Water Table Fluctuations Resulting From Management Under the Drought Recovery Policy and the Green Book, 1989 to 2000

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INTRODUCTION

Groundwater pumping under the Inyo/Los Angeles Long Term Groundwater Management Agreement (Agreement) is governed by monitoring results and decision rules described in the Green Book, and by the Drought Recovery Policy (DRP). The DRP adopted in 1991 committed Inyo and Los Angeles to manage pumping conservatively because it was judged inappropriate to adopt the untested methods of the Green Book during conditions of drought and depressed water levels. The Green Book procedures determine when wells can be operated based in part on the vegetation conditions when wells were turned off. The procedures probably would not protect vegetation if it had already declined before they could be implemented as was the case in 1991. Operationally, conservative pumping management to promote water level recovery under the DRP entailed not operating some wells despite their On-status under the Green Book. The Owens Valley experienced several years with favorable runoff in the late 1990's, but the effects of high pumping during runoff years 1987-89 and drought on the water table and vegetation persist in some areas (Manning, 2002). Los Angeles Department of Water and Power consultants have concluded that the termination of the DRP is appropriate (Montgomery-Watson-Harza, 2001), suggesting that they believe conservative pumping management under the DRP is no longer required and that pumping should be governed by provisions of the Agreement and Green Book.

The Green Book procedures utilizing soil water measurements and transpiration predictions would govern well operation if the DRP were terminated. Some components of the Green Book either have been replaced or are the subject of existing proposals, but these have dealt only with methods for monitoring and data analysis. Previous analyses by Inyo County and cooperative studies suggested that more fundamental changes to the management strategy (On/Off) are necessary to provide rational recommendations for pumping amounts and locations. Foremost among the deficiencies in the On/Off procedures are failure to account for the beneficial effect of a shallow water table on the vegetation and the absence of provisions for timely water table recovery after soil water is exhausted (Steinwand, 2000a; Or and Groeneveld, 1994). Also, pumping recommendations are not based on the magnitude of water table drawdown or the cumulative effect of nearby pumping. These deficiencies result in ineffective management, where decisions to cease pumping fail to produce the intended effect of raising the water table to replenish soil water because the initial drawdown is large or because the recovery rate is slowed by nearby pumping. Another weakness is the absence of provisions to consider prediction and measurement error. Finally, the On/Off procedures ignore the condition of the vegetation relative to baseline within the area potentially affected by pumping.

The final measure of the effectiveness of a pumping strategy, even a technically flawed one, is whether the vegetation and water supply goals of the Agreement are met. The reliable water supply goal has not been defined quantitatively, and hence, is difficult to test. Vegetation changes measured since 1991 reflect only one pumping strategy, the DRP, and it is not yet possible to accurately model vegetation response to different pumping scenarios. Monitoring has shown, however, that vegetation decline and recovery was concurrent with the decline and recovery of the water table (Manning, 2002) consistent with the expected response of phreatophytic vegetation. Reverting to On/Off to govern pumping undoubtedly would allow greater pumping than in recent years, but no analysis has been conducted of what conditions may result from that decision. Because future conditions under any pumping management depend on unpredictable runoff, simulation of the past may provide the best insight into the expected performance of the Green Book procedures. The purpose of this study was to evaluate the effect of adhering to the Green Book procedures to manage pumping by simulating the water table fluctuations that would have occurred since 1989 without the restrictions of the DRP.

METHODS

We estimated the amount of pumping allowed in the absence of the DRP for each runoff year, 1989-1999 and then simulate the water table fluctuations produced by the alternative pumping scenarios. Multiple linear regression models relating water table elevation to pumping and runoff for several shallow test wells in the valley were used.

Allowable Pumping

To estimate allowable pumping under Green Book management, it was necessary to know both the amount of available soil water and the vegetation water requirement at each monitoring site. We used the observed values at the monitoring sites and assumed that there was no feedback between pumping-induced declines in the water table and available soil water and vegetation water requirement. This assumption was unavoidable because existing models linking groundwater, soil water, and vegetation response are inadequate to simulate precisely the time series of allowable pumping and water table changes. For this analysis, the most important feedback was that between allowable pumping and sites switching from On-status to Off-status. If this feedback was strong, it would have resulted in less allowable pumping than estimated here. The converse was less of a concern because under the DRP, wells in On-status were not operated, and it is doubtful that less pumping would have occurred without the DRP. Even though feedback undoubtedly exists in any On/Off scenario, the insensitivity of monitoring site On/Off status to changes in the monitoring site data (Steinwand, 2000b) and that fact that on average slightly less than half of the sites were in On-status suggest that the feedback between pumping and site status may have little effect on the results (Figure 1). The type

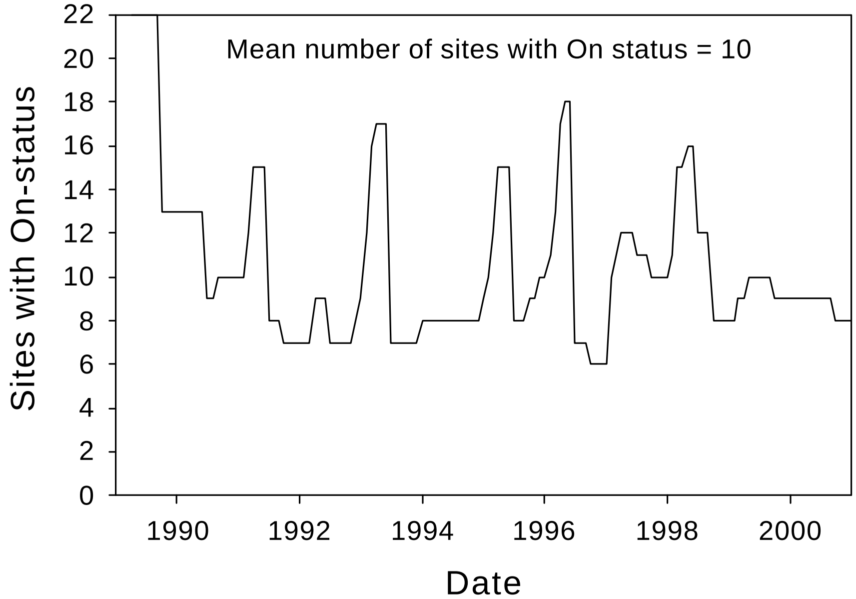

Figure 1. Number of monitoring sites in On-status each month since 1989.

of analysis reported here, therefore, provides a reasonable approximation of the time series of allowable pumping.

Allowable pumping from each well during runoff years 1989 to 1999 was determined using the instantaneous capacity for the time period (monthly time step) that the well could have been operated under existing Green Book provisions (Table 1). Wellfield and Owens Valley runoff-year pumping totals were calculated by summing individual well pumping amounts. Instantaneous well capacities were obtained from the Final Environmental Impact Report (FEIR, City of Los Angeles Dept. of Water and Power and County of Inyo, Table 9-10). For replacement wells installed after the FEIR was prepared, the capacity was determined from the average of several monthly pumping totals converted into instantaneous rates. For some replacement wells, it was apparent that they have only been operated for periods less than a full month. In these instances, the average pumping rate was calculated using pumping rates for several periods presented in LADWP monthly well reports.

Allowable pumping from wells linked to On/Off sites included operation at full capacity of all linked wells when in On-status. The first On/Off date was October 1, 1989, when all but one monitoring site had been instrumented. Before that date, wells linked to monitoring sites were assumed to have been operated as they actually were operated. We assumed that operation of Bishop Cone wells and wells exempt for a specific purpose would have been unaffected by Green Book/DRP constraints. Allowable pumping for those wells was set equal to the actual pumping that occurred,

Table 1. Pumping well linkage, instantaneous pumping capacities and sources used in this report to calculate allowable pumping amounts.

Wellfield	Linkage/Exemption	Well	capacity	Notes
Laws	LW1	246W	2.2	FEIR Table 9-10
	LW1	398W	2.7	mean rate for several months full operation
	LW1	247W	5.3	FEIR Table 9-10
	LW1	248W	4.4	FEIR Table 9-10
	LW1	249W	4.0	FEIR Table 9-10
	LW2	236W	4.6	FEIR Table 9-10
	LW2	239W	3.2	FEIR Table 9-10
	LW2	243W	2.3	FEIR Table 9-10
	LW2	244W	2.6	FEIR Table 9-10
	LW3	240W	2.3	FEIR Table 9-10
	LW3	241W	1.3	FEIR Table 9-10
	LW3	242W	1.2	FEIR Table 9-10
	LW3	399W	1.3	mean rate for several months full operation
	LW3	376EM	3.0	FEIR Table 9-10
	LW3	377EM	2.7	FEIR Table 9-10
	unlinked	245W	1.4	FEIR Table 9-10
	unlinked	387EM	4.5	FEIR Table 9-10
	unlinked	388EM	5.6	FEIR Table 9-10
	Nik and Nik	385EM		allowable pumping set equal to actual pumping
	Nik and Nik	386EM		allowable pumping set equal to actual pumping
	Exempt, town supply	354W		allowable pumping set equal to actual pumping
	Exempt, irrig. & no impact	365W		allowable pumping set equal to actual pumping
Big Pine	BP1	210W	2.4	FEIR Table 9-10
	BP1	378EM	5.0	FEIR Table 9-10
	BP1	379EM	4.3	FEIR Table 9-10
	BP1	389EM	4.2	FEIR Table 9-10
	BP2	220W	3.1	FEIR Table 9-10
	BP2	229W	1.5	FEIR Table 9-10
	BP2	374W	5.4	FEIR Table 9-10
	BP2	375EM	5.6	FEIR Table 9-10
	BP3	222W	1.3	FEIR Table 9-10
	BP3	223W	2.8	FEIR Table 9-10
	BP3	231W	2.0	FEIR Table 9-10
	BP3	232W	1.9	FEIR Table 9-10
	BP4	331W	10.4	FEIR Table 9-10
	Exempt, no impact	218W	3.5	FEIR Table 9-10
	Exempt, no impact	219W	4.1	FEIR Table 9-10
	Exempt, hatchery	330W		allowable pumping set equal to actual pumping
	Exempt, hatchery	332W		allowable pumping set equal to actual pumping
	Exempt, town supply	341		allowable pumping set equal to actual pumping
	Exempt, town supply	352W		allowable pumping set equal to actual pumping
	Exempt, hatchery backup	409W		allowable pumping set equal to actual pumping
Taboose-Aberdeen	TA3	106	2.4	FEIR Table 9-10
	TA3	110W	5.0	FEIR Table 9-10
	TA3	111W	3.2	FEIR Table 9-10
	TA3	114W	3.2	FEIR Table 9-10
	TA4	342W	11.8	FEIR Table 9-10
	TA4	347W	12.8	FEIR Table 9-10
	TA5	349W	13.6	FEIR Table 9-10

Table 1. [cont].

	TA6	109W	3.9	FEIR Table 9-10
	TA6	370W	2.9	FEIR Table 9-10
	Exempt, no impact	118W	2.9	FEIR Table 9-10
Thibaut-Sawmill	TS1	159W	1.4	FEIR Table 9-10
	TS2	155W	1.1	FEIR Table 9-10
	TS3	103W	1.6	FEIR Table 9-10
	TS3	104W	1.1	FEIR Table 9-10
	TS3	382EM	1.8	FEIR Table 9-10
	TS4	380EM	3.2	FEIR Table 9-10
	TS4	381EM	3.4	FEIR Table 9-10
	Exempt, hatchery	351W	17.4	allowable pumping set equal to actual pumping
	Exempt, hatchery	356W	9.3	allowable pumping set equal to actual pumping
Ind.-Oak	IO1/ exempt, irrigation	61W	2.3	allowable pumping set equal to irrigation pumping when in Off-status
	IO1	77W	3.0	FEIR Table 9-10
	IO1	400W	3.2	mean rate from Monthly Well Report
	IO1	391W	4.3	FEIR Table 9-10
	IO2	63W	2.5	FEIR Table 9-10
	Exempt, town supply	357W		allowable pumping set equal to actual pumping
	Exempt, no impact	59W	2.9	FEIR Table 9-10
	Exempt, no impact	60W	4.4	FEIR Table 9-10
	Exempt, no impact	65W	4.6	FEIR Table 9-10
	Exempt, no impact	383EM	2.4	FEIR Table 9-10
	Exempt, no impact	384EM	1.7	FEIR Table 9-10
	Exempt, town supply	384A		allowable pumping set equal to actual pumping
	Exempt, no impact	57W	4.0	FEIR Table 9-10
	Exempt, no impact	401W	5.5	mean rate for several months full operation
Symmes-Shepherd	SS1	69W	3.9	FEIR Table 9-10
	SS1	68W	2.0	mean rate for several months full operation
	SS1	392W	2.7	mean rate from Monthly Well Report
	SS1	66W	3.0	mean rate for several months full operation
	SS1	393W	3.1	FEIR Table 9-10
	SS2	74W	1.7	FEIR Table 9-10
	SS2	67W	3.1	didn't contribute to pumping during this period
	SS2	394W	5.1	mean rate from Monthly Well Report
	SS2	73W	3.9	didn't contribute to pumping during this period
	SS2	395W	5.3	mean rate from Monthly Well Report
	SS3	92W	3.1	FEIR Table 9-10
	SS3/Exempt, irrigation	99EM	3.3	FEIR Table 9-10
	SS3/Exempt, irrigation	402EM	3.4	allowable pumping set equal to irrigation pumping when in Off-status
	SS3	96W	3.1	FEIR Table 9-6
	SS3	396W	4.9	mean rate for several months full operation
	SS4	75W	3.0	FEIR Table 9-10
	SS4	345W	5.0	FEIR Table 9-10
Bairs-George	BG2	76W	2.6	FEIR Table 9-10
	BG2	95W	1.1	FEIR Table 9-10
	BG2	403W	1.3	mean rate from Monthly Well Report
	BG2/Exempt, irrigation	343W	1.5	FEIR Table 9-10
	BG2	348W	3.1	FEIR Table 9-10

Table 2. Replacement well date of initial operation.

Original well/ Replacement well	Wellfield	Original well Pumping Ends	Replacement well pumping begins	Date of Switch for this analysis
246W/398W^	Laws	March 1990	April 1994	May 1992
242W/399W	Laws	November 1991	May 1992	May 1992
77W/400W	Ind.-Oak	January 1991	December 1993	May 1992^^
57W/401W	Ind.-Oak	January 1991	June 1992	April 1992 ^^
99W/402W	Symmes-Shep.	June 1986	April 1992	April 1992
68W/392W	Symmes-Shep.	August 1989	August 1989	August 1989
66W/393W	Symmes-Shep.	October 1989	December 1992	November 1989^^
67W/394W	Symmes-Shep.	April 1989	September 1989	August 1989^^
73W/395W	Symmes-Shep.	April 1989	August 1989	August 1989
96W/396W	Symmes-Shep.	February 1990	March 1990	March 1990
95W/403W	Bairs-George	March 1990	December 1992	December 1992

^: The first record in the Inyo County Water Department database for replacement well pumping is May 1977; obviously an error. May 1992 is when 398W first is shown in the LADWP Monthly Well Reports, Book A.
^^: Month when replacement well is first shown in the LADWP Monthly Well Reports, Book A.

and unlinked wells and wells exempt for no impact were assumed to have been operated at full capacity. The transition from existing wells to replacement wells was assumed to be instantaneous although it probably took several months to complete. This was a necessary assumption given the lack of precise information of when replacement wells became operational. Dates of the transition used for this analysis are given in Table 2. LADWP operational constraints such as aqueduct capacity limitations or maintenance were ignored because necessary data were not available. No pumping for testing purposes or freeze protection from Off-status wells was included in the allowable pumping estimates.

Methods to calculate vegetation water requirements were changed in July, 1998 to conform with the Section III of Green Book, and a proposal to rely on transpiration coefficients (Kc) to perform the calculation was made to the Technical Group in 2000. Had those methods been used since the inception of the Agreement restrictions in 1989, the On/Off status at monitoring sites would likely have been different. Allowable pumping under these alternative On/Off scenarios was also estimated for comparison.

Simulated water table fluctuations

Indicator well regression models for twenty-seven shallow monitoring wells were used to simulate water table fluctuations under the various levels of allowable pumping developed in the previous section (Figure 2). The three scenarios simulated were the effect of pumping managed under On/Off as it was historically calculated, On/Off as it would have been calculated under Green Book Section III, or On/Off as it would have been calculated using the Kc method (Steinwand, 2000b). The indicator models relate

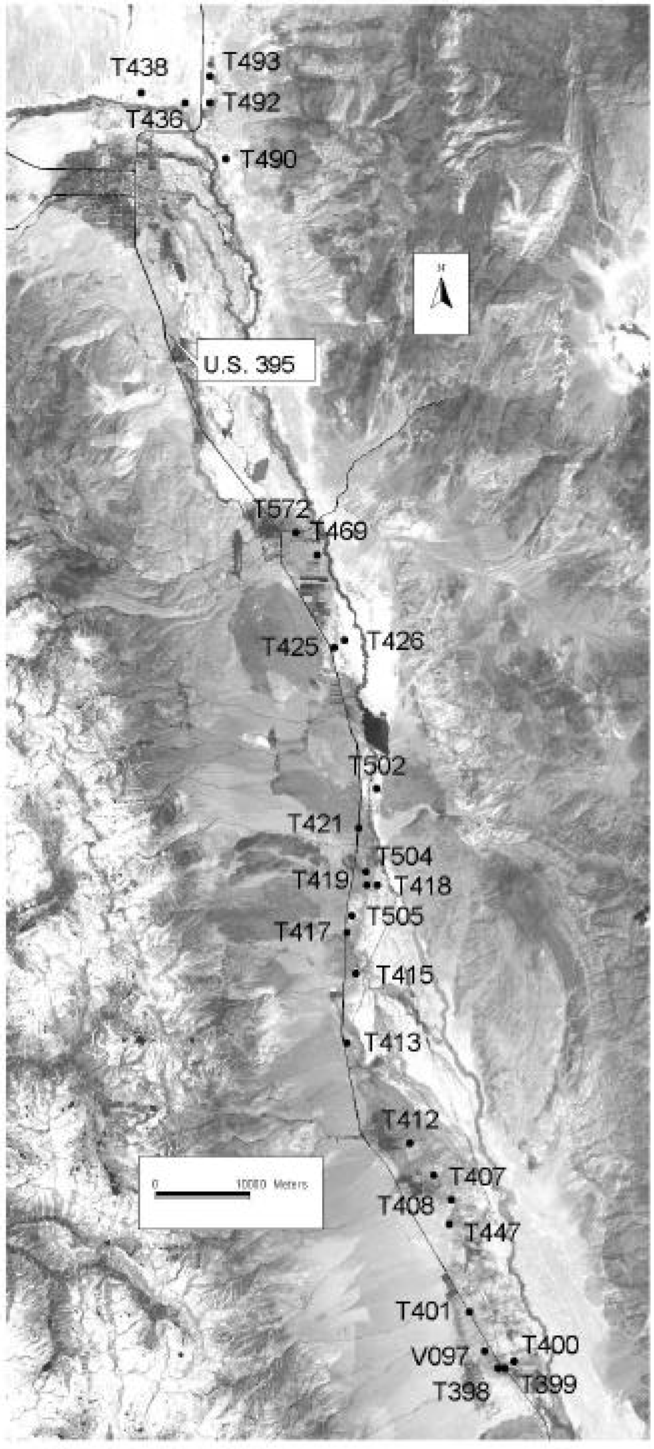

Figure 2. Locations of indicator wells used in this report.

wellfield pumping and recharge to changes in water table elevation in shallow monitoring wells using multiple linear regression (Harrington, 1998; 1999). Regression models are empirical and may perform poorly for combinations of pumping and recharge that deviate from the data from which the models were derived. This was not a concern here because the range of pumping and recharge in the simulations was also present in the regression data sets. The models included data for years up through 1999, and no pumping or runoff values simulated were outside the range of data in the models. Such models have been updated periodically and have been used by both Inyo County and LADWP to evaluate annual operations plans under the DRP. The wells were chosen based on the length of their period of record, their responsiveness to pumping and recharge, and their statistical robustness. These wells are not necessarily in areas of sensitive vegetation, but are indicators of wellfield wide trends in the water table. The independent variables in each model are the April water table elevation, pumping over the next twelve months in the wellfield, and a variable correlated to recharge. Most of the regression models use Owens Valley runoff over the twelve month period as an independent variable correlated with recharge; however, the models for the Laws wellfield use diversions from the Owens River into the McNally canals as an independent variable correlated with recharge. The dependent variable (the model prediction) is the water table elevation twelve months later. Thus, the models use a twelve month time step, propagating from April to April. April is used as the start of the year because it is when LADWP produces its Annual Operations Plan, it is the start of the start of spring snowmelt runoff, it is the start of the irrigation season, and for many shallow wells, it is within one month of the high or low stand of the annual periodicity in water level.

