Elevation Dependent Management of the Edwards Aquifer: A Linked Mathematical and Dynamic Programming Approach

Draft Article

The Edwards Aquifer(EA) underlies the San Antonio area of Texas including much of Uvalde, Medina, Bexar, Comal, Hays, and Kinney counties. The water use in the western counties (Kinney, Uvalde, and Medina counties) is largely agricultural while use in Bexar, Comal and Hays counties is mainly industrial, and municipal. The EA also supports springs at San Marcos and New Braunfels(Comal Springs) which provide habitat for endangered species(Longley, 1992).

The EA region has a problem. Average annual recharge is about 637,000 acre feet (af) while average pumping is around 480,000 af which includes 300,000 af for municipal and industrial usage and 180,000 for agriculture [USGS,1997]. That level of total pumping leaves only 150,000 af of water to support springflow which is much lesser than the historic average springflow, 350,000 af. In the early 1993, a district federal court upheld the endangered species lawsuit and ordered that pumping be reduced to protect springflow (Bunton). Susequently the legislature passed Senate Bill 1477(SB1477) which requires the Edwards Aquifer Authority(EAA) to reduce pumping to 400,000 af by 2008. Also, the EAA is charged with protecting springflow. The EAA coupled with the municipal agencies in the region are actively trying to manage total pumping. Drought management plans, dry year irrigation buyouts, and lawn watering prohibitions are just a few of the items formulated and to some extent implemented within the last five years.

A number of analyses have been done on EA economic, hydrological, and environmental issues Dillion's work(1991), and McCarl et al.(1993), Williams(1996), Lacewell and McCarl(1995), Keplinger et al.(1997 and 1998), Schiable et al(1999) and Watkins and McKinney(1999). All of these analyses have used static equilibrium modeling under stochastic recharge with all the pieces excepting the Watkins and McKinney assuming the aquifer begins each year at the average of the ending year elevations. Watkins and McKinney model a two stage decision with current investment and the 5 years of typical operation model over ten stochastic 5 year recharge sequences from the historic weather set.

All the studies examine the optimal level of pumping, but one very important issue is ignored. Namely in the EA region the EAA is charged with and attempting to manage total pumping. The EAA now uses information in the late fall about the available stock of water in the form of an aquifer elevation reading to guide it's efforts. However there is uncertainty about recharge and the big issue is what should be the relationship between EA pumping and November water level readings. This study addresses the dynamic issue of optimum pumping and optimum target ending elevation given a reading on initial elevation. A stochastic dynamic programming approach using data developed from a stochastic mathematical programming with recourse formulation of the aquifer will be used to address this question. The analysis will also examine the consequences of potential policies regarding water use restriction and springflow protection.

Peculiarities of the EA

Before discussing modeling approaches to the EA it is worthwhile briefly discussing the few of its characteristics as they influence our methodology. The EA is a Karstick aquifer. It is a fractured limestone formation which comes to the surface at the Eastern and Western parts of the aquifer. The aquifer recharges and discharges rapidly compared to most aquifers. The Western part is at the higher elevation and is where the recharge turns. Rivers flowing across the limestone outcropping often lose virtually all of their flow into the aquifer. On the Eastern side there are two of the largest springs in western part of United States which are entirely fed by aquifer waters. These springs shelter endangered species. They also provide a substantial portion of the base flow of the Guadalupe and Blanco rivers. In the EA there is a flow constricting area which causes water transmission to be quite long and also to some degree separates the hydrological characteristics of the aquifer into two parts. Agriculture uses most of its water out of the western part of the aquifer while San Antonio and its surrounding area use water for Industrial and Municipal purposes. Recharge generally exceeds annual use. There is a large reservoir of water below the level of the springflow orifices.

The EA is to be managed by the EAA. In the authorizing legislation the EAA is charged with reducing total pumpage from current levels down to levels that are initially 10 percent and later 20 percent lower as time goes on. The authority is also charged with protecting the endangered species by insuring springflow and is authorized to reduce pumpage even further if conditions merit.

The aquifer while having storage characteristics leaks and does not permitted long-term storage for water at aquifer elevation levels above the spring orifices. For example in 19xx the aquifer received in excess of two million acre-feet of recharge and rose to record high levels, but by two years later after two years of moderately low recharge where usage was in excess of recharge by xx,000 acre-feet the aquifer had fallen to virtually a record low level. The EAA can plan for some aquifer storage but cannot count on long-term storage to the extent provided by other aquifer systems.

The Edwards aquifer water retention characteristics differ from the majority of aquifer situations. The question of interest herein is: Given the stochastic recharge, elevation level dependent spring discharge and stochastic usage as conditioned by weather what is the optimal level of pumping or the amount of water retained. The problem is analogous to the development of a rule curve for a leaky reservoir(see Wurbs for Discussion).

