Report GAM Run 09-019: Groundwater Model Runs to Estimate Monthly Average Discharge from Barton Springs under Alternative Pumping Scenarios and Alternative Initial Conditions

by William R. Hutchison[1], Ph.D., P.E., P.G.
Melissa E. Hill[2], Ph.D., P.G.
Texas Water Development Board
Groundwater Resources Division
(512) 463-5067[1]
(512) 463-1742[2]

June 1, 2011

STATE OF TEXAS
WILLIAM RAY HUTCHISON
96287
LICENSED
PROFESSIONAL ENGINEER
William R Hutchison
6/1/11

STATE OF TEXAS
WILLIAM R. HUTCHISON
GEOLOGY
286
LICENSED
PROFESSIONAL GEOSCIENTIST
William R Hutchison
6/1/11

STATE OF TEXAS
MELISSA E. HILL
GEOLOGY
1316
LICENSED
PROFESSIONAL GEOSCIENTIST
Melissa E. Hill
6/1/11

The seals appearing on this document were authorized by William R. Hutchison, P.E. 96287, P.G. 286, and Melissa E. Hill, P.G.1316 on June 1, 2011.

REPORT GAM RUN 09-019: GROUNDWATER MODEL RUNS TO ESTIMATE MONTHLY AVERAGE DISCHARGE FROM BARTON SPRINGS UNDER ALTERNATIVE PUMPING SCENARIOS AND ALTERNATIVE INITIAL CONDITIONS

by William R. Hutchison[1], Ph.D., P.E., P.G.
Melissa E. Hill[2], Ph.D., P.G.
Texas Water Development Board
Groundwater Resources Division
(512) 463-5067[1]
(512) 463-1742[2]
June 1, 2011

EXECUTIVE SUMMARY:

A suite of model simulations were run to estimate discharges at Barton Springs under alternative pumping scenarios and alternative initial conditions. Fifteen simulations were completed that involved 3 different initial conditions (low-, intermediate-, and high-flow conditions described in the Methods section) and 5 pumping scenarios with annual averages of 3,847; 4,469; 5,437; 6,796; and 16,311 acre-feet per year. The purpose for these scenarios was to evaluate the effect of antecedent conditions and pumping on spring flow. Each of these scenarios included 342 7-year simulations extending from 1648 through 1995 for a total of 28,728 months.

Results for the simulations showed that simulated discharges for Barton Springs at or below 11 cubic-feet per second (equivalent to the estimated minimum discharges during the 1950 to 1956 drought-of-record) occurred at a relative frequency of 5 percent using starting heads at low-flow conditions and an annual average pumpage of 6,796 acre-feet per year with the 2002 well spatial distribution. The 2002 well spatial distribution is assumed to be comparable to current groundwater withdrawal rates. Discharges from Barton Springs at or below 9 cubic-feet per second occurred at a relative frequency of 4 percent, followed by 2 percent or less for 7, 5, and 3 cubic-feet per second. The relative frequency for simulating discharges at or below 11 cubic-feet per second decreases to 0 percent using an annual average pumpage of 6,796 acre-feet per year with starting heads at intermediate- or high-flow conditions.

Simulated discharges from Barton Springs at or below 11 cubic-feet per second for 3 or more consecutive months occurred at a relative frequency of 3 percent using starting heads at low-flow conditions with an annual average pumpage of 6,796 acre-feet per year with the 2002 well spatial distribution. Discharges at or below 9 cubic-feet per second for 3 or more consecutive months occurred at a relative frequency of 2 percent, using those same starting head conditions, pumpage quantities and distributions, followed by 1 percent or less for 7, 5, and 3 cubic-feet per second. The relative frequency for simulating discharges at or below 11 cubic-feet per second for 3 or more consecutive months decreases to 0 percent using an annual average pumpage of 6,796 acre-feet per year with starting heads at intermediate- or high-flow conditions.

Simulated discharges from Barton Springs were most sensitive to changes in starting head conditions using 4 out of the 5 pumping scenarios, specifically, those with annual averages of 3,847; 4,469; 5,437; and 6,796 acre-feet per year. The exception to this was the pumping dataset with an annual average pumpage of 16,311 acre-feet per year. Simulated discharges were less sensitive to starting head conditions and more sensitive to pumping under this pumping scenario.

REQUESTOR:

Mr. Rick Illgner (of the Edwards Aquifer Authority) on behalf of Groundwater Management Area 10.

DESCRIPTION OF REQUEST:

Mr. Illgner requested a model run with monthly average discharges from Barton Springs of 11, 9, 7, 5, and 3 cubic-feet per second during a drought-of-record using a groundwater flow model calibrated to the 1950 through 1956 drought-of-record.

METHODS:

The existing groundwater availability model for the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer (Scanlon and others, 2001) was calibrated based on data from 1989 to 1998. Thus, the calibration did not include the historic drought-of-record that lasted from 1950 through 1956, when the estimated minimum discharges of 11 cubic-feet per second occurred at Barton Springs. Due to the nature of the model run request, it was apparent that the confidence in results from the existing model would be lower than results from a model that had been calibrated during the drought-of-record period. In order to develop results that would be more useful, the existing model was recalibrated for the period January 1943 to December 2004 (Hutchison and Hill, in preparation). The recalibrated model consists of 745 monthly stress periods. The first stress period is set to steady-state conditions with the remaining 744 monthly stress periods set to transient conditions. The model was calibrated using 152 target wells from the Texas Water Development Board groundwater database and estimated/measured springflows provided by the Barton Springs/Edwards Aquifer Conservation District. Simulated discharges at Barton Springs using the recalibrated model satisfactorily simulate the minimum estimated discharges of 11 cubic-feet per second that occurred during the historic drought-of-record in July and August of 1956.

This suite of simulations consisted of a 3 by 5 matrix (15 scenarios) with three different starting head conditions using low-, intermediate-, and high-flow conditions, and five annual average pumping datasets with quantities of 3,847; 4,469; 5,437; 6,796; and 16,311 acre-feet per year. Each of the scenarios included 342 7-year simulations extending from 1648 through 1995 based on a tree-ring dataset from Cleaveland (2006). Every 7-year simulation consisted of 84 monthly stress periods. The purpose for these scenarios was to evaluate the effect of starting heads or flow conditions at the start of a drought and pumpage on simulated discharges.

Simulated heads for February 1957 from the recalibrated model were used as the low-flow starting head conditions. Simulated heads for June 1992 were selected as the starting heads for high-flow conditions, and January 2004 simulated heads were selected for our intermediate-flow starting heads.

Groundwater pumping scenarios were developed based on pumping quantities and their distributions simulated in 1982, 1987, and 2002 from the recalibrated model's well package. The 2002 pumping was multiplied by a factor of 1.25 and 3 to achieve 2 additional well datasets.

