Simulation of Water Table Fluctuations at Permanent Monitoring Sites to Evaluate Groundwater Pumping

Aaron Steinwand and Robert Harrington
Inyo County Water Department

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INTRODUCTION

Groundwater pumping under the Inyo/Los Angeles Agreement (Agreement) is managed by procedures contained in the Green Book and the Drought Recovery Policy (DRP). The DRP temporarily established additional criteria to govern preparation of annual pumping plans. Under the DRP, the Green Book monitoring and management procedures were instituted but the pumping recommendations were not strictly followed partially because Green Book procedures often permitted pumping near degraded vegetation with deep water tables. Previous cooperative studies (Or and Groeneveld, 1994) and Inyo County reports (Steinwand, 2000) suggested that unsound recommendations resulted from failure to consider important properties of the environment, most importantly, groundwater levels. In a companion report, Steinwand and Harrington (2003) concluded that adhering to the Green Book procedures during 1989-1999 probably would have resulted in greater water table declines during the 1990's drought and less subsequent recovery than occurred under the DRP. Those studies suggest that the Green Book On/Off procedures are inadequate to manage groundwater pumping to meet the Agreement's goals.

A straightforward approach to manage pumping would select a pumping scenario based on the effect on depth to the water table because it is affected directly by pumping and largely controls vegetation conditions. Water table depth can be predicted with much higher confidence than soil water and vegetation water requirements and can be evaluated using risk analysis. Basing the pumping decisions on the water table would allow managers to avoid scenarios with a high risk of causing water table drawdown not tolerated by the vegetation. The purpose of this study was to simulate water table depth as a function of pumping for several years at the permanent monitoring sites and to quantify the probability of water table recovery associated with each scenario.

METHODS

This analysis relied on regression models developed previously to indicate water table response to pumping and recharge in wellfields (Harrington, 2001). This section describes the development of three components necessary to perform the simulations including examination of soil water data to determine water table targets, regression analyses to link indicator wells and permanent monitoring sites, and Monte Carlo simulation of water table recovery and prediction uncertainty.

Depth to Water Target

Analyzing the effects of LADWP pumping proposals on water table decline and potential for recovery requires selection of the target depth to water (DTW) that the water table must return to after drawdown. The appropriate target is the DTW that if periodically attained would accomplish the goals of the Agreement. That value is site specific and not known, partially because it depends on imprecise ecological and water supply management goals and also because the hydrologic conditions necessary to avoid significant declines in vegetation cover or vegetation conversion to more xeric communities are poorly understood.

DTW targets were based on the soil water recharge observed at most monitoring sites when the water table rose in the late 1990's. The intent was to select a target DTW in the test well that corresponded with increased soil water at the vegetation transect. Though the target DTW necessary to accomplish the goals of the Agreement cannot be determined precisely, it is safe to assume that it is shallower than the DTW when the root zone initially begins to wet up as water table recovery occurs. When the majority of the access tubes at a site showed groundwater reaching the root zone (2 or 4 m for meadow and scrub communities respectively), the DTW in the associated monitoring well was set as the lower limit for the target. The 2 and 4 m root zones were used because the purpose for turning wells off in the present management scheme is to allow water table recovery to recharge the soil water above 2 or 4 m. In reality, rooting depth and density are variable and are impractical to measure precisely or predict. In instances when the wetting in the root zone occurred more than once, the average DTW was calculated. The analysis relied on the test well historically linked to the monitoring sites because of the longer record of simultaneous soil water and DTW measurements. At sites where groundwater had not reached the root zone or at sites where rapid soil water recharge occurred between measurements (often due to spreading), the DTW of initial wetting was estimated by adding the observed height of capillarity to the root zone depth. This analysis requires water table elevation in the wells where predictions are to be made, not at the monitoring site transect; therefore, the target DTW was not adjusted for elevation differences between the test well and transect.

All DTW targets used in this analysis were above the depth of initial wetting and were chosen using the following rationale. At sites where the water table had been within one foot of the root zone or higher, the targets were set at one foot below the root zone (seven sites). At sites where the water table had not been within a foot of the root zone, the target was set at the highest level attained during 1984-87 and before vegetation mapping if the period of record was sufficient (two sites). At sites where there was no water level record for the baseline period the target was set at one foot above the shallowest depth attained in the late 1990’s (five sites). One foot was an arbitrary choice aimed at setting a DTW target that was reasonably attainable and still above the depth of initial wetting. Three sites (LW3, BP4, TA5) had water levels below the root zone, but the soil/groundwater relationship was not straightforward because the soil was wet when initially monitored and/or because the test well was not located at the site. Table 1 summarizes the specification of the DTW target for each monitoring site.

Previously, Inyo County and Los Angeles have relied on the mean April DTW for 1985-87 as a target for recovery based on the assumption that DTW in these years supported the vegetation during the baseline mapping period. Most monitoring site wells were installed after 1987, and determining baseline DTW would require model predictions. Such predictions are possible using the indicator well/monitoring site regressions described below, but uniformly applying the 1985-87 average as the target was rejected because the underlying assumption is not justified. For 14 of the 17 monitoring sites used here, the baseline DTW includes measurements taken after the vegetation was mapped (Table 2). Baseline vegetation measurements obviously were not influenced by water table conditions that occurred after the baseline conditions were measured. Also, the baseline DTW was below the depth at which wetting occurred at six sites, suggesting that periodically achieving baseline would not have the intended effect of recharging soil water in the root zone. Baseline vegetation conditions were related to high water levels that occurred before and during vegetation mapping. A quantitative description of the relationship of vegetation conditions and water levels could provide more defensible targets than were developed for this study. Until that knowledge is developed, however, the modest DTW targets in this report were used because they were based on empirical data and more defensible rationale than the 1985-1987 baseline DTW.

Simulation of Water Fluctuations

Water level predictions were based on multiple linear regression models at indicator wells (Harrington, 1998; 1999; 2001) that have been used by both Inyo County and LADWP for evaluating wellfield-scale pumping proposals. All indicator well models use initial water level elevation and pumping as independent variables. Most of these regression models use Owens Valley runoff as an independent variable correlated with recharge, but the models for the Laws wellfield use diversions from the Owens River into the McNally canals as the independent variable correlated with recharge (Harrington, 2001). The models were updated using data through the 2000-2001 runoff-year.

Past experience applying the indicator well models has shown that the choice of wellfield pumping as the independent variable produced different assessments of the effects of wellfield pumping for each indicator well. To reduce the number of recommendations for a wellfield, we developed multiple linear regression models for the indicator wells using the pumping from the pumping wells linked to a monitoring site and the nearest exempt wells (Green Book, Table I.A). Exempt wells were included because they probably affect the indicator well locations and because they were included in the wellfield pumping variable in the original model. Even though the regression diagnostics for the models were acceptable, in only six out of seventeen instances did the revised pumping variable improve the regression statistics, usually by only small amounts. Nearly identical regression statistics suggest that this was a case where one independent variable was replaced with a correlated variable providing little improvement in the predictive capability. Also, stability of the regression coefficients should be assessed

Table 1. Depth to water from land surface in the monitoring site test well required for initial wetting of root zone and the targets used for the simulations.

Monitoring site	Test well	Root zone (m)	DTW of initial wetting (m)	Target DTW (m)	Rationale for target depth to water
LW1	795T	4	5.1	4.3	One foot below the root zone
LW2	V001G	2	4.4	3.8	Highest water level attained before baseline vegetation mapping
LW3	574T	2	5.3	2.8	Highest water level attained in the late 1990's
BP1	798T	3	3.7	3.3	One foot below the root zone
BP2	799T	4	5.3	4.8	One foot above the highest water level attained in the late 1990's
BP3	567T	4	4.7	4.3	One foot below the root zone
BP4	800T	4	6.0	5.0	Well not at site. Approximate depth when lower half of root zone wetted
TA3	505T	2	5.7	4.5	Highest water level attained before baseline vegetation mapping
TA4	586T	2	3.8	2.3	One foot below the root zone
TA5	801T	2	6.2	3.9	Highest water level attained in the late 1990's
TA6	803T	2	3.1	2.8	One foot above the highest water level attained in the late 1990's
TS1	807T	2	3.0		No appropriate indicator well/monitoring site model
TS2	806T	2	3.6	3.3	One foot above the highest water level attained in the late 1990's
TS3	581T	2	NA		No appropriate indicator well/monitoring site model
TS4	804T	2	2.6		No appropriate indicator well/monitoring site model
IO1	809T	2	4.3	2.3	One foot below the root zone
IO2	548T	4	3.3		No appropriate indicator well/monitoring site model
SS1	V009G	4	4.8	4.3	One foot below the root zone
SS2	646T	4	5.4	5.3	One foot above the highest water level attained in the late 1990's
SS3	561T	4	4.5		No appropriate indicator well/monitoring site model
SS4	811T	4	6.1	4.5	One foot above the highest water level attained in the late 1990's
BG2	812T	4	5.8	4.3	One foot below the root zone

Table 2. Monitoring site and mapping dates for the U.S. Geological survey quadrangle (Green Book, p.35)

Monitoring site	USGS quadrangle	Vegetation mapping dates	Baseline DTW years after mapping
LW1	Laws	February 1987- April 1987	none
LW2	Laws	February 1987- April 1987	none
LW3	Laws	February 1987- April 1987	none
BP1	Big Pine	September 1986- January 1987	April 1987
BP2	Big pine	September 1986- January 1987	April 1987
BP3	Fish Springs	September 1986	April 1987
BP4	Tinemaha	July 1986- August 1986	April 1987
TA3	Blackrock	March 1986- June 1986	April 1987
TA4	Blackrock	March 1986- June 1986	April 1987
TA5	Tinemaha	July 1986- August 1986	April 1987
TA6	Blackrock	March 1986- June 1986	April 1987
TS2	Blackrock	March 1986- June 1986	April 1987
IO1	Independence	September 1984- September 1985	April 1986, 1987
SS1	Independence	September 1984- September 1985	April 1986, 1987
SS2	Independence	September 1984- September 1985	April 1986, 1987
SS4	Manzanar	October 1985- November 1985	April 1986, 1987
BG2	Manzanar	October 1985- November 1985	April 1986, 1987

before adopting the linked and exempt well pumping variable because management recommendations resulting from those models may alter the historic pattern of drawdown and well interference within the wellfield. The remainder of this analysis retained the wellfield pumping variable, but it may be valid to use the linked and exempt well pumping variable if the small loss in predictive capability was offset by the ability to derive a single pumping recommendation for a wellfield.

Except for rare instances, soil water/vegetation monitoring information is lacking for the indicator well locations. It was essential, therefore, to develop the linkage from indicator well locations to locations more suited for analysis. We developed the linkage to existing monitoring sites because of the presence of monitoring data from those sites and the familiarity of this management program. Some permanent monitoring sites may not function effectively under existing On/Off management (Steinwand, 2000), but they still may be useful for evaluating the drawdown and recovery rate of groundwater levels because of their proximity to pumping wells. Locations of monitoring site and indicator wells discussed in this report are shown in Figure 1.

Hydrographs of indicator wells were related to the hydrographs of monitoring site wells by regressing the April water level in the indicator well against the April water level in the monitoring site well. The monitoring site hydrographs cannot be regressed directly to pumping because the test well period of record of the monitoring site wells is too short, usually less than 14 years. The annual time step beginning in April was chosen to conform with the time step in the indicator well models, and is appropriate because the intended use of the models is to evaluate operations plans prepared each April.

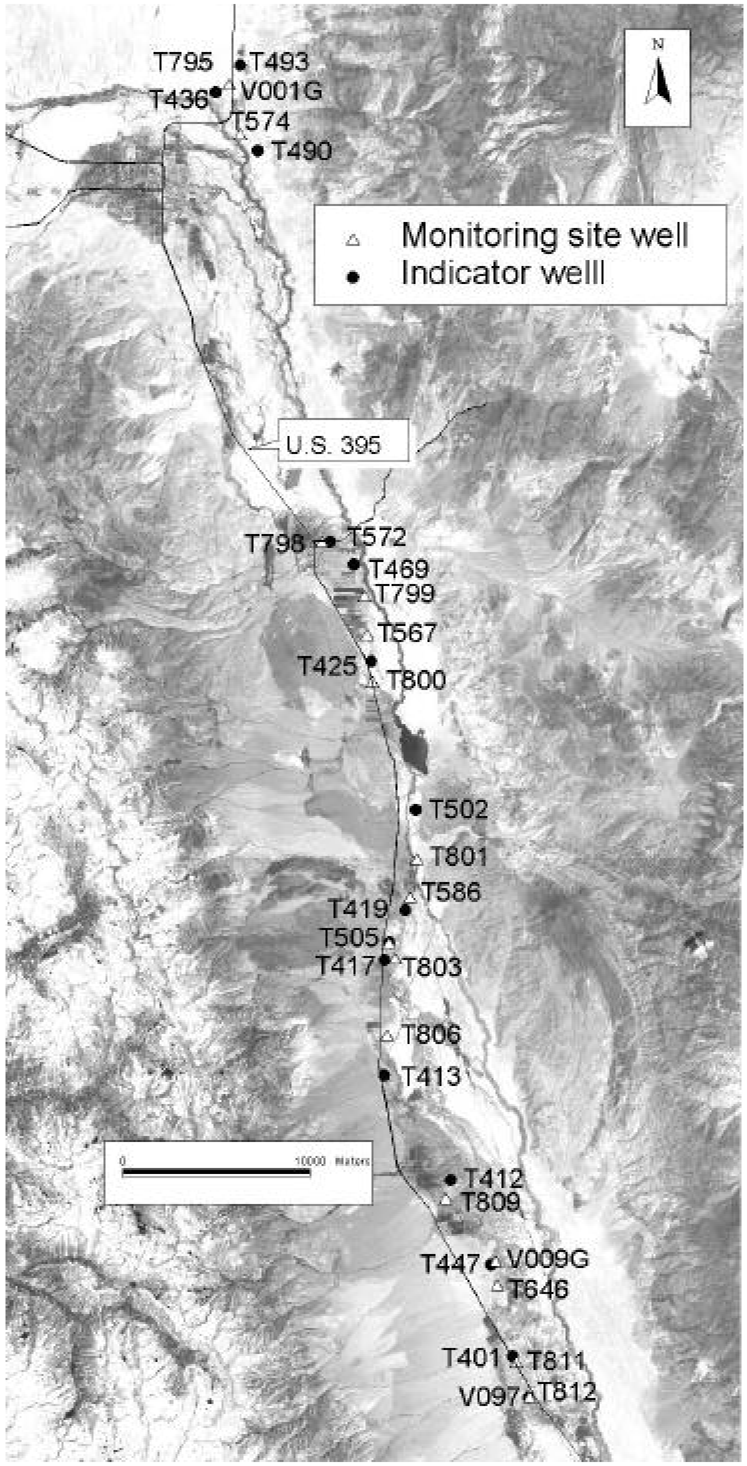

Figure 1. Locations of indicator and monitoring site wells discussed in this report

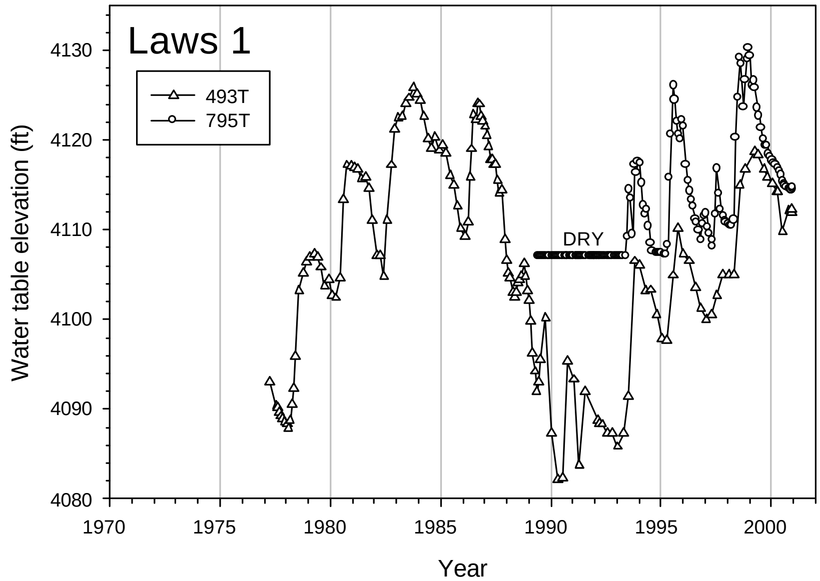

Figure 2. Water table elevation in LW 1 test well (795T) and indicator well 493T.

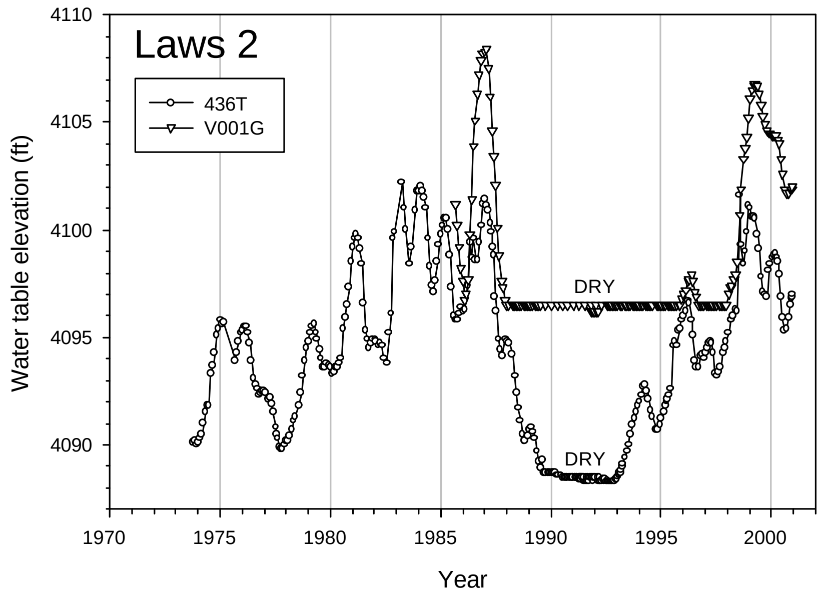

Figure 3. Water table elevation in LW 2 test well (V001G) and indicator well 436T.

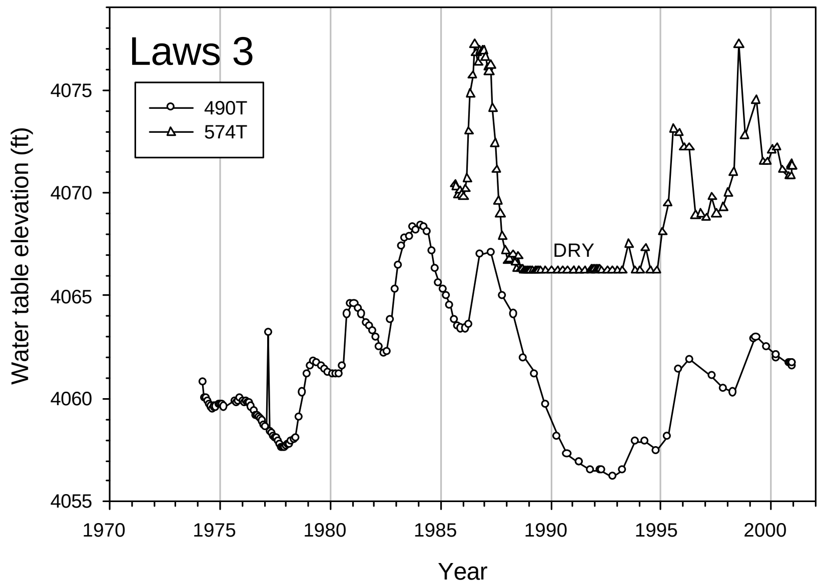

Figure 4. Water table elevation in LW 3 test well (574T) and indicator well 490T.

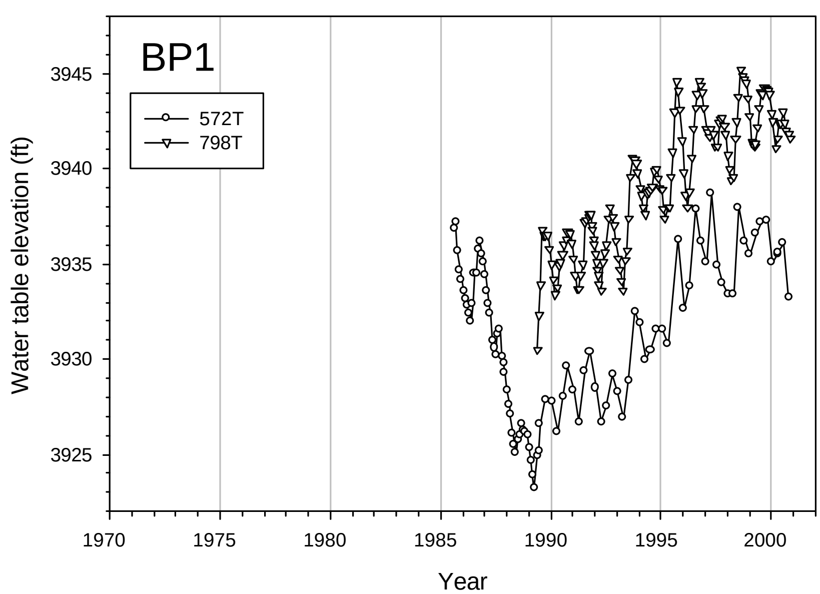

Figure 5. Water table elevation in BP1 test well (798T) and indicator well 572T.