Modeling Tradeoffs Between Current Pumping and Water Retention

Modeling of tradeoffs between current pumping and future stocks has been the subject of resource economists and hydrologists for many years. A commonly used technique for such modeling has been dynamic programming. Conceptually the dynamic programming formulation we will use is much the same as the one used in Burt or Wurbs and is as follows:

$$(1) \quad f_t(Q_t) = \underset{X_t}{MAX} \sum_{R_t} [G(X_t, Q_t, R_t) + b * f_{t+1}(z(Q_t, R_t, X_t))] h(R_t)$$

$$(2) \quad Q_{t+1} = z(Q_t, R_t, X_t)$$

$$(3) \quad Q_1 = \bar{Q}$$

where $f_t(Q_t)$ is discounted total economic returns from aquifer pumping and water retention at time t for water storage amount Q_t. $G(X_t,Q_t,R_t)$ is expected net regional benefits at time t from pumping decision X_t under stock of water Q_t in the aquifer when recharge state R_t occurs. $ is the discount factor and is equal to $(1+d)^{-1}$, where d is the discount rate. $f_{t+1}(z(Q_t,R_t,X_t))$ is the discounted net regional benefits from leaving a stock of water (Q_{t+1}) in the aquifer where $z(Q_t,R_t,X_t)$ gives the stock next period given this periods stock, pumping and recharge. Finally, h(R) is the probability or recharge event R. The initial stock of water is given by the equation for Q_1 and the time horizon chosen is long enough that the value of water in the last periods is set to zero. This is a stochastic dynamic program.

Several items complicate the application of this formulation. Pumping in the EA is done behalf of three distinctly different parties. In particular ,agricultural, industrial and municipal usage is all have very different demand characteristics (McCarl et al.). Further depending upon whether pumping usage is on the Eastern or western side of the so-called Knippa Gap, which restricts flow, the reaction of aquifer elevation and spring flow is quite different (McCarl et al.). There are also significant physical differences in the effects of pumping on springflow depending upon the timing of pumping during the year. Conceptually then we would not use one pumping variable but rather a variable with three dimensions the first of which depicted users , the second East and West, and the third months. Also the agricultural returns to pumping usage in different months depend on crop mix and irrigation strategy. To compactly represent this we transformed the decision variable to ending elevation and computed elevation as a function of usage, recharge and initial elevation.

$$(4) \quad f_t(Q_t) = \underset{Q_{t+1}}{MAX} \sum_{R_t} [G(Q_t, Q_{t+1}, R_t) + b^* f_{t+1}(Q_{t+1})] h(R_t)$$

$$(5) \quad Q_1 = \overline{Q}$$

Embodied in the ending elevation decision, are the pumping withdrawals by each party, crop mix selection, irrigation strategy, and pumping lifts.

There are three key needs implicit in the recursive equation approach. The first is there is a set of data needed on the net value of moving from elevation Q_t to Q_{t+1} under recharge state R_t (the numerical values of the G function). The second is a need for a link between the elevation variable and the large number of pumping variables so that we may both recover pumping data given an elevation choice and link initial elevation, recharge and pumping to final elevation. This was accomplished by employing an auxiliary optimization model derived from McCarl et al following the work of Sweeny and Tatum; Mcfarland; and Kilmer , Spreen and Tilley.

EDSIM-DP Overview

The model used to generate the information for the dynamic program herein is an adaptation of EDSIM (McCarl et al 1998) hereafter called EDSIM-DP. EDSIM-DP depicts pumping use by the agricultural, industrial and municipal sectors while simultaneously calculating pumping lift, ending elevation and springflow. EDSIM-DP is stochastic with the stochastic events defined by rainfall, aquifer recharge, crop water demand and yields. 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.

An algebraic representation of the fundamental relationships in EDSIM-DP follows (for more details on the general features of EDSIM see McCarl et al (1998)). All variables are typed in upper case, while parameters are typed in lower case.

Objective Function: The unifying force in EDSIM-DP is the objective function. It is a two stage stochastic programming with recourse model (Dantzig,1955, Ziari, McCarl and Stockle(1995). The model is solved as one simultaneous model, but includes variables at two "stages" of uncertainty. The first ("stage 1") set of variables depicts crop mix decisions which are constant across an initial elevation and all states of nature chosen based on average 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).

$$(6) \quad \text{maximize} \; -\sum_p \sum_k \sum_q acrecost_{pkq} \, AGMIX_{pkq}$$
$$+ \sum_r prob_r \Big[\sum_p \sum_c \sum_s \sum_q netaginc_{rcsq} \, AGPROD_{prcs}$$
$$+ \sum_p \sum_m \int mprc_{prm}(MUN_{prm}) \, d\,MUN_{prm}$$
$$+ \sum_p \sum_m \int iprc_{prm}(IND_{prm}) \, d\,IND_{prm} \Big]$$

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

The first stage contains decision variables which are constant across all stochastic outcomes and appears in the first line of the equation and depicting the cost (acrecost) of establishing the crop mix times acres (AGMIX) by place(p),mix choice(k) and irrigated or dryland choice(q).