The recalibrated model used a series of rainfall-recharge regression relationships to drive recharge estimates. In order to develop recharge estimates for the simulations, rainfall values were based on reconstructed values of rainfall for 1648 through 1995 based on the composite of 6 post oak tree-ring chronologies for South Central Texas (Cleaveland, 2006). For example, if the annual average reconstructed rainfall for 1648 is 12.9 inches and the average annual reconstructed rainfall for 1648 through 1995 is 15.4 inches per year, then the percent of rainfall for 1648 is 84 percent. A lookup table of the rainfall values used in the recalibrated model which extends from January 1943 through December 2004 was created. If the annual average rainfall percentage for a given year in the recalibrated model matched the percentage for a given year based on the reconstructed value using the tree-ring record, then the regression relationship developed for the precipitation indices for each recharge zone in the recalibrated model was used to generate a monthly rainfall rate that would be used for the drought-of-record simulations. The recharge zones roughly correlate to the various sub-watersheds that occur where the Edwards (Balcones Fault Zone) Aquifer is exposed at land surface. If an exact match was not identified, then the next closest match was selected and adjusted, or scaled to match the percentage based on the reconstructed values using the tree-ring record.

MODEL DESCRIPTION:

The recalibrated model for the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer (Hutchison and Hill, in preparation) was used for this analysis:

- the model consists of one layer representing the Edwards (Balcones Fault Zone) Aquifer. The first stress period of the model is set to steady-state conditions with the remaining 744 monthly stress periods set to transient conditions,
- the calibrated time frame for the model extends from January 1943 through December 2004, including the historic 7-year drought-of-record that lasted from 1950 through 1956,
- simulated discharges at Barton Springs using the transient model satisfactorily match the minimum estimated discharges of 11 cubic-feet per second that occurred in July and August of 1956,
- the absolute residual mean for 152 target wells is 31 feet, and the standard deviation divided by the range is 0.096,
- additional information regarding the recalibrated transient model will be provided in a separate model report (Hutchison and Hill, in preparation),
- we used the MODFLOW-2000 (Harbaugh and others, 2000) groundwater flow simulator with the Geometric Multigrid (GMG) solver (Wilson and Naff, 2004) for model calibration and for simulations requested by Groundwater Management Area 10,
- there are four main components to the water budget in the recalibrated Barton Springs model: recharge, pumpage, discharge to springs, and storage change,

- recharge (inflows) includes both focused recharge at karst features along Onion, Little Bear, Bear, Slaughter, Williamson, and Barton creeks, in addition to distributed rainfall falling on the outcrop area. Recharge was simulated using the MODFLOW Recharge Package,

- pumpage (outflows) refers to both domestic (rural) and non-domestic (point) groundwater well withdrawals. Wells were simulated using the MODFLOW Well Package,

- discharge (outflows) refers to springflows at Barton and Cold Springs. Discharge was simulated using the MODFLOW Drain Package. In the recalibrated model, discharge is the larger component of outflows relative to pumpage,

- storage change refers to the difference between inflows (recharge) and outflows (pumpage and discharge). Negative values indicate water is being removed from storage, whereas positive values indicate water is being added to storage.

RESULTS:

Figure 1 show the curves for the relative frequency of monthly simulated discharges at or below 11, 9, 7, 5, and 3 cubic-feet per second for each of the starting head conditions (low-, intermediate-, and high-flow conditions) using annual groundwater withdrawal quantities of 3,847; 4,469; 5,437; 6,796; and 16,311 acre-feet per year. Results show that simulated discharges at or below 11 cubic-feet per second, which are equivalent to the estimated minimum discharges during the 1950 to1956 drought-of-record, occurred at a relative frequency of 5 percent with an annual pumpage of 6,796 acre-feet per year using the 2002 well spatial distribution and starting heads at low-flow conditions. Discharges at or below 9 cubic-feet per second occurred at a relative frequency of 4 percent, using those same starting heads, pumpage quantities and distributions, followed by 2 percent or less for 7, 5, and 3 cubic-feet per second. However, using an annual pumpage of 16,311 acre-feet per year with the 2002 well spatial distribution and starting heads at low- flow conditions, increased the relative frequency of simulated discharges at or below 11 cubic-feet per second to 17 percent. The relative frequency for simulating discharges at or below 11 cubic-feet per second decreases to 0 percent using an annual average pumpage of 6,796 acre-feet per year with starting heads at intermediate- or high-flow conditions. Relative frequencies of simulating discharges at or below 11, 9, 7, 5, and 3 cubic-feet per second for each of the starting head conditions and well datasets are summarized in Table 1.

Plots of simulated discharges (at and below 15 cubic-feet per second) versus annual average pumping with starting heads at low-, intermediate-, and high-flow conditions are shown in Figure 2. Note the dataset with the highest pumping quantities (16,311 acre-feet per year) simulates a cessation of flow regardless of the starting head conditions.

Curves for the relative frequency of simulated discharges for 3 or more consecutive months at or below 11, 9, 7, 5, and 3 cubic-feet per second are shown in Figure 3 for each of the starting head conditions (low-, intermediate-, and high-flow conditions) using annual average groundwater withdrawal quantities of 3,847; 4,469; 5,437; 6,796; and 16,311 acre-feet per year. Results indicate that these longer duration low discharge events typically occur less frequently than the shorter duration (month) low discharge events previously discussed. For example, simulated discharges at or below 11 cubic-feet per second for 3 or more consecutive months occurred at a relative frequency of 3 percent using starting heads at low-flow conditions with an annual average pumpage of 6,796 acre-feet per year with the 2002 well spatial distribution. Discharges at or below 9 cubic-feet per second for 3 or more consecutive months occurred at a relative frequency of 2 percent, using those same starting head conditions, pumpage quantities and distributions, followed by 1 percent or less for 7, 5, and 3 cubic-feet per second. The relative frequency of simulated discharges at or below 11 cubic-feet per second for 3 or more consecutive months using the dataset with an annual average pumpage of 16,311 acre-feet per year with the 2002 well spatial distribution is 12 percent. The relative frequency for simulating discharges, for 3 or more consecutive months, at or below 11 cubic-feet per second decreases to 0 percent using an annual average pumpage of 6,796 acre-feet per year with starting heads at intermediate- or high-flow conditions. Relative frequencies of simulating discharges for 3 or more consecutive months at or below 11, 9, 7, 5, and 3 cubic-feet per second for each of the starting head conditions and well datasets are summarized in Table 2.

The results suggest that simulated discharges are more sensitive to starting head conditions for 4 out of the 5 well datasets (Figure 4). However, simulated discharges become more sensitive to groundwater pumping under higher pumping scenarios.