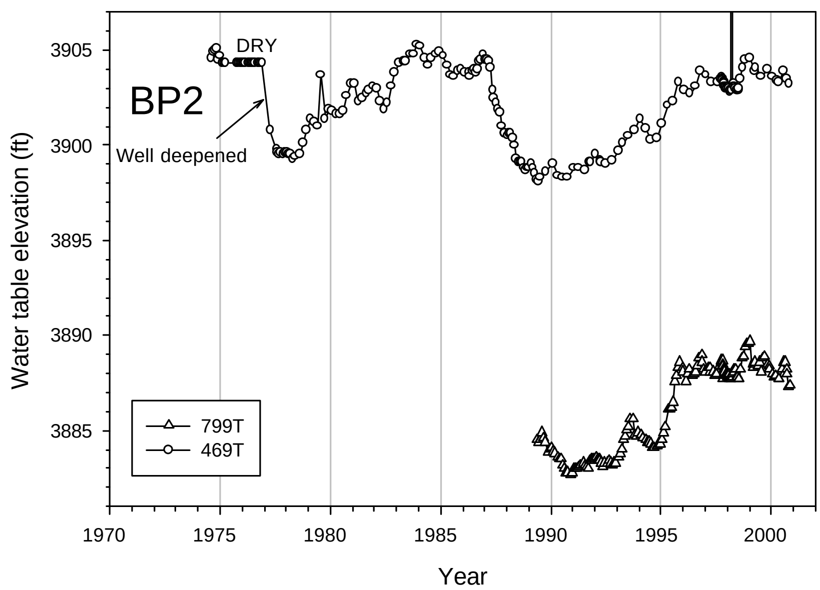

Figure 6. Water table elevation in BP2 test well (799T) and indicator well 469T.

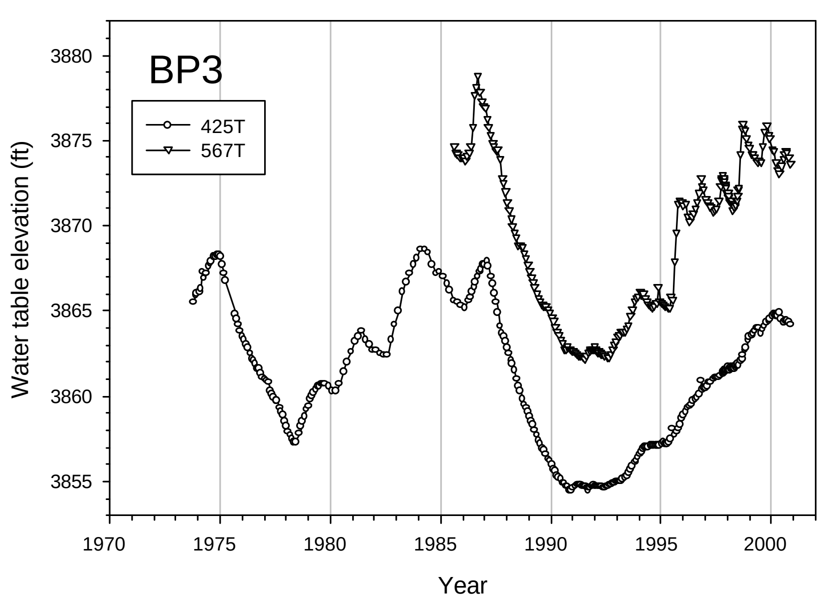

Figure 7. Water table elevation in BP3 test well (567T) and indicator well 425T.

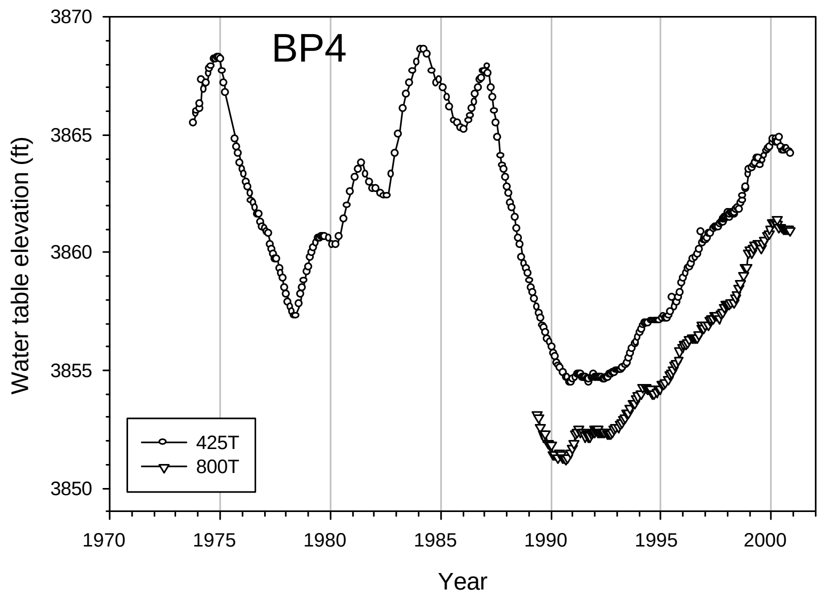

Figure 8. Water table elevation in BP4 test well (800T) and indicator well 425T.

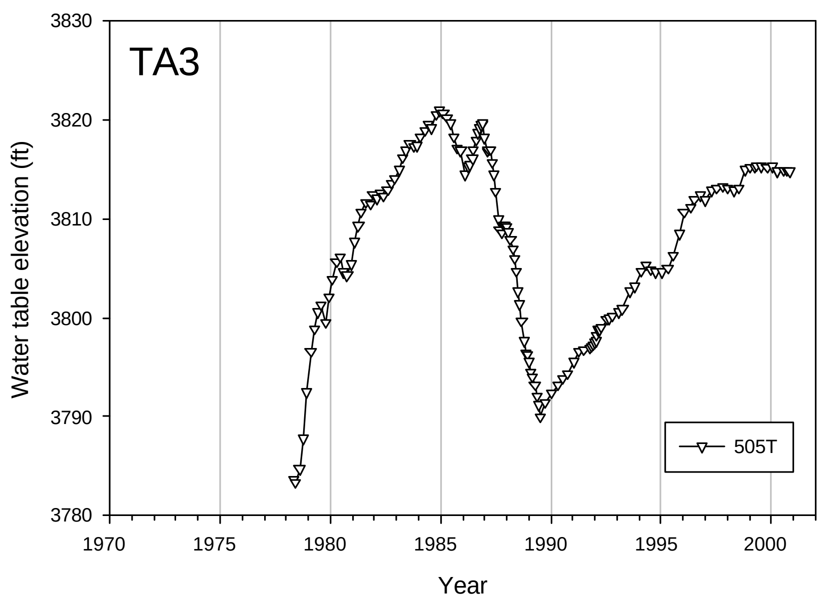

Figure 9. Water table elevation in TA3 test well (505T). 505T is an indicator well

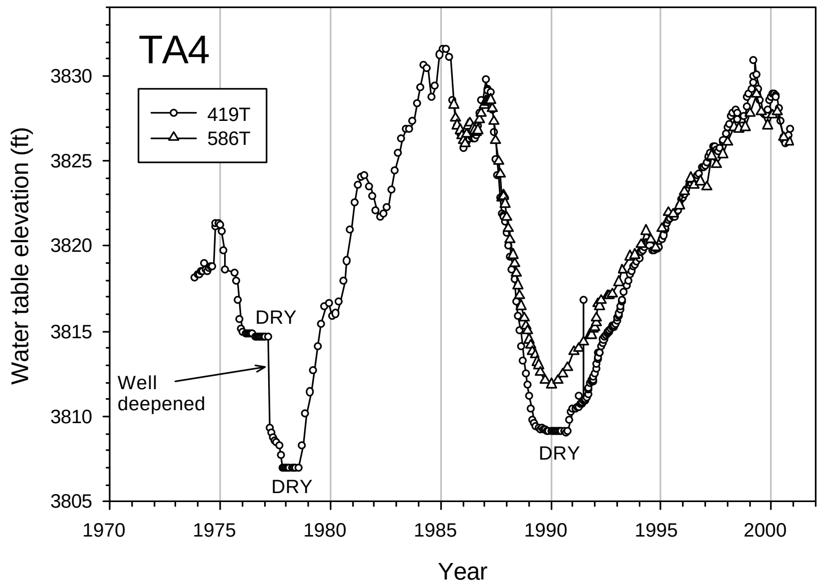

Figure 10. Water table elevation in TA4 test well (586T) and indicator well 419T.

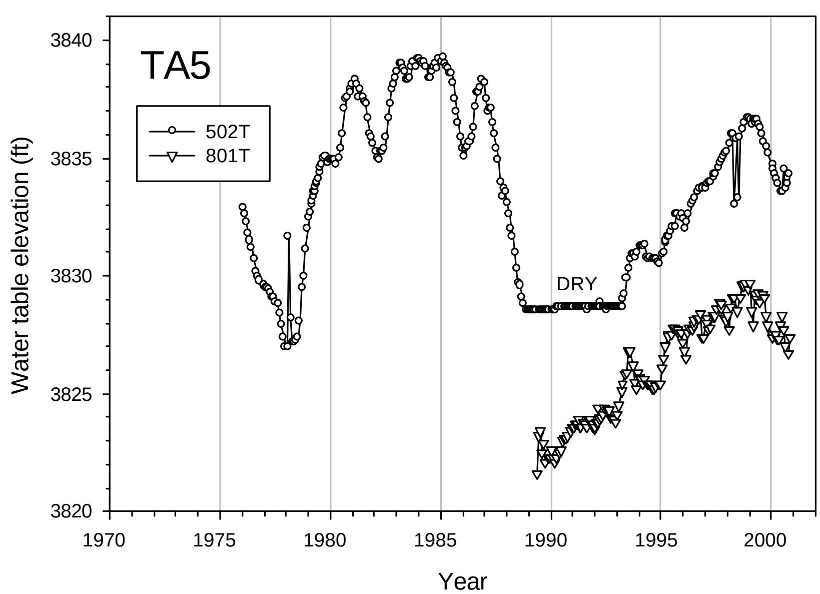

Figure 11. Water table elevation in TA5 test well (801T) and indicator well 502T.

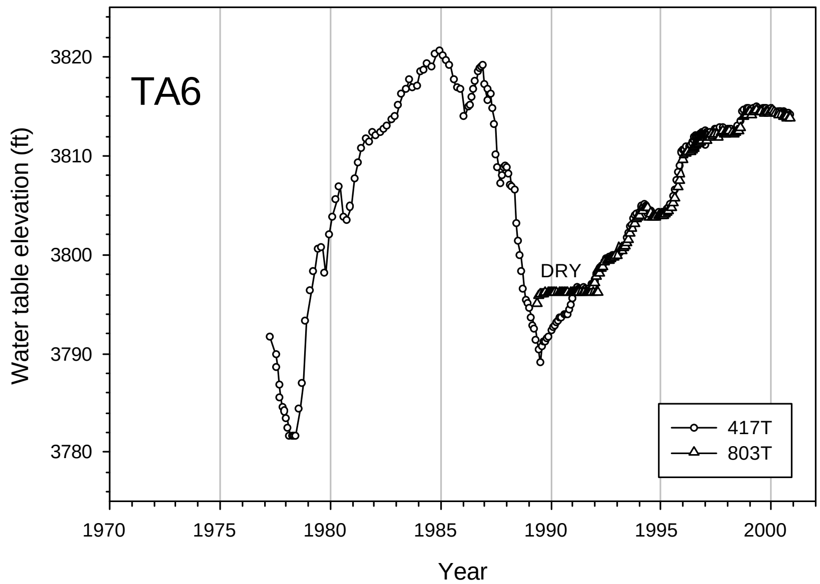

Figure 12. Water table elevation in TA6 test well (803T) and indicator well 417T.

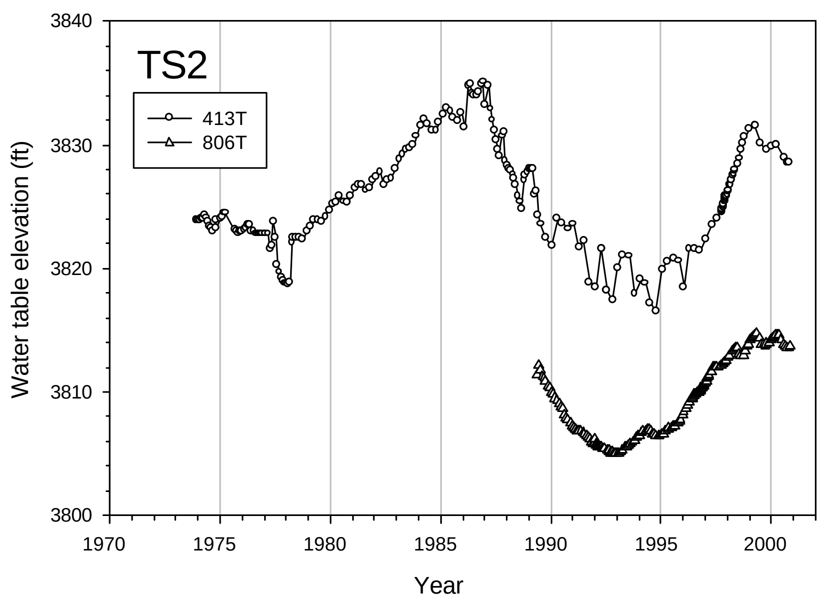

Figure 13. Water table elevation in TS2 test well (806T) and indicator well 413T.

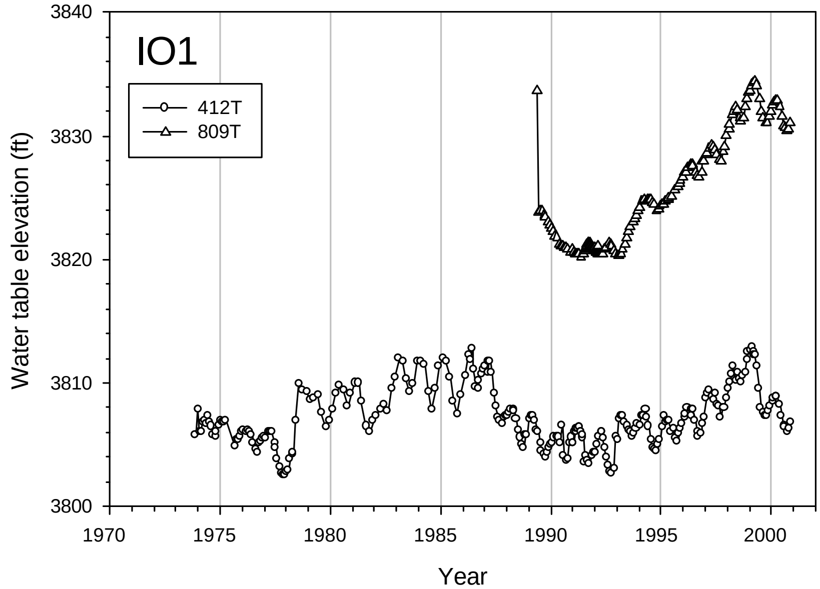

Figure 14. Water table elevation in IO1 test well (809T) and indicator well 412T.

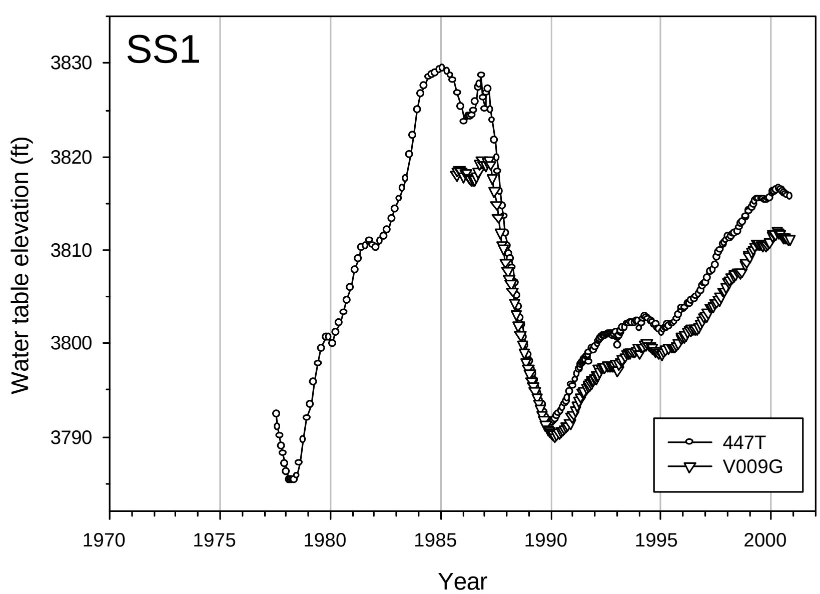

Figure 15. Water table elevation in SS1 test well (V009GT) and indicator well 447T.

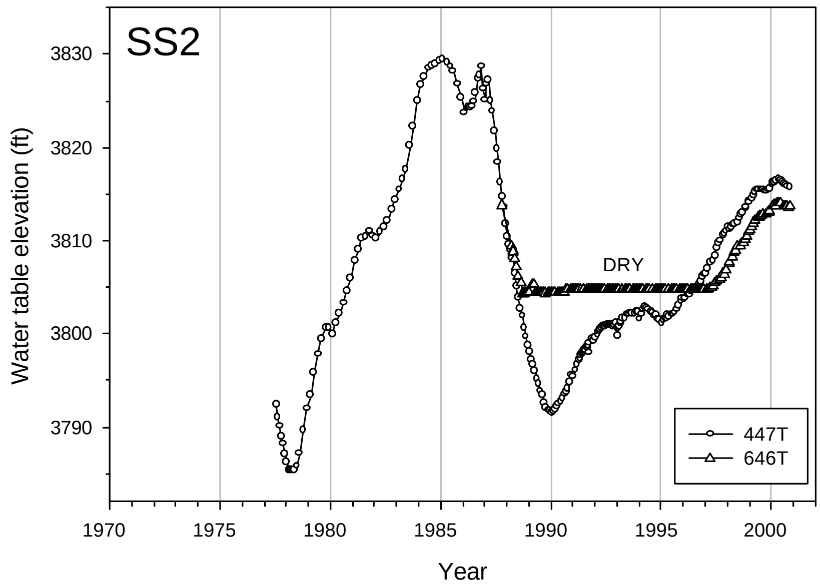

Figure 16. Water table elevation in SS2 test well (646T) and indicator well 447T.

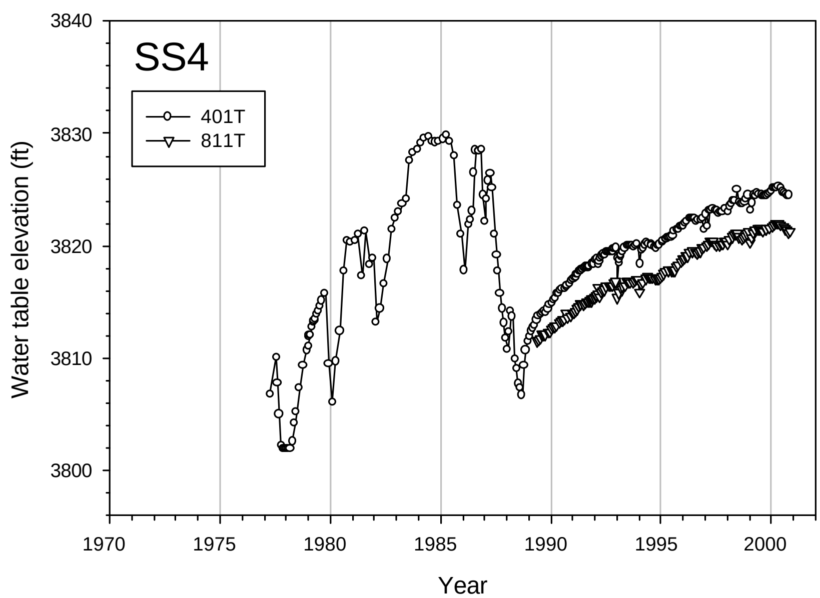

Figure 17. Water table elevation in SS4 test well (811T) and indicator well 401T.