The second stage contains decision variables defined by state of nature (r) and are weighted by probability(prob including:

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

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

Total Farm Land Availability – total acreage allocated to irrigated or dryland use cannot exceed the total land historically irrigated by place p.

$$(7) \qquad \sum_q AGLAND_{pq} \le landavail_p \;\; \text{for all } p$$

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

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

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

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

$$(10)\quad ENDWAT_{wr} = rendi_{w} + \sum_{m} rendr_{w}\, rech_{rm} + \sum_{w_2} rende_{ww_2}\, INITWAT_{w_2} + \sum_{w_2} rendu_{ww2} \sum_{p \in reg(w_2)} \sum_{m} \left(MUN_{prm} + IND_{prm} + \sum_{c} \sum_{s} wateruse_{prcsm}\, AGPROD_{prcs1} \right) \quad \text{for all } w, r$$

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

$$(11)\quad ENDWAT_{wr} \geq \overline{ENDWAT_{w}} \quad \text{for all } w \;\&\; r$$

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

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

$$(12)\quad INITWAT_{w} = \overline{INITWAT_{w}} \quad \text{for all } w$$

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

Employing EDSIM-DP in the Dynamic Programming Analysis

The dynamic program needs data on the term $G(Q_t , Q_{t+1}, R_t)$ in equation (3). EDSIM-DP gives the net value of water use given a beginning and ending elevation across all states of nature. Given a solution the returns for each state of nature can be used. Thus the initial elevation in equation (12) and the ending elevation in (11) where systematically varied in 10 foot intervals from 570 to 680 feet above sea level for the J17 well in San Antonio to provide the data for the G term. This creates 12*12 pairs possible J-17 well starting and ending elevations. The resultant state of nature dependent evaluations of equation (6) depicts the total social welfare to municipal, industrial and agricultural interests arising for a elevation pair and for a recharge state. Artificial variables were also added to the model to allow impossible cases to occur but at a very high cost (i.e. it is not possible to go from the lowest initial to the highest final under most recharge events).

Model Experimentation and Results

Three water use scenarios were simulated in this study.

1) Current unrestricted pumping
2) A 400,000 af total pumping limit as mandated by legislation for the year 2008
3) Springflow limits of 200, 150, 100, and 50 cubic feet per second.

Unrestricted Pumping

Table 1 shows the average economic and hydrological results with respect to each starting elevation with unlimited pumping. As starting elevation is increased from 580 to 680, the ending elevation increased and interacted as about 650, like in figure 1. Spring flows including Comal Spring flows and San Marcos flows, being extremely aquifer elevation sensitive, increase with starting and ending aquifer levels.

Agricultural income increased from 5.58 million at 580 starting elevation to 8.51 million(52% increasing) at 680 starting elevation while M&I surplus increased by 3 million(0.6% increaseing). Total welfare is the summation of agricultural income, M&I surplus, and authority welfare and increased by 4.62 million(1% increasing). Agricultural, M&I, and total water use increased while their pumping cost decreased as the starting elevation increased.

2. Pumping limits and Comal Springflow limits

As discussed above, SB1477 imposes 400,000 af pumping limits in the longer term which is implemented as the sum of the industrial, municipal, and agricultural water use variables in the model to not exceed this pumping limit. On the other hand, the EAA is charged with maintaining springflow. In order to investigate the implications of maintaining springflow, the third scenario requires alternative 50, 100, 150, and 200 cfs of minimum of Comal flow during each and every month.

Table 2 shows the comparisons of hydrological effects of alternative water management plans giving six different starting elevations in J-17 well. The number under BASE run in table 2 are the average optimal solutions from the model while the number under other two scenarios are the differences with respect to BASE run. As 400,000 af of pumping limits is implemented, the optimal ending elevation, Comal flow, and San Marcos flow increase run giving all six starting elevations. However, it causes agricultural, M&I, and total water usage decreasing. The positive marginal effects for Comal flow, San Marcos flow due to 400 k af pumping limits increases as the starting elevation increase. The negative marginal effects for agricultural, M&I, and total water use due to 400 k af pumping limits increase as given starting elevation increase. For example, the total water use will be decreased by 76 thousand af given 580 starting elevation and will be decreased by 125 thousand af under 680 starting elevation. It explains that the 400 k af pumping limits caused a negative water use and a positive impacts on spring flow and such magnitude effects increased as starting elevation increased. Similarly, when the limit on springflow are implemented, optimal ending elevation, Comal flow, and San Marcos flow have positive effects with respect to BASE run while agricultural and M&I water use are negative impacts. All of these hydrological effects due to spring flow limit decrease as the given starting elevation increase.

The hydrological effects of alternative water management plans during drought year(1963 as example) and high recharge year(1976) are listed in tables 3 and 4. Table 3 shows that the hydrological effects due to alternative water management plans during drought year are larger than the average effects ib table 2 while the effects in the high recharge year in table 4 are smaller than the average effects.

Table 5 shows the welfare comparison effects of alternative water management plans given the 640 starting elevation in J-17 well. As 400,000 af of pumping limits is implemented, the agricultural income, M&I surplus, and total welfare decreased by 2.12, 7.62, and 3.02 million dollars(29.7%, 1.60%, and 0.62% deduction) respectively while the water agencies or water right holders increase by 6.73 million dollars increased. Such welfare decreasing results from the water use decreased. Similar, when the springflow limit is implemented, the agricultural income, M&I surplus, and total welfare were decreased and the magnitude is larger as the more springflow is limited.