Two suites of model runs were conducted. The first suite used the historic record of observed Owens Valley runoff and pumping under the DRP to evaluate whether the indicator well models adequately model multiple year pumping/runoff scenarios by comparing the model results with the observed hydrographs. The modeled historic hydrographs were also necessary to evaluate the relative magnitudes of allowable pumping induced deviations from the observed hydrograph versus model error. For the analysis of indicator well regressions to be viable, the modeled hydrographs should approximate the actual observed hydrographs. Two methods of simulating the observed hydrograph were used: the first method, referred to as “updated,” used the observed water table at the start of each year, pumping, and runoff to predict the water table elevation one year in the future. The second method, referred to as "no update," used the model-generated water table elevation as the initial condition for each time step. The second suite of simulations used the allowable pumping rates developed for On/Off, Green Book Section III, and Kc methods to estimate the water table fluctuations that would have occurred under those management scenarios for the period 1989-1999.

RESULTS

Allowable Pumping

Under On/Off rules, several monitoring sites tend to stay in On-status due to perennially sufficient soil water to sustain the low vegetation cover and several sites tend to stay in Off-status due to relatively large vegetation water requirements or dry soil. Before 1996, the temporary increases in the number of sites with On-status each winter was largely the result of exaggerated soil water contents (often in excess of the precipitation) measured with the psychrometer-based methods (Figure 1). The temporary nature of this monitoring artifact limited the effect on allowable pumping. More importantly, exempt/unlinked wells and the six or seven perennially On-status sites (primarily LW1, LW2, BP3, TA5, TS2, SS3, BG2) for which pumping could have proceeded for a longer period dominate allowable pumping. After 1996, adoption of more stable soil water monitoring methods and methods that predict larger vegetation water requirements (adopted in 1998) stabilized the fluctuation in the number of On-status sites except for the short-lived increase in 1998 due to low turn-on requirements derived with previously used methods. It is also apparent that the rising water table observed throughout the wellfields during the late 1990's did not result in numerous sites changing from Off-status to On-status, further justifying our argument that site status is relatively insensitive to water table fluctuations even though vegetation and/or soil water is sensitive.

In all years, the Owens Valley total allowable pumping using the On/Off history greatly exceeded the actual pumping with most of the difference arising from Laws, Big Pine, and Taboose-Aberdeen wellfields (Figures 3-10). In no instance did the allowable pumping exceed the historic high pumping levels suggesting subsequent analyses did not rely on unrealistic or exaggerated allowable pumping totals. After 1989, the allowable pumping varied over a fairly narrow range between 140,000 to 160,000 ac-ft/year. Probable reasons for the relatively constant allowable pumping were the 76,000 to 81,000 ac-ft/year of pumping capacity not subject to the On/Off rules (Table 3) and the inherent insensitivity of the On/Off rules to changing monitoring methods and environmental conditions (Steinwand, 2000b). If the Green Book Section III or Kc vegetation water requirements had been in effect, adhering to the On/Off rules would have restricted pumping considerably, but allowable pumping using either method still would have exceeded actual pumping under the Drought Recovery Policy by 20,000 ac-ft/year or more (Figure 3).

Simulated Water Table Fluctuations

In Figures 11-37, the top graph (a) shows the first suite of water level simulations and the observed hydrographs, and the bottom graph (b) shows the simulations of the alternative pumping management scenarios. In general, it is evident from Figures 11a-37a that the indicator well models reproduce the observed hydrograph rather accurately. We expected that the updated method of reproducing the observed hydrograph would be more accurate than the no-update method because it uses the observed depth to water at the start of each yearly time step, whereas the no-update simulation is informed by the observed depth to water only once at the start of the simulation and uses the modeled water table elevation to initiate subsequent time steps. However, Figures 11a-37a generally reveal that the no-update simulation was as accurate as the updated simulation. This shows that the indicator well regression models are sufficiently robust to assess how alterations in pumping and/or runoff (or diversions into the McNally canals in Laws)

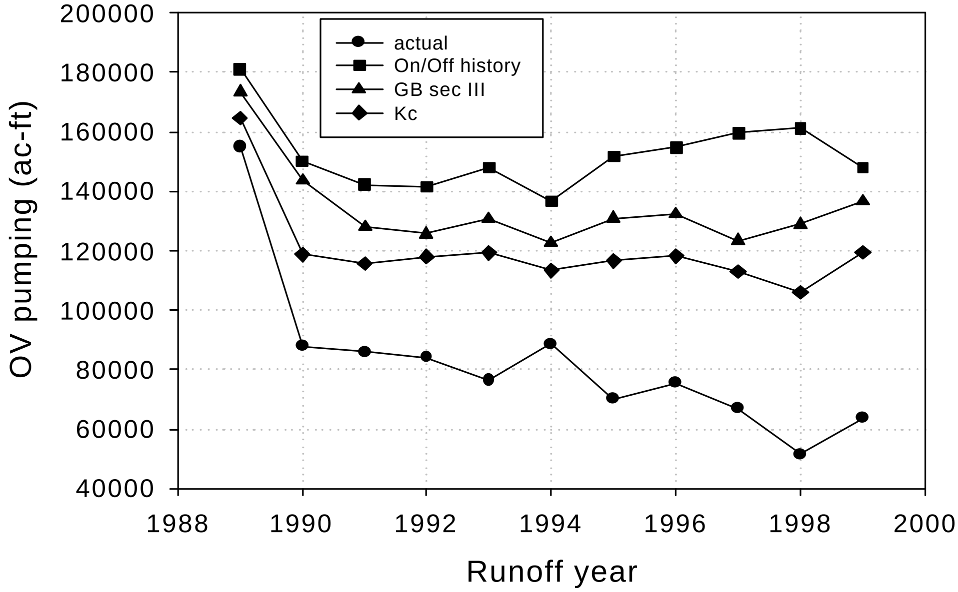

Figure 3. Estimated pumping allowed in the Owens Valley according to the On/Off history, the Green Book section III, and Kc management scenarios.

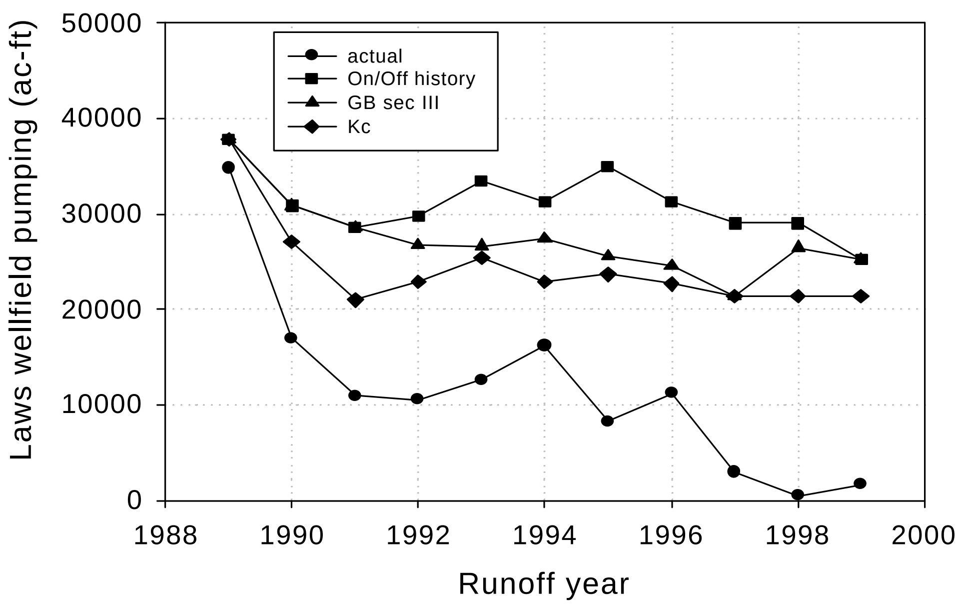

Figure 4. Estimated pumping allowed in the Laws wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

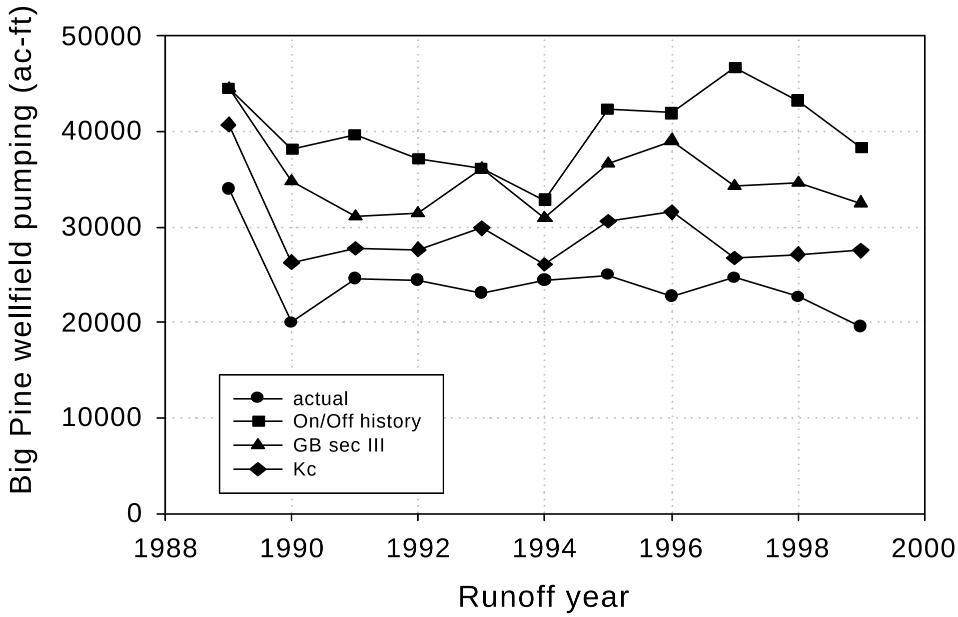

Figure 5. Estimated pumping allowed in the Big Pine wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

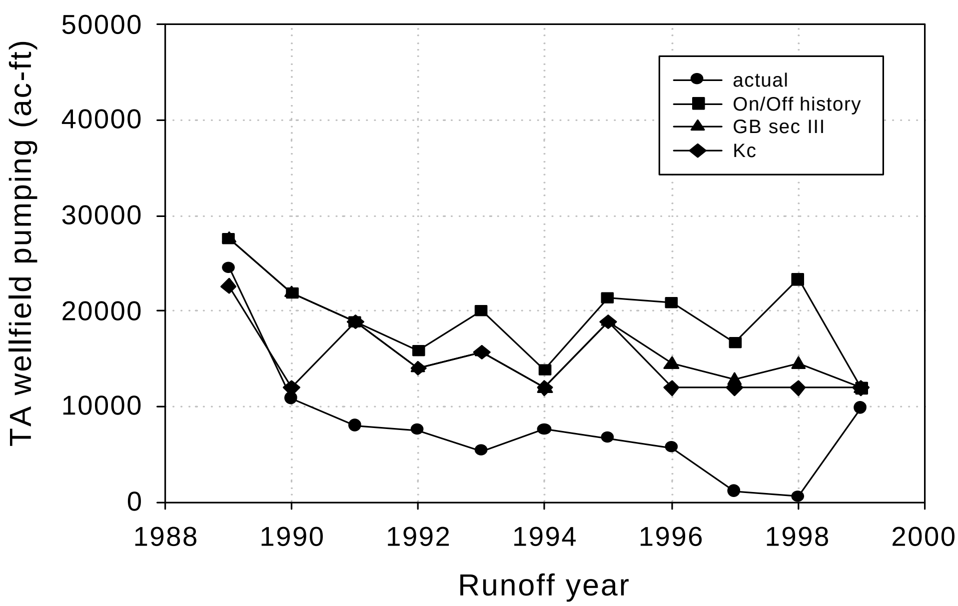

Figure 6. Estimated pumping allowed in the Taboose-Aberdeen wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

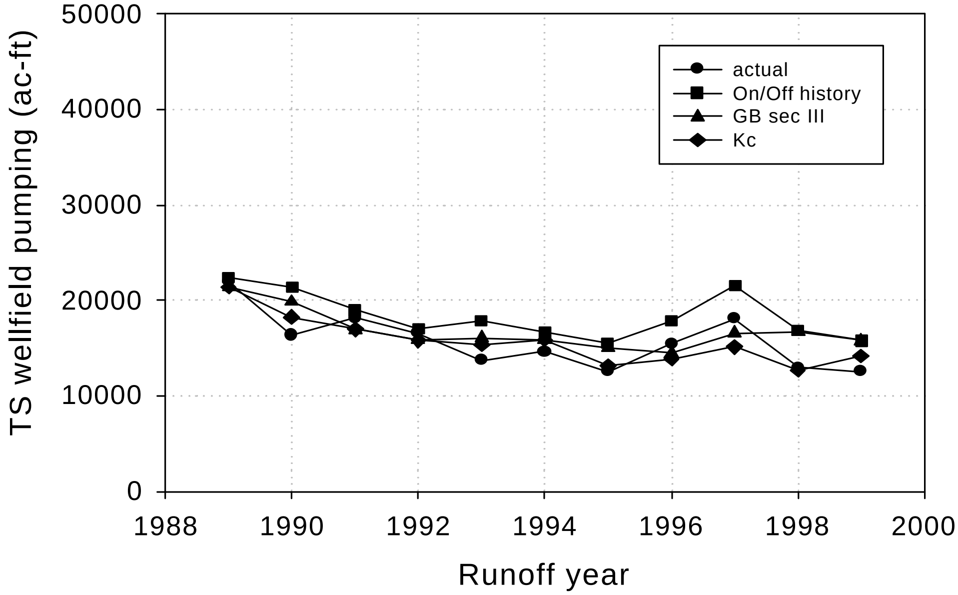

Figure 7. Estimated pumping allowed in the Thibaut-Sawmill wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

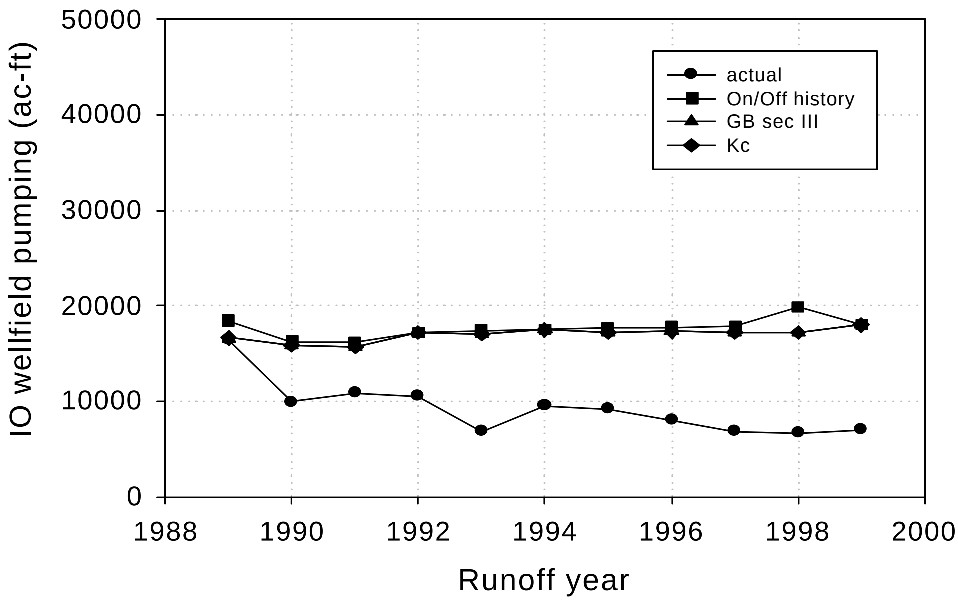

Figure 8. Estimated pumping allowed in the Independence-Oak wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