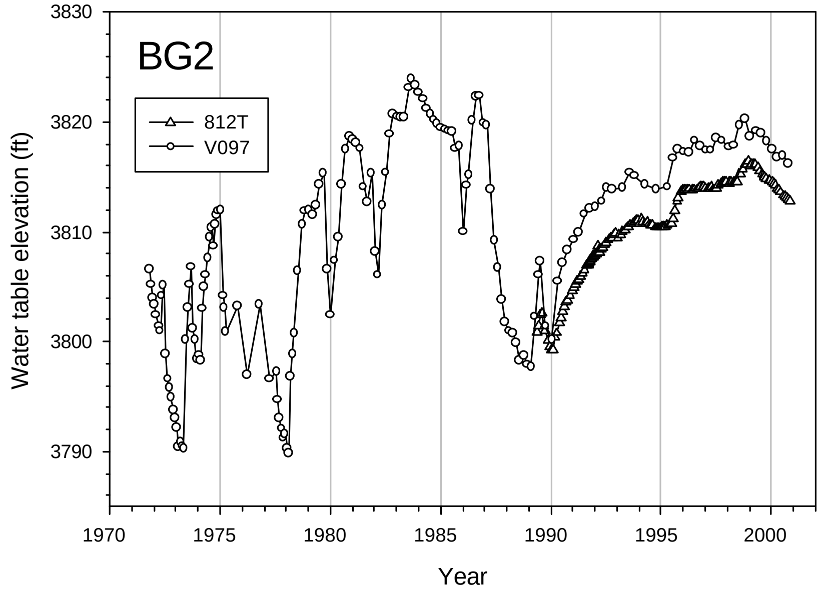

Figure 18. Water table elevation in BG2 test well (812T) and new indicator well 097V.

The choice of which indicator well to link to each monitoring site was based on inspection of the hydrographs for parallelism and similarity of hydrologic response (Figures 2-18). This choice was not as straightforward as simply using the closest indicator well to each monitoring site. For example, 493T provides a better match for 795T at Laws 1 than 436T because even though 436T is closer to the monitoring site, both 493T and 795T are situated near the Lower McNally Canal which results in similar hydrographs.

Evaluating pumping and recovery requires accurate predictions of water table levels several years in advance. Indicator wells with acceptable capability to perform multiple year simulations were chosen to link to monitoring site test wells (Steinwand and Harrington, 2003). Indicator well 413T did not perform well in simulations longer than a couple of years (Steinwand and Harrington, 2003), but it was used in this analysis because of the poor agreement of the hydrograph at TS2 with any other indicator wells in the Thibaut-Sawmill wellfield. Most often, the April measurements for the pairs of wells were taken on the same day or within a few days of each other. Error introduced by using measurements taken on different days is included in the regression model error and was accounted for in the simulations. Dry well reads were not used. A spreadsheet was developed to simulate water table depths and to calculate the probability that the water table at the monitoring site will be at or above a target elevation one, two, and three years in the future as a function of wellfield pumping conducted in the first year. In the second

Table 3. Minimum wellfield pumping values used for the Monte Carlo simulations.

Wellfield	Minimum pumping**^**
	ac-ft/year
Laws	500
Big Pine	24000
Taboose-Aberdeen	0
Thibaut-Sawmill	12400
Independence-Oak	7000
Symmes-Shepherd	1200
Bairs-George	500

^: Approximate values to meet fixed uses supplied by pumping. Minimum pumping in Bairs-George was set at 500 ac-ft/year to assume 343W could be operated if creek flows are low.

and third years, pumping was set to the minimum for the wellfield. The period that the vegetation could be separated from the water table without violating the goals of the Agreement is not known. A three-year period was selected to span multiple years and still provide a manageable amount of data to process. Practically, there is not a computational limitation on the number of years to simulate, but the prediction error increases asymptotically as the simulation period increases. Simulations included 5000 iterations and were conducted using the program @RISK (Palisade Corp., 1997) within Microsoft Excel spreadsheets.

Each simulation used the combination of the indicator well and monitoring site/indicator well regressions to predict the water level at a permanent monitoring site (Equations 1 and 2),

$$h_{ind} = b_o + b_1 ho_{ind} + b_2 P + b_3 R + e_{ind} \quad \textbf{(1)}$$

$$h_{ms} = d_o + d_1 h_{ind} + e_{ms} \quad \textbf{(2)}$$

where: h_{ind} is the final head in the indicator well at the end of the runoff year (feet above mean sea level), ho_{ind} is the initial head in the indicator well, P is wellfield pumping, R is valley-wide runoff (or, in Laws, McNally canal diversion), b_0, b_1, b_2, and b_3 are regression coefficients, and e_{ind} is standard error of the indicator well model. In Eq. 2, h_{ms} is the final head at the monitoring site at the end of the runoff year, h_{ind} is as defined previously, d_0 and d_1 are regression coefficients, and e_{ms} is standard error of the indicator/monitoring site model. For the first year of the simulations, 2002-03, the initial ho_{ind} was the April 2002 water level. Water level predictions for April 2004 and 2005 used the previous year's predicted water level using Eq. 1 as the initial head. In 2002-03, several pumping levels were simulated and runoff was set equal to the 2002 LADWP runoff forecast. For 2004 and 2005 predictions, pumping was fixed at the minimum for the wellfield (Table 3), and runoff (R) was a stochastic variable drawn randomly with

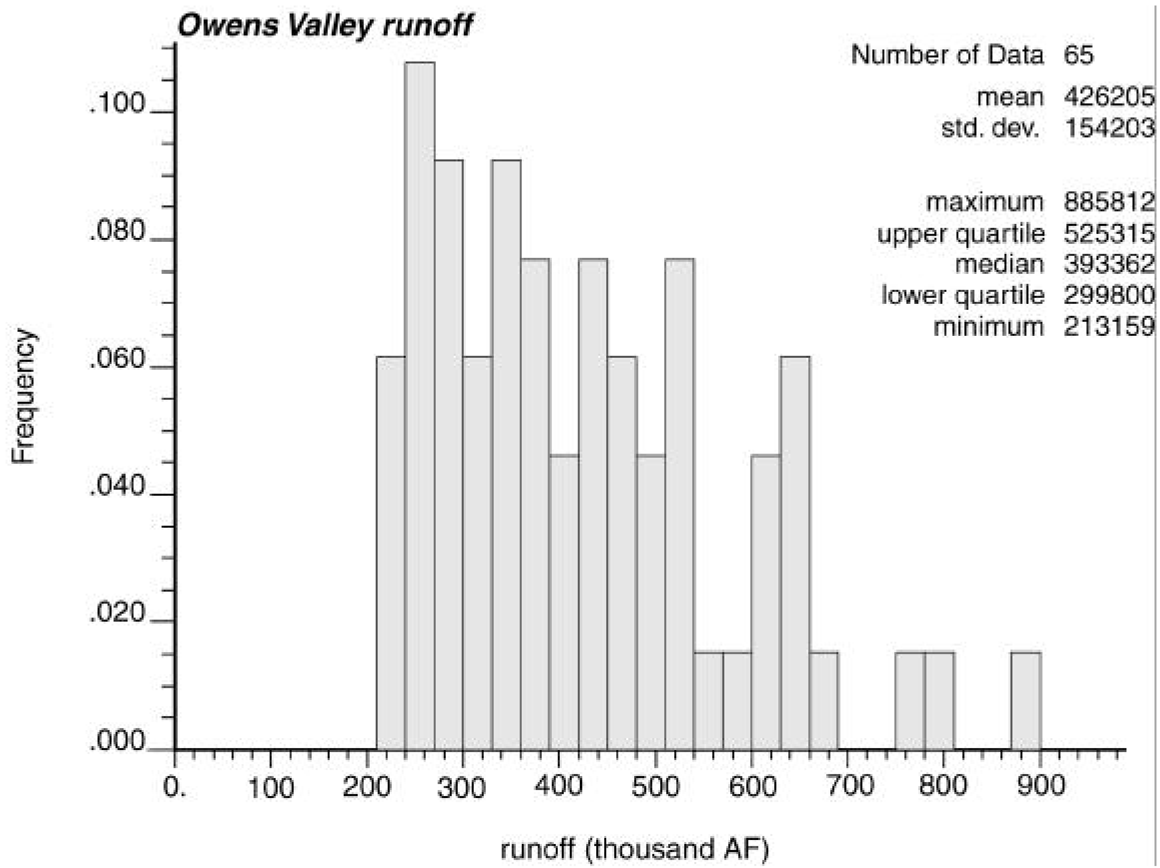

Figure 19. Histogram of Owens Valley runoff and lognormal distribution model parameters.

replacement from a lognormal distribution developed from the existing runoff record (Figure 19). For the Laws wells, the McNally canal diversion in 2002-03 was zero, and for 2004 and 2005 predictions, the McNally canal diversion was set at 22,500 ac-ft when Owens Valley runoff exceeded 596,687 ac-ft (140% of the mean of the lognormal runoff distribution). No canal releases were included in the model when Owens Valley runoff was lower than 140% of the mean. This was designed to approximate the frequency of canal operation LADWP suggested as likely to occur in the future (Inyo County Notice of Dispute, October 13, 2000, p. 18). It would be possible to model other scenarios to examine the effect of McNally operations on water levels in Laws, but that is beyond the scope of this report.

Model runs for several sites demonstrated nearly constant water levels for three years under average runoff and minimum pumping prompting a second set of deterministic simulations to estimate the water table depth under steady-state conditions of average runoff and minimum pumping. This depth should approximate the long-term average DTW for the most conservative management alternative and provide a basis to qualitatively assess other pumping alternatives. Pumping greater than the minimum or lower runoff would result in water levels lower than the depth at steady-state, and water levels higher than the steady-state depth would only be attained if pumping were minimized and runoff were greater than average. Deterministic simulations were performed for each monitoring site except those in Laws. The Laws models were not tested because they rely on a subjective rule to govern recharge diversions. Initial conditions and range in pumping were the same as for the probabilistic simulations, but succeeding years were simulated with fixed minimal pumping and mean runoff (426,205 ac-ft/year). Beginning DTW each year of the simulation relied on the previous year's predicted h_{ind}, and the models were allowed to run until the predicted h_{ms} changed less than 0.2 ft across the range of initial pumping (i.e. starting depths for recovery) and between years.

Reliance on two regression models and simulated runoff conditions in multi-year predictions potentially could produce large prediction error. It was necessary, therefore, to develop methods to quantify modeling error. The bootstrap method described by Harrington (2001) was used because it provided similar estimates of prediction uncertainty for the regression models as analytical methods and was convenient to incorporate into the Monte Carlo simulations. Uncertainty in the predictions arising from fitted regression coefficients was tabulated by resampling the independent variables from the original dataset and recomputing the regression coefficients from the new data set during each iteration. Model error was accounted for by perturbing the result of the indicator well and indicator/monitoring site models by randomly selecting a value from a normal distribution with zero mean and standard deviation equal to the model standard error (e_{ind} and e_{ms} in Eqs. 1 and 2). Modeling error in 2004 and 2005 predictions was lumped with the variability introduced by randomly selecting R.

RESULTS

DTW Target Depths

The DTW when groundwater began to enter the root zone at permanent monitoring sites and the target depths used for this analysis are given in Table 1. At sites where the test well was in close proximity to the monitoring site, the DTW lower limit was usually 1.0 to 1.8 meters below the root zone, narrowing the subjective selection for a DTW target.

As described above, target selection was not straightforward, and no single method is likely to provide satisfactory results for all sites. Sensitivity analysis is a commonly applied technique to guide selecting a value for poorly understood parameters contained in models. In this example, however, the sensitivity of the recovery probability to the target elevation could not shed light on how precisely the target must be known because the sensitivity depended largely on the initial conditions. For example, if the recovery probability was small because the mean predicted h_{ms} was far below the target, the model was insensitive to raising the target elevation, suggesting it would not need to be precisely known. For the same situation, however, the model result may be sensitive to lowering the target elevation providing the opposite conclusion. The closer the predicted h_{ms} to the target, the more sensitive the probability value would be to altering the target. Because the initial conditions affect h_{ms} and probability of recovery, conclusions from a sensitivity analysis of target elevation are only true for a specific set of conditions and would be of little use to refine targets derived based on management.

Table 4. Indicator well and indicator well/monitoring site well regression coefficients determined using standard regression techniques and by the Monte Carlo simulation. n is number of data points in the regression model.

			Indicator well coefficients						Indicator well/monitoring site coefficients			
Mon. site well	Ind. well	Source	Runoff or McNally div.	pumping	initial head	intercept	r^2	n	Indicator well head	intercept	r^2	n
LW1, T795	T493	MC	0.0004132	-0.0003566	0.63627	1493.74			0.688383	1286.281		
		Std Reg.	0.0004077	-0.0003514	0.63673	1491.84	0.95	25	0.709494	1199.726	0.86	9
LW2, V001g	T436	MC	0.0001427	-0.0001401	0.57022	1760.60			2.315967	-5389.54		
		Std Reg.	0.0001401	-0.0001378	0.56609	1798.94	0.94	23	2.260477	-5162.14	0.91	8
LW3, T574	T490	MC	0.0001275	-0.0000548	0.74700	1027.10			0.871082	533.5778		
		Std Reg.	0.0001275	-0.0000524	0.74104	1051.28	0.94	26	0.871772	530.7624	0.86	10
BP1, T798	T572	MC	0.0000120	-0.0002097	0.46629	2098.82			0.748305	995.7192		
		Std Reg.	0.0000118	-0.0001993	0.44770	2171.64	0.86	14	0.740869	1024.908	0.96	10
BP2, T799	T469	MC	0.0000035	-0.0001054	0.68771	1219.94			1.051069	-214.749		
		Std Reg.	0.0000036	-0.0001054	0.68276	1239.18	0.96	24	1.039501	-169.596	0.94	13
BP3, T567	T425	MC	0.0000093	-0.0001473	0.79935	774.65			1.053074	-196.078		
		Std Reg.	0.0000093	-0.0001412	0.80136	766.75	0.97	27	1.051924	-191.661	0.96	17
BP4, T800	T425	MC	0.0000093	-0.0001468	0.80029	771.01			0.90201	375.0943		
		Std Reg.	0.0000093	-0.0001412	0.80136	766.75	0.97	27	0.904041	367.2593	0.98	13
TA3, T505		MC	0.0000065	-0.0002274	0.75556	931.69						
		Std Reg.	0.0000098	-0.0002263	0.71166	1097.19	0.90	22				
TA4, T586	T419	MC	0.0000091	-0.0002419	0.71470	1090.05			0.773978	864.6296		
		Std Reg.	0.0000091	-0.0002480	0.71614	1084.58	0.98	21	0.771665	873.4776	0.99	16
TA5, T801	T502	MC	0.0000060	-0.0001079	0.60418	1516.51			0.469968	2025.901		
		Std Reg.	0.0000059	-0.0001104	0.59325	1558.44	0.89	19	0.477711	1996.224	0.80	10
TA6, T803	T417	MC	0.0000102	-0.0002034	0.70556	1120.05			0.944462	211.4591		
		Std Reg.	0.0000098	-0.0002263	0.71166	1097.19	0.90	22	0.936328	242.4614	0.99	13
TS2, T806	T413	MC	0.0000065	-0.0001118	0.84691	584.66			0.834674	618.0111		
		Std Reg.	0.0000064	-0.0001302	0.83674	623.88	0.87	27	0.820306	672.9426	0.85	13
IO1, T809	T412	MC	0.0000070	-0.0000601	0.45891	2058.26			2.395609	-5295.53		
		Std Reg.	0.0000072	-0.0000559	0.44114	2125.84	0.80	25	2.241346	-4708.29	0.67	12
SS1, V009g	T447	MC	0.0000116	-0.0007000	0.84737	580.55			0.873705	477.3064		
		Std Reg.	0.0000120	-0.0007279	0.84339	595.63	0.96	20	0.87226	482.7974	0.99	17
SS2, T646	T447	MC	0.0000100	-0.0007353	0.85944	535.51			0.868024	501.0986		
		Std Reg.	0.0000120	-0.0007279	0.84339	595.63	0.96	20	0.859576	533.3608	0.90	7
SS4, T811	T401	MC	0.0000098	-0.0005016	0.56442	1662.45			0.971337	106.4659		
		Std Reg.	0.0000099	-0.0004911	0.56870	1646.07	0.86	24	0.970107	111.1634	1.00	13
BG2, T812	V097	MC	0.0000097	-0.0026511	0.29021	2704.68			1.136696	-525.043		
		Std Reg.	0.0000100	-0.0025853	0.29701	2678.63	0.87	29	1.132367	-508.533	1.00	13

goals and vegetation requirements. Further target refinement should be based on vegetation response to water table depths

Simulated Water Table Fluctuations

Model performance

Regression coefficients and diagnostics for the indicator wells and the paired monitoring site/indicator wells are given in Table 4. The indicator wells were chosen based on their predictive capability, and the updated versions used here still met the selection criteria. With few exceptions, the degree of correlation between the indicator wells and monitoring site wells was high suggesting that these models also would be excellent relationships to rely upon. The mean regression coefficients resulting from the Monte Carlo simulation closely matched the coefficients derived using standard regression techniques for both sets of models (Table 4). The Monte Carlo h_{ms} predictions, therefore, should reproduce predictions produced by deterministic model simulations as is more commonly done. For TS1, IO2, TS3, and SS3 no adequately correlated indicator well was identified, and the regressions for indicator well monitoring site pairs at IO1 and TA5 were rather poor. An indicator well regression for site TS4 could be prepared, but this location may not be strongly affected by pumping other than from exempt fish hatchery wells. The lack of an adequate relationship for some sites due to inadequate monitoring site placement, pumping well linkage, or test well record remains a problem to be solved.

The average standard deviation in the mean h_{ms} each year is given in Table 5. In most cases the prediction error was acceptable and increased slightly for longer simulation periods. TA3 and IO1 may be exceptions where the relatively large prediction error (in 2005) suggests the models should be used cautiously. The large prediction error at LW1, LW2, and BG2 reflects the history of large fluctuations in the water table at these sites (Figures 1 and 2). At seven sites, the error in the 2003 predictions increased as the amount of 2002-03 pumping increased (Figures 20-36). This reflects increasing contribution from the error in the pumping coefficient in the indicator well model as pumping increased. The average in Table 5 included results for all pumping values, but for the seven sites, the prediction error increased with increasing pumping.

Monte Carlo simulations

The results of the Monte Carlo simulations are presented in Figures 37-53. The top graph in each figure shows the probability that the final water table elevation in the monitoring site well (h_{ms}) exceeded the target elevation, and the bottom graph shows the mean predicted h_{ms}. Only sites SS1 and BG2 had April 2002 water levels above the target depth; at all other sites, the initial water level was below the target depth. Initial water levels below the target and the relatively low runoff forecast in 2002 reduced the probability that even the lowest pumping levels in the first year would produce water levels above the target in April 2003. As expected, for all monitoring sites, as first-year pumping increases, the probability decreases that the water level will be above the target in subsequent years. For all sites, the probability of reaching the target after minimal

Table 5. Average standard deviation in mean predicted h_{ms} for each year of the simulation and all initial pumping amounts.

	h_{ms} Mean standard deviation (ft)		
Year	2003	2004	2005
Monitoring site			
LW1	3.16^	4.13	4.51
LW2	2.95^	4.11	4.53
LW3	1.33	1.73	1.95
BP1	2.25^	2.83	3.30
BP2	1.14	1.03	0.76
BP3	1.23	2.07	2.46
BP4	0.86	1.66	2.02
TA3	3.30	4.47	5.25
TA4	1.09	1.74	2.02
TA5	0.87	1.1	1.21
TA6	3.33	4.45	5.1
TS2	2.03	2.49	2.81
IO1	4.37	5.42	5.66
SS1	2.31^	3.30	3.92
SS2	2.92^	3.61	4.18
SS4	3.00^	3.69	3.91
BG2	3.84^	4.34	4.37

^: Standard deviation of the predicted h_{ms} increases at higher pumping levels and decreases at lower pumping levels.

pumping in 2003-04 and 2004-05 increased, but at only four sites was the probability of attaining the target greater than 50%. A 50% probability of recovery occurs when the predicted h_{ms} is approximately equal to the target. Results for each wellfield are discussed in more detail below.