CONCLUSIONS:

Based on the results from these analyses, significant increases from current annual average pumpage quantities would likely increase the relative frequency (percent) of low discharge events during a drought periods regardless of the antecedent conditions. Also, the simulated results presented in these analyses will likely differ if point or non-domestic groundwater withdrawal quantities increase appreciably near the head springs due to capture (Bredehoeft and Durbin, 2009).

LIMITATIONS:

The groundwater model used in completing this analysis is the best available scientific tool that can be used to meet the stated objective(s). To the extent that this analysis will be used for planning purposes and/or regulatory purposes related to pumping in the past and into the future, it is important to recognize the assumptions and limitations associated with the use of the results. In reviewing the use of models in environmental regulatory decision making, the National Research Council (2007) noted:

> "Models will always be constrained by computational limitations, assumptions, and knowledge gaps. They can best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. Scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or to prove that a given model is correct in all respects for a particular regulatory application. These characteristics make evaluation of a regulatory model more complex than solely a comparison of measurement data with model results."

A key aspect of using the groundwater model to evaluate historic groundwater flow conditions includes the assumptions about the location in the aquifer where historic pumping was placed. Understanding the amount and location of historic pumping is as important as evaluating the volume of groundwater flow into and out of the district, between aquifers within the district (as applicable), interactions with surface water (as applicable), recharge to the aquifer system (as applicable), and other metrics that describe the impacts of that pumping. In addition, assumptions regarding precipitation, recharge, and streamflow are specific to a particular historic time period.

Because the application of the groundwater model was designed to address regional scale questions, the results are most effective on a regional scale. The TWDB makes no warranties or representations relating to the actual conditions of any aquifer at a particular location or at a particular time.

It is important for groundwater conservation districts to monitor groundwater pumping and overall conditions of the aquifer. Because of the limitations of the groundwater model and the assumptions in this analysis, it is important that the groundwater conservation districts work with the TWDB to refine this analysis in the future given the reality of how the aquifer responds to the actual amount and location of pumping now and in the future. Historic precipitation patterns also need to be placed in context as future climatic conditions, such as dry and wet year precipitation patterns, may differ and affect groundwater flow conditions.

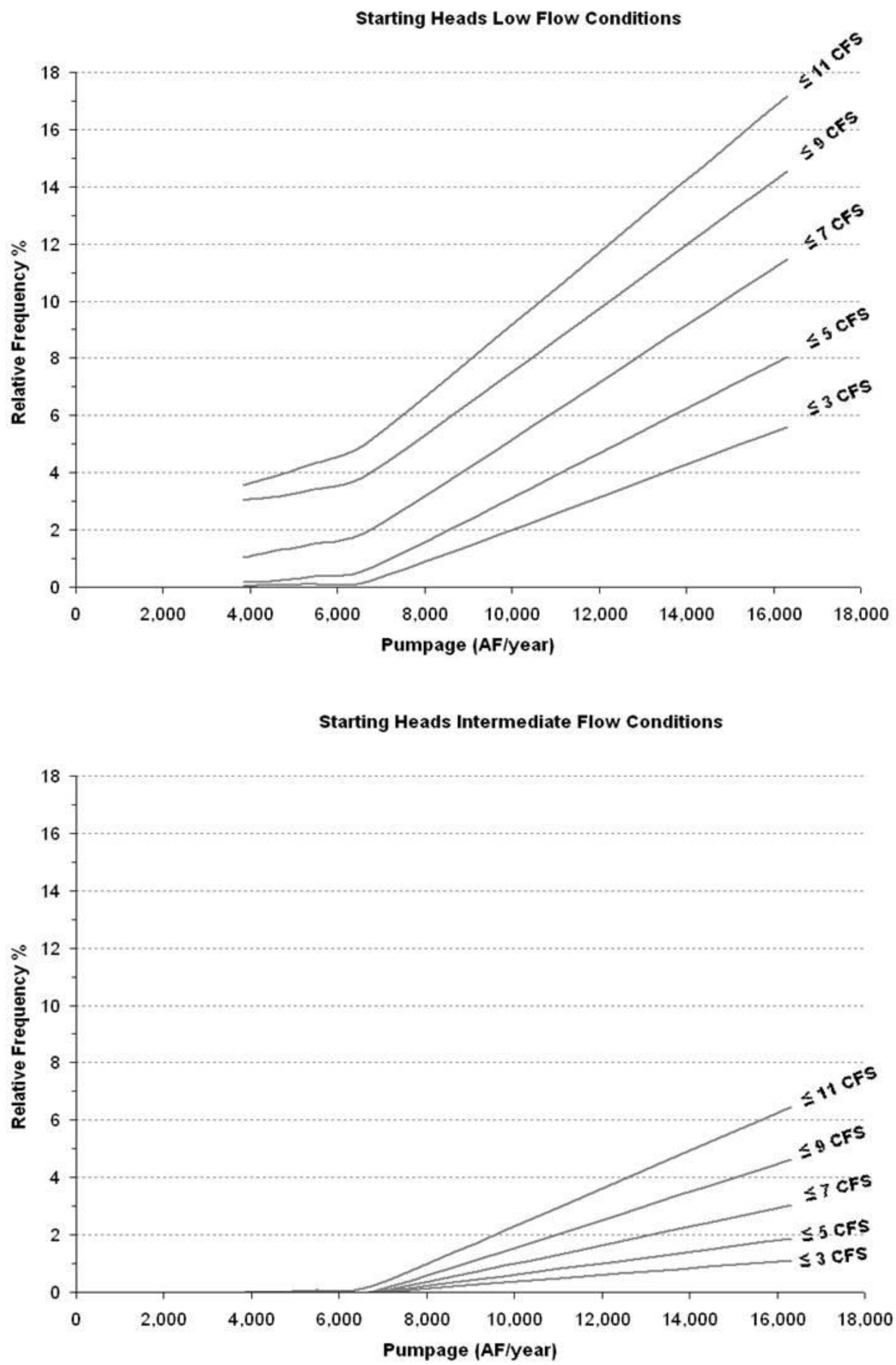


Figure 1. Curves for annual average pumpage (acre-feet per year) versus the relative frequency (percent) for 11, 9, 7, 5, and 3 cubic-feet per second with starting heads at low-flow conditions (top) and intermediate-flow conditions (bottom).