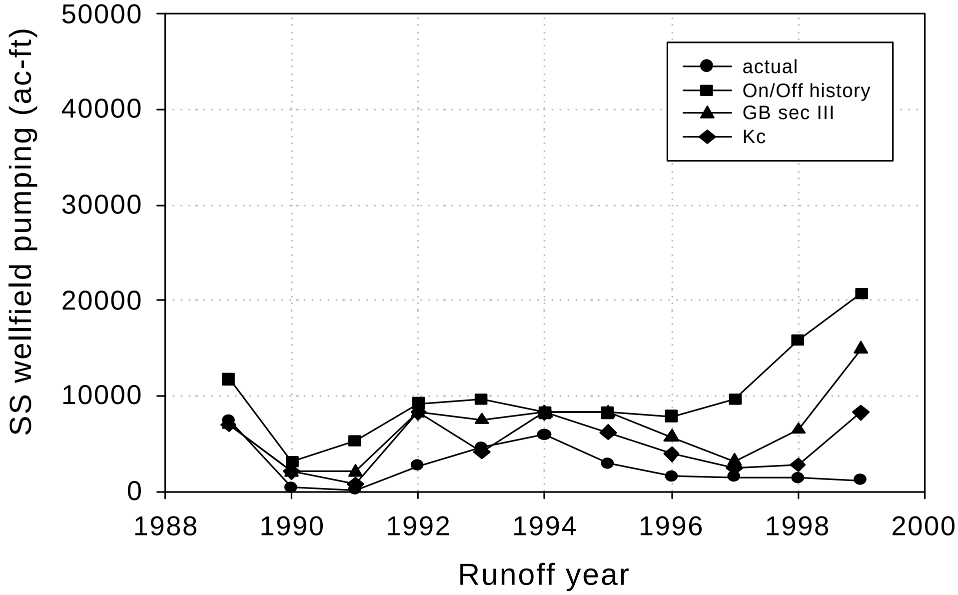

Figure 9. Estimated pumping allowed in the Symmes-Shepherd wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

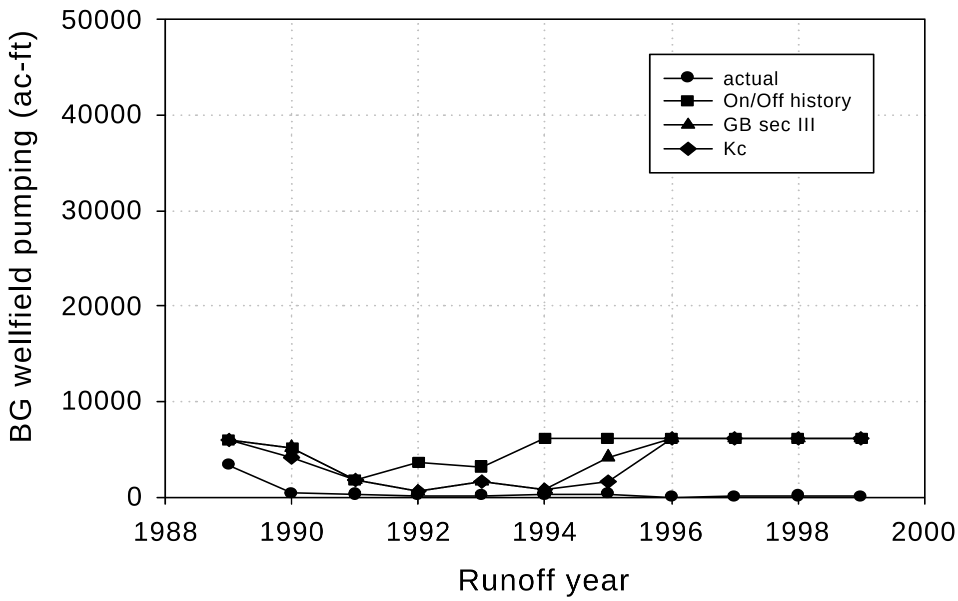

Figure 10. Estimated pumping allowed in the Bairs-George wellfield according to the On/Off history, the Green Book section III, and Kc management scenarios.

Table 3. Annual allowable pumping of unlinked and exempt wells.

Wellfield	Laws	Bishop	BP	TA	TS	IO	SS	BG	Total
R.O. Year									
	Acre-feet/year								
1989	9560	10692	28301	2096	13331	16615	0	300	82772
1990	9480	11874	24854	2096	12594	15814	0	166	78197
1991	9507	11624	26295	2096	12510	15671	0	231	79427
1992	9489	10124	25725	2096	12515	17164	1189	110	79939
1993	11594	8702	25555	2096	12639	16987	1242	106	80385
1994	9496	8919	25140	2096	12579	17477	1305	176	78346
1995	9497	4283	24830	2096	11501	17162	1236	73	71781
1996	9502	9869	27219	2096	13078	17306	1534	0	81537
1997	9513	10821	26746	2096	12721	17394	1247	0	81537
1998	9502	4556	27125	2096	12428	17180	1163	0	76317
1999	9501	10764	25005	2096	12525	17972	1167	0	80268

would affect water levels over periods of several years. The results also show that modeling errors essentially cancelled each other in multiple year simulations further suggesting this is an appropriate use of these models.

The water table simulations of the alternative management strategies reveal that to varying degrees, On/Off allowed for slower water table recovery than Green Book Section III, which allowed for slower water table recovery than Kc (Figures 11b-37b). On/Off, Green Book Section III, and Kc all result in lower water levels than observed, because the DRP resulted in lower pumping than any of the alternative On/Off management schemes.

Figures 11a-15a show that the regression models for Laws are quite robust in modeling multiple year scenarios. In the Laws area, pumping under On/Off, Green Book Section III, or Kc is substantially higher than the actual pumping that occurred under the DRP (Figure 4), which results in substantially lower water levels under the simulated allowable pumping scenarios (Figures 11b-15b). The difference is greater in the central part of the wellfield (wells 436T, 492T, and 493T) than on the edges (wells 438T and 490T) because of the greater sensitivity of the central part of the wellfield to pumping.

Figures 16a-19a show that the regression models for the Big Pine wellfield are quite robust in modeling multiple year scenarios. The Big Pine wellfield is subject to a sustained high level of pumping to supply the Fish Springs Hatchery (Figure 5), and the On/Off and Green Book Section III scenarios result in substantially lower water levels than the Kc scenario. The On/Off history scenario produced greater drawdown during the height of the drought in the early-1990's and retarded recovery during the late 1990's (Figures 16b-19b).

Like the Laws and Big Pine wellfields, the regression models for Taboose-Aberdeen wellfield are quite robust for predicting multiple year scenarios (Figures 20a-26a). In the Taboose-Aberdeen wellfield, the alternative management scenarios cause somewhat lower water tables, with On/Off being somewhat lower than either Green Book Section III or Kc (Figures 20b-26b). While substantial recovery would probably have been achieved under the various On/Off management strategies, they would not have provided as quick or as much recovery as was achieved under the DRP.

The simulations in the Thibaut-Sawmill wellfield provided less satisfactory results than any other wellfield. Figure 27a shows that for well 413T, the no-update method of simulating the observed hydrograph was somewhat inaccurate, indicating that the model is unreliable for assessing impacts on the water table due to alterations in pumping and recharge over periods of several years. The model performed adequately for 2-year predictions, however. Well 415T provided an accurate model that showed Kc resulting in higher water levels than On/Off or Green Book Section. III (Figure 28a). Similar to the Taboose-Aberdeen wellfield, though the various On/Off strategies would have provided for some recovery, it would not have been as quick or as much as was achieved under the DRP.

Although not as robust as the models for Laws, Big Pine, and Taboose-Aberdeen wellfields, the regression models for the Independence-Oak wellfield permit an assessment of multiple year pumping scenarios (Figures 29a-31a). In the Independence-Oak wellfield, wells 407T and 408T show dramatically lower water levels due to On/Off, Green Book Section III, or Kc compared with the observed hydrograph (Figures 29b-31b), but 412T is relatively insensitive to pumping (Figure 31b). The lack of recovery in wells 407T and 408T under all versions of On/Off was not due to the On/Off rules themselves, but due to the large amount of exempt pumping in the Independence-Oak wellfield. Actual pumping was approximately half the exempt well capacity. Also, the models for 407T and 408T are more sensitive to pumping than recharge compared with 412T (cf. Table 2 and Figure 8).

Multi-year simulations of water levels in well 401T and 447T in the Symmes-Shepherd wellfield reproduced the observed hydrograph well indicating that the models are sufficiently robust for simulating multiple year scenarios. Water levels under the alternative management scenarios were lower than observed, especially under On/Off (Figures 32b and 33b). The models predicted that the various On/Off management scenarios would have permitted a significant decline in the water table after the mid-1990's. Like Big Pine, Kc would have permitted substantially greater recovery than the historic On/Off or Green Book Section III scenarios.

The regression models for the Bairs-George wellfield are quite robust for modeling multiple year pumping scenarios (Figures 34a-37a). The indicator wells for the Bairs-George wellfield shows lower water levels under all three alternative management scenarios, especially after the mid-nineties when pumping under the alternative scenarios would have been allowed to increase (Figure 34b-37b).

Generally, vegetation cover in reinventoried parcels failed to recover to baseline values unless the water table recovered approximately to the levels reached during the 1985-87 period (Manning, 2002). Using the average April water level for 1985-1987 as a target for water level recovery, among the twenty-seven indicator wells modeled here, fourteen were observed to have recovered to baseline, fourteen were modeled to recover under the updated simulations, and seventeen were modeled to recover under the no-update simulations. Under the historic On/Off scenario and the Green Book section III scenarios, no wells recovered, and under the Kc scenario, two wells recovered to baseline. It follows, therefore, that vegetation in more areas would have remained below baseline under any of the On/Off implementations.

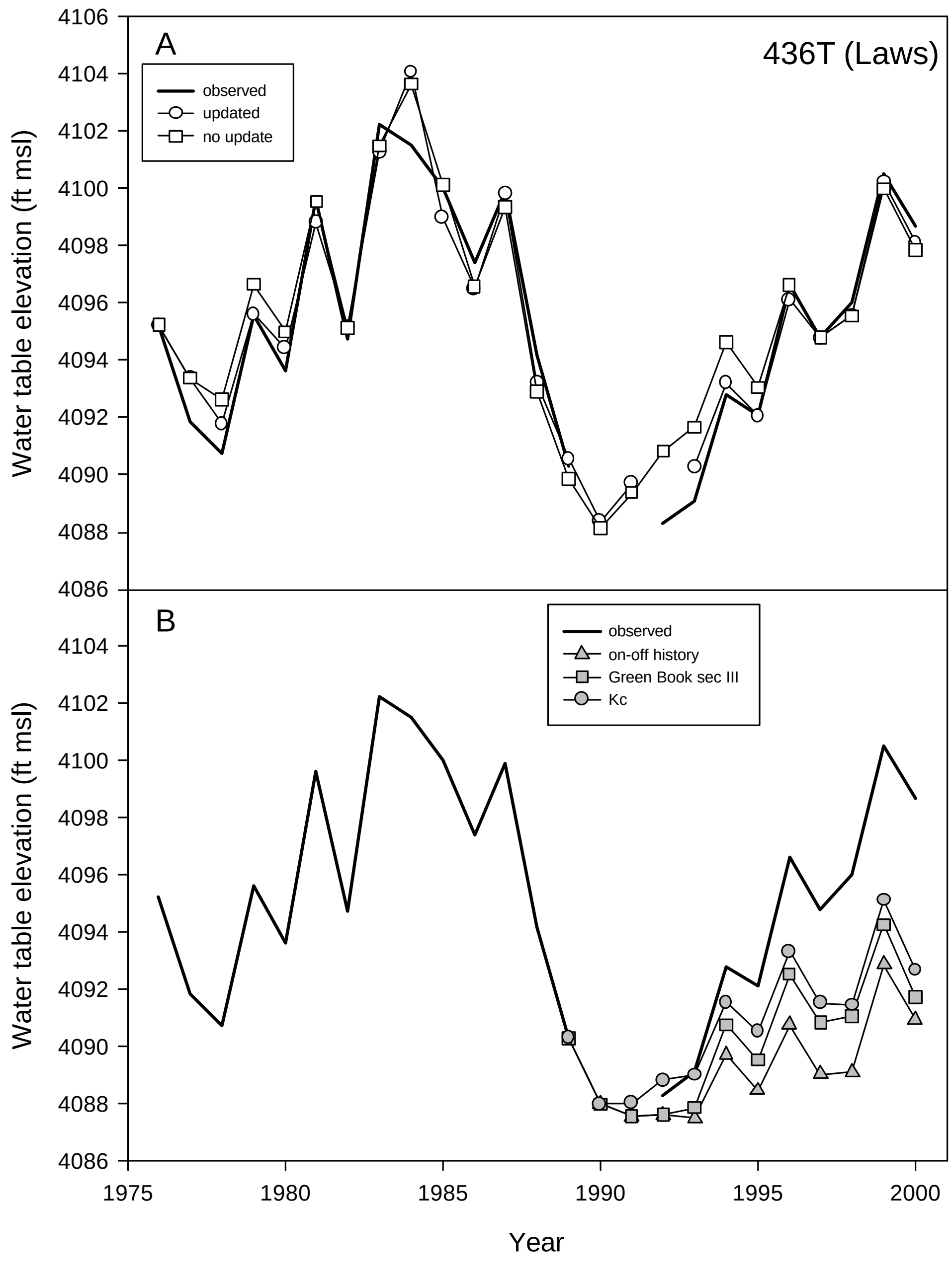

Figure 11. (a.) Indicator well 436T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

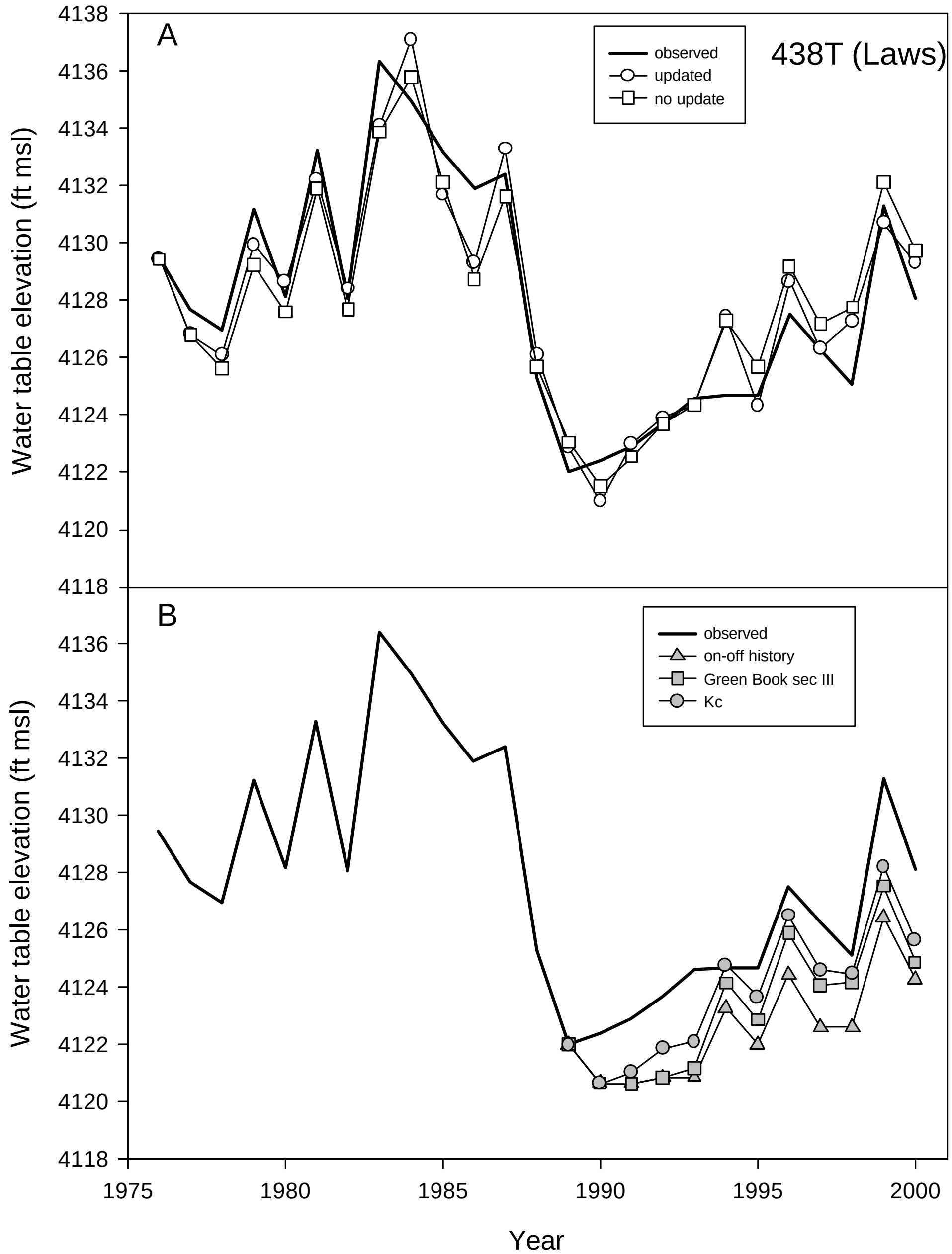

Figure 12. (a.) Indicator well 438T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