The three Laws sites each had less than 10% chance for recovery to the target values during the simulation period (Figures 37-39a). The low recovery probability almost certainly reflects the rule adopted to govern releases to the McNally canals. On average, recharge was negligible for the 2004 and 2005 predictions. The water level at LW3 was much less affected by pumping than at LW1 and LW2, and the probability of recovery to the target was lower demonstrating the greater importance of recharge relative to pumping in the LW3 model. The effect of the initial head variable can be seen in the predicted h_{ms} for LW1 and LW2 (Figures 37b and 38b). The predicted increase in water levels in April 2004 and 2005 is greater at higher levels of pumping (i.e. lower ho_{ind} for the 2004 and 2005 simulations) than at lower levels of pumping. Even though these are statistical and not physically-based models, this result may reflect that the recovery rate of a cone of depression is proportional to the gradients created by pumping. All monitoring sites exhibited this pattern to various degrees. Water levels were predicted to change little at all three sites after three years of pumping limited to 500 ac-ft/year (Figures 37-39b). This nearly steady-state condition when pumping and recharge from the McNally canals were small suggests that simply restricting pumping without

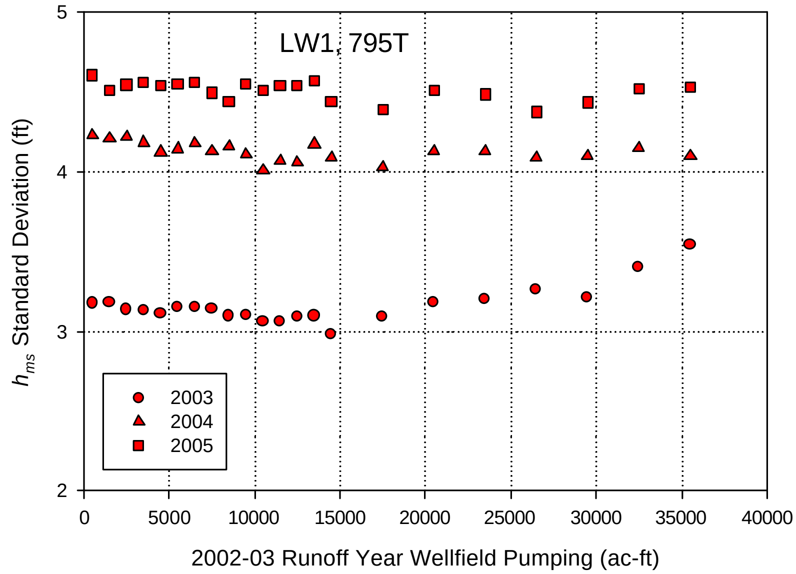

Figure 20. Standard deviation of the predicted h_{ms} at LW1, 795T, for each year as a function of pumping in runoff year 2002-2003.

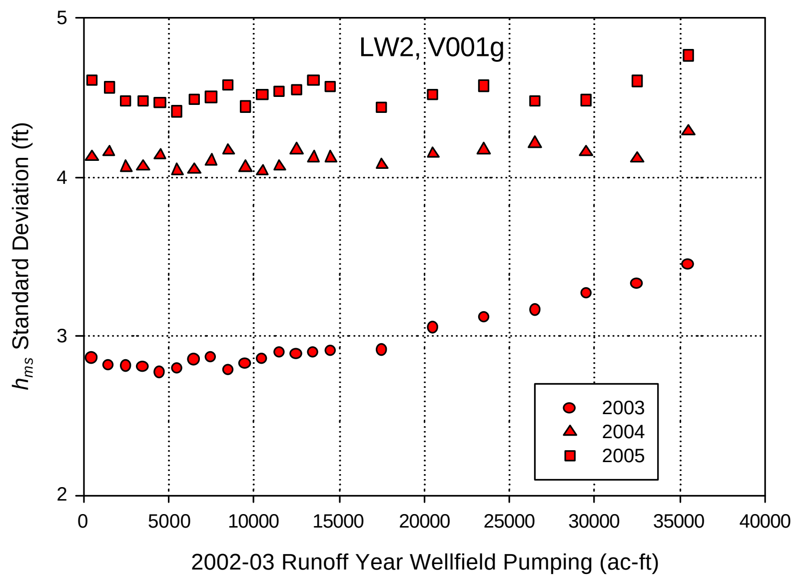

Figure 21. Standard deviation of the predicted h_{ms} at LW2, V001g, for each year as a function of pumping in runoff year 2002-2003.

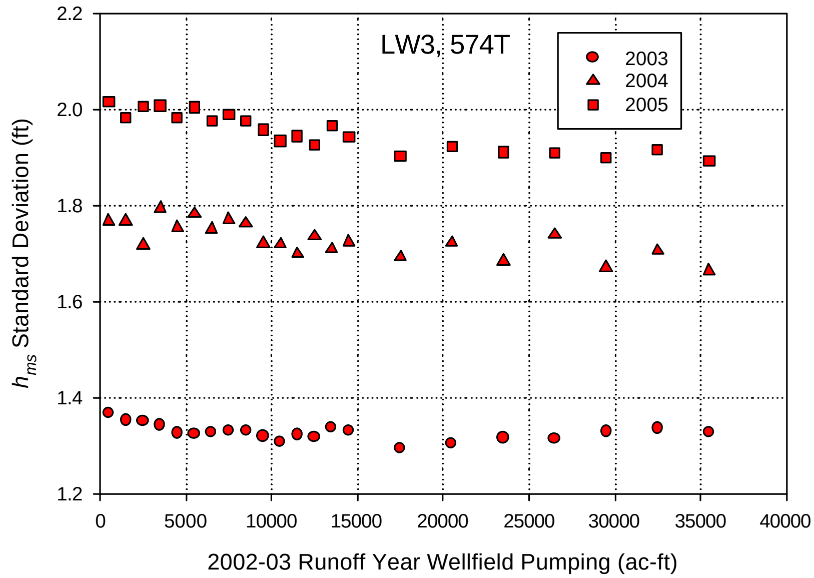

Figure 22. Standard deviation of the predicted h_{ms} at LW3, 574T, for each year as a function of pumping in runoff year 2002-2003.

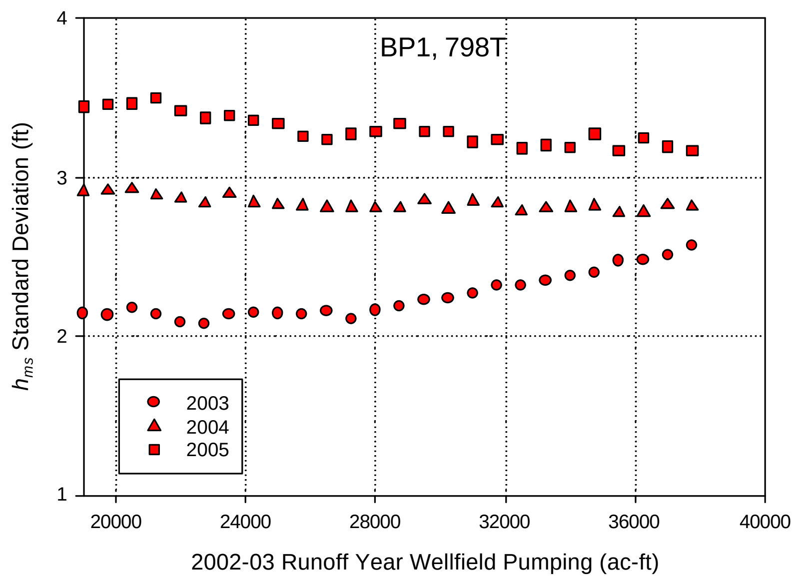

Figure 23. Standard deviation of the predicted h_{ms} at BP1, 798T, for each year as a function of pumping in runoff year 2002-2003.

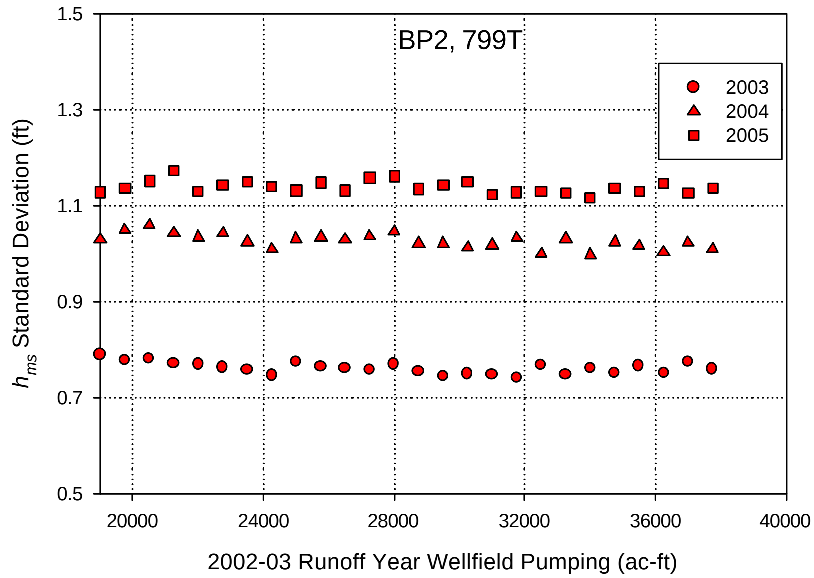

Figure 24. Standard deviation of the predicted h_{ms} at BP2, 799T, for each year as a function of pumping in runoff year 2002-2003.

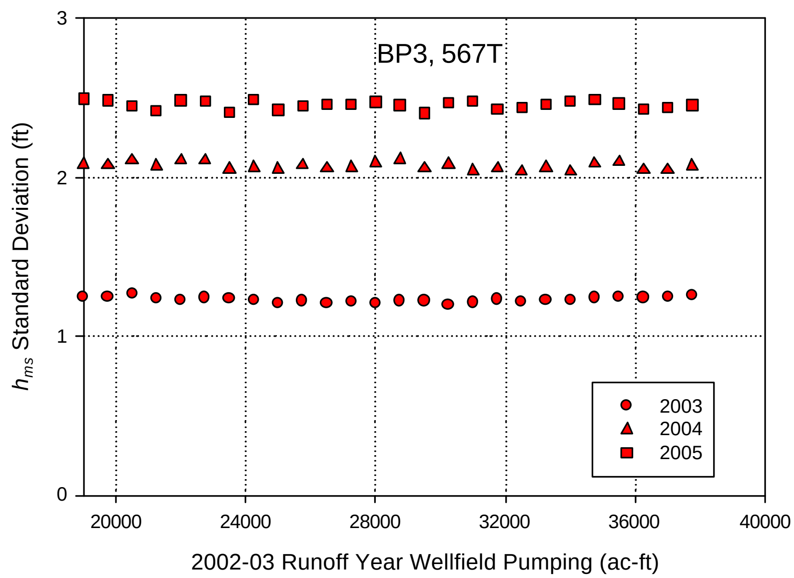

Figure 25. Standard deviation of the predicted h_{ms} at BP3, 567T, for each year as a function of pumping in runoff year 2002-2003.

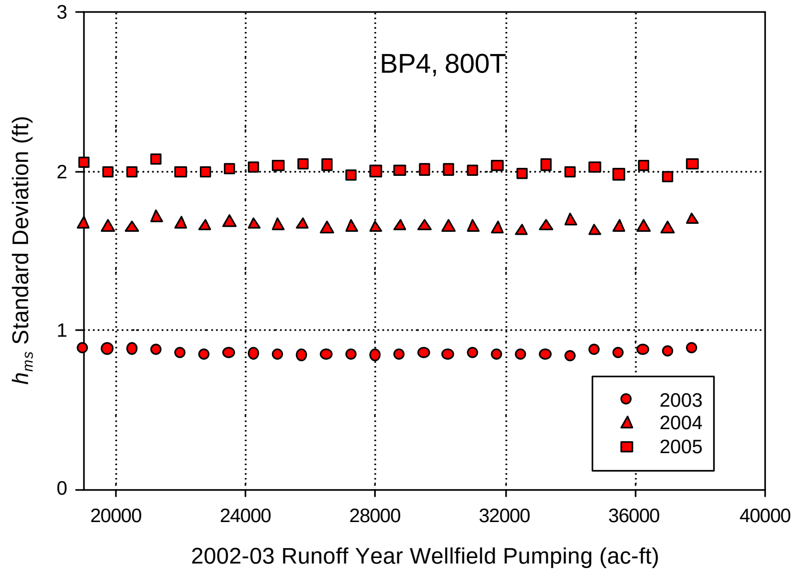

Figure 26. Standard deviation of the predicted h_{ms} at BP4, 800T, for each year as a function of pumping in runoff year 2002-2003.

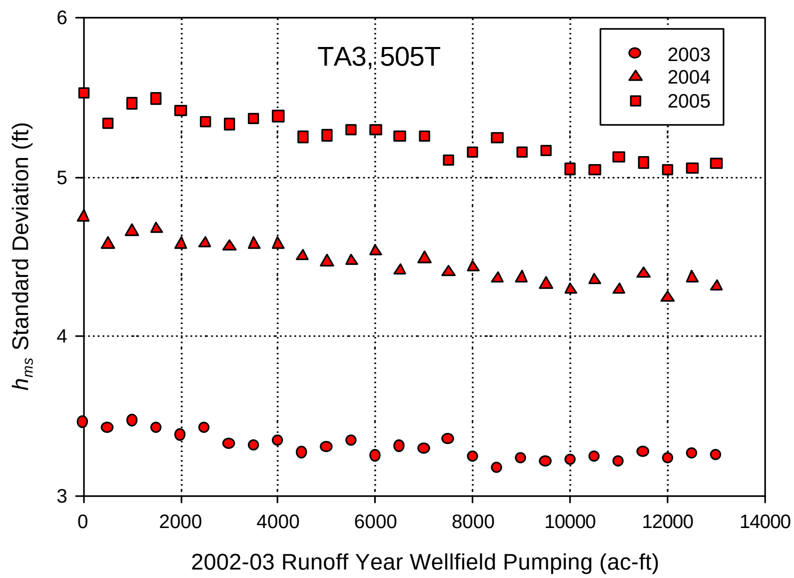

Figure 27. Standard deviation of the predicted h_{ms} at TA3, 505T, for each year as a function of pumping in runoff year 2002-2003.

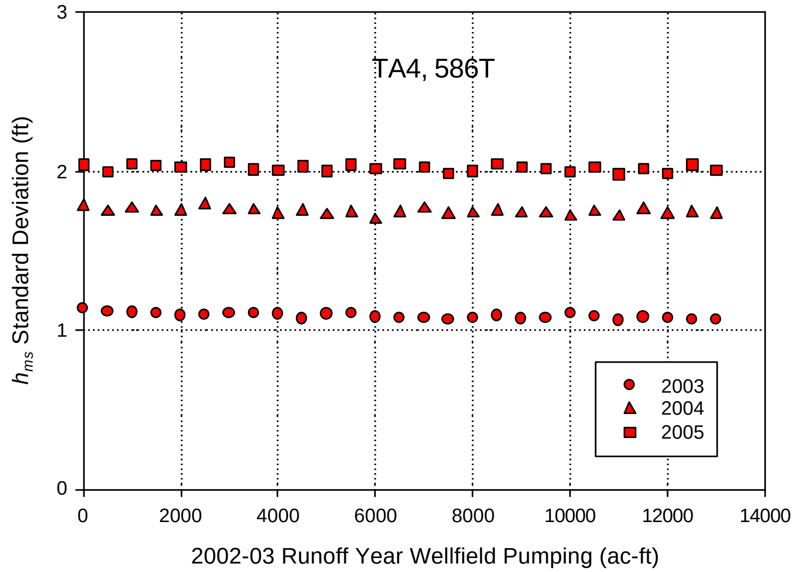

Figure 28. Standard deviation of the predicted h_{ms} at TA4, 586T, for each year as a function of pumping in runoff year 2002-2003.

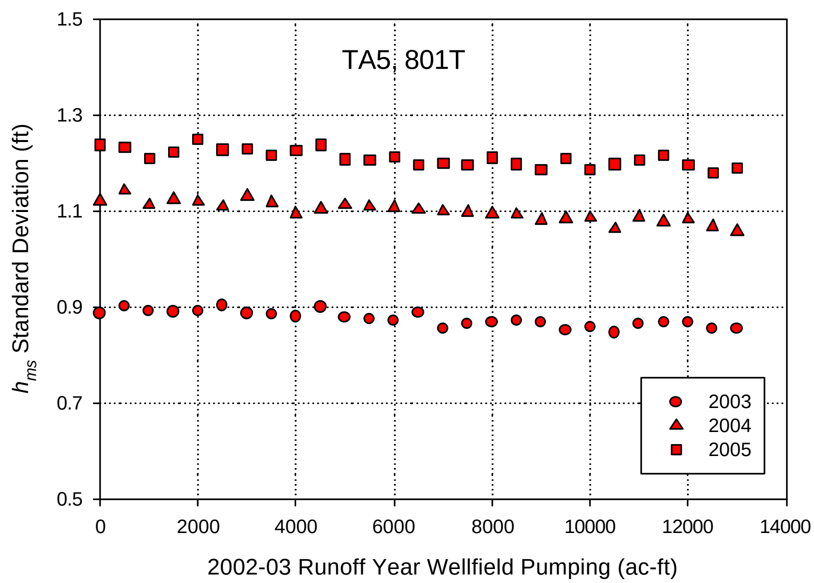

Figure 29. Standard deviation of the predicted h_{ms} at TA5, 801T, for each year as a function of pumping in runoff year 2002-2003.

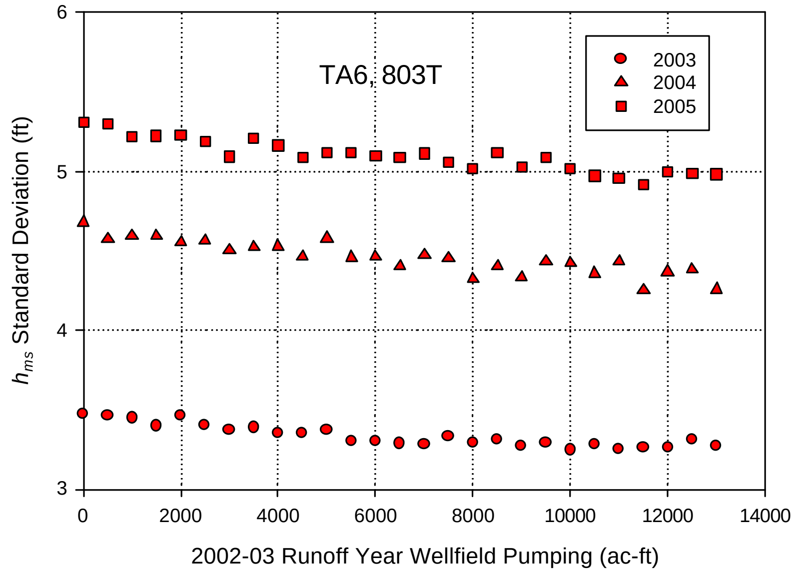

Figure 30. Standard deviation of the predicted h_{ms} at TA6, 803T, for each year as a function of pumping in runoff year 2002-2003.

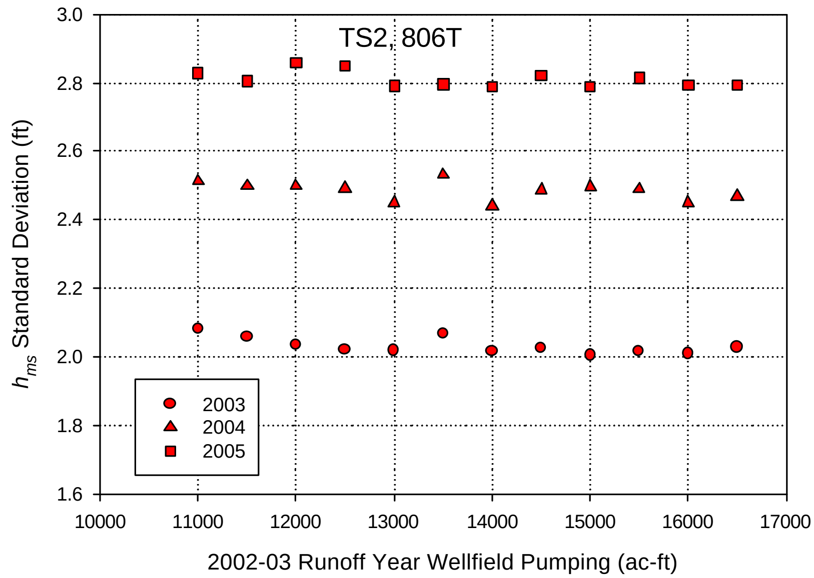

Figure 31. Standard deviation of the predicted h_{ms} at TS2, 806T, for each year as a function of pumping in runoff year 2002-2003.