Concluding Comments

A linked of MP and DP methodology is applied in EA analysis. The key point for linking the MP and DP is to find the possibly feasible value for state variable and then solved for both MP and DP. In EA analysis, starting elevation is defined as a state variable instead of pumping level because pumping decision will create a very complex connection with other variables. The optimal ending elevations in time t-1 equals the starting elevation in time t and this equation is defined as the transition equation in solving DP procedure. The starting elevation in J-17 well is selected as from 570 to 680 af above sea level and each starting elevation could match with other 11 ending elevations which is from 570 to 680 af too.

Three experiments are simulated here. The BASE run represents the current EA situation while other alternative water management plans including 400,000 af pumping limit and the springflow limit represent other two scenarios. The hydrological effects of these alternative water management plans show the water demand in agriculture and M&I sector decreased and results in welfare deduction. However, the Comal flow and San Marcos flow level will increase with these pumping limit and springflow limit. The empirical results also indicated that such hydrological effects will be large as the starting elevation increase from 580 to 680. Furthermore, these hydrological effects under a drought year have a big impact than the average effects.

Table 1 Results across various Starting Elevations under unrestricted pumping

Solution Item		Starting Elevation					
		580	600	620	640	660	680
Optimal Ending elevation	feet at j-17	601	611	629	644	657	669
Avg Comal Flow	1000 af	1	6	37	103	174	243
Avg. San Marcos Flow	1000 af	41	48	56	63	71	78
Avg Net Ag Income	Million Dollars	5.58	6.42	6.80	7.14	7.84	8.51
Avg Net M&I Surplus	Million Dollars	472.41	473.90	473.31	475.27	475.13	475.48
Avg Elevation Rent	Million Dollars	7.59	6.52	7.31	5.86	6.25	6.21
Avg Net Total Welfare	Million Dollars	485.58	486.84	487.42	488.27	489.23	490.20
Avg Ag-Water Use	1000 af	152	165	162	170	173	183
Avg M&I Water Use	1000 af	324	333	330	341	341	342
Avg Total Water Use	1000 af	476	498	492	511	514	525

Table 2. Average Hydrological Comparisons between Alternative Pumping Limits

		Starting Elevation	Base	Pumping Limits in 400k af	Springflow Limits in Cubic Feet per Second			
					50	100	150	200
Ending Elevation	feet at j-17	580	601	6	24	31	32	39
		600	611	14	32	33	35	40
		620	629	11	15	22	36	37
		640	644	11	1	6	18	30
		660	657	12	1	1	6	13
		680	669	11	4	4	6	6
Comal Flow	1000 af	580	1	0.6	9	13	17	20
		600	6	3	3	8	12	15
		620	37	23	30	50	81	117
		640	103	31	3	16	40	63
		660	174	31	-1	-1	7	22
		680	243	32	2	3	4	5
Comal Flow	Probability	580	0.91	0.91	0	0	0	0
		600	0.91	0.69	0	0	0	0
		620	0.48	0.13	0	0	0	0
		640	0.48	0	0	0	0	0
		660	0	0	0	0	0	0
		680	0	0	0	0	0	0
San Marcos Flow	1000 af	580	41	1.7	5.4	5.9	6.0	6.7
		600	48	2.3	6.5	6.7	6.7	3.9
		620	56	2.0	2.9	4.8	6.9	7.0
		640	63	2.6	0.3	1.4	3.6	5.5
		660	71	2.6	-0.1	-0.1	0.6	1.9
		680	78	2.6	0.2	0.2	0.4	0.4
Agri-Water Use	1000 af	580	152	-55	-152	-151	-151	-151
		600	165	-69	-165	-165	-165	-165
		620	162	-65	-62	-83	-161	-162
		640	170	-71	-1	-21	-71	-95
		660	173	-64	1	1	-9	-37
		680	183	-75	-2	-3	-5	-6
M&I Water Use	1000 af	580	324	-21	-52	-91	-98	-138
		600	333	-29	-80	-88	-95	-117
		620	330	-28	-21	-62	-116	-120
		640	341	-40	-10	-23	-39	-97
		660	341	-49	4	4	-15	-31
		680	342	-50	-6	-6	-9	-10

Total Water Use	1000 af	580	476	-76	-204	-243	-249	-289
		600	498	-98	-245	-253	-261	-283
		620	492	-93	-83	-145	-277	-283
		640	511	-117	-11	-44	-109	-192
		660	514	-114	5	5	-24	-68
		680	525	-125	-8	-9	-14	-16

(Note) The probability for Comal Spring Flow represents that the probability of a zero Comal Spring Flow in August.