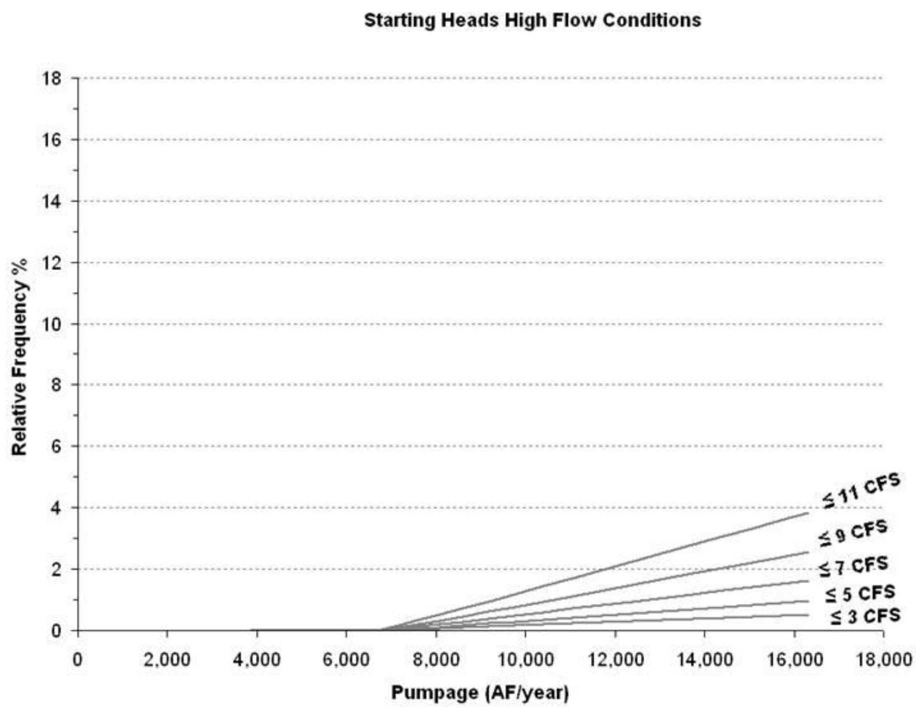


Figure 1 (continued). Curves for annual average pumpage (acre-feet per year) versus the relative frequency (percent) of simulated discharges at or below 11, 9, 7, 5, and 3 cubic-feet per second with starting heads at high-flow conditions.

Table 1. Summary of starting head conditions, annual average pumpage, frequency of months simulated at or below 11 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 11 cubic-feet per second. Total number of months simulated was 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of months simulated at 11 cubic-feet per second or lower	Relative frequency (percent) of months at 11 cubic-feet per second or lower
Low	3,847	1,026	4
	4,469	1,099	4
	5,437	1,245	4
	6,796	1,491	5
	16,311	4,930	17
Intermediate	3,847	0	0
	4,469	4	0
	5,437	18	0
	6,796	70	0
	16,311	1,857	6
High	3,847	0	0
	4,469	0	0
	5,437	1	0
	6,796	10	0
	16,311	1,102	4

Table 1 (continued). Summary of starting head conditions, annual average pumpage, frequency of months simulated at or below 9 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 9 cubic-feet per second. Total number of months simulated was 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of months simulated at 9 cubic-feet per second or lower	Relative frequency (percent) of months at 9 cubic-feet per second or lower
Low	3,847	869	3
	4,469	906	3
	5,437	983	3
	6,796	1,157	4
	16,311	4,181	15
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	13	0
	16,311	1,328	5
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	736	3

Table 1 (continued). Summary of starting head conditions, annual average pumpage, frequency of months simulated at or below 7 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 7 cubic-feet per second. Total number of months simulated was 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of months simulated at 7 cubic-feet per second or lower	Relative frequency (percent) of months at 7 cubic-feet per second or lower
Low	3,847	294	1
	4,469	356	1
	5,437	438	2
	6,796	582	2
	16,311	3,292	11
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	870	3
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	470	2

Table 1 (continued). Summary of starting head conditions, annual average pumpage, frequency of months simulated at or below 5 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 5 cubic-feet per second. Total number of months simulated was 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of months simulated at 5 cubic-feet per second or lower	Relative frequency (percent) of months at 5 cubic-feet per second or lower
Low	3,847	49	0
	4,469	62	0
	5,437	109	0
	6,796	200	1
	16,311	2,308	8
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	539	2
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	278	1

Table 1 (continued). Summary of starting head conditions, annual average pumpage, frequency of months simulated at or below 3 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 3 cubic-feet per second. Total number of months simulated was 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of months simulated at 3 cubic-feet per second or lower	Relative frequency (percent) of months at 3 cubic-feet per second or lower
Low	3,847	6	0
	4,469	15	0
	5,437	30	0
	6,796	66	0
	16,311	1,605	6
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	316	1
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	153	1