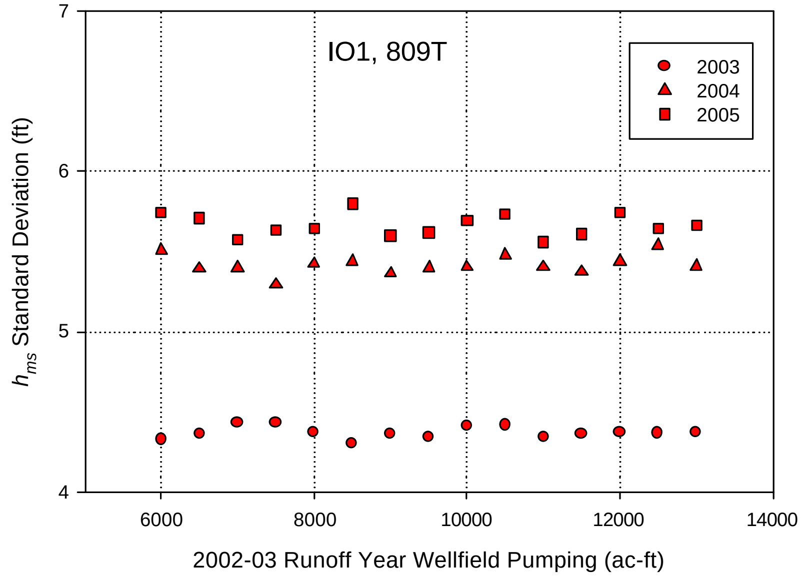

Figure 32. Standard deviation of the predicted h_{ms} at IO1, 809T, for each year as a function of pumping in runoff year 2002-2003.

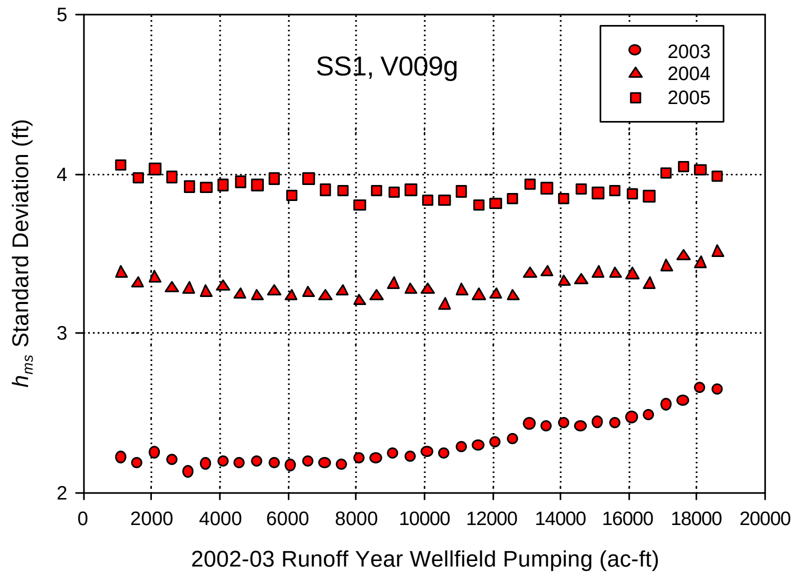

Figure 33. Standard deviation of the predicted h_{ms} at SS1, V009g, for each year as a function of pumping in runoff year 2002-2003.

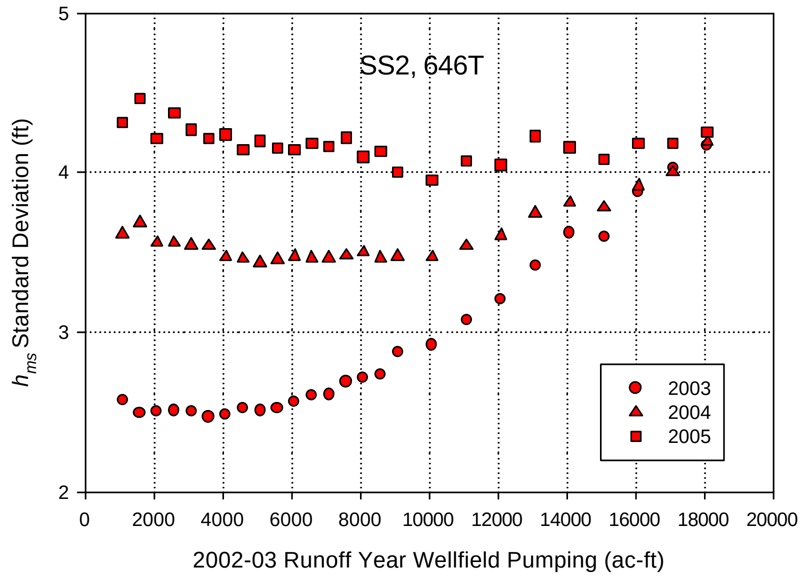

Figure 34. Standard deviation of the predicted h_{ms} at SS2, 646T, for each year as a function of pumping in runoff year 2002-2003.

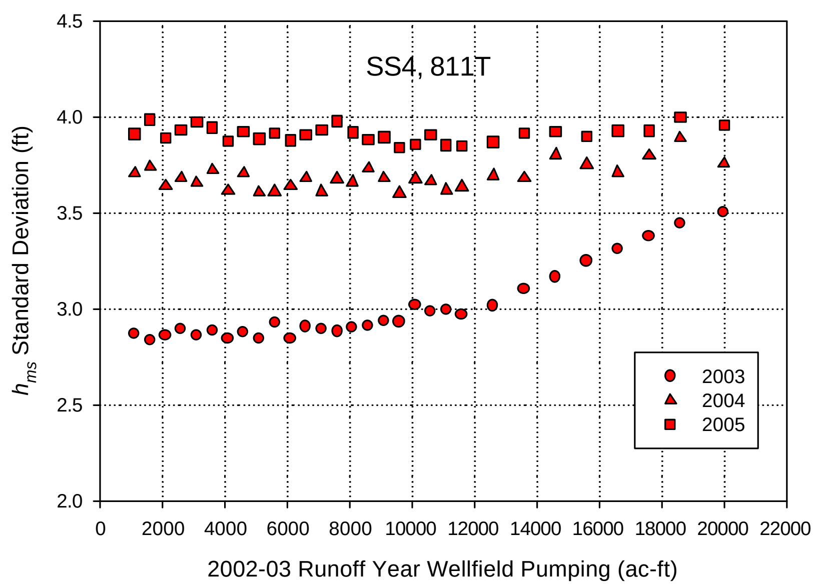

Figure 35. Standard deviation of the predicted h_{ms} at SS4, 811T, for each year as a function of pumping in runoff year 2002-2003.

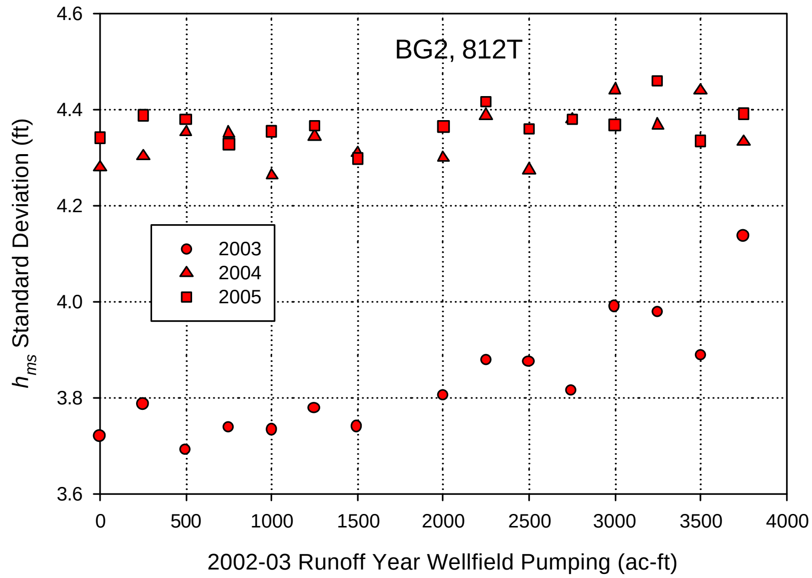

Figure 36. Standard deviation of the predicted h_{ms} at BG2, 812T, for each year as a function of pumping in runoff year 2002-2003.

greater Owens River diversions into the McNally canals than modeled here would be unlikely to produce water levels much above April, 2002 levels.

Like the Laws sites, BP1, BP2, and BP3 (Figures 40–42) had less than 10% chance of recovery to the target during the simulation period regardless of pumping in 2002-03. BP4, however, exhibited a larger probability of recovery (almost 45% in April 2005) because the initial water level was less than one foot below the target (Figure 43). The steady-state condition predicted for the combination of relatively large minimal pumping by exempt wells and average runoff for BP1, BP2, and BP3 were below the target confirming that the target will be attained only after multiple years of unusually high runoff (Table 6). Additionally, all the Big Pine models exhibited near steady-state conditions at minimum pumping levels for the short period simulated suggesting that exceeding the predicted 2003 water levels much would be achieved only with above normal runoff even if pumping were held at the minimum. Because attaining the targets or even depths much above predicted 2003 levels seems strongly dependent on above-normal runoff, we performed a deterministic model run using higher than normal runoff (130% of the mean) in 2004 and 2005 at BP3 (Figure 42b). Even after two years of favorable runoff conditions, the target was not attained regardless of the pumping conducted in the first year. The large exempt well pumping capacity in Big Pine, therefore, will hinder efforts to periodically raise the water table to the target levels at three of the monitoring sites.

Table 6. Steady state water table elevation after several years of normal runoff and minimal pumping. Model runs converged when h_{ms} changed by less than 0.2 ft. between years and across the range of pumping in 2002-03.

Site/test well	Target Elevation	Steady-state Elevation	Steady-state Depth to Water
	(ft amsl)	(ft amsl)	(m)
BP1, 798T	3943.78	3938.36	4.95
BP2, 799T	3890.86	3887.55	5.81
BP3, 567T	3874.80	3871.77	5.22
BP4, 800T	3859.3	3859.44	4.96
TA3, 505T	3820.84	3819.35	4.95
TA4, 586T	3828.56	3832.19**^**	1.19
TA5, 801T	3829.71	3829.23	4.05
TA6, 803T	3815.52	3818.60**^**	1.86
TS2, 806T	3815.58	3812.96	4.10
IO1, 809T	3834.06	3828.11	4.11
SS1, V009G	3808.8	3823.68**^**	-0.24 (above land surface)
SS2, 646T	3815.32	3825.66**^**	2.15
SS4, 811T	3823.14	3821.70	4.94
BG2, 812T	3811.30	3810.91	4.42

^: Steady-state elevation is outside the regression model data range.

The TA wellfield is not subjected to high minimal pumping or managed recharge, and the simulation results reflect this. The TA monitoring sites generally had much higher probability of recovery to the target levels than either Laws or Big Pine (Figures 44-47a). Also, water levels were predicted to increase at all sites if pumping were kept near the minimum, suggesting that water levels above 2002 could be achieved with minimum pumping and average runoff. Steady-state DTW was above the target depths for TA4 and TA6 (Figures 45 and 47b). It seems possible to attain the water table targets at TA4 and TA6 with consecutive years of near normal runoff if pumping were restricted, but not at TA3 or TA5 although the difference between the target and steady-state depth for these sites was small (Table 6).

TS2 was the single site modeled in the TS wellfield (Figure 48). Because of the high minimum pumping, the probability of recovery to the target was small (<15%), and the predicted h_{ms} increased little in years with minimal pumping. Interestingly, this site also demonstrated a weak response to pumping for the range of values simulated. This site will not decline much with one year of pumping greater than the minimum, but it also will not recover unless runoff were above normal (Table 6).

Results for IO1 closely resembled the results for TS2, probably because the Independence-Oak wellfield is also subjected to relatively high minimal pumping. IO1, however, had slightly quicker recovery under normal runoff conditions and minimal pumping than TS2 (Figure 49).

The monitoring sites in the SS wellfield exhibited the highest probability of recovery to the target, largely because the 2002 initial water levels were just below the target or even above (SS1) (Figures 50-52). The sensitivity of the models to pumping,

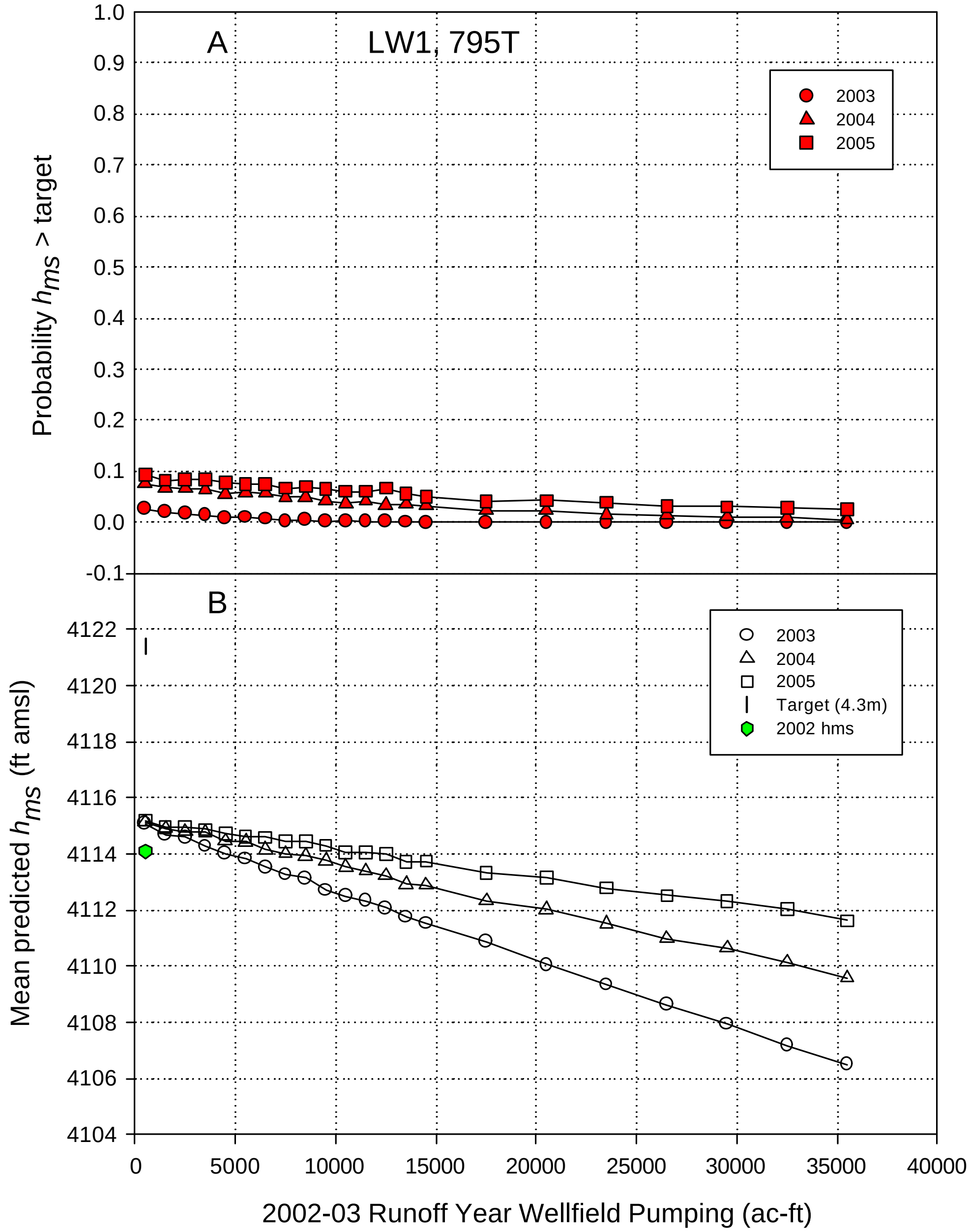

Figure 37. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at LW1, 795T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 500 ac-ft/year.

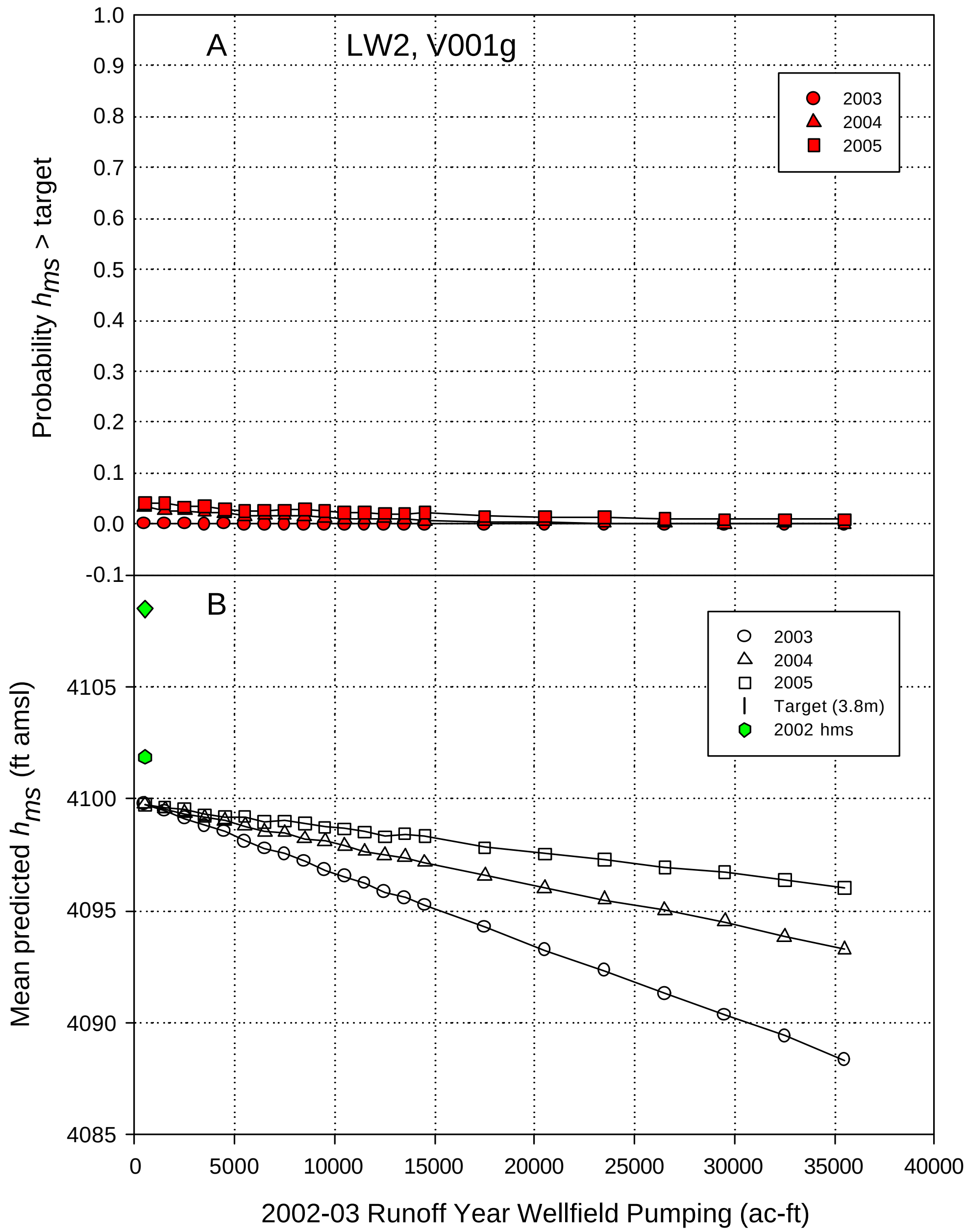

Figure 38. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at LW2, V001G, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 500 ac-ft/year.

