecast only considers the cumulative use and recharge up to a particular month. Thus, the regression equation for August will consider the initial water level and all pumping use in recharge from

January through August. This equation is defined for each spring during each month for each recharge state.

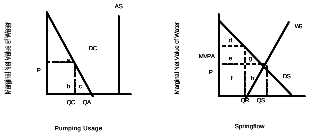
Subscript Definitions

p	county where production occurs
z	pumping lift zone
r	recharge state of nature
m,m*	month of the year
k	crop mix alternative
c	crop
s	irrigation strategy
w,w_2	region where reg(w) indexes the counties in this region
s	spring
reg (w)	set of counties in region w

Parameter Definitions

$acrecost_{cs}$	Per acre variable costs including costs of (fertilizer, seed etc. but excluding harvest and pumping) associated with crop c when the crop is irrigated under irrigation strategy s (note s = 0 covers dryland).
agcosti	Per acre foot of water pumped agricultural pumping cost component which is independent of lift.
agcostl	Lift dependent agricultural pumping costs incurred per acre foot pumped per foot that water has to be lifted.
$agdiff_{pz}$	Difference from overall regional average pumping lift that is incurred when water is pumped in county p, and lift zone z.
$dmix_{pck}$	Proportion of crop c in dry land mix alternative k, in county p, where $\sum_c dmix_{pck} = 1$, for all p and k.
$dryincome_{rc}$	Dryland production net income for crop c under recharge state r.
$dryyield_{rc}$	Dry land yield for crop c under recharge state r.
$harvcost_c$	Harvest cost per unit of yield for crop c.
$imix_{pck}$	Proportion of crop c in irrigated mix alternative k, in county p, where $\sum_c imix_{pck} = 1$, for all p and k.
$iprc_{prm}(IND_{prm})$	Inverse demand function for industrial water in county p, under recharge state r, in month m.
$irrincome_{rcs}$	Irrigated production net income excluding pumping cost for crop c under recharge state r using irrigation strategy s.
$irrland_{pz}$ I	inventory of irrigable land in county p lift zone z.
$irryield_{rcs}$	Irrigated yield for crop c, under recharge state of nature when irrigated using strategy s.
micosti	Per acre foot pumping cost for municipal and industrial water which is independent of lift.
micostl	Per acre foot pumping cost of municipal and industrial water which depends on number of feet that the water is lifted.
$midiff_p$	The municipal and industrial pumping lift difference from regional average lift.
$mprc_{prm(}MUN_{prn})$	Inverse demand curve for municipal water in county p, under recharge state r, in month m.
$price_c$	Price of crop c.
$prob_r$	Probability of the r^{th} state of nature.
$rech_{rm}$	Amount of recharge obtained under the r^{th} state of nature during the m^{th} month.
$rende_{ww2}$	Regression equation parameter on the effect of using water in region W_2 on the ending elevation of the reference well in region w.

$rendi_w$	Intercept from the regression for predicting ending elevation of the reference well in region w.
$rendr_w$	Effect of recharge in the regression equation given the effect of recharge on ending elevation in well w.
$rendu_{ww2m}$	Effect of using of total pumping usage in region W_2 on the ending elevation of the reference well in region w.
$rsprne_{smw2}$	The effect of water use in region w on springflow at $spring_s$ in the month m.
$rsprni_{sm}$	Regression based intercept for the prediction of springflow in $spring^s$ in month m.
$rsprnr_{smm*}$	The effect of recharge in month m, on springflow at spring s, during the month m.
$sprnu_{smwm*}$	The effect of usage in region w, month m*, on springflow at spring s, during month m.
$wateruse_{prcsm}$	Water use in county p month m under recharge r when irrigating crop c under irrigation strategy s.
zero $lift_w$	Elevation of the reference well in region w at which there would be zero pumping lift.



Variables

$AGCOST_{prz}$	Agricultural pumping cost per unit of water used in county p, recharge state r, zone z
$AGLIFT_{pzr}$	Number of feet water needs to be lifted for agricultural usage in county p, lift zone z, under state of nature r.
$AGWATER_{pzrm}$	Total agricultural water use in county p lift zone z under recharge state r in month m.
$DRYMIX_{pk}$	Dryland crop mixes for county p, for alternative k.
$DRYPROD_{pzrc}$	Dryland production in county p, under recharge state r for crop c.
$ENDWAT_{wr}$	Ending water level of a reference well in region w, under state of nature r.
IND_{prm}	Industrial usage in county p, during state nature r, from month m.
$INITWAT_w$	Initial water level of the reference well in region w.
$IRRMIX_{pzk}$	Amount of irrigated crop mix used in county p, lift zone z of mix alternative k.
$IRRPROD_{pzrcs}$	Irrigated production in county p, lift zone z, recharge state r, crop c and irrigation strategy s.
$LIFT_{wr}$	Amount of feet the average well over the whole region w, lifts water under recharge state r.
$MILIFT_{pr}$	Amount of feet that municipal and industrial water is lifted in region p, under state of nature r.
$MIPCOST_{pr}$	Per acre foot cost of lifting municipal and industrial water in region p, under state of nature r.
MUN_{prm}	Municipal usage in county p, during state of nature r, for month m.
$MAKEDRY_{pz}$	Irrigated acres converted to dryland in county p from lift zone z.
$SPRNFLO_{srm}$	Springflow in spring s, under recharge state of nature r, in month m.