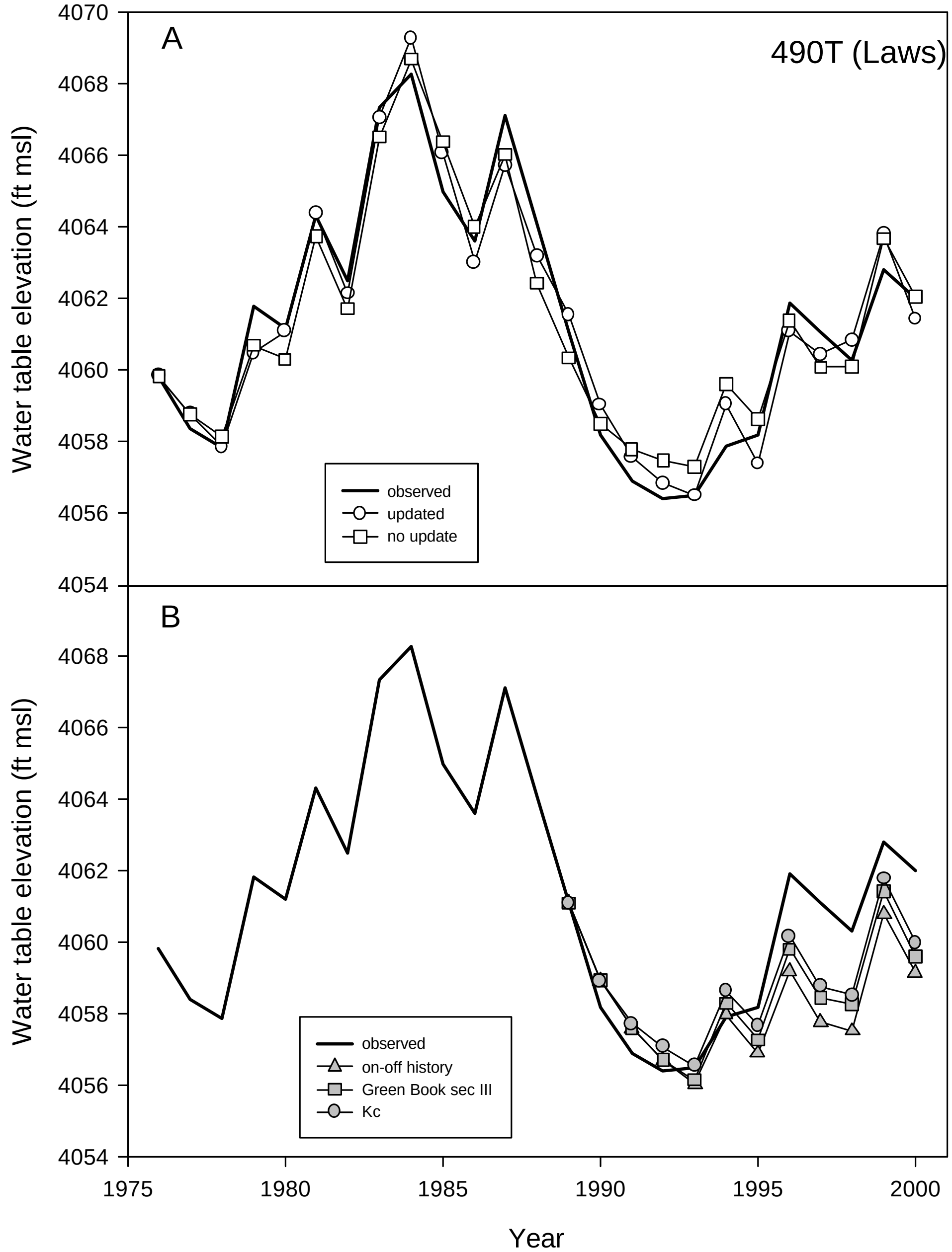

Figure 13. (a.) Indicator well 490T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

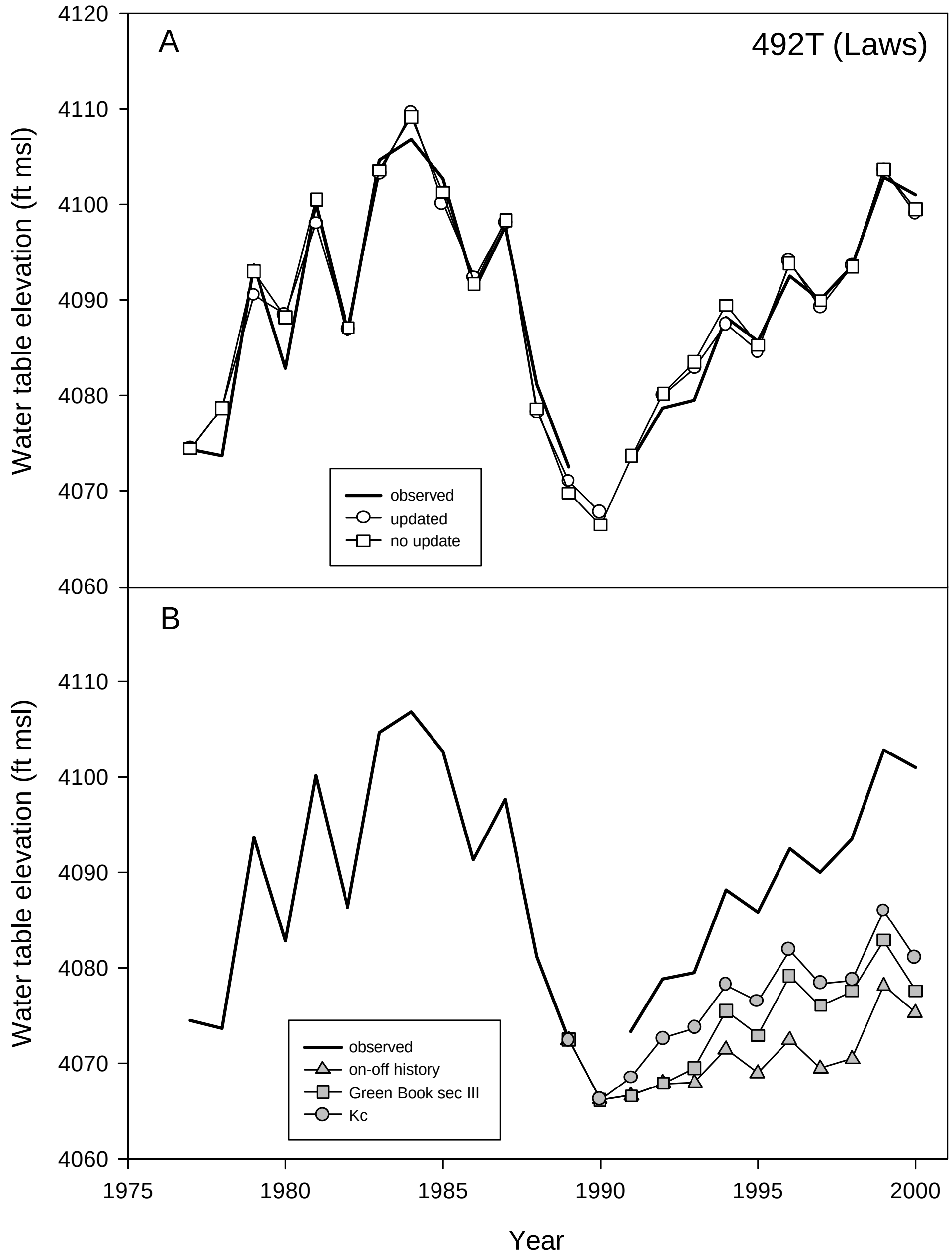

Figure 14. (a.) Indicator well 492T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

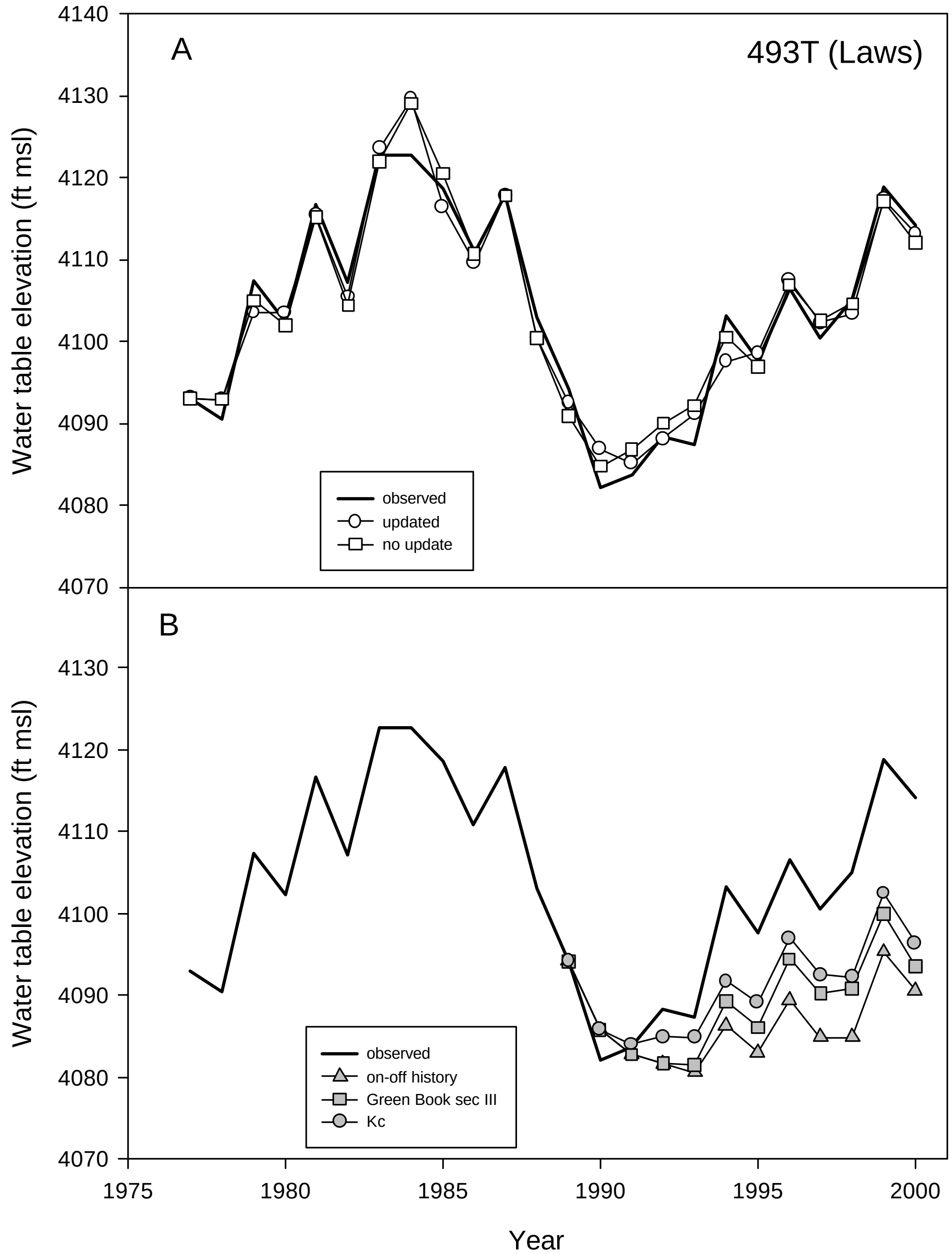

Figure 15. (a.) Indicator well 493T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

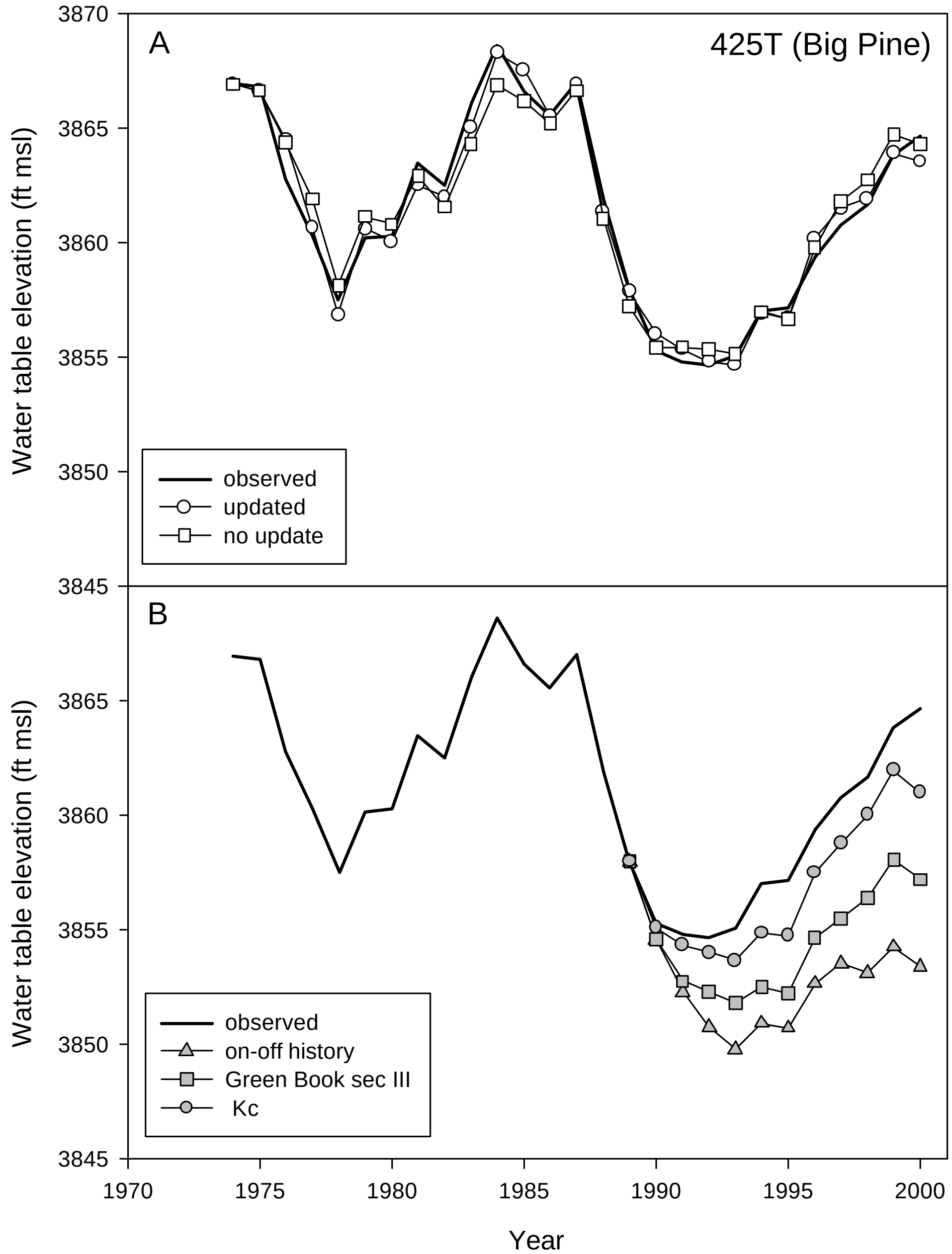

Figure 16. (a.) Indicator well 425T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

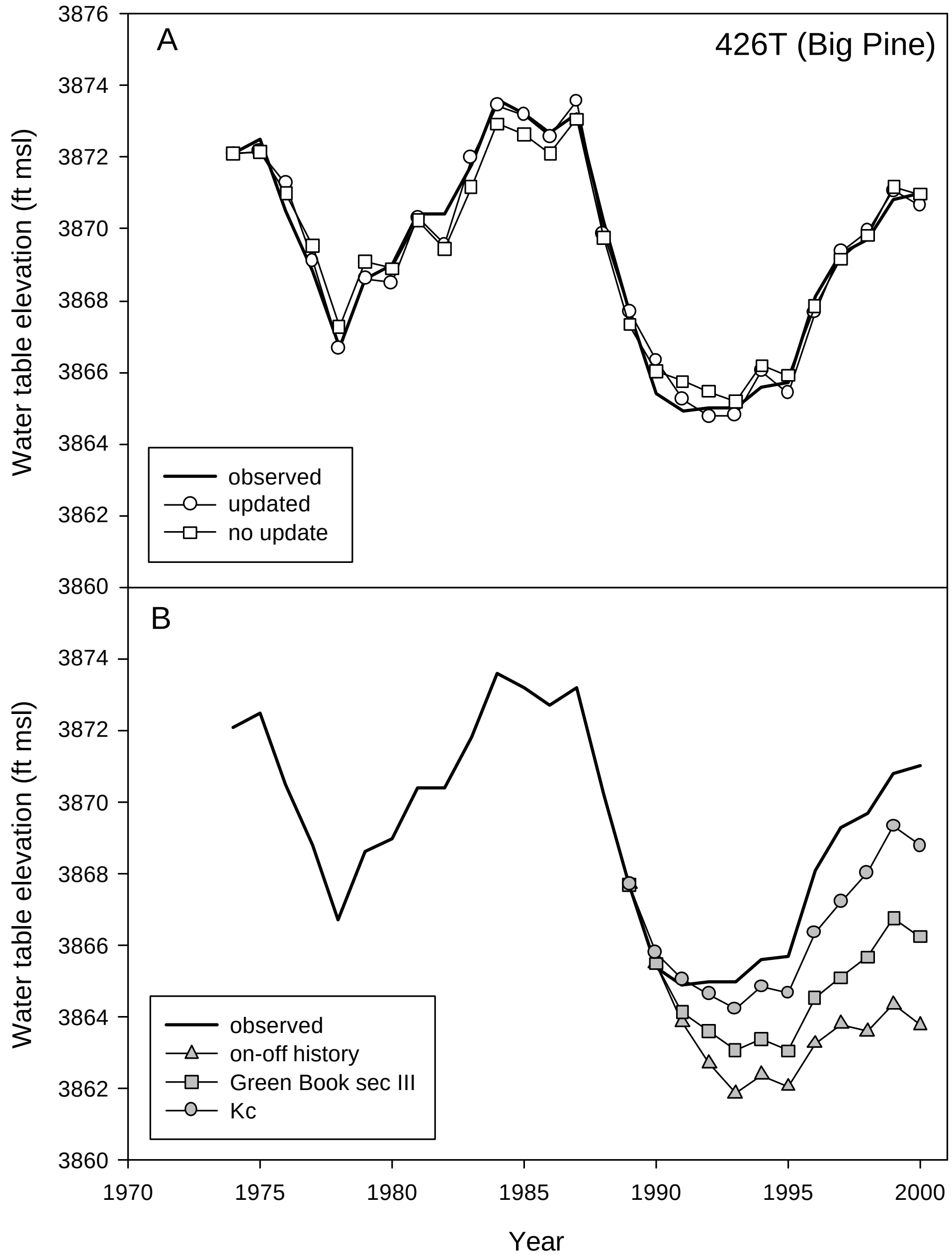

Figure 17. (a.) Indicator well 426T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