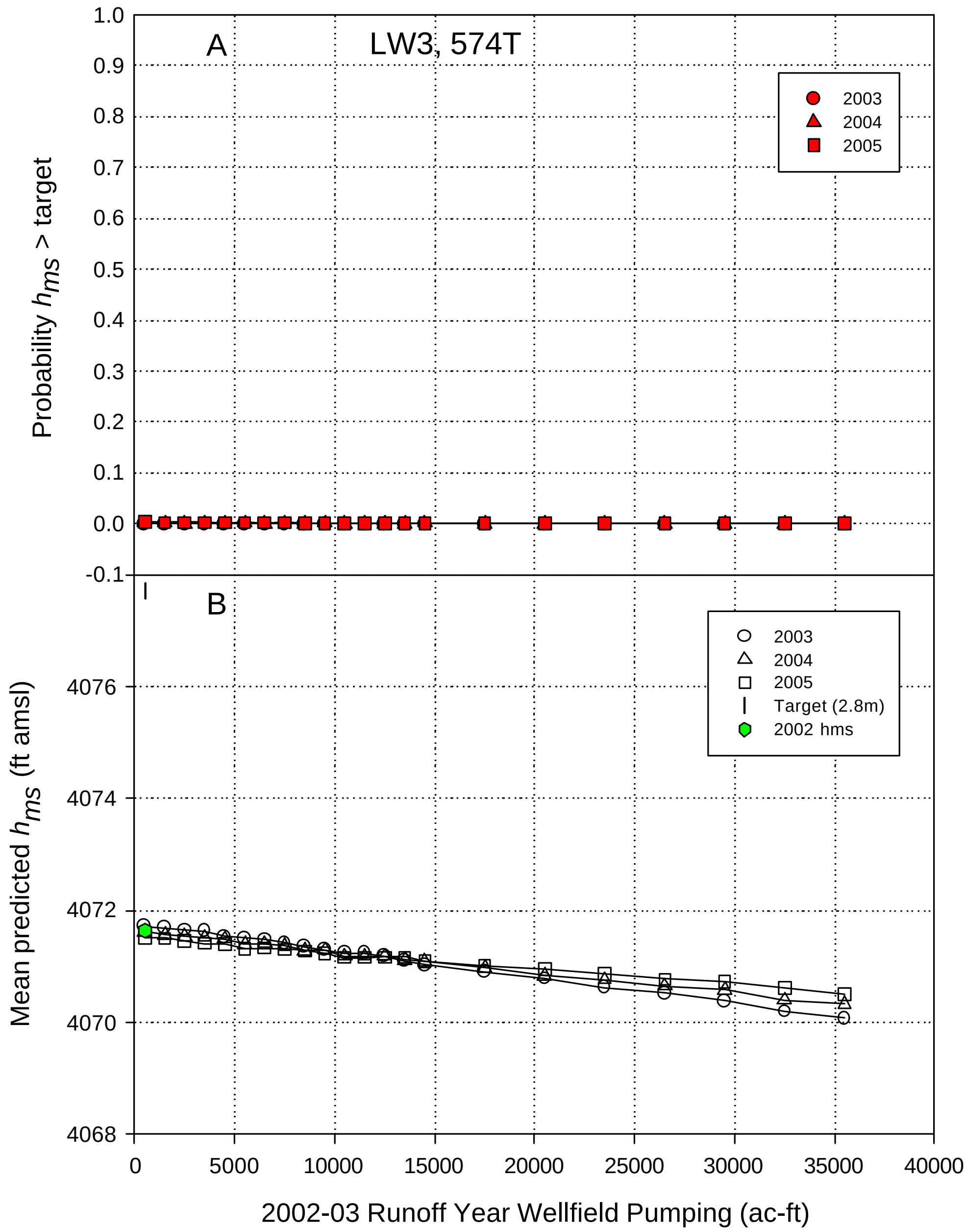

Figure 39. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at LW3, 574T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 500 ac-ft/year.

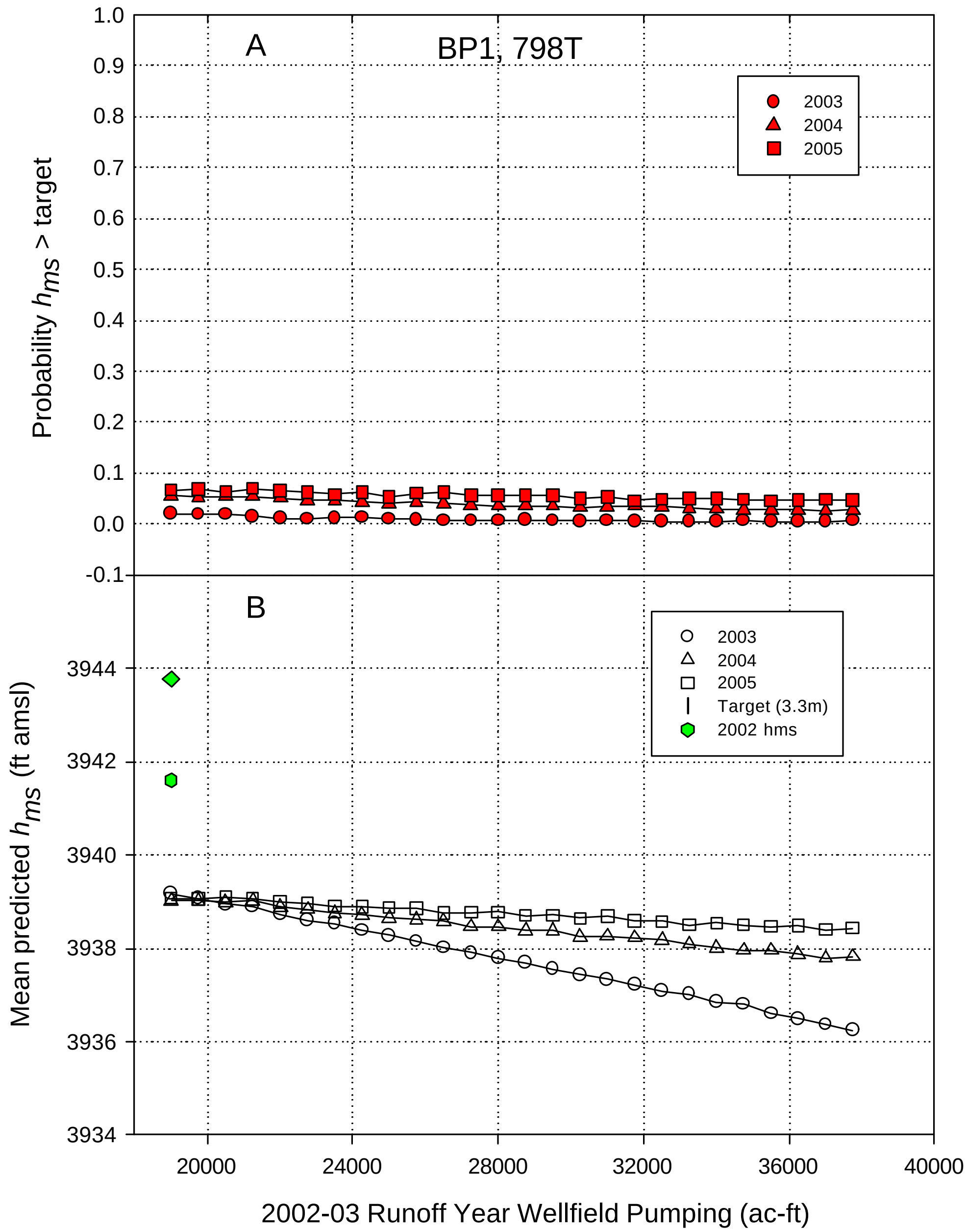

Figure 40. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at BP1, 798T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 24000 ac-ft/year.

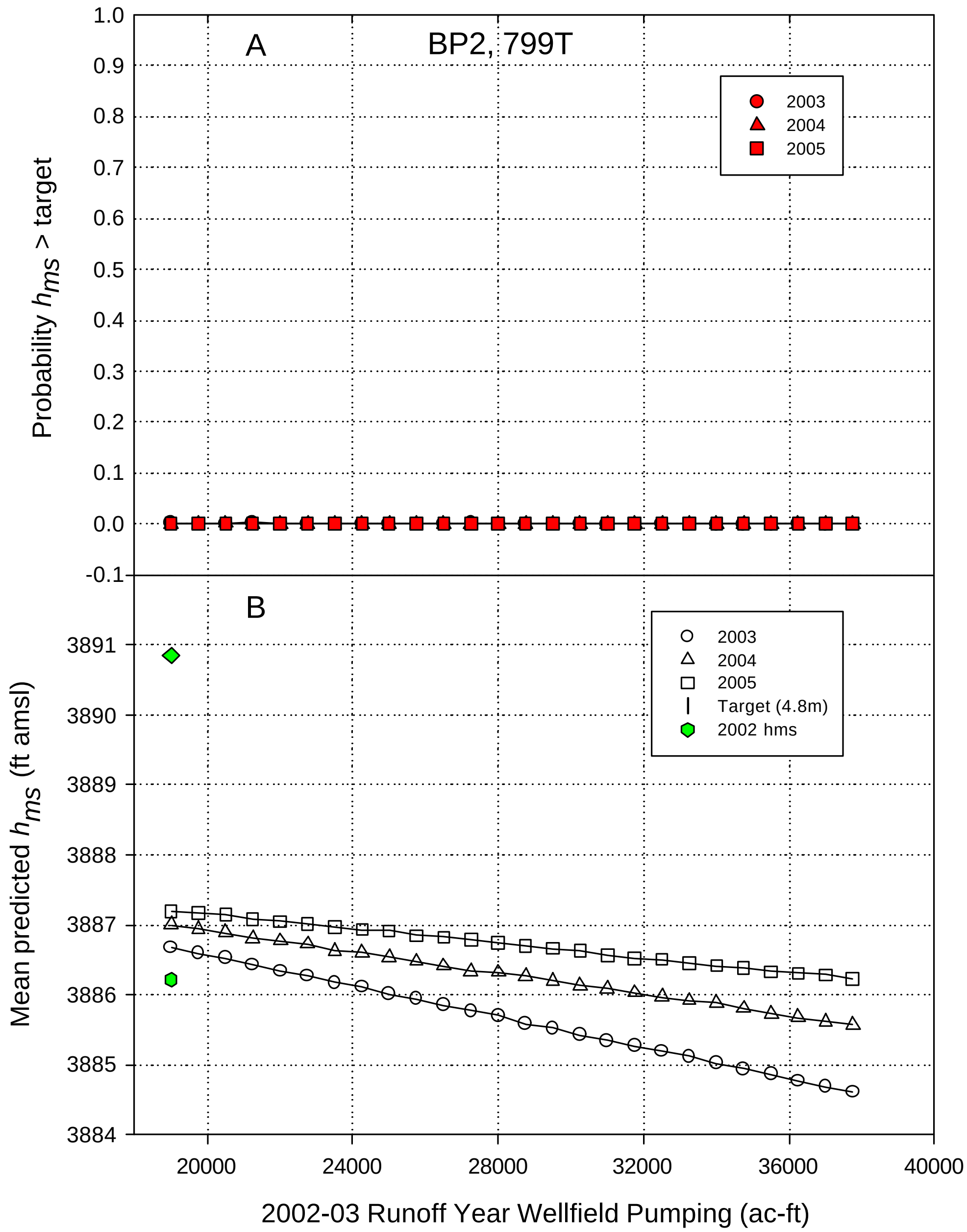

Figure 41. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at BP2, 799T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 24000 ac-ft/year.

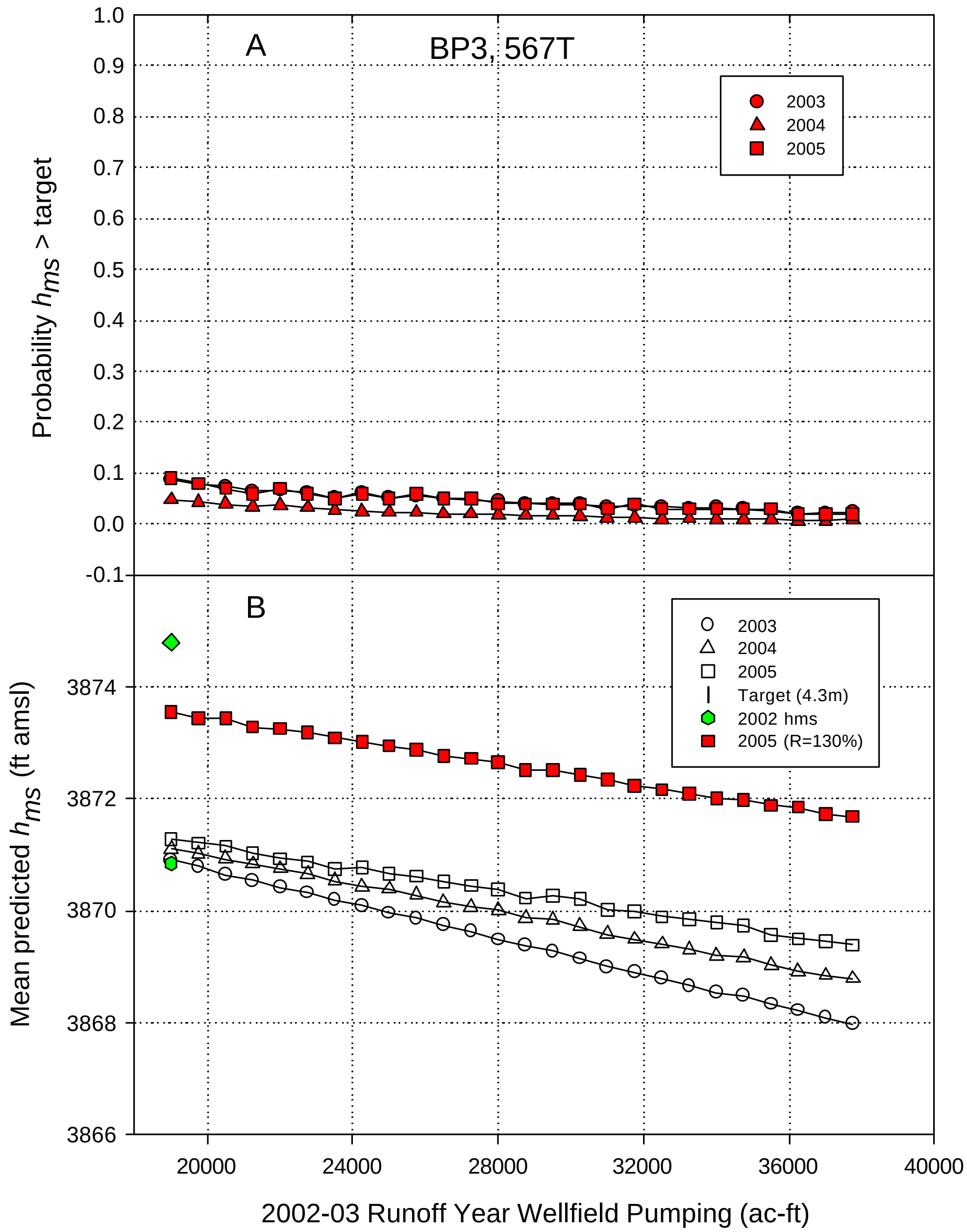

Figure 42. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at BP3, 567T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 24000 ac-ft/year. Results for 2005 with R fixed at 552767 ac-ft (130% of mean R) for two years are also shown

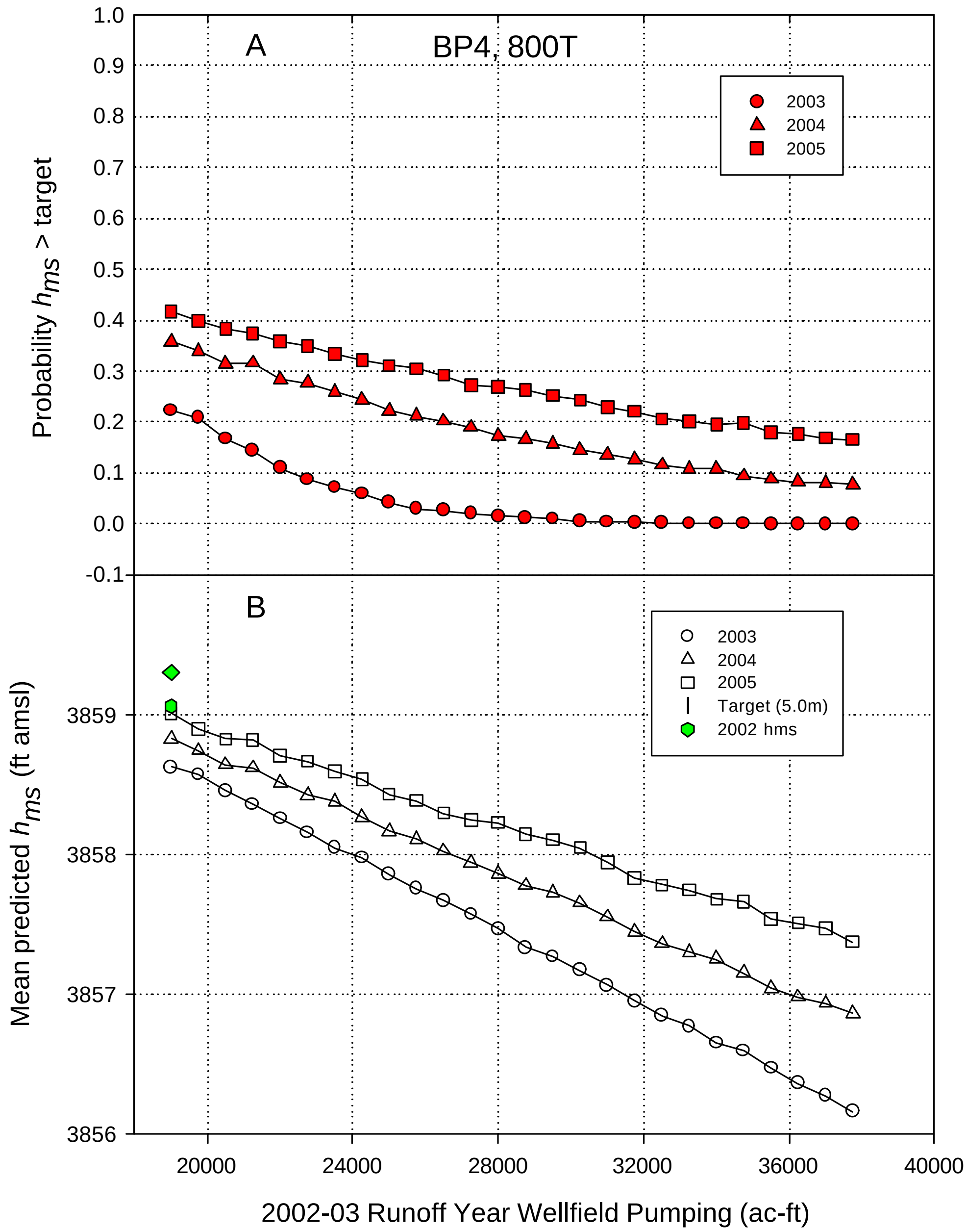

Figure 43. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at BP4, 800T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 24000 ac-ft/year.

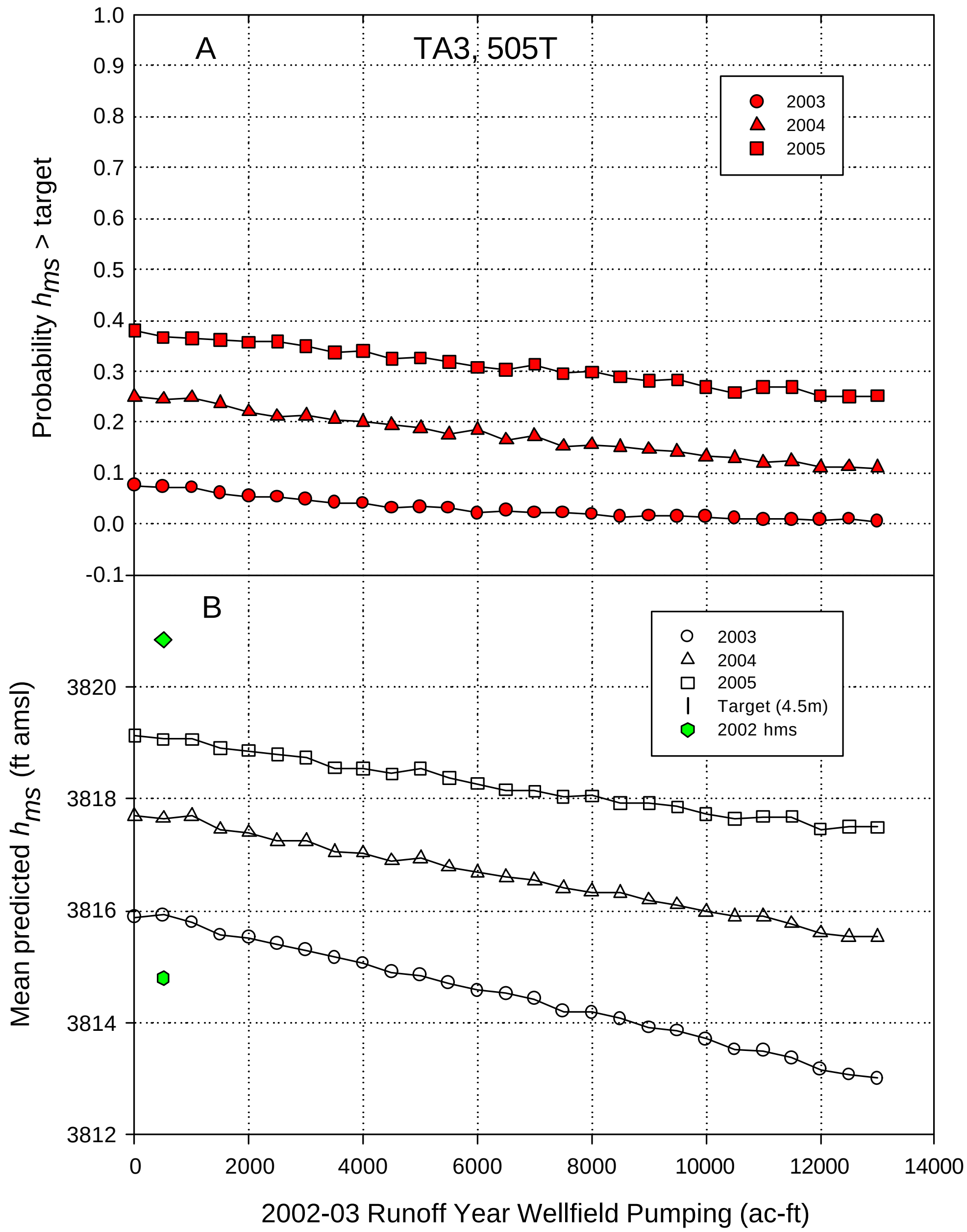

Figure 44. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at TA3, 505T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 0 ac-ft/year.