Table 3. Hydrological Comparisons between Alternative Pumping Limits in Drought(1963) Year

		Starting Elevation	Base	Pumping Limits in 400k af	Springflow Limits in Cubic Feet per Second			
					50	100	150	200
Ending Elevation	feet at j-17	580	590	10	30	40	40	50
		600	600	20	40	40	40	50
		620	620	10	20	30	50	50
		640	630	20	10	20	30	50
		660	650	20	0	0	10	20
		680	660	20	0	0	10	10
Comal Flow	1000 af	580	0*	0*	40	83	120	170
		600	0*	0*	39	121	158	195
		620	2*	26*	52	77	110	146
		640	64	37	18	40	68	95
		660	144	39	0	0	18	40
		680	205	40	0	0	18	19
San Marcos Flow	1000 af	580	32	1.9	6.8	7.3	7.3	8.4
		600	39	3.2	8.5	8.5	8.5	8.7
		620	47	2.1	4.6	6.7	8.8	8.8
		640	54	3.2	1.5	3.5	5.9	8.2
		660	62	3.4	0	0	1.5	3.5
		680	69	3.3	0	0	1.6	1.6
Agri-Water Use	1000 af	580	173	-69	-173	-173	-173	-173
		600	186	-71	-186	-186	-186	-186
		620	182	-79	-82	-121	-183	-183
		640	198	-88	-25	-59	-109	-153
		660	191	-70	0	0.01	-22	-65
		680	210	-103	0	-0.1	-27	-27
M&I Water Use	1000 af	580	329	-33	-81	-140	-141	-202
		600	350	-64	-147	-147	-143	-188
		620	329	-33	-54	-126	-196	-196
		640	348	-58	-34	-63	-99	-189
		660	329	-52	0	0	-37	-57
		680	347	-54	0	0.1	-32	-32
Total Water Use	1000 af	580	502	-102	-254	-313	-314	-375
		600	536	-135	-333	-333	-329	-374
		620	511	-112	-136	-247	-379	-379
		640	546	-146	-59	-122	-208	-342
		660	520	-122	0	0	-59	-122
		680	557	-157	0	0	-59	-59

(Note)* represents a zero Comal Spring Flow in August given in that starting elevation.

Table 4. Hydrological Comparisons between Alternative Pumping Limits in High Recharge(1976) Year

		Starting Elevation	Base	Pumping Limits in 400k af	Springflow Limits in Cubic Feet per Second			
					50	100	150	200
Ending Elevation	feet at j-17	580	600	10	30	40	40	40
		600	610	20	40	40	40	40
		620	630	20	0	20	40	40
		640	650	10	0	0	10	20
		660	660	10	10	10	10	10
		680	670	10	10	10	10	10
Comal Flow	1000 af	580	0*	0*	72	121	158	195
		600	0*	5	66	102	139	172
		620	45	32	10	45	87	125
		640	116	32	0	3	21	44
		660	187	29	1	9	9	10
		680	258	29	0	0	0	0
San Marcos Flow	1000 af	580	43	2.3	6.1	7.1	7.1	7.1
		600	50	2.7	6.7	6.7	6.7	6.7
		620	58	2.8	0.9	4.3	7.2	7.2
		640	66	2.8	0	0.2	1.8	4.0
		660	73	2.5	0	0.8	0.8	0.8
		680	81	2.5	0	0	0	0
Agri-Water Use	1000 af	580	152	-64	-152	-152	-152	-152
		600	152	-63	-152	-152	-152	-152
		620	155	-66	-26	-63	-155	-155
		640	155	-66	0	-8	-58	-63
		660	158	-54	-22	-22	-22	-26
		680	158	-52	0	0	0	0
M&I Water Use	1000 af	580	339	-27	-57	-116	-116	-116
		600	341	-30	-85	-85	-85	-85
		620	343	-32	14	-35	-114	-114
		640	345	-34	0	1	4	-50
		660	347	-50	-4	-4	-4	0
		680	349	-55	0	0	0	0
Total Water Use	1000 af	580	491	-90	-209	-268	-268	-268
		600	493	-93	-237	-237	-237	-237
		620	498	-98	-12	-98	-269	-269
		640	500	-100	0	-7	-54	-113
		660	505	-104	-26	-26	-26	-26
		680	507	-107	0	0	0	0

Table 5. Welfare Comparisons between Alternative Pumping Limits with 640 starting elevation

		Base	Pumping Limits in 400k af	Springflow Limits in Cubic Feet per Second			
				50	100	150	200
Average Welfare							
Net Agri-Income	Million Dollar	7.14	-2.12	0.23	-0.47	-2.54	-3.65
			(-29.70)	(3.22)	(-6.58)	(-35.574	(-51.12)
Net M&I Surplus	Million Dollar	475.27	-7.62	-1.87	-5.44	-10.89	-43.36
			(-1.60)	(-0.4)	(-1.14)	(-2.29)	(-9.12)
Authority Surplus	Million Dollar	5.86	6.73	1.64	4.53	8.78	31.84
			(114.85)	(27.98)	(77.30)	(149.83)	(543.34)
Net Total Welfare	Million Dollar	488.27	-3.02	0.2	-1.38	-4.65	-15.17
			(-0.62)	(0.04)	(-0.28)	(-0.95)	(-3.11)