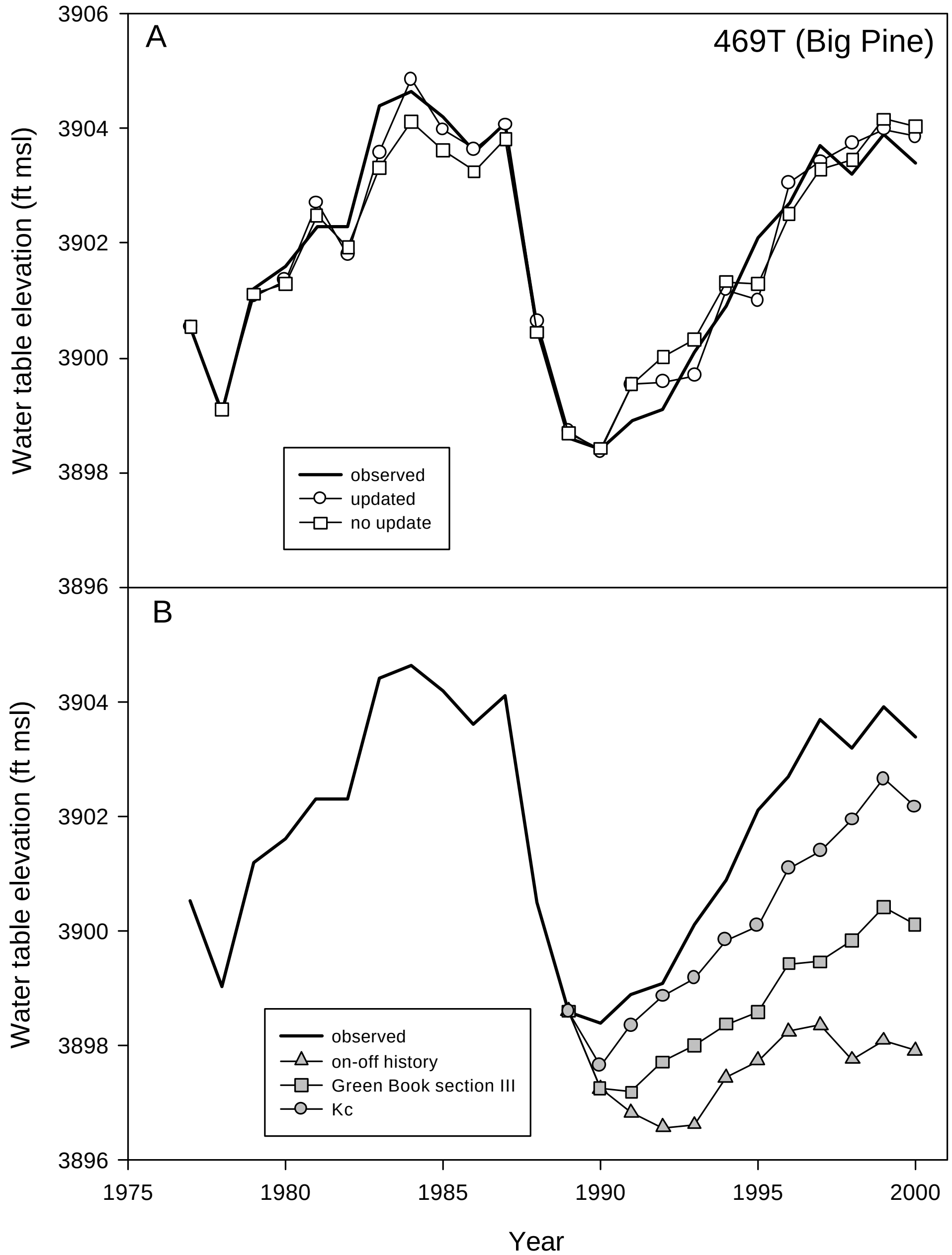

Figure 18. (a.) Indicator well 469T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

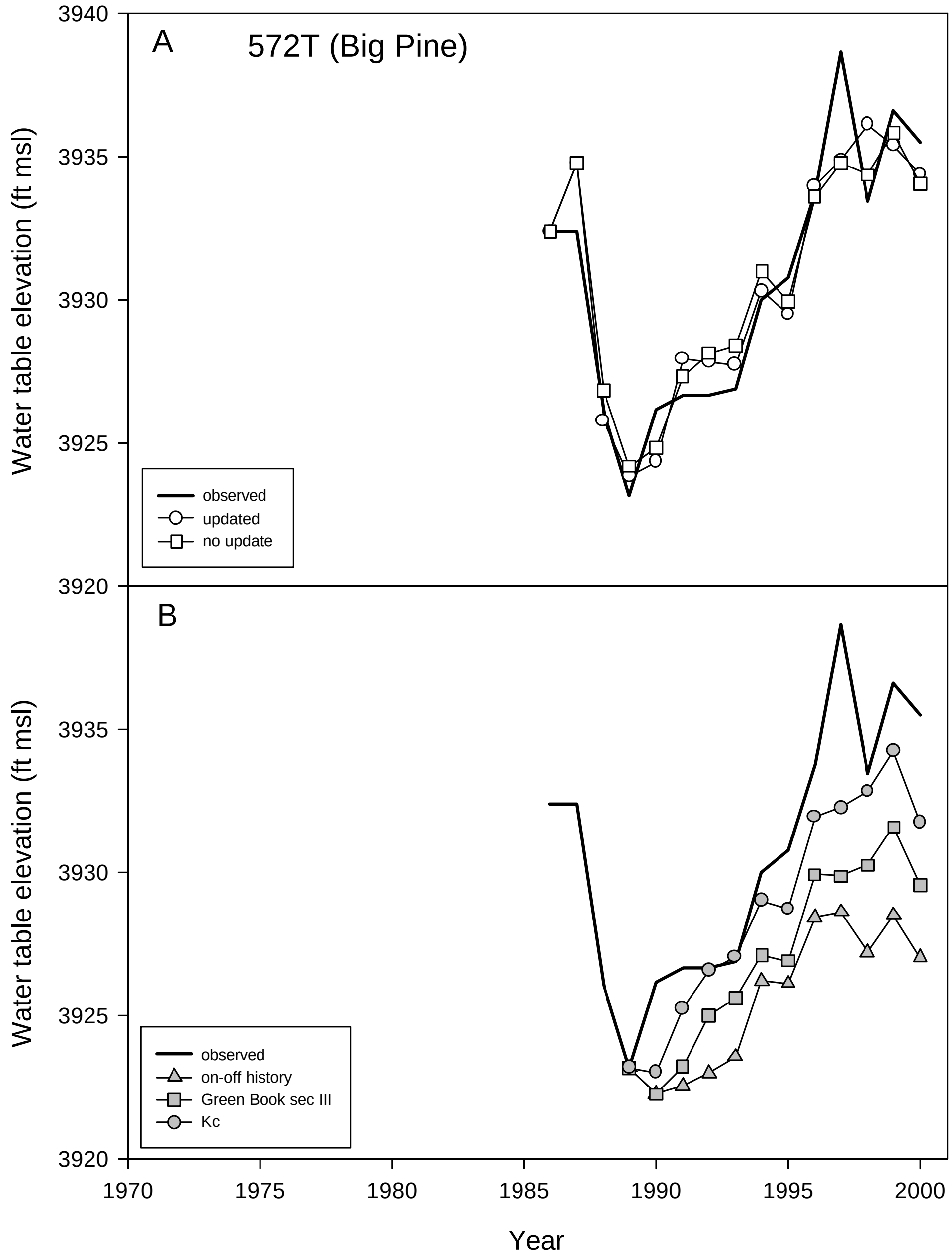

Figure 19. (a.) Indicator well 572T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

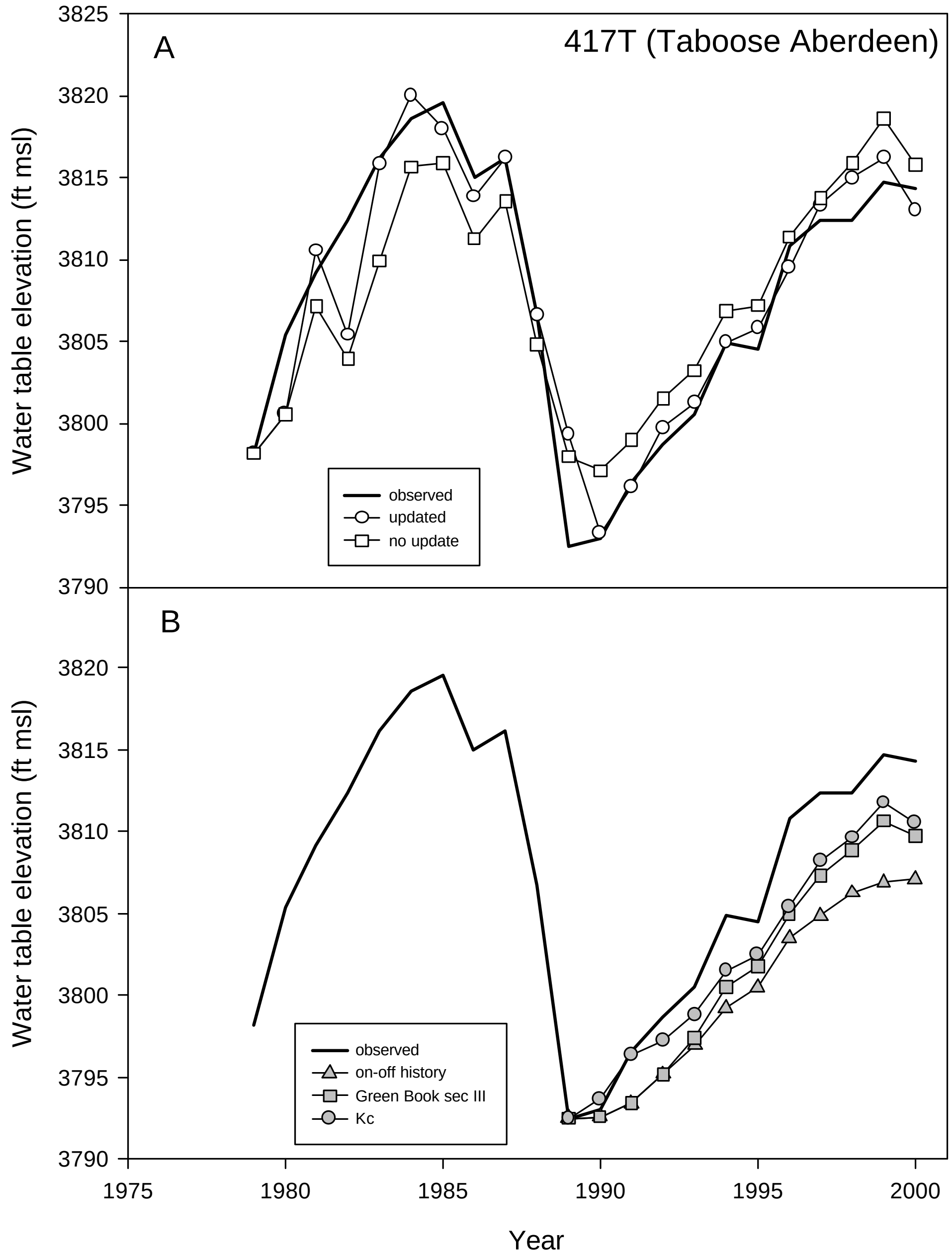

Figure 20. (a.) Indicator well 417T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

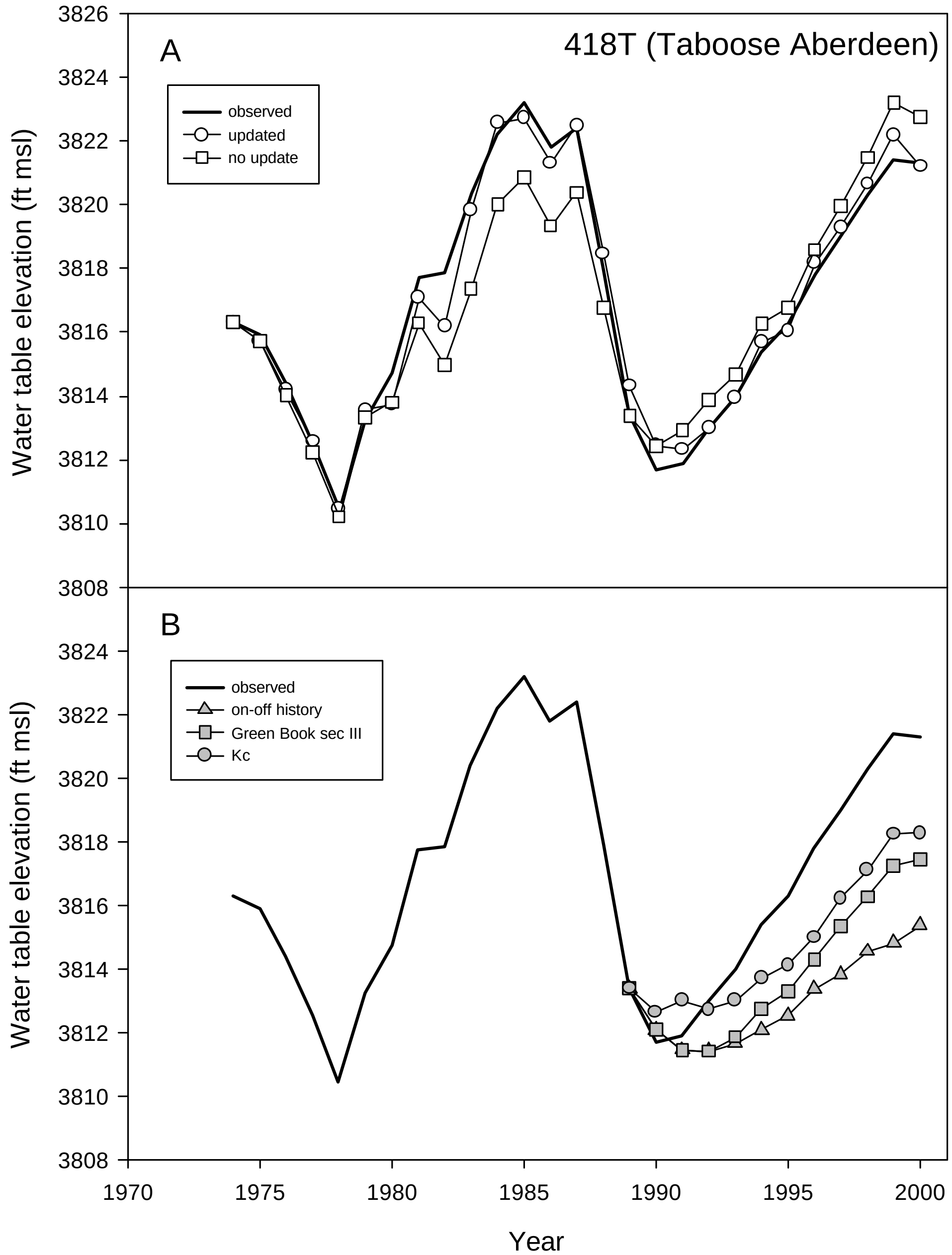

Figure 21. (a.) Indicator well 418T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

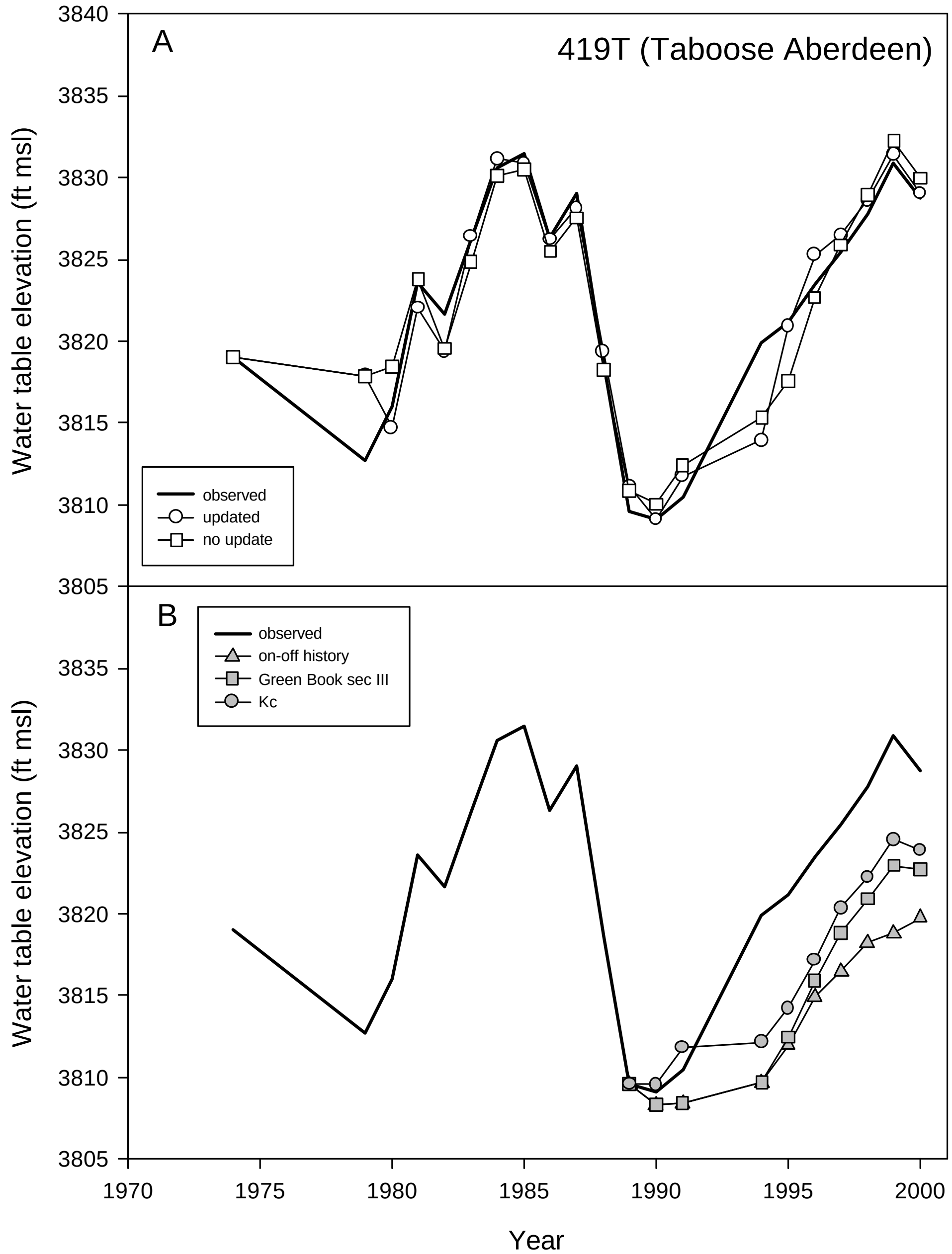

Figure 22. (a.) Indicator well 419T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