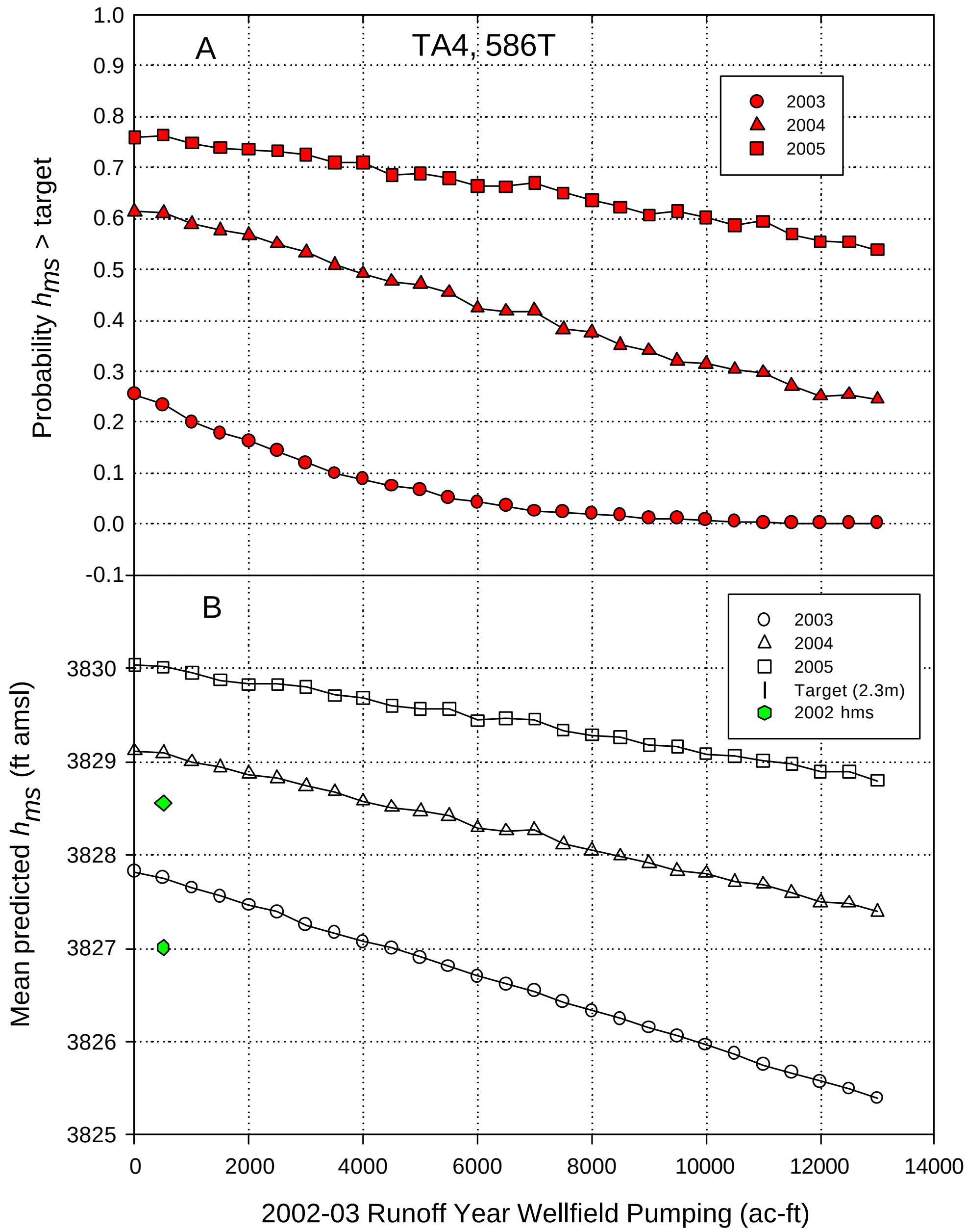

Figure 45. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at TA4, 586T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 0 ac-ft/year.

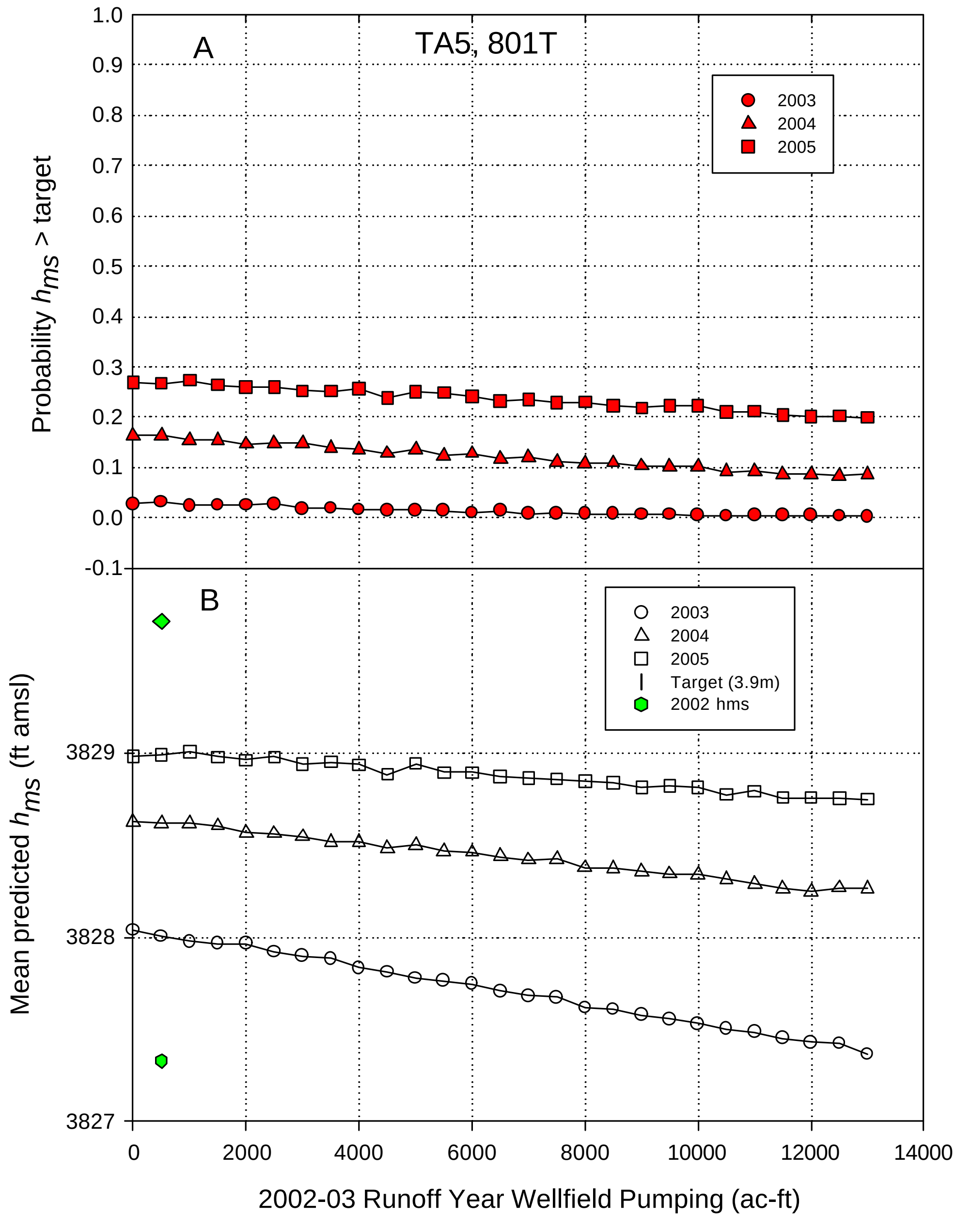

Figure 46. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at TA5, 801T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 0 ac-ft/year.

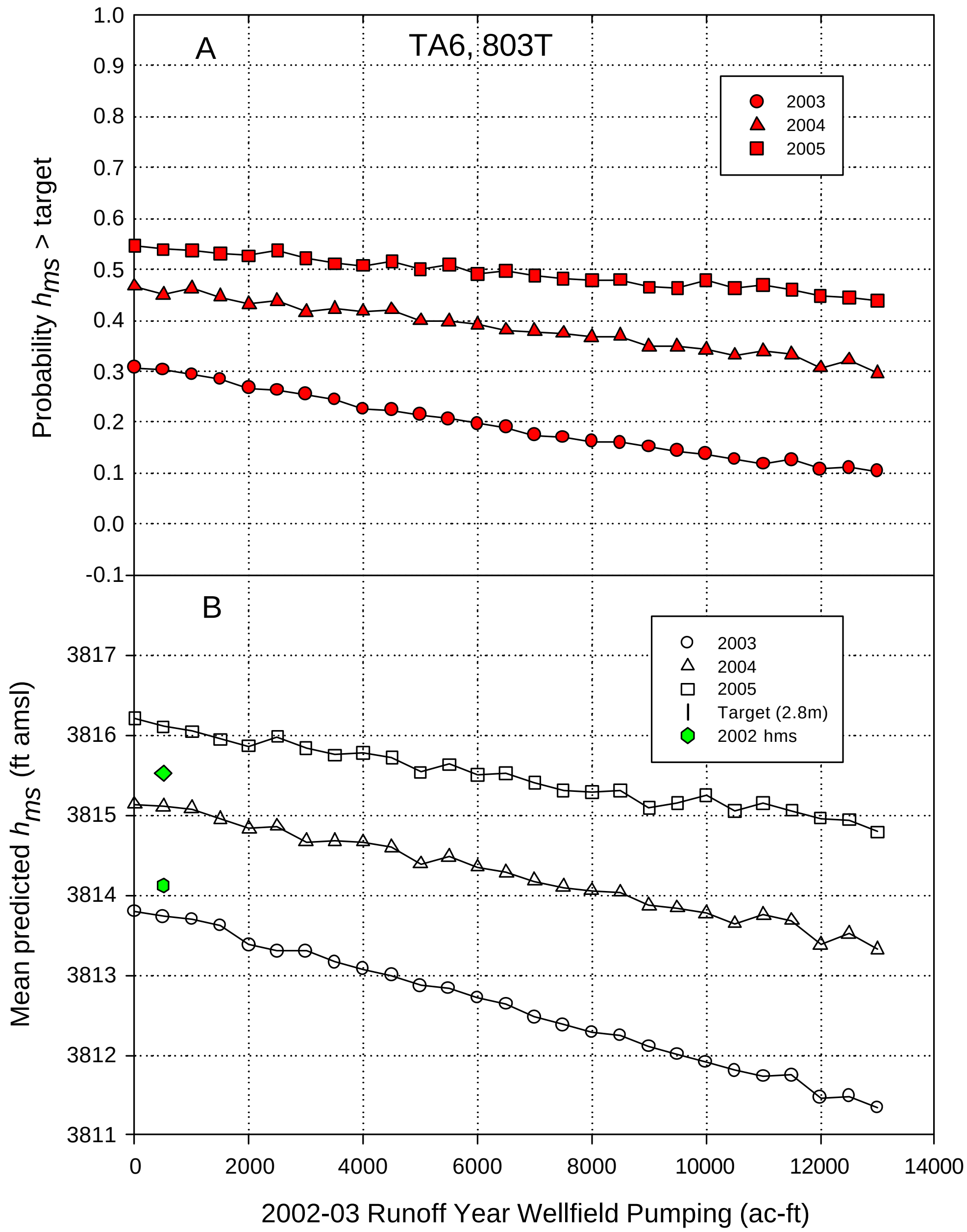

Figure 47. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at TA6, 803T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 0 ac-ft/year.

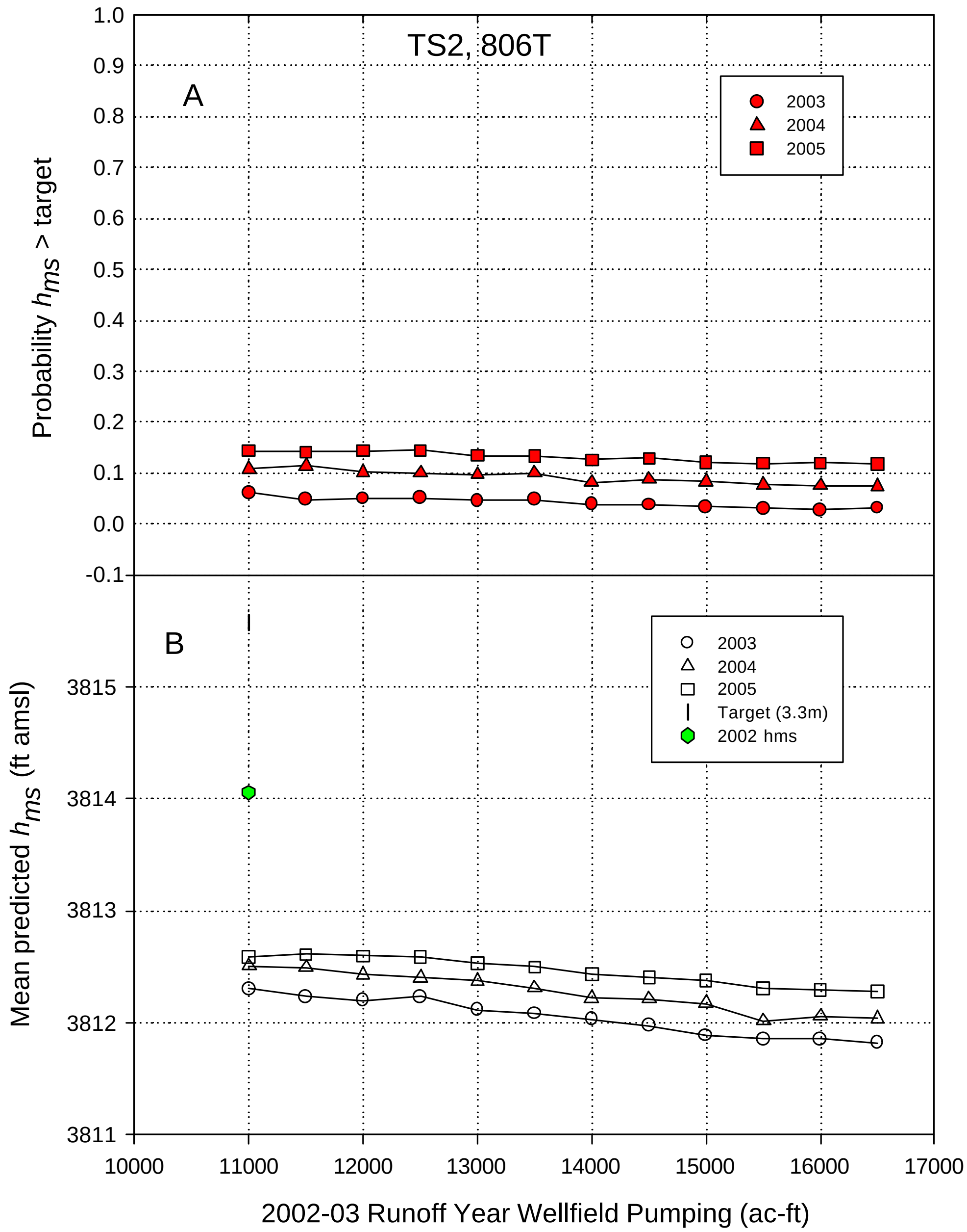

Figure 48. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at TS2, 806T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 12400 ac-ft/year.

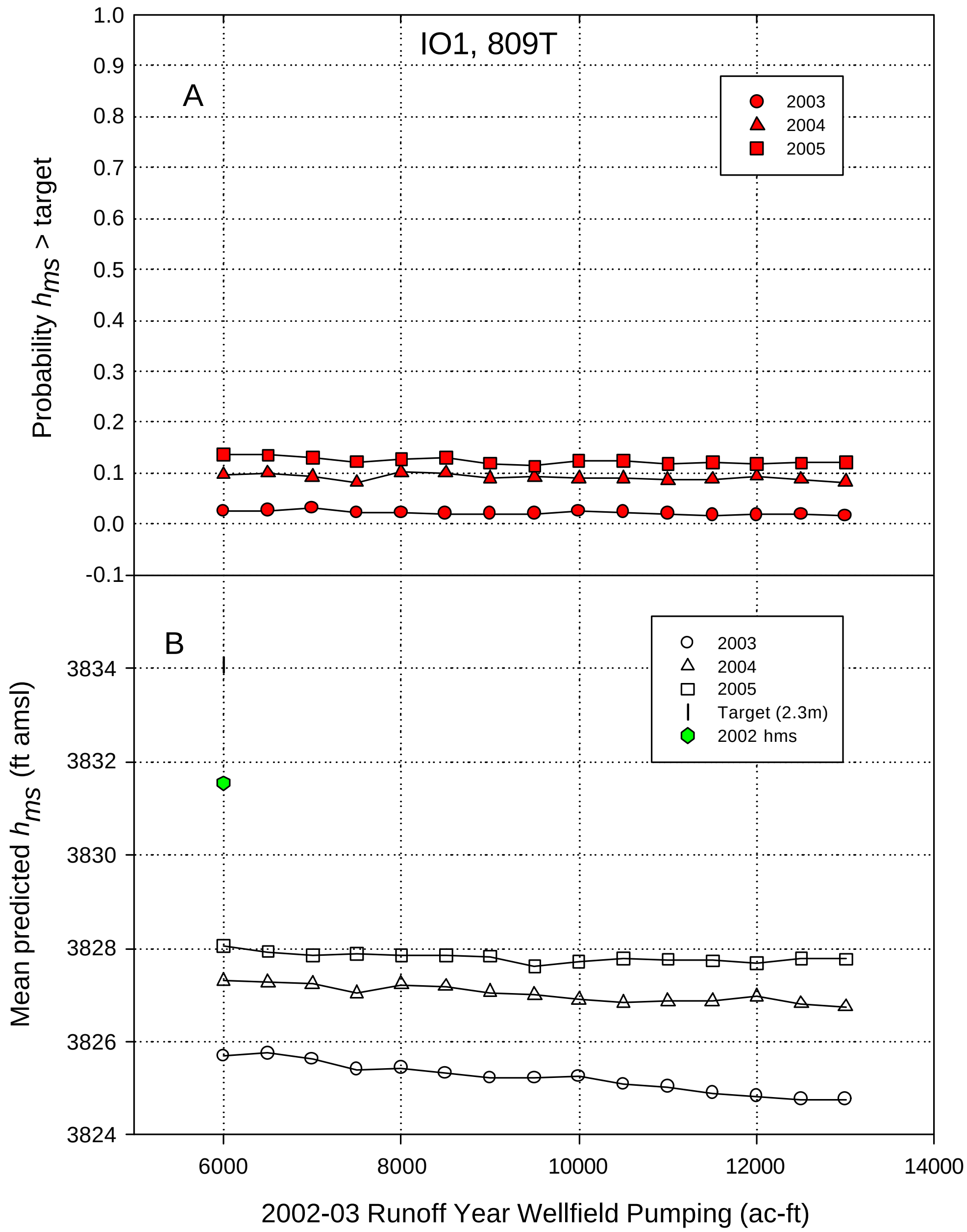

Figure 49. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at IO1, 809T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 7000 ac-ft/year.