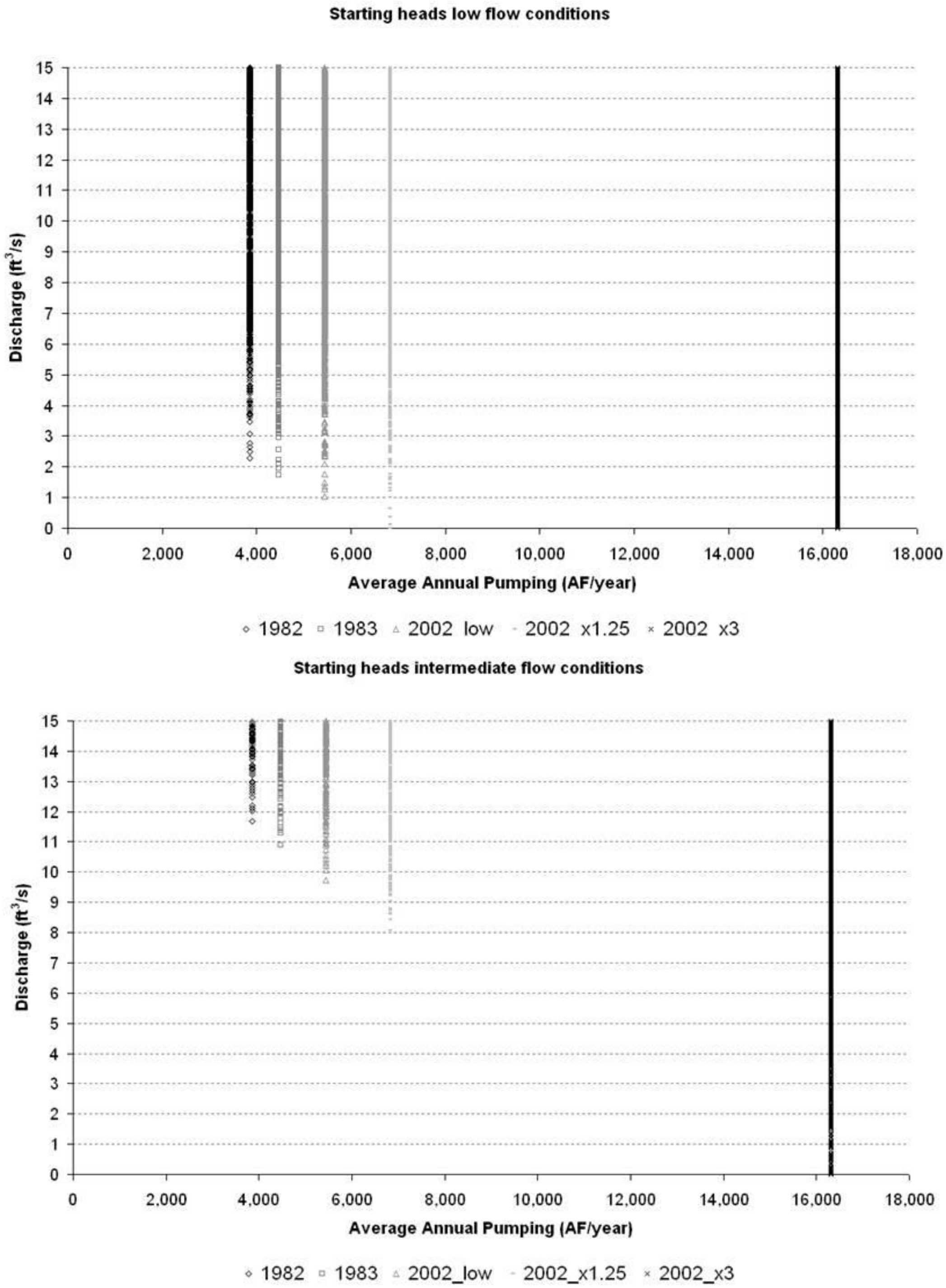


Figure 2. Plot of simulated discharges at 15 cubic-feet per second or below versus pumpage with starting heads at low-flow conditions (top) and intermediate-flow conditions (bottom).

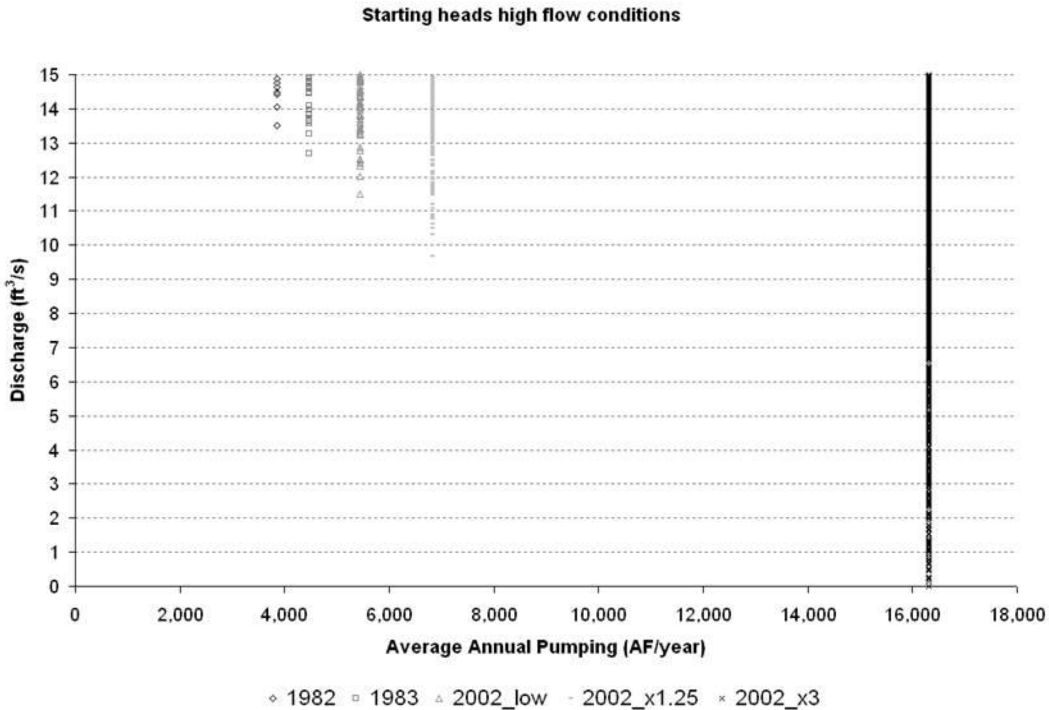


Figure 2 continued. Plot of simulated discharges at 15 cubic-feet per second or below versus pumpage with starting heads at high-flow conditions.