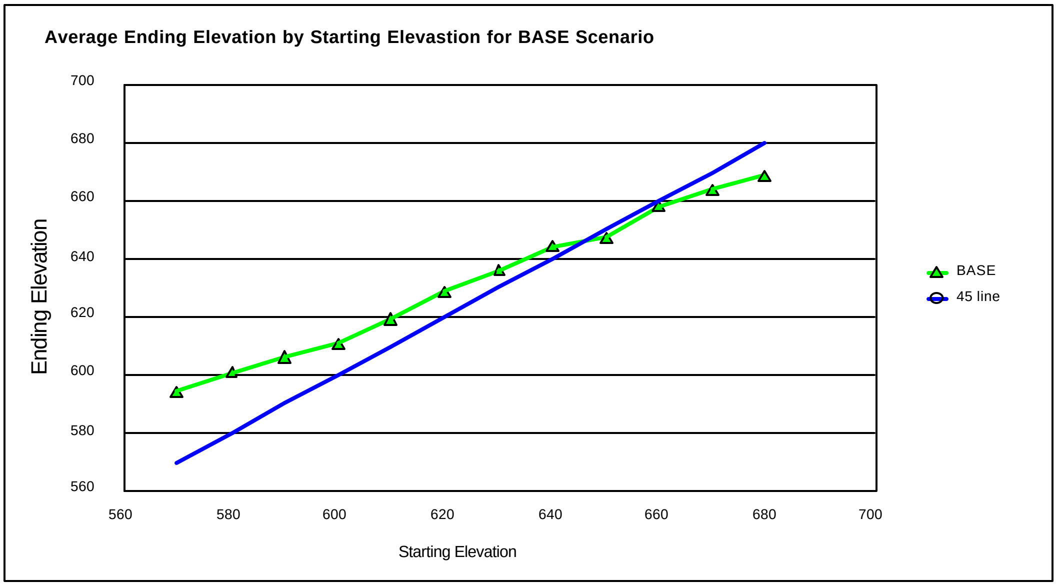
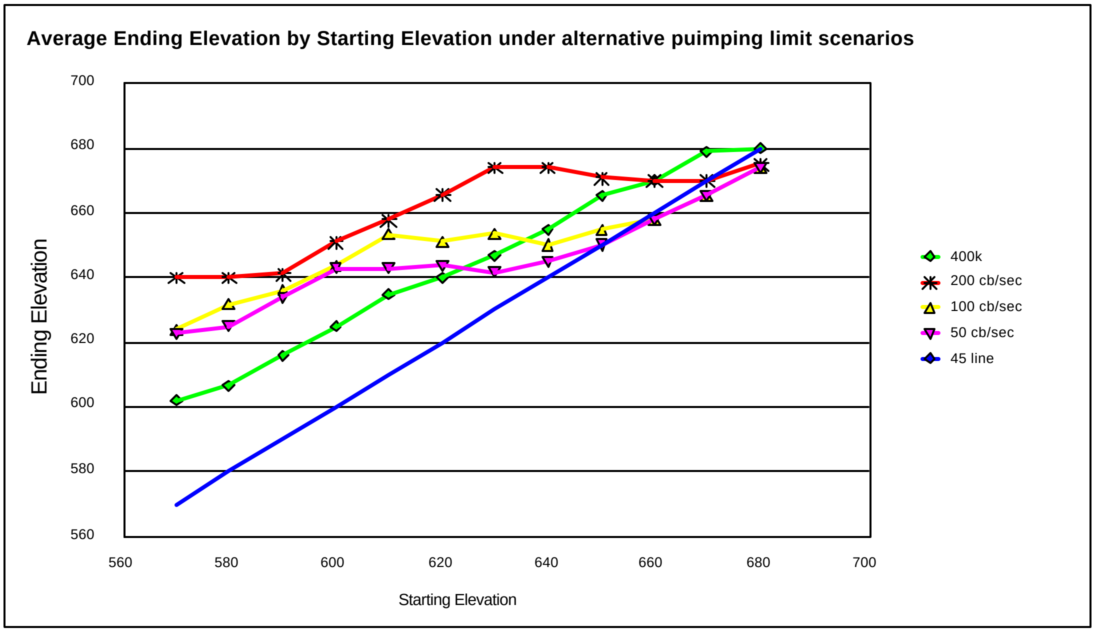
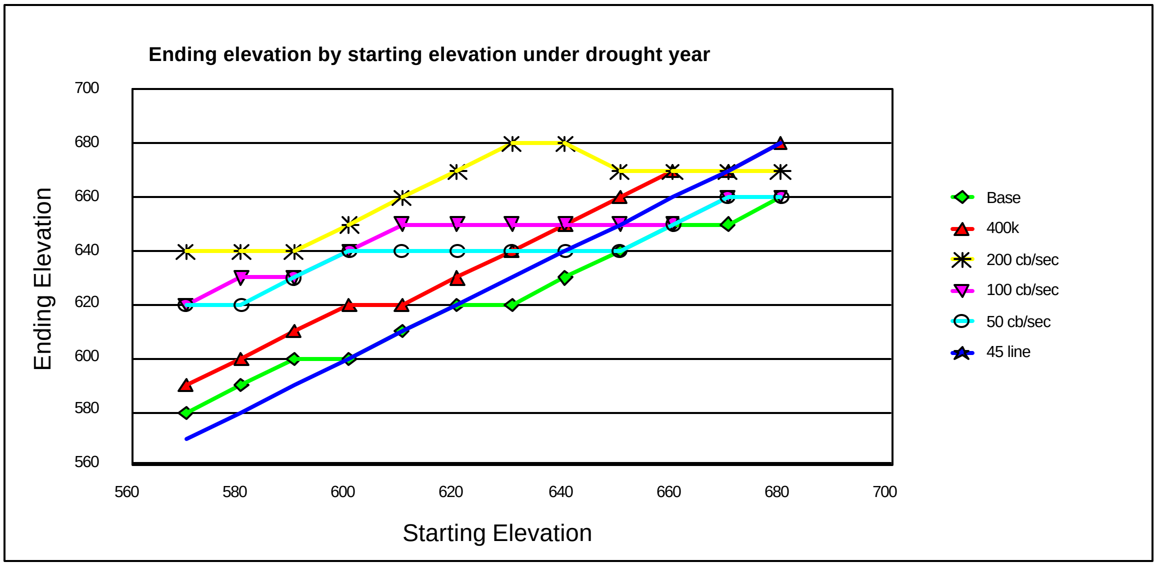