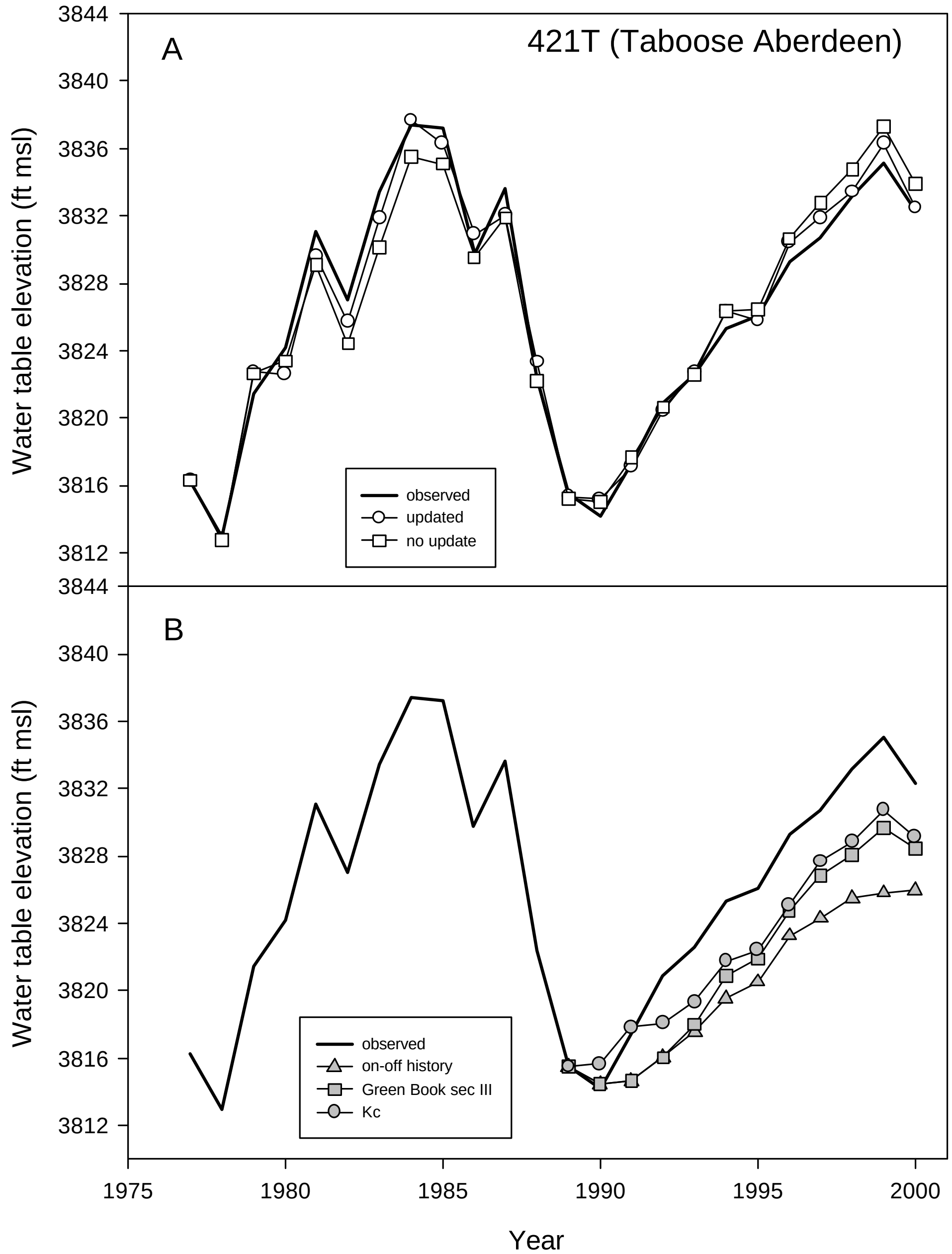

Figure 23. (a.) Indicator well 421T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

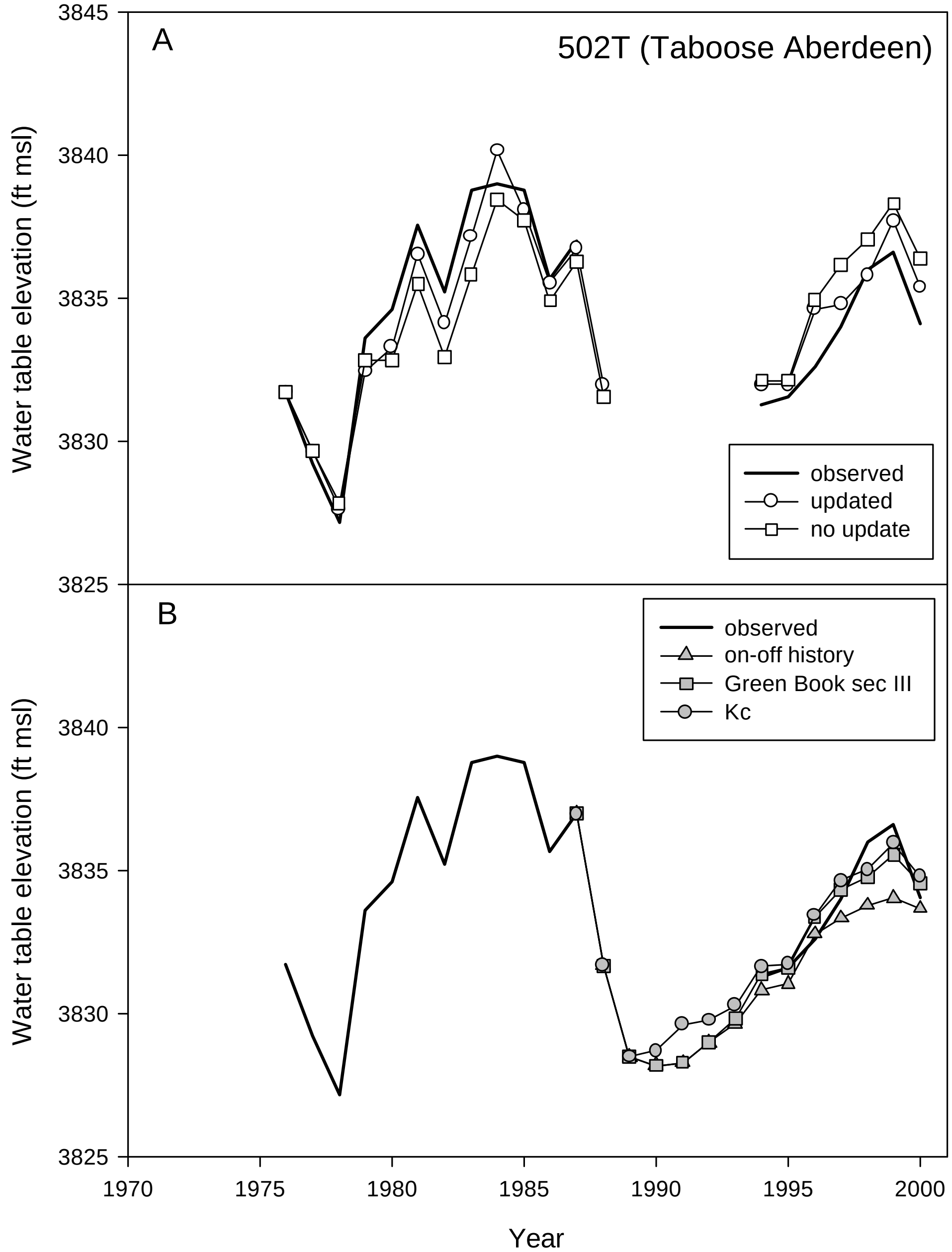

Figure 24. (a.) Indicator well 502T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

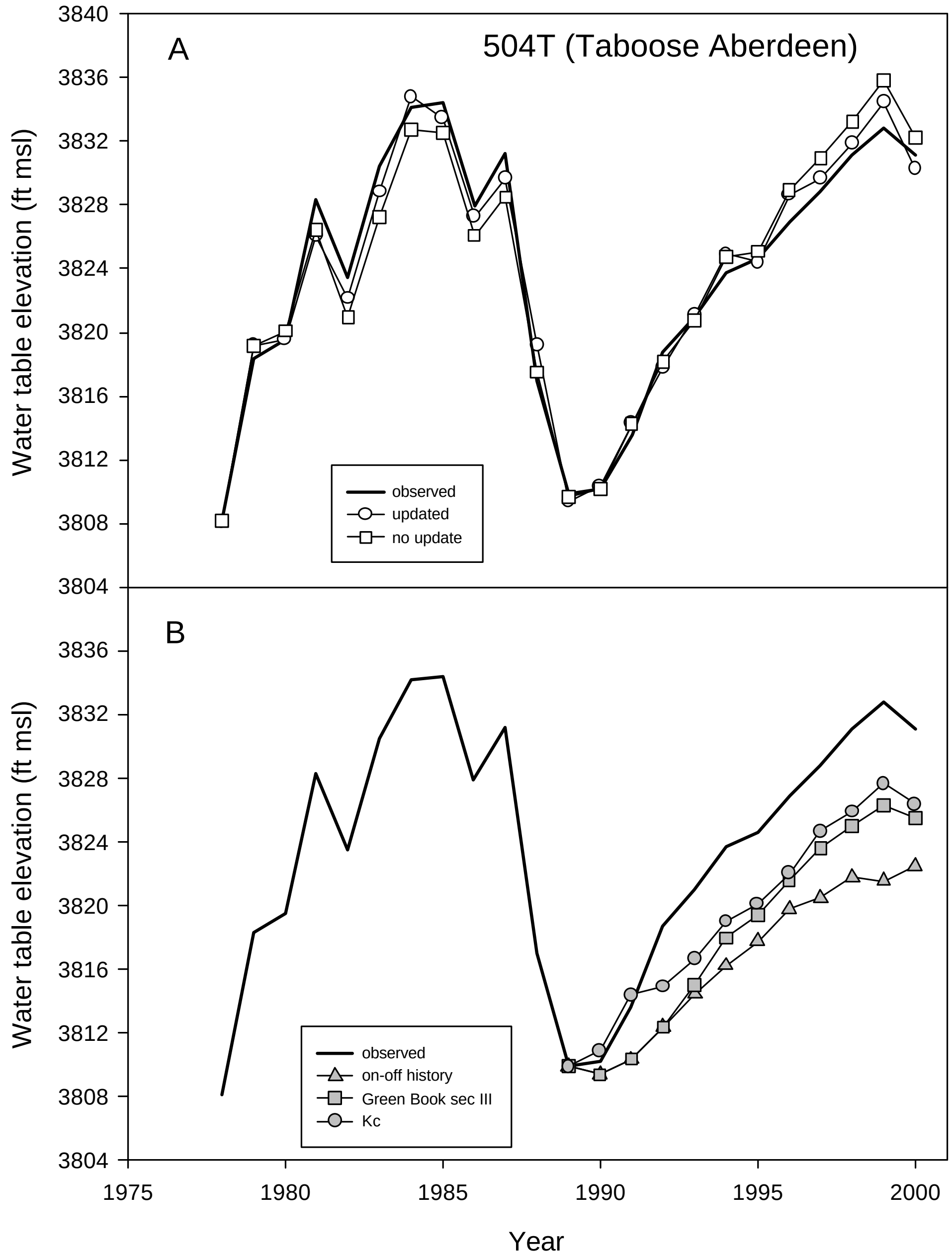

Figure 25. (a.) Indicator well 504T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

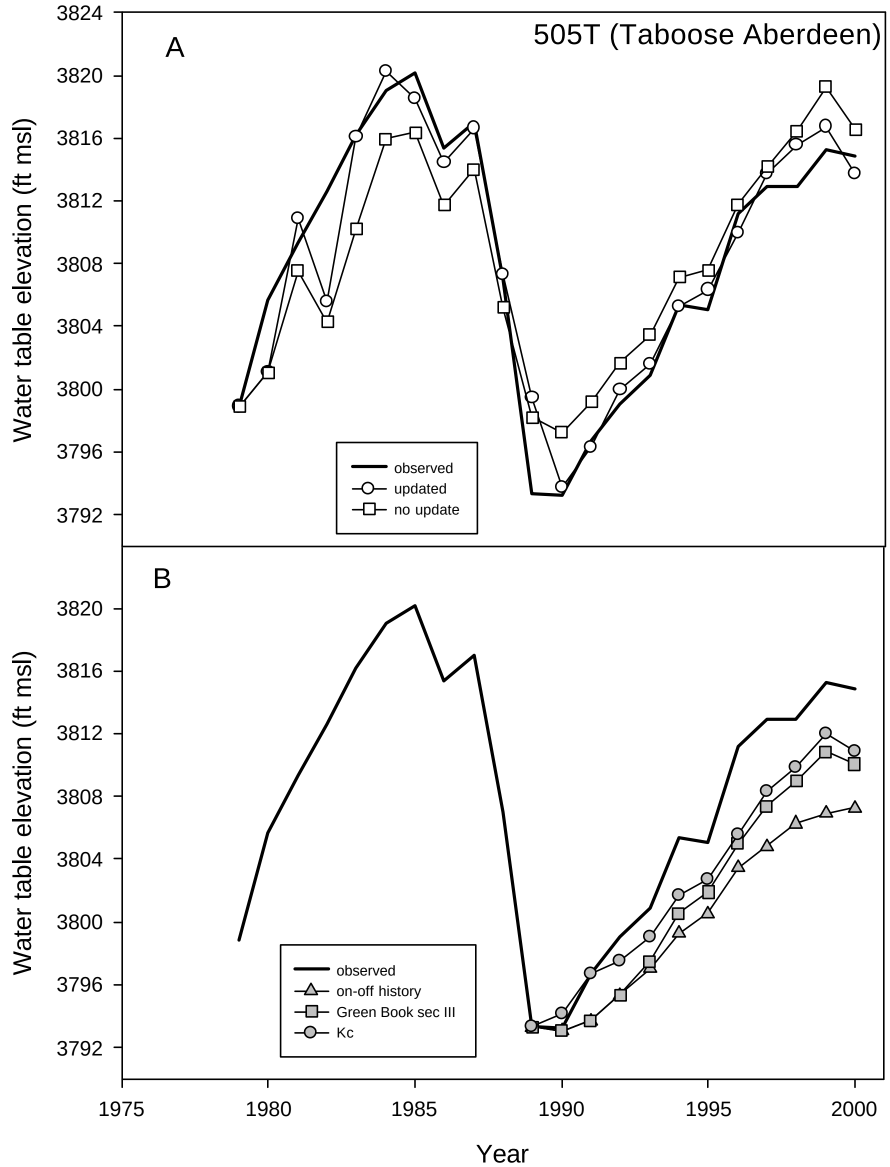

Figure 26. (a.) Indicator well 505T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

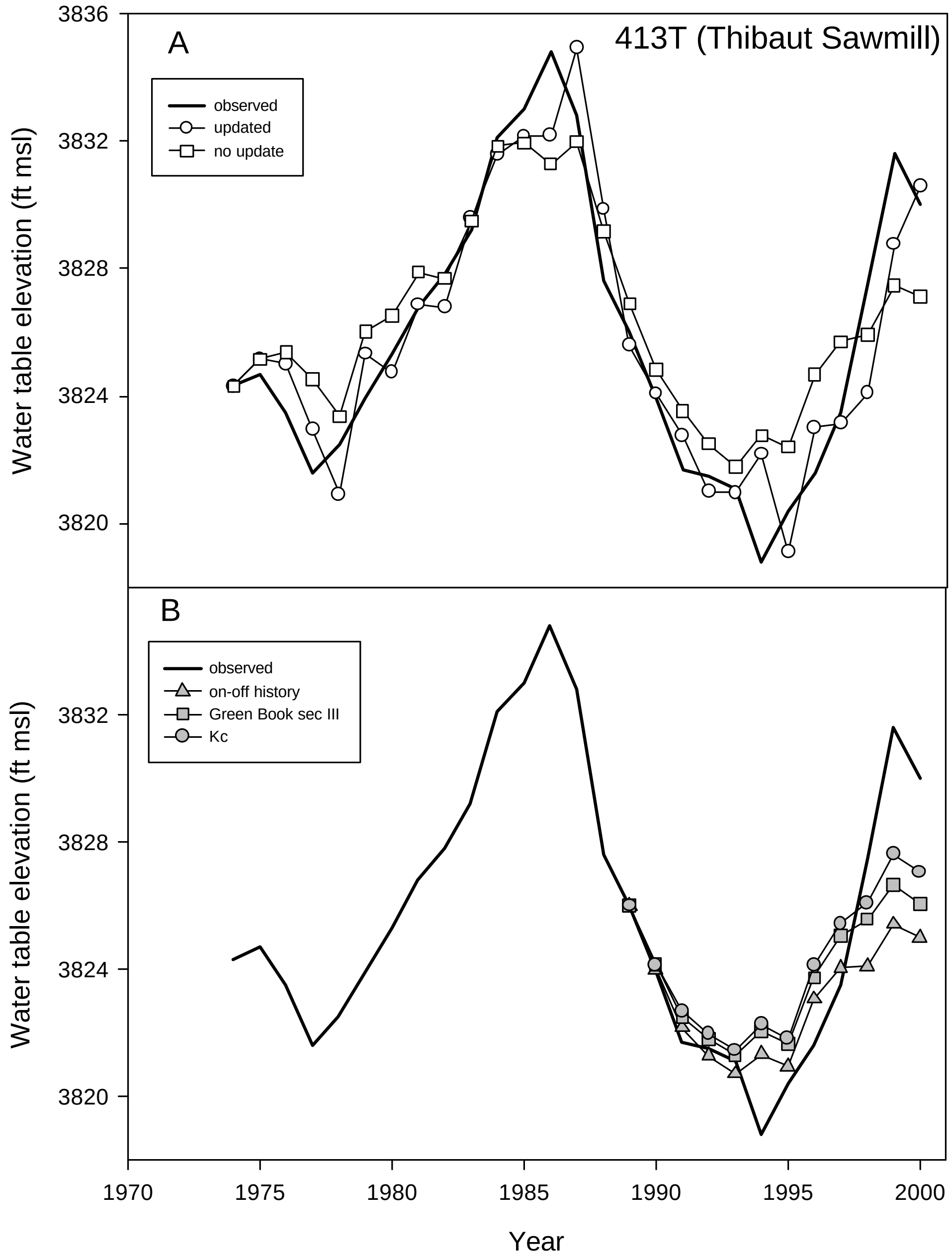

Figure 27. (a.) Indicator well 413T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

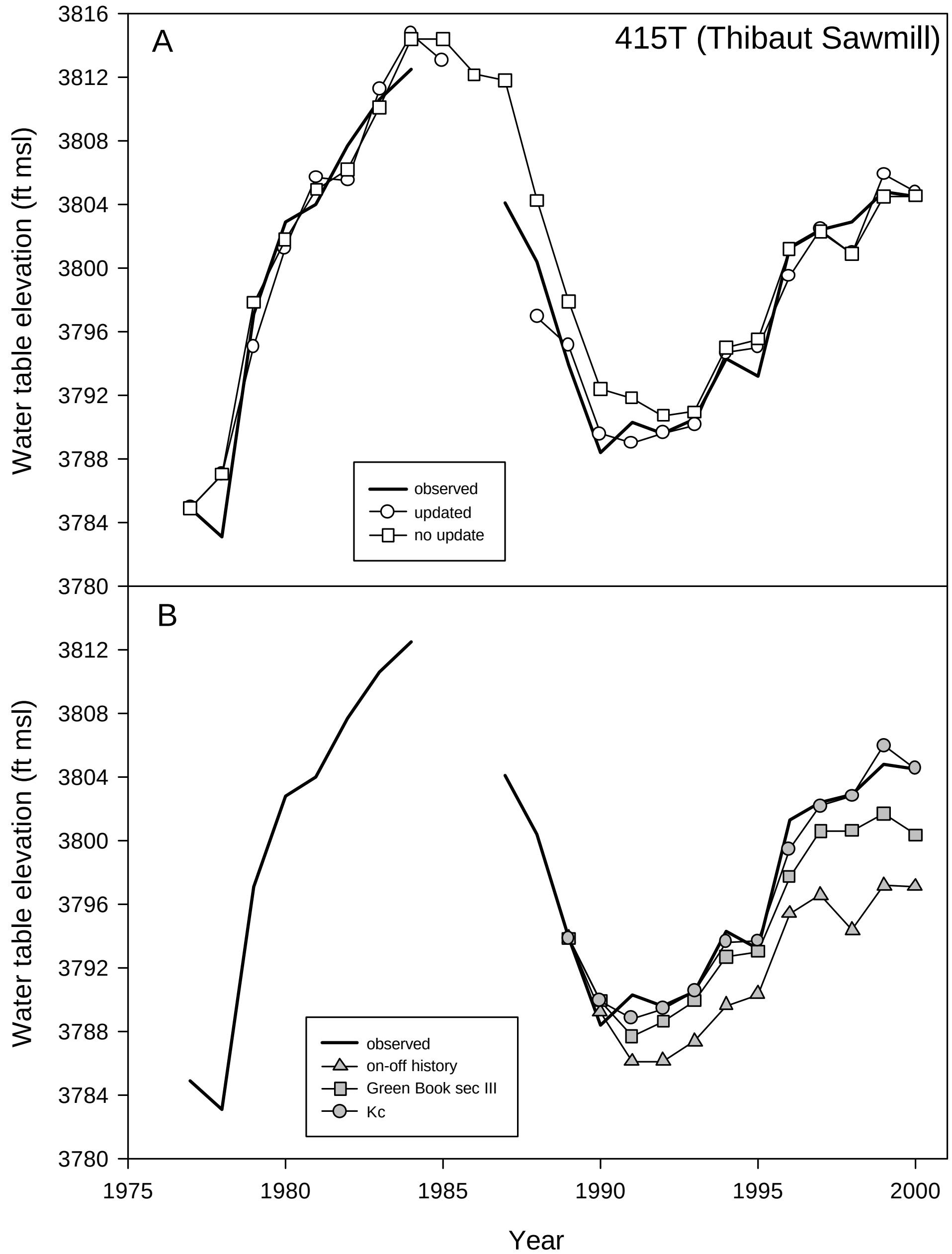

Figure 28. (a.) Indicator well 415T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

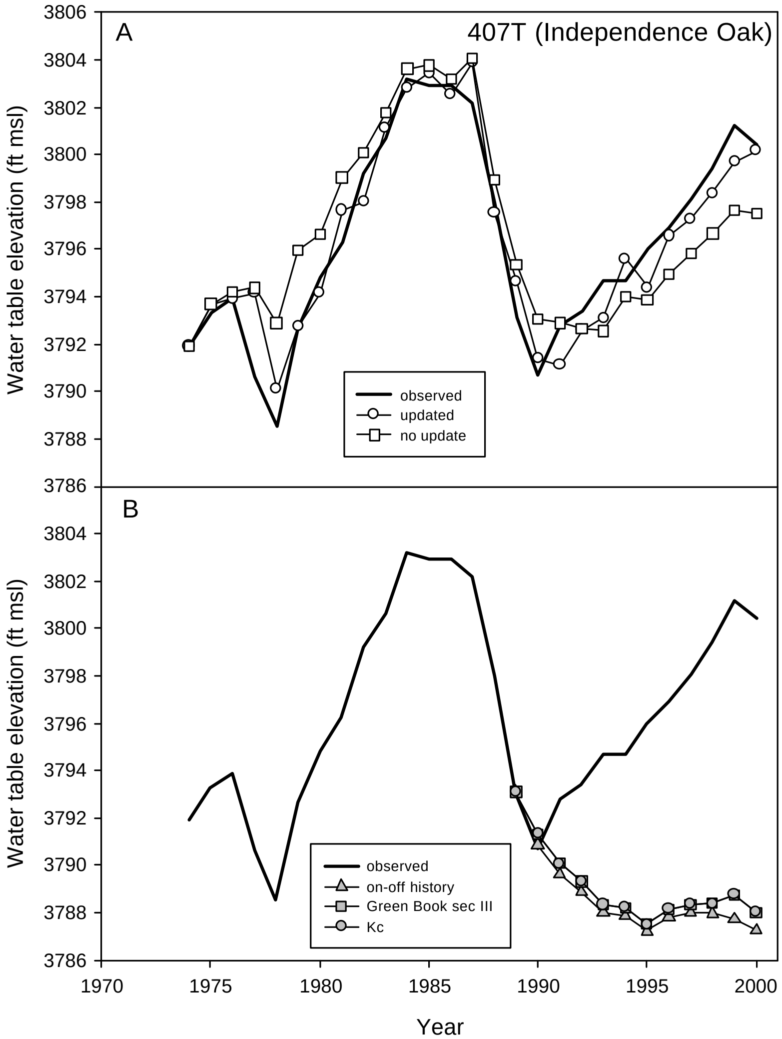

Figure 29. (a.) Indicator well 407T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

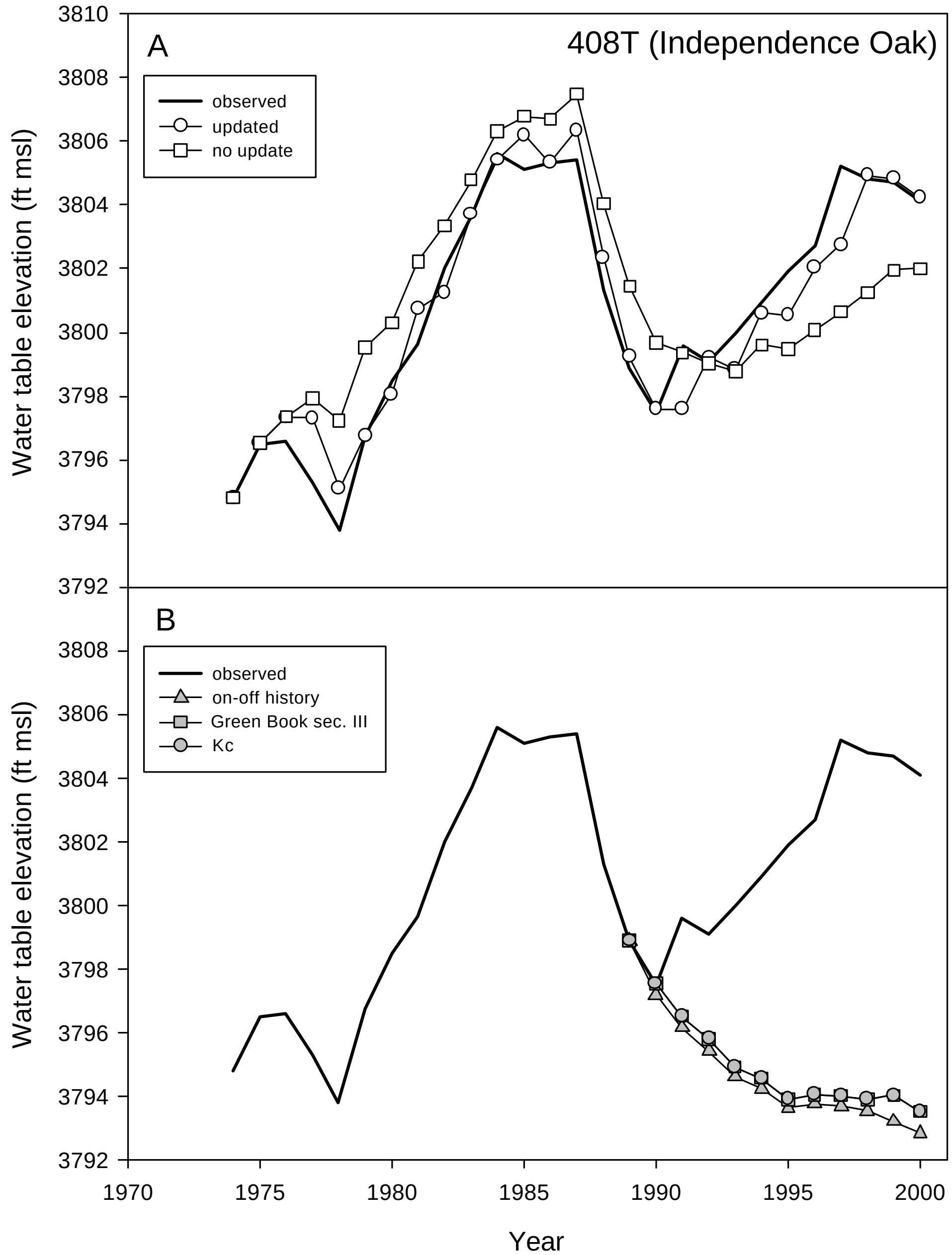

Figure 30. (a.) Indicator well 408T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

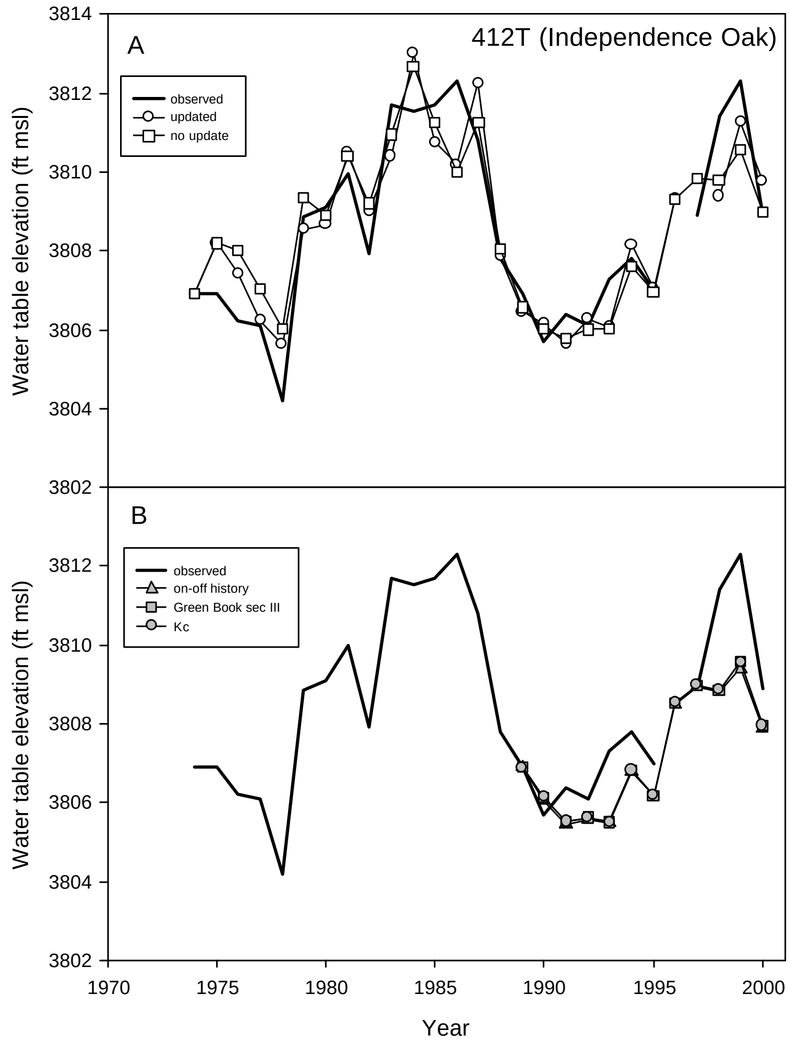

Figure 31. (a.) Indicator well 412T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

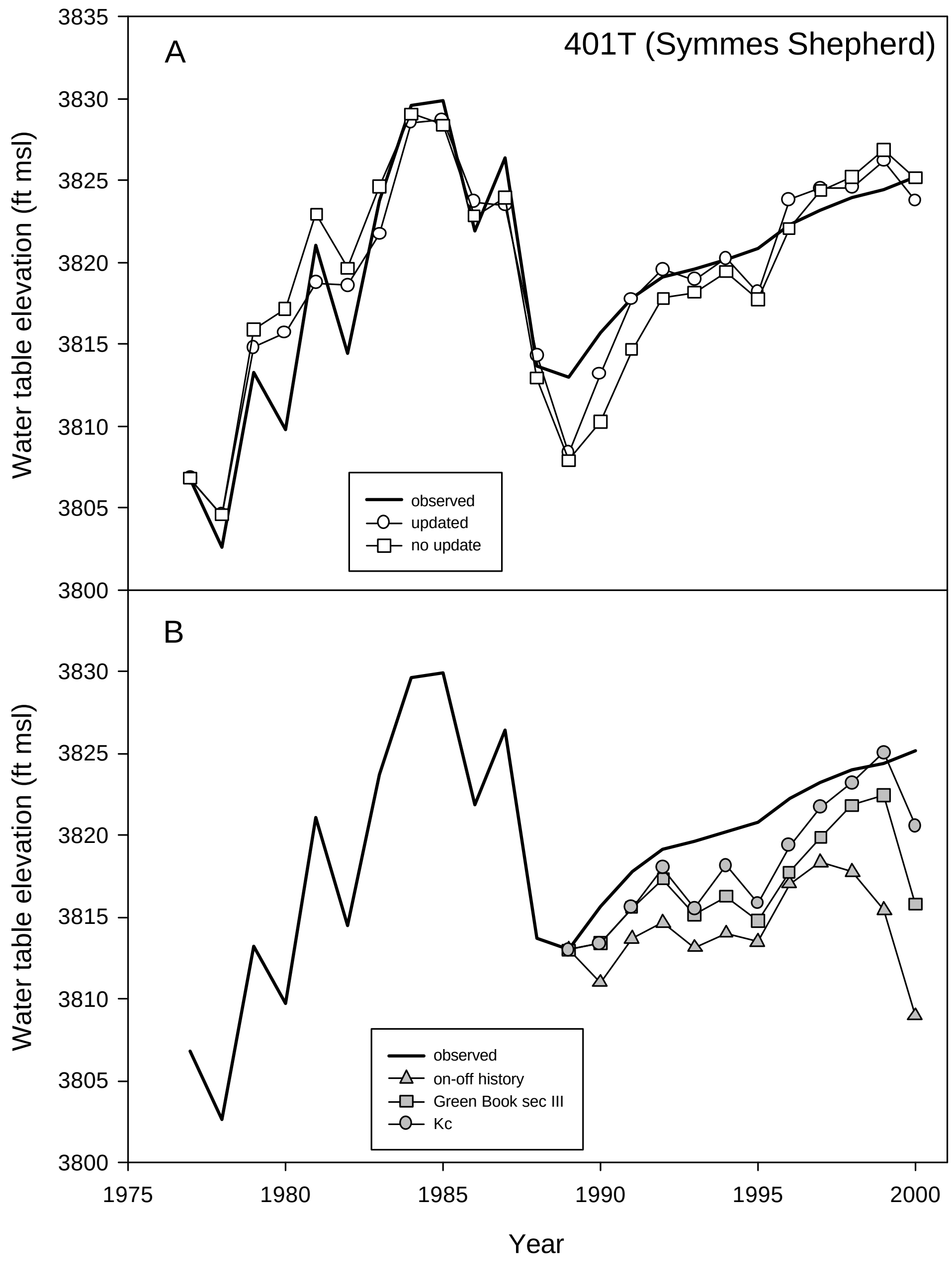

Figure 32. (a.) Indicator well 401T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

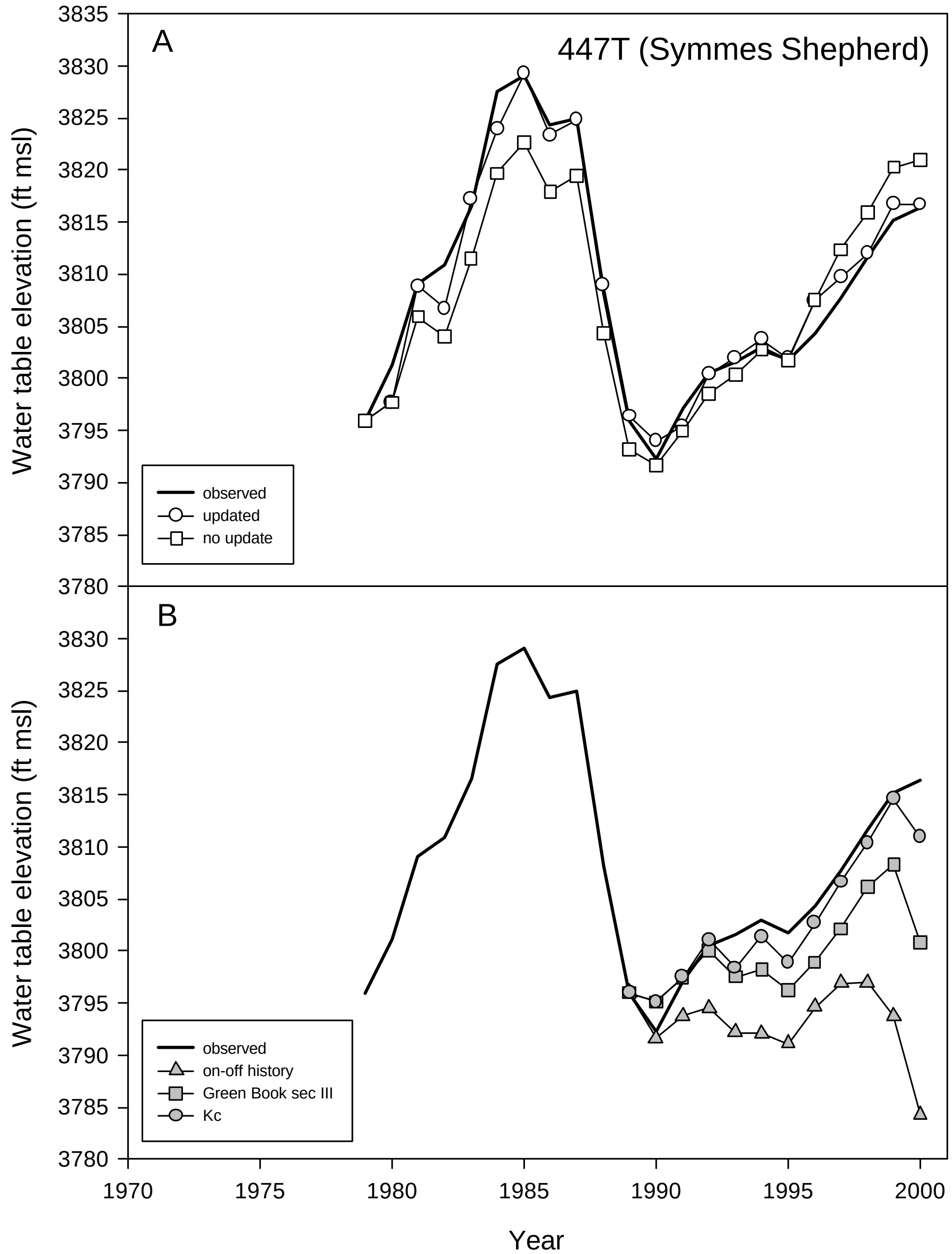

Figure 33. (a.) Indicator well 447T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