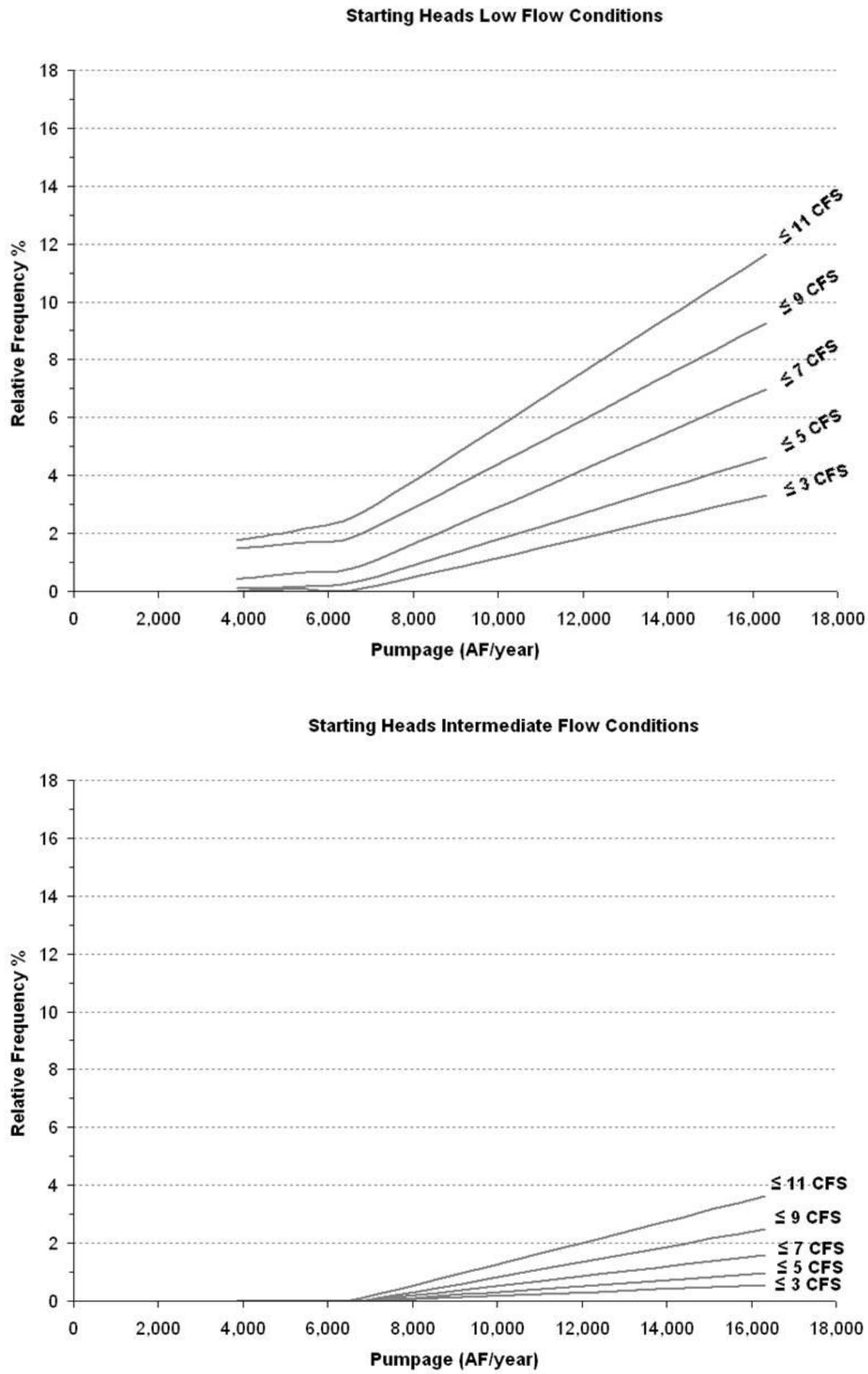


Figure 3. Curves for annual average pumpage (acre-feet per year) versus the relative frequency (percent) of simulated discharges for 3 or more consecutive months at or

below 11, 9, 7, 5, and 3 cubic-feet per second with starting heads at low-flow conditions (top) and intermediate-flow conditions (bottom).

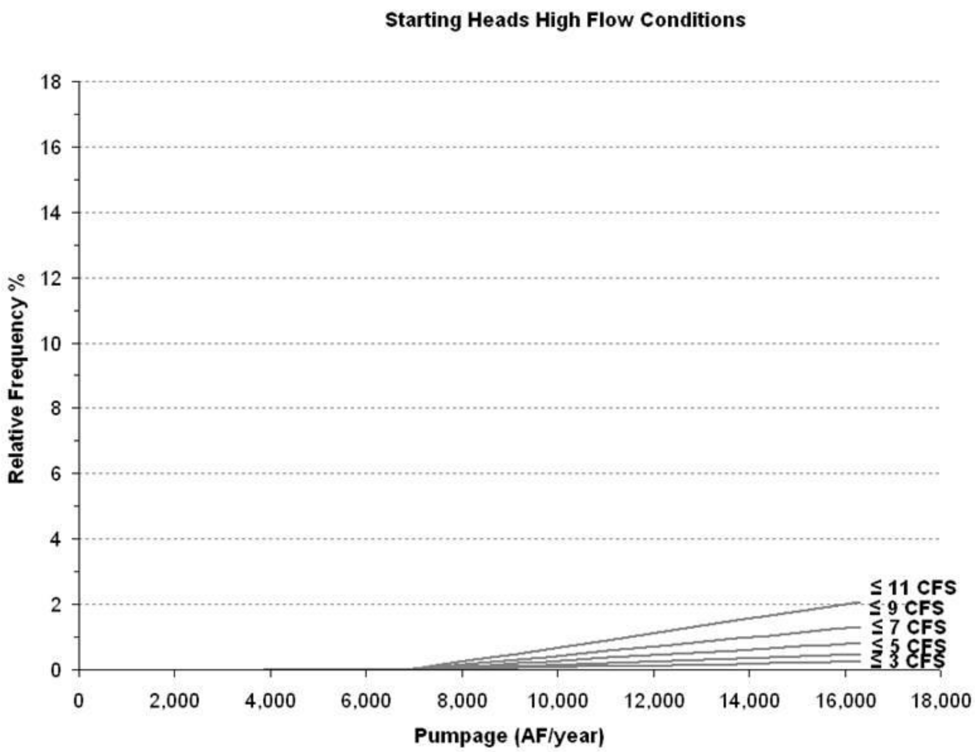


Figure 3 continued. Curves for annual average pumpage (acre-feet per year) versus the relative frequency (percent) of simulated discharges for 3 or more consecutive months at or below 11, 9, 7, 5, and 3 cubic-feet per second with starting heads at high-flow conditions.

Table 2. Summary of starting head conditions, annual average pumpage, frequency of 3 or more consecutive months simulated at or below 11 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 11 cubic-feet per second. Total number of months simulated is 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of 3 or more consecutive months simulated at 11 cubic-feet per second or lower	Relative frequency (percent) of 3 or more consecutive months at 11 cubic-feet per second or lower
Low	3,847	511	2
	4,469	545	2
	5,437	625	2
	6,796	786	3
	16,311	3,342	12
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	25	0
	16,311	1,041	4
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	600	2

Table 2 (continued). Summary of starting head conditions, annual average pumpage, frequency of 3 or more consecutive months simulated at or below 9 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 9 cubic-feet per second. Total number of months simulated is 28,728.

Starting heads	Annual average pumpage(acre-feet per year)	Frequency of 3 or more consecutive months simulated at 9 cubic-feet per second or lower	Relative frequency (percent) of 3 or more consecutive months at 9 cubic-feet per second or lower
Low	3,847	422	1
	4,469	447	2
	5,437	489	2
	6,796	574	2
	16,311	2,659	9
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	711	2
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	378	1

Table 2 (continued). Summary of starting head conditions, annual average pumpage, frequency of 3 or more consecutive months simulated at or below 7 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 7 cubic-feet per second. Total number of months simulated is 28,728.