Figure 1. Ending Elevation by Starting Elevation under BASE Run





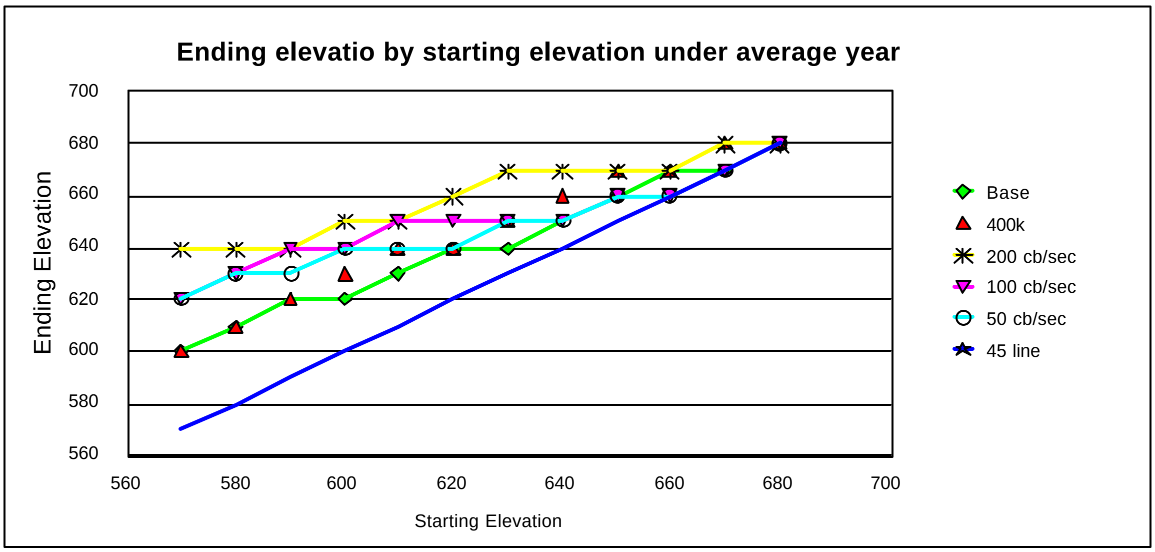
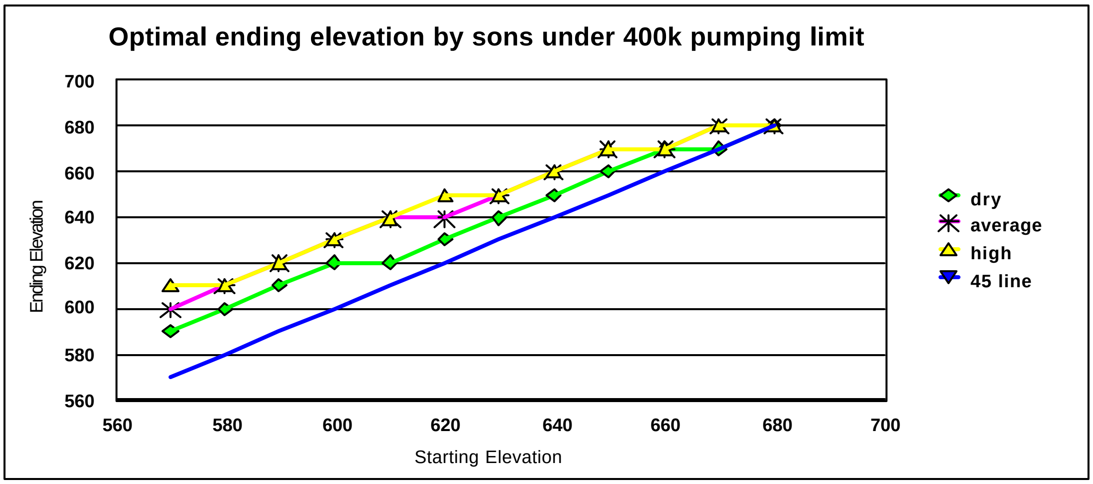
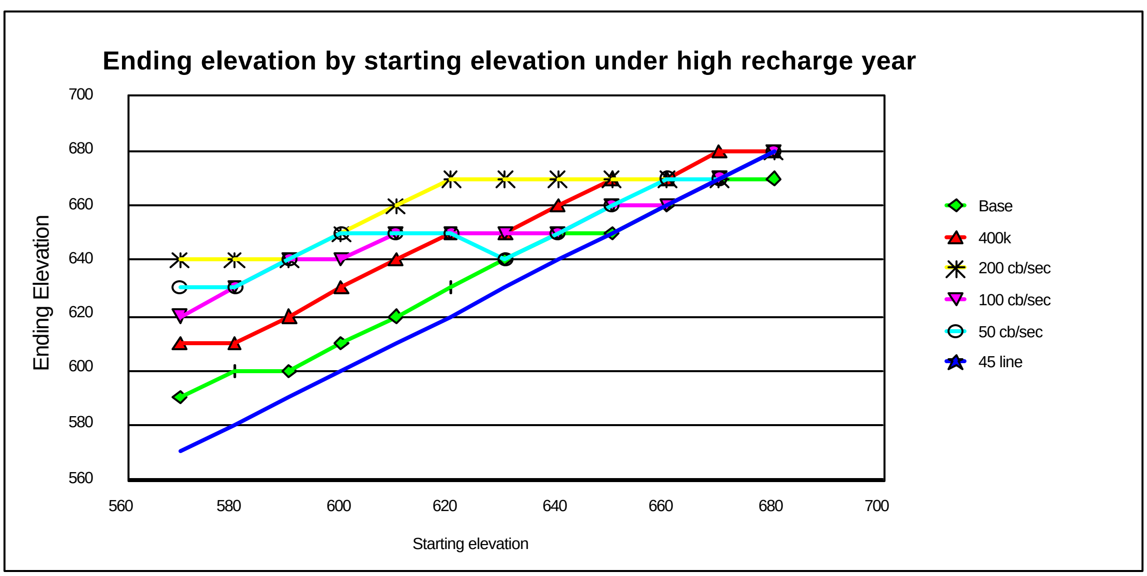
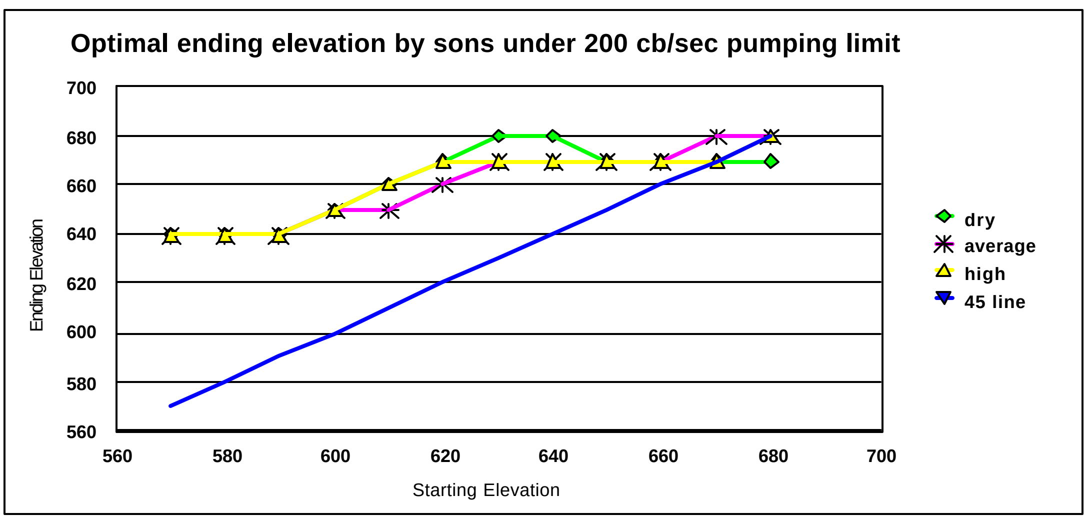


Figure 2. Ending Elevation by Starting Elevation under Alternative Pumping Limits


Optimal ending elevation by sons under BASE run
700
680
660
640
620
600
580
560
Ending Elevation
560
580
600
620
640
660
680
700
Starting Elevation
low recharge
average
high recharge
45 line


Optimal ending elevation by sons under 400k pumping limit
700
680
660
640
620
600
580
560
Ending Elevation
560
580
600
620
640
660
680
700
Starting Elevation
dry
average
high
45 line


Ending elevation by starting elevation under high recharge year
700
680
660
640
620
600
580
560
Ending Elevation
560
580
600
620
640
660
680
700
Starting elevation
Base
400k
200 cb/sec
100 cb/sec
50 cb/sec
45 line


Optimal ending elevation by sons under 200 cb/sec pumping limit
Ending Elevation
Starting Elevation
700
680
660
640
620
600
580
560
560
580
600
620
640
660
680
700
dry
average
high
45 line

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