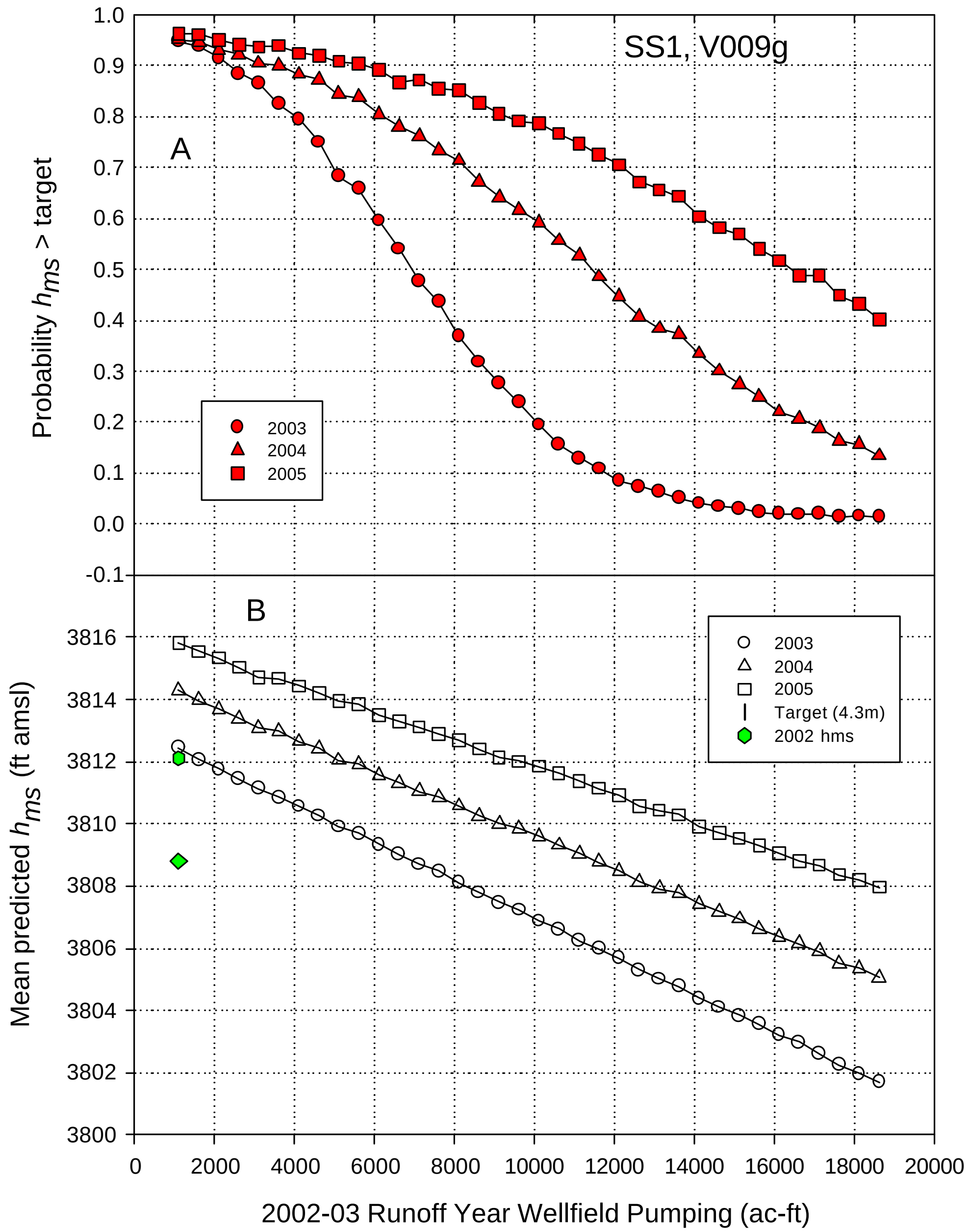

Figure 50. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at SS1, V009G, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 1200 ac-ft/year.

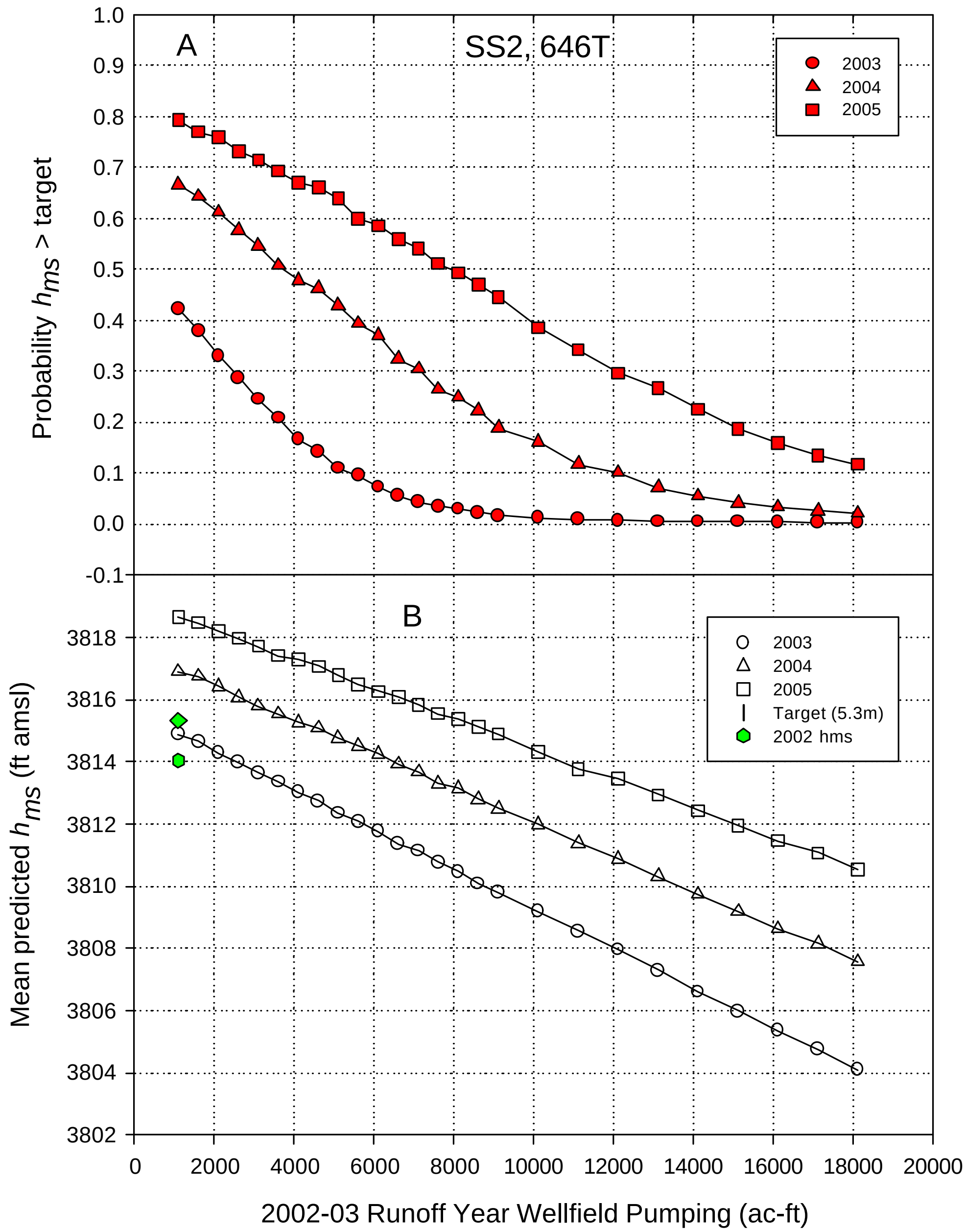

Figure 51. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at SS2, 646T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 1200 ac-ft/year.

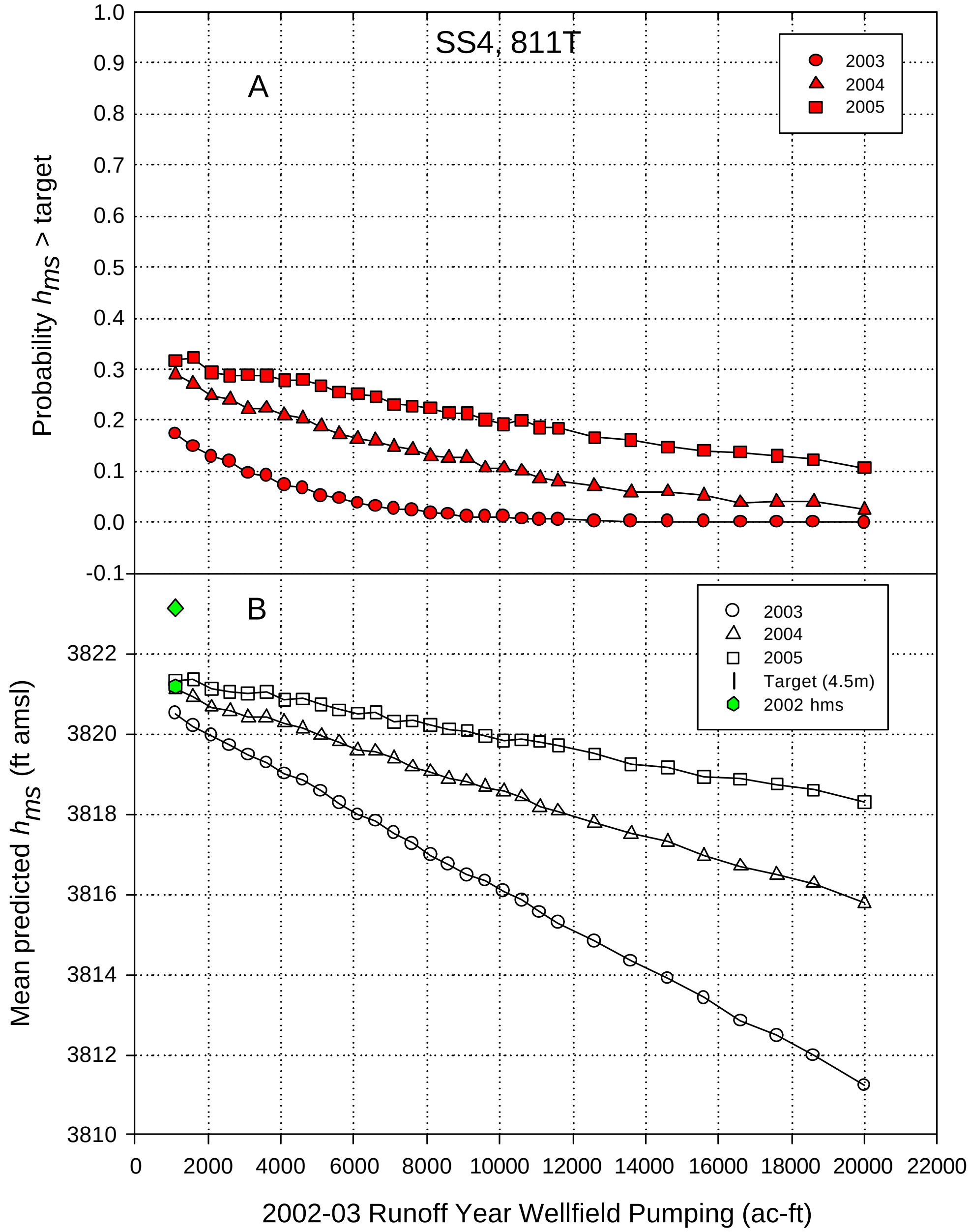

Figure 52. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at SS4, 811T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 1200 ac-ft/year.

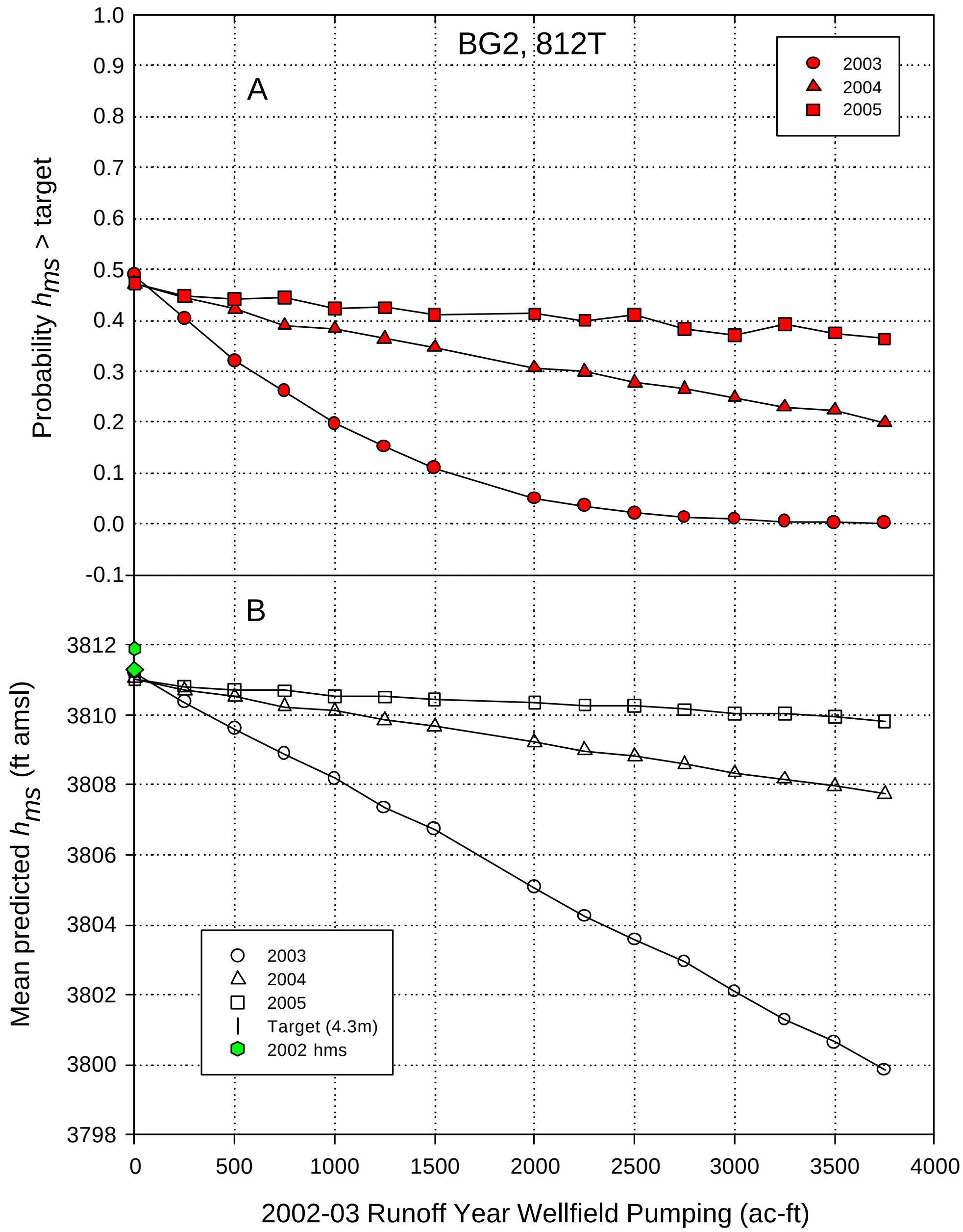

Figure 53. (a) The probability of predicted April water level at or above the target level and (b) mean predicted April water level at BG2, 812T, as a function of pumping in runoff year 2002-2003. Pumping in 2004 and 2005 was 500 ac-ft/year.

however, was apparent for all the sites, and the probability of water levels occurring above the target rapidly diminished as pumping in 2002 increased. Interestingly, the steady-state elevation for SS1 is above the soil surface. This isn't a physically unrealistic result because the test well (V009G) is located near a former spring vent. The reason we haven't observed water levels approaching the steady-state elevation is probably due to the slow recovery rate. The model runs at SS1 and SS2 needed 25 years to converge, the longest period required by any model. These results should be applied cautiously, however, because the predicted steady-state elevation was outside the data range used in the models. The water level at SS4 changes little with minimal pumping and near normal runoff and appeared to be nearer a steady-state condition than either SS1 or SS2. Apparently, attaining the target at SS4 will require above normal runoff conditions even if pumping were restricted to the minimum value (Table 6). Unlike other sites, the steady-state elevation for water levels at SS4 is not as easily attributed to a relatively high constant pumping stress. Simulations with minimum pumping reduced to zero showed that the steady-state elevation was approximately 1 foot higher but still below the target.

For BG2, the target and initial water level differed by a few inches (Figure 53), and the water levels predicted for 2003, 2004, and 2005 were virtually identical with minimal pumping and near normal runoff conditions. Hence, the probability of recovery for those scenarios was about 50% because the predicted h_{ms} was almost at the target. The effect of pumping above the minimum is readily apparent, but the recovery from depths below the target is rapid and nearly complete after two years of normal runoff and minimal pumping. The steady-state elevation was just below the target (Table 6), but if minimal pumping were set to zero, the steady-state elevation exceeded the target by 1.5 feet. Because the system appears to be near equilibrium, raising the water table much above the target would require no pumping and above normal runoff or spreading to artificially recharge the aquifer.

CONCLUSIONS AND RECOMMENDATIONS

Regression models and Monte Carlo methods were developed to assess the multiple year effects of LADWP annual pumping and McNally canal operation on water table decline and probability of recovery at permanent monitoring sites used in On/Off determinations. For most sites, unless the initial water table depth was near the target depth, the probability of recovery was low even at minimum pumping for three years. This was partially due to the low runoff forecasted in 2002-03, but it was also because the long term average water table depth is below the target depth for several sites even if pumping were held to the wellfield minimum. For LW1, LW2, LW3, BP1, BP2, BP3, TA3, TA5, TS2, IO1, SS4, and BG2, the water table target will only be achieved in periods of above-normal runoff, regardless of whether pumping is held to the minimum or not. This does not mean that pumping at all levels would be compensated by higher runoff in wetter years. The likelihood of achieving the target depth was sensitive to the initial water table level simply because the more recovery necessary to achieve a target, the less likely it would be achieved within a given time interval. It would be possible, however, to adapt probabilistic simulation methods to estimate a water level within striking distance of a target depth given some estimate of how frequent the water table must return to meet the goals of the Agreement. For the Laws sites, this study showed that even with reduced pumping the water table targets will be achieved very rarely if recharge is reduced from less frequent canal operations than in the past.

Spreadsheet construction for the Monte Carlo simulation was relatively simple, and multiple pumping/runoff scenarios can be evaluated simultaneously within minutes making this approach viable for routine use. The method is flexible, provides an estimate of prediction uncertainty, and can accommodate differing initial DTW, target elevations, and forecasted runoff conditions. However, it relies on input variables at the wellfield or valley-wide scale, so it is not applicable to analyzing the effect of individual pumping wells or local recharge operations. This method could be adapted to account for higher levels of pumping in subsequent years if the water table was predicted to return to the target level and could be used to assess various scenarios for McNally canal operations in combination with pumping in Laws. Finally, if the method proves useful to evaluate annual operations plans, it potentially could be adopted into a management strategy and incorporated into the Green Book.

Additional analyses and research are needed before a proposal to revise the Green Book can be assembled, but the developments presented here are promising and should be pursued by the Technical Group. The water table triggers contemplated here could simply be joined with the existing On/Off scheme as an additional set of rules governing operation of pumping wells, where pumping proceeds under the additional limitation that the water table would have an agreed upon probability of recovering to a target within a specified amount of time. In the simplest form, the water table triggers could replace the soil water and vegetation water use triggers currently used. The primary advantage would be that the variables governing management would be simpler to define, measure, and predict. For example, the Green Book procedures rely on measurements and models to make predictions that control well operation, but spatial and temporal variability of the input measurements and uncertainty in the models are difficult to quantify and are simply ignored. Subsequent analyses and Technical Group discussions should:

1) Refine DTW targets. The DTW target depends on both the management goals for vegetation, and the plant physiological requirements to meet those goals. The mechanisms used in this report were based variously on water table conditions during the baseline mapping and the root zones defined in the Green Book. It is unknown if these targets will actually attain the management goals.

2) Predict the buffer period provided by stored soil water. The augmentation of Green Book On/Off procedures described above requires that a period of time be specified during which recovery would take place. The length of this time period depends on the tolerance of the vegetation to disconnection of its roots from the water table, and its ability to recover once the water table reconnects. This period of time is as yet unknown.

3) Develop methods to synthesize multiple pumping recommendations into a single value for the wellfield. Annual pumping plans are typically presented and evaluated on a wellfield by wellfield basis, but each wellfield may have several monitoring site models associated with it. To utilize these techniques to assess annual pumping plans, a mechanism should be devised to combine the several model results into a single recommendation for the wellfield. A combination of models with wellfield or linked well pumping variables is one possible solution.

4) Test suitability of the monitoring site locations using numerical groundwater models to estimate the location and extent of drawdown of the pumping recommendations derived at the permanent monitoring sites, and

5) Assess whether the existing vegetation/soil water/water level monitoring program is sufficient to provide adequate feedback to adjust pumping if the predictions are wrong or the goals of the Agreement are not being met.

The capability to model water levels and prediction uncertainty is important, but it alone cannot provide concrete recommendations for pumping. Because groundwater predictions rely greatly on unknown future runoff conditions, the best information that science can provide is the probability of a preferred outcome such as recovery to a target. The techniques developed here ultimately require a subjective decision of the acceptable risk to Inyo County and Los Angeles that a pumping decision will result in water table fluctuations within certain bounds. Under the Agreement, those bounds must necessarily consider the type of ecological changes allowed and not allowed by the goals of the Agreement. After these steps are completed, the resulting pumping recommendations can be assessed against the reliable water supply goal.

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