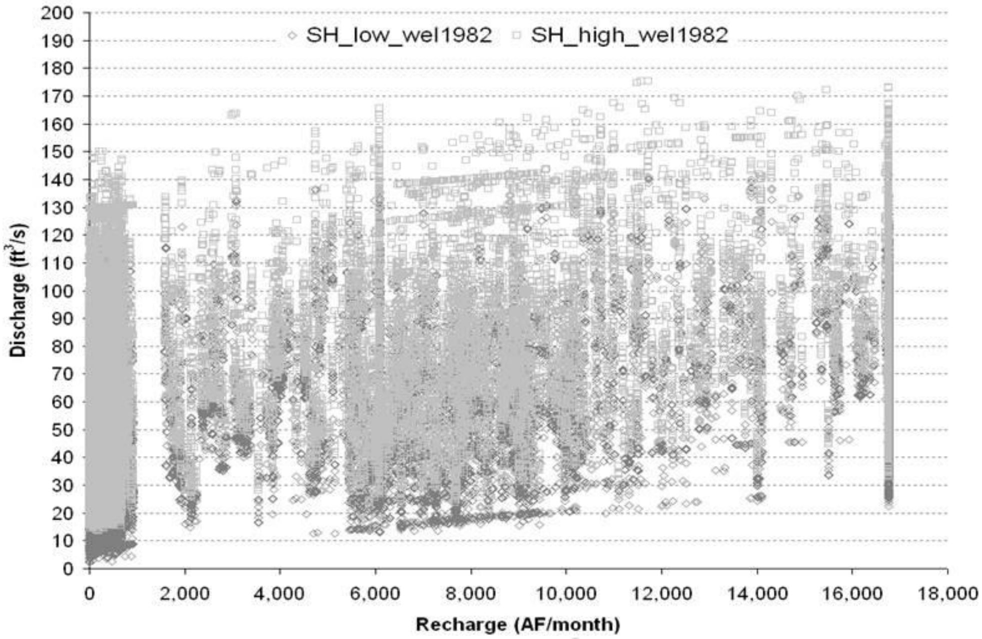
Starting heads	Annual average pumpage(acre-feet per year)	Frequency of 3 or more consecutive months simulated at 7 cubic-feet per second or lower	Relative frequency (percent) of 3 or more consecutive months at 7 cubic-feet per second or lower
Low	3,847	123	0
	4,469	149	1
	5,437	193	1
	6,796	262	1
	16,311	2,006	7
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	453	2
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	237	1

Table 2 (continued). Summary of starting head conditions, annual average pumpage, frequency of 3 or more consecutive months simulated at or below 5 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 5 cubic-feet per second. The total number of months simulated is 28,728.

Starting heads	Annual average pumpage(acre-feet per year)	Frequency of 3 or more consecutive months simulated at 5 cubic-feet per second or lower	Relative frequency (percent) of 3 or more consecutive months at 5 cubic-feet per second or lower
Low	3,847	27	0
	4,469	34	0
	5,437	52	0
	6,796	109	0
	16,311	1,328	5
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	277	1
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	140	0

Table 2 (continued). Summary of starting head conditions, annual average pumpage, frequency of 3 or more consecutive months simulated at or below 3 cubic-feet per second, and the relative frequency (percent) of months simulated at or below 3 cubic-feet per second. The total number of months simulated is 28,728.

Starting heads	Annual average pumpage (acre-feet per year)	Frequency of 3 or more consecutive months simulated at 3 cubic-feet per second or lower	Relative frequency (percent) of 3 or more consecutive months at 3 cubic-feet per second or lower
Low	3,847	4	0
	4,469	5	0
	5,437	18	0
	6,796	31	0
	16,311	955	3
Intermediate	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	160	1
High	3,847	0	0
	4,469	0	0
	5,437	0	0
	6,796	0	0
	16,311	69	0



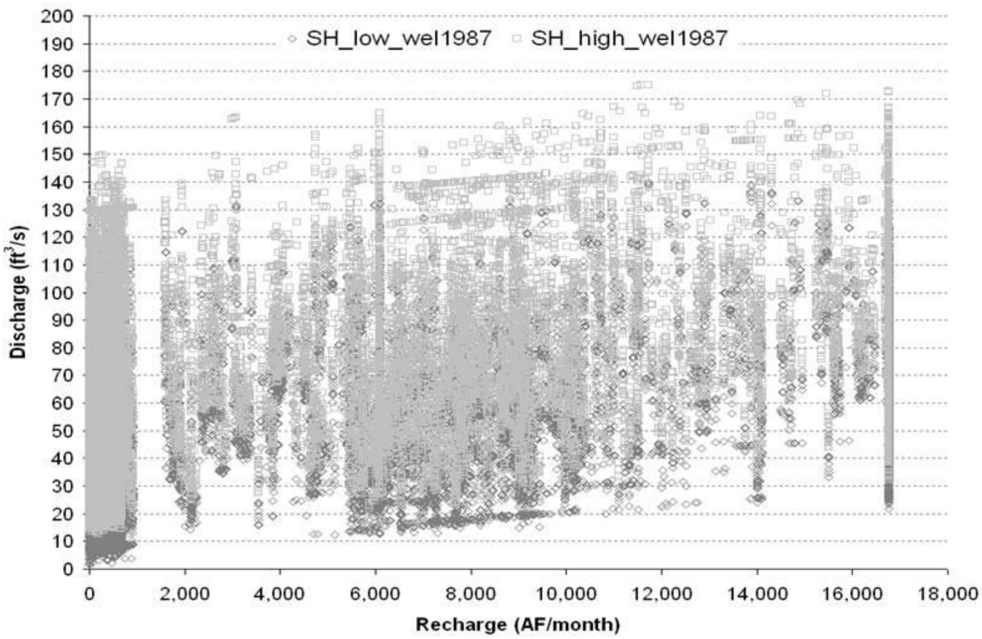


Figure 4. Plots of recharge versus simulated discharges for starting heads at low- and high-flow conditions with the 1982 (3,847 acre-feet) and 1987 (4,469 acre-feet) pumpage quantities.