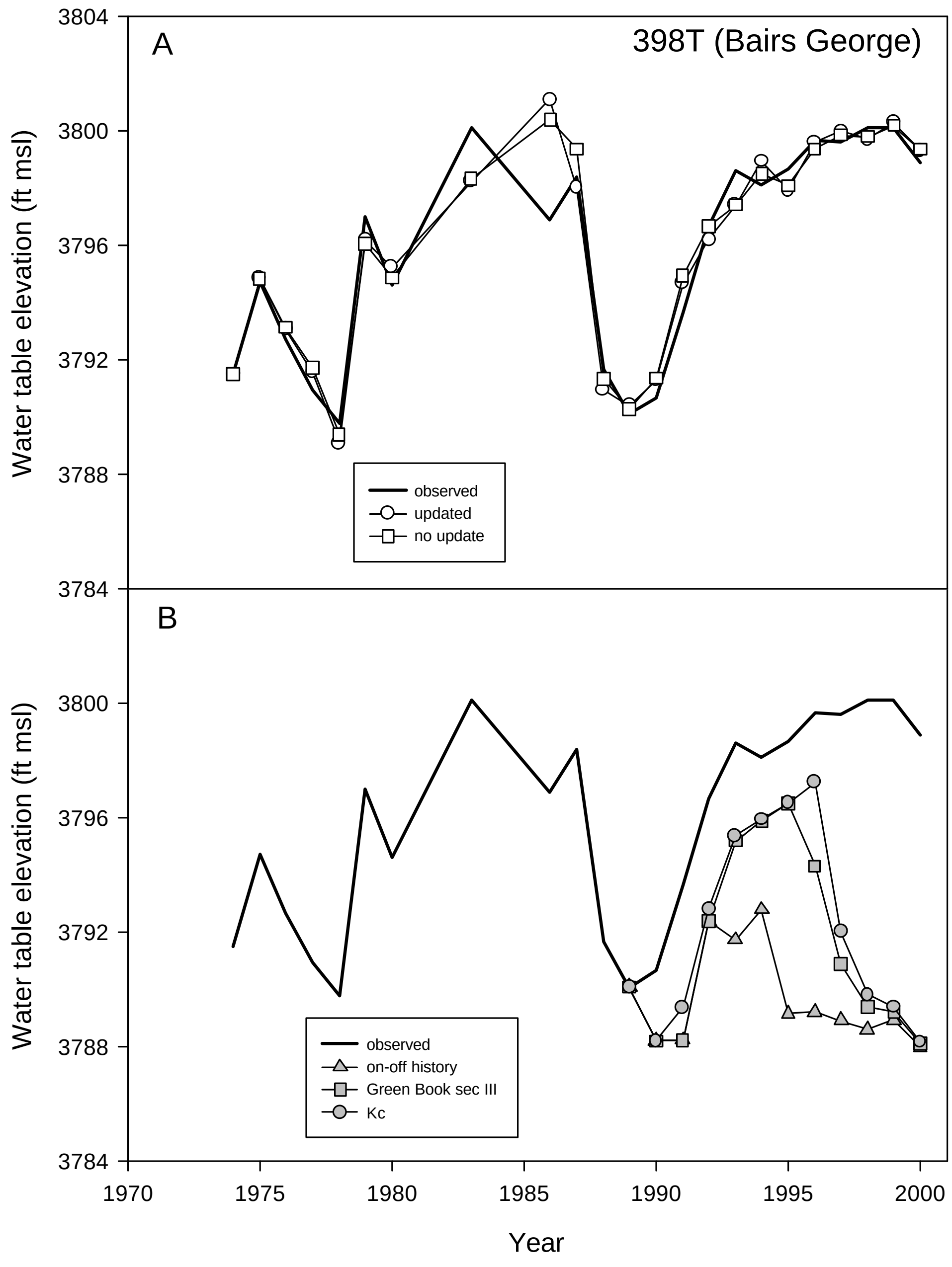

Figure 34. (a.) Indicator well 398T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

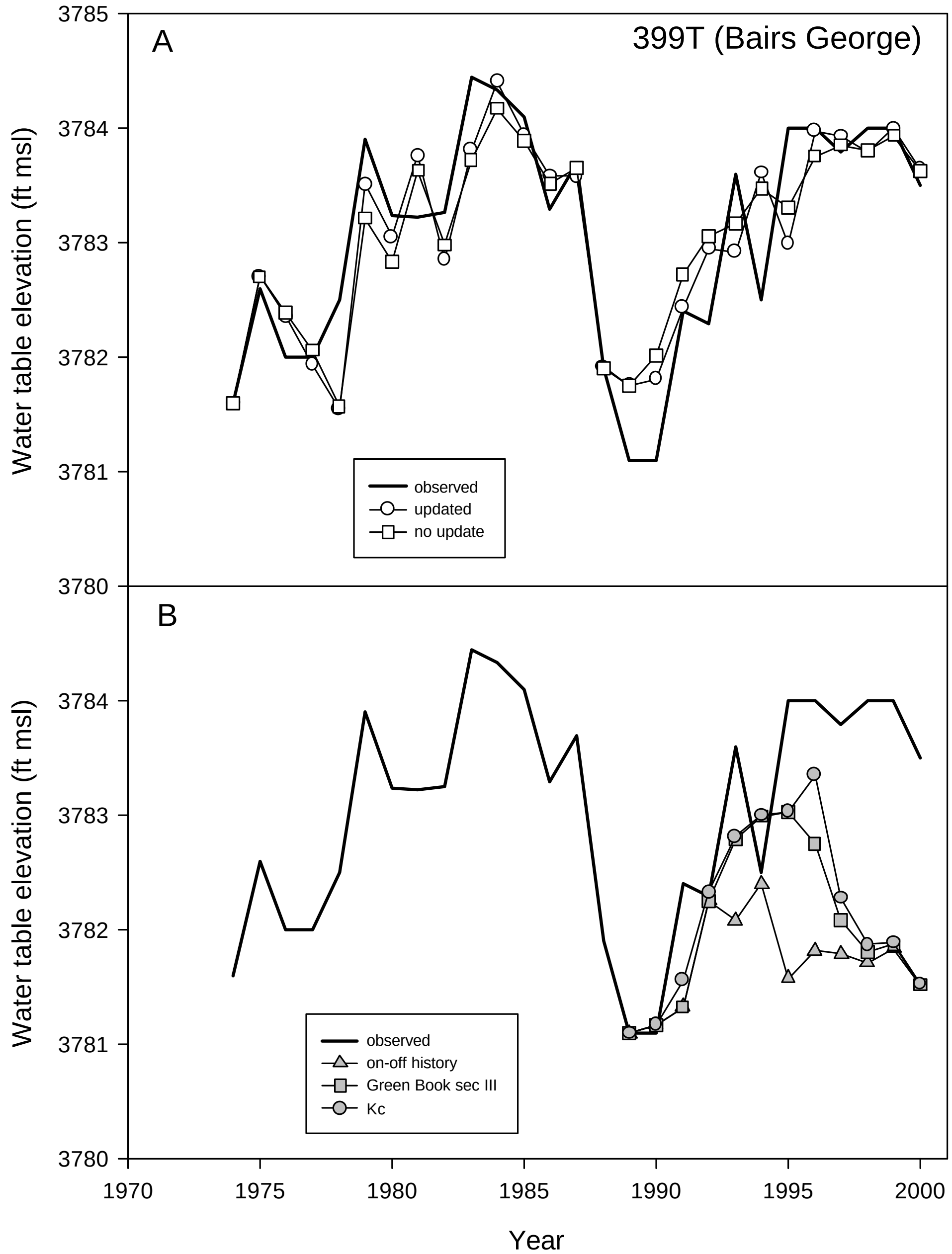

Figure 35. (a.) Indicator well 399T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

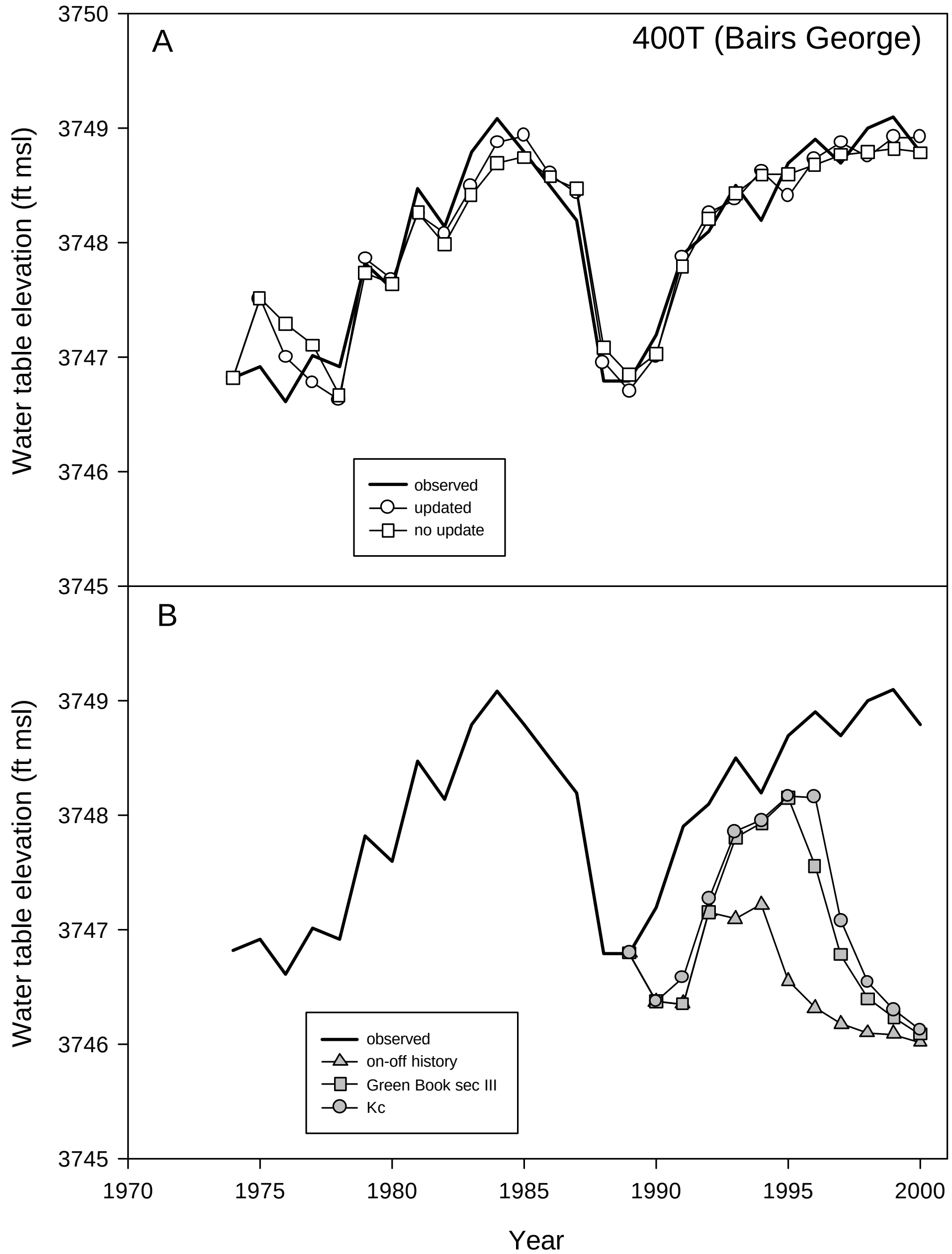

Figure 36. (a.) Indicator well 400T actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

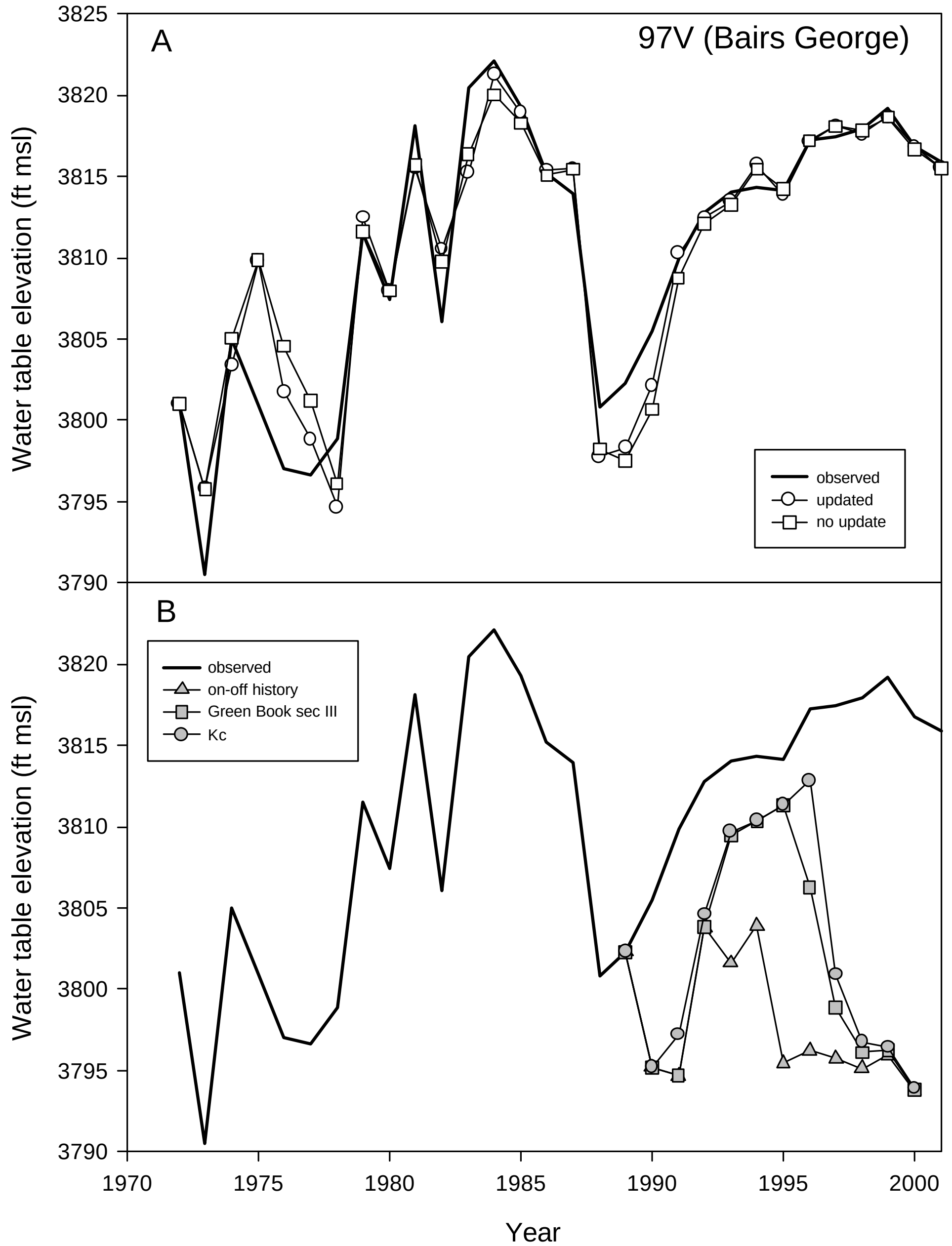

Figure 37. (a.) Indicator well 97V actual and modeled hydrographs and (b) synthetic hydrographs using the estimated allowable pumping for three management scenarios.

CONCLUSIONS AND RECOMMENDATIONS

This analysis showed that the indicator well regression models effectively modeled the history of water table fluctuations and are sufficient to assess how alterations in pumping and/or runoff (or diversions into the McNally canals) would affect water levels over periods of several years. Predictions of the allowable pumping through time must be considered approximate because information how the simulated water levels would have affected monitoring site On/Off status is lacking. The relatively stable number of monitoring sites with On-status under changing soil water and vegetation conditions suggests, however, that this analysis provided a reasonable approximation of the time series of allowable pumping under the various On/Off management scenarios had they been implemented. It is safe to conclude that there would have been less water table recovery had any of the three versions of the Green Book rules for pumping been followed for the period 1989-1999. Qualitatively, this suggests that vegetation recovery under the various forms of On/Off management examined here would have been less than the incomplete recovery achieved under the DRP. In addition, we make the following recommendations:

1. New management procedures should be developed based on water levels, rather than relying solely on measurements of soil water and predicted vegetation water requirements. This study ignored the feedback relationship between On/Off status and water table depth because the technology to model this relationship precisely is difficult and possibly infeasible to construct. We think the feedback is weak; nevertheless, this unavoidable assumption reveals a fundamental uncertainty in any assessment of the environmental consequences of adhering to On/Off procedures. Adding water level information to management decisions would be advantageous because it responds directly to pumping, provides the earliest and most direct warning of a future decrease in subirrigation available to phreatophytes, and can be predicted much more accurately than soil water and vegetation water requirements.

2. The Kc method is based on more extensive data than current methods (Steinwand, 2000b) and should be incorporated into On/Off procedures. These results suggest, however, that simply inserting the Kc estimates into the Green Book procedures is unlikely to protect vegetation from pumping induced water deficits.

3. The cumulative effect of exempt and non-exempt wells should be evaluated and considered when setting annual pumping programs. This will require an assessment of the vulnerability and areal extent of groundwater dependent vegetation as well as computation of the cumulative radii of influence of the wells proposed to be operated.

4. Pumping should be continue to be managed conservatively as was done under the DRP until a new method is developed to manage pumping to replace or augment the On/Off procedures. The On/Off procedures would have produced less water level recovery the 1990's than the DRP casting doubt on the future sustainability of vegetation conditions by following On/Off to govern pumping.

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