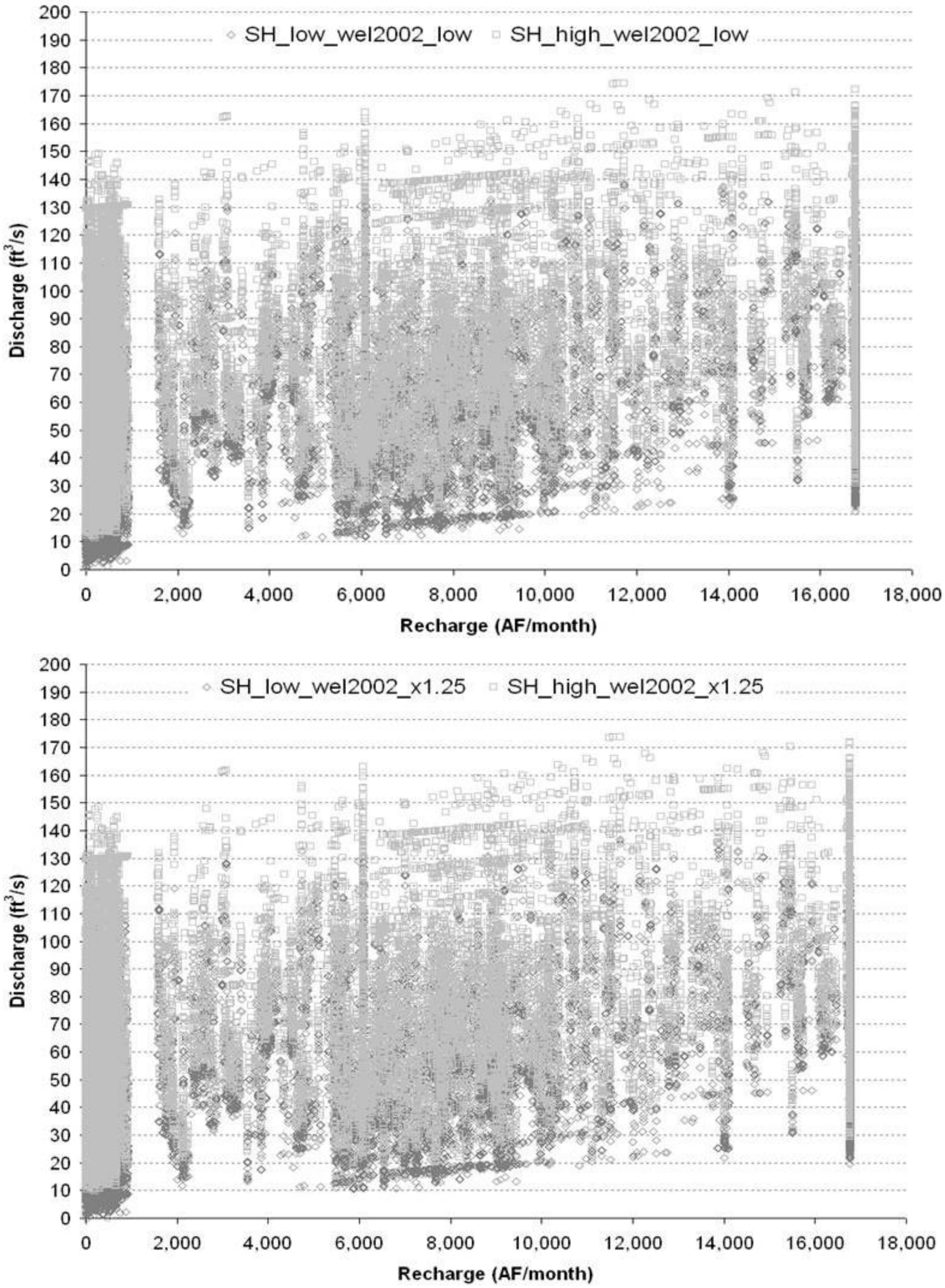


Figure 4 continued. Plots of recharge versus simulated discharges for starting heads at low- and high-flow conditions with the 2002 low (5,437 acre-feet) and 2002 low pumpage quantities multiplied by a factor of 1.25 (6,796 acre-feet).

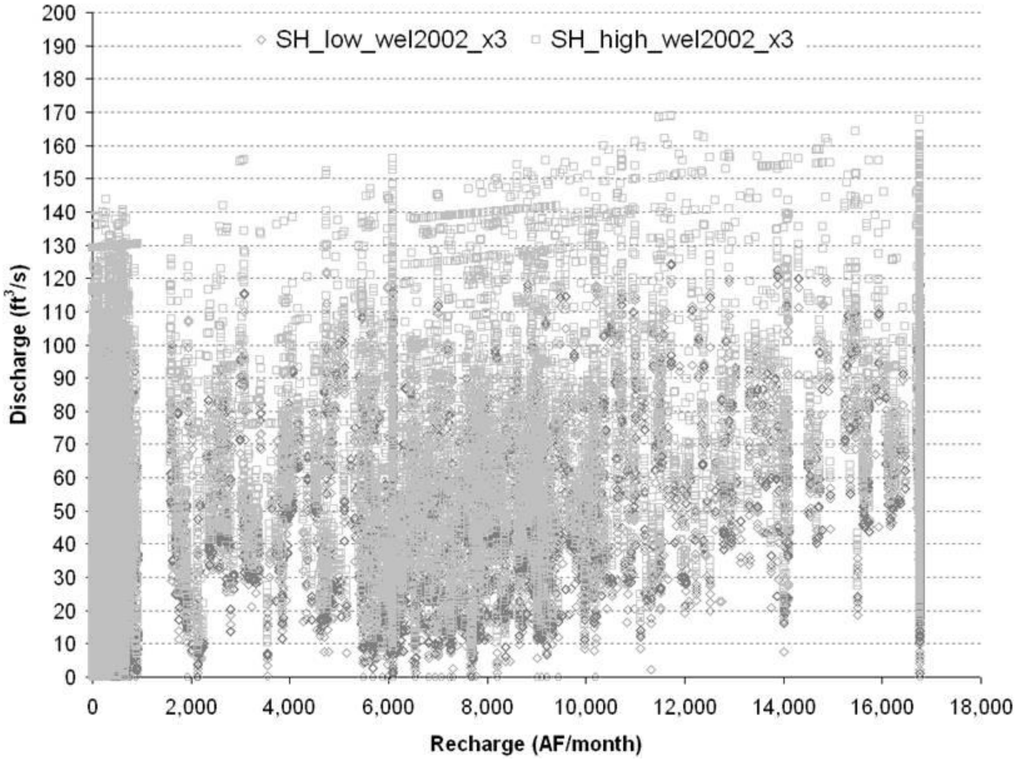


Figure 4 continued. Plots of recharge versus simulated discharges for starting heads at low- and high-flow conditions with the 2002 low pumpage quantities multiplied by a factor of 3 (16,311 acre-feet). Note that using these relatively higher pumpage quantities result in lower simulated discharges even when using starting heads at high-flow conditions.

REFERENCES:

Bredehoeft, J. and Durbin, T., 2009, Ground water development-the time to full capture problem: Ground Water, vol. 47, no. 4, p. 506-514.

Cleaveland, M.K., 2006, Extended chronology of drought in the San Antonio area, revised report: University of Arkansas, 29 p. http://www.gbra.org/Documents/Reports/TreeRingStudy.pdf

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model-user guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hutchison, W.R. and Hill, M.E., in preparation, Recalibration of the Edwards (Barton Springs segment) model: Texas Water Development Board.

Scanlon, B.R., Mace, R.E., Smith, B., Hovorka, S., Dutton, A.R., and Reedy, R., 2001, Groundwater availability of the Barton Springs segment of the Edwards aquifer, Texas: Numerical simulations through 2050: Bureau of Economic Geology, 36 p.

Wilson, J.D. and Naff, R.L., 2004, The U.S. Geological Survey modular ground-water model-GMG linear equation solver package documentation: U.S. Geological Survey Open-File Report 2004-1261, 